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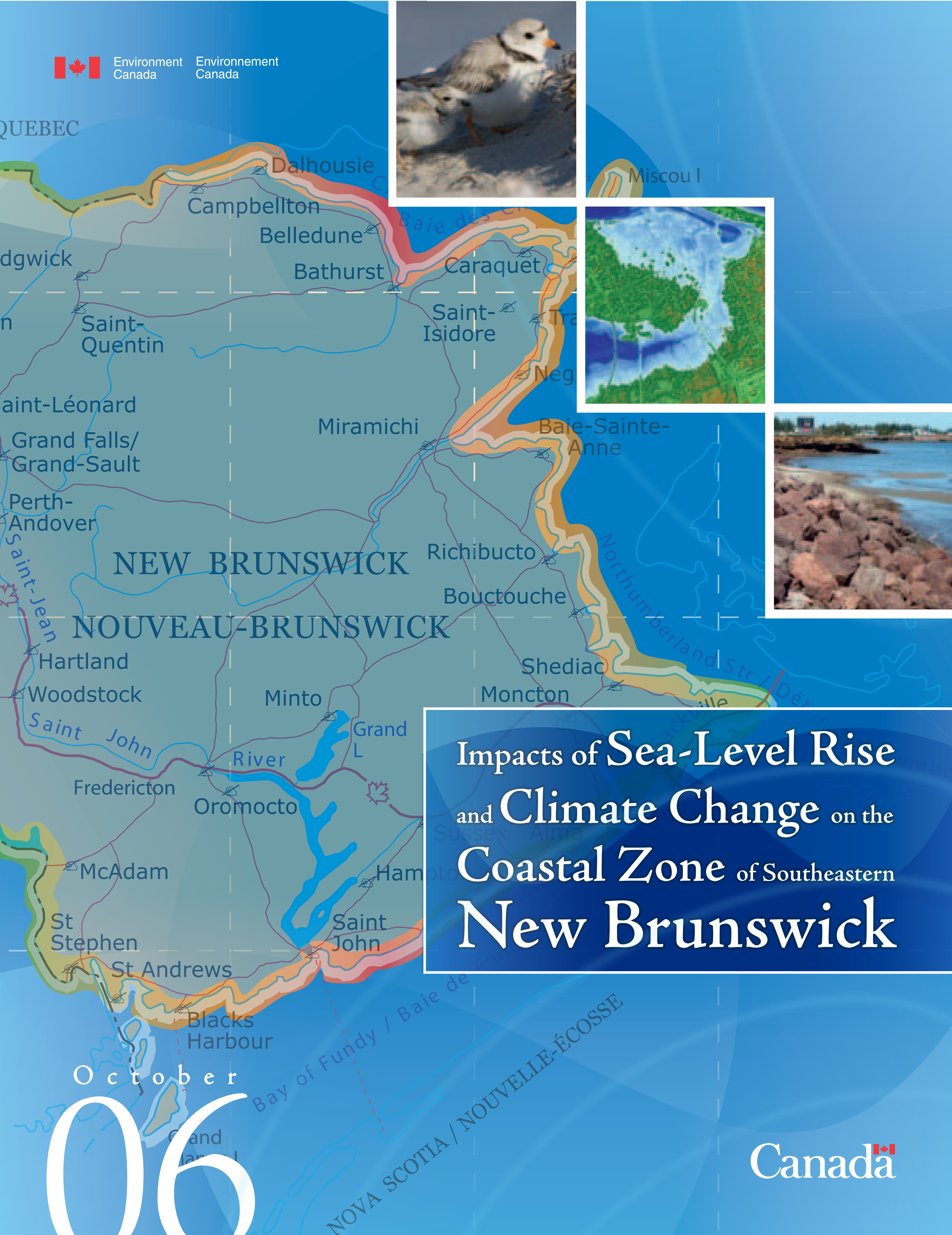

Impacts of Sea-Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick

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1. Abstract

The objective of this three-year (2003–2006) multidisciplinary research project was to quantify the impacts of climate change — specifically, sea-level rise, storm surge and coastal erosion — on the Gulf of St. Lawrence coastal zone of southeastern New Brunswick. The results of the study will support sustainable management, community resilience and the development of adaptation strategies.

Light detection and ranging (LiDAR) data have been used to generate a detailed digital elevation model (DEM) of the coast, critical for delineating flooding and inundation zones, natural protection structures such as coastal dunes, and backshore elevation for estimating sediment supply from shore erosion. Meteorological, geological and hydrographic studies include investigations into measured and forecast sea-level changes due to crustal subsidence and climate change. This project modelled the benchmark storm-surge events of January 21, 2000 (declared a disaster by the federal government), and October 29, 2000, and developed a “maximum potential” storm surge along this coast, given our understanding of historical events. These ranges of storm-surge events along with the proposed climate-change-induced sea-level-rise scenarios have been placed on the DEM to identify areas along the New Brunswick Gulf of St. Lawrence coast that will be vulnerable to flooding, coastal erosion and inundation over the next 100 years. These impacts are being defined in terms of likely risk, with scales of inland penetration of storm surges based on the scenarios presented and their effect on infrastructure, industry and coastal ecosystems.

The coastal zone of southeastern New Brunswick is home to several threatened species of plants and animals. An important aspect of the ecosystem research is to determine how sea-level rise and future storm events will impact critical habitat and species at risk.

2. Executive Summary

2.1 Introduction

Coastal ecosystems and communities around the world are widely recognized to be vulnerable to rising sea levels and other climate-change impacts, as documented in the various assessment reports of the Intergovernmental Panel on Climate Change (IPCC). In Canada, many parts of the coast have been shown to have significant sensitivity to sea-level rise and associated storm impacts. Areas with the highest sensitivity include parts of the Atlantic coast, particularly in the southern Gulf of St. Lawrence, including sections of the New Brunswick Gulf coast. In this region, sea level is already rising, with demonstrable impacts. Accelerated sea-level rise under greenhouse warming is expected to exacerbate these impacts, increasing the need for adaptation to minimize damage and costs. Threats in this area come primarily from impacts of coastal flooding and erosion, and damage can occur due to forced sea-ice movement caused by storm surge in winter, as was the case with the benchmark storm of January 21, 2000. This coast is also exposed and highly sensitive to wave action during storms in the ice-free season, as demonstrated by shoreline and infrastructure damage experienced in the storm of October 29, 2000. Similar, yet less intense, events occurred again in 2001 and 2002, and other events in 2004. The Boxing Day storm of 2004 caused some damage similar to that witnessed on January 21, 2000.

Light detection and ranging (LiDAR) data have been used to generate a detailed digital elevation model (DEM) of the coast, critical for delineating flooding and inundation zones, natural protection structures such as coastal dunes, and backshore elevation for estimating sediment supply from shore erosion. Meteorological, geological and hydrographic studies include investigations into measured and forecast sea-level changes due to crustal subsidence and climate change. This project modelled the benchmark storm-surge events of January 21, 2000 (declared a disaster by the federal government), and October 29, 2000, and developed a “maximum potential” storm surge along this coast, given our understanding of historical events. These ranges of storm-surge events along with the proposed climate-change-induced sea-level-rise scenarios have been placed on the DEM to identify areas along the New Brunswick Gulf of St. Lawrence coast that will be vulnerable to flooding, coastal erosion and inundation over the next 100 years. These impacts are being defined in terms of likely risk, with scales of inland penetration of storm surges based on the scenarios presented and their effect on infrastructure, industry and coastal ecosystems. The coastal zone of southeastern New Brunswick is home to several threatened species of plants and animals. An important aspect of the ecosystem research is to determine how sea-level rise and future storm events will impact critical habitat and species at risk.

The overall objective of this project was to quantify the impacts of climate change — specifically, sea-level rise, storm surge and coastal erosion — on the Gulf of St. Lawrence coastal zone of southeastern New Brunswick. The results of the study will support sustainable management, community resilience and the development of adaptation strategies.

2.2 Summary of findings

2.2.1 Sea-level rise and regional subsidence

Sea level has been rising along the southeastern coast of New Brunswick for several thousand years, gradually flooding Northumberland Strait and the seaward reaches of rivers draining the study area, pushing the shoreline landward and causing vertical growth and landward migration of salt marshes. These changes are continuing slowly and have become evident over a period of several decades. Climate warming, through ocean thermal expansion and melting of ice on the continents, is expected to raise the mean sea level on a global basis by a few decimetres over the coming century, accelerating historical rates of relative sea-level rise (the rise of water level relative to fixed points on land) in Atlantic Canada.

The observed relative sea-level rise results from a combination of regional subsidence and rising sea level in the Northwest Atlantic. The subsidence is a product of glacial loading and unloading more than 10 000 years ago, leading to gradual collapse and migration of a marginal forebulge (area of uplift) that developed around the margins of the North American ice sheets, and additional water loading of the seabed in the Gulf of St. Lawrence as global mean sea level rose more than 100 m from its lowest level during glacial times. Global sea level has continued to rise, accelerating in the second half of the 20th century to a current rate of about 17 cm/century. Because of a gradient in subsidence across the region, the observed relative sea-level rise is less in the northwest and greater in the southeast of the project area. The long tide-gauge record at Charlottetown, Prince Edward Island, dating back more than 95 years, shows a relative sea-level rise of 32 cm over the past century. At the other end of the study area, the relative sea-level rise at Escuminac is estimated to be about 23 cm over the same time interval. This regional tilting will continue in the future. Therefore, we conclude that future rates of relative sea-level rise will also show a gradient across the region.

Our analysis of isostatic subsidence and tilting presented above and of regional sea-level rise based on the Third Assessment Report of the IPCC, published in 2001, leads to the following estimates of relative sea-level rise for the coming century (2000–2100) across the study region:

• Cape Jourimain	59 ± 35 cm
• Shemogue	57 ± 35 cm
• Cap-Pelé	56 ± 35 cm
• Shediac	54 ± 35 cm
• Bouctouche	53 ± 35 cm
• Kouchibouguac	51 ± 35 cm
• Escuminac	50 ± 35 cm

These rates of sea-level rise need to be considered in the context of storm impacts and associated hazards. During large storms, storm surges cause coastal flooding, large waves cause erosion and infrastructure damage, and sea ice sometimes moves ashore, with damaging effects. Because storm-water levels and waves are superimposed on the mean sea level, rising mean sea level has an important effect on the levels of flooding and wave attack, with implications for ecological and socio-economic impacts and the adaptation measures that need to be taken to reduce losses. These issues are explored in later sections of the report.

2.2.2 Storm-surge, wind, wave and ice climatology

The entire digital inventory of water-level data in the southern Gulf of St. Lawrence was examined in this report to establish the storm-surge climatology of the project study area and to identify extreme storm surges and water-level events. Most storms affecting the southern section of the study area have impacts elsewhere in the Northumberland Strait. The long-term Charlottetown data are therefore crucial to this study, since they allow for an assessment of storm conditions through the decades and demonstrate both the fundamental importance of the storm of January 21, 2000, and the fact that sea-level rise has already played a role in extreme water levels through the period of the data.

The tide-gauge record at Charlottetown is one of the longest available in eastern Canada; it goes back to 1911 and is very complete back to 1938. The water-level record at Escuminac goes back to 1973 but, when combined with earlier records from nearby Pointe-Sapin, goes back to 1963 (43 years). Water-level data from Pointe-du-Chêne are more limited and span the period from 1971 to 1992. The Pointe-du-Chêne tide gauge was re-established for the purpose of this project, and new data from 2003 to 2006 were collected, capturing some very important storms.

Storm-surge events in excess of 60 cm were extracted from the Charlottetown water-level record, taking sea-level rise into account and interpolating where possible for missing events from data at adjacent tide-gauge sites. These events were then collated by decade (1940s to 1990s), by half-decade, by year and by month.

Water-level data from 1960 to 1998 were chosen to represent the storm-surge climatology for Charlottetown. Generally speaking, storm surges above 60 cm are frequent events in Charlottetown, occurring about eight times a year on average (compared with, for instance, about two or three times a year on average along the Atlantic coast in Halifax). Storm surges of 100 cm or more occur on average about once a year. Storm-surge events above 120 cm are uncommon and occur on average about three times a decade. No events were found in excess of 160 cm. Storm surges at Charlottetown are mainly associated with the stormy period of the late fall and winter. Averaged statistics show an increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there are few occurrences in the period from May to September. Storm surges show great variability in frequency from one year to the next, owing to the great range in frequency, severity and track of the storms themselves. Decadal statistics indicate that the storm surges at Charlottetown appear to have become somewhat more frequent from the 1940s to the 1960s and that the larger surges (>120 cm) did not occur at all in the 1940s and 1950s (nor in the somewhat incomplete data prior to that) but show up thereafter. The 1960s, 1970s and 1980s were strong storm-surge decades, with more than two 80-cm events on average each year, and the 1980s showed more than one 100-cm event on average each year. The 1990s generally saw fewer storm surges, although there were a few particularly big events. Many large storm-surge events have shown up since the year 2000. Half-decade statistics draw attention to the fact that some periods are more active than others, particularly the early 1960s and the late 1980s, which were periods of climatologically more frequent northeasterly gales. The period since 2000 has also been very active.

On January 21, 2000, a fierce winter storm caused extensive flooding of coastal areas in southeastern New Brunswick and all along Northumberland Strait, including Pointe-du-Chêne and the downtown waterfront areas of Summerside and Charlottetown in Prince Edward Island. In Charlottetown, this storm brought a new record water level of 4.22 m above Chart Datum (CD), which exceeded the previous record (set exactly 39 years earlier) by 39 cm. This storm (and the flood levels it reached through the region) is the definitive benchmark flooding event for this project. Other extreme storm-surge and water-level events have been identified at Charlottetown, and the water-level data have been systematically adjusted to the year 2000 to demonstrate the impacts that sea-level rise, through the period of the existing data, has already had on extremes of water level and on coastal flooding. When sea-level rise is taken into account, the difference between the new and old record water levels at Charlottetown is reduced to 27 cm.

A storm-surge climatology has also been developed for the Escuminac/Pointe-Sapin area just to the north of the present study area (using 28 years of data) and for Pointe-du-Chêne (using 15 years of data). Storm surges at Escuminac/Pointe-Sapin are similar in frequency, timing and size to those at Charlottetown for the period 1960–2004. On average, there are about seven events each year in excess of 60 cm, with close to one event each year above 100 cm. There is great variability in frequency from one year to the next, with no obvious trend. Nine storm surges above 120 cm have been identified at Escuminac/Pointe-Sapin for the period 1963–2005, compared with 13 events at Charlottetown for the period 1960–2005. The very large storm surges were a little more frequent at Escuminac, with three events in excess of 150 cm identified (not including the storm of January 21, 2000) as opposed to two at Charlottetown. The largest recorded storm surge was 160 cm in height on March 17, 1976. These storm surges are mainly associated with the stormy period of the late fall and winter. As at Charlottetown, there was an observed increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there were few occurrences in the period from May to September.

Storm surges at Pointe-du-Chêne are larger and more frequent than those at Escuminac or Charlottetown, although their distribution through the year is, of course, similar, since they are usually caused by the same storms. Ten events above 60 cm are observed per year on average, with two to three events above 100 cm/year on average. Storm surges above 150 cm occur once every two or three years, and storm surges as high as 200 cm have been recorded (198 cm on March 17, 1976, and 200 cm on January 21, 2000), representing the largest recorded storm surges in Atlantic Canada known to the authors of the present report.

With global warming, sea-level rise is forecast to accelerate. As storms come and go in the coastal zone, large storm surges will eventually phase with sufficiently large tides to produce new record water levels in the study area and at Charlottetown. Additionally, with time, flooding at any given lower level will increase dramatically in frequency, and this point is demonstrated quantitatively at Charlottetown and Pointe-du-Chêne through an exceedance count of the existing data (adjusted for sea-level rise) above various thresholds.

Synoptic weather maps were examined for storms that have given rise to storm surges of 90 cm or more at Charlottetown and 110 cm or more at Pointe-du-Chêne, and track maps were produced. These storms are mainly extratropical marine storms that deepen explosively off the east coast and pass to the east of the study area, usually accompanied by a period of northeasterly or northerly gale- or storm-force winds across the Gulf of St. Lawrence. The geometry of these storms is usually favourable for bringing large seas into the study area (in the absence of sea ice). The history of tropical cyclones in the study area has been examined using the U.S. National Hurricane Center's hurricane database (HURDAT) or "best tracks" (1851–2004). Although less common than extratropical storm events, tropical cyclones can be very powerful and occur during the tropical weather season (June to November) when there is no wave protection from sea ice. Historically, tropical storms have been an important contributor to the ongoing process of coastal erosion in the region.

The highest water levels at the tide-gauge sites of Charlottetown, Escuminac/Pointe-Sapin and Pointe-du-Chêne were used to identify the benchmark storms of the last 40 years, and these are presented as case studies with emphasis on storm impacts. The case studies illustrate, among other things, the important protective role that sea ice plays during the winter months and draw attention to the enhanced rates of coastal erosion that are probable with a shorter ice season in a future warmer climate. The case studies also illustrate the importance of the storm-surge forecasting program to emergency response and short-term mitigation and the value of LiDAR data in real-time flood mapping.

A brief literature survey of flooding events in the area serves to highlight other important storms that predate the tide-gauge data and reminds us that flooding and coastal erosion in the study area are ongoing processes and that damage to coastal infrastructure is nothing new.

It is clear that the flood levels observed during the storm of January 21, 2000, are close to the maximum levels that can be reached in today's climate. However, this storm occurred at a time when the shoreline was protected by sea ice. The storm of October 29, 2000, in comparison, was accompanied by very large waves on elevated water levels and was very damaging to shorelines and coastal infrastructure. It is the worst storm that we know of in the last 40 years in terms of wave damage and coastal erosion. Conditions would have been considerably worse if the storm had been in phase with the higher high tide of the day. Worse circumstances in terms of wave damage can therefore occur today and may indeed have occurred in the past, and we do not need the addition of sea-level rise due to climate change to achieve this.

Measured and hindcast records of wind speeds and directions and of wave heights and periods (with directions, as available) were investigated to identify the winds and wind events that are most important in forming waves affecting the shorelines of the southern Gulf of St. Lawrence, to identify any trends in past storminess and forcing of coastal erosion in the study area and to attempt to predict future forcing to 2100.

Winds that appear most effective at generating waves impacting the study area are from the northeast and are associated with the passage of tropical, transitioning or extratropical low-pressure systems typically tracking to the north and northeast. These tend to occur during the autumn and winter months, but they are effective at generating waves only during the ice-free months, when effective fetch is longest. We investigated the AES40 wind data set for a node at the entrance to western Northumberland Strait. Notable periods of high frequency of occurrence of northeasterly autumn winds greater than 40 km/h include 1960, 1962–1966, 1967–1968, 1970, 1974–1982, 1985, 1987–1989, 1991, 1993, 1998–2001 and 2004. We identified 58 wind events with winds over 40 km/h for at least six hours, occurring in the autumn and with mean northeasterly directions. The annual occurrence of these events shows an apparent increasing trend.

Wave buoys deployed as part of this study captured three important wave events affecting the study area: December 7, 2003; Sub-tropical Storm Nicole (October 11–12, 2004); and December 27, 2004. These northeasterly wind events brought waves up to 4.8 m significant height and 10.0-second peak period. The arrangement of the buoys allows demonstration that waves entering western Northumberland Strait decrease in height towards the south and east.

A wave hindcast record near the western entrance to the Strait indicates that periods of increased occurrence of waves greater than 3 m from the northeast in the autumn occurred in 1960–1966, 1968, 1970, 1974, 1977–1981, 1986–1988, 1991, 1998–2000 and 2003–2004. A list of 53 autumn events with waves greater than 3 m for at least six hours and mean northeasterly directions was developed and shows no meaningful trend in annual event frequency since 1960.

Daily mean AES40 wind speeds were used to statistically downscale general circulation model scenario variables and predict wind speeds to 2100. Wind directions were not successfully downscaled. The results suggest that no significant change in wind speeds is expected to occur; however, as the variance in wind speed was underpredicted, this is not indicative of extreme events. An overall decrease in event frequency is suggested, but this is expected to be accompanied by an increase in frequency of the most extreme events. Using the downscaled wind speeds and the correlation of wind speed to wave height in the hindcast data set, we determined that wave heights are also not expected to change significantly to 2100. Similarly to winds, however, wave height variance was not well predicted, and extreme wave events are not represented. Wave events will likely follow a scenario similar to that for winds, with an added complication.

Wave formation is currently dampened in the winter months by sea ice. We describe a scenario in which sea ice is expected to decrease in the southern Gulf of St. Lawrence. This will allow winter storms to generate waves, thus increasing the overall frequency of wave events and the frequency of severe events.

Based on the ice charts from the Canadian Ice Service, we developed an accurate climatology of sea ice in the Gulf of St. Lawrence. Examination of the total accumulated ice coverage in the Gulf shows high interannual variability as well as some cycles that can be associated with the North Atlantic Oscillation and other environmental parameters.

Our records also indicate a decreasing trend in ice cover and duration of the ice season, which, however, is not statistically significant. It is believed that the presence of ice has a dampening effect on storm surges and waves that cause flooding and erosion. Ice severity indices have been calculated and should be used in studies attempting to demonstrate this relationship quantitatively.

Even though this study did not attempt to determine the exact correlation of ice with storm surges and wave erosion, it is still a qualitative observation that the presence of ice has a dampening effect. We therefore surmise that in a future warmer climate with reduced ice concentration and thickness in the Gulf of St. Lawrence, storm surges and wave erosion may be more severe.

Other issues that were not addressed in this study include direct damage caused by ice being carried onshore by wind stress and ice pressure, as observed in the January 21, 2000, storm; and implications of the potential loss of the seasonal protective barrier of landfast ice in a future warmer climate.

2.2.3 Storm-surge and meteorological modelling

In this study, we developed an approach to evaluate flooding risk along the New Brunswick coast of the Gulf of St. Lawrence that is based on sea-level observations, extremal analysis and a storm-surge model developed by Dalhousie University. The approach included the installation of two new tide gauges to provide independent sea-level data to test the model, as well as the analysis of historical sea-level observations made over the last century. Considerable effort was expended to make the information useful to non-scientists. For example, an open-access web site was developed to provide daily flood forecasts to the general public. We also developed new ways of visualizing flooding risk that could be readily understood by concerned members of the community.

The two new tide gauges were installed at Pointe-du-Chêne and Wood Islands. These locations were chosen in order to obtain data in areas where too few observations were available to allow the skill of our storm-surge model to be accurately evaluated. Subsequent analysis suggests that the one-day forecasts of the storm-surge model at these gauges have an accuracy better than 10 cm.

A 40-year hindcast of storm surges was performed for the Northwest Atlantic to quantify the return period of extreme sea levels. We were encouraged to find that the standard deviation of the hindcast error (the difference between the observed tidal residuals and the surges reconstructed by the model) is typically 8 cm and compares well with the typical operational forecast error. The surge hindcasts also exhibited the same seasonal and interannual variations in standard deviation as the observed residuals. Having demonstrated the quality of the hindcast, we produced maps of the standard deviation of surges for the Northwest Atlantic by season. As expected, the surge variance was highest during the fall and winter. We also showed that the regions with the highest surge variance were in the southern Gulf of St. Lawrence and along the eastern shore of Newfoundland.

To estimate the frequency of extreme total sea levels (in contrast to extreme surges), we added the tide and other physical processes not resolved by the storm-surge model. An important point to note is that the approach in this study requires only a few years of hourly sea-level observations to estimate multidecadal return levels of total sea level. Overall, the predicted 40-year return levels of total sea level (tide plus surge) are within about 10 cm of the observed 40-year return levels. The method was also adapted to calculate the return period of extreme events over any season of interest.

Allowing for changes in the frequency and severity of storms (based on climate-change scenarios) is difficult, and ultimately such changes should be based on reliable climate-change scenarios from global climate models. Given that such downscaled forcing fields were not available, we carried out some sensitivity studies of the effect of changes in the surge distribution on the frequency of extreme total sea levels and compared the impacts with those of sea-level rise. The effect of significant changes in storminess, represented by large changes in the distribution of the surges, on the return period of extreme sea levels was found to be less than the effect of the large sea-level rise predicted for some areas of the study region (e.g., Scotian Shelf). This does not imply that changes in storm severity have little impact on the return period of extreme events. Rather, this sensitivity study suggests that in regions where sea-level rise over the next century is considerable (in the order of 1 m), it alone will result in a dramatic reduction in the return period of extreme events.

With the availability of a DEM, it was possible to downscale the results of an extremal analysis to produce maps of the return period of flood extent. The return-period maps presented in this study have the advantage of simplicity. They are easy to understand and allow rapid visual identification of areas most at risk of flooding. They can therefore be used by planners and policy-makers to identify zones where development should be limited, adaptation measures put in place or ecosystem management considered.

A set of return-period maps, covering regions close to Shediac Bay, is presented in Section 5 of the report (Annex A). The methodology used to calculate the maps is based on extreme return levels calculated from the Pointe-du-Chêne sea-level record. For the remaining regions, maps have been produced to depict flooding extents that resulted from the January 21, 2000, storm with present sea levels and with a 60-cm sea-level-rise scenario. These maps are also presented in Section 5 of the report (Annex B).

It should be noted that in Shediac Bay, the current 40-year storm-surge return level is expected to become closer to a 5-year return level with a 60-cm sea-level-rise scenario, expected by 2100.

2.2.4 LiDAR digital elevation models and flood-risk mapping

LiDAR mapping involves an aircraft emitting laser pulses towards the ground and measuring the travel time of the pulse to and from the point of reflection. The laser scan is acquired by rapid repetition of the laser-pulse transmitter and cross-track deflection of the beam using an oscillating mirror to produce a zigzag pattern of laser hits on exposed surfaces below the aircraft.

LiDAR surveys in southeastern New Brunswick were carried out in 2003 and 2004 in order to build a high-resolution DEM of flood-prone areas along the coast for most of the study area. Additional LiDAR products in the form of digital surface models (showing buildings and trees) and intensity backscatter maps were also constructed for the survey areas. These surveys met the accuracy specifications and provided the high-resolution point sampling along the coast required to construct the DEM as a basis for flood-risk and flood-depth mapping. The flood extents and flood depths associated with the January 2000 storm surge have been qualitatively validated by field visits to sites where the water levels are known. The extents of the flooding associated with the January 2000 storm generally agree, and the flood depths are typically within 10 cm of observed water depths. The elevation datum for the LiDAR DEM was taken to be Canadian Geodetic Vertical Datum 1928 (CGVD28) or orthometric zero. This is about 20 cm below mean water level as determined at the Pointe-du-Chêne tide gauge.

Using innovative methods to model hydraulic pathways to low-lying areas landward of causeways and other barriers, it was possible to determine potential flood extents at 10-cm intervals up to a water level of 4 m above mean sea level for the survey areas. This allowed near-continuous flooding simulations and animations to be constructed. The ability to generate a full sequence of water levels allows emergency measures and planning officials to access more information for use in designing disaster-mitigation and climate-change adaptation plans.

Repetitive LiDAR surveys at La Dune de Bouctouche demonstrated the utility of this technology to measure change in dune systems. A significant amount of change was mapped between the 2003 and 2004 DEMs. The modifications of the dune morphology are attributed to a significant storm event that occurred on February 19–20, 2004. The precision of the technology enables the detection of vertical changes on the order of decimetres in the elevation of coastal features, as demonstrated by erosion of the dune crests observed in this study.

In summary, the airborne LiDAR topographic mapping provided the high-resolution DEM required as an essential foundation for assessment of flooding and erosion hazards in all other components of the project.

2.2.5 Coastal erosion

Southeastern New Brunswick is an area of low relief developed on flat-lying, friable, sandstone bedrock. As described in Section 2.2.1, the area was flooded by the sea immediately after deglaciation, after which the land rose and relative sea level fell to expose large parts of the floor of Northumberland Strait. For the past 8500 years, the sea level has been rising against the land, gradually pushing back the shoreline in a process of long-term flooding and coastal erosion. There is thus nothing new in the trend of coastal retreat observed over recent decades, but the impact on human habitation and infrastructure is increasing as the rate of waterfront development accelerates.

The rate of coastal erosion is primarily a function of mean water level (driven by relative sea-level rise), storm and wave forcing, sediment supply, and the form and response of the shore zone (coastal morphodynamics). Where there is no excess sand supply, the rate of coastal retreat is likely to be correlated with the rate of relative sea-level rise, other factors being equal.

Although large quantities of sand are present along the New Brunswick coast, much of this is stored in coastal dunes (largest in the north) or in large tidal bedforms (largest in the southeast). The volumes of sand in the immediate shore zone are limited. Some sites, such as the mouths of Shemogue and Little Shemogue harbours, have extensive multiple bar and tidal bedform complexes of sand on the inner shoreface, but these are thin, and the beaches themselves are invariably thin. For this reason, despite the limited wave energy, rapid changes in the shoreline can occur when beaches and low barriers are overtopped and breached in storms. Evidence from old maps shows that some former barrier beaches or spits (such as in the Robichaud and Cocagne areas) have disappeared, leaving only hints of their former presence in shoals on the shoreface. A low sand ridge mapped in 8- to 10-m water depth off Pointe-Sapin is believed to be a similar relict barrier beach abandoned on the inner shelf.

The present study has shown that rapid changes have occurred in the form and extent of some spits in the Shemogue area during the past 60 years of the airphoto record (since 1944), while others in the same area (Grants Beach) have remained stable. The large spit and barrier island system in Kouchibouguac National Park has high dunes that prevent overtopping and act as a buffer against storm-wave attack. However, there are a number of low areas where inlets have opened or closed at various times over the past century, causing abrupt changes that affect coastal stability and habitat conditions, both on the barrier itself and in the adjacent lagoons, marshes and other coastal habitats. Despite the high dunes in this area, large sections of the Kouchibouguac barrier system are low enough to be overtopped in a major storm with high surge and waves. However, the sand volumes are high enough to limit the rate of coastal retreat. The large flying spit at Bouctouche (La Dune de Bouctouche) has moderately high dunes and multiple dune ridges, particularly in its distal part. Other parts of this system have narrow dunes or none at all. In these areas, particularly the proximal (updrift) part, overtopping, breaching and landward barrier migration have occurred in response to major storms or storm intervals since the earliest airphotos in the 1940s, and long before that.

Some sections of the coast consist of low sandstone or till cliffs, up to a few metres in height, typically showing long-term (multidecadal) erosion rates between 0.1 and 0.4 m/year. Although these rates are slow, some roads and buildings have been partially destroyed and abandoned (e.g., in the area of Cap Lumière). Erosion impacts on infrastructure and buildings, including homes, are locally important. Homes and other buildings have been damaged or destroyed by storm waves and storm-driven sea ice in several locations within the past decade. Large sections of the coast are now protected by seawalls, rubble mounds or other structures, and this hardening of the coast has accelerated over the past 20 years. However, the long-term efficacy of these adaptation measures is questionable, and many will require substantial investment in maintenance, reconstruction or replacement to maintain their protective function.

Rates of coastline change on beaches, spits and barriers range from negative to positive. Erosion rates greater than 0.5 m/year are common on many beaches, and some sites show even higher rates. The point of attachment of the Pointe-aux-Bouleaux spit retreated at an average rate of 2.4 m/year between 1944 and 2001. In other cases, local sand supply is sufficient to maintain the shoreline position or prograde seaward. Some spits have extended in length, showing typical patterns of deposition and growth in the distal (downdrift) area, while erosion, overtopping and rollover, or bypassing has occurred in the narrow proximal section (near the point of attachment to the coast). In very general terms, this is the pattern observed at La Dune de Bouctouche. Other systems, such as Grants Beach (east side of Little Shemogue Harbour), have maintained a dynamic equilibrium between intervals of dune cut and intervening deposition. Such systems may be continuing to accumulate sand from updrift sources in the bay mouth or on the inner shelf. In other cases, where sand volumes are low, spit truncation or breaching has occurred. At Cap Bimet, the end of the spit has completely disappeared. The spit on the east side of Shemogue Harbour (Shemogue Head spit) was breached prior to 1971 and eventually split into two by 2001, exposing the large salt marsh behind to wave erosion and washover. The vulnerability of this spit to overtopping and breaching was enhanced by its northwesterly exposure, low crest elevation, narrow width and limited sand volume. Major changes in the morphology and extent of the spit opposite (on the west side of the estuary) may also have been a factor. These observations underscore the importance of changes in coastal morphology (which may create changes in wave shoaling and energy at particular sites), of waves and storm surges associated with individual large storms or clusters of storms and of preconditioning by erosion of dunes or other changes in the shore zone. Combinations of these factors may trigger rapid change. If sand is available and supplied to the site, breaches can be repaired (infilling of the former dredged channel through La Dune de Bouctouche is an example), but morphological changes sometimes lead to positive feedback, increasing susceptibility to storm damage. The Petit-Cap spit in Shemogue Harbour has built an entirely new and realigned spit ridge seaward of the 1944 spit, fed by erosion of the updrift beaches at rates of between 0.2 and 0.8 m/year.

These results demonstrate the highly variable nature of coastal response to storm forcing as well as gradual changes associated with sea-level rise and climate change. It is unrealistic to attempt a common projection of future response over the entire study area. However, there are several common points of understanding that can be applied to the analysis of individual sites.

Most sites currently experiencing erosion can be expected to show continuing erosion in the future, and rates are likely to increase. Therefore, planning and development should not be based simply on historical rates of erosion, but should add an appropriate additional setback to account for more rapid erosion over the life of a structure or other development.

The rate of regional subsidence declines from the southeast to the northwest. As a result, the most rapid rates of relative sea-level change will be in the southeast. This is also the area where the barriers and dune volumes are smallest, making them more sensitive to rapid change. Systems in this area with higher dunes (such as Grants Beach) will be more stable, but accelerating sea-level rise, reduced sea ice or other climate-related changes may increase the sensitivity even at these sites. Some increase in the rate of cliff erosion can be expected, but the rates are likely to remain less than 0.5 m/year in most places, particularly where sandstone is exposed at the base of the cliff.

Farther north, from Bouctouche to Kouchibouguac, much larger dune volumes and higher crest elevations will partly offset the higher wave energy in this region. Nevertheless, some areas are extremely sensitive to erosion or overtopping, including the proximal part of La Dune de Bouctouche, where a sequence of storms beginning in 2000 removed the dune ridge and led to successive washover events, which deposited sand sheets across the barrier crest and the marsh behind. A large breach also developed halfway out the spit. Similar extensive breaching has occurred in the past, notably in the early 1940s, and storm clustering (successive large storms within a few years) is an important factor. However, accelerating rates of relative sea-level rise and possible increases in storm intensity may lead to more frequent and more severe impacts in the future. There is no immediate likelihood of spit detachment at Bouctouche, but the highest average rates of shoreline erosion along the spit since 1944 (almost 2 m/year in one section) are between 6.0 and 8.5 km down-spit, just before the downdrift transition to long-term progradation. We conclude that the possibility of detachment within 30–50 years cannot be ruled out.

Losses of coastal salt marsh have occurred in the region from excessive infilling for development. Coastal squeeze is already a concern at a number of sites in the study area, where roads and fill present hard boundaries to marsh expansion. Some salt marshes in the area may experience loss of area through erosion of the seaward margin, degradation of the marsh surface and gradual expansion of low marsh at the expense of high marsh. Impacts for many coastal habitats are discussed in greater detail in Section 2.2.6.

Management of coastal erosion in a changing climate will be most successful if it considers all aspects of the coastal system in the area of concern. This involves analysis of the relevant coastal cell and its sediment budget, as well as environmental forcing (sea level, storms, surges, waves, wind and ice) and interactions among various components of the coast, including the whole system above and below water. Such an integrated approach is needed to ensure a full understanding of the system, so that adaptation measures adopted in one location are not counterproductive in another. Sections 2.2.8 and 2.2.9 below suggest further considerations in the development of appropriate and effective adaptation strategies.

2.2.6 Ecosystem impacts

The research on the impacts of sea-level rise and climate change focused on coastal habitat and associated wildlife. The short duration of this work necessitated the use of existing data sources on wildlife resources and habitat requirements. It is hoped that this study will encourage future research on coastal wildlife populations and habitat to incorporate analyses of the impacts of sea-level rise and climate change.

An analysis of the DEM showed that a flood level of 2.55 m above DEM datum (approximate present mean water level), as occurred in the storm of January 21, 2000, results in the flooding of 1397 ha of upland, 1634 ha of coastal marsh, 388 ha of dune, 159 ha of swamp and 226 ha of beach. The average depth of flooding for the 2.55-m storm flood was determined to be 0.84 m for swamp, 1.13 m for dune, 1.58 m for beach and 1.64 m for coastal marsh. These analyses indicate that large areas of coastal habitat will be influenced by future increased water levels associated with storm surges superimposed on rising sea level.

Whereas there were limited data on vertical accretion rates for salt marshes and sediment dynamics of beaches and dunes along the Northumberland Strait, a retrospective airphoto-based analysis was conducted at five study sites. These analyses provided insight on how marshes, dune habitat and beaches have responded to past storms and changes in sea level, as a basis for considering how they may respond in future.

For Cape Jourimain, the area of vegetated salt marsh was 28% (88 ha) less in 2001 than in 1944. This change was primarily due to the construction of a road through the marsh in 1966, which changed the hydrology and also physically destroyed some marsh area. For Shemogue, there was 5% (15 ha) less vegetated salt marsh in 2001 compared with 1944, and open water increased by 18% (9 ha). These changes at Shemogue were consistent with the hypothesis that marsh vertical accretion and horizontal migration were not sufficient to compensate for rising sea levels. The amount of vegetated salt-marsh area decreased by 27% (23 ha) for the Aboiteau study site, with visible evidence that 24 ha of coastal wetland had been infilled between 1944 and 2001. For Shediac, 40 ha of human infrastructure were built in coastal wetland and 9100 m of seawall were constructed during the period between 1944 and 2001, with a 21% (19 ha) decrease in vegetated salt marsh. There was a 35% (19 ha) decrease in vegetated salt marsh and infilling of 19 ha of coastal wetland in the Cocagne area between 1944 and 2001.

At all study sites, the amount of beach and dune habitat was lower in 2001 than in 1944, with a greater decline in beach habitat compared with dune habitat. For Cape Jourimain, there was 22% less beach and dune habitat in 2001 compared with 1944; for Shemogue, there was 8% less; at Aboiteau, there was an overall decline of 12%; for the Shediac study area, there was a decline of 32% in the area of beach and dune habitat between 1944 and 1971, with little additional loss occurring between 1971 and 2001; and in Cocagne, beach area decreased by 40%. Removing sand from beaches for the production of aggregate during the period between 1944 and 1971 probably had an impact on beach area in the region, as did the expansion of hard shore protection. The loss of beach habitat during the last 60 years makes any additional loss of beach habitat in the future due to sea-level rise more critical from both a wildlife habitat and a recreational perspective. An increasing demand for beach recreational areas coupled with decreasing availability due to sea-level rise and climate change would increase human development and disturbance pressures on those beaches that currently provide wildlife habitat.

For the Aboiteau, Shediac and Cocagne study sites, there was a substantial increase in the amount of hardened shoreline present in 2001 compared with the earlier periods. The amount of hardened shoreline in 2001 was 8324 m in Aboiteau, 9408 m in Shediac and 13 287 m in Cocagne. Hardening of the shoreline has an impact on the amount of beach available for recreational and wildlife habitat purposes and also reduces sediment supply, which could lead to more beach loss in the future.

Overall, the results of these retrospective airphoto analyses indicate that our ability to understand and manage the impacts of climate change on coastal ecosystems will be confounded by human activities in the coastal zone and that rising sea levels have the potential to further reduce salt-marsh, beach and dune habitat in areas that have already lost a substantial amount due to human activities.

The relationship between vascular plant species' zonation and surface elevation in salt marshes along the coastline of the Northumberland Strait was determined and compared with results from the Bay of Fundy. Results indicate that elevation can be used to predict the impacts of sea-level rise on coastal wetland plant communities.

The potential impacts of sea-level rise and storm surge on colonial-nesting gulls and terns were evaluated by determining which colonies would flood under the different scenarios of sea-level rise and storm-surge flooding. Of the known nesting sites in the study area, only Cocagne Bar would be flooded at mean water level by a sea-level rise of 60 cm, but many, if not all, are vulnerable to destruction by flooding or wave runup in a large storm, even without further sea-level rise. Most (11/14) nesting locations would be impacted by a storm surge combined with tide to reach a water level of 2.55 m above DEM datum. The largest Common Tern colony in the study area (Tern Island in Kouchibouguac National Park) contained over 6020 nests in 2005 and would be flooded at a water level of 2.55 m above DEM datum. A summer storm event comparable to the January 21, 2000, storm would therefore have a devastating impact on the breeding success of the Common Tern population in New Brunswick along the Gulf of St. Lawrence. However, accelerated sea-level rise leads to an increased probability of maximum storm-water levels reaching this level.

We also examined the potential impacts of sea-level rise and storm surges on nesting Red-breasted Mergansers on four barrier islands in Kouchibouguac National Park. The elevation of most nests was higher than 0.60 m but well below the maximum observed storm flood level of 2.55 m above DEM datum. Impacts on nesting Red-breasted Mergansers are not hypothetical, as a storm in 1993 resulted in many nests being flooded and an annual reproductive success of only 22%. Sea-level rise and increased frequency and intensity of summer storm surges would have a negative impact on Red-breasted Merganser nesting success.

The endangered Atlantic Canadian breeding population of Piping Plover was estimated at only 255 breeding pairs in 2003. Breeding habitat availability and suitability for Piping Plovers were studied in an effort to predict the impacts of projected sea-level rise on habitat. Analyses indicated that beaches currently occupied by Piping Plovers are longer, have a greater mean width and have a greater area of sand than beaches that do not have nesting Piping Plovers. In addition, occupied beaches have a greater number of dune breaches, have access to back bays, outflows or ephemeral pools, and have less human development than non-occupied beaches. Coastline changes over time were mapped and measurements were taken for two beaches in the Shemogue area. There were no obvious trends detected in habitat change; rather, these analyses indicated temporal variability presumably related to storm events. It is known that Piping Plovers prefer to use the early-succession habitat created by dune breaches and that the conversion of spits to barrier islands through storms also improves habitat suitability. The hypothesis that sea-level rise and climate change will result in a decrease in preferred breeding habitat for Piping Plovers needs to be further tested and quantified. The observation that Piping Plovers predominantly use protected beaches indicates the importance of managing human impacts now and in the future as society responds to rising sea levels. To successfully manage Piping Plover habitat, it is important to increase our understanding of which beaches will be negatively impacted by sea-level rise.

The number of adult Piping Plovers attempting to breed and reproductive success at Kouchibouguac National Park during the period 1985–2005 were highly influenced by summer storm-surge events. In 1985, there were no young raised to fledging, and many nests were flooded. Water-level data from the Escuminac tide gauge showed a storm event and water levels above 2.0 m CD on June 8, 1985. There was also lower than average reproductive success in 1991 associated with a major storm event on June 14, 1991, when a water level of 2.12 m CD was recorded at Escuminac. Breeding success was once again low in 1993, and field observations indicated nest-flooding events, with a recorded water level of 2.07 m CD at Escuminac. An examination of historical water levels at Point Escuminac indicated that nine 60-cm or greater storm-surge events during the Piping Plover nesting season occurred during the period 1964–2004. There was one event during the period 1964–1969, one during the 1970s, three during the 1980s and four events during the 1990s. There have been no events yet during the 2000s. Assuming co-occurrence with high tides, some or many of these storm events would have had an impact on reproductive success and perhaps on population dynamics during the past 20 years. Currently, there is no statistical evidence that the frequency of June storms is increasing in the southern Gulf of St. Lawrence, but increased frequency of summer surges would have a negative impact on Piping Plover populations. This may require actions to protect nests and eggs from flooding.

An analysis of Piping Plover population dynamics was conducted in order to understand how changes in climate and habitat may affect Piping Plover populations. These analyses suggested that during the period 1998–2003, there was population stability in southern Nova Scotia (+0.4% per year) and a decline in the Gulf of St. Lawrence (−3.5% per year). The negative growth projected for the Gulf was largely driven by low estimated juvenile post-fledging survival. Threats to juveniles following departure from nesting beaches need to be quantified. Similarly, population growth in both subpopulations was particularly sensitive to changes in adult survival. Very little is understood about the threats to Piping Plover survival during migration and overwintering periods. It would therefore appear that efforts to protect Piping Plovers from predators and human disturbance on breeding beaches have been successful and that annual climate-induced variability in reproductive success or habitat conditions is not controlling population growth at present. We suggest that future recovery efforts for Piping Plovers should quantify and manage the largely unknown sources of both adult and juvenile mortality during non-breeding seasons while maintaining current levels of nesting-habitat protection.

Overall, our analyses indicate that coastal ecosystems have a natural capacity to respond to climate and water-level variability. Human alteration and disturbance have historically had a larger impact on coastal wildlife habitat and wildlife populations than sea-level rise and climate change. Any future impacts of sea-level rise and climate change could be exacerbated by development pressures or infrastructure protection projects. Continued monitoring of climatology, water levels, wildlife populations and habitat is required in order to develop adaptation strategies that will protect both human infrastructure and wildlife habitat from increased water levels and storm-surge events.

2.2.7 Socio-economic impacts

Sea-level rise, coastal erosion and increased intensity and frequency of storm-surge events have significant socio-economic impacts on coastal communities, ecosystems and various economic sectors. This analysis has evaluated some of the costs and benefits associated with adapting to these impacts through both a community-engagement and a case-study approach.

Important elements of this project are the engagement of the community and building upon local knowledge and understanding of coastal-change processes and adaptation. The following are among the key findings from the community-engagement process:

- Initial interviews in the communities showed that attitudes towards the impacts of extreme events were primarily reactive; however, it is very much in the interests of the communities to adopt a more proactive approach.

- The community-engagement process enabled this research to respond more effectively to the needs of the communities and propose relevant recommendations for adaptation. It also provided an opportunity to increase the communities' awareness of climate change.

- For this study to help in building local capacity for adaptation to climate change, the communities in the study area will have to take ownership and interpret the results in their local context, involving all appropriate stakeholders and decision-makers.

Case studies were chosen to represent the types of impacts and issues expected under climate change and to enable a detailed analysis. The information and data used to estimate the economic impacts are limited to the geographical area of each case study. While the methodology and approaches used in this analysis are transferable, the results will not be directly applicable to other geographical locations.

The effects of climate change are an increasing concern for tourism operators in southeastern New Brunswick, because ecotourism and cultural tourism sectors have developed rapidly in the last decade, and tourism operations are feeling the effects of erosion and storm surges from extreme storms. The Bouctouche area was selected as a case study to evaluate the economic impacts associated with climate change on the tourism industry. This case study estimated the economic benefits to the tourism sector of implementing adaptation measures. Conversely, this analysis estimated the economic losses as a result of the tourism sector failing to mitigate or protect itself from the impacts of sea-level rise, coastal erosion and storm-surge events. Some key findings from the Bouctouche case study follow:

- Many visitors to Bouctouche recognize that climate change is impacting coastal communities across eastern North America. Through thoughtful adaptation and mitigation strategies, the tourism sector of Bouctouche may see economic growth. In contrast, failure to adapt to climate change may result in losses to the tourism sector. Appropriate adaptation measures will be a key element in determining if the tourism industry in the Bouctouche area grows or declines over time as a result of the consequences of climate change.

- Under an optimistic scenario, whereby the tourism sector manages climate-change impacts through adaptation strategies, there is a potential for economic gains, compared with the estimated baselines, in Kent County and New Brunswick. Employment in Kent County could increase by 8–18%, and gross domestic product (GDP) in Kent County could increase by 11–19%. Provincial and federal tax revenues could potentially increase by 11–18%.

- Under the pessimistic scenario, whereby the tourism sector does not adapt to climate-change impacts, there is a potential for economic losses, compared with the estimated baselines, in Kent County and New Brunswick. Employment in Kent County could decrease by 25–30%, and GDP in Kent County could potentially decrease by 25–27%. Provincial and federal tax revenues could potentially increase by 24–28%.

Property and infrastructure within coastal communities of southeastern New Brunswick are also threatened by sea-level rise and storm-surge events. After the January 21, 2000, storm-surge event, declared a disaster by the federal government, there were 198 damage claims submitted to the New Brunswick Emergency Measures Organization, 43 of which were eligible for funding totalling close to $1.5M (K. Wilmot, New Brunswick Emergency Measures Organization, pers. comm.). In order to understand the magnitude of these impacts on coastal communities, the Shediac Bay case study has identified those properties that are at risk of flooding and has quantified the potential damage costs associated with storm-surge events. In addition, the analysis has estimated some of the types of costs associated with retreat, protection and accommodation adaptation options. Key findings from this case study include the following:

- Future scenarios were developed by community stakeholders based on storylines that described changes to key drivers. Under an optimistic economic development scenario, the community identified 10 new residential zones (estimated value $114.1M), expansion of three commercial zones, expansion of two marinas and nine new green zones. Under a pessimistic economic development scenario, the community identified five new residential zones (estimated value $26.7M), closure of some commercial enterprises, new public services and one new green zone. This study estimated damage costs to residential properties. All new residential zones identified under both the optimistic and pessimistic scenarios are estimated to be either at no risk of flooding or at minimal risk of flooding (less than 0.5 m flood depth); therefore, damage costs to new residential zones identified under both scenarios are assumed to be zero.

- Non-residential property and infrastructure in the Shediac Bay case-study area are at risk of flooding during storm-surge events. A storm-surge event with a water level 2.5 m above DEM datum (approaching the January 21, 2000, storm-water level) places approximately 1639 existing properties in the Shediac Bay case-study area at risk of flooding to some depth. The total assessed value of these properties is estimated at $117.9M. In the event of a storm surge with a water level 3.0 m above DEM datum, approximately 2003 existing properties in the case-study area are at risk of flooding to some depth. The total assessed value of these properties is estimated to be $139.3M.

- In the event of a storm surge with a 2.5-m water level above DEM datum in the Shediac Bay case-study area, it is estimated that 277 residential properties (including cottages) would incur damage. The total assessed value of these properties is $21.7M, and the estimated structural damage costs are close to $7.1M, approximately 33% of the total assessed values. If the storm flood level reached 3.0 m above DEM datum, it is estimated that 644 residential properties would incur damage. The total assessed value of these properties is estimated to be close to $48.9M, and the estimated structural damage costs are close to $17.6M, approximately 36% of the total assessed values.

- Minimizing the impacts of sea-level rise and flooding from storm-surge events can be achieved through implementing adaptation strategies. When evaluating various adaptation strategies, the full costs and benefits of each strategy should be incorporated into the decision-making process. Although this analysis has not assessed the total costs and benefits associated with specific adaptation options, it has estimated some of the possible costs associated with generic adaptation options. If retreat is an option under consideration, the estimated minimum compensation required for 94 property owners with properties in Flood Classes 4, 5 and 6[1] is close to $3.4M, and the total forgone property tax revenue (provincial and municipal) is estimated to be $100K annually. A few protection and accommodation options have also been estimated based on dialogue with various communities and stakeholders. The estimated capital cost to build a seawall, based on various discussions with community members, is $1,000 per square metre of base surface[2].

The results from this analysis should not be interpreted literally, as they are estimates based on the best available information. They can be used as indicators and estimates of magnitude to educate and raise awareness. They can also be applied to local decision-making processes concerning governance, coastal zone management and adaptation.

2.2.8 Adaptation strategies

Finding the crucial balance between stakeholders' unique environmental, social, political and economic interests is dependent upon participation of a wide range of stakeholders, including residents, community leaders and government representatives, among others. Each brings unique expertise, insights, priorities and power to the community adaptation process. Effective adaptation strategies — ones that are implemented and have goals that respect local values — come from the ground up (i.e., from the community affected), rather than from the top down.

National and provincial strategies can be effective only if they address local issues and conditions; provide opportunities for local input and respect local values; and provide resources and expertise to the communities expected to implement the strategies. Even

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[1] Flood Classes 4, 5 and 6 imply flooding depths of, respectively, >1.5–2.0 m, >2.0–2.5 m and >2.5 m.

[2] Based on personal communication with New Brunswick sea-level-rise study team and members of the case-study community

the best-intentioned provincial or national initiatives, if not effectively implemented at the local level, can lead to lack of trust and can even undermine the goals of the strategies.

Critical elements in developing community-level responses to sea-level rise and storm-surge threats are awareness of the issues, building of trust and communication, sharing of information and expertise, and having a champion (an individual or group) to lead the process. Successful community adaptation relies on continually fortifying the local conceptual lens by increasing the community's adaptive capacity and implementing best practices.

There needs to be a balance in adaptation strategy design between addressing isolated issues and developing a comprehensive plan that addresses every dimension of the problem. The latter may require more research and organization than communities can absorb and still make meaningful changes. The former fails to address the needs of all stakeholders and can lead to strategies that further deteriorate other situations. Each community is unique and must determine its own balance.

Adaptation strategies need to include a wide spectrum of approaches, from policy and law to engineering and technology. Environmentally sensitive approaches can also be effective in minimizing change and cost. Raising public awareness and changing cultural values and perspectives can also be cost- and results-effective.

Past examples of adaptation in the study area include abandonment of erosion- and flood-prone lands and retreat from the coast. In many cases, older homes and infrastructure (except for port- and fishing-related infrastructure) were located well back from the coast and on higher ground. Low-value cottages were located along the shore but did not represent a large capital investment. More recently, the pattern of development in the region has been partly driven by market demand for homes with a view of the sea. Improved road infrastructure has favoured greater commuting distances, enabling those working in the growing Moncton economy to live along the coast. The result has been highly maladaptive, with expensive homes constructed along the coast in places where ice incursion, flooding and storm waves, and coastal erosion are all threats to the long-term stability and safety of the structure. Similarly, the demand for coastal land has encouraged infilling and reclamation of coastal wetlands, reducing available habitat.

Appropriate adaptation strategies may take many forms and may include components at different scales. The provincial Coastal Zone Protection Policy provides an umbrella for coastal management and adaptation measures at a local level. Communication and coordination of efforts between various levels of government, community leadership, local organizations and citizens are essential ingredients for success. Hard and soft engineering, land-use regulation, innovative development policies and designs, land trading and institutional arrangements to promote exchange of ideas are among the many options that communities may consider to reduce future impacts and costs.

Communities need and want information and access to expertise. A simple web page giving "where to go if…" instructions can centralize desired data, foster communication and satisfy a large number of needs.

Local researchers at community colleges and universities can provide an effective link between communities beginning to organize and government agencies shaping regional and provincial policies and plans.

To be most effective, strategies for adapting to climate change need to be "owned" and driven by the local communities that are directly affected. Efforts to mobilize action at the local level require the support of planning agencies and governments at all levels.

2.2.9 Building adaptive capacity

The coastal area selected for this study offered various examples, from ecotourism to suburban development, of community activities that will be affected by climate change. The integration of the human dimension from the social and economic risk perspectives into environmental assessment might help planners and decision-makers in those communities to deal with future projects. Few projects have integrated these aspects within a high-precision geographic information system in the past. However, as shown here, such an approach can lead to greater understanding of the linkages between various components of the ecosystem and the human communities. The main advantage of such an approach is to bring recommendations regarding ways to enhance the adaptive capacity of communities and to reduce vulnerabilities to climate change through suggested tools such as environmental impact assessments and strategies such as protection, accommodation or retreat.

One of the main reasons often cited for the limited inclusion of climate-change impacts and adaptations into a community planning and decision-making process is the lack of methodologies and clear directions on how to integrate such parameters into the planning process. Most communities do not completely understand the issues regarding climate change and the potential impacts they may face. Among the possible tools that can help communities, the environmental impact assessment process should ensure that climate-change considerations are included prior to any new development projects being started. Similarly, discussion should occur regarding the need to enhance the flexibility and the adaptive management of the New Brunswick Coastal Zone Protection Policy in order to adaptively respond to climate-change impacts.

Adaptive capacity is linked to the potential actions that communities can initiate to help promote sustainable development. Some components of the ecosystem can be controlled and managed; for other components, control of the impacts is not possible, and communities must adapt to change. In addition, climate-change impacts are complex in the way in which they can influence, either directly or indirectly, some components of the ecosystem. In this project, the level of vulnerability varied greatly as a function of the location, exposure, adaptive capacity and resilience of the infrastructure. For La Dune de Bouctouche and the Village of Bouctouche, tourism along the coast is certainly more at risk than many other socio-economic activities of the region, such as agriculture. On the other hand, the results from Pointe-du-Chêne showed that human infrastructure (e.g., housing and wharves) is more vulnerable due to the greater pressure that human development projects have exerted over the past decade. The need for better planning in this case is greater, since more socio-economic activities may be threatened by climate-change impacts in the near future.

One conclusion that can be drawn from this research project is that without relevant information, adaptation policies and planning may not be fully effective. This applies to information on changes in climate forcing and physical forcing as well as biophysical impacts in the coastal zone. Adequate information is equally critical to ensure that social considerations can be integrated into the adaptation planning process, and also into more general planning and policy-making that incorporate awareness of potential climate-change impacts. Climate change is rarely the primary issue in any community-planning context, but incorporation of climate-change impacts and proactive adaptation measures in all environmental assessment, planning and development activities is one way to avoid expensive mistakes and in many cases will result in the most cost-effective adaptation.

Although the information is still not complete, the visualization of scenarios using maps to portray different outcomes helps community participants to evaluate their own personal risks in terms of a possible future reality. The descriptive models can gradually be quantified using the level of risk, exposure, adaptive capacity and vulnerability of the components applicable to the communities. This will help define the real degree of adaptive capacity and vulnerability of the communities and their natural ecosystems.

3. Introduction

A Canada-wide overview of coastal sensitivity to sea-level rise, published by the Geological Survey of Canada in 1998 (GSC Bulletin 505), shows regions of low, moderate and high sensitivity along the Pacific, Arctic and Atlantic coasts. On a national basis, among the most severely threatened coastal areas are parts of the Atlantic coast, including sections of the New Brunswick coast along the Gulf of St. Lawrence. In this region, sea level is already rising, with demonstrable impacts, and accelerated sea-level rise under greenhouse warming is expected to exacerbate these impacts, with concomitant changes in adaptation requirements. Threats in this area come primarily from impacts of coastal flooding and erosion and damage due to the impacts of ice caused by storm surge in winter. Parts of this study area are highly exposed to wave action during storms in the ice-free season, as demonstrated by shoreline and infrastructure damage experienced on October 29, 2000. Similar, yet less intense, events occurred again in 2002, with higher frequency, and a few other events occurred in 2004. Of significant interest, the Boxing Day storm of 2004 caused some damage similar to that witnessed on January 21, 2000.

Despite the lack of recent tidal records in this area, the team has done much work to fill the gap. During the storms of January 21, 2000 (declared a disaster by the federal government), and October 29, 2000, the team and others went to the affected areas and gathered invaluable data on flooding, water levels, ice damage, infrastructure damage and coastal erosion.

The study area is on the Northumberland Strait coast of New Brunswick and stretches from Kouchibouguac National Park to Cape Jourimain, which comprises the area of highest scientific interest and significant priority for governments and coastal stakeholders. The evolving coastline of Kouchibouguac National Park is an important area from the standpoint of understanding potential changes to infrastructure and ecosystems in a nationally designated park. The New Brunswick Gulf coast south of Cap Lumière faces increasing pressures of coastal development and is important for ecosystem sustainability. The Bouctouche area has the Irving Eco-Centre’s La Dune de Bouctouche (damaged during the October 29, 2000, storm); it has the tourist and historic site Le pays de la Sagouine (which was flooded on January 21 and October 29, 2000); this community has been at the forefront of planning initiatives for regional sustainable development and has seen rapid growth in ecotourism services over the past few years.

The shores in Cocagne Bay and Shediac Bay are becoming increasingly built up and are vulnerable to coastal impacts because of low coastal slope and erodible substrate. Longer-term economic effects need to be considered in planning and regulations. Shediac Bay is a complex coastal and watershed area and is highly vulnerable to coastal flooding. Nearby Parlee Beach is a valuable provincial asset and tourist resort. Shemogue Harbour and Little Shemogue Bay offer areas of little coastal development, with undeveloped salt marshes where ecosystem baseline studies can be conducted. This work should have direct implications for the socio-economic impacts of climate change in New Brunswick coastal areas and communities and should lead to the development of potential adaptation strategies. The results will be relevant to the coastal communities, several economic sectors, individual landowners, fisheries interests, harbour authorities, ecologists and managers and planners at all levels of government and in the private sector.

The impacts of rising sea level and other aspects of climate change in coastal regions can include:

- higher and more frequent flooding of wetlands and adjacent shores;
- expanded flooding during severe storms and high tides;
- increased nearshore wave energy;
- upward and landward migration of beach profiles;
- accelerated coastal retreat, including dune and cliff erosion, breaching of coastal barriers and destabilization of coastal inlets;
- saline intrusion into coastal freshwater aquifers;
- damage to coastal infrastructure;
- impacts on coastal ecosystems; and
- broad impacts on the coastal economy.

The overall project objective was to quantify the impacts of climate change — specifically, sea-level rise, storm surge and coastal erosion — on the Gulf of St. Lawrence coastal zone of southeastern New Brunswick. The results of the study will support sustainable management, community resilience and the development of adaptation strategies.

4. Project components

4.1 Sea-level rise and regional subsidence

Donald L. Forbes[2]*, George S. Parkes,[1] and Lorne A. Ketch[1]

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4.1.1 Introduction and long-term context

4.1.1.1 Background and objectives

This section of the report presents an analysis of observed water levels and other evidence for relative sea-level rise in the southern Gulf of St. Lawrence, with a particular focus on the southeastern coast of New Brunswick (Figure 1). It has evolved from an earlier report prepared as part of a similar study on the coast of Prince Edward Island (Parkes et al., 2002), and some material from the earlier report is incorporated here as required to support the analysis in New Brunswick.

Sea level has been rising relative to the land in the Maritime provinces for many thousands of years (Grant, 1970; Shaw et al., 2002; Gehrels et al., 2004). This results from a combination of global mean sea-level rise (Church et al., 2004) and long-term postglacial isostatic adjustment of the earth's crust combined with the effects of ocean loading on the shelf, reflected as subsidence throughout the southern Maritimes (Walcott, 1972; Peltier, 1996, 2004; Dyke and Peltier, 2000; Douglas and Peltier, 2002). The water-level changes that we observe are slow but become significant over a few decades. Storm effects are superimposed on the mean sea level, which therefore exerts the major long-term control on the level of flooding and wave attack (Zhang et al., 1997; Forbes et al., 2004). Climate warming, through ocean thermal expansion and melting of ice on the continents, threatens to raise the mean sea level on a global scale by several decimetres over the coming century (Church et al., 2001; IPCC WG1, 2001), accelerating historical rates of relative sea-level rise in Atlantic Canada.

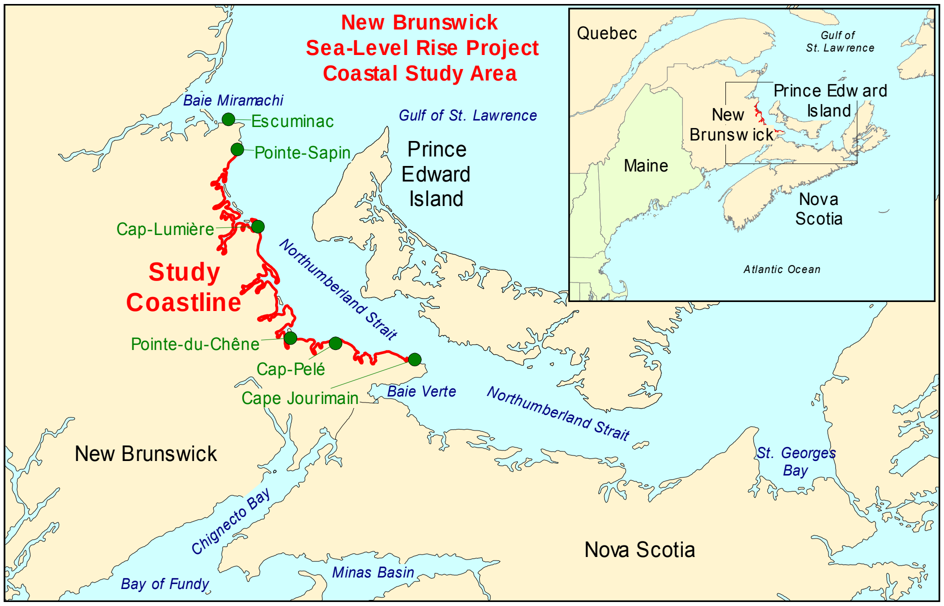

Figure 1. Southern Gulf of St. Lawrence region, showing the study area in southeastern New Brunswick (highlighted in red).

In this section of the report, we summarize the geological evidence for long-term relative sea-level rise and then examine the instrumental record of water-level data in southeastern New Brunswick (Figure 1) to establish the recent local trends. Finally, we review the latest published projections to establish plausible future rates of eustatic sea-level rise due to global warming, and we evaluate the other factors affecting future relative sea levels on a regional basis. The result is a set of relative sea-level projections for the coming century (2000–2100) at various locations along the southeastern coast of New Brunswick.

4.1.1.2 Long-term rates of relative sea-level rise in the region

Following the Last Glacial Maximum, parts of Prince Edward Island and western New Brunswick were covered by the remains of regional ice caps until at least 13 000 radiocarbon years before present (13 ka) or later. However, rapid iceberg calving had removed ice from much of the central Gulf of St. Lawrence by 14 ka (Josenhans and Lehman, 1999). Marine shells dated between 10.5 and 12.6 ka indicate that the western end of Prince Edward Island and the eastern New Brunswick lowlands were ice-free and submerged at that time (Kranck, 1972; Prest, 1973; Rampton et al., 1984; Shaw et al., 2002).

Shaw et al. (2002) have compiled isobases (lines of equal elevation) at 1-ka intervals from published geological data on sea-level change in the Atlantic provinces. Using these data and a digital elevation and bathymetric model for the region, they present maps of the paleogeography at 13, 12, 11, 10, 9, 8 and 6 ka. These show initial withdrawal of the sea from lowland New Brunswick until much of the floor of Northumberland Strait was dry between 9.0 and 7.5 ka (approximately 8500 to 10 500 calendar years before present [cal yr BP]). Following the lowstand, relative sea level rose rapidly, at rates as high as 120 cm/century (12 mm/year) or more, from 8600 to 7800 cal yr BP, then decelerated progressively to 6000 cal yr BP (Shaw et al., 2002; Forbes et al., 2004). The 6-ka isobases show greater subsidence to the east in Prince Edward Island and in the upper Bay of Fundy, with lesser rates from the Shediac area north along the coast to the Miramichi (Shaw et al., 2002). In the study area, relative sea level has risen from 10 to 20 m over the past 6000 years. Extrapolating from data outside the study area, Gehrels et al. (2004) published maps showing rates of relative sea-level rise over the past 1000, 2000 and 3000 years. These suggest a spatial gradient consistent with other data, the mean rate over the past 1000 years decreasing from 1.2 m (12 cm/century) near Charlottetown to 0.8 m (8 cm/century) at Miramichi.

Parkes et al. (2002) and Forbes et al. (2004) show that over the past 2000 years, the rate of relative sea-level rise in the Charlottetown area was reduced to about 20 cm/century. Over the past 100 years, the rate has accelerated to 32 cm/century at Charlottetown (see analysis of tide-gauge records below). This may reflect the beginnings of a climate-warming effect or may be related to short-term fluctuations in regional sea level, such as those reported by Shaw and Ceman (1999). Evidence from elsewhere supports an interpretation of accelerated sea-level rise in the region over the past 100–150 years (Gehrels et al., 2002; Church and White, 2006).

4.1.2 Recent sea-level trends determined from water-level data

4.1.2.1 Data sources and preprocessing

4.1.2.1.1 Tide-gauge data

Figure 2 shows tide-gauge locations in the southern Gulf of St. Lawrence. These tide gauges are owned and maintained by the Canadian Hydrographic Service (CHS). The exceptions to this are the Belledune and present Pointe-du-Chêne tide gauges, which are owned by the Belledune Port Authority and Dalhousie University, respectively, but maintained by CHS. During the 1990s, several tide gauges that were previously part of the Permanent Water Level Network were decommissioned (Pointe-du-Chêne and Dalhousie in 1992; Rustico and Pictou in 1996). The Pointe-du-Chêne tide gauge was re-established in 2003 by partners in this project. Water-level data from these tide gauges are archived and maintained by the Marine Environmental Data Service (MEDS) in Ottawa.

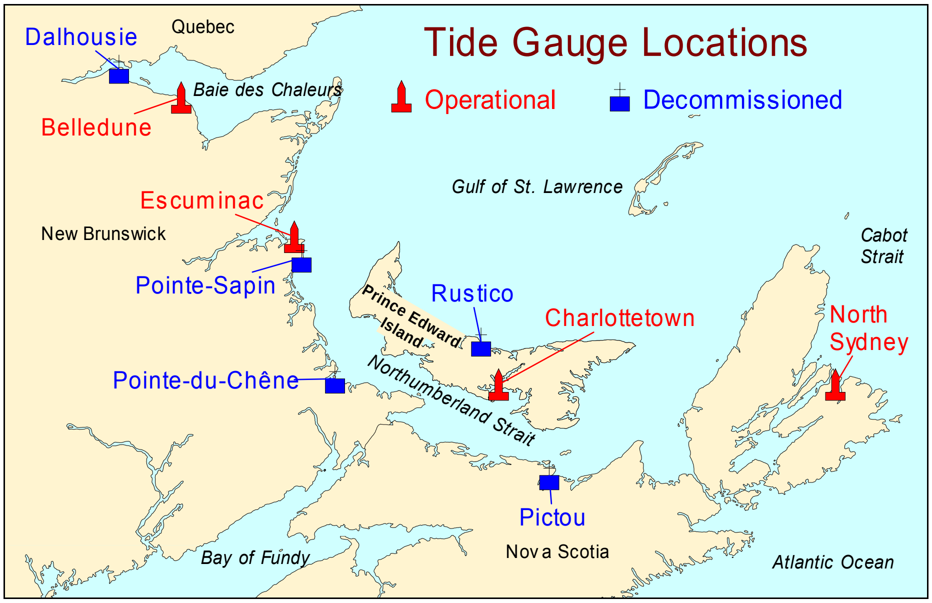

Figure 2. Tide-gauge locations around the southwestern Gulf of St. Lawrence. Stations marked in red are operational. Stations marked in blue have been decommissioned.

To examine water levels and storm-surge events, we obtained from MEDS the entire inventory of water-level data for the southern Gulf of St. Lawrence. This included the following data files:

- Hourly observations, 1911–2005, at Charlottetown, Prince Edward Island
- Hourly observations, 1973–2005, at Escuminac, New Brunswick
- Hourly observations, 1971–1992 and 2003–2005, at Pointe-du-Chêne, New Brunswick
- Hourly observations, 1972–1996, at Rustico, Prince Edward Island
- Hourly observations, 1965–1996, at Pictou, Nova Scotia
- Hourly observations, 1963–1975, at Pointe-Sapin, New Brunswick
- Hourly observations, 1999–2005, at Belledune, New Brunswick

4.1.2.1.2 Predicted astronomical tides

Predicted astronomical tides for Charlottetown, Escuminac, Pointe-du-Chêne, Pictou and Rustico were provided by CHS for the years 1900–2000 inclusive. Additionally, tidal predictions were obtained from CHS for Pointe-Sapin and Belledune for the respective records of water-level data. CHS has the responsibility for generating Canada's official tidal predictions, as found in the *Canadian Tide and Current Tables* (CHS, 2001).

4.1.2.1.3 Preprocessing the MEDS data

Tide-gauge data from Escuminac, Pointe-du-Chêne, Rustico and Pictou have been through the MEDS quality-control process, as have the data from Charlottetown from November 1961 onwards. Charlottetown data from 1911 to November 1961 are not quality-checked and were found to be quite incomplete prior to 1938. Although the Charlottetown data from November 1961 to December 1998 represented quality-controlled data, some problems remained. Problems existed in the original data, and other problems were perhaps introduced by the MEDS data-extraction software. Preprocessing of the water-level data was required to tightly structure the data files; then software was written to bring the MEDS data sets and the CHS-predicted tides together to calculate residuals and to isolate and examine storm-surge events, case by case.

4.1.2.1.4 Errors in the data sets

The water-level data sets and the predicted astronomical tides and their residuals were all examined visually to identify obvious data errors. Additionally, the data and the residuals at adjacent tide-gauge sites were visually examined simultaneously to further identify and cross-reference any such problems. Several types of problems were found, as enumerated by Parkes et al. (2002). Briefly, these included:

1. missing data;
2. occasional (positive and negative) spikes in the data;
3. phasing problems between the predictions and the observations, representing timing errors in the data and generating periodic residuals of varying size;
4. drifts in the calibration of the tide gauge, causing periods of elevated or depressed means and residuals;
5. data archived with the wrong date–time stamp;
6. interpolated data;
7. a short period at Pointe-du-Chêne (October 1980) when the data appeared to be inverted;
8. short periods in the 1920s at Charlottetown when missing data were coded as zero (i.e., Chart Datum) rather than using the 9999 missing data code; and
9. a short period in Charlottetown (October 1954) when one particular tidal excursion was repeated several times and the remainder of the month was displaced to the wrong date–time.

4.1.2.2 An examination of mean water levels

Prior to calculating means at the various tide-gauge sites, obvious spikes and other data errors were removed from the data. No attempt was made to remove timing errors from the data sets, since these would have no detrimental impact on the calculated means. Some further discussion and examples of data errors are presented in Section 4.2 on storm-surge climatology.

4.1.2.2.1 Annual and monthly mean water levels at Charlottetown

Annual mean water levels were calculated for Charlottetown, Prince Edward Island. Results are plotted in Figure 3. The water levels are in centimetres above Chart Datum. The average of the annual means is 162.63 cm. A linear regression is shown through the data.

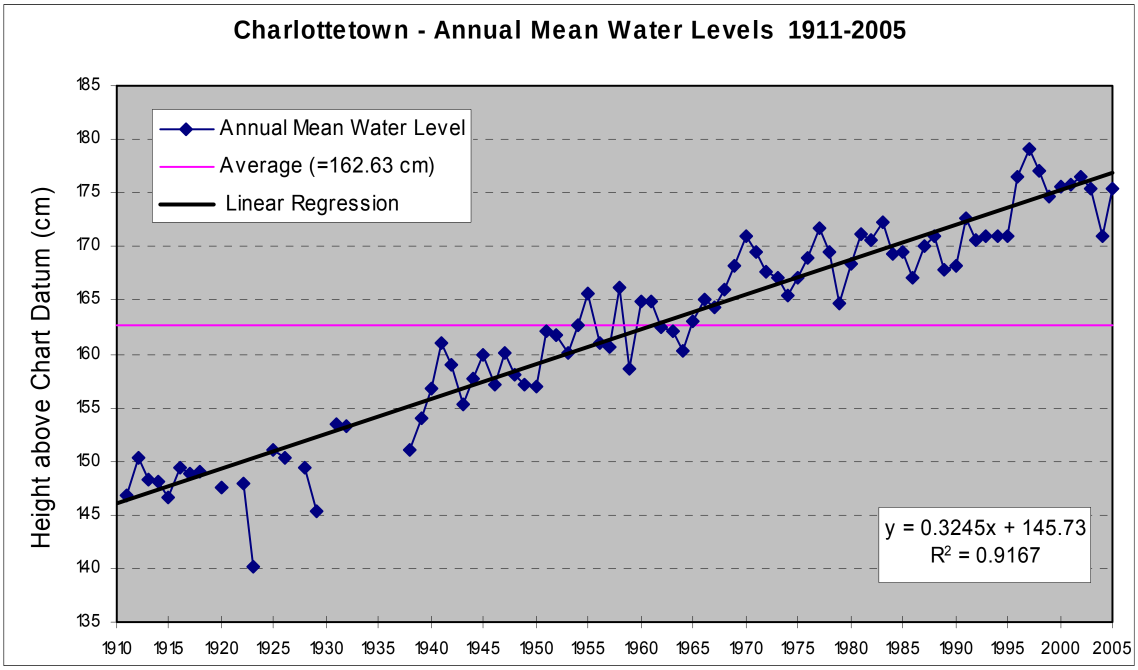

Figure 3. Annual mean water levels (in cm above Chart Datum) for Charlottetown water-level data, 1911–2005.

Monthly mean water levels were also calculated for Charlottetown. Results are shown in Figure 4. The average of the monthly means is 163.64 cm. The units of the x-axis are months, so the slope of the linear trends must be scaled by 1200 to obtain trends in cm/century. These data indicate a rate of sea-level rise of 31.4 cm/century. The same data are shown in Figure 5 together with one-year (in fact, 13-month) and three-year (in fact, 37-month) running means.

Seasonal variability is clearly evident in the plot of monthly means, with a gradual rise in mean sea level as seen previously in the plot of annual means. Figure 5 shows that recent rates of sea-level rise have fluctuated somewhat, as has previously been observed by Shaw et al. (1992), Forbes et al. (1997) and Manson (1999) at Halifax.

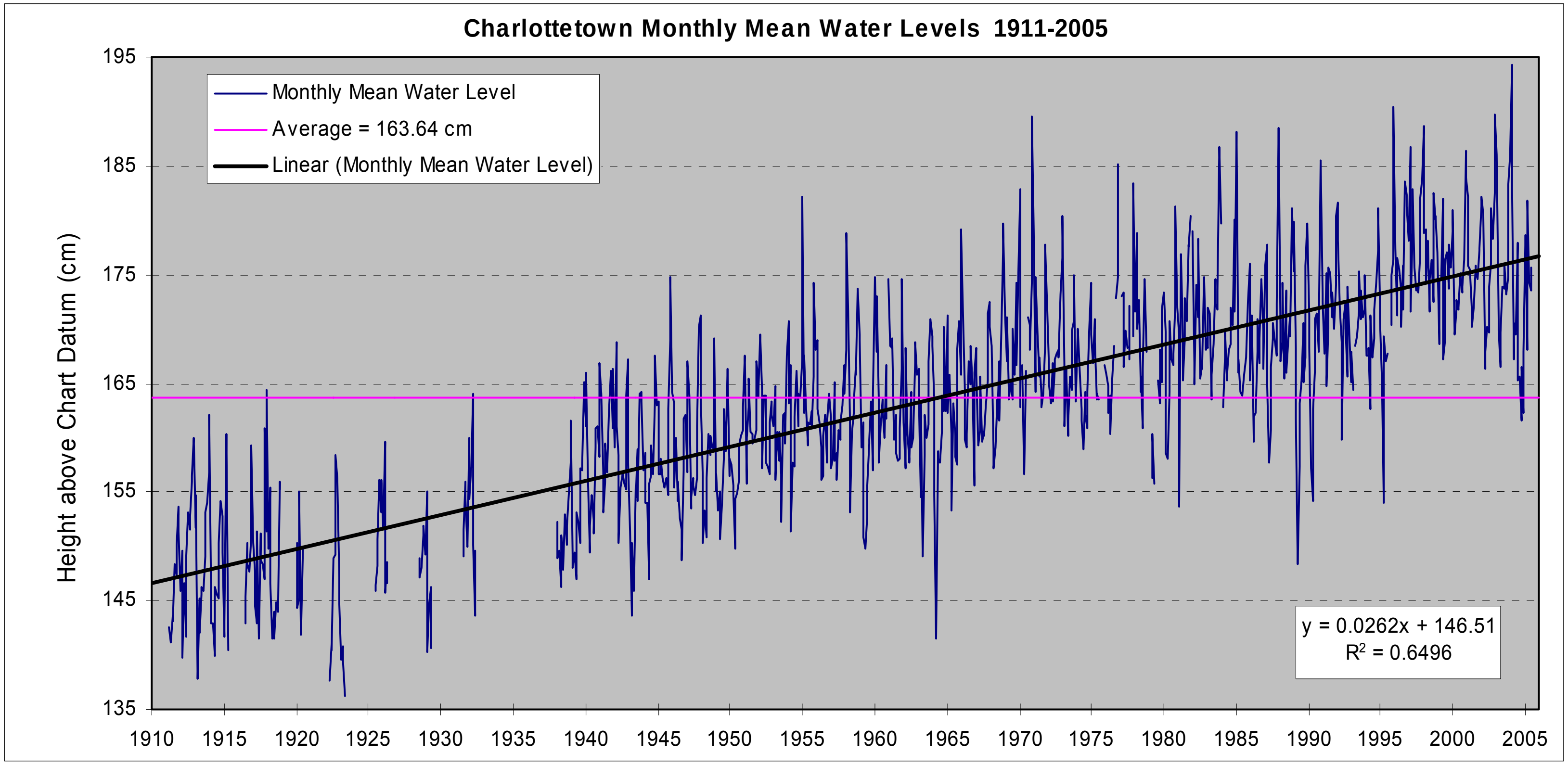

Figure 4. Monthly mean water levels (in cm above Chart Datum) for Charlottetown water-level data, 1911–2005.

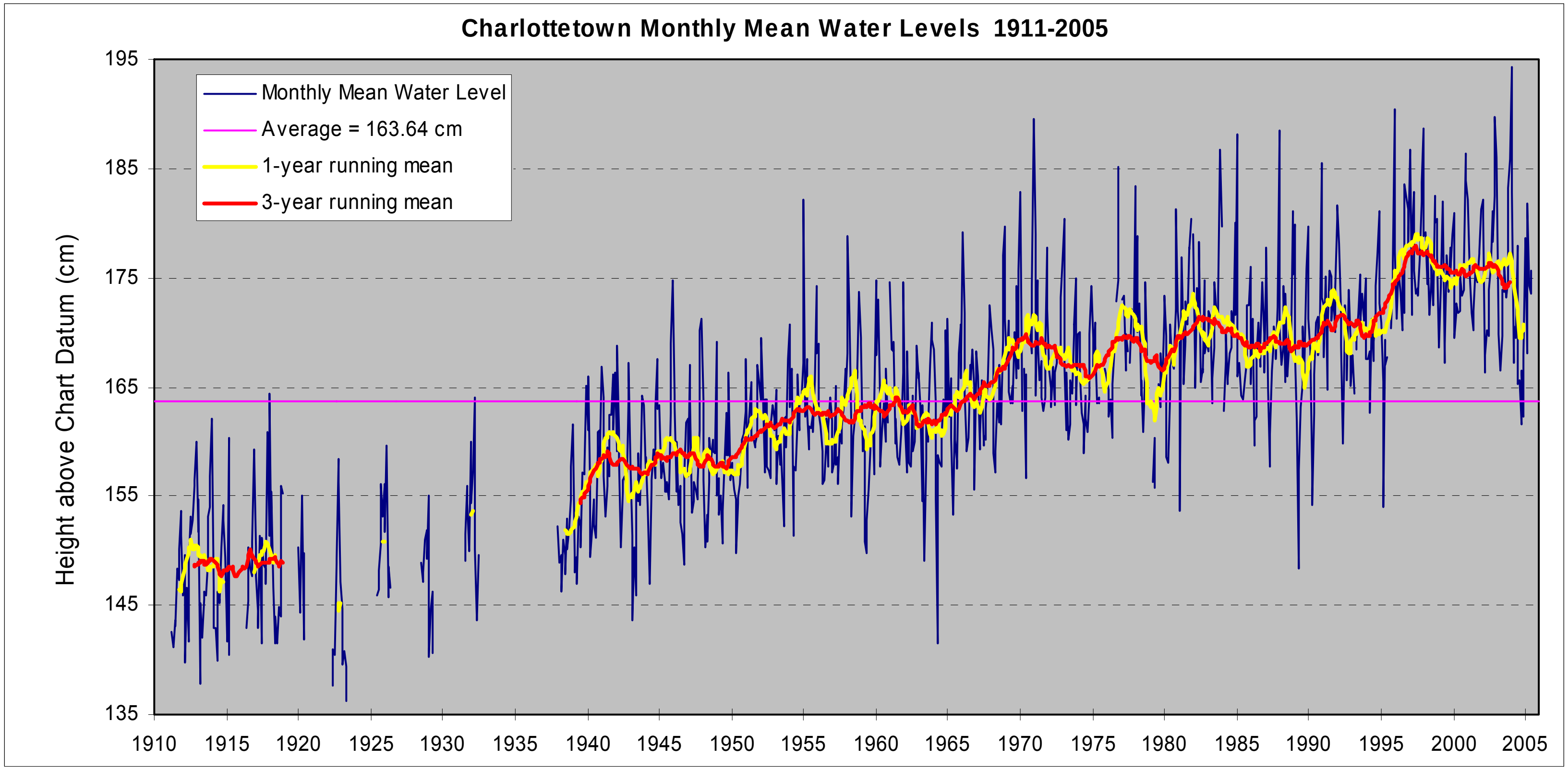

Figure 5. Monthly mean water levels (in cm above Chart Datum) for Charlottetown water-level data, 1911–2005, with one- and three-year running means.

To examine the seasonal variability, all years of Charlottetown data that were practically complete (<10% missing data) were identified, and the means for those years were plotted on a month-by-month basis. Sixty-three years qualified for this analysis, and results are shown in the three-dimensional plot in Figure 6.

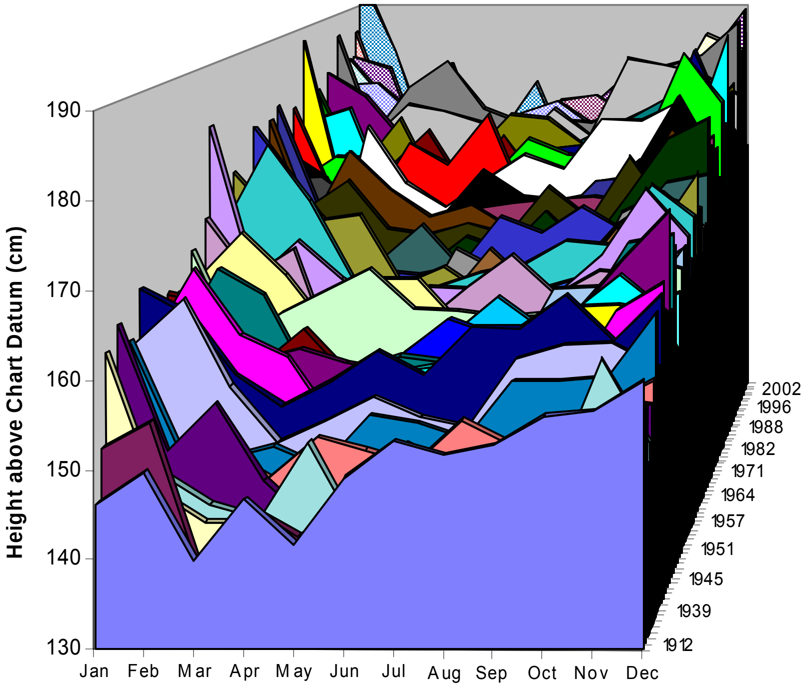

Figure 6. Monthly mean water levels at Charlottetown (in cm above Chart Datum), 1910–2004, for years with <10% missing data.

Generally, there is a tendency for elevated monthly means in the fall and winter and depressed monthly means in the warm-weather months. This is further examined by plotting the difference between the monthly mean and annual mean for each year (with <10% missing data) and averaging the values. The results of this are shown in Figure 7 for Charlottetown and, for the sake of comparison, in Figure 8 for Pictou, the nearest tide-gauge site to Charlottetown. Twenty years of data are shown in the Pictou analysis.

The above monthly mean sea-level anomaly values calculated for Charlottetown were used to correct annual means for missing data (Figure 9). These adjustments ranged from +0.93 cm in 1978 (when 27.9% of the data were missing, mainly in November, December and January) to −0.72 cm in 1928 (when the first six months of the year were missing, representing 49.7% of the data), with an average absolute value of 0.13 cm. The two outliers 1923 and 1929 (two of only five years with more than 50% missing data) are eliminated from the data set in Figure 10. These adjustments have only a small impact on the regression values. Figures 9 and 10 represent our final graphs for relative sea-level rise over the history of the available tide-gauge data at Charlottetown, indicating a trend of approximately 32 cm/century. This value is in good agreement with values published by other investigators: Grant (1970), 26 cm/century (1938–1968 data); Lane & Associates (1986), 29 cm/century (1965–1984 data); Shaw and Forbes (1990), 30.7 cm/century (1938–1988 data) and 31.2 cm/century (1907–1988 data); Carrera et al. (1991a,b), 32 cm/century at Charlottetown (1911–1989 data) or 36 cm/century using their method of propagating differences (in this case, from Halifax).

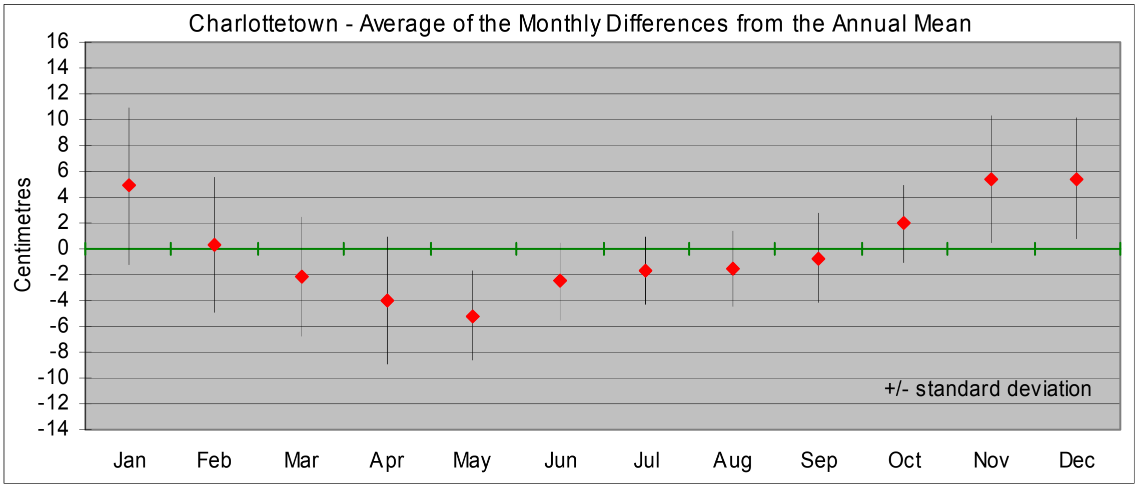

Figure 7. Averages of the monthly differences from the annual mean for Charlottetown water-level data.

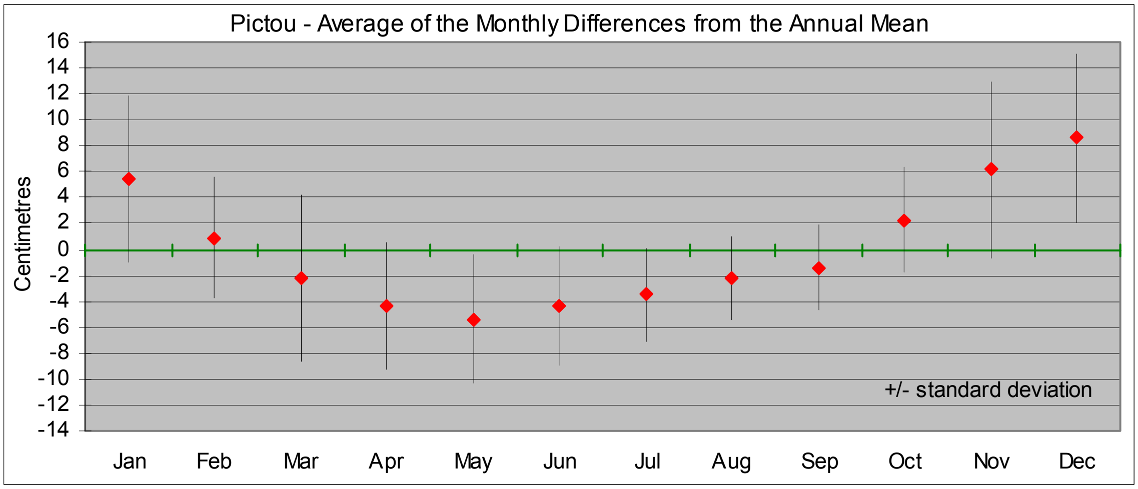

Figure 8. Averages of the monthly differences from the annual mean for Pictou water-level data.

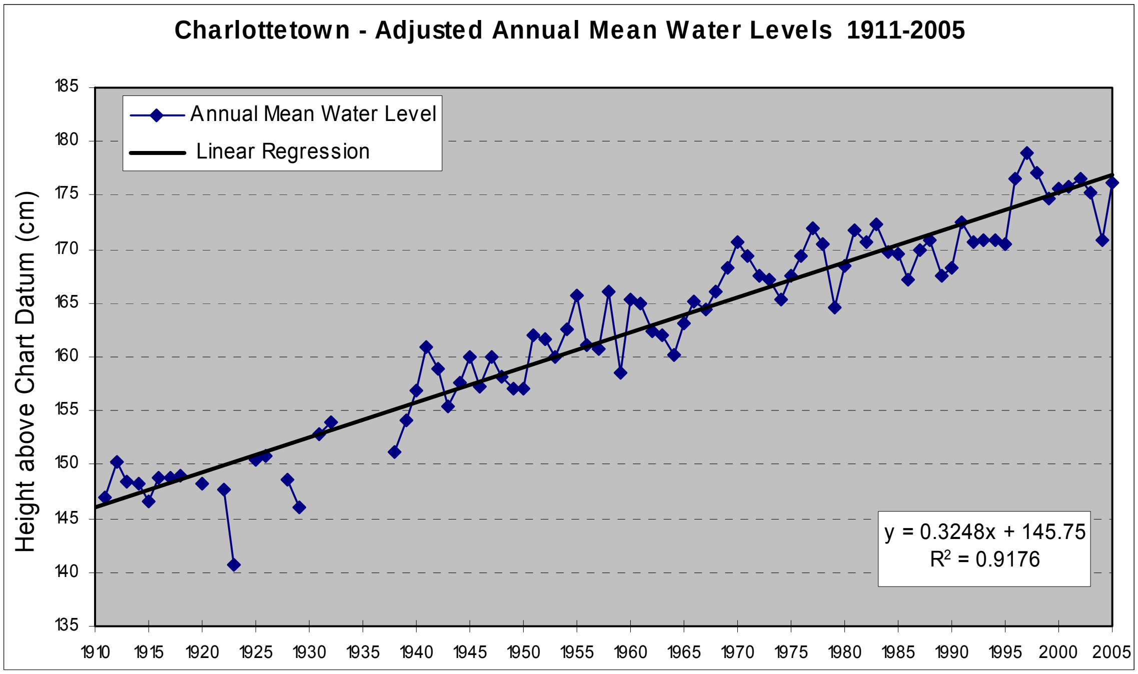

Figure 9. Charlottetown water-level data, annual means, 1911–2005 (adjusted for missing data).

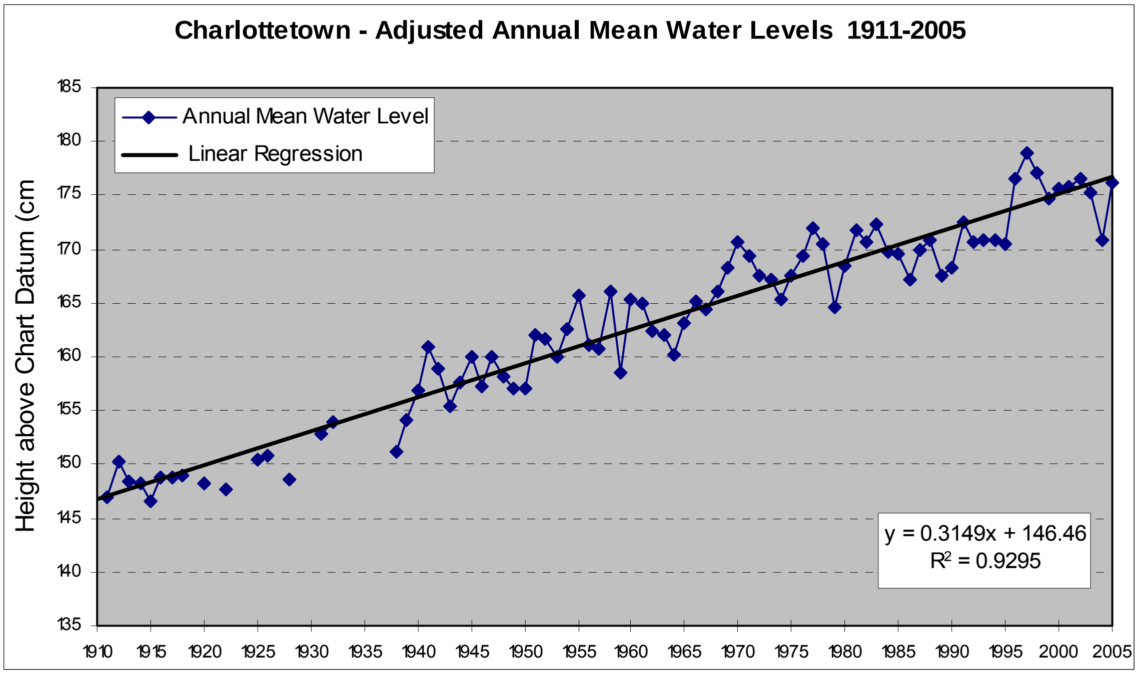

Figure 10. Charlottetown water-level data, annual means, 1911–2005 (adjusted for missing data and with outliers 1923 and 1929 removed).

4.1.2.2.2 Annual and monthly mean water levels at Escuminac and Pointe-du-Chêne

Escuminac data are available for the years 1973–2005. Pointe-du-Chêne data are available for the years 1971–1992 and 2003–2005. The percentages of missing data each year and each month at Escuminac and Pointe-du-Chêne are shown in Attachment D (Section 4.2.15). Annual mean water levels were calculated for Escuminac and Pointe-du-Chêne and are shown in Figures 11, 12 and 13. Years 1971, 1992 and 2003 were eliminated from the plots for Pointe-du-Chêne, since 88.5%, 80.9% and 70.4% of the annual data were missing. The water levels are in centimetres above Chart Datum.

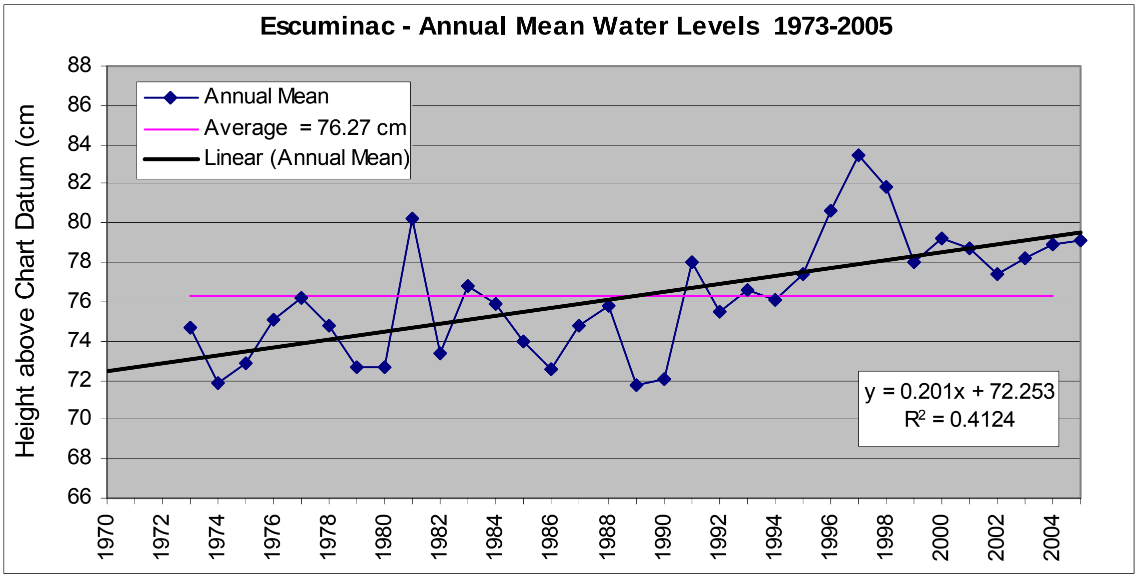

Figure 11. Annual mean water levels (in cm above Chart Datum) for Escuminac water-level data, 1973–2005.

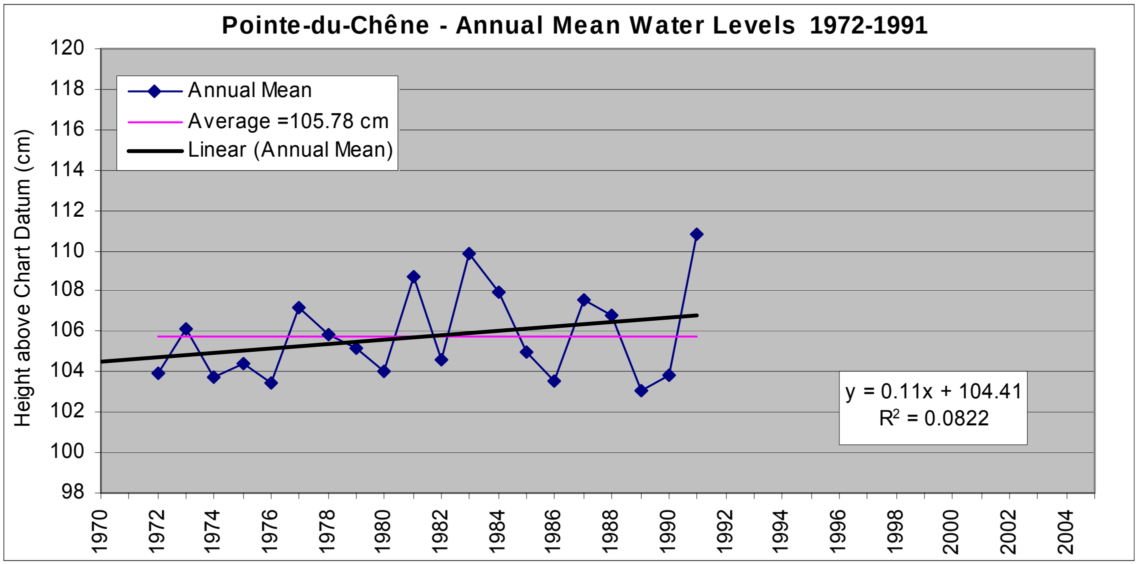

Figure 12. Annual mean water levels (in cm above Chart Datum) for Pointe-du-Chêne water-level data, 1972–1991.

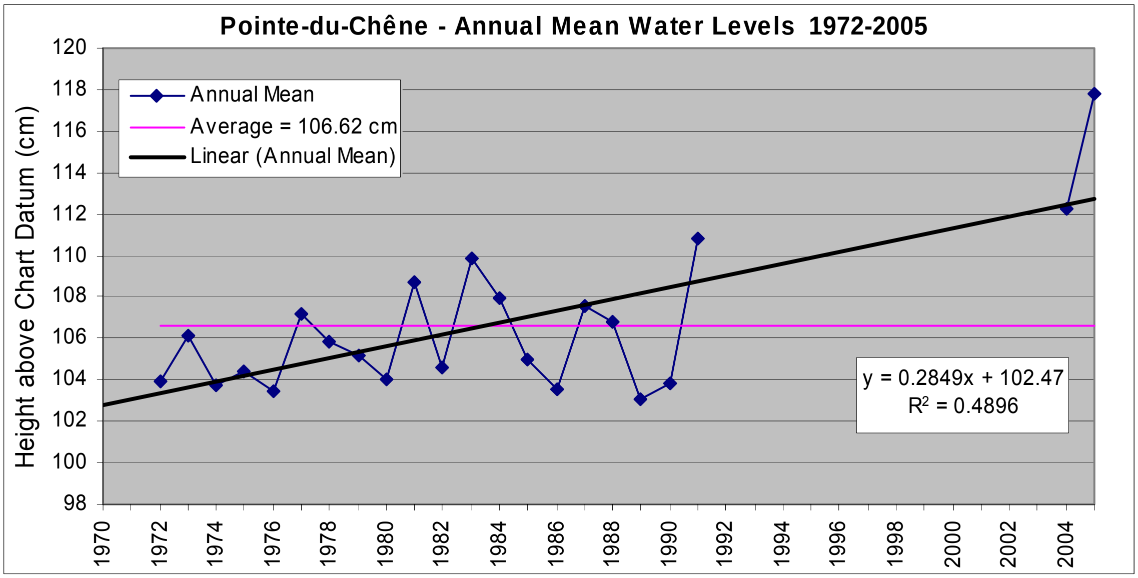

Figure 13. Annual mean water levels (in cm above Chart Datum) for Pointe-du-Chêne water-level data, 1972–2005.

For the sake of comparison, the x- and y-axes in these plots are drawn to the same scale. The linear regression through the data from Escuminac shows a positive trend of 20 cm/century. Data from 1972 to 1991 at Pointe-du-Chêne (Figure 12) show a positive trend of 11 cm/century; however, when data from 2004 and 2005 are included, the trend changes to 28 cm/century. R^2 values are low due to the weather-driven variability of annual mean sea level and the limited inventory of data.

Years in which the data were practically complete (<10% missing data) were identified (20 years for Escuminac and 11 years for Pointe-du-Chêne), and Figures 14 and 15 show the average of the difference between the monthly mean and annual mean for each year. Largest positive values (particularly at Pointe-du-Chêne) are in the late fall and early winter, with largest negative values in the late winter and early spring. The graphs seem to reflect similar characteristics, with a small positive value in July, and are somewhat different from the same plots (Figures 7 and 8) for Charlottetown and Pictou.

The above monthly mean sea-level anomaly values calculated for Escuminac and Pointe-du-Chêne were used to correct annual means for missing data (Figures 16 and 17). At Escuminac, these adjustments ranged from +0.26 cm in 1974 (when 16.4% of the data were missing, entirely in July and August) to −0.40 cm in 1993 (when 17.6% of the data were missing, mainly in the winter), with an average absolute value of 0.09 cm. At Pointe-du-Chêne, these adjustments ranged from +0.74 cm in 1976 (when 25.3% of the data were missing, including December and approximately one-third of November) to −0.34 cm in 1973 (when 7.8% of the data were missing, mainly in February), with an average absolute value of 0.20 cm.

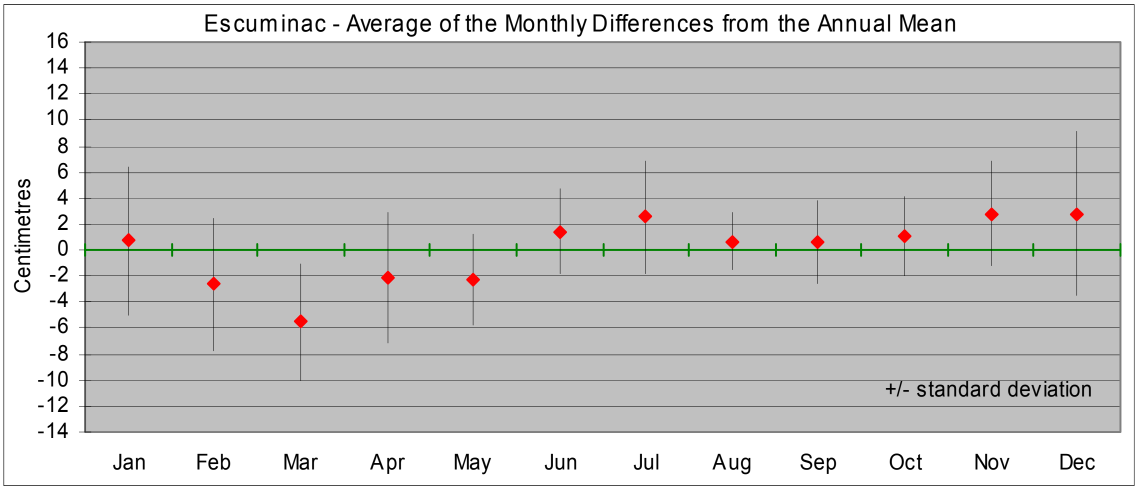

Figure 14. Averages of the monthly differences from the annual mean for Escuminac water-level data.

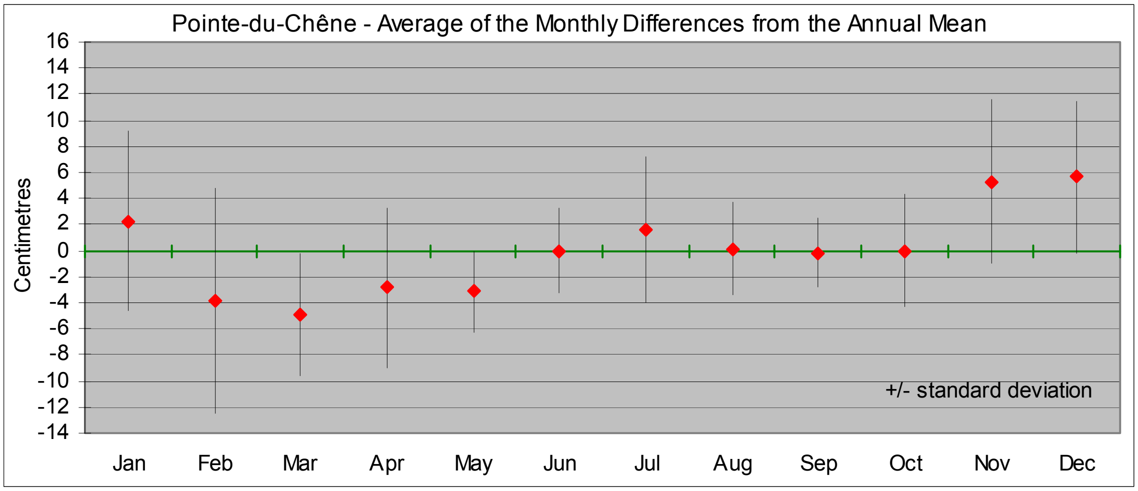

Figure 15. Averages of the monthly differences from the annual mean for Pointe-du-Chêne water-level data.

Monthly mean water levels were calculated for Escuminac and Pointe-du-Chêne and are shown in Figures 18 and 19, together with linear trend lines and one-year (in fact, 13-month) and three-year (in fact, 37-month) running means. For the sake of comparison, the x- and y-axes are again drawn to the same scale. These plots and Figures 11, 12 and 13 (the plots of annual mean water levels) illustrate the difficulties of trying to calculate long-term means simply from point values of short-record data sets. This is discussed further in subsequent sections.

These adjustments raise the slope slightly for both sites, with negligible change in the R^2 values.

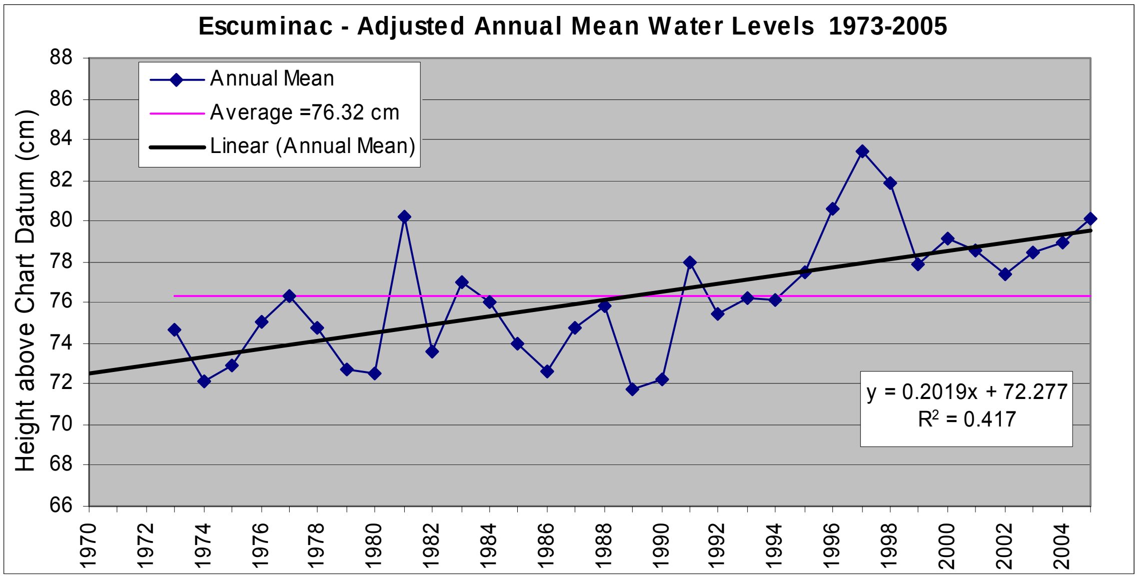

Figure 16. Annual mean sea level at Escuminac adjusted for missing data.

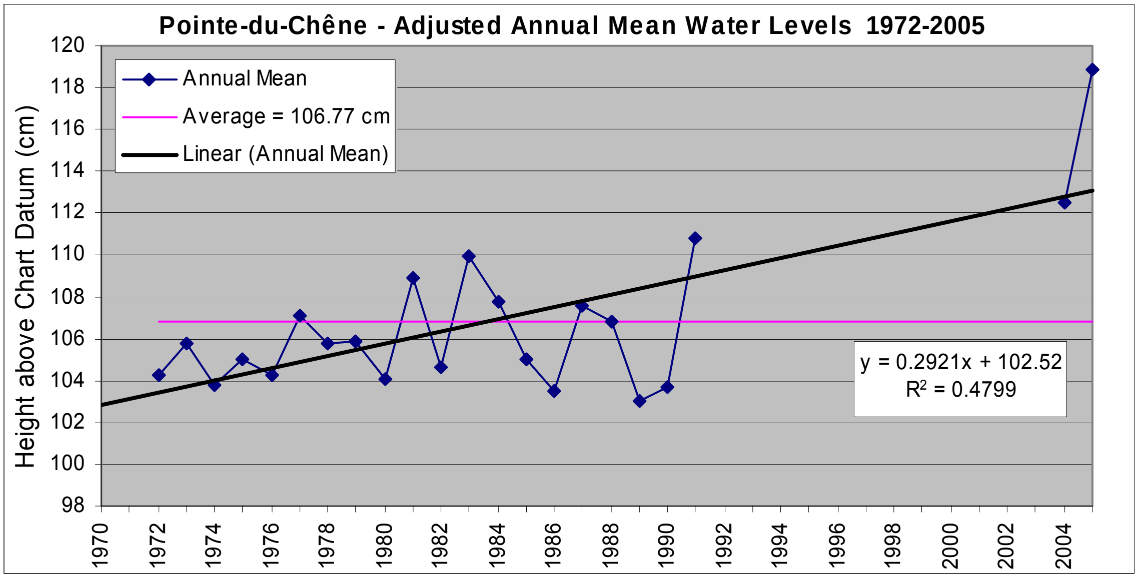

Figure 17. Annual mean sea level at Pointe-du-Chêne adjusted for missing data.

Water-level data exist for Pointe-Sapin (near Escuminac; see Figure 1) for the period October 1963 to September 1975. Neither the data nor the corrected data, however, can be used for an analysis of means, but the corrected data are very useful for studying storm surges and flooding during that period.

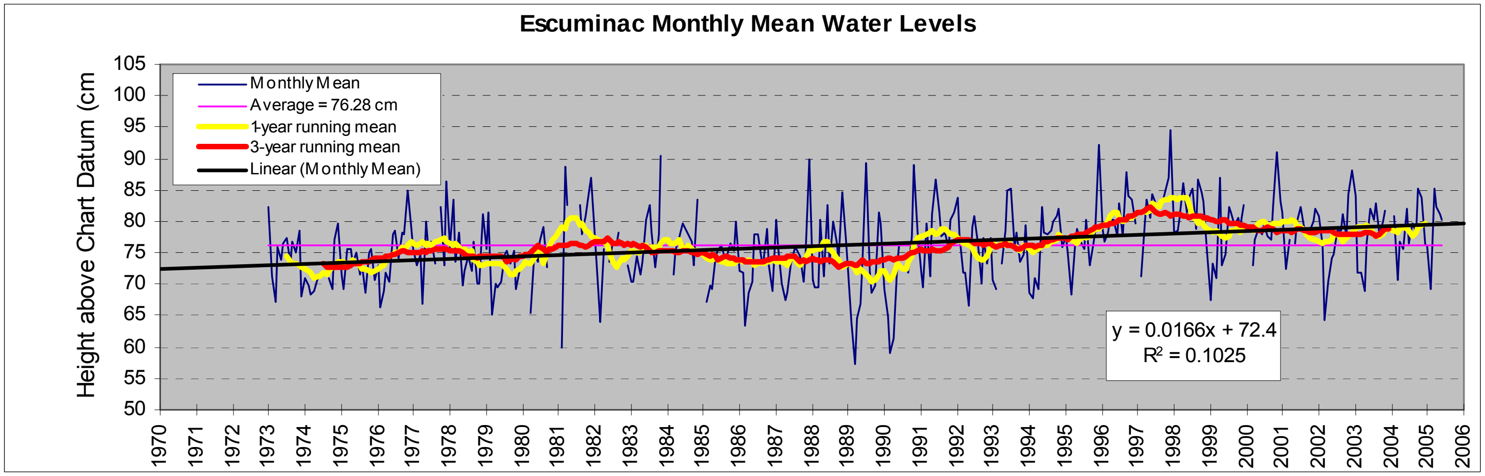

Figure 18. Monthly mean water levels (in cm above Chart Datum) for Escuminac water-level data, 1972–2005, with one- and three-year running means.

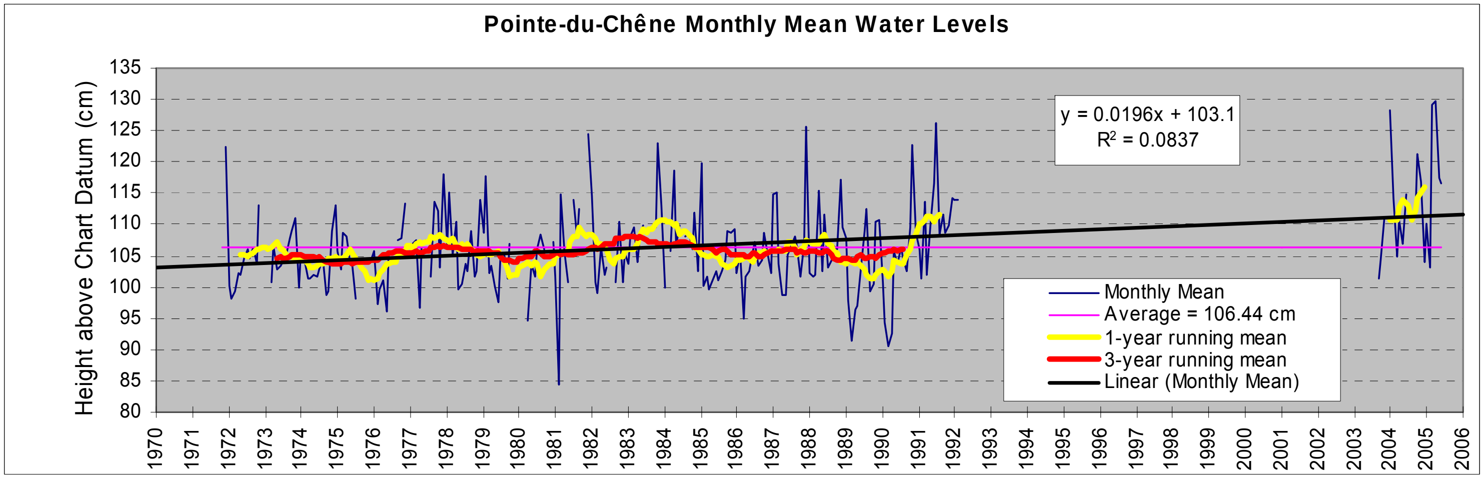

Figure 19. Monthly mean water levels (in cm above Chart Datum) for Pointe-du-Chêne water-level data, 1971–2005, with one- and three-year running means.

4.1.3 Normalizing water levels for atmospheric pressure

4.1.3.1 Atmospheric pressure

Monthly mean atmospheric-pressure data were compiled for Charlottetown (1900–2005), Chatham (1900–2005) and Halifax (1900–2005). Mean sea level (MSL) pressures were derived from the measured station pressures. Monthly mean MSL pressure was observed to vary considerably over the 1900–2005 record from 997.0 hPa (February 1901) to 1023.4 hPa (March 1903). The mean of the monthly mean MSL pressure over this period is 1013.64 hPa, which is close to the running means and close to standard atmospheric pressure of 1013.25 hPa (= millibars). During the period of the Charlottetown water-level data (1911–2005), monthly mean MSL pressure (Figure 20) at Charlottetown ranged from 999.8 hPa (January 1985) to 1023.2 hPa (December 1936 and January 1937), a difference of 23.4 hPa. It is generally accepted that the surface of the ocean responds to changes in atmospheric pressure much like an inverted barometer. If we assume an isostatic response to pressure change, then this 23.4 hPa variation in monthly mean MSL pressure corresponds to a pressure-induced variation of 23.4 cm in monthly mean sea level itself.

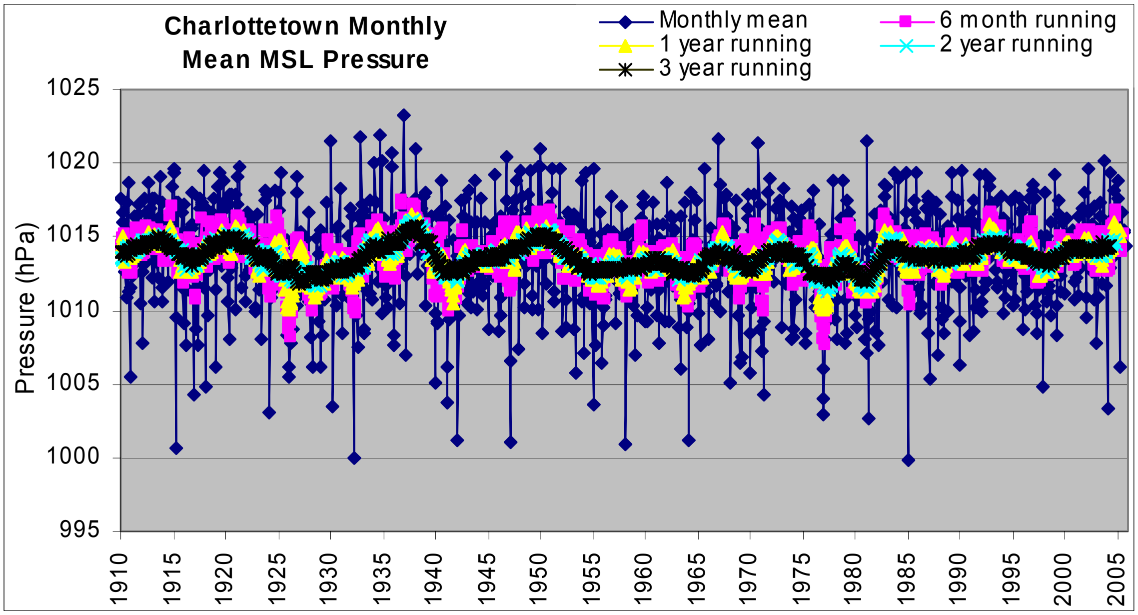

Figure 20. Monthly mean MSL pressure at Charlottetown, 1910–2005, with running means.

Figure 21 shows the monthly MSL pressure anomaly calculated for Charlottetown as the difference between mean monthly mean for each month and the overall mean. Note that pressure tends to be relatively low during the winter months and relatively high during the late summer and the early fall. The variance of monthly mean MSL pressure is also greater during the winter months due to the variability of atmospheric pressure accompanying the winter storms.

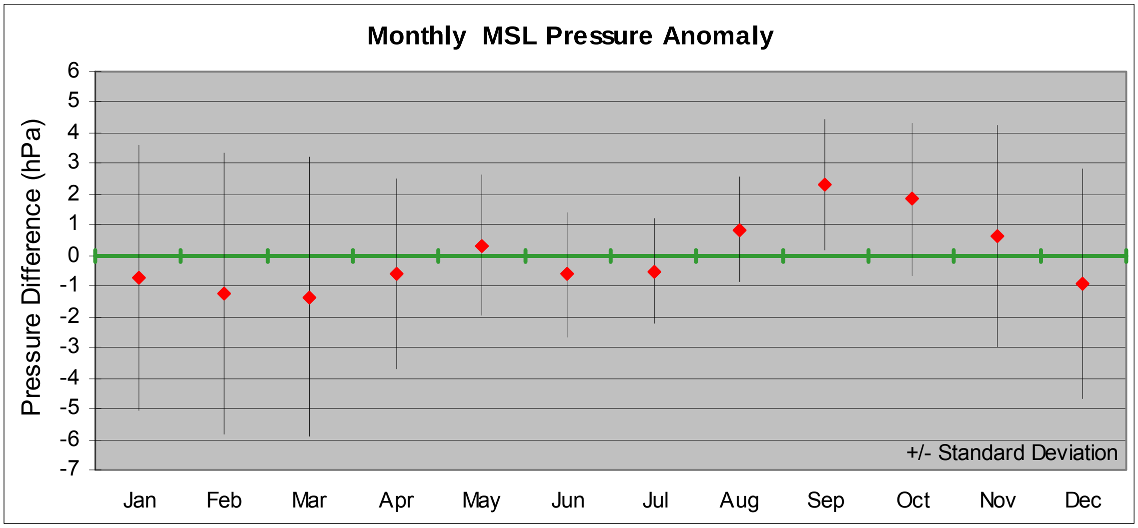

Figure 21. Monthly MSL pressure anomaly at Charlottetown, 1900–2002.

4.1.3.2 Adjusting the Charlottetown water-level data for variations in pressure

Figure 22 shows the monthly mean water levels at Charlottetown (as previously shown in Figure 5) together with the same data adjusted for the variation in monthly mean MSL pressure at Charlottetown, assuming an isostatic adjustment of 1.0 cm/hPa (or millibar) (0.1 m/kPa) from the overall mean (1013.6 hPa). This correction is weighted according to the percentage of missing data — i.e., if one third of the data are missing, only two thirds of the correction is made. Eight of these monthly values are corrected using MSL pressures from Chatham (Miramichi). This adjustment can be seen to account for a significant part of the observed variability in monthly mean sea levels.

The outlier April 1989 stands out as being anomalously low: 37% of the data in this month were missing, and a comparison with Pictou (the nearest tide gauge to Charlottetown) shows that the missing data would have elevated the monthly mean.

Figure 23 shows monthly mean water levels at Charlottetown adjusted for the variation in monthly mean MSL pressure at Charlottetown together with a linear trend line through the data and time-centred one- and three-year running means. The outlier (April 1989) has been removed. The trend line shows sea level rising at a rate of 31.8 cm/century.

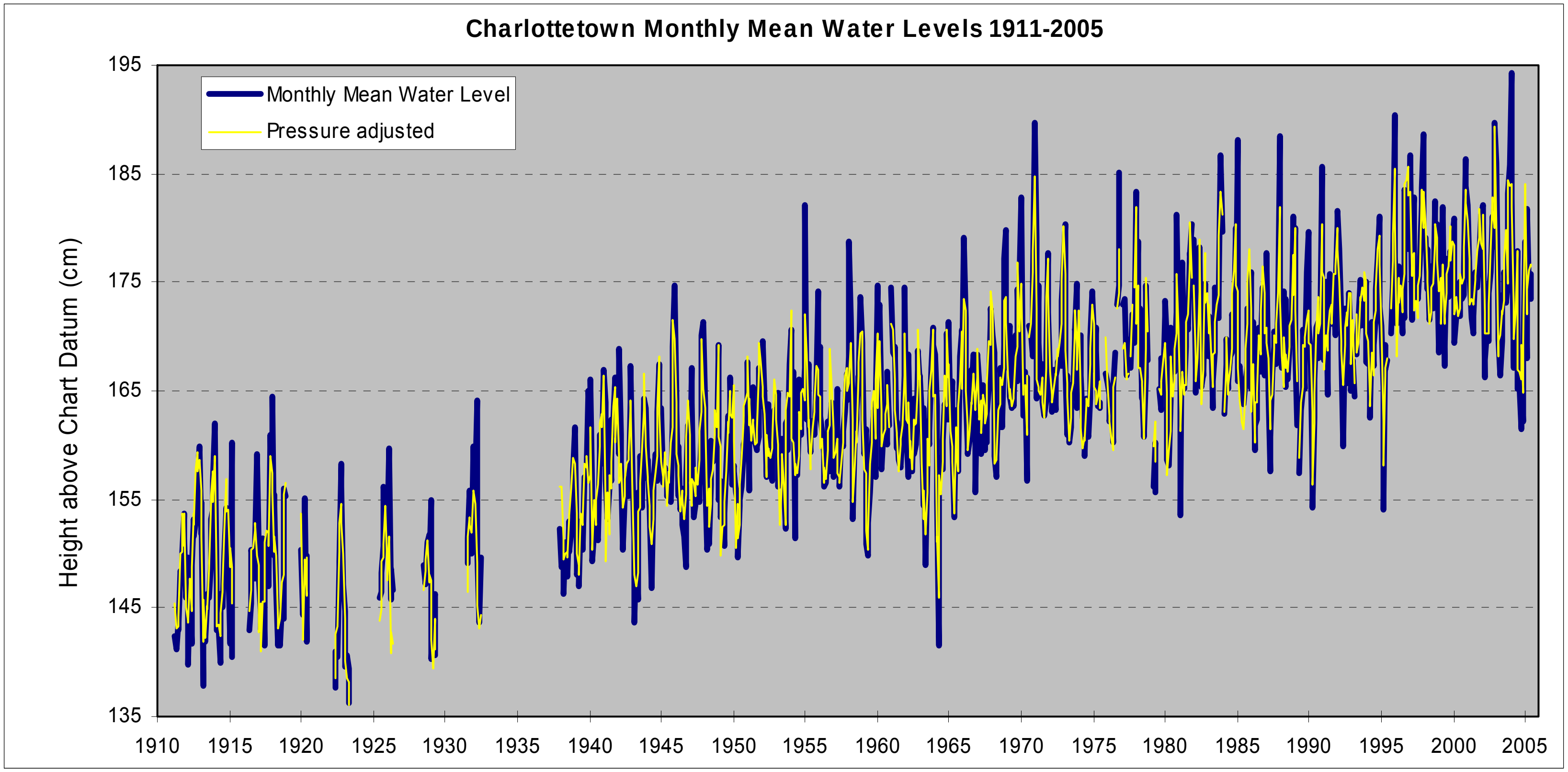

Figure 22. Charlottetown monthly mean sea levels and monthly mean sea levels adjusted for variation in atmospheric pressure.

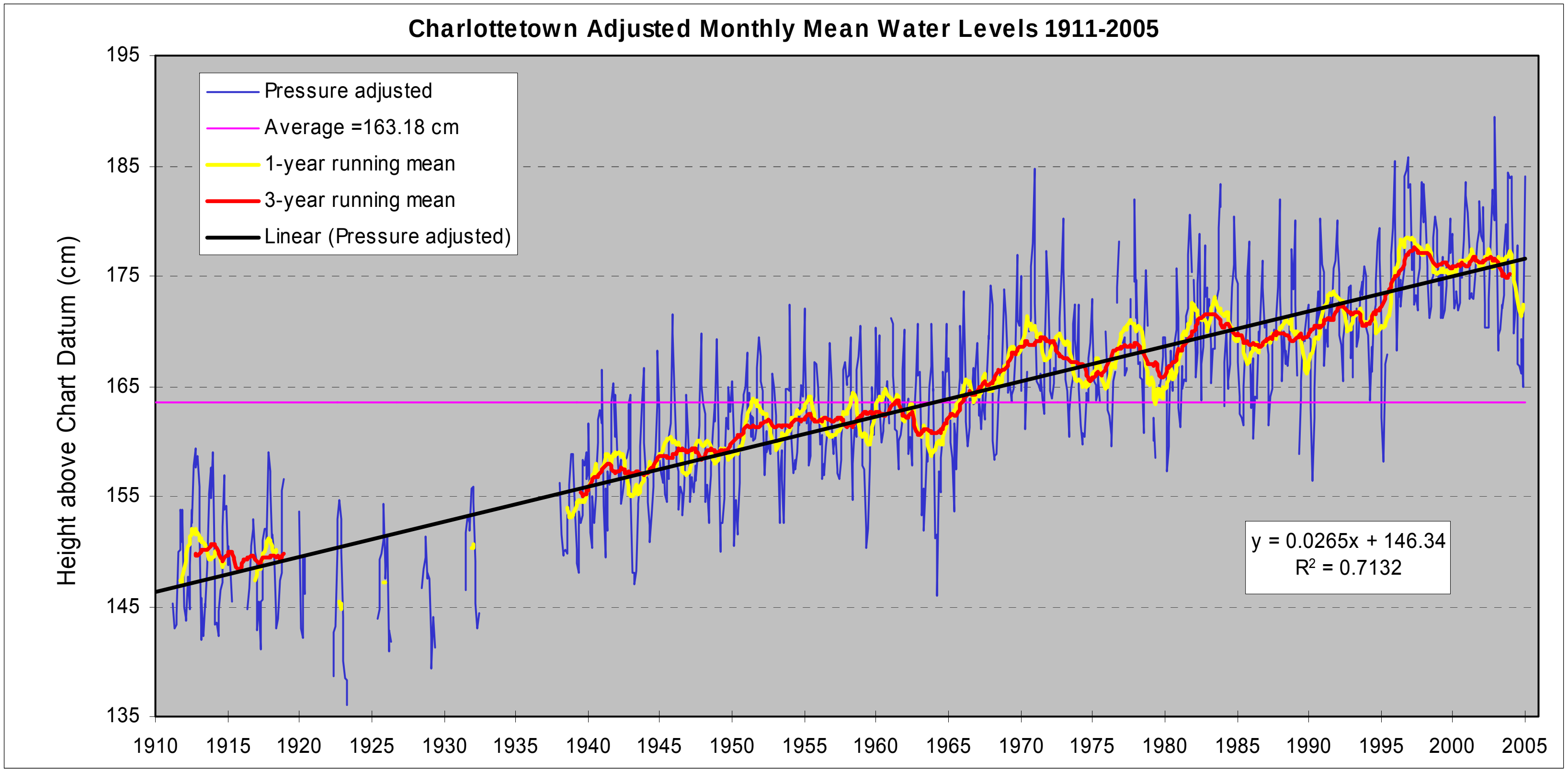

Figure 23. Charlottetown monthly mean sea levels adjusted for variation in atmospheric pressure together with running means.

Figure 24 shows adjusted annual mean sea level at Charlottetown (as shown previously in Figure 10) further adjusted, assuming an isostatic response, for the impacts of pressure variations weighted according to the number of data that are present each month of the year. This annual correction factor (P_{annual}) is not the same as the difference in annual mean pressure from the overall average annual mean pressure (1013.6 hPa). The P_{annual} correction factor is defined as the sum of the number of observations present each month of the year multiplied by that monthly MSL pressure anomaly divided by the total number of observations present in the year. If most of the observations are therefore missing, especially during a month of unusually high or low monthly mean atmospheric pressure, then those few remaining observations will make less impact on the annual correction factor than if all the observations were present.

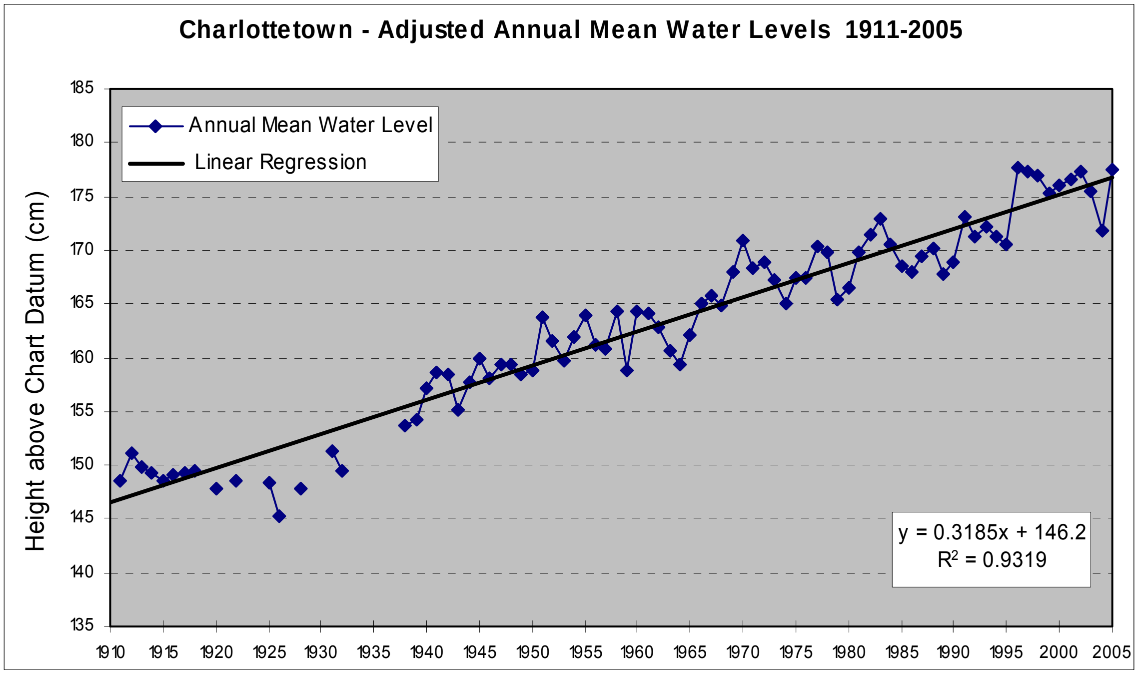

Figure 24. Charlottetown water-level data, annual means, 1911–2005 (adjusted for missing data and for variation in atmospheric pressure; outliers 1923 and 1929 removed).

The value of the slope of the regression stays approximately the same at 32 cm/century. The R^2 value improves slightly.

Figure 25 (upper panel) shows the one-year (in fact, 13-month) running means of the Charlottetown monthly water-level data together with the one-year running means of the monthly water-level data adjusted for the monthly variation in atmospheric pressure. The annual mean water levels can be thought of as a subset of these data. Monthly mean water levels for months with more than 50% missing data were omitted. The data points dropped out of the plot when more than 10 of the necessary 13 consecutive monthly mean records were unavailable.

Figure 25 (lower panel) shows the three-year (in fact, 37-month) running means of the Charlottetown monthly water-level data together with the three-year running means of the monthly water-level data adjusted for the variation in atmospheric pressure. This is a somewhat smoother version of the record of sea level than the plots of annual mean sea levels (notice the increased R^2 values). No adjustment was made here for missing data, except that the data points dropped out of the plot when more than 30 of the necessary 37 consecutive monthly mean records were unavailable.

The slope of the linear regression through the plot of the one-year running means gives a value for sea-level rise of 30.12 cm/century. For the three-year running means, the linear trend indicates a mean rate of sea-level rise of 30.36 cm/century (unadjusted data) and 30.12 cm/century (data adjusted for monthly variation in atmospheric pressure). These values are somewhat lower than those calculated from annual mean water level (Figures 3, 9, 10 and 23) because of the diminished influence of the water-level data from the 1920s.

Figure 26 shows the same data as Figure 25, but this time with a fourth-order polynomial trend line. R^2 values improve somewhat from the linear fits; however, there remains a danger in this type of analysis. The upward inflection of the line in recent years suggests that sea level has risen faster in the last couple of decades (e.g., from 1985) than in the period prior to that (e.g., from 1960). However, the trend line also shows earlier variations (including a flat or slight downward trend early in the data, which, interestingly enough, shows up in the three-year running mean plot despite the absence of the low 1920s data due to their sparsity). No reliable conclusions can be drawn on the rate of acceleration, if any, of relative sea-level rise at Charlottetown.

It should be noted that some earlier water-level data for Charlottetown (1907–1911) exist in the published literature (Dawson, 1917), but not in digital format in the MEDS archive.

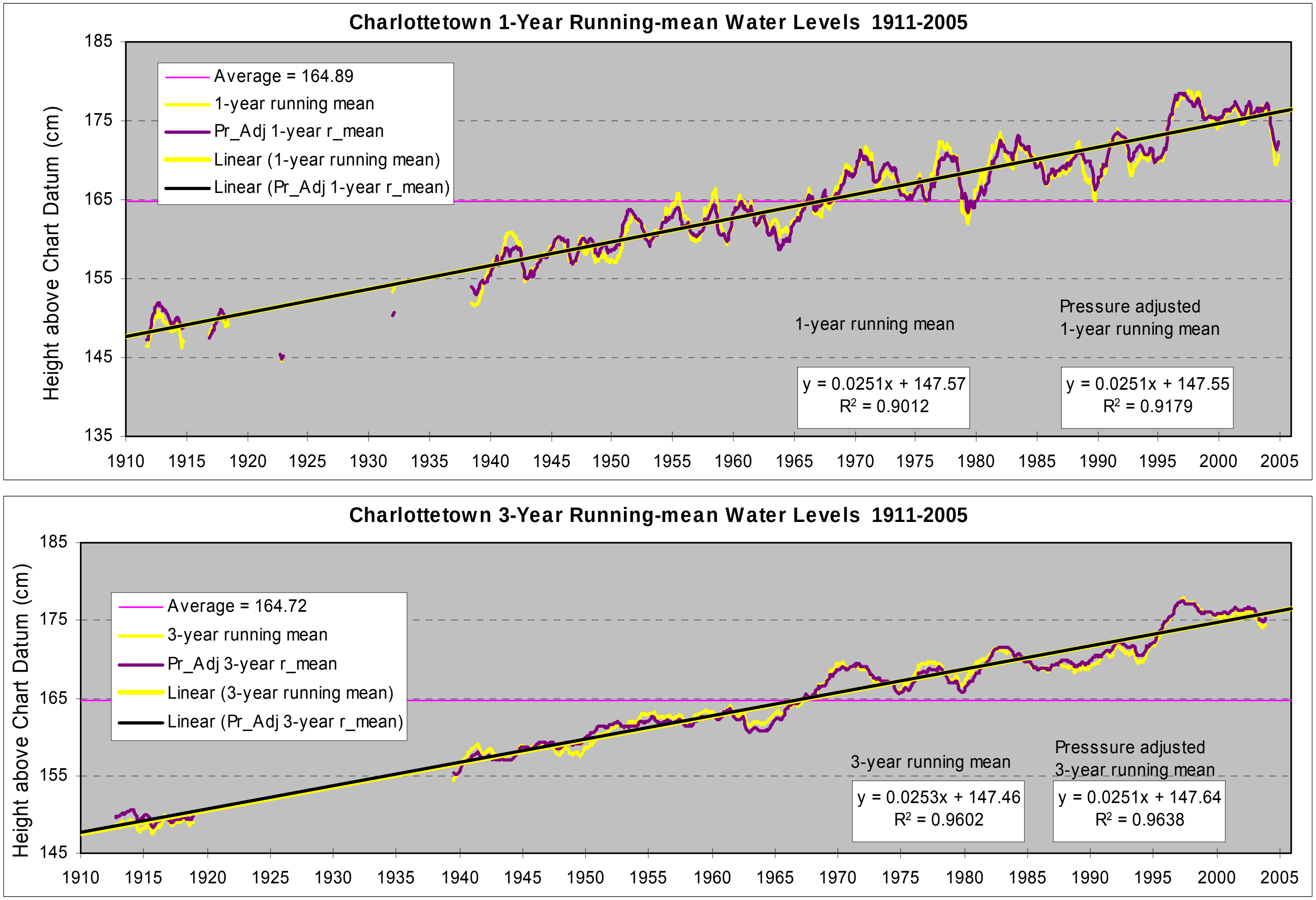

Figure 25. One-year (above) and three-year (below) running means of Charlottetown monthly and adjusted monthly water-level data, 1911–2005.

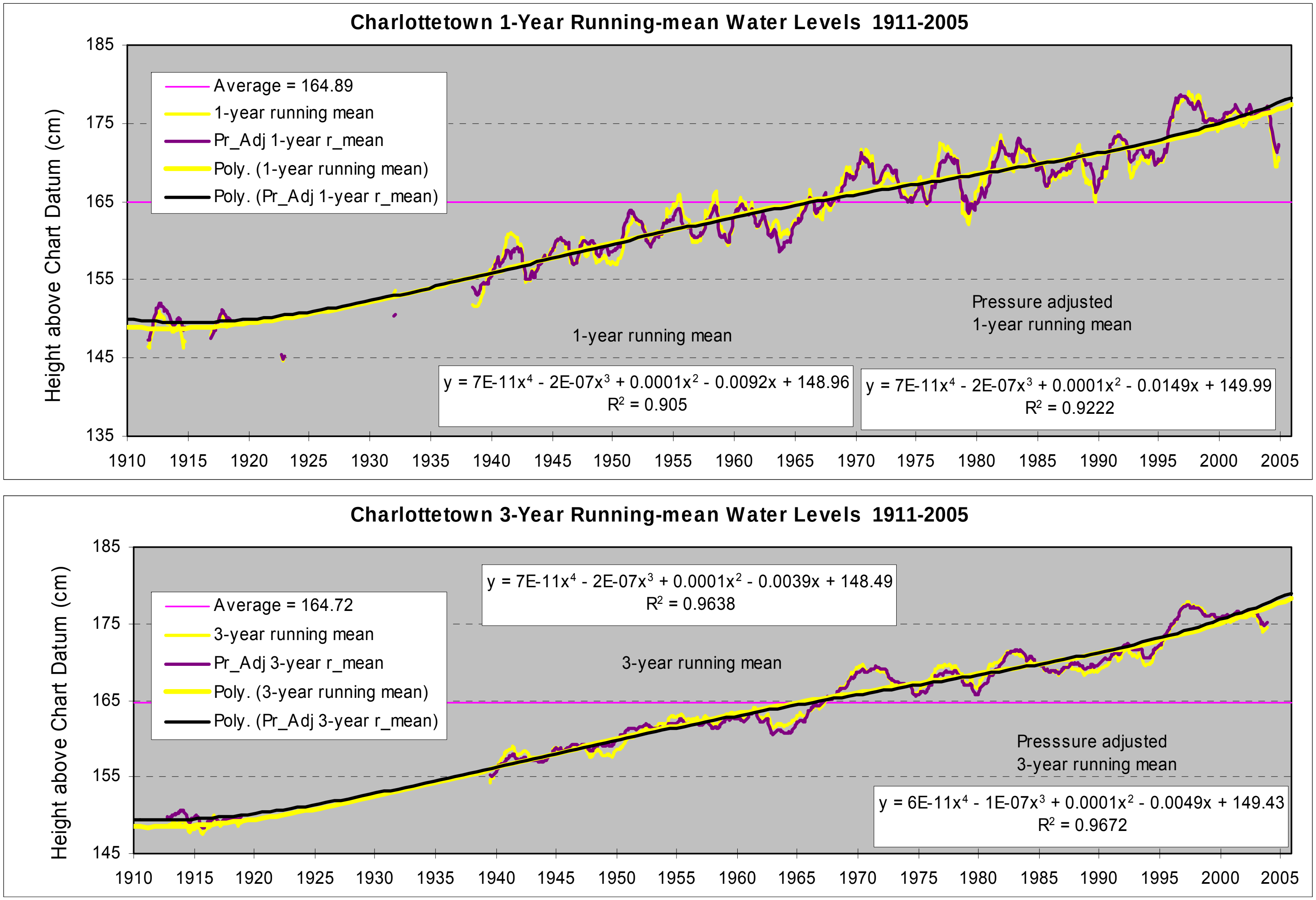

Figure 26. One-year (above) and three-year (below) running means of Charlottetown monthly and adjusted monthly water-level data, 1911–2005.

4.1.3.3 Adjusting the Escuminac and Pointe-du-Chêne data for variations in pressure

Figure 27 shows the monthly mean water levels at Escuminac (as previously shown in Figure 18) together with the same data adjusted for the variation in monthly mean MSL pressure. Monthly mean MSL pressure data come mainly from Chatham, New Brunswick. When Chatham pressures were missing (October 1991 to January 1994 and December 1997 to May 1999), values were substituted from pressure data at Point Escuminac. The exceptions to this were December 1997 and January 1998, when both Chatham and Escuminac data were missing, so pressures from Charlottetown were used. The corrections assume an isostatic adjustment of 1 cm/hPa (or millibar) (0.1 m/kPa) from the overall mean (1973–2005) of 1013.54 hPa at Escuminac and Chatham. This adjustment can be seen to account for a significant part of the observed variability in monthly mean sea levels.

Figure 28 shows the monthly mean water levels at Pointe-du-Chêne (as previously shown in Figure 19) together with the same data adjusted for the variation in monthly mean MSL pressure. Monthly mean MSL pressures were taken from Moncton. The corrections assume an isostatic adjustment of 1 cm/hPa from the overall mean pressure of 1013.78 hPa at Moncton for the period of the water-level data.

Figures 29 and 30 show monthly mean water levels at Escuminac and Pointe-du-Chêne, adjusted for the variation in monthly mean MSL pressure as described above, together with a linear trend and time-centred one- and three-year running means. For the sake of comparison, the x- and y-axes are drawn to the same scale. The trend lines indicate a rate of sea-level rise of 23.28 cm/century at Escuminac and 27.12 cm/century at Pointe-du-Chêne.

Figures 31 and 32 show adjusted annual mean sea levels at Escuminac and Pointe-du-Chêne (as shown previously in Figures 16 and 17) further adjusted, assuming an isostatic adjustment, for the effects of pressure variations weighted according to the number of data available for each month of the year. At Escuminac, these adjustments range from a reduction of the annual mean sea level by 2.22 cm in 1976 to an increase in the annual mean sea level by 1.39 cm in 1996. At Pointe-du-Chêne, they range from a lowering of annual mean sea level by 2.34 cm in 1981 to raising it by 1.17 cm in 1984. The linear trends increase slightly at both locations, and R^2 values improve.

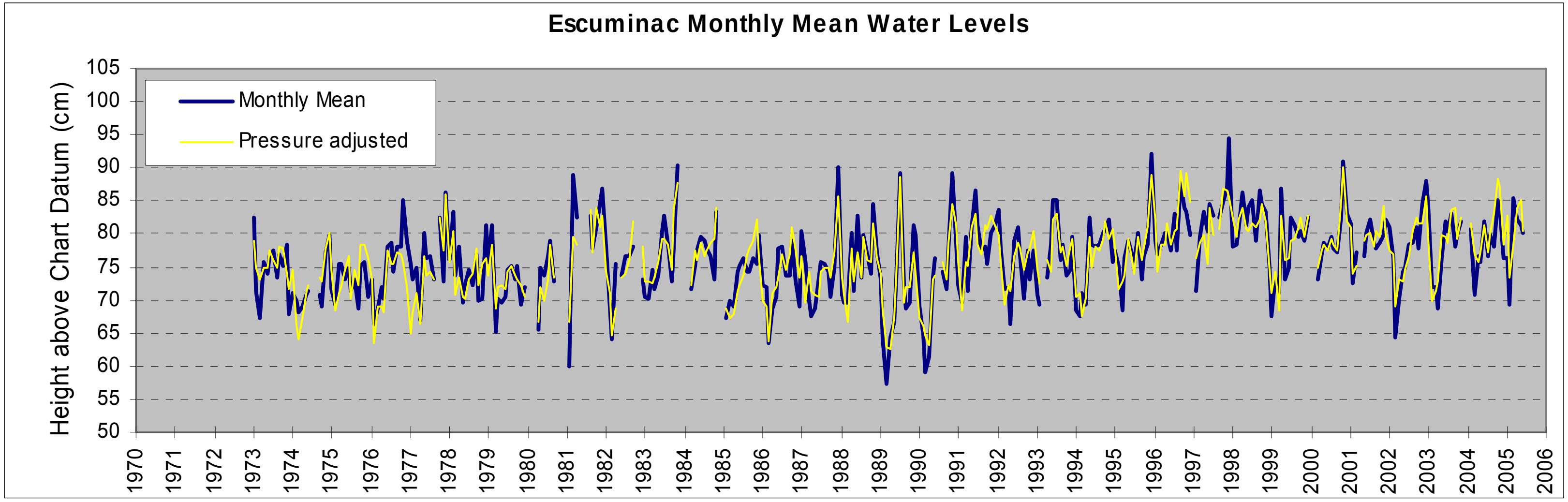

Figure 27. Escuminac monthly mean water levels and monthly mean water levels adjusted for variations in atmospheric pressure.

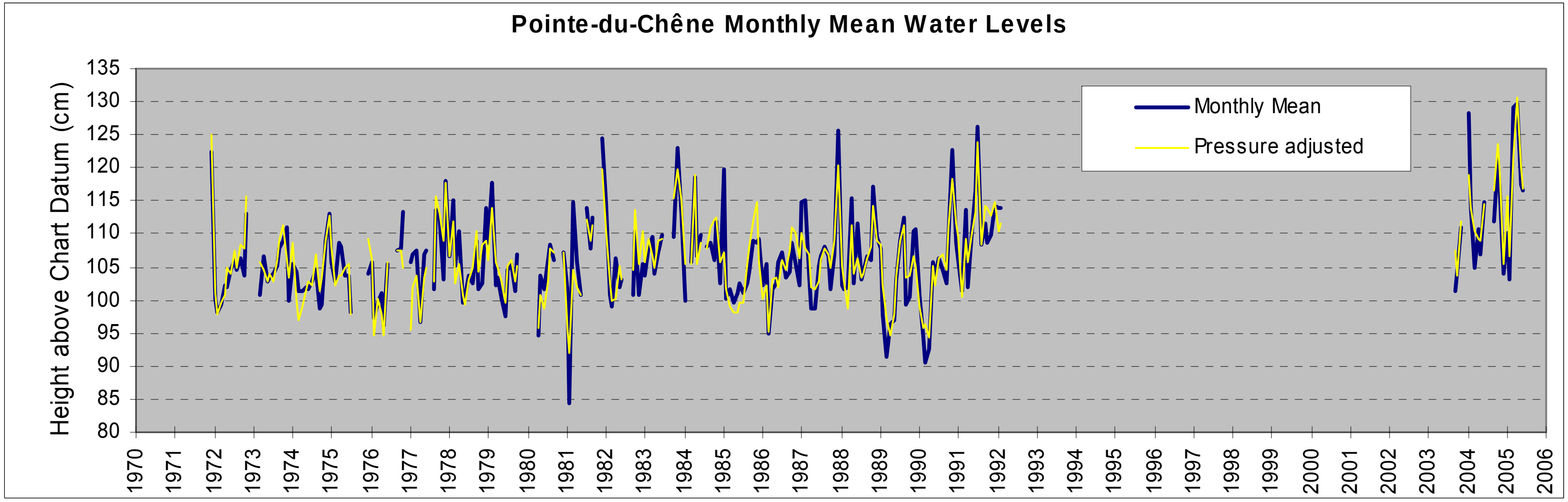

Figure 28. Pointe-du-Chêne monthly mean water levels and monthly mean water levels adjusted for variations in atmospheric pressure.

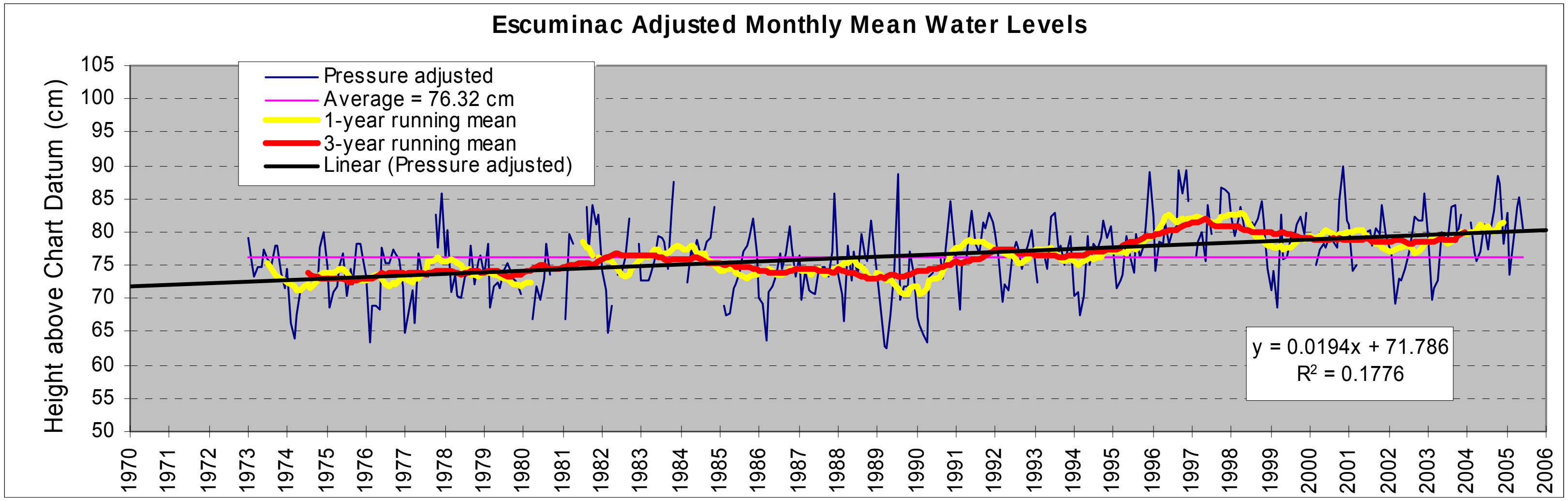

Figure 29. Escuminac monthly mean sea levels adjusted for variations in atmospheric pressure together with running means.

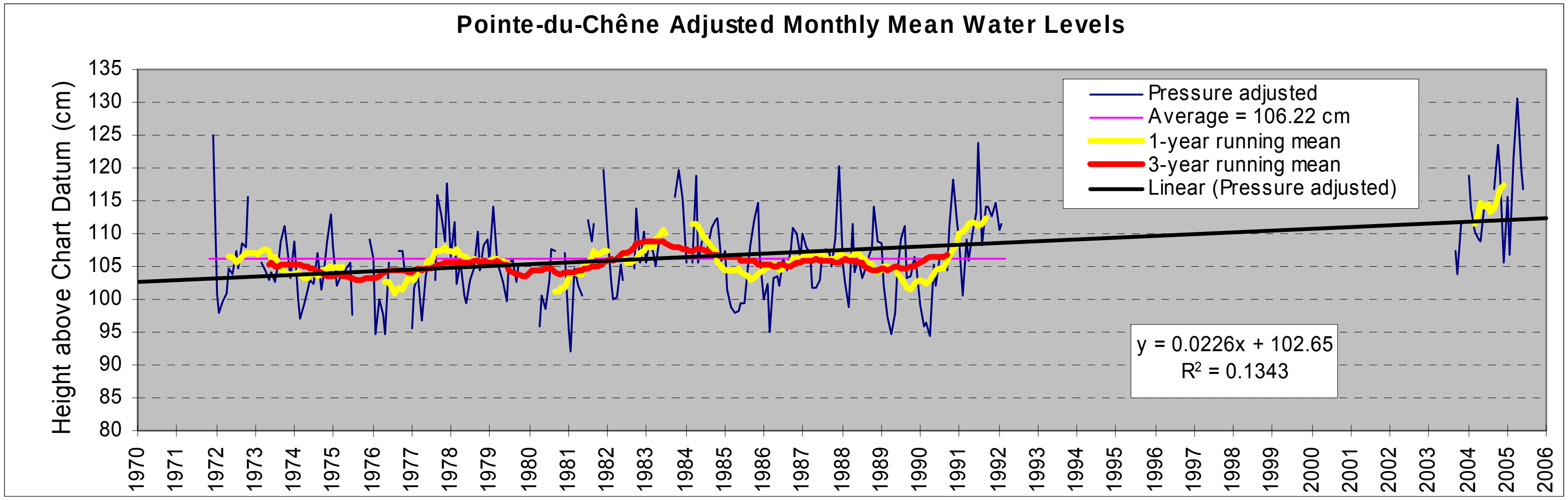

Figure 30. Pointe-du-Chêne monthly mean sea levels adjusted for variations in atmospheric pressure together with running means.

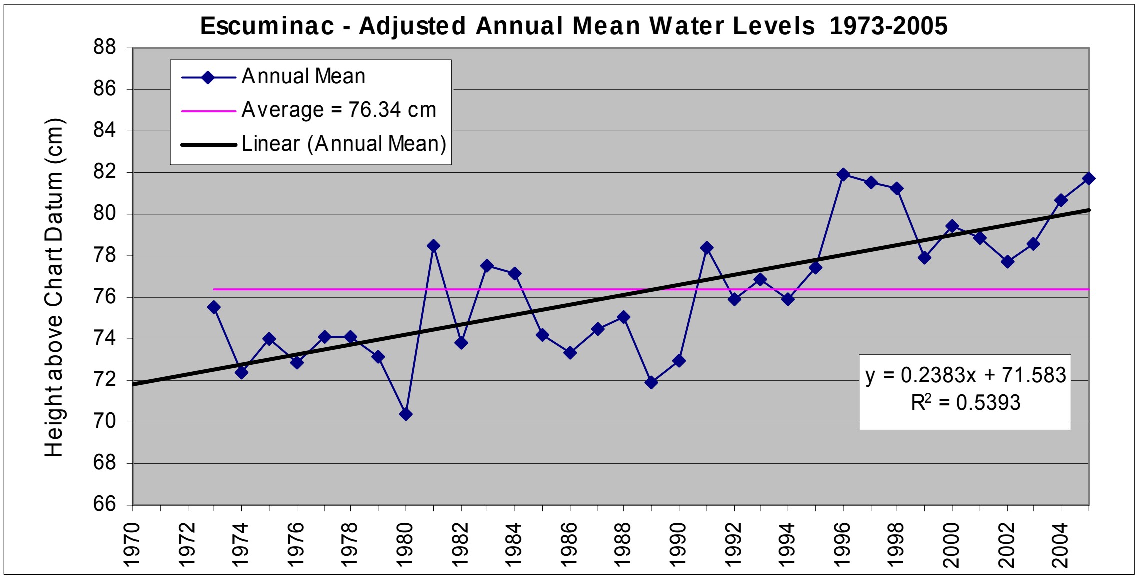

Figure 31. Escuminac water-level data, annual means, 1973–2005, adjusted for missing data and for variations in atmospheric pressure.

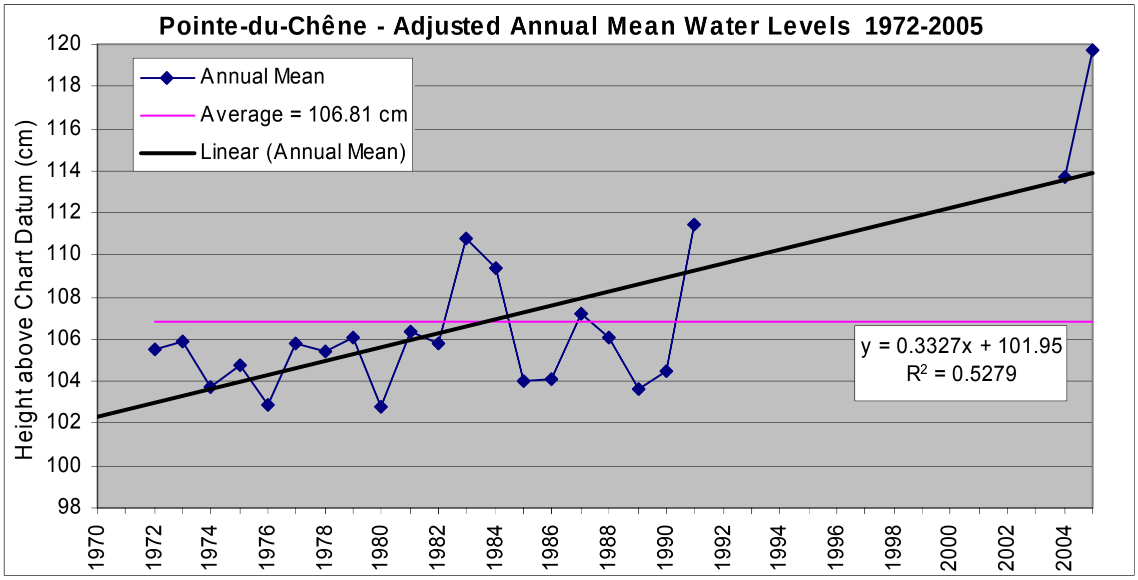

Figure 32. Pointe-du-Chêne water-level data, annual means, 1972–2005, adjusted for missing data and for variations in atmospheric pressure.

4.1.4 Estimating longer-term sea-level trends at Escuminac and Pointe-du-Chêne using methods of propagating differences

Carrera et al. (1991a) warned of the difficulties in calculating linear trends from short data sets (less than 40 years) and the contamination of such results by low-frequency oceanic signals. They pointed out that more reliable linear trends based on short records can be obtained using methods of propagating differences. In this section, we first propagate the differences in linear trends between Charlottetown, Escuminac and Pointe-du-Chêne water-level data, during periods of overlapping data, to the Charlottetown long-term sea-level trend (~32 cm/century) to estimate long-term rates of sea-level rise at Escuminac and Pointe-du-Chêne. We then take a slightly different approach and propagate the trend of the differences in monthly mean sea levels between Escuminac and Charlottetown and between Pointe-du-Chêne and Charlottetown to the Charlottetown long-term trend.

4.1.4.1 Propagating differences in linear trends

4.1.4.1.1 Escuminac versus Charlottetown

Figure 33 shows annual mean water levels at Escuminac for the 33 years of record, 1973–2005 (as previously shown in Figure 11), together with Charlottetown annual mean water levels for the same period. The Charlottetown water levels have been shifted (for display purposes) by the difference in the means of the annual mean water levels at these two stations (i.e., 95.01 cm has been subtracted from the Charlottetown data). Over this period, Escuminac sea levels rose at a rate of about 20.1 cm/century, while Charlottetown water levels were rising at a mean rate of 28.3 cm/century. The difference between these trends is 8.2 cm/century. Charlottetown water levels over the longer period of water-level data, 1911–2002, rose at a mean rate of about 32 cm/century (see Figures 3, 9 and 10), suggesting that the longer-term mean rate of sea-level rise at Escuminac should be closer to about 23.8 cm/century.

Figure 34 shows annual mean water levels at Escuminac for the 33 years of record, 1973–2003, adjusted for missing data and for variations in atmospheric pressure (as previously shown in Figure 30), together with Charlottetown annual mean water levels for the same period, adjusted in the same way and also shifted (for display purposes) to a common mean sea level datum (by subtracting 95.16 cm from the Charlottetown data). As seen in Figures 22 and 23, such adjustments tend to decrease the variability over the short term (monthly mean sea level in particular, but also annual mean sea level), with decreased impacts over the mid-term (three-year running mean of sea level) and minimal impact on the regression slopes over the scale of a century (Figure 24). In Figure 34, R^2 values have increased and the plots of mean sea level are arguably more coherent. The rates of sea-level rise have increased at both stations. The Charlottetown trend is close to 32 cm/century, indicating that the long-term trend at Escuminac is about 23.6 cm/century.

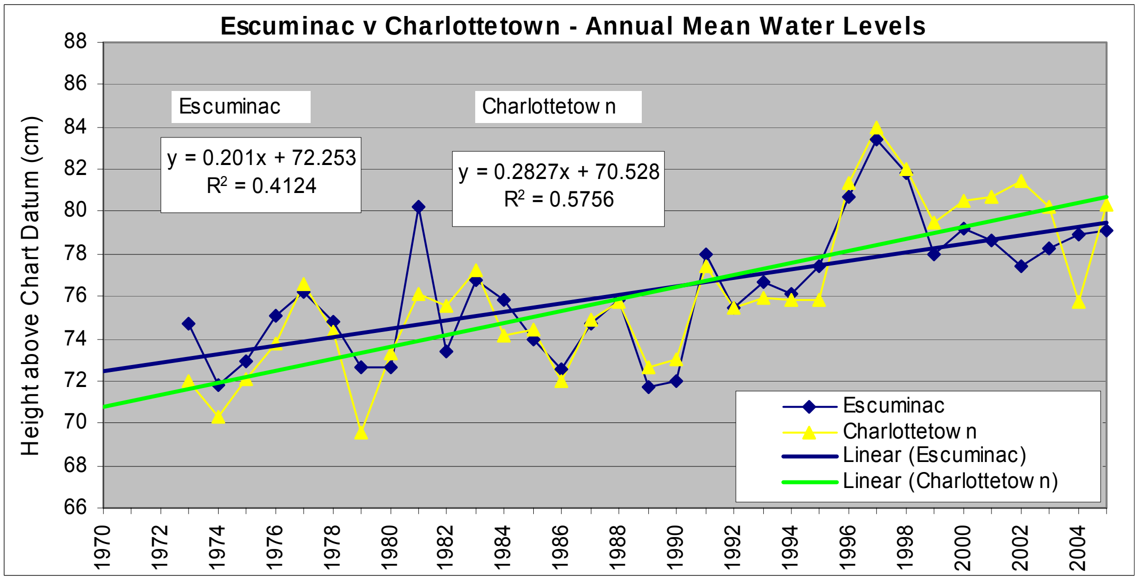

Figure 33. Escuminac annual mean water levels and Charlottetown annual mean water levels (shifted to the same scale by subtracting 95.01 cm) for the period 1973–2005.

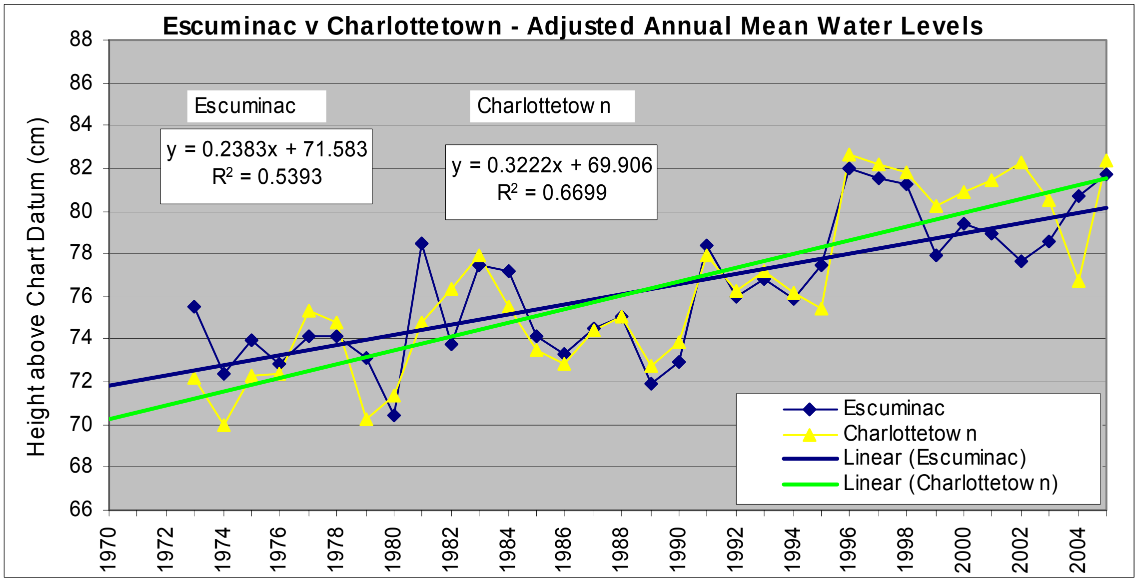

Figure 34. Escuminac annual mean water levels and Charlottetown annual mean water levels (shifted to the same scale by subtracting 95.16 cm) adjusted for missing data and normalized for variations in atmospheric pressure, for the period 1973–2005.

4.1.4.1.2 Pointe-du-Chêne versus Charlottetown versus Escuminac

Figure 35 shows annual mean water levels at Pointe-du-Chêne for its 20 years of record, 1972–1991 (as previously shown in Figure 12), together with adjusted Charlottetown annual mean water levels for the same period. The Charlottetown water levels have been shifted (for display purposes) by the difference in the means of the annual mean water levels at these two stations over this period (i.e., 63.29 cm has been subtracted from the Charlottetown data). Over this period, Pointe-du-Chêne sea levels rose at a mean rate of about 11 cm/century, while Charlottetown water levels were rising at a rate of 15.16 cm/century. In other words, at Pointe-du-Chêne, the relative sea level was rising at a rate of 4.16 cm/century less than at Charlottetown. Subtracting from the long-term trend at Charlottetown, this suggests that the long-term mean rate of relative sea-level rise in the Pointe-du-Chêne area is 27.1 cm/century.

Figure 36 shows annual mean water levels at Pointe-du-Chêne for the 20 years of record, 1972–1991, adjusted for missing data and for variations in atmospheric pressure (as previously shown in Figure 31), together with Charlottetown annual mean water levels for the same period, adjusted in the same way and also shifted (for display purposes) to a common mean sea level datum (by subtracting 63.08 cm from the Charlottetown data). R^2 values and the slopes of sea-level rise have both increased slightly. In this plot, the relative sea level was rising at 16.65 cm/century at Charlottetown and at 12.45 cm/century at Pointe-du-Chêne, a difference of 4.2 cm/century, suggesting a long-term trend in the Pointe-du-Chêne area of 27.8 cm/century.

Figure 37 shows annual mean water levels at Pointe-du-Chêne for 19 of its 20 years of record, 1973–1991, together with adjusted Escuminac annual mean water levels for the same period. The Escuminac water levels have been shifted (for display purposes) by the difference in the means of the annual mean water levels at these two stations over this period (i.e., 31.36 cm has been added to the Escuminac data). Over this period, Pointe-du-Chêne sea level rose at a rate of about 9.59 cm/century, while Escuminac water level rose at a rate of 3.17 cm/century, a difference of 6.42 cm/century. If we assume that Escuminac water levels are rising at 23 cm/century, this suggests that the long-term rate of relative sea-level rise in the Pointe-du-Chêne area is 29.4 cm/century.

Figure 38 shows annual mean water levels at Pointe-du-Chêne and Escuminac for the same 19-year period of common record, 1973–1991, adjusted for missing data and for variations in atmospheric pressure, with Escuminac water levels shifted (for display purposes) to a common mean sea level datum (by adding 31.57 cm). R^2 values and the slopes of sea-level rise have both increased slightly, but the R^2 values remain very low. In this analysis, relative sea level at Pointe-du-Chêne is rising at 13.95 cm/century, whereas at Escuminac the rate is 7.75 cm/century, a difference of 6.20 cm/century. Taking the long-term rate at Escuminac to be 23 cm/century, this indicates a long-term trend of 29.2 cm/century at Pointe-du-Chêne.

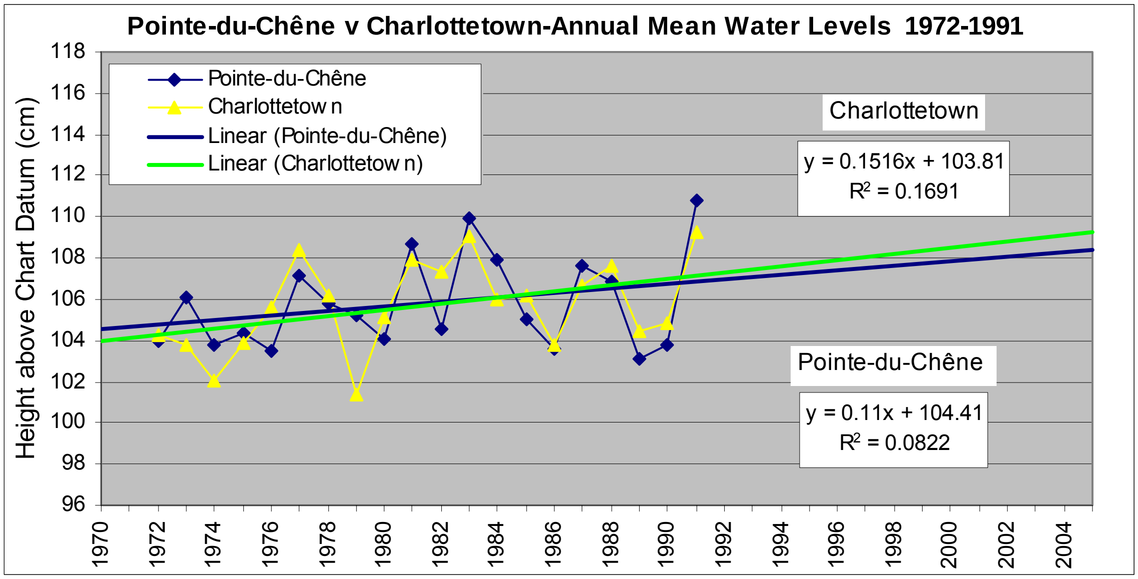

Figure 35. Pointe-du-Chêne annual mean water levels and Charlottetown annual mean water levels (shifted to the same scale by subtracting 63.29 cm) for the period 1972–1991.

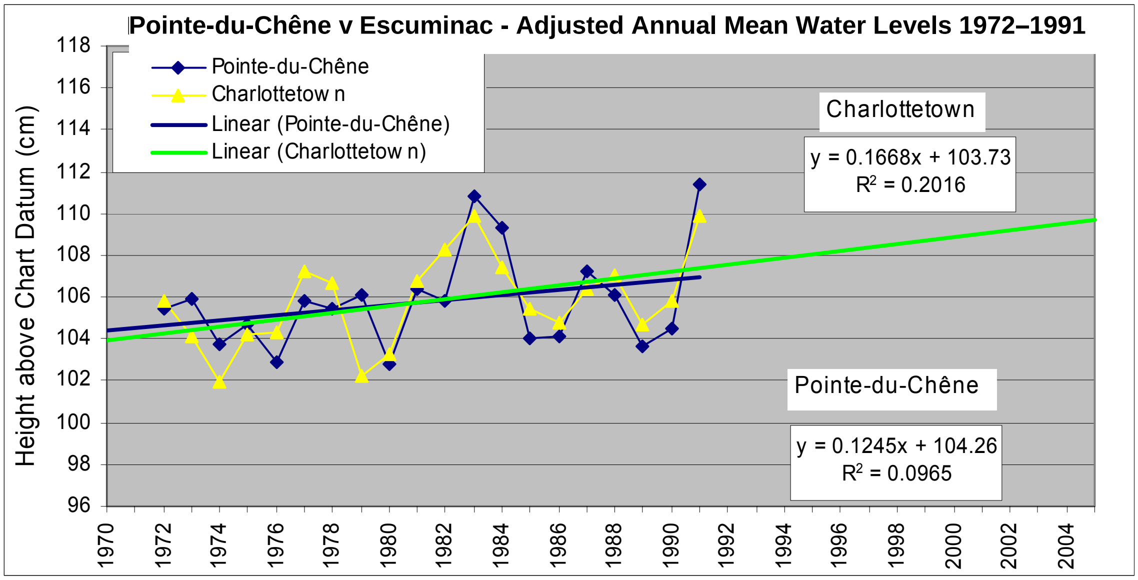

Figure 36. Pointe-du-Chêne annual mean water levels and Charlottetown annual mean water levels (shifted to the same scale by subtracting 63.08 cm) adjusted for missing data and normalized for variations in atmospheric pressure, for the period 1972–1991.

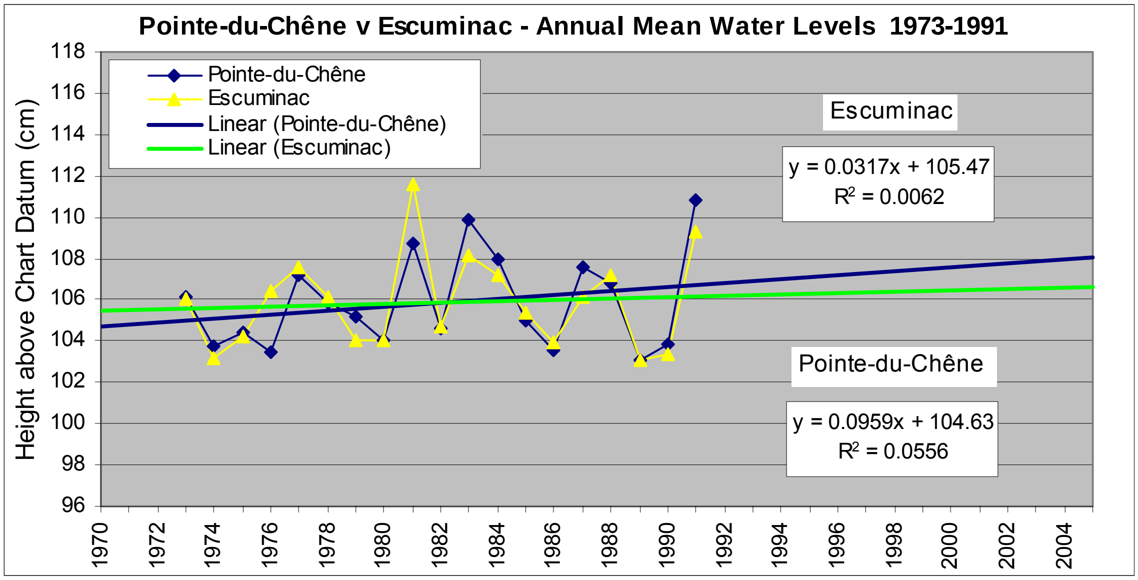

Figure 37. Pointe-du-Chêne annual mean water levels and adjusted Escuminac annual mean water levels (shifted to the same scale by adding 31.36 cm) for the period 1973–1991.

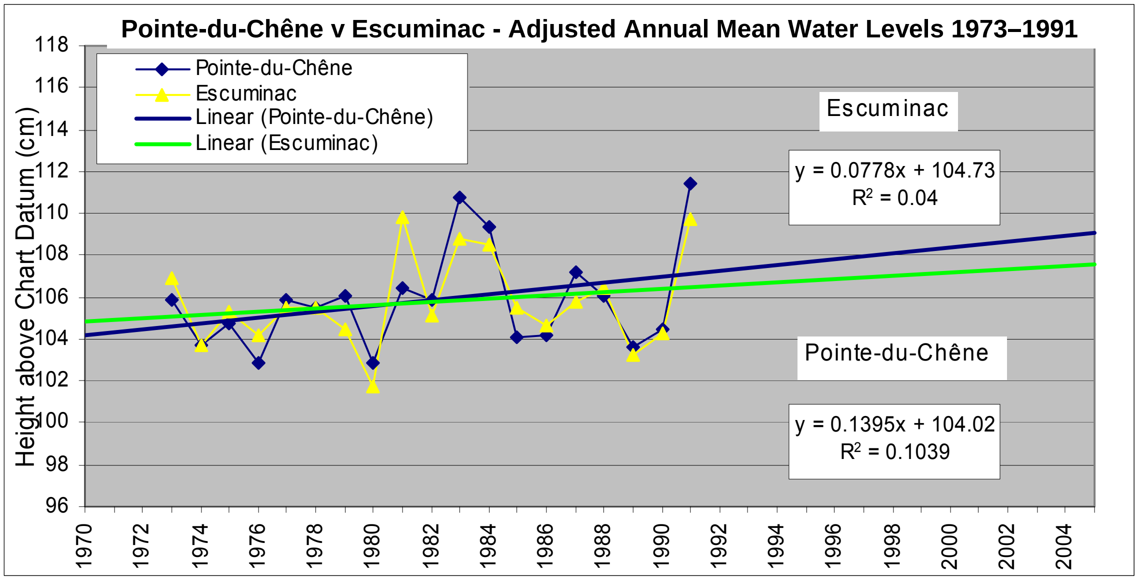

Figure 38. Pointe-du-Chêne annual mean water levels and Escuminac annual mean water levels (shifted to the same scale by adding 31.57 cm) adjusted for missing data and normalized for variations in atmospheric pressure, for the period 1972–1991.

4.1.4.2 Propagating linear trends from differences in monthly means

Carrera et al. (1991a,b) compiled a map of vertical crustal movements in Canada based on a detailed analysis of available water-level data at that time from Canada and the United States. The authors obtained the differences between water levels at adjacent tide-gauge sites in an effort to cancel out oceanic noise, then generated linear trends through the differences, and then propagated these to trends of long-term tide-gauge sites in the region to obtain realistic estimates of sea-level rise.

This same technique is used in Figures 39–48, where monthly mean sea levels are analyzed at different tide-gauge sites during periods of overlapping data. Monthly mean sea levels from both sites are excluded from these plots if more than 50% of the data are missing at either site. It is important to note that the units on the x-axes are months. Therefore, the computed linear trends must be multiplied by 1200 to obtain rates of sea-level rise in cm/century.

Figure 39 shows monthly mean sea levels at Charlottetown and Escuminac for the period of common record, together with the differences (Charlottetown minus Escuminac) and their linear trends. Charlottetown shows a linear trend of 28.70 cm/century, while Escuminac has a linear trend of 20.88 cm/century. The linear trend of the differences is 7.80 cm/century. The difference in the linear trends between Charlottetown and Escuminac is therefore 7.82 cm/century. When subtracted from the long-term sea-level trend of 32 cm/century for Charlottetown, this suggests that Escuminac has a long-term trend of 24.2 cm/century. If we propagate the linear trend of the differences to the Charlottetown long-term sea-level trend, this also gives an estimate of 24.2 cm/century for the mean rate of relative sea-level rise at Escuminac.

These same data adjusted for the variation of monthly mean atmospheric pressure are shown in Figure 40. In this case, Charlottetown shows a linear trend of 33.48 cm/century, Escuminac has a linear trend of 24.00 cm/century, and the differences (Charlottetown minus Escuminac) have a linear trend of 9.60 cm/century. The difference in the linear trends between Charlottetown and Escuminac is therefore 9.48 cm/century, suggesting that Escuminac has a long-term trend of 23.5 cm/century. If we propagate the linear trend of the differences from the Charlottetown long-term sea-level trend of 32 cm/century, we obtain an estimate for sea-level rise in the Escuminac area of 23.4 cm/century.

Figure 41 shows monthly mean sea levels at Charlottetown and Pointe-du-Chêne for the earlier Pointe-du-Chêne record from 1972 to 1992, together with the differences in water level (Charlottetown minus Pointe-du-Chêne) and their linear trends. Charlottetown shows a linear trend of 20.40 cm/century, Pointe-du-Chêne has a linear trend of 12.36 cm/century, and the difference between the data sets has a linear trend of 8.04 cm/century. The difference in the linear trends between Charlottetown and Pointe-du-Chêne is also 8.04 cm/century. When subtracted from the Charlottetown long-term sea-level trend of 32 cm/century, this suggests that Pointe-du-Chêne has a long-term trend of 24.0 cm/century, the same result as we obtain by propagating the linear trend of the differences from Charlottetown.

The same data adjusted for monthly mean atmospheric pressure are shown in Figure 42. Here, Charlottetown shows a linear trend of 22.20 cm/century, Pointe-du-Chêne has a linear trend of 13.68 cm/century, and the difference between the data sets has a linear trend of 8.52 cm/century. The difference in the linear trends between Charlottetown and Pointe-du-Chêne is also 8.52 cm/century. When subtracted from the Charlottetown long-term sea-level trend of 32 cm/century, this suggests that Pointe-du-Chêne has a long-term trend of 23.5 cm/century.

Figure 43 shows monthly mean sea levels at Charlottetown and Pointe-du-Chêne for the entire period of the Pointe-du-Chêne data from 1971 to 2005, together with the differences in the water levels (Charlottetown minus Pointe-du-Chêne) and their linear trends. Charlottetown shows a linear trend of 21.48 cm/century, Pointe-du-Chêne has a linear trend of 24.60 cm/century, and the differences have a linear trend of −3.00 cm/century. The difference in the linear trends between Charlottetown and Pointe-du-Chêne is therefore 3.12 cm/century (with Pointe-du-Chêne rising faster). When added to the Charlottetown long-term sea-level trend of 32 cm/century, this suggests that Pointe-du-Chêne has a long-term trend of 35.1 cm/century. If we propagate the linear trend of the differences from the Charlottetown long-term sea-level trend, we obtain an estimate for sea-level rise in the Pointe-du-Chêne area of 35.0 cm/century.

The same data adjusted for the variation of monthly mean atmospheric pressure are shown in Figure 44. Here, Charlottetown shows a linear trend of 25.44 cm/century, Pointe-du-Chêne has a linear trend of 27.6 cm/century, and the differences between the data sets have a linear trend of −2.16 cm/century. The difference in the linear trends between Charlottetown and Pointe-du-Chêne is also 2.16 cm/century. Adding the difference to the Charlottetown long-term sea-level trend of 32 cm/century, we obtain an estimate of 34.2 cm/century for the long-term relative sea-level rise at Pointe-du-Chêne.

Figure 45 shows monthly mean sea levels at Escuminac and Pointe-du-Chêne for the period of the overlapping data in the original Pointe-du-Chêne record (1972–1991), together with the differences in the water levels (Pointe-du-Chêne minus Escuminac) and their linear trends. Pointe-du-Chêne has a linear trend of 11.88 cm/century, Escuminac has a linear trend of 6.48 cm/century, and the differences between the data sets have a linear trend of 5.40 cm/century. The difference in the linear trends between Pointe-du-Chêne and Escuminac is also 5.40 cm/century. If we assume that the rate of relative sea-level rise at Escuminac is 23 cm/century, then this gives us an estimate for sea-level rise in the Pointe-du-Chêne area of 28.4 cm/century.

The same data adjusted for the variation of monthly mean atmospheric pressure are shown in Figure 46. Here, Pointe-du-Chêne has a linear trend of 17.80 cm/century, Escuminac shows a linear trend of 11.16 cm/century, and the differences between the data sets have a linear trend of 6.72 cm/century. The difference in the linear trends between Escuminac and Pointe-du-Chêne is 6.64 cm/century. If we assume that the rate of sea-level rise at Escuminac is 23 cm/century, these give estimates of 29.6 and 29.7 cm/century for the long-term mean rate of relative sea-level rise in the Pointe-du-Chêne area.

Figure 47 shows monthly mean sea levels at Escuminac and Pointe-du-Chêne for the entire period of the overlapping data at Pointe-du-Chêne (1972–2005), together with the differences in the water levels (Pointe-du-Chêne minus Escuminac) and their linear trends. Pointe-du-Chêne has a linear trend of 23.16 cm/century, Escuminac has a linear trend of 14.76 cm/century, and the differences have a linear trend of 8.40 cm/century.

The difference in the linear trends between Pointe-du-Chêne and Escuminac is also 8.40 cm/century. Taking the rate of sea-level rise at Escuminac to be 23 cm/century, this gives us an estimate for sea-level rise in the Pointe-du-Chêne area of 31.4 cm/century.

The same data adjusted for the variation of monthly mean atmospheric pressure are shown in Figure 48. Here, Pointe-du-Chêne has a linear trend of 30.24 cm/century, Escuminac has a linear trend of 22.20 cm/century, and the differences have a linear trend of 8.04 cm/century. The difference in the linear trends between Pointe-du-Chêne and Escuminac is also 8.04 cm/century. Adding this to the rate of 23 cm/century at Escuminac, this gives us an estimate for sea-level rise in the Pointe-du-Chêne area of 31.0 cm/century.

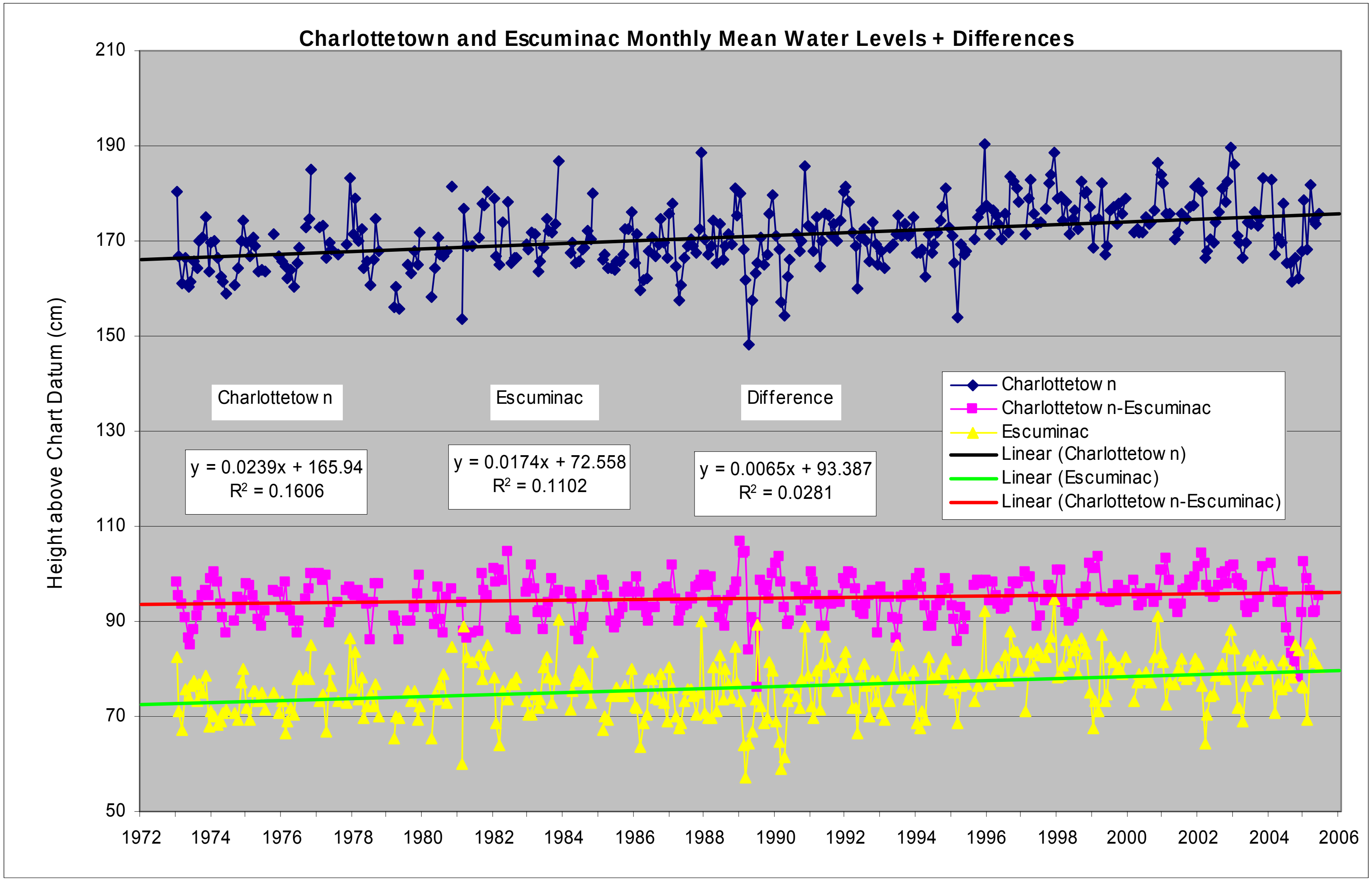

Figure 39. Monthly mean sea levels at Charlottetown and Escuminac, 1973–2005, and their differences.

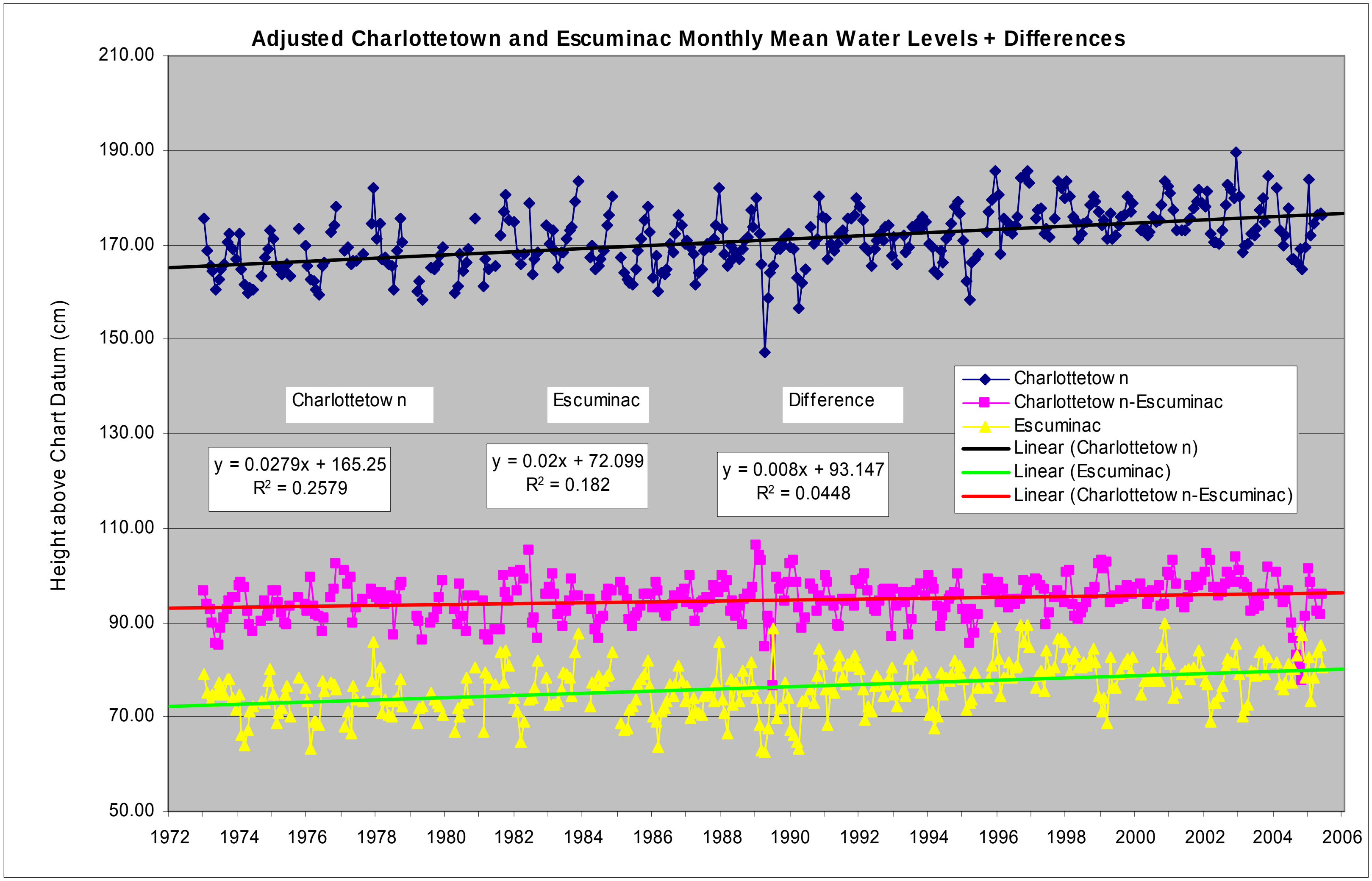

Figure 40. Adjusted monthly mean sea levels at Charlottetown and Escuminac, 1973–2005, and their differences.

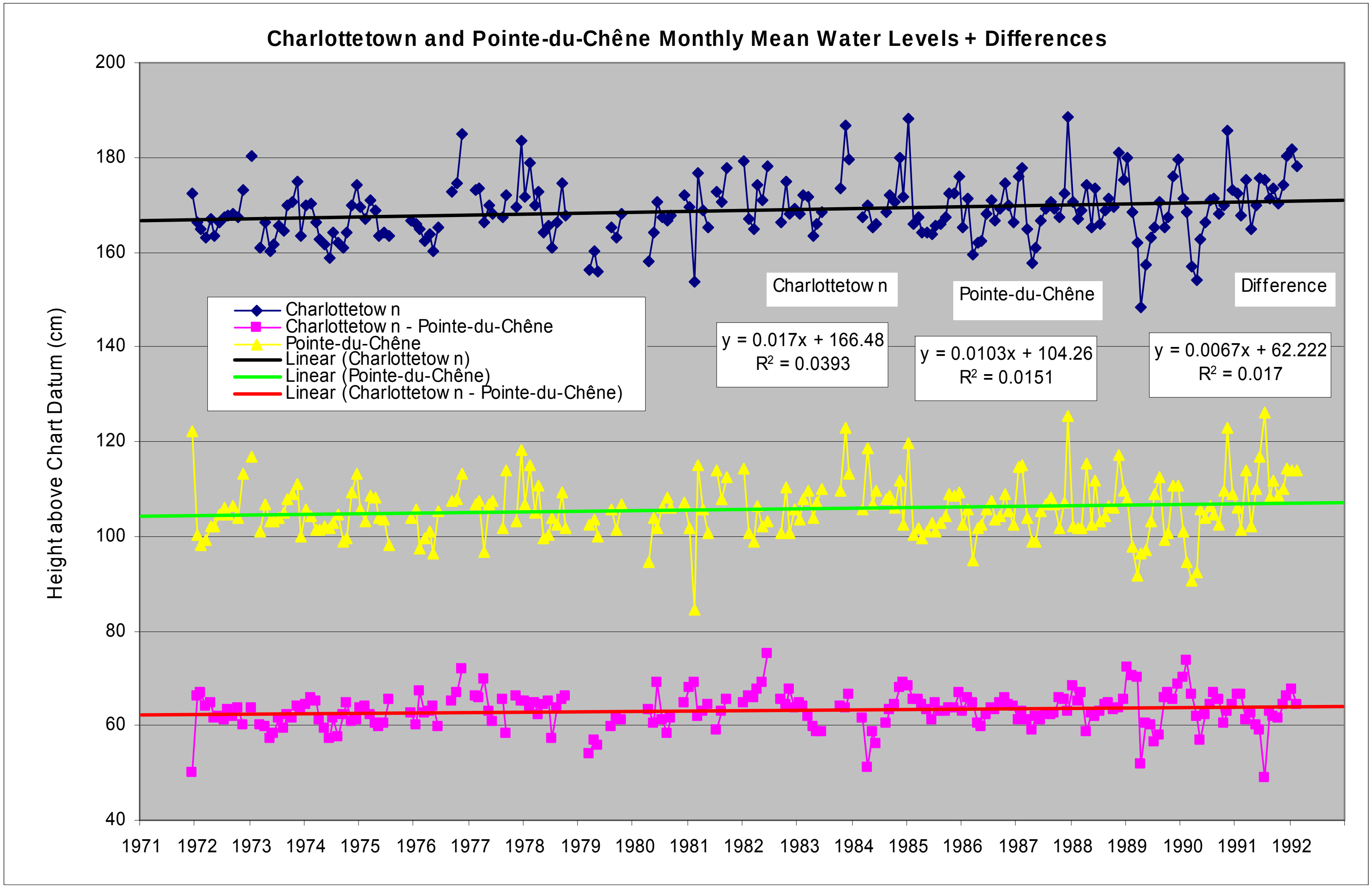

Figure 41. Monthly mean sea levels at Charlottetown and Pointe-du-Chêne, 1972–1992, and their differences.

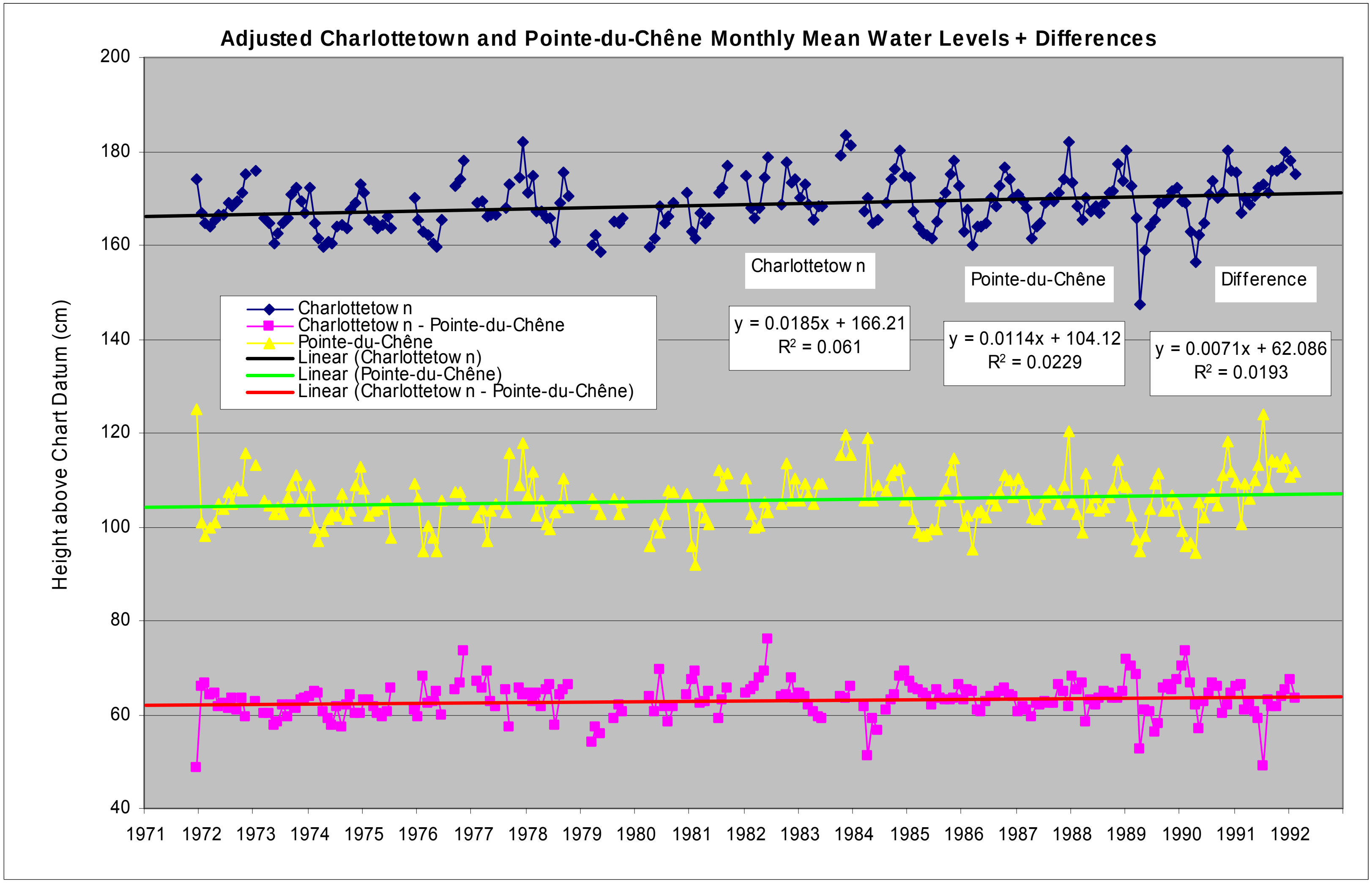

Figure 42. Adjusted monthly mean sea levels at Charlottetown and Pointe-du-Chêne, 1972–1992, and their differences.

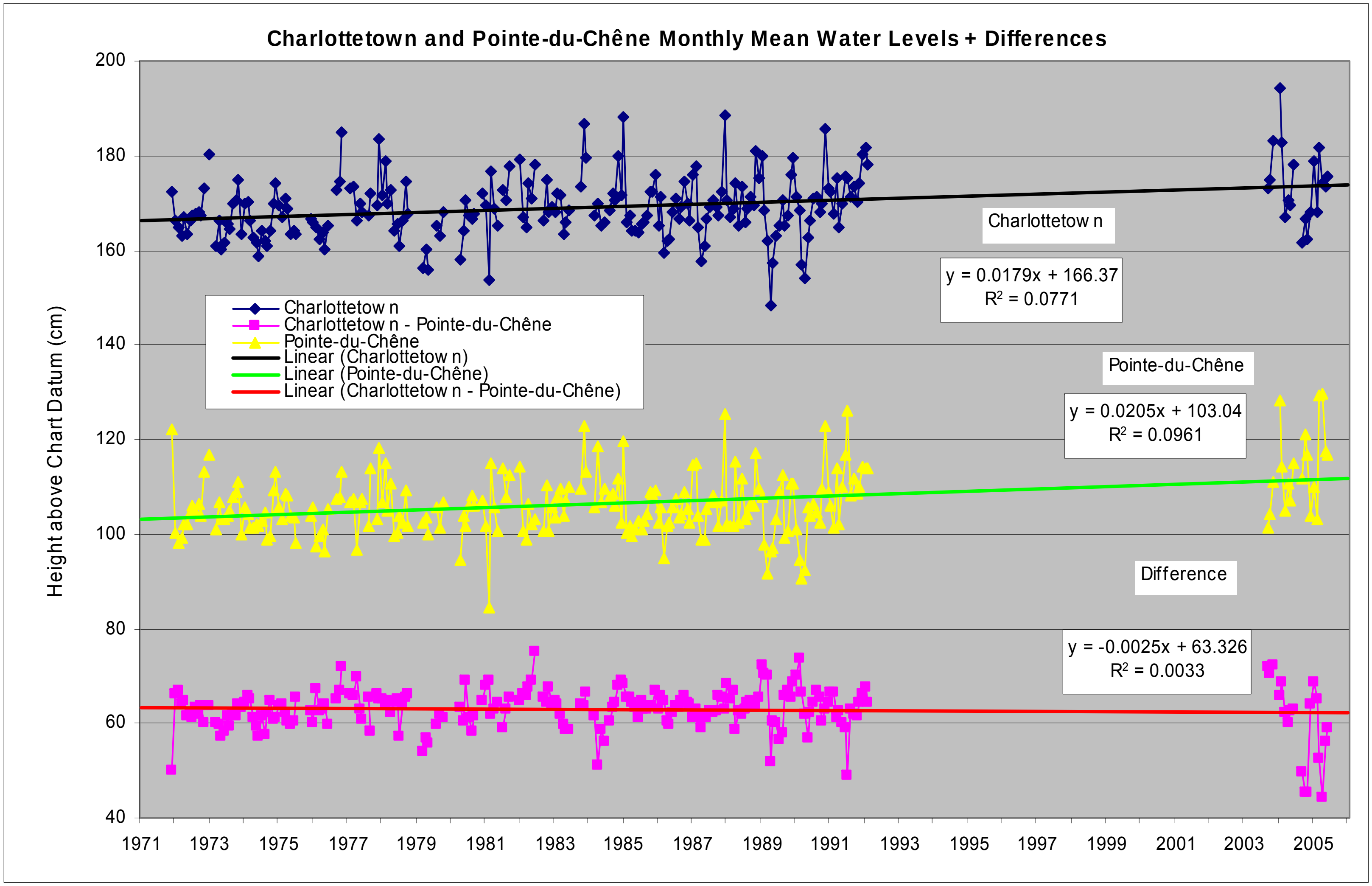

Figure 43. Monthly mean sea levels at Charlottetown and Pointe-du-Chêne, 1972–2005 and their differences.

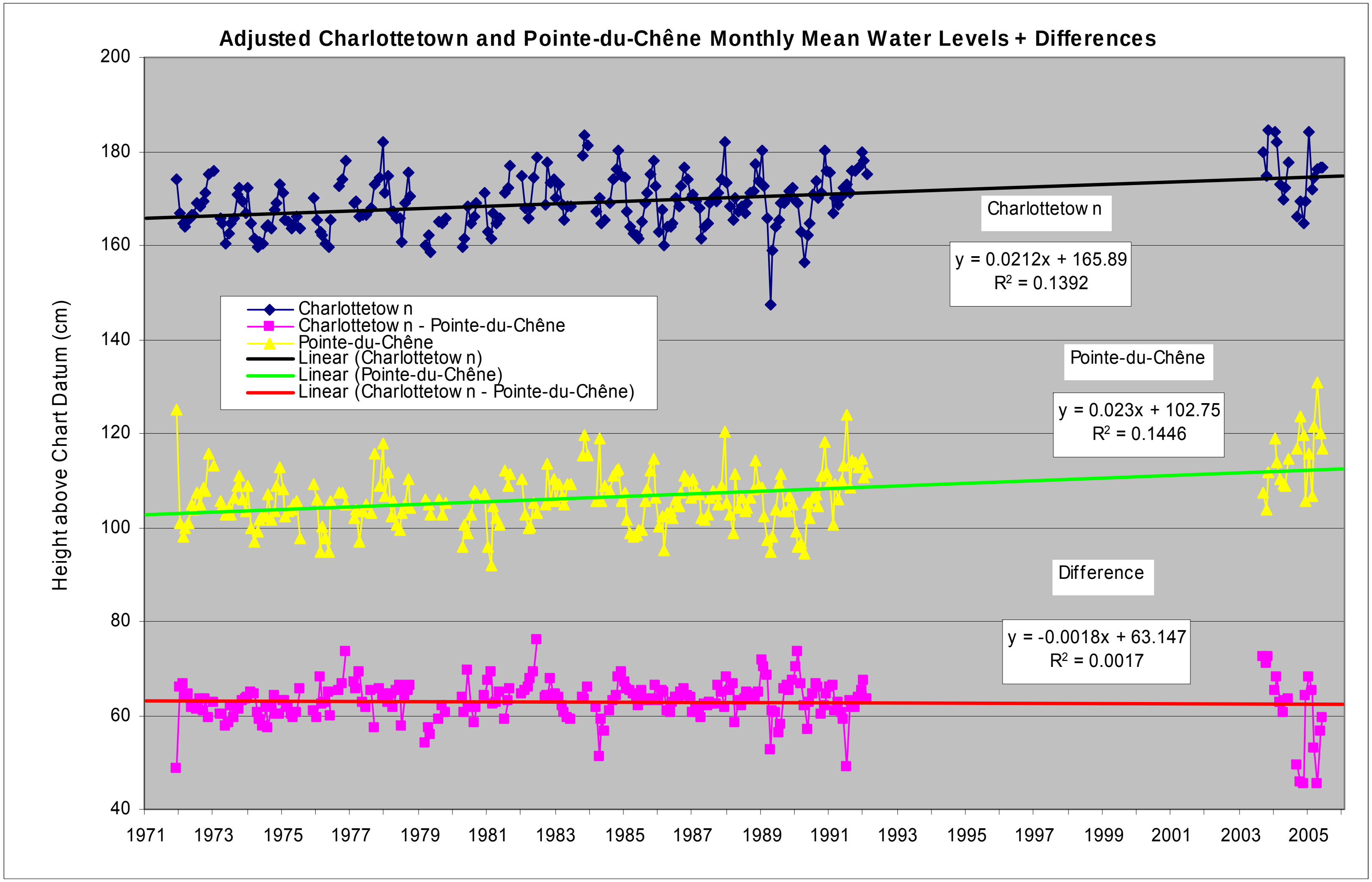

Figure 44. Adjusted monthly mean sea levels at Charlottetown and Pointe-du-Chêne, 1972–2005 and their differences.

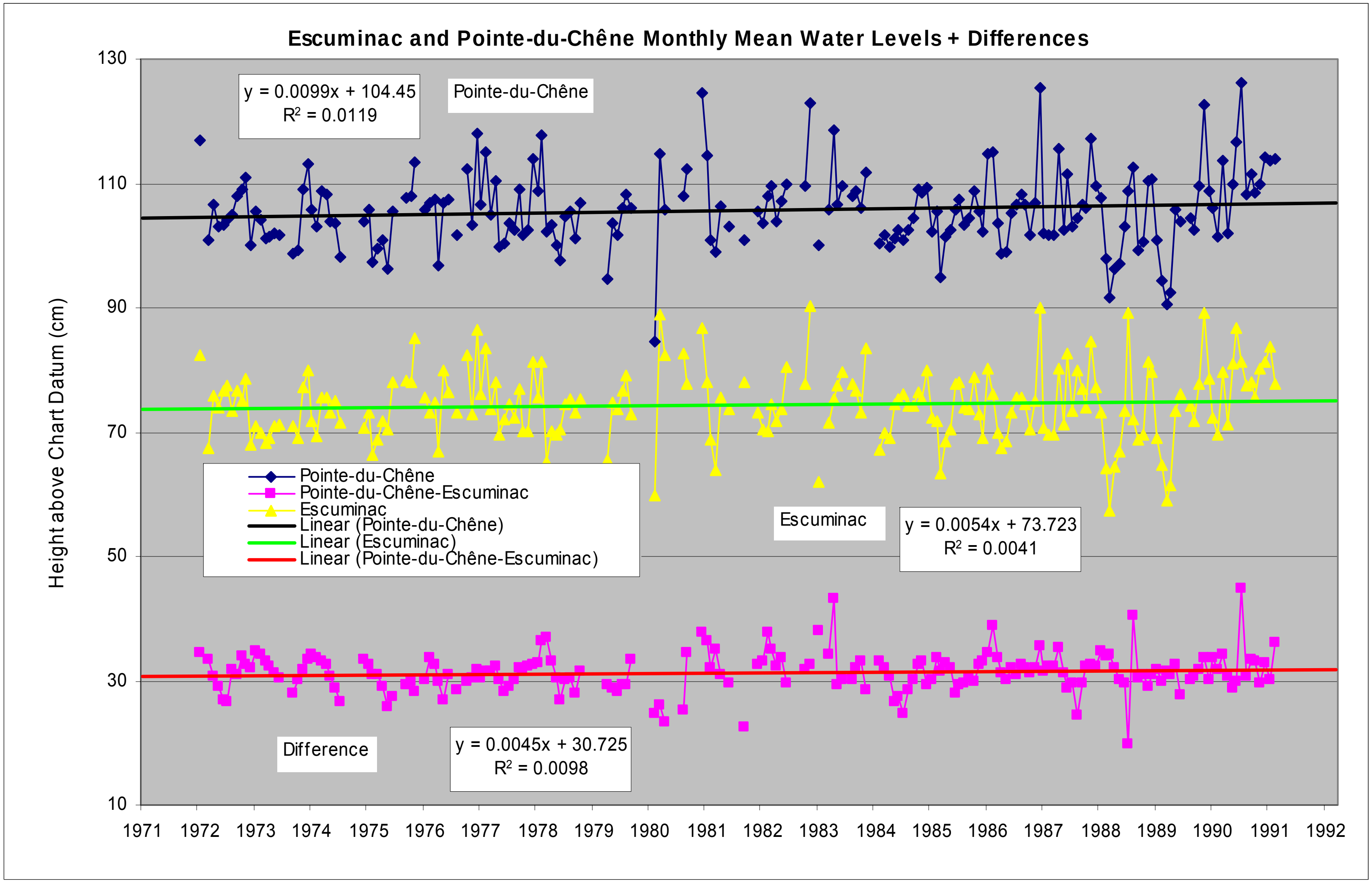

Figure 45. Monthly mean sea levels at Escuminac and Pointe-du-Chêne, 1972–1991, and their differences.

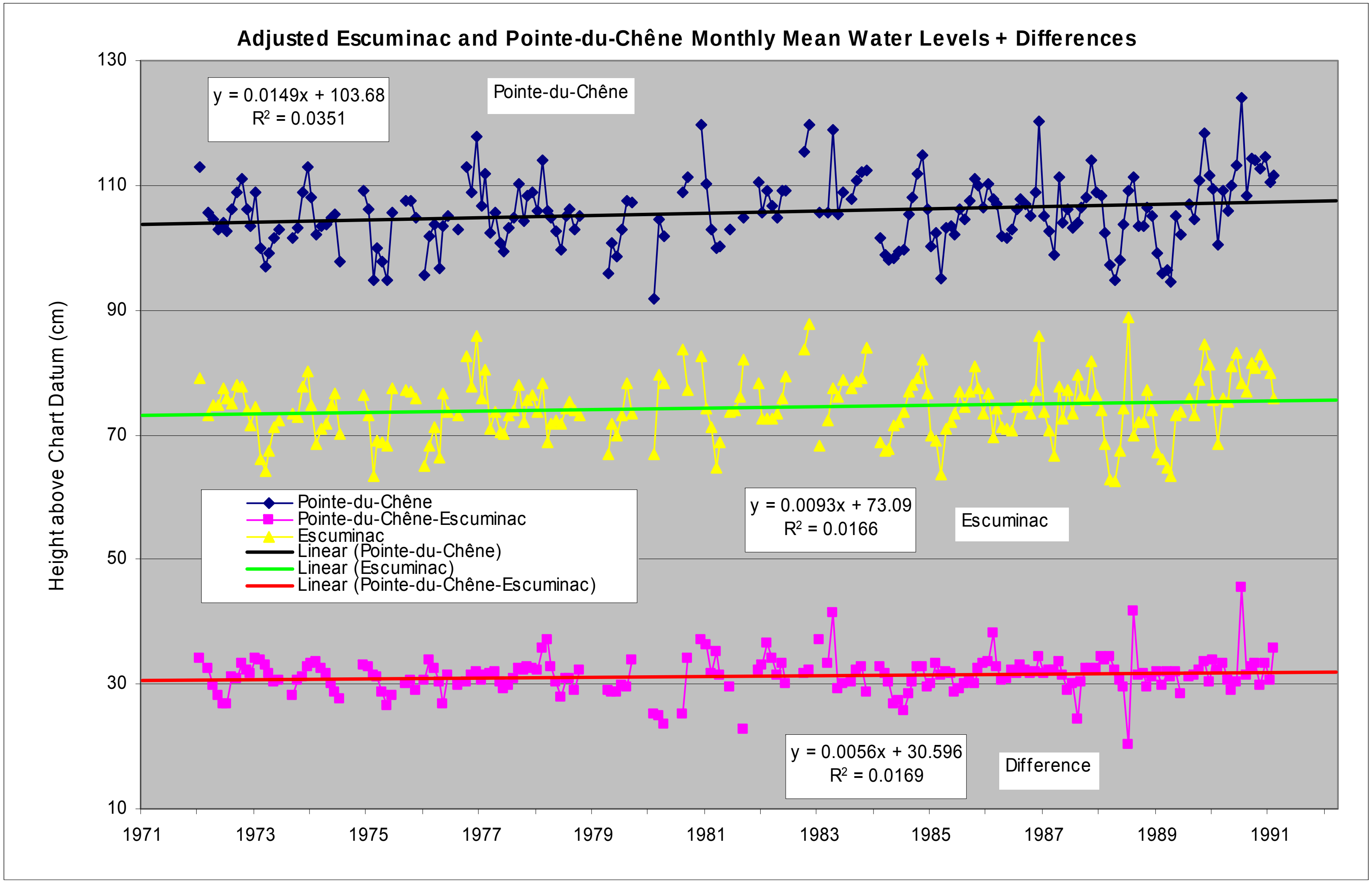

Figure 46. Adjusted monthly mean sea levels at Escuminac and Pointe-du-Chêne, 1972–1991, and their differences.

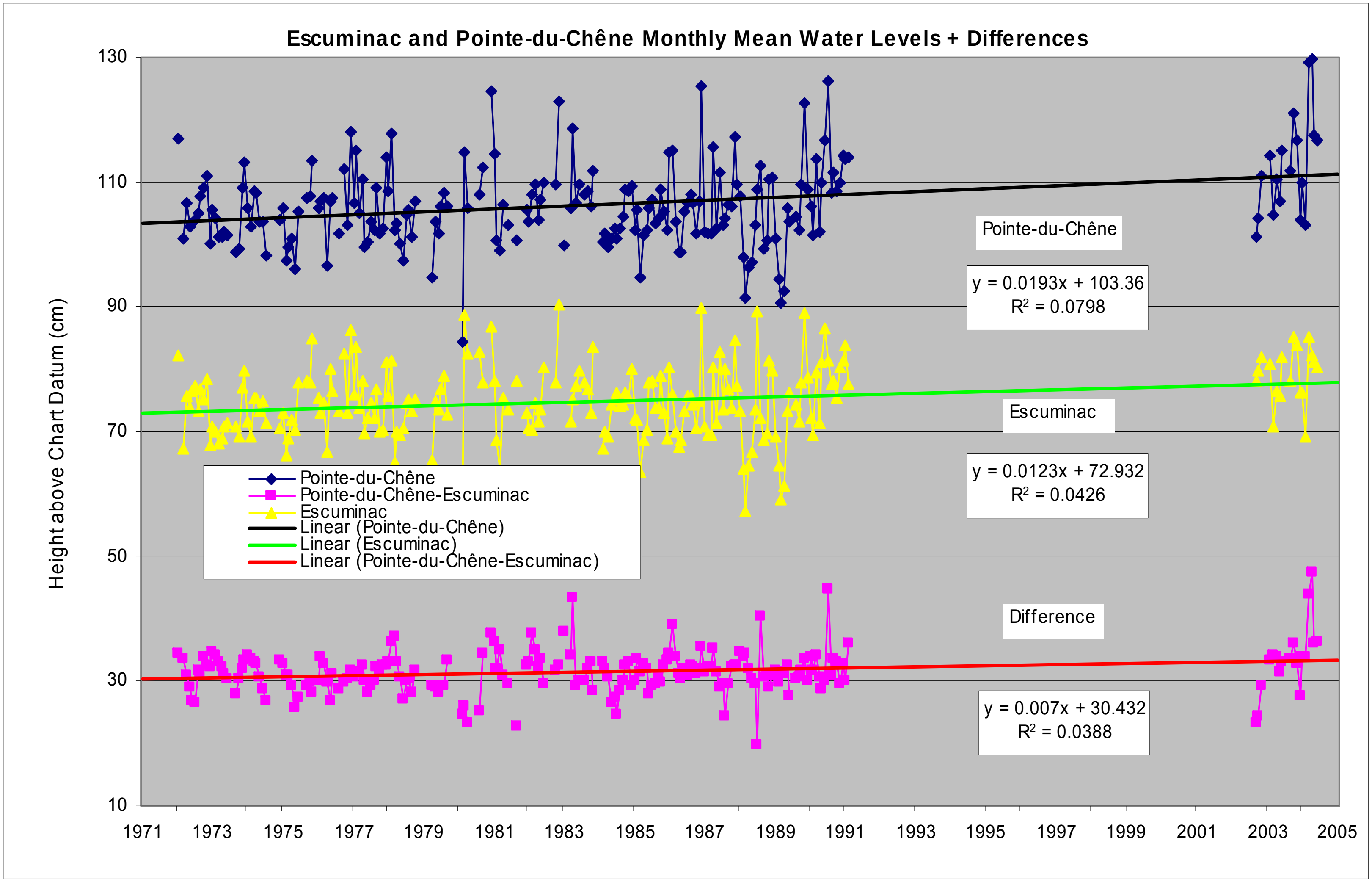

Figure 47. Monthly mean sea levels at Escuminac and Pointe-du-Chêne, 1972–2005 and their differences.

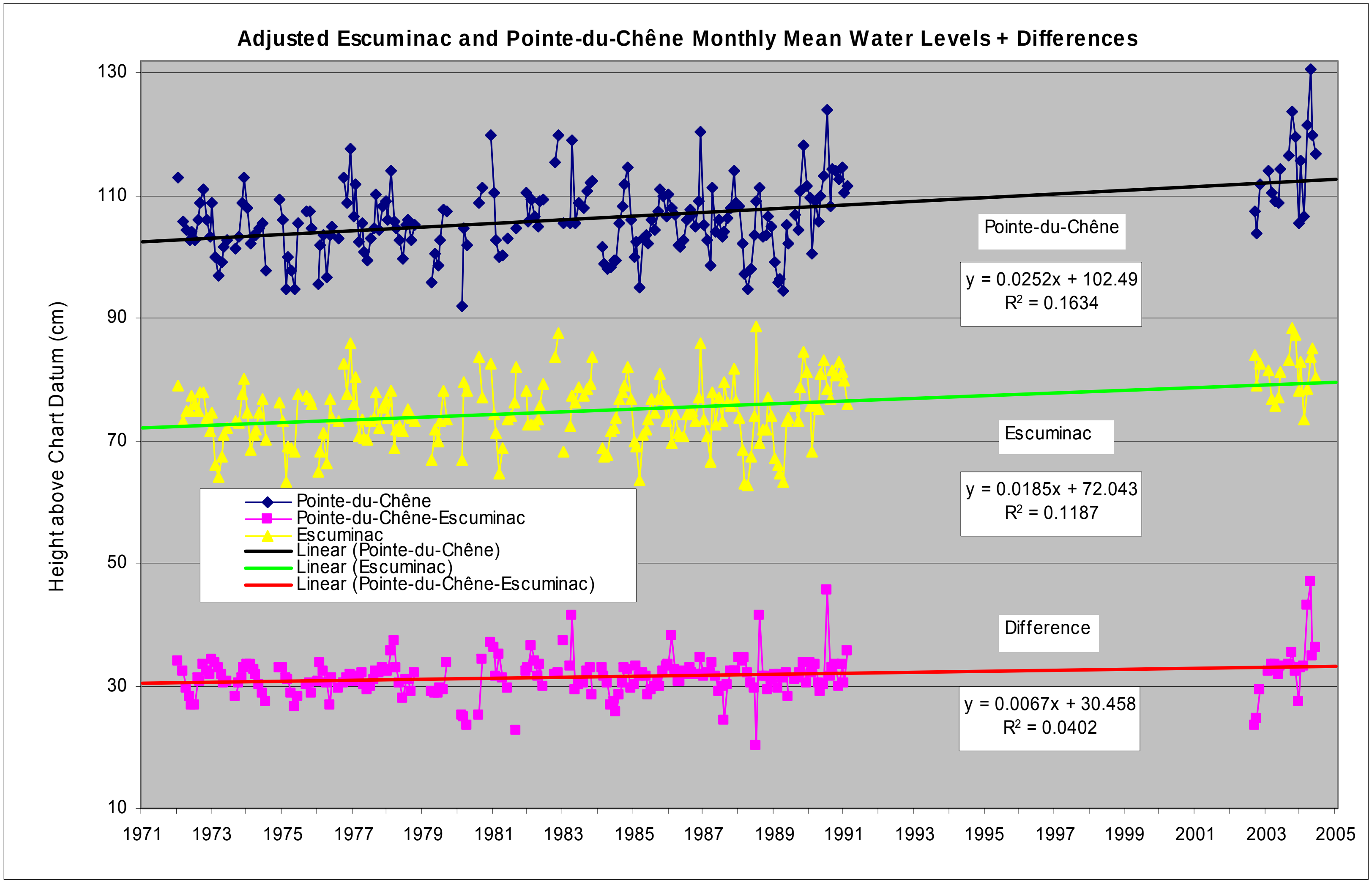

Figure 48. Adjusted monthly mean sea levels at Escuminac and Pointe-du-Chêne, 1972–2005 and their differences.

4.1.5 Summary of water-level analysis and comparisons with earlier work

4.1.5.1 Linear trends from individual station records

In the preceding sections, we have estimated trends in water-level data at Charlottetown (1911–2005), Escuminac (1973–2005) and Pointe-du-Chêne (1971–1992 and 2003–2005) using various methods.

As shown in Table 1, trends of relative sea-level rise have been computed for Charlottetown and Escuminac by linear regression of annual mean water levels (A), annual means adjusted for missing data (B) and annual means further adjusted to account for the annual variations in atmospheric pressure (C), as described in earlier sections. Relative sea-level rise has also been calculated from monthly mean water levels (D) and from the monthly means normalized for the month-to-month variation in atmospheric pressure (E).

Table 1. Trends of relative sea-level rise (cm/century) at Charlottetown (Prince Edward Island) and Escuminac (New Brunswick) computed from unadjusted and adjusted data as described in the text. In columns B and C, the values for Charlottetown are adjusted with outliers (1923 and 1929) removed.

Site	A^{annual}	B^{annual}	C^{annual}	$D^{monthly}$	$E^{monthly}$
Charlottetown (1911–2005)	32.5[1]	31.5[2]	31.9[3]	31.4[4]	31.8[5]
Escuminac (1973–2005)	20.1[6]	20.2[7]	23.8[8]	19.9[9]	23.2[10]

Sources: [1] Figure 3, [2] Figure 10, [3] Figure 24, [4] Figure 4, [5] Figure 23, [6] Figure 11, [7] Figure 16, [8] Figure 31, [9] Figure 18, [10] Figure 29.

Note: Monthly regression trends are multiplied by 1200 to obtain cm/century.

The 95-year record of water-level data at Charlottetown is one of the longest in Atlantic Canada. Over this period, the signal of sea-level rise is so strong that accounting for the variance associated with missing data and atmospheric pressure has little impact on the trend (31–32 cm/century). The plot of monthly mean water levels normalized for the month-to-month variation of atmospheric pressure provides the best available time series for this important station and shows a long-term trend of relative sea-level rise at Charlottetown of 32 cm/century (Figure 23).

The 33-year inventory of water-level data at Escuminac yields similar, although less consistent, results in this analysis of means, indicating trends of 20–24 cm/century. Normalizing for the year-to-year and month-to-month variability of atmospheric pressure yields the higher values of around 24 cm/century (annual) and 23 cm/century (monthly).

In Table 2, the Pointe-du-Chêne data set is analyzed for two record lengths. The original data set comprising 22 years of record (1971–1992) is analyzed first. This older record is then combined with the newer data from 2003–2005, designated P-d-C (71-05).

The estimated trend at Pointe-du-Chêne changes dramatically with the inclusion of the new data from 2003–2005. Furthermore, there is a large difference in the estimates for the full length of record between the trends estimated from annual data and those determined from the monthly means. This may be because of missing data and the short record length for the 2003–2005 data. Because the new gauge was installed in the fall of

2003, 70% of the data for that year are missing, leaving only two annual data points (2004 and 2005) for the annual time series 1971–2005. For the same full length of record, the analysis of monthly means normalized for the variation in atmospheric pressure indicates a trend of about 27 cm/century (Table 2 and Figure 30).

Table 2. Trends of relative sea-level rise (cm/century) at Pointe-du-Chêne (New Brunswick) for two lengths of record, 1971–1992 and 1971–2005 (with no data for the years 1993–2002), computed from unadjusted and adjusted data as described in the text.

Site	A^{annual}	B^{annual}	C^{annual}	$D^{monthly}$	$E^{monthly}$
P-d-C (71-92)	11.0[1]	9.32	12.45	11.04	13.3
P-d-C (71-05)	28.5[2]	29.2[3]	33.3[4]	23.5[5]	27.1[6]

Sources: [1] Figure 12, [2] Figure 13, [3] Figure 17, [4] Figure 32, [5] Figure 19, [6] Figure 30. Full analysis of P-d-C short data set is not included in the text).
Note: Monthly regression trends are multiplied by 1200 to obtain cm/century.

4.1.5.2 Linear trends from propagation of differences

As noted previously, Carrera et al. (1991a), among others, have warned of the large sampling errors that can contaminate estimates of linear trends from short data sets (less than 40 years). Sampling bias can result from low-frequency atmospheric and oceanic effects, resulting in slowly varying relative sea-level trends at multiyear to decadal scales. This is evident in the Charlottetown record, as seen from the low-pass filtered time series in Figures 23 and 25. Water levels from short record lengths can provide a basis for more reliable estimates of linear trends when methods of propagating differences are used (e.g., Carrera et al., 1991a; Mainville and Craymer, 2005).

As presented in Section 4.1.4 above, we have followed this approach and propagated the Charlottetown long-term sea-level trend to the two New Brunswick stations (Escuminac and Pointe-du-Chêne) by analysis of the differences in linear trends during periods of overlapping data and of the trends in the water-level differences. This provides estimates of relative sea-level rise for Escuminac and Pointe-du-Chêne without the biases in the shorter records resulting from longer-term variability of water levels in the southern Gulf of St. Lawrence. In the following presentation, a mean value of 32 cm/century is adopted as the reference trend at Charlottetown.

4.1.5.2.1 Long-term relative sea-level rise at Escuminac

Results are shown in Table 3 for annual mean water levels (F), annual mean water levels adjusted for the annual variation of atmospheric pressure (G), monthly mean water levels (H) and monthly mean water levels adjusted for the variation of atmospheric pressure (I).

Table 3. Revised estimates of linear trends in relative sea level (cm/century) at Escuminac, obtained by propagating the differences from Charlottetown for years and months of common record.

Site	F^{annual}	G^{annual}	$H^{monthly}$	$I^{monthly}$
Escuminac	23.8[1]	23.6[2]	24.2[3]	22.4[4]

Sources: [1] Figure 33, [2] Figure 34, [3] Figure 39, [4] Figure 40.
Note: Monthly regression trends are multiplied by 1200 to obtain cm/century.

During the 33-year record of water levels at Escuminac, when the annual trend there was 20.1 cm/century (Table 1), the equivalent trend at Charlottetown was 28.3 cm/century (Figure 33). The difference between these rates is 8.2 cm/century. When adjusted for missing data and atmospheric pressure, the equivalent trends at Escuminac and Charlottetown were 23.8 and 32.2 cm/century, respectively, yielding a difference of 8.4 cm/century and an adjusted long-term trend at Escuminac of 23.6 cm/century.

As shown previously, the equivalent analysis of the difference in monthly mean water levels (Figure 40) shows a trend of 24.0 cm/century at Escuminac (for adjusted monthly means) and a trend for the same months of record at Charlottetown of 33.5 cm/century (a difference of 9.5 cm/century). An alternative computation of the linear trend in the differences between monthly means gives a trend of 9.6 cm/century. Using the latter as the preferred value, we obtain an adjusted trend of 22.4 cm/century at Escuminac over the longer term (Table 3). Results from this analysis of adjusted water-level data are consistent, indicating that the long-term relative sea-level rise in the Escuminac area, as estimated from tide-gauge data, ranges from 22 to 24 cm/century. This validates the trend determined independently from the Escuminac data alone (Table 1). Therefore, in the following analysis, we adopt a value of 23 cm/century for the recent long-term trend at Escuminac.

4.1.5.2.2 Long-term relative sea-level rise at Pointe-du-Chêne

Results obtained by propagating differences to Pointe-du-Chêne are less definitive (Table 4). The early record (1971–1992) now shows much larger rates of sea-level rise (23–28 cm/century) than the direct analysis of trends (Table 2, A–E). These values are closer to but still less than the original results (27–33 cm/century) for the longer record (1971–2005) in Table 2 (A–E) above. However, the propagation of differences from Charlottetown for the longer record (1971–2005) gives results that are unrealistically high (34–44 cm/century). This result is highly dependent on the accuracy of the recent data, both at Pointe-du-Chêne and at Charlottetown. Also, if there were a levelling issue at Pointe-du-Chêne (with either the present gauge or the earlier one), then results using the combined data set would be questionable. Furthermore, we note that the Charlottetown annual mean for 2004, which spans more than 40% of the time frame of the recent data (50% for the annual data), is anomalously low compared with those for other recent years. In contrast, at Escuminac, the 2004 water levels are not anomalously low. Hence, we reject the Pointe-du-Chêne trends computed for the 1971–2005 record by propagation from Charlottetown.

Table 4. Revised estimates of linear trends in relative sea level (cm/century) at Pointe-du-Chêne, obtained by propagating the differences from Charlottetown for years and months of common record.

Site	F^{annual}	G^{annual}	$H^{monthly}$	$I^{monthly}$
P-d-C (71-92)	27.8[1]	27.8[2]	24.0[3]	23.5[4]
P-d-C (71-05)	43.4	43.7	35.0[5]	34.2[6]

Sources: [1] Figure 35, [2] Figure 36, [3] Figure 41, [4] Figure 42, [5] Figure 43, [6] Figure 44.
Note: Monthly regression trends are multiplied by 1200 to obtain cm/century.

Finally, we propagate the differences between Escuminac and Pointe-du-Chêne from the longer-term sea-level trend estimated for Escuminac (23 cm/century) as an independent approach to estimate sea-level rise at Pointe-du-Chêne. Results are shown in Table 5 for monthly mean water levels (J) and monthly mean water levels adjusted for the variation of atmospheric pressure (K).

Table 5. Revised estimates of linear trends in relative sea level (cm/century) at Pointe-du-Chêne, obtained by propagating the differences from Escuminac for months of common record.

Site	$J^{monthly}$	$K^{monthly}$
Pointe-du-Chêne (72-92)	28.4[1]	29.7[2]
Pointe-du-Chêne (72-05)	31.4[3]	31.0[4]

Sources: [1] Figure 45, [2] Figure 46, [3] Figure 47, [4] Figure 48.
Note: Monthly regression trends are multiplied by 1200 to obtain cm/century.

We note that propagating differences for the full Pointe-du-Chêne data set, including the recent 2003–2005 data (71-05), leads to rather variable and inconclusive results, which generally seem too high (particularly annual means). Working with the earlier data set alone (71-92) yields more consistent results, once differences are propagated with respect to the Charlottetown and Escuminac long-term trends. If we also eliminate the results from propagating recent differences in monthly means from the Charlottetown long-term trend (where the influence of 2004 may be undesirable), then we are left with the summary results shown in Table 6.

Table 6. Summary of retained estimates for the recent relative sea-level trend (cm/century) at Pointe-du-Chêne (from Tables 2, 4 and 5 above).

Site	A	B	C	D	E	F	G	H	I	J	K
P-d-C (71-92)						28	28	24	24	28	30
P-d-C (71-05)	29	29	33	24	27					31	31

We therefore conclude that long-term relative sea-level rise in the Pointe-du-Chêne area, calculated from tide-gauge data alone, is somewhat uncertain, but is probably in the range of 25–30 cm/century (Table 6). We recognize that there is a larger margin of error here due to the short period of the water-level data and to the strong response of water levels in this area to atmospheric forcing. Collection of more water-level data from this site in future years is highly desirable to clarify results and to support co-location with a continuous global positioning system (GPS) station (see below).

Carrera et al. (1991a), in their analysis of Escuminac data for 1973–1988, estimated a linear trend of 3 cm/century from point values but an adjusted trend of 21 cm/century when propagating the mean sea-level rise from Halifax (35 cm/century) to the linear trend of the differences in Escuminac and Charlottetown water-level data. This impressive result is similar to the result that we have obtained here from an analysis of twice as many data. At Pointe-du-Chêne, presumably using 1972–1988 data (most of the record available to us), Carrera et al. (1991a) computed a linear trend of 12.6 cm/century (cf. Figure 13 and Table 2 A) from point values alone, but adjusted the value to 30 cm/century when propagating the rate of mean sea-level rise at Halifax to the linear trend of the differences in Pointe-du-Chêne and Charlottetown water-level data. Our estimates fit well into the map of relative sea-level rise from Carrera et al. (1991a) (Figure 49).

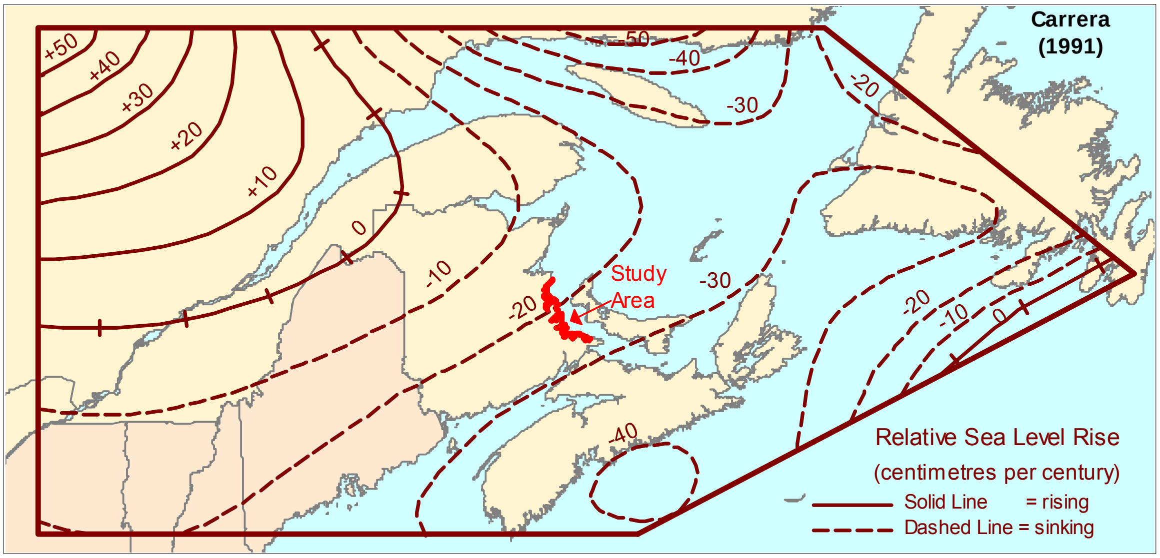

Figure 49. Map of relative sea-level rise in the Maritimes region (after Carrera et al., 1991a).

4.1.6 Components of sea-level rise in southeastern New Brunswick

The observed sea-level rise at specific locations, as described in the foregoing sections, is the apparent change of sea level in relation to fixed points on the land (the relative sea-level rise). It is not a direct measure of rising sea level, but a combination of changes in the level of the sea and of any vertical motion of the land surface. At large time scales, the latter can be very significant, as seen in the long-term relative sea-level history and resulting paleogeography for the region (Shaw et al., 2002).

The global mean sea level (or equipotential surface) is a function of the total ocean mass (Chambers et al., 2000), the bathymetry of the ocean basins, the variable density of seawater, geographic variation in the Earth's gravitational field and feedback associated with perturbations in the Earth's rotation rate caused by changes in the glacial and ocean load distribution around the globe (Wu and Peltier, 1984). Solar and lunar gravitational effects cause periodic tides ranging from about 12 hours to the 18.6-year nodal cycle, but have no significant effect on mean sea level. Other gravitational effects can exert a significant influence on regional sea level.

Woodward (1888) demonstrated that self-gravitation in the surface load derived from glacial meltwater added to the ocean would lead to non-uniform sea-level change, with sea level actually falling over a significant region close to the source of melting (Farrell and Clark, 1976). The gravitational attraction of large ice masses such as the Greenland and Antarctic ice caps is sufficient to deflect the mean sea level upward in their vicinity. Mitrovica et al. (2001) demonstrated the large geographic variation and contrasting patterns of sea-level change due to melting ice in Greenland, Antarctica and mountain glaciers and ice sheets. If eustatic sea-level change is defined as the change in global mean sea level due to a change in the total ocean volume (the net change in glacial ice mass divided by the mean density of seawater within an appropriately defined mixing volume), the change of regional sea level in Atlantic Canada would be <20% of the global eustatic contribution from Greenland ice melt, ~110% from the Antarctic ice melt and ~90% from mountain ice sources. Mitrovica et al. (2001) cite these patterns as at least a partial explanation for anomalously low historical rates of relative sea-level rise in northwestern Europe, roughly 0.11 m over the past century (Lambeck et al., 1998; Woodworth et al., 1999), compared with estimates of 0.15–0.19 m over the same time interval for the North American east coast (Gornitz, 1995; Mitrovica and Davis, 1995; Peltier, 1996). However, geographic differences in relative sea-level change may also be attributed to differences in ocean thermal expansion and circulation (Church et al., 2004).

Thermal expansion over recent decades has been estimated to be in the range between 0.7 and 1.1 mm/year (7–11 cm/century) from combined atmosphere–ocean general circulation models and about 1 mm/year (10 cm/century) from observations, while changes in total water mass due to glacial mass-balance adjustments are estimated to be between −0.2 and 0.0 mm/year for Antarctica and between 0.0 and 0.1 mm/year for Greenland (Church et al., 2001). While the regional implications of glacial meltwater contributions may be well represented in recent models (Milne et al., 1999; Mitrovica et al., 2001), the geographic variation in thermal expansion is less well understood. It is also estimated that long-term adjustment to past climate change in the Greenland and Antarctic ice caps may account for 0.0–0.5 mm/year global sea-level rise over the past century (Church et al., 2001).

The component of relative sea-level change due to vertical motion in the earth's crust can vary significantly over relatively short distances, the length scale depending on the mantle viscosity and elastic response to changing surface loads. Both rapid and long-term tectonic motion may also be a factor. In eastern New Brunswick, the dominant component of vertical motion is the postglacial isostatic responses to removal of the regional ice load approximately 12 000 years ago and subsequent reloading by water rising back into the southern Gulf of St. Lawrence over the past 9000 years (Shaw et al., 2002). The isostatic response may be complex in time, in part related to the postulated migration of a marginal forebulge through the region as the Laurentide ice sheet retreated to centres over Labrador and Hudson Bay (Walcott, 1972; Gehrels et al., 2004).

4.1.6.1 Vertical motion in eastern New Brunswick

We follow three lines of evidence to estimate the vertical motion in eastern New Brunswick. Estimates of global sea-level rise over the past 135 years are in the range of about 1.7 ± 0.3 mm/year (17 ± 3 cm/century), with an acceleration of 0.013 ± 0.006 mm/year^2 (Church and White, 2006). Although there is significant geographic variation in the rates (Church et al., 2004), if we assume that these rates apply regionally in the southern Gulf of St. Lawrence, subtraction from the observed water-level records gives estimates of the vertical motion. For Charlottetown, the rate of subsidence computed by this method is 15 ± 3 cm/century; for Escuminac, the rate is 6 ± 3 cm/century.

Other evidence comes from geodetic levelling (Vaníček and Nagy, 1980) and gravity measurements (Forbes et al., 2001). The latter have high uncertainty due to the relatively short time interval of observations and cannot yet provide a reliable estimate of subsidence for Charlottetown (A. Mainville, Geodetic Survey Division, pers. comm., 2000). Estimates of vertical crustal motion by Vaníček and Nagy (1980) and Koohzare et al. (2005) use a combination of tidal analysis and geodetic levelling data. As levelling data along the Halifax–Québec railway line indicate maximum subsidence in the vicinity of the isthmus linking Nova Scotia to New Brunswick (Grant, 1970), it is plausible to suppose that subsidence may be greater in the Moncton–Shediac region than farther north along the eastern coast of New Brunswick. The recent reconstruction of vertical motion by Koohzare et al. (2005) shows the rate of subsidence diminishing from 15 cm/century at Charlottetown to about 8 cm/century at Shediac/Pointe-du-Chêne to 0 cm/century in the vicinity of Cap Lumière (Figure 50). This interpretation suggests a rate of uplift of about 10 cm/century at Escuminac, which is not consistent with the water-level analysis presented above. Although the general pattern of tilting for the study area is supported by our data, we believe that it is less extreme than shown in Figure 50 and that a small component of subsidence remains at Escuminac. On the other hand, the rate of subsidence shown for Charlottetown is the same value (15 cm/century) deduced above by subtraction of estimated sea-level rise. Note that this is less by 5 cm/century than the value that was used in the earlier study of impacts in Prince Edward Island (McCulloch et al., 2002; Parkes et al., 2002).

At Pointe-du-Chêne, if we add the vertical motion of 8 cm/century (Figure 50) and the sea-level rise of 17 cm/century used above, we obtain an estimate of relative sea-level rise in the Shediac area of 25 cm/century, at the low end of the range computed above in Section 4.1.5.2 (Table 6). In view of our revision at Escuminac and evidence for slightly higher relative sea-level rise at Pointe-du-Chêne, we adopt an estimate of 10 cm/century for the Shediac area. Another point to note in Figure 50 is that there is a strong gradient east along the coast from Shediac (10 cm/century) to Cape Jourimain (15 cm/century), the latter having the same value as Charlottetown, according to this interpretation.

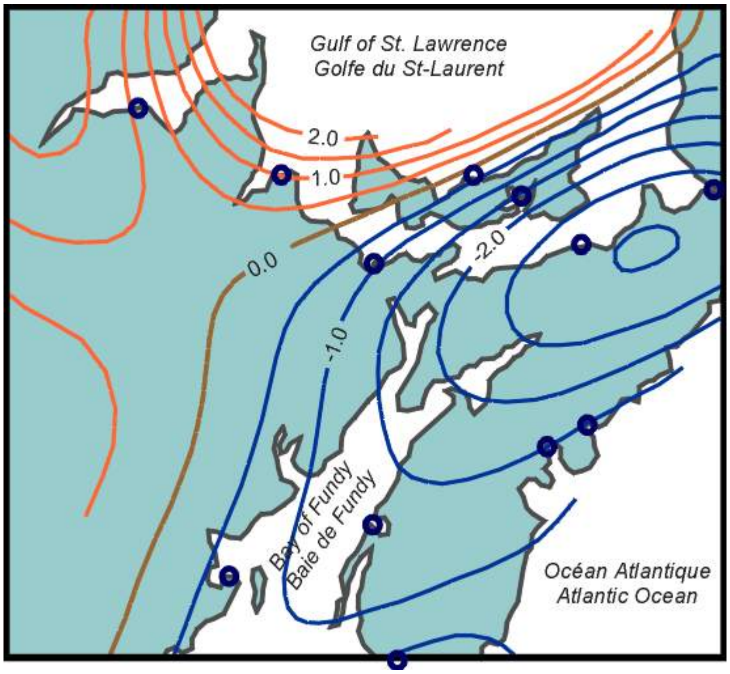

Figure 50. Vertical crustal motion in the Maritime provinces derived from tide-gauge data and geodetic levelling using cubic spline polynomials (after Koohzare et al., 2005). Open circles show locations of tide gauges used in the analysis. Isolines in blue denote subsidence, and lines in orange denote uplift (both in mm/year).

Finally, we consider the available data on vertical motion from direct measurements using GPS receivers. A number of epoch sites have been established in the region over the past decade. These are stable monuments reoccupied at intervals of months to years for GPS observations, typically over 1–5 days. Preliminary results from two stations, one in Bathurst and the other in Moncton, are shown in Figures 51 and 52. The values obtained from these measurements over 10 years from 1994 to late 2003 show subsidence of 3.44 mm/year and 3.82 mm/year at Bathurst and Moncton, respectively, relative to a reference station at Algonquin Park (Ontario). Using a value of 2.9 ± 0.6 mm/year uplift at Algonquin from Henton et al. (2004), these measurements indicate subsidence of about 5 mm/year (5 cm/century) at Bathurst and 9 mm/year (9 cm/century) at Moncton, consistent with other estimates determined above.

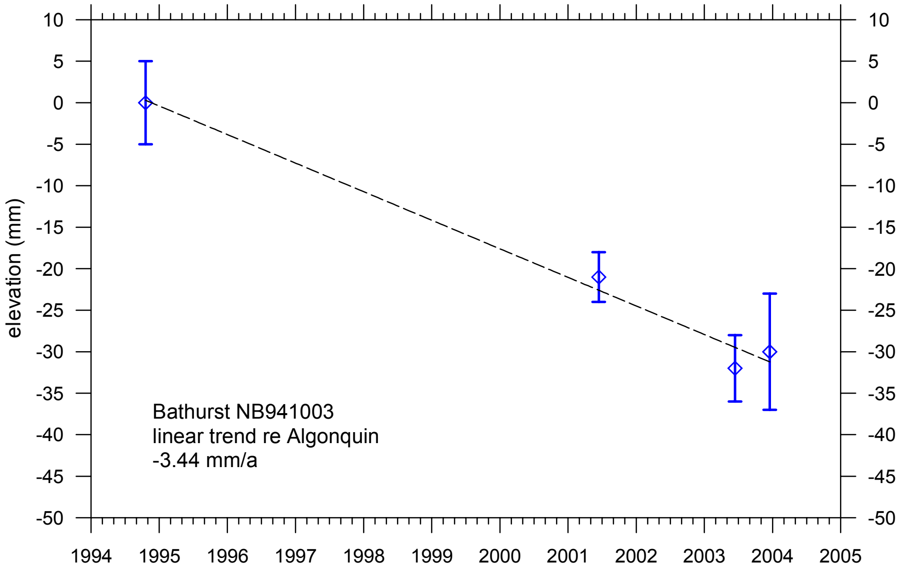

Figure 51. Vertical motion determined by epoch GPS measurements at Canadian Base Network (CBN) site NB941003, Bathurst, New Brunswick. Motion relative to Algonquin, Ontario (data courtesy of M. Craymer and J. Henton, Geodetic Survey Division, Natural Resources Canada, Ottawa).

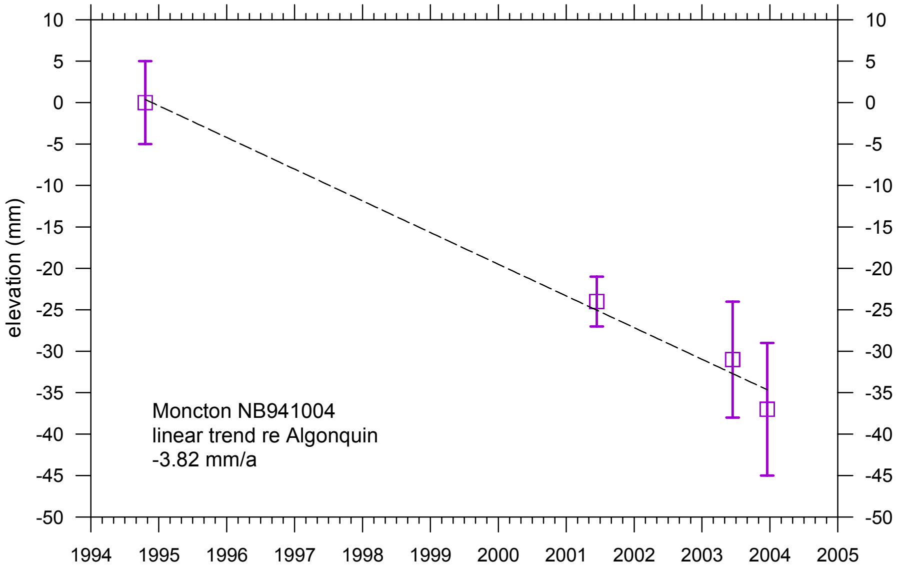

Figure 52. Vertical motion determined by epoch GPS measurements at Canadian Base Network (CBN) site NB941003, Bathurst, New Brunswick. Motion relative to Algonquin, Ontario (data courtesy of M. Craymer and J. Henton, Geodetic Survey Division, Natural Resources Canada, Ottawa).

As part of this project, stations for continuous GPS monitoring have been established close to each of the tide gauges in the study area, at Escuminac and Shediac/Pointe-du-Chêne. Continuous GPS measurements were initiated at each site in the early summer of 2005 (30-second sampling, downloaded to Geodetic Survey of Canada offices in Ottawa on a daily basis, positions computed weekly). Each of the monuments was tied to the tide-gauge reference benchmarks by geodetic first-order levelling in the summer of 2005. The station at Escuminac is still operating, but the monument and GPS antenna near the town hall in Shediac were damaged beyond repair in the fall of 2005. A new monument was installed enabling the Shediac station to be re-activated in November 2006. Data from these stations, combined with nearby water-level measurements, should permit accurate determination of vertical motion and sea-level rise within about 10 years.

4.1.6.2 Sea-level rise in the study area

Rising global sea level is one of the most confidently predicted impacts of climate warming, with major implications for coastal communities around the world (IPCC WG2, 2001; McLean et al., 2001). The latest published analysis by the Intergovernmental Panel on Climate Change (IPCC WG1, 2001; Church et al., 2001) predicts an increase in global sea level from 1990 to 2100 (110 years) between 0.09 and 0.88 m, with a central value of 0.48 m, based on the 35 Special Report on Emission Scenarios (SRES) emission scenarios described in IPCC WG1 (2001). Normalized to 100 years, this central value is >2.5 times the average rate of global sea-level rise during the 20th century, as deduced from tide-gauge data (Church and White, 2006).

The regional implications of the IPCC global predictions for relative sea-level rise in southeastern New Brunswick are less clear. The latest IPCC projections of global sea-level rise based on the IS92a scenario, as used in the Second Assessment Report (IPCC WG1, 1996), incorporate the following components (Church et al., 2001):

- thermal expansion of 0.11–0.43 m, accelerating through the 21st century;
- a glacier contribution of 0.01–0.23 m;
- a Greenland contribution of −0.02 to 0.09 m; and
- an Antarctic contribution of −0.17 to 0.02 m.

Given the results of Mitrovica et al. (2001), suggesting that the Greenland contribution might amount to less than 20% of its global total in the North Atlantic region, while the Antarctic contribution may be slightly increased, it seems reasonable to conclude that these eustatic components are poorly predicted at present and may be mutually compensating (Gregory and Lowe, 2000). It is noteworthy that the contribution from mountain glaciers and small ice sheets is substantial and likely to be close to the global average in the North Atlantic region.

The contribution of ocean thermal expansion, potentially the largest component of future sea-level rise, is also difficult to evaluate on a regional basis (Forbes et al., 2001). Outputs from nine different experiments using a variety of models (Figure 11.13 in Church et al., 2001) show a wide range in the global distribution of thermal expansion. The resulting sea-level rise over 100 years in Atlantic Canada ranges from <0.1 m in one model to >0.6 m in another, but most results fall between 0.2 and 0.4 m. We conclude that no consensus exists yet on the proportion of global thermal expansion to be expected in our region.

The foregoing discussion indicates that we have no adequate basis for adopting regional projections of future sea-level rise under climate warming that differ significantly from the global projections of Church et al. (2001). We also note that the models show accelerating sea-level rise, with much slower rates early in the 21st century compared with later.

4.1.6.3 Projected rates of relative sea-level rise, 2000–2100

Based on the conclusions in Section 4.1.6.2, we have adopted the central IPCC value of 48 cm for sea-level rise, equivalent to 44 cm over 100 years (2000–2100), with an estimated uncertainty of ±30 cm. When we combine this estimate with the vertical-motion estimates determined in Section 4.1.6.1, we obtain the projections shown in Table 7 for various sites in the study area.

Table 7. Projections of vertical motion and relative sea-level rise for various sites in the study area in southeastern New Brunswick (see text for details).

Site	Vertical motion (cm), 2000–2100	Relative sea-level rise (cm), 2000–2100
Cape Jourimain	15 ± 5	59 ± 35
Shemogue	13 ± 5	57 ± 35
Cap-Pelé	12 ± 5	56 ± 35
Shediac	10 ± 5	54 ± 35
Bouctouche	9 ± 5	53 ± 35
Kouchibouguac	7 ± 5	51 ± 35
Escuminac	6 ± 5	50 ± 35

4.1.7 Summary and conclusions

Sea level has been rising along the southeastern coast of New Brunswick for several thousand years, gradually flooding Northumberland Strait and the seaward reaches of rivers draining the study area, pushing the shoreline landward and causing vertical growth and landward migration of salt marshes. These changes are continuing slowly and have become evident over several decades. Climate warming, through ocean thermal expansion and melting of ice on the continents, is expected to raise the mean sea level on a global basis by a few decimetres over the coming century, accelerating historical rates of relative sea-level rise (rise of water level relative to fixed points on land) in Atlantic Canada.

The observed relative sea-level rise results from a combination of regional subsidence and rising sea level in the northwestern Atlantic. The subsidence is a product of glacial loading and unloading more than 10 000 years ago, leading to gradual collapse and migration of a marginal forebulge (area of uplift) that developed around the margins of the North American ice sheets and additional water loading of the seabed in the Gulf of St. Lawrence as global mean sea level rose more than 100 m from its lowest level during glacial times. Global sea level has continued to rise, accelerating in the second half of the 20th century to a current rate of about 17 cm/century. Because of a gradient in subsidence across the region, the observed relative sea-level rise is less in the northwest and greater in the southeast of the project area. The long tide-gauge record at Charlottetown, Prince Edward Island, dating back more than 95 years, shows a relative sea-level rise of 32 cm over the past century. At the other end of the study area, the relative sea-level rise at Escuminac is estimated to be about 23 cm over the same time interval. This regional tilting will continue in the future. Therefore, we conclude that future rates of relative sea-level rise will also show a gradient across the region.

Our analysis of isostatic subsidence and tilting presented above and of regional sea-level rise based on the Third Assessment Report of the IPCC, published in 2001, leads to the following estimates of relative sea-level rise for the coming century (2000–2100) across the study region:

• Cape Jourimain	59 ± 35 cm
• Shemogue	57 ± 35 cm
• Cap-Pelé	56 ± 35 cm
• Shediac	54 ± 35 cm
• Bouctouche	53 ± 35 cm
• Kouchibouguac	51 ± 35 cm
• Escuminac	50 ± 35 cm

These rates of sea-level rise need to be considered in the context of storm impacts and associated hazards. During large storms, storm surges cause coastal flooding, large waves cause erosion and infrastructure damage, and sea ice sometimes moves ashore with damaging effects. Because storm-water levels and waves are superimposed on the mean sea level, rising mean sea level has an important effect on the levels of flooding and wave attack, with important implications for ecological and socio-economic impacts and the adaptation measures that need to be taken to reduce losses. These issues are explored in later parts of the report.

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4.2 Storm-surge, wind, wave and ice climatology

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4.2.1 Introduction

Storm surges are meteorological effects on sea level and can be defined at the coast as the difference between the observed water level and the predicted astronomical tide. Storm surges can be positive or negative and may therefore raise or lower sea level from its predicted value. Storm surges occur everywhere along our coastlines and can occur anywhere in the tidal cycle or may last over several tidal cycles. Large positive storm surges at times of high tide are events that lead to coastal inundation. Elevated sea levels also enhance wave attack and coastal erosion and in the presence of ice and ice pressure can lead to ice ride-up and pile-up. Any assessment of the possible increased risks of coastal flooding in a future warmed climate must include an assessment of the present storm-surge climatology and the flooding-event history of the region. To this end, statistics of storm-surge events in excess of 60 cm are developed in this section of the report, and extreme water levels and past flooding events are examined.

Much of the work presented in this section, but particularly the water-level analysis at Charlottetown (the long-term tide gauge in the region), was developed by the present authors in an earlier study (*Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island*, Appendix 1, Part 2: Storm-Surge Climatology; in McCulloch et al., 2002) and has been updated in this section. Some revisiting and reanalysis of data occurred; however, since this analysis is somewhat subjective, it was decided to keep this process down to a minimum. Some data that have not been reanalyzed are also presented here for completeness sake, rather than simply referencing the earlier document.

4.2.2 Data sources and preprocessing

4.2.2.1 Tide-gauge data

To examine storm-surge events, the entire inventory of water-level data for the southern Gulf of St. Lawrence was ordered from the Marine Environmental Data Service (MEDS) in Ottawa (tide-gauge locations are shown in Figure 1).

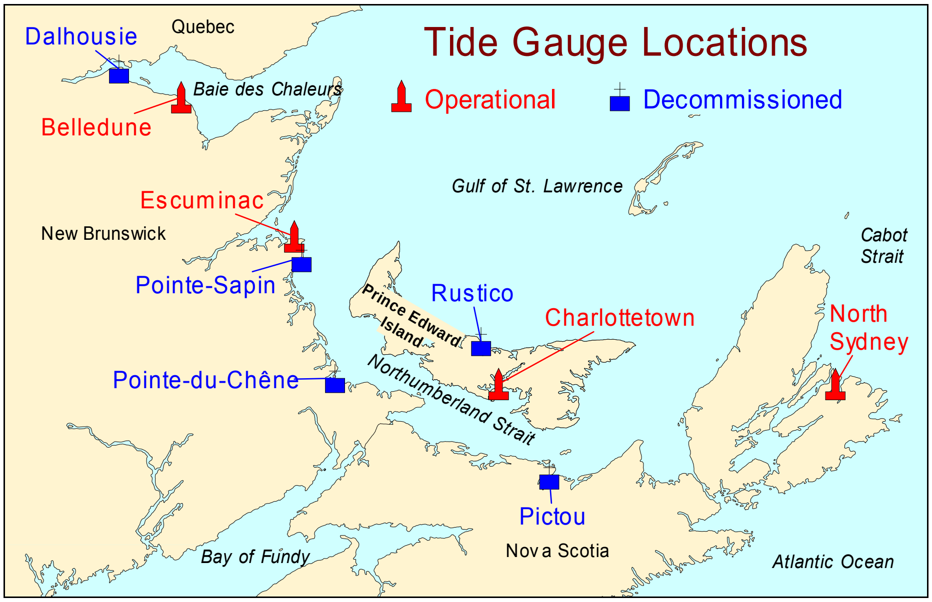


Figure 1. Tide-gauge locations around the southern Gulf of St. Lawrence. Stations marked in red are operational. Stations marked in blue have been decommissioned.

This included the following data files, which will be the principal data sets for this analysis:

- Hourly observations, 1973–2005, at Escuminac, New Brunswick
- Hourly observations, 1971–1992 and 2003–2005, at Pointe-du-Chêne, New Brunswick
- Hourly observations, 1911–2005, at Charlottetown, Prince Edward Island
- Hourly observations, 1963–1975, at Pointe-Sapin, New Brunswick
- Hourly observations, 1965–1996, at Pictou, Nova Scotia
- Hourly observations, 1999–2005, at Belledune, New Brunswick
- Hourly observations, 1972–1996, at Rustico, Prince Edward Island

Water levels are given with respect to local Chart Datum (CD), which is defined by the Canadian Hydrographic Service (CHS) in the *Canadian Tide and Current Tables* (CHS, annual) as the plane of lowest normal tides.

4.2.2.2 Predicted astronomical tides

Predicted astronomical tides for the various tide-gauge sites were obtained from the CHS in British Columbia (CHS-Pacific) for the years 1900–2003 inclusive. CHS has the responsibility of generating Canada's official tidal predictions, as found in the Department of Fisheries and Oceans' *Canadian Tide and Current Tables*. The tidal predictions are the ones that were obtained for the Prince Edward Island sea-level rise project and are based on W.R. Crawford's tidal analyses at the Institute of Ocean Science in July 1997. Tidal predictions for 2004 were obtained from CHS in Dartmouth, Nova Scotia (CHS-Atlantic), and are based on new constituents and means from a reanalysis of water-level data (where available) from the year 2000 (Charles O'Reilly, CHS, pers. comm.).

4.2.2.3 Preprocessing the MEDS data

Tide-gauge data at Pointe-du-Chêne, Escuminac, Rustico, Pictou, Belledune and Pointe-Sapin have been through the MEDS quality-control process, as have the data at Charlottetown from November 1961 onwards. Charlottetown data from January 1911 to October 1961 are not quality-checked and were found to be quite incomplete prior to 1938. Although the Charlottetown data from November 1961 to December 1998 represented quality-controlled data, some problems still remained. Preprocessing of the water-level data was required to structure the data files (see Section 4.1), then the MEDS data sets and the CHS predicted tides were brought together to calculate residuals (the arithmetic difference between the two) and to isolate and examine storm-surge events, case by case.

4.2.2.4 Errors in the data set

The water-level data sets and the predicted astronomical tides and their residuals were all examined visually to identify obvious data errors. Additionally, the data and the residuals at adjacent tide-gauge sites were visually examined simultaneously to further identify and cross-reference such problems. A number of problems were found. These included:

1. missing data (large sections of observed data were missing from the original data sets or were excluded by the quality-control process);
2. occasional (positive and negative) spikes in the data;
3. phasing problems between the predictions and the observations owing to timing errors in the data and generating periodic residuals of varying size;
4. drifts in the calibration of the tide gauge, causing periods of elevated or depressed means and residuals;
5. data archived with the wrong date–time stamp (generating anomalous residuals);
6. interpolated data (non-real data for short periods substituted by MEDS);
7. a short period at Pointe-du-Chêne (October 1980) when the data appeared to be inverted;
8. short periods in the 1920s' Charlottetown data when missing data were coded as zero (i.e., Chart Datum) rather than using the conventional 9999 missing data code; and
9. a short period in the Charlottetown data (October 1954) when one particular tidal excursion was repeated several times and the remainder of the month was displaced to the wrong date–time.

4.2.2.5 An examination of means

Prior to collating storm-surge events for the Prince Edward Island report, an assessment was made of relative sea-level rise over the period of the water-level data sets in order to normalize the residuals (Parkes et al., 2002a). Final results for Charlottetown water-level data (the long-term tide gauge in the region) are reproduced in Figure 2 and show a change of approximately 32 cm/century over the history of the tide-gauge data. This graph has been brought up to date (2005) in this present study and still shows a long-term trend of 32 cm/century. Using this long-term sea-level trend and water-level data at Escuminac and Pointe-du-Chêne, we estimate that the rate of relative sea-level rise is 20–25 cm/century at Escuminac and 25–30 cm/century at Pointe-du-Chêne (*S*ection 4.1.5).

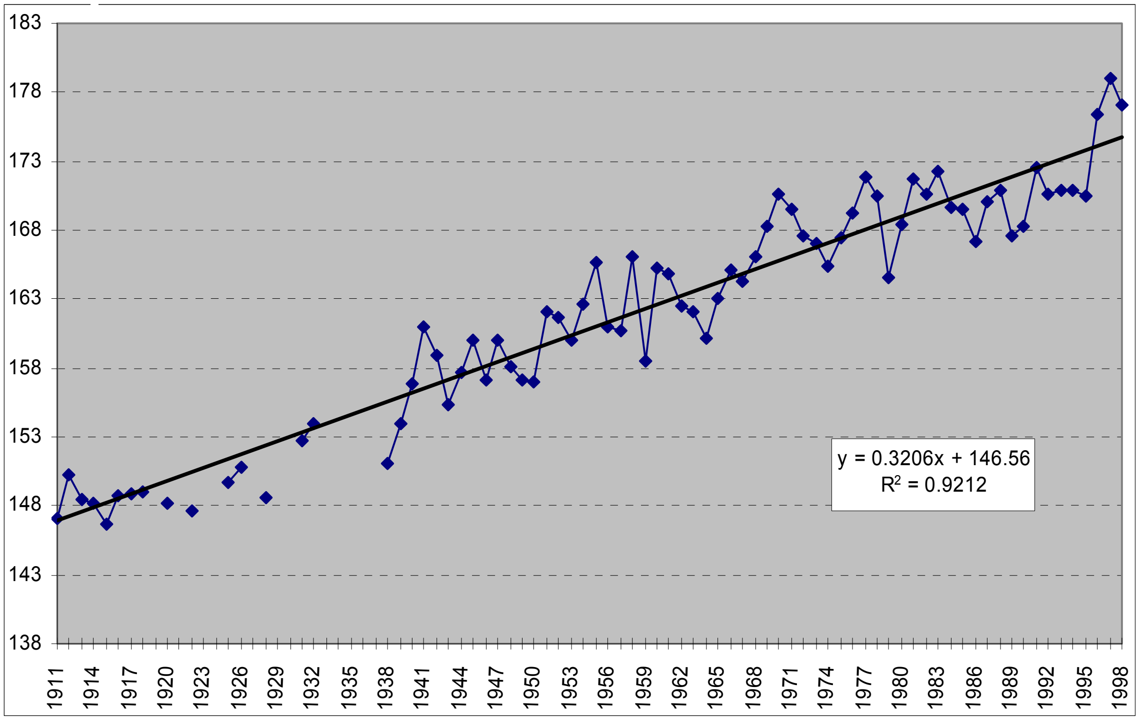


Figure 2. Annual mean water levels (in cm above Chart Datum) at Charlottetown, 1911–1998. The linear regression through the data indicates a sea-level rise of approximately 32 cm/century (from Parkes et al., 2002a).

4.2.3 Storm surges at Charlottetown

4.2.3.1 Adjusting the Charlottetown data set

To examine storm-surge events, the predicted tides must be subtracted from the observed water-level data, and the residuals must be collated. Observed water levels go back to 1911, and the apparent size and number (above any given threshold) of storm surges diminish the further back in time that we look, since tidal predictions are generated with one mean sea-level value (tidal analysis mean = Z_0), and not with a mean sea-level trend. At Charlottetown, Z_0 was calculated by CHS from a tidal analysis of one year of data centred around October 1980. To normalize this, either the predicted astronomical tides or the observed water-level data must be adjusted for relative sea-level rise.

Z_0 at Charlottetown (in our predictions from W.R. Crawford in 1997) is 1.676 m above CD. In Figure 2, the regression line through the annual means crosses 1.676 m at decimal year 1976.60 (see regression equation). The year 1977 was therefore taken as the year closest to Z_0, and the observed water-level data, for the purposes of our analysis, were increased for previous years at a rate of 32 cm/century and decreased for subsequent years at the same rate.

4.2.3.2 Storm surges at Charlottetown, 1960–2005

Predicted astronomical tides for Charlottetown were subtracted from the adjusted observed water-level data for the period 1960 to October 2005 (45 years inclusive — the MEDS quality-checked data set, plus 1960 and early 1961 data, to complete the 1960s).

Residuals in excess of 60 cm were collated as events. In 2004 and 2005, residuals above 0.52 cm were counted as events (due to a change in Z_0 in the tidal predictions). Sometimes the time series of the residuals will rise and fall through the event threshold, and the count of “events” is therefore somewhat subjective. To qualify as separate events in this analysis, it was decided that the events must have peaks separated by at least 12 hours and must subsequently pass through a trough of less than 40 cm. Additionally, any two “events” that qualify must also show up as separate events at an adjacent tide-gauge site (for Charlottetown, the nearest and best site for this purpose is Pictou).

In addition to the height of the storm surge, the maximum water level reached during the event was also noted. This was evaluated to the highest observed water level associated with the storm-surge event while the surge level was in excess of 40 cm. This was usually different from the water level at the time of the peak surge.

In total, 350 events were identified during the period 1960–2005, and these, together with the maximum water level reached during the event (in cm above CD), are shown plotted in chronological order in Figure 3, by ascending storm-surge height in Figure 4, and by ascending highest water level in Figure 5. It should be remembered that water levels have been adjusted for sea-level rise. The maximum water level reached during the event is not the actual observed water level, but may be thought of as the level that the event would have reached if it had occurred in 1977.

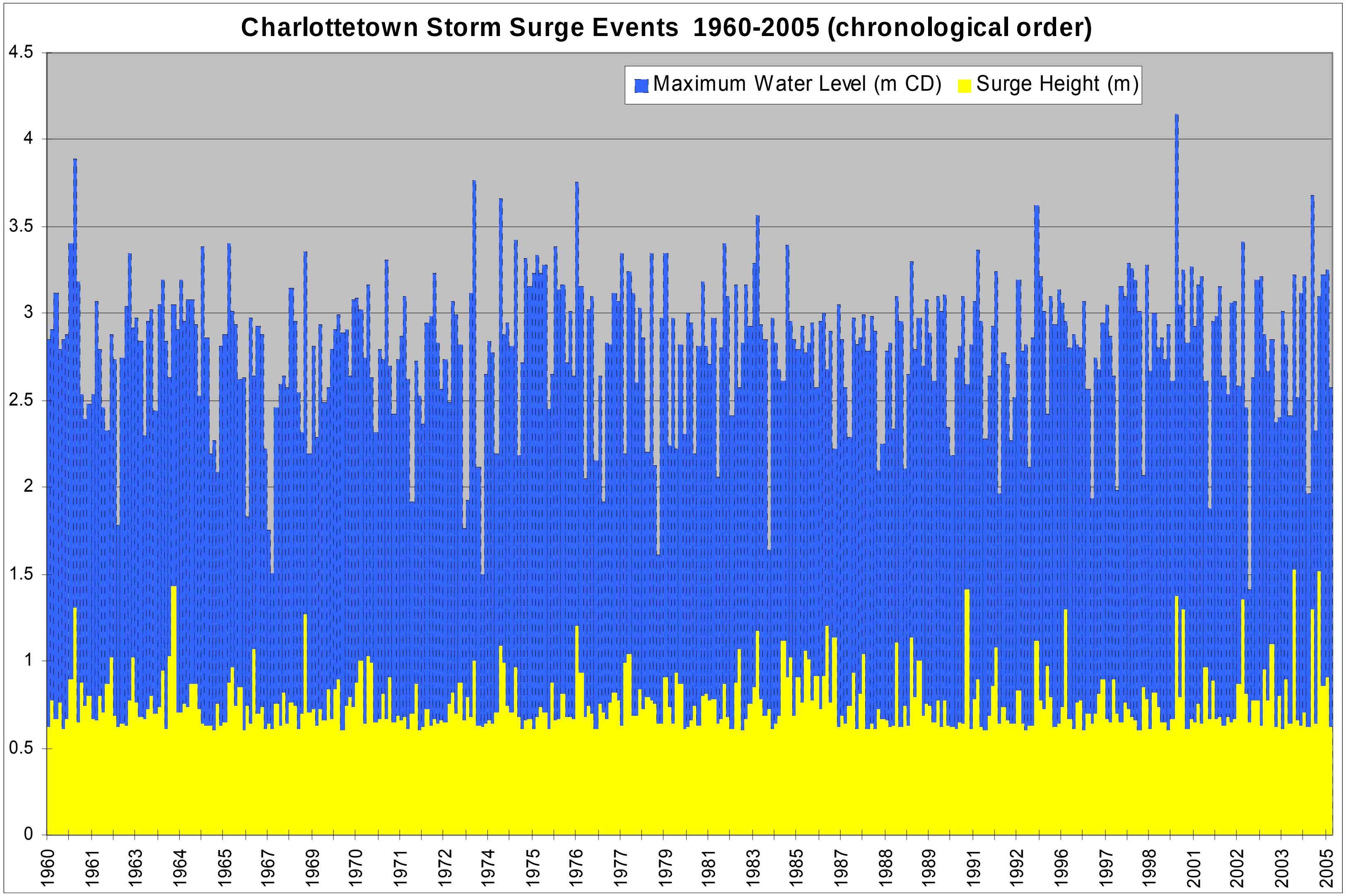


Figure 3. All observed storm-surge events in Charlottetown, 1960–2005, arranged in chronological order.

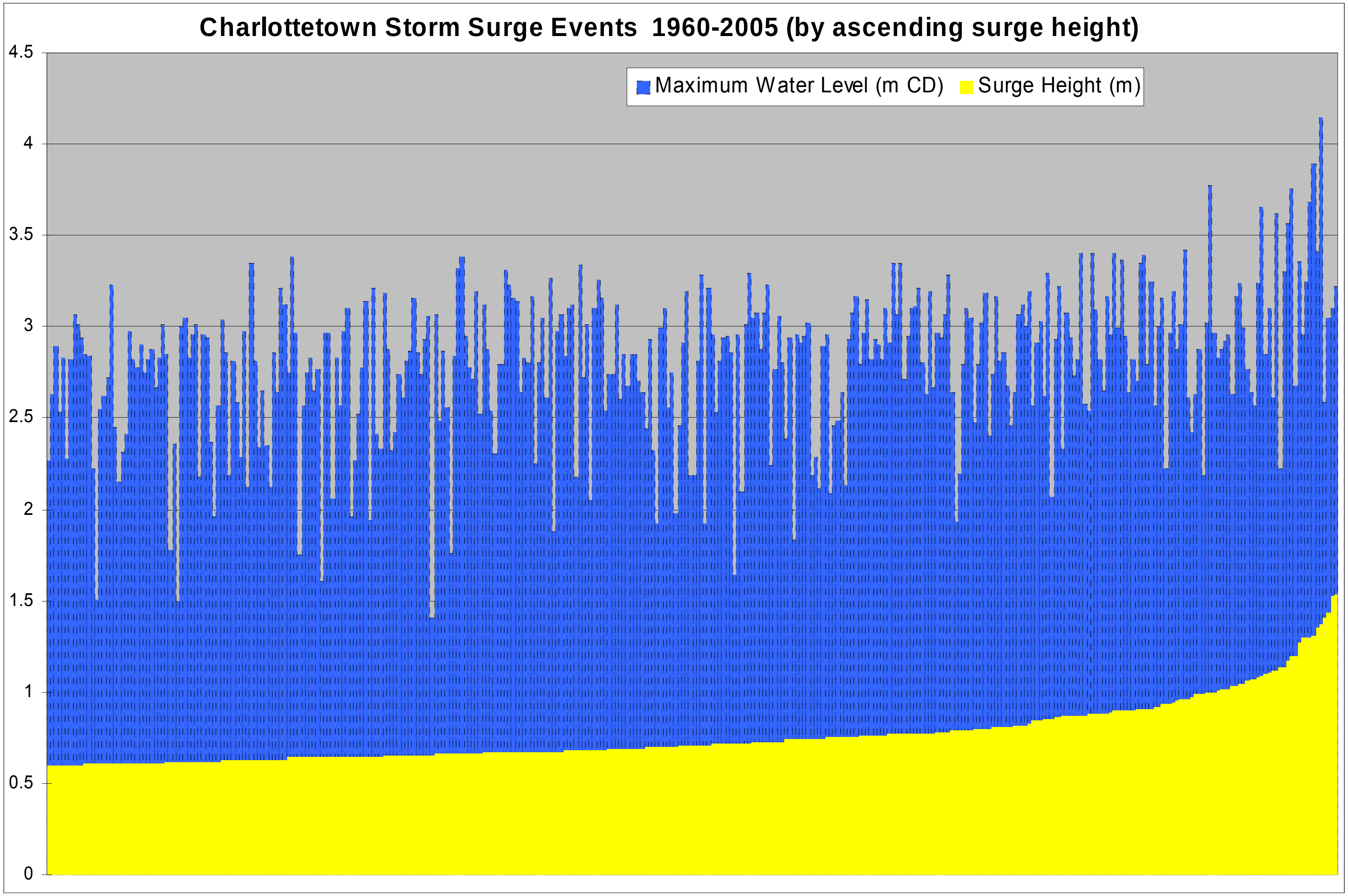


Figure 4. All observed storm-surge events in Charlottetown, 1960–2005, arranged in ascending order of storm-surge height.

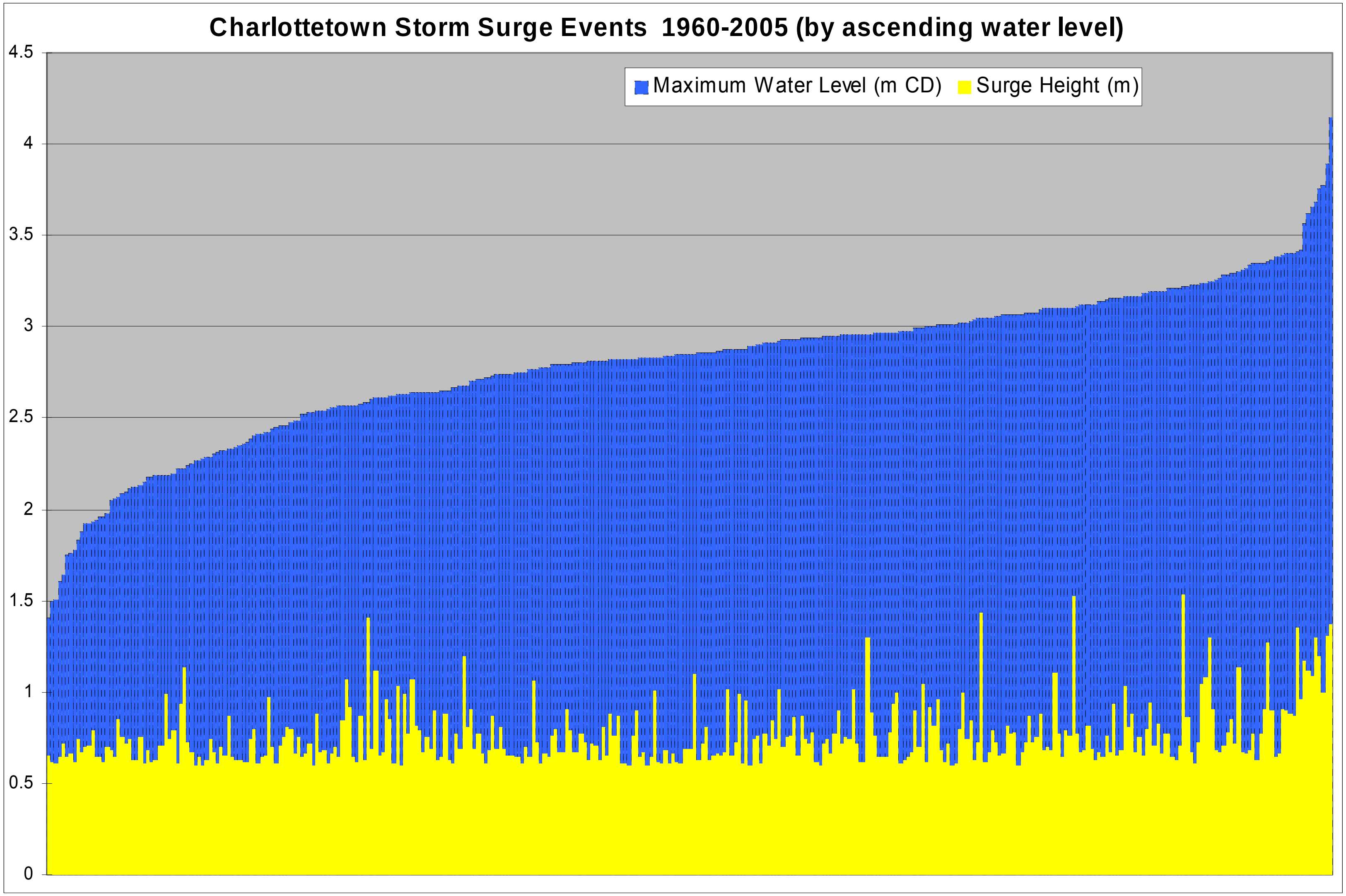


Figure 5. All observed storm-surge events in Charlottetown, 1960–2005, arranged in ascending order of maximum observed water level.

4.2.3.3 Accounting for missing data at Charlottetown, 1960–2005

The following is an extension of the analysis in Section 2.3.3 ("Accounting for missing data at Charlottetown 1960–1998") in Parkes and Ketch (2002b), for the Prince Edward Island sea-level rise project. It is reproduced here and updated with new data for 1999–2005. Since 1999, there have been very few missing data.

Attachment A (Section 4.2.15.1) is a summary of missing data at Charlottetown on a month-by-month basis, including the years 1960–2005. Visual inspection of the residuals from the various tide-gauge sites shows that the Charlottetown residuals have a closer resemblance to Pictou residuals than to those from any other site. Pictou also has the second longest record after Charlottetown and was used where possible to fill in for missing storm-surge events.

The observed water-level data at Pictou were corrected for relative sea-level rise in the same fashion as for the Charlottetown data (i.e., 32 cm/century from 1977). Storm-surge events were then extracted using the same rationale as at Charlottetown. Storm-surge peak values for the same events at both Pictou and Charlottetown are shown plotted on the scatter diagram in Figure 6. This represents 130 storm-surge events where both Pictou and Charlottetown storm surges were in excess of 60 cm. A best-fit linear regression line is shown through the data, with the regression line forced through the origin of the scatter diagram. This diagram shows that storm surges in Pictou and Charlottetown are similar in size.

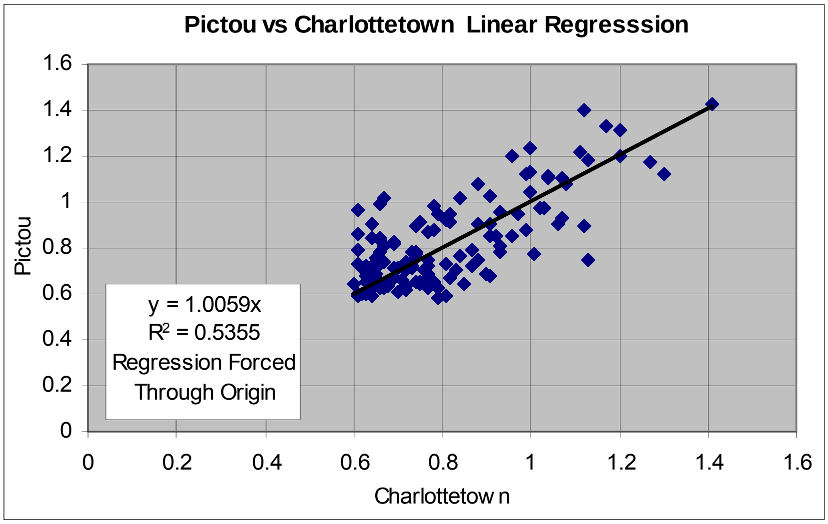


Figure 6. Storm-surge peak values, Pictou versus Charlottetown.

Most of the time, when Charlottetown data were missing, Pictou data were present (Parkes and Ketch, 2002b, "Attachment B: A comparison of periods of missing data at Charlottetown and Pictou"). When Pictou data were absent, the missing events were filled in from the Pointe-du-Chêne data. The observed water-level data at Pointe-du-Chêne were also corrected for relative sea-level rise in the same fashion as for the Charlottetown data (i.e., 32 cm/century from 1977). Storm-surge events were then extracted using the same rationale as applied to Charlottetown. Peak values for the same storm-surge events at Pointe-du-Chêne and Charlottetown are shown plotted on a scatter diagram in Figure 7. This represents 102 surge events where both Pointe-du-Chêne and Charlottetown storm surges were in excess of 60 cm.

A best-fit linear regression line (that is forced through the origin) is shown through the data. Greater variability can be seen here than between Charlottetown and Pictou (Figure 6). The figure shows that storm surges at Pointe-du-Chêne are generally larger than at Charlottetown, by an average factor of 1.14. When Charlottetown and Pictou data were missing, events at Pointe-du-Chêne were scaled down by 0.88 and counted as events at Charlottetown.

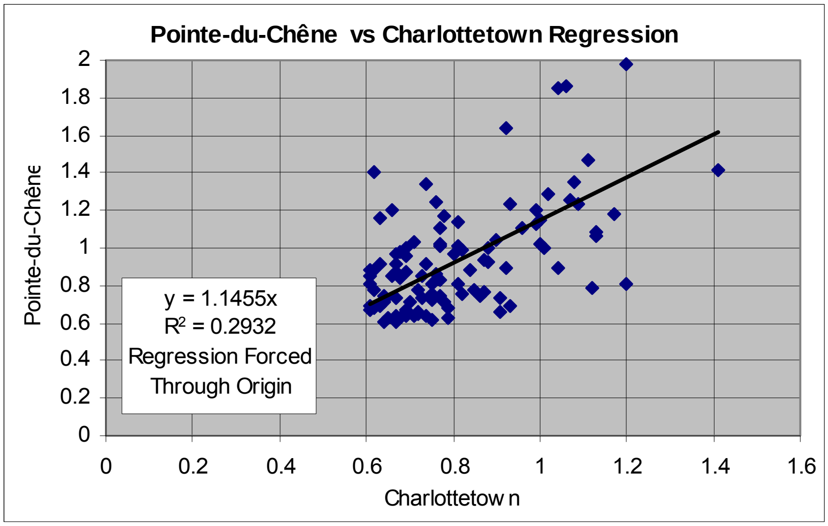


Figure 7. Storm-surge peak values, Pointe-du-Chêne versus Charlottetown.

There were short periods when Charlottetown, Pictou and Pointe-du-Chêne data were all missing. Under these circumstances, data from Escuminac and Rustico were scanned for events, but only one such event was identified. The new data for 1999–2005 were very complete, but periods of missing data were scanned for events at other sites. No such events were found. However, it is noted that there were no other data available to cross-check a short three-day period of missing data in November 2000.

In total, eight interpolated events were taken from the Pictou tide-gauge record, seven events were taken from Pointe-du-Chêne and one event was taken from Escuminac and Rustico. These interpolated events represents a mere 4% of the data set.

4.2.4 Climatology of storm surges at Charlottetown

Canadian Climate Normals (Environment Canada, 1993) are a series of volumes of climate data for temperature, precipitation, wind and other variables, comprising statistics over a 30-year period that represent the climatology of the region. The 30-year period is one recommended by the World Meteorological Organization to define normals. The selection of this number of years was somewhat arbitrary; however, it was considered to be sufficiently long to eliminate year-to-year variability. For our purposes, the quality-controlled, 43-year water-level data set from November 1961 to December 2004 at Charlottetown will be used to define the climatology of storm surges there. Data from 1960 and the first part of 1961 will also be included to round out the decade of the 1960s and to capture the high-water-level event known to have occurred on January 21, 1961 (therefore, 45 years in total).

4.2.4.1 Storm-surge climatology at Charlottetown, 1960–2004

The average numbers of storm-surge events per year above various thresholds are shown in Figure 8. All storm-surge events at Charlottetown (including interpolated data) are shown by year and category (defined by thresholds at 10-cm intervals) in Figure 9. The same data are displayed in individual graphs above thresholds of 60, 80, 100 and 120 cm in Figure 10. The distribution of storm surges (for data for 1960–1998) above thresholds by month is shown in Figure 11. These data represent the climatology of storm surges at Charlottetown.

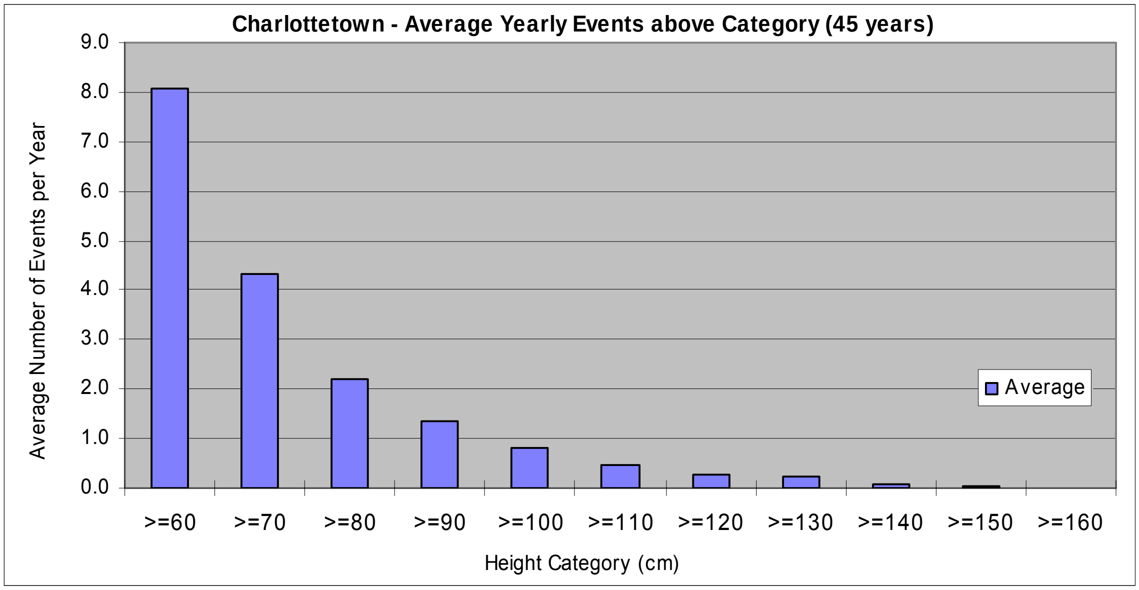


Figure 8. Average number of storm surges per year above threshold at Charlottetown, 1960–2004.

Generally speaking, storm surges above 60 cm are frequent events in Charlottetown, occurring about eight times a year on average (compared with, for instance, twice a year along the Atlantic coast in Halifax; Galbraith, 1979; Parkes et al., 1997). Thirty storm-surge events were identified at 100 cm or more, representing almost one such event on average every year. Storm-surge events above 120 cm are uncommon (13 such events identified) and occur on average about three times a decade. Two events were found at 150 cm. Storm surges at Charlottetown are mainly associated with the stormy period of the late fall and winter. Averaged statistics show an increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there were few occurrences in the period from May to September. Storm surges show great variability in frequency from one year to the next, due to the great interannual range in frequency and in severity of the storms themselves (Lambert, 1996;

Hirsch et al., 1999; Manson et al., 2002b) and of their tracks. During the years 1960–2004, there were times when the storm surges were clustered; however, it is difficult to see any obvious trends in the data. Nevertheless, storm surges above 120 cm do appear to have become a little more frequent of late.

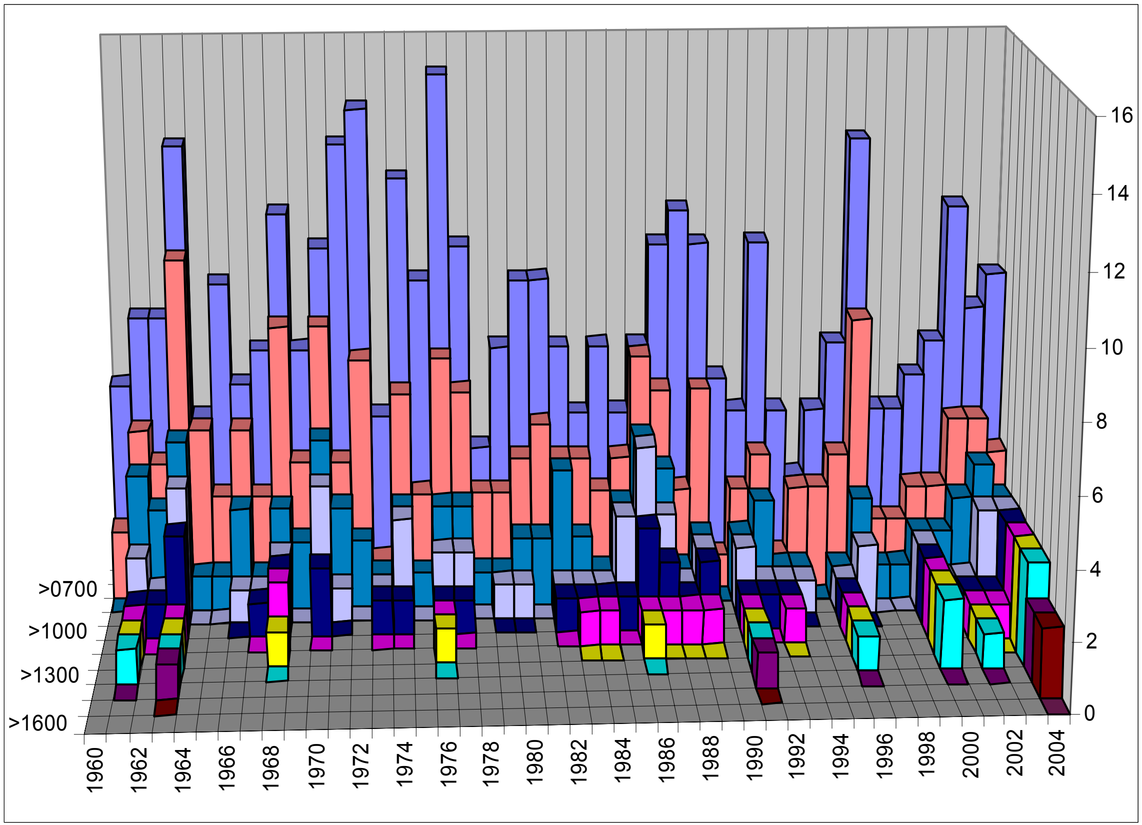
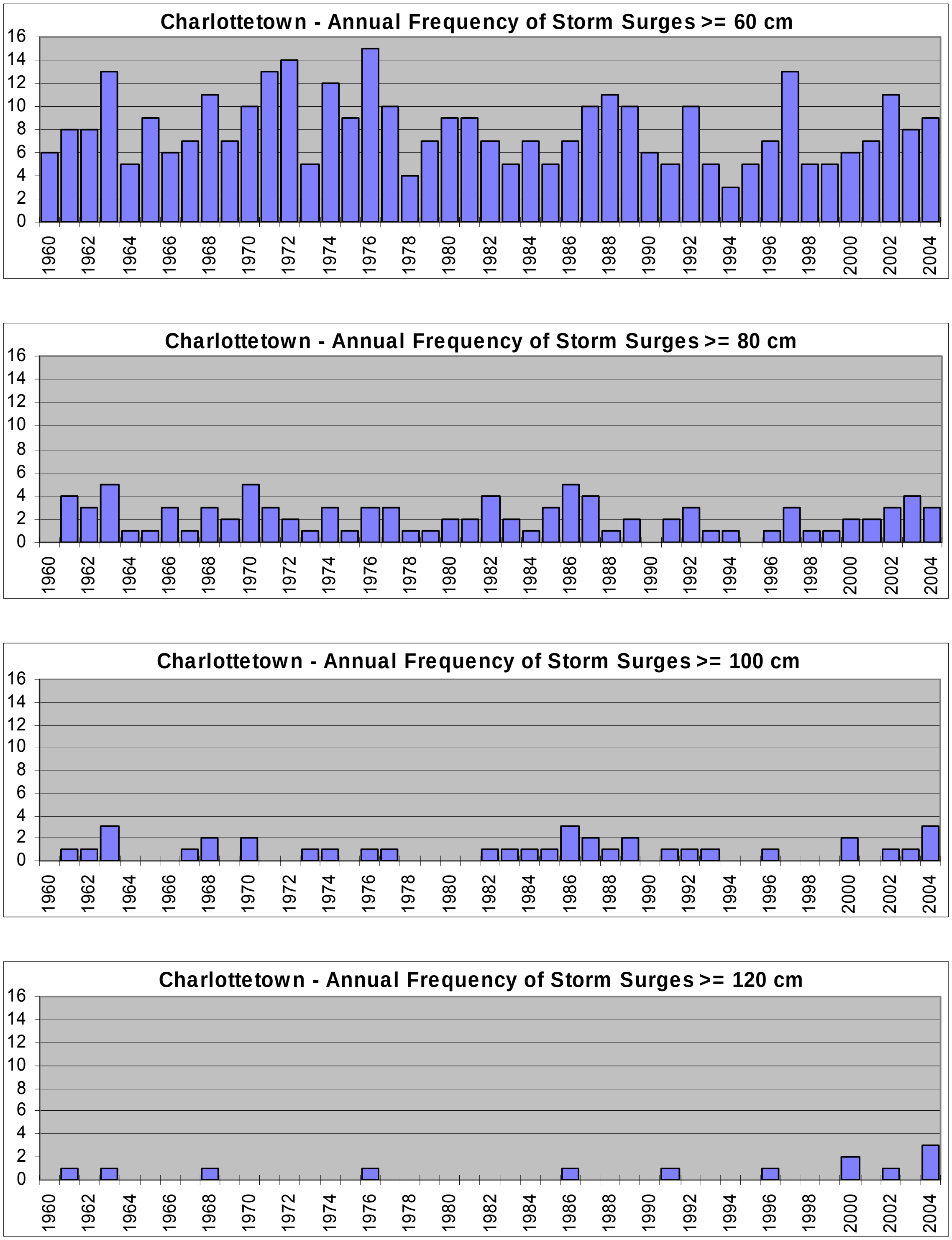


Figure 9. Storm-surge events above thresholds at Charlottetown, 1960–2004.



Charlottetown - Annual Frequency of Storm Surges >= 60 cm

Charlottetown - Annual Frequency of Storm Surges >= 80 cm

Charlottetown - Annual Frequency of Storm Surges >= 100 cm

Charlottetown - Annual Frequency of Storm Surges >= 120 cm

Figure 10. Storm surges at Charlottetown above thresholds of 60, 80, 100 and 120 cm, 1960–2004.

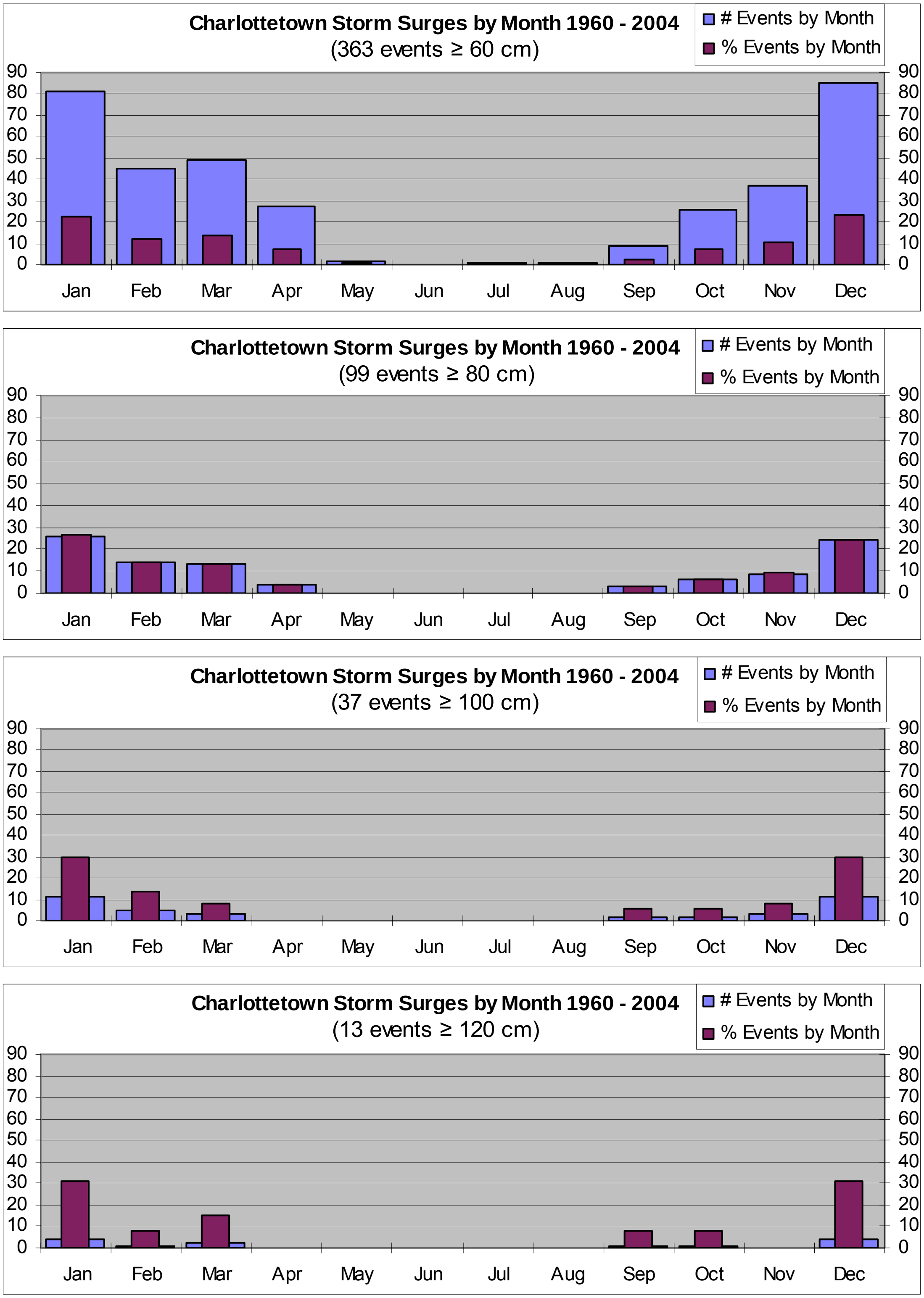


Figure 11. Charlottetown storm surges above thresholds of 60, 80, 100 and 120 cm, 1960–2004, by month.

4.2.4.2 Charlottetown water-level data, 1911–1959

Storm surges in excess of 60 cm were extracted from the Charlottetown water-level data for the period 1911–1959, together with the maximum water level reached during each event. Although these data have not been through the MEDS quality-control process, visual inspection revealed that, on the whole, the data are of very good quality. Occasional spikes were eliminated from the data set, as were short periods of large phasing errors. Occasionally, the data could not be reconciled with the predicted tides, and these data were excluded from the analysis. Missing storm-surge events during this period could not be interpolated from other tide gauges, because we have no digital data from nearby gauges. It can be seen, however, from Attachment A in Section 4.2.15.1 (monthly missing data, 1911–1959) that the data are almost complete for the period 1938–1959.

Results are plotted in chronological order in Figure 12. Storm surges at Charlottetown from 1911 to 1959 are shown by year above thresholds of 60, 80, 100 and 120 cm in Figure 13, together with the annual percentage of missing data.

All observed storm-surge events at Charlottetown (i.e., excluding interpolated events) for the periods 1911–1959 and 1960–1998 are collated in Figure 14 and plotted in chronological order.

Later in this section of the report (Sections 4.2.8 and 4.2.9) we examine the storm tracks of those weather systems that generated storm surges of 90 cm or more at Charlottetown. We also examine the signature in the Charlottetown water-level data of tropical cyclones moving through the region.

Although the earliest digital tide-gauge data for Charlottetown archived at MEDS are from 1911, a tide gauge was actually established there in October 1907 (Dawson, 1917). There were also some occasional earlier observations going back to 1896, and the extremes of these observations are listed by Dawson against arbitrary benchmarks. It is interesting to note that Dawson does not make reference to any flooding along the Charlottetown waterfront during his observations.

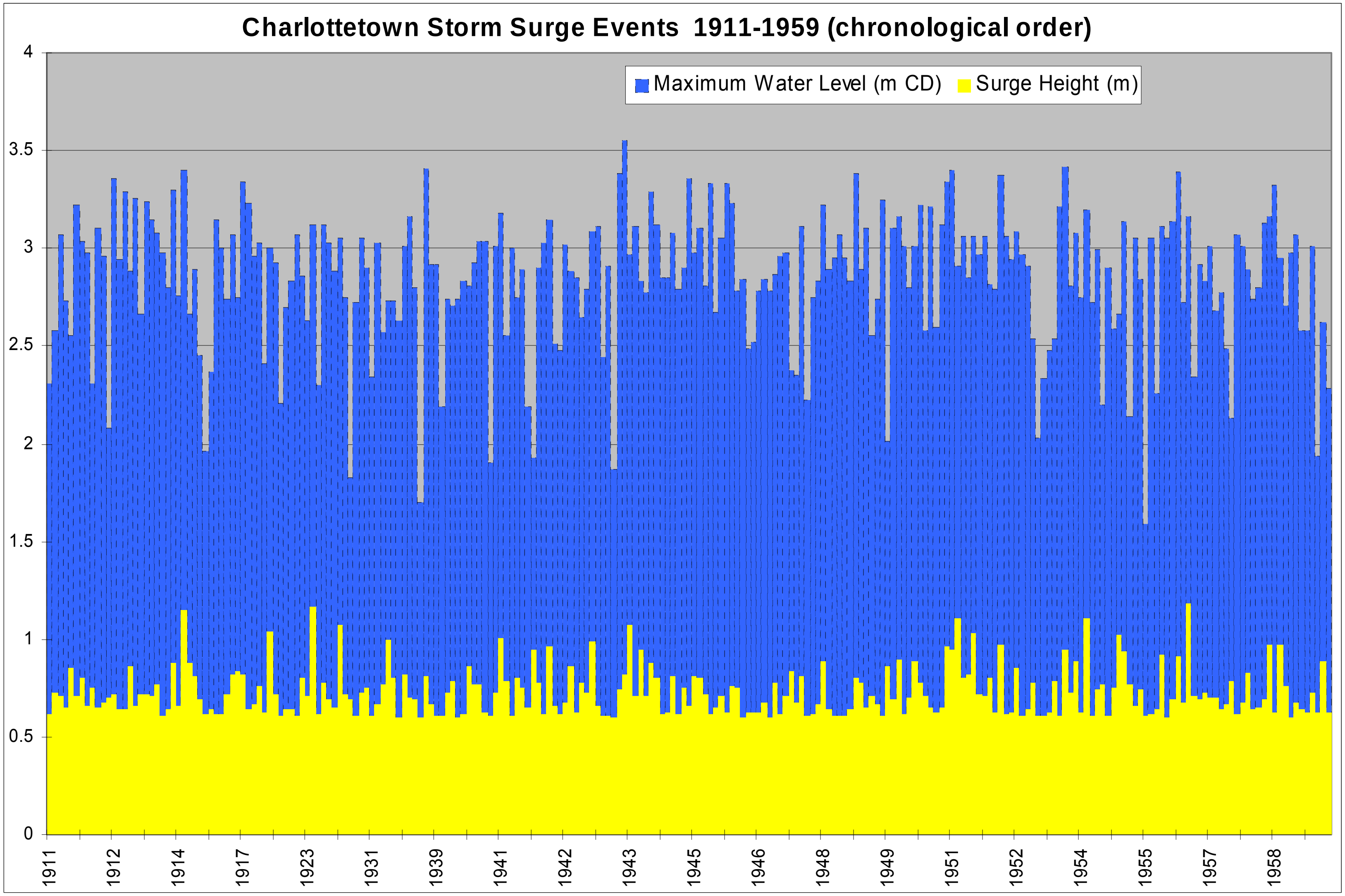


Figure 12. All observed storm-surge events >60 cm in Charlottetown, 1911–1959, arranged in chronological order.

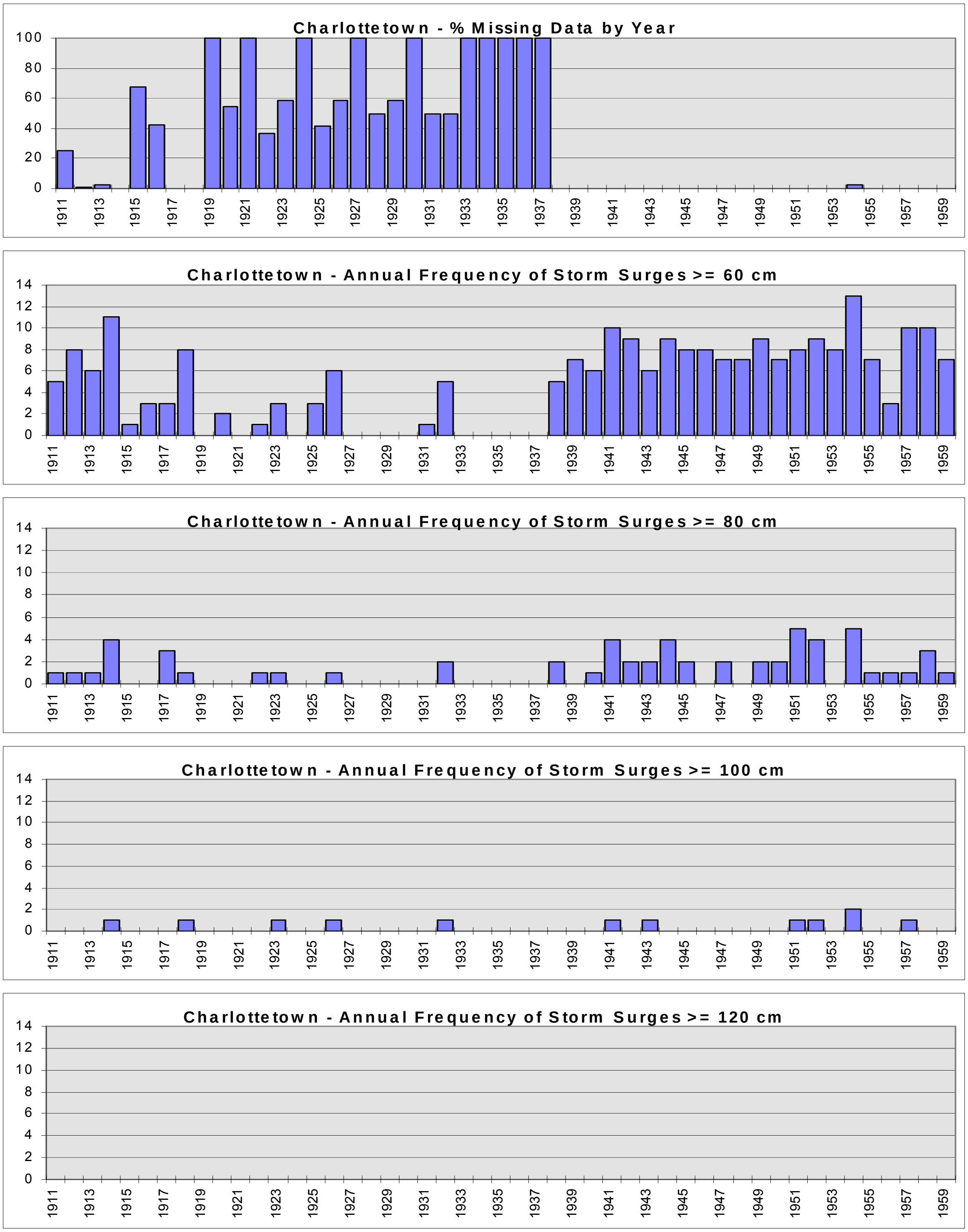


Figure 13. Storm surges at Charlottetown above threshold of 60, 80, 100 and 120 cm, 1911–1959, and plot of missing data.

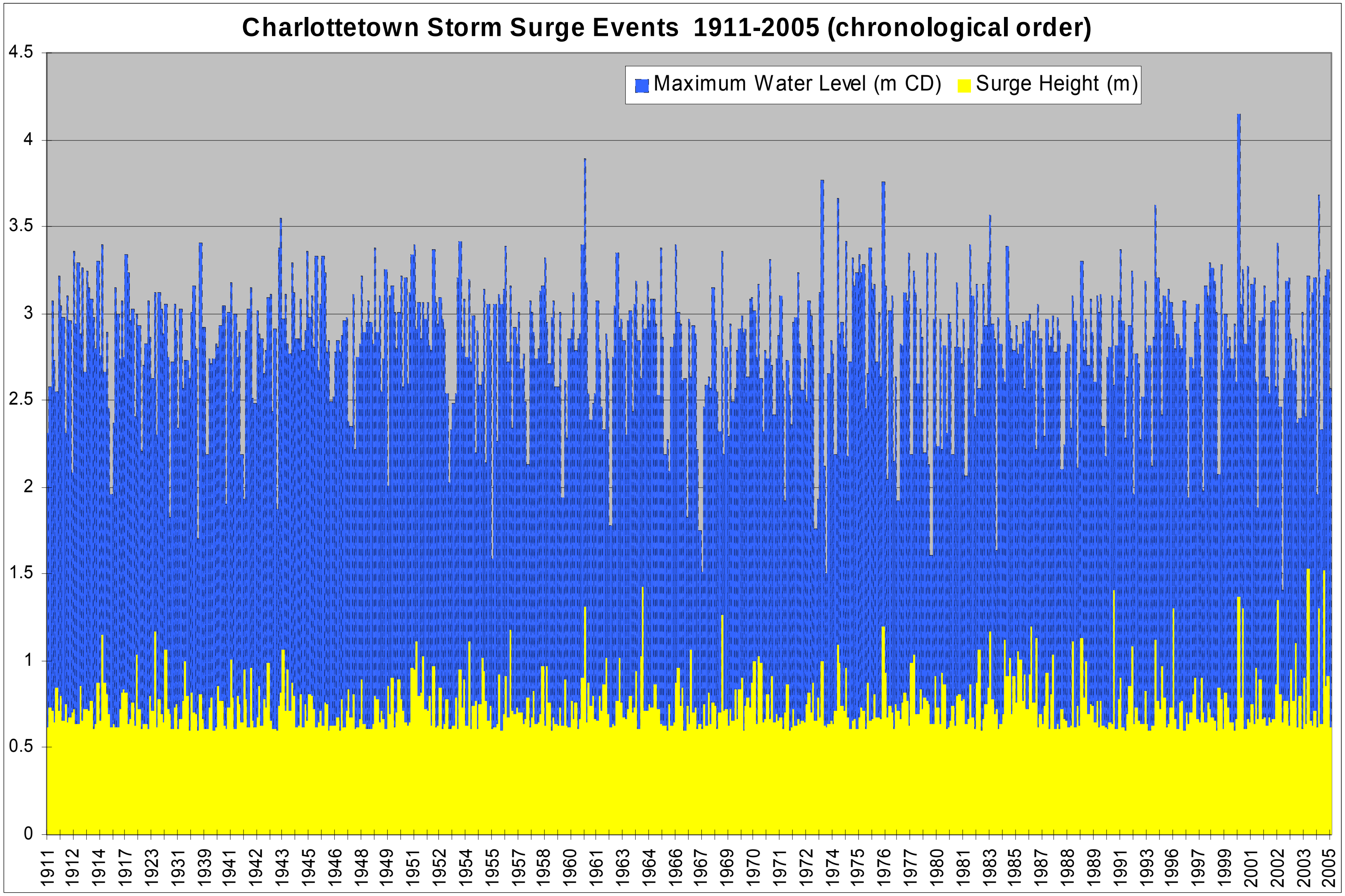


Figure 14. All observed storm-surge events >60 cm in Charlottetown, 1911–2005, arranged in chronological order.

4.2.4.3 Decadal statistics of storm surges at Charlottetown

The storm-surge data from 1938 to 2005 at Charlottetown represent a database with very few missing data. In Figures 15–20, the data have been collated by decade from the 1940s to the 1990s, and these data are shown combined in one histogram in Figure 21.

Storm surges appear to have become a little more frequent from the 1940s to the 1960s; in particular, the larger surges (>120 cm) not present at all in the 1940s and 1950s (nor recorded in earlier years; see Figure 13) show up thereafter, although they remain uncommon events. The 1970s and 1980s were strong storm-surge years, with more than two 80-cm events on average each year, and the 1980s show more than one 100-cm event on average each year. The 1990s saw generally fewer storm surges, although there were a few particularly big events.

In Figure 22, the same data are displayed in five-year bins. Some periods are seen to be much more active than others, in particular the early 1960s and the late 1980s. Below, it is noted that these were periods of frequent northeasterly gales. The period since 2000 has also been very active.

Storm-surge records over long periods can be used to characterize changes in storm frequency and intensity, although results might be inconclusive unless supplemented by nearby sites on differently facing coastlines, since storm tracks are also important. Zhang et al. (1997) investigated long-term tide-gauge records at Atlantic City, New Jersey, and Charleston, South Carolina. They found interdecadal variations but no discernible secular long-term trend in activity or storminess during the 20th century. The area off the eastern seaboard of North America is, however, one of frequent cyclogenesis and of explosively deepening low-pressure systems (Sanders and Gyakum, 1980; Manson et al., 2002b), so any trends in intense storms may have a larger signature farther north. Lambert (1996), in his investigation of intense extratropical northern hemisphere winter cyclone events in 1899–1991, identified an increase in the number of intense storms after 1970 in the North Atlantic as a whole. Changes in extreme storm surges are considered further in Section 4.3 of this report.

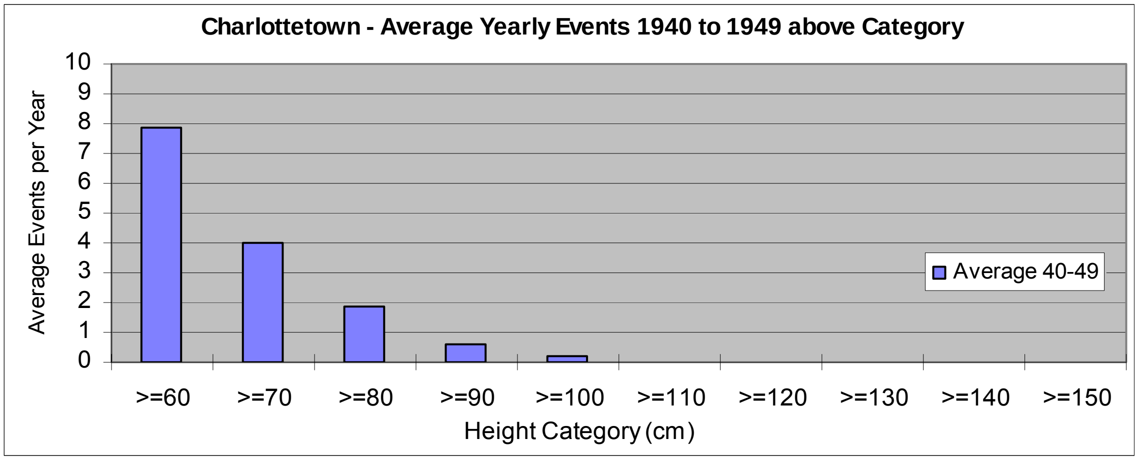


Figure 15. Average storm-surge annual frequency during the 1940s above thresholds.

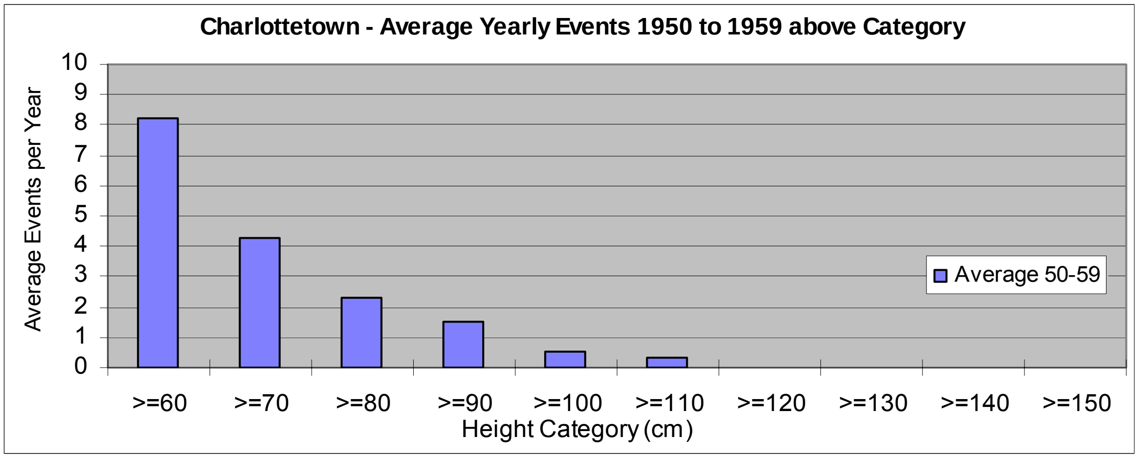


Figure 16. Average storm-surge annual frequency during the 1950s above thresholds.

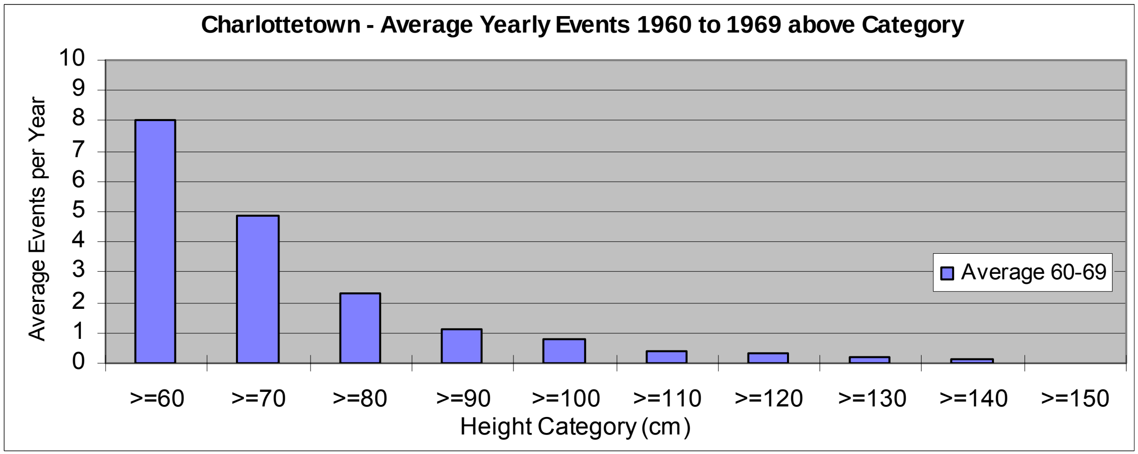


Figure 17. Average storm-surge annual frequency during the 1960s above thresholds.

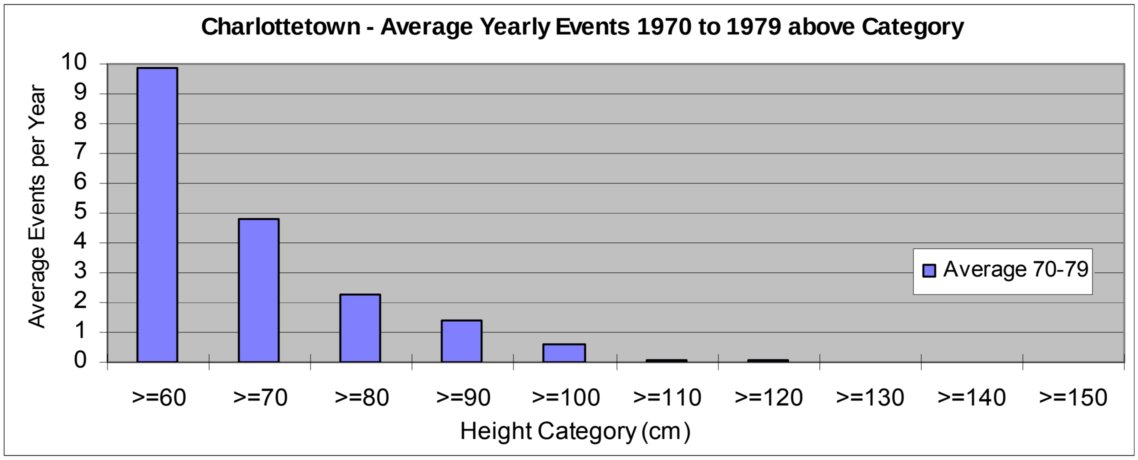


Figure 18. Average storm-surge annual frequency during the 1970s above thresholds.

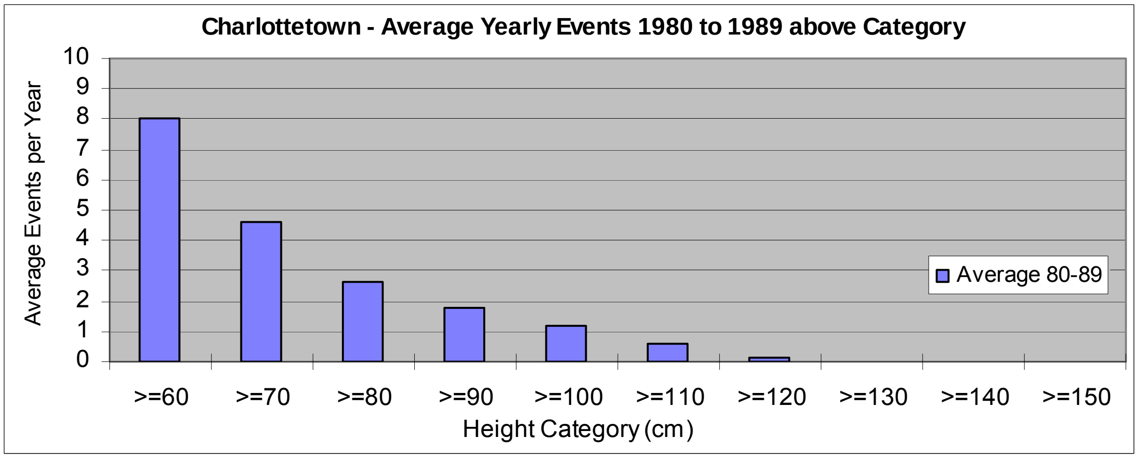


Figure 19. Average storm-surge annual frequency during the 1980s above thresholds.

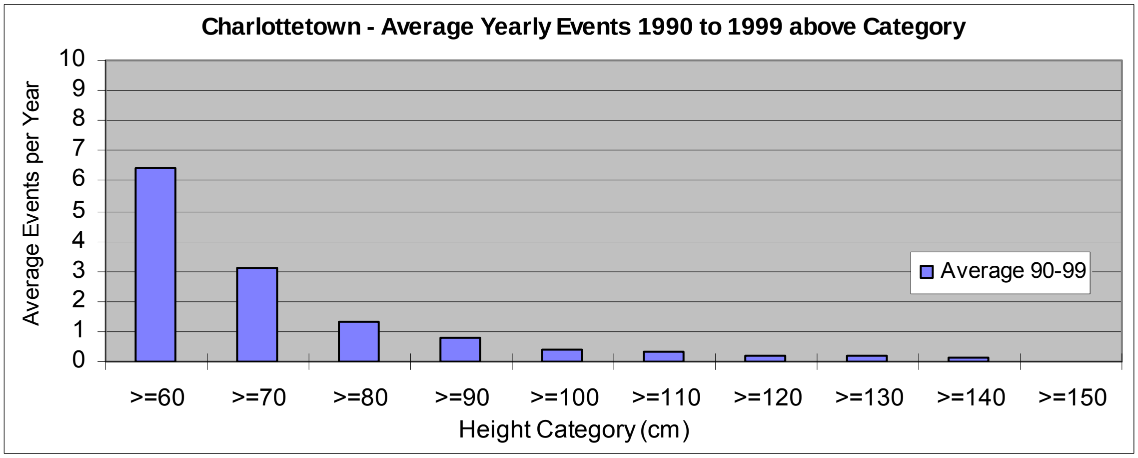


Figure 20. Average storm-surge annual frequency during the 1990s above thresholds.

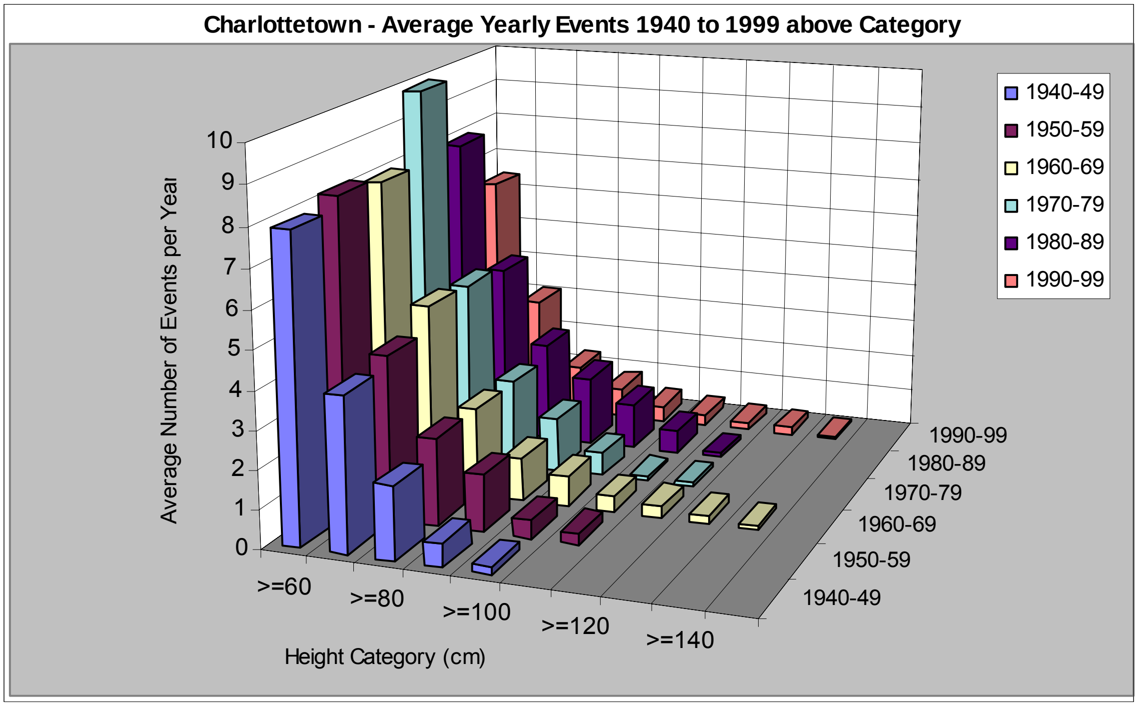


Figure 21. Average number of storm surges per year above threshold by decade at Charlottetown.

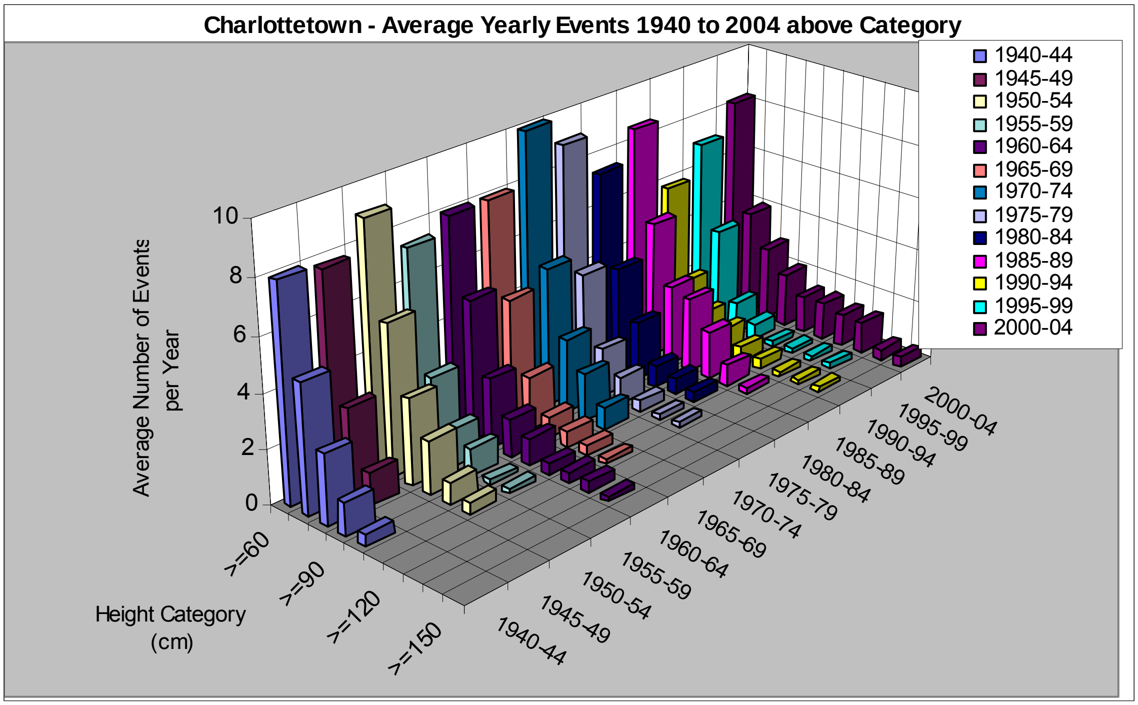


Figure 22. Average number of storm surges per year above threshold by half-decade at Charlottetown.

4.2.4.4 Adjusting the water levels to the year 2000

In the previous analysis, all water-level data were adjusted to the year 1977, assuming a linear sea-level rise of 32 cm/century. These data are now adjusted to the year 2000 by adding 7.36 cm to the water-level values (storm-surge values are already normalized and require no further adjustment). This therefore represents the approximate water level that any storm-surge event from the past might have reached, had it occurred in the year 2000.

Figure 23 shows all observed storm-surge events in 1911–2005 (i.e., interpolated events are not included) in chronological order, and Figure 24 shows them by ascending maximum water level.

Table 1 lists the top 10 storm surges from this analysis (1911–2005), together with a qualitative description of where the storm surge peaked in the tidal cycle (i.e., near/at high tide, low tide, etc.). Also listed are the maximum observed water levels reached during the event and the water level that the events would have reached if they had occurred in the year 2000. Table 2 lists the top 10 observed water-level events in this analysis (1911–2005) and the top 11 water levels that would have been reached if all events had occurred in the year 2000. The same data are displayed graphically in Figure 25 (the top 10 storm surges), Figure 26 (the top 10 observed water levels) and Figure 27 (the top 11 water levels with data adjusted to the year 2000).

Seawater begins to flood the waterfront in Charlottetown at a level of about 3.6 m above CD (Webster et al., 2002). A storm surge of less than 60 cm combined with highest predicted tide (2.91 m CD) cannot reach this level. Of all the storm-surge events noted in the period 1911–2005, only seven events have reached this level and had some flooding impact on the Charlottetown waterfront. The water level of the January 21, 2000, storm stands 38 cm above the level of the January 21, 1961, storm (the Kennedy Inaugural Storm). If sea-level rise is taken into account, then nine of these storms would have caused some flooding of the waterfront if they had occurred in the year 2000, and the water level of the January 21, 2000, storm now stands only 26 cm above the adjusted level of the Kennedy Inaugural Storm. This is the best example that we can find in this data set to illustrate the impacts of relative sea-level rise on flood risk with time.

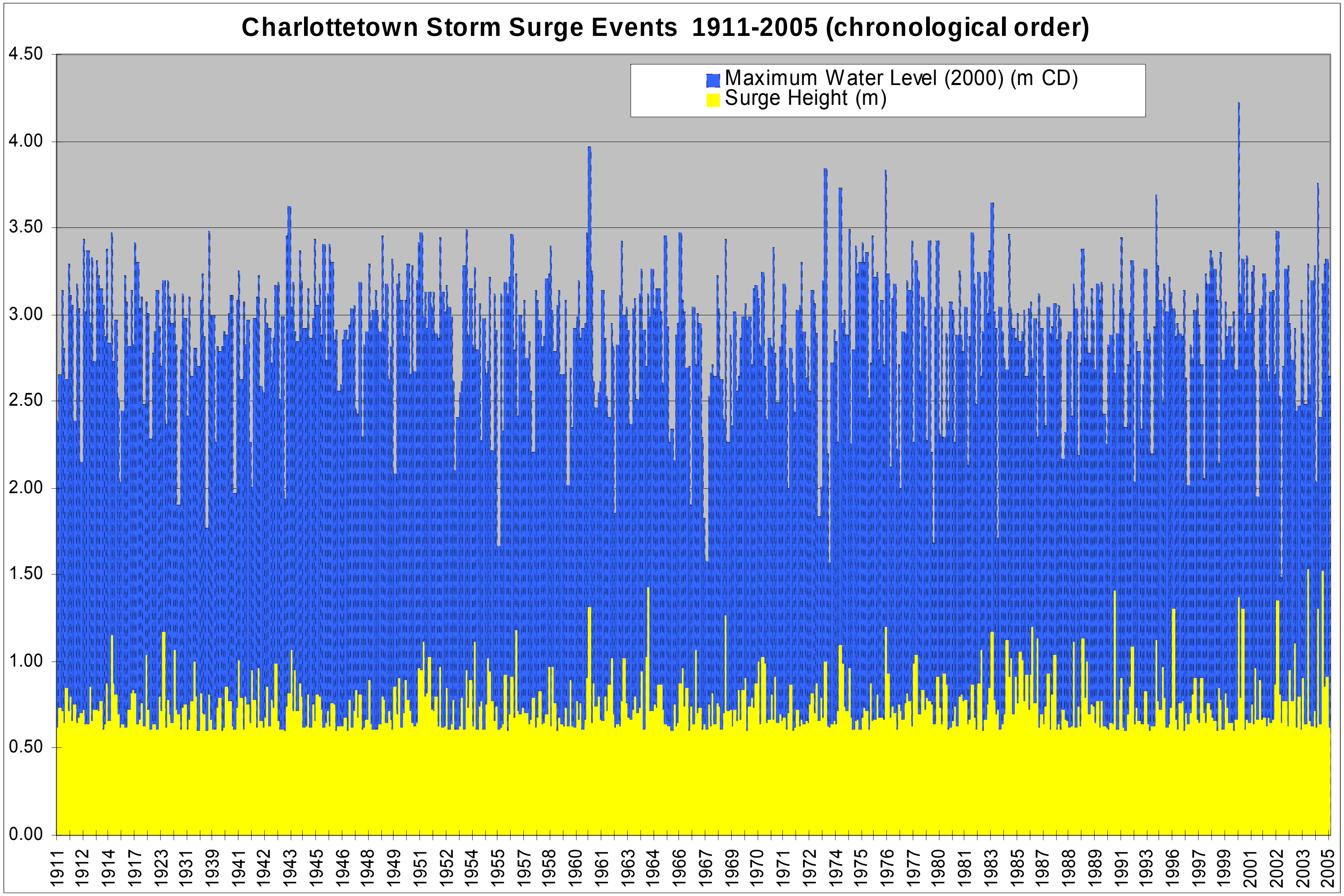


Figure 23. All observed storm surges in Charlottetown from 1911 to 2005 brought to the year 2000.

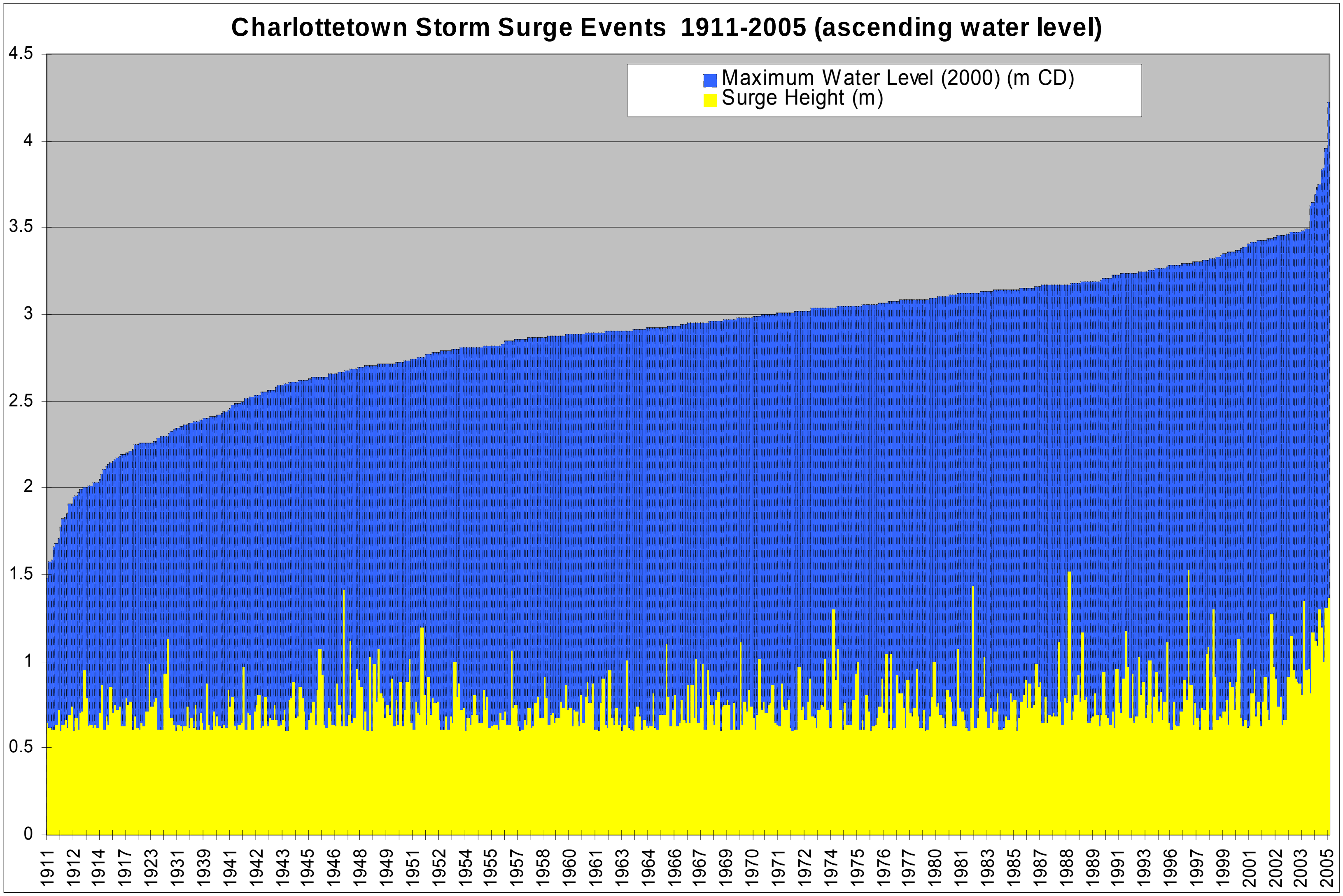


Figure 24. All observed storm surges in Charlottetown from 1911 to 2005 arranged in order of maximum water level in the year 2000.

Table 1. Charlottetown: Top 10 storm-surge events, 1911–2005.

Date	Storm-surge height (m CD)	Maximum observed water level (m CD)	Maximum water level (m CD) (2000)	Tide cycle
January 17, 2004	1.53	3.31	3.29	Low
December 27, 2004	1.52	3.19	3.17	Low
December 19, 1963	1.43	3.01	3.12	Low
March 12, 1991	1.41	2.63	2.66	Low
January 21, 2000	1.37	4.22	4.22	High
September 12, 2002	1.35	3.49	3.48	Mid
January 21, 1961	1.31	3.84	3.96	Nearly high
January 15, 1996	1.30	3.02	3.03	Mid
October 29, 2000	1.30	3.33	3.32	Low
February 19, 2004	1.30	3.77	3.75	High

Table 2. Charlottetown: Top 10 water-level events, 1911–2005.

By observed water level			By water level year 2000		
Date	Maximum observed water level (m CD)	Surge height (m CD)	Date	Maximum water level (m CD) (2000)	Surge height (m CD)
January 21, 2000	4.22	1.37	January 21, 2000	4.22	1.37
January 21, 1961	3.84	1.31	January 21, 1961	3.96	1.31
February 19, 2004	3.77	1.30	January 21, 1973	3.84	1.00
January 21, 1973	3.76	1.00	March 17, 1976	3.83	1.20
March 17, 1976	3.76	1.20	February 19, 2004	3,75	1.30
December 30, 1993	3.67	1.12	February 5, 1974	3.73	1.09
February 5, 1974	3.65	1.09	December 30, 1993	3.69	1.12
December 25, 1983	3.59	1.17	December 25, 1983	3.64	1.17
September 12, 2002	3.49	1.35	December 1, 1943	3.62	0.82
December 1, 1943	3.44	0.82	January 12, 1954	3.49	0.95
			October 20, 1974	3.49	0.96

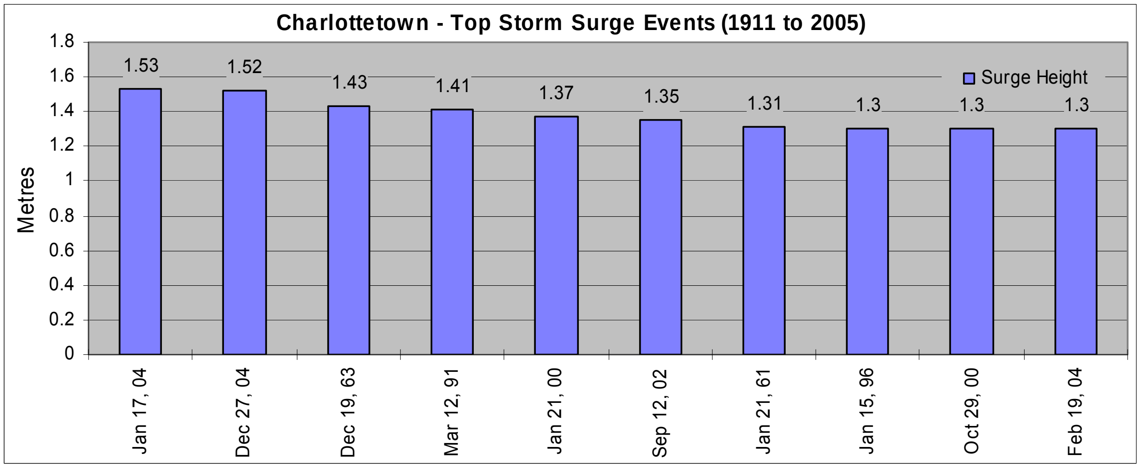


Figure 25. The top 10 storm-surge events at Charlottetown.

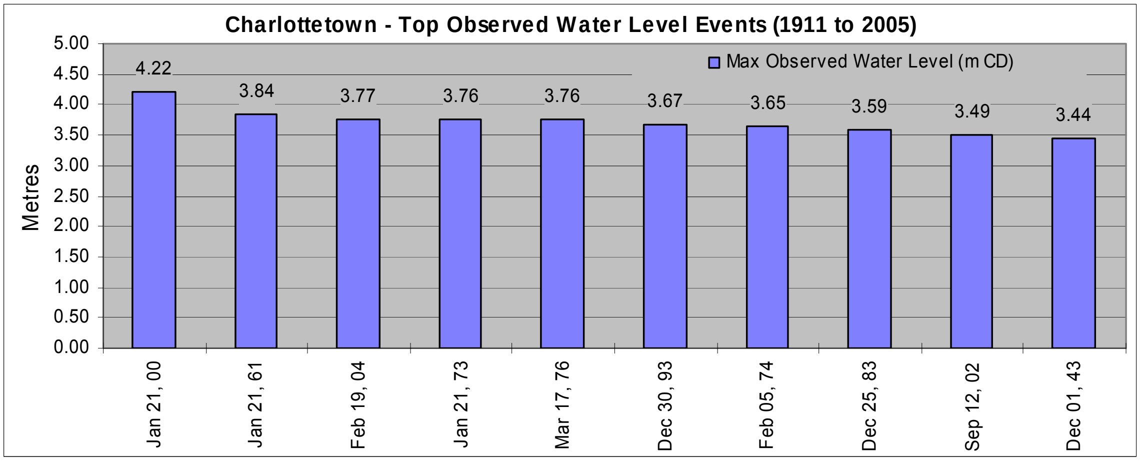


Figure 26. The top 10 observed water levels at Charlottetown.

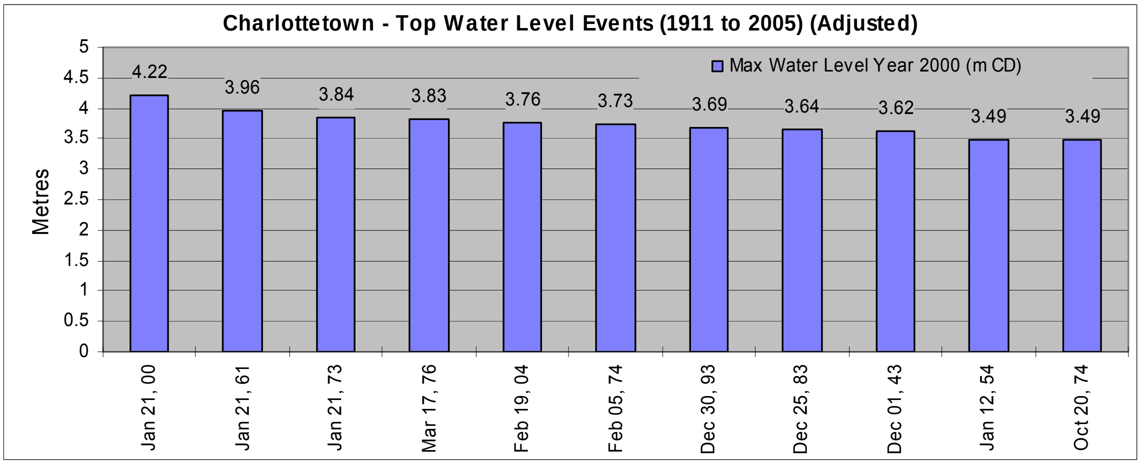


Figure 27. The top 11 water levels at Charlottetown (adjusted to year 2000).

In Supporting Document 6 of the Prince Edward Island sea-level rise report (Thompson et al., 2002), an extreme-value analysis of water levels at Charlottetown was developed to estimate the return periods of extreme water levels. Changes in the probability of flooding were then addressed under plausible climate-change scenarios. In the future, not only will flooding occur at higher levels, but flooding at any given level will increase in frequency. On November 6, 1994, a water level of 3.42 m CD was reached at Charlottetown when a 51-cm storm surge came in phase with one of the highest possible astronomical tides (predicted at 2.86 m CD). To demonstrate the potential increase in the frequency of flooding, we cannot just look at storm-surge events, but we must also look at water-level exceedances. Our water-level data from 1960 to 2005 (46 years) last over two nodal modulations of the tidal cycle (18.6 years), with approximately 2.68 years' worth of data missing in total. Our interpolated storm-surge events allow us to explore the likelihood of missed exceedances in excess of 3.6 m CD, since such a water level would have involved at least a 60-cm storm surge. There were no such missed exceedances. The number of observed water levels that crossed various thresholds during this period is listed in Table 3 (column 2). Exceedances of 3.2–3.5 m CD are scaled directly for missing data during this period in column 3. Note the large increase in exceedance frequency at the lower levels. Assuming that the climatology of storms stays the same and that relative sea-level rises at 30 cm/century (approximately its present rate), then column 5 shows the frequency of exceedances per year around the year 2100. Whereas we can expect one exceedance of 3.6 m CD every six years or so at present, by the year 2100 we could expect one such exceedance on average each year, with one event every 10 years or so in excess of 4.0 or 4.1 m CD. The water level of 4.22 m CD that occurred on January 21, 2000, would come in at 4.52 m CD. Table 3 demonstrates that with sea-level rise and global warming, not only will flooding move to higher levels, but also the floods at the lower levels will become much more frequent.

Table 3. Average annual frequency of water-level exceedances at Charlottetown in the year 2000 (based on 1960–2005 water-level data) and the year 2100 (assuming present storm climatology and present rate of sea-level rise).

Column 1	Column 2	Column 3	Column 4	Column 5
Level (m CD)	No. of events, 1960–1998 (data adjusted to year 2000), above threshold	Column 2 scaled for missing data	No. of events on average per year above threshold (year 2000)	No. of events on average per year above threshold (year 2100)
≥3.2	101	107	2.35	?
≥3.3	43	46	1.01	?
≥3.4	22	23	0.51	?
≥3.5	8	9	0.20	2.35
≥3.6	8	8	0.17	1.01
≥3.7	6	6	0.13	0.51
≥3.8	4	4	0.09	0.20
≥3.9	2	2	0.04	0.17
≥4.0	1	1	0.02	0.13
≥4.1	1	1	0.02	0.09
≥4.2	1	1	0.02	0.04

Column 1	Column 2	Column 3	Column 4	Column 5
Level (m CD)	No. of events, 1960–1998 (data adjusted to year 2000), above threshold	Column 2 scaled for missing data	No. of events on average per year above threshold (year 2000)	No. of events on average per year above threshold (year 2100)
≥4.3	0	0	0	0.02
≥4.4	0	0	0	0.02
≥4.5	0	0	0	0.02

4.2.5 Storm surges at Pointe-du-Chêne and Escuminac

4.2.5.1 Adjusting the Pointe-du-Chêne data set

Pointe-du-Chêne data are available for the years 1971–1992 and during the period from 2003 to October 31, 2005. Annual and monthly means at Pointe-du-Chêne are plotted in Section 4.1 of this document, where a linear trend of 25–30 cm/century was calculated.

The observed water-level data at Pointe-du-Chêne were therefore corrected for relative sea-level rise at a rate of 25 cm/century in a similar fashion as for the Charlottetown data (i.e., from 1977). Storm-surge events were then extracted using the same procedure as at Charlottetown. A total of 232 storm-surge events in excess of 60 cm were identified, and these are shown plotted in chronological order in Figure 28, by ascending storm-surge height in Figure 29, and by ascending highest water level in Figure 30. The water level associated with the storm of January 21, 2000, was not measured by a tide gauge but is also shown in these plots. This level itself was measured by Donald Forbes shortly after the event; it is a benchmark level in the history of flooding in this area and is featured throughout this report and this project. The flood was levelled in at 3.62 m CD. This adjusts to an equivalent level in 1977 of 3.56 m CD. The tide that afternoon was predicted at 1.56 m CD, representing a storm-surge value of 2.06 m. All storm-surge events are shown in Figure 31 above thresholds of 60, 90, 120 and 150 cm, together with the percentage of missing data each year. These represent all observed storm surges of 60 cm or more in the inventory of water-level data at Pointe-du-Chêne.

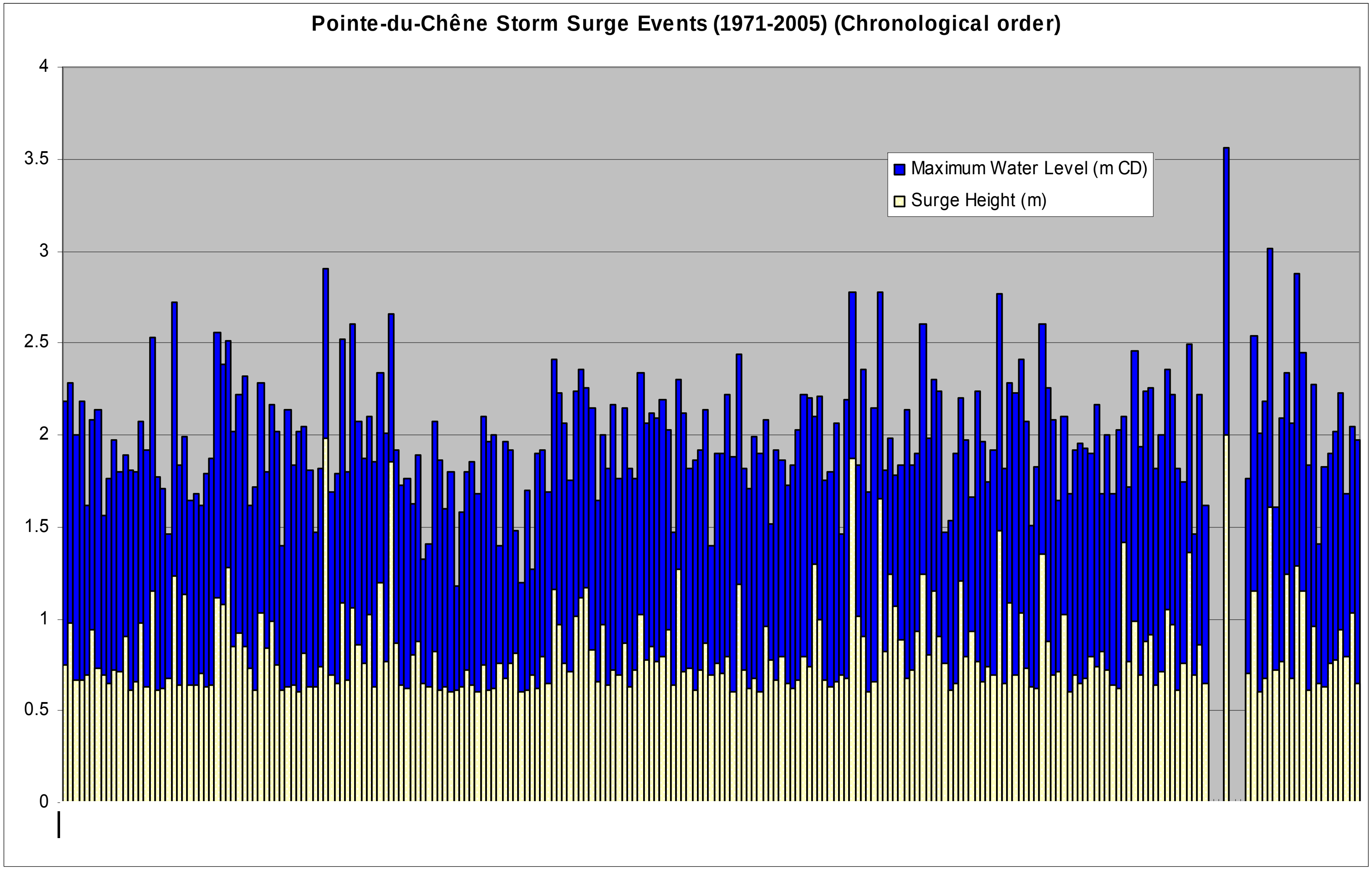


Figure 28. All observed storm-surge events >60 cm at Pointe-du-Chêne, 1971–2005, arranged in chronological order.

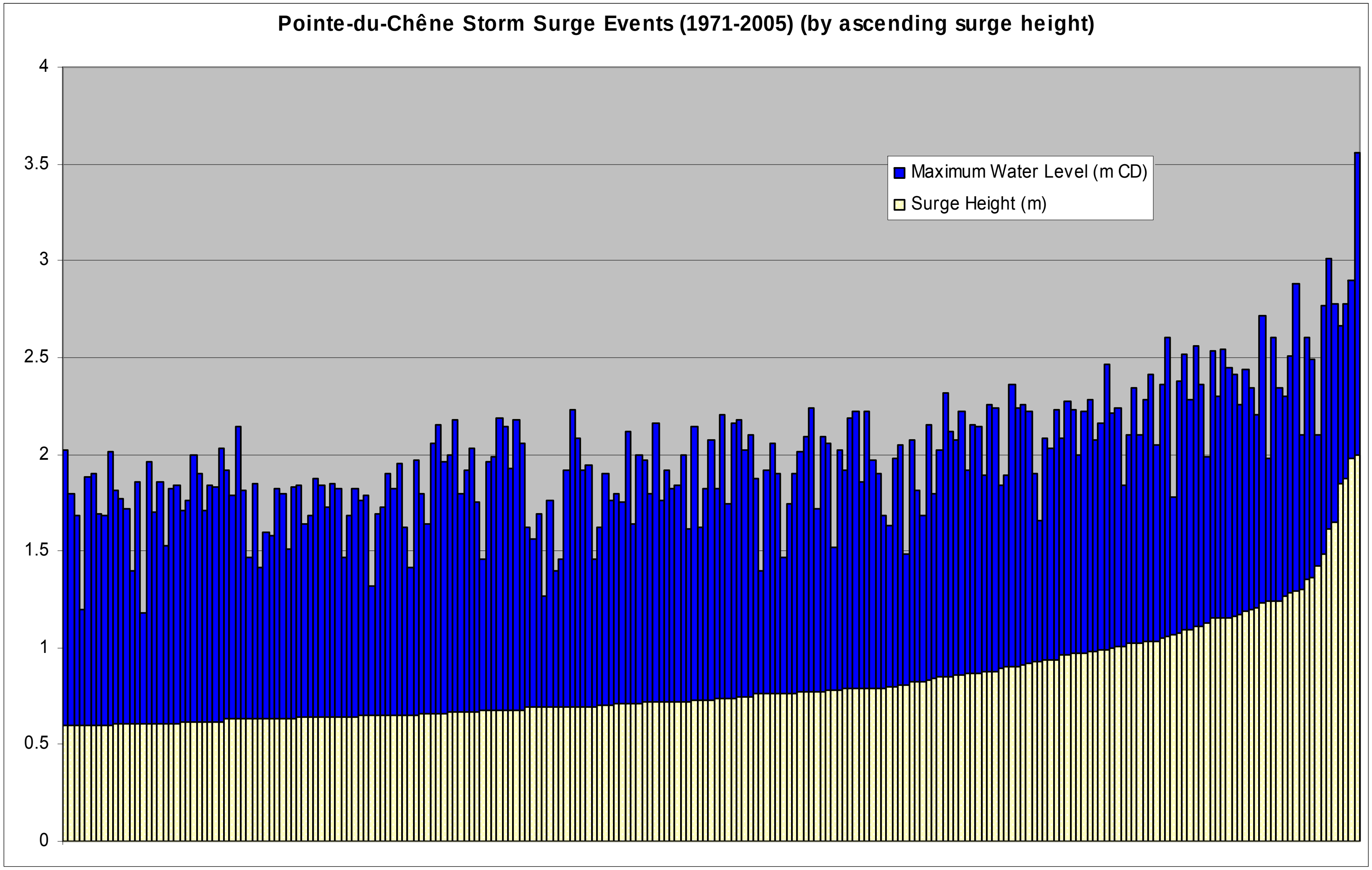


Figure 29. All observed storm-surge events >60 cm at Pointe-du-Chêne, 1971–2005, arranged by ascending storm-surge height.

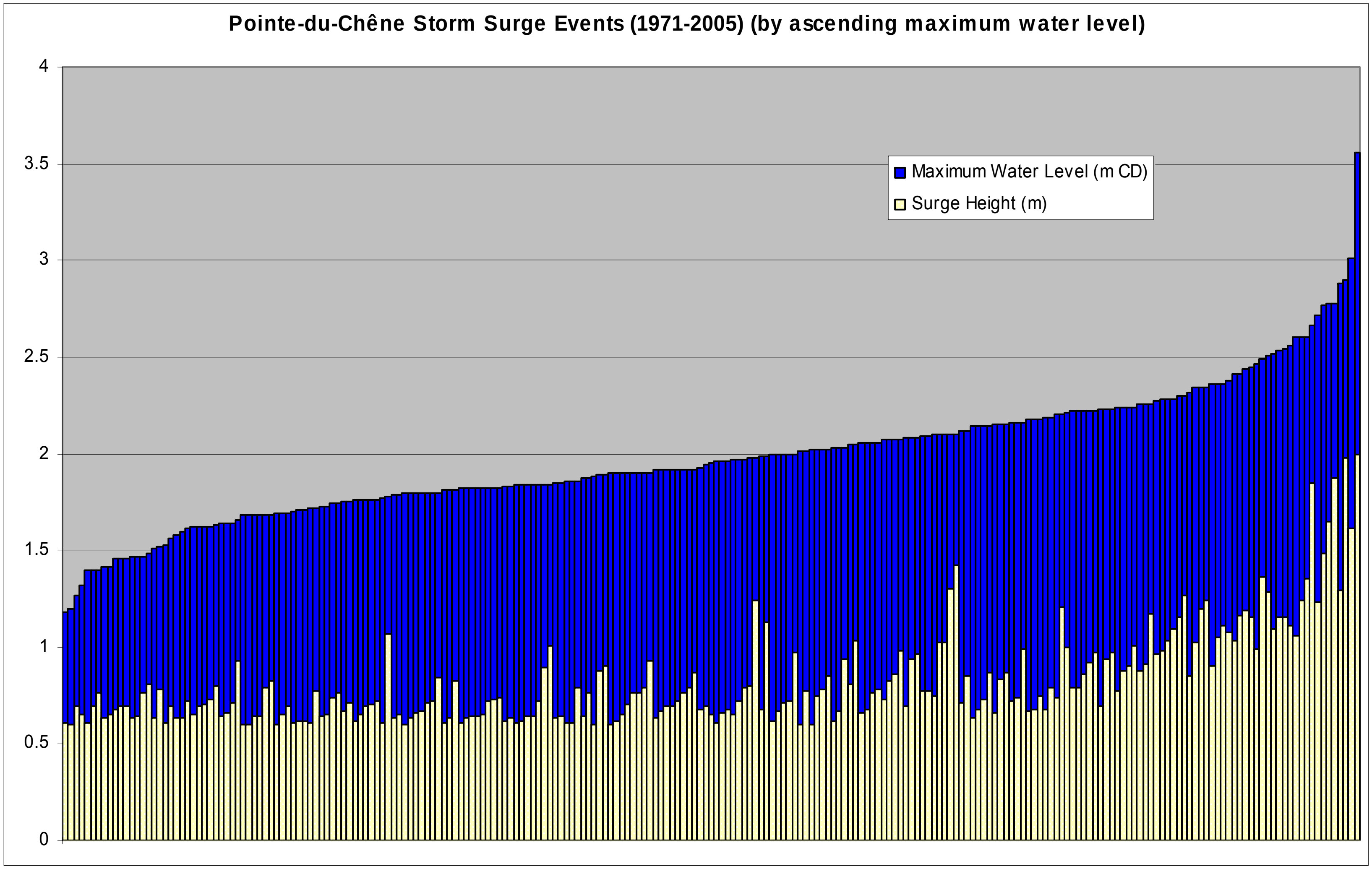


Figure 30. All observed storm-surge events >60 cm at Pointe-du-Chêne, 1971–2005, arranged by ascending water level.

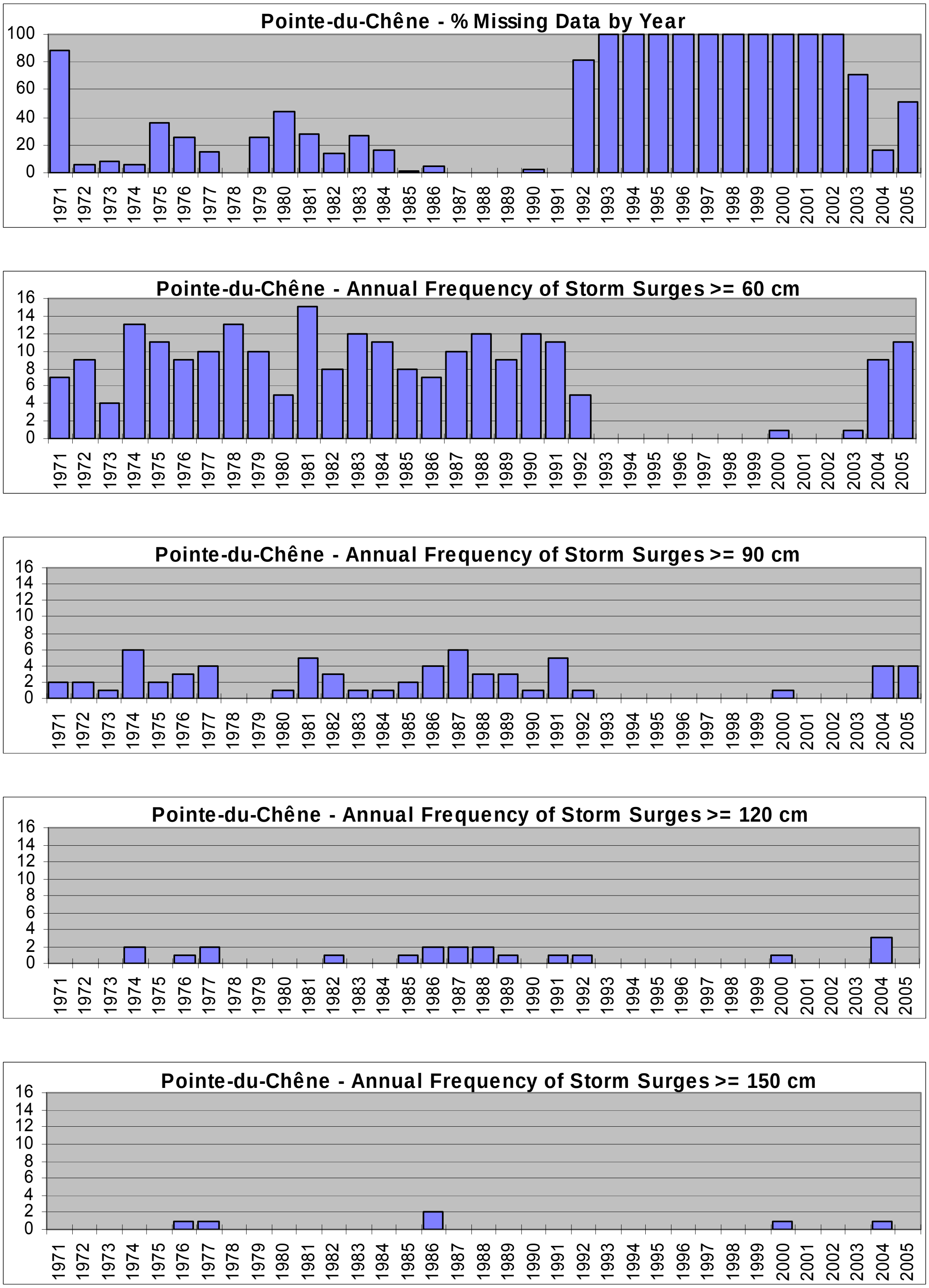


Figure 31. Storm surges at Pointe-du-Chêne above 60, 90, 120 and 150 cm, and plot of missing data.

4.2.5.2 Adjusting the Escuminac and Pointe-Sapin data sets

Escuminac water-level data are available for the period from January 1973 to October 2005. Annual and monthly means at Pointe-du-Chêne are plotted in Section 4.1 of this document, where a linear trend of 20–23 cm/century was calculated.

The observed water-level data at Escuminac were therefore corrected for relative sea-level rise at a rate of 20 cm/century in a similar fashion as for the Charlottetown data (i.e., from 1977). Storm-surge events were then extracted using the same procedure as at Charlottetown. A total of 211 storm-surge events in excess of 60 cm were identified.

Pointe-Sapin data are available for the period from January 1963 to September 1975. These data have an overlap with Escuminac data for the period from January 1973 to September 1975. The two sites are in relatively close proximity. In this analysis, Pointe-Sapin data prior to 1973 are appended to the Escuminac data set. When tidal predictions for Escuminac are subtracted from Pointe-Sapin data, the resulting residuals are a little noisier than the Escuminac residuals themselves; nonetheless, there is a good fit.

An error of about 17.89 cm was identified in Pointe-Sapin data prior to August 1971. This has since been confirmed by MEDS, which reports that it has found documentation that there was an adjustment to the benchmark elevation (BM TS5 1962) of 18.2 cm on September 14, 1971. In this analysis, Pointe-Sapin data prior to September 1971 were therefore lowered by 18 cm. The entire database was then adjusted by 20 cm/century from 1977. Storm-surge events were then extracted using the same procedure as for Charlottetown. A total of 64 storm-surge events in excess of 60 cm were identified. Additionally, Pointe-Sapin data for July and August 1974 were scanned for storm-surge events, since these data were missing at Escuminac; however, no events were found.

The storm-surge events for Pointe-Sapin and Escuminac are shown plotted in chronological order in Figure 32. The break in the data is where the site changes. The events are plotted by ascending storm-surge height in Figure 33 and by ascending highest water level in Figure 34. The water level associated with the storm of January 21, 2000, is missing from these data and has not been captured by field surveys; however, anecdotal reports from the area attest to it being higher than other levels in living memory.

All storm-surge events are shown in Figure 35 above thresholds of 60, 90, 120 and 150 cm, together with the percentage of missing data each year. These represent all observed storm surges of 60 cm or more in the inventory of water-level data at Pointe-Sapin and Escuminac.

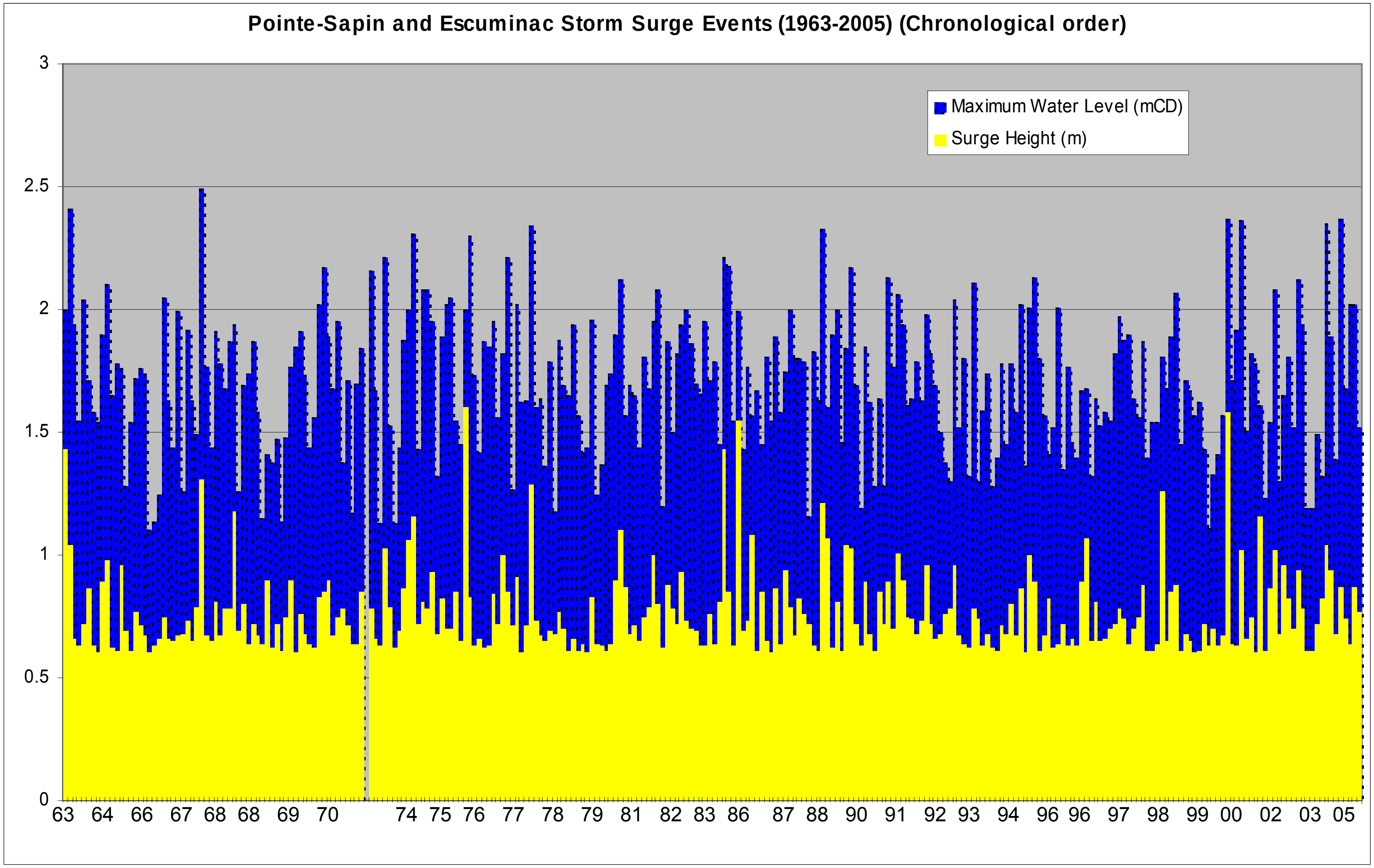


Figure 32. All observed storm-surge events >60 cm at Pointe-Sapin and Escuminac, 1963–2005, arranged in chronological order.

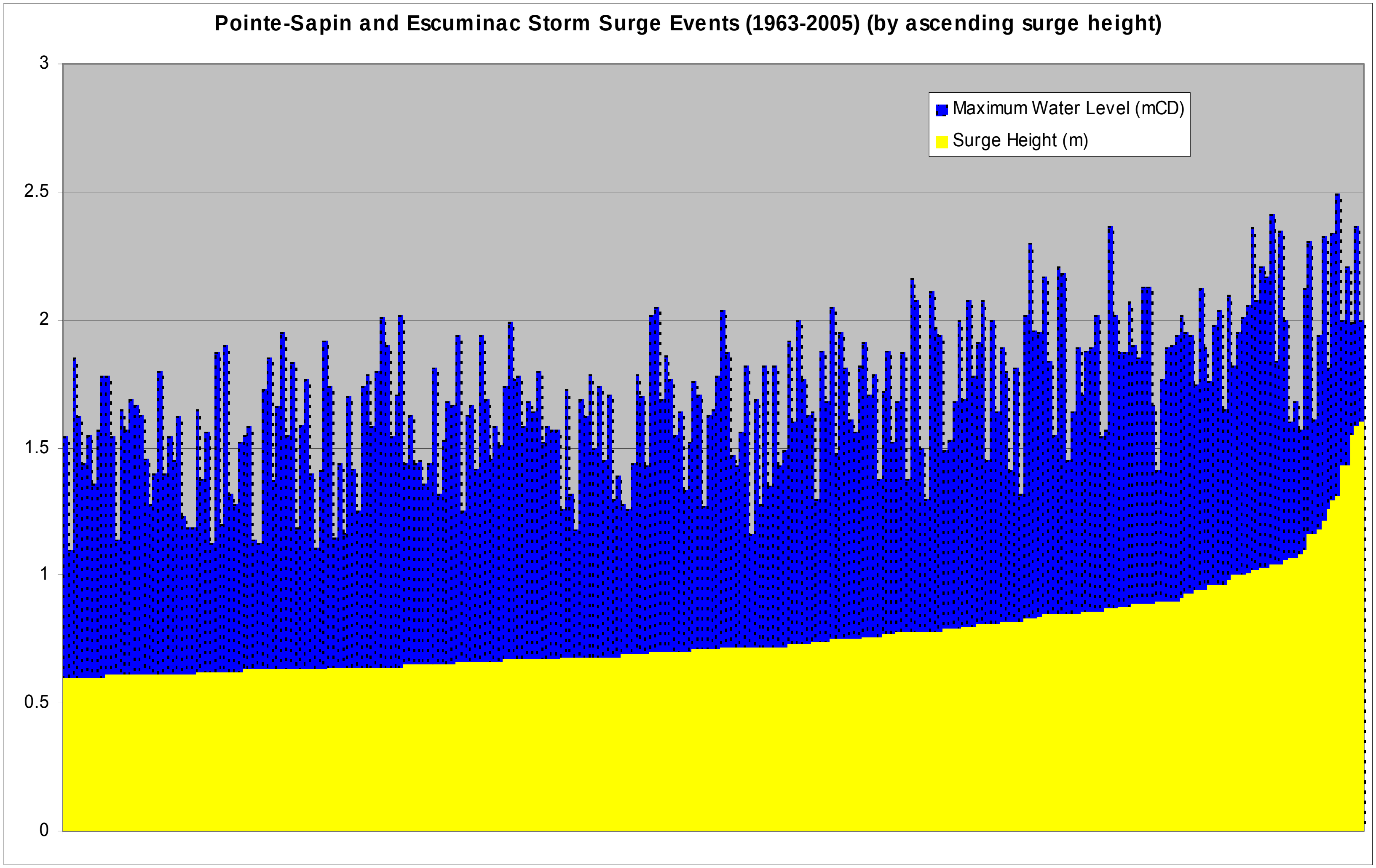


Figure 33. All observed storm-surge events >60 cm at Pointe-Sapin and Escuminac, 1963–2005, arranged by ascending storm-surge height.

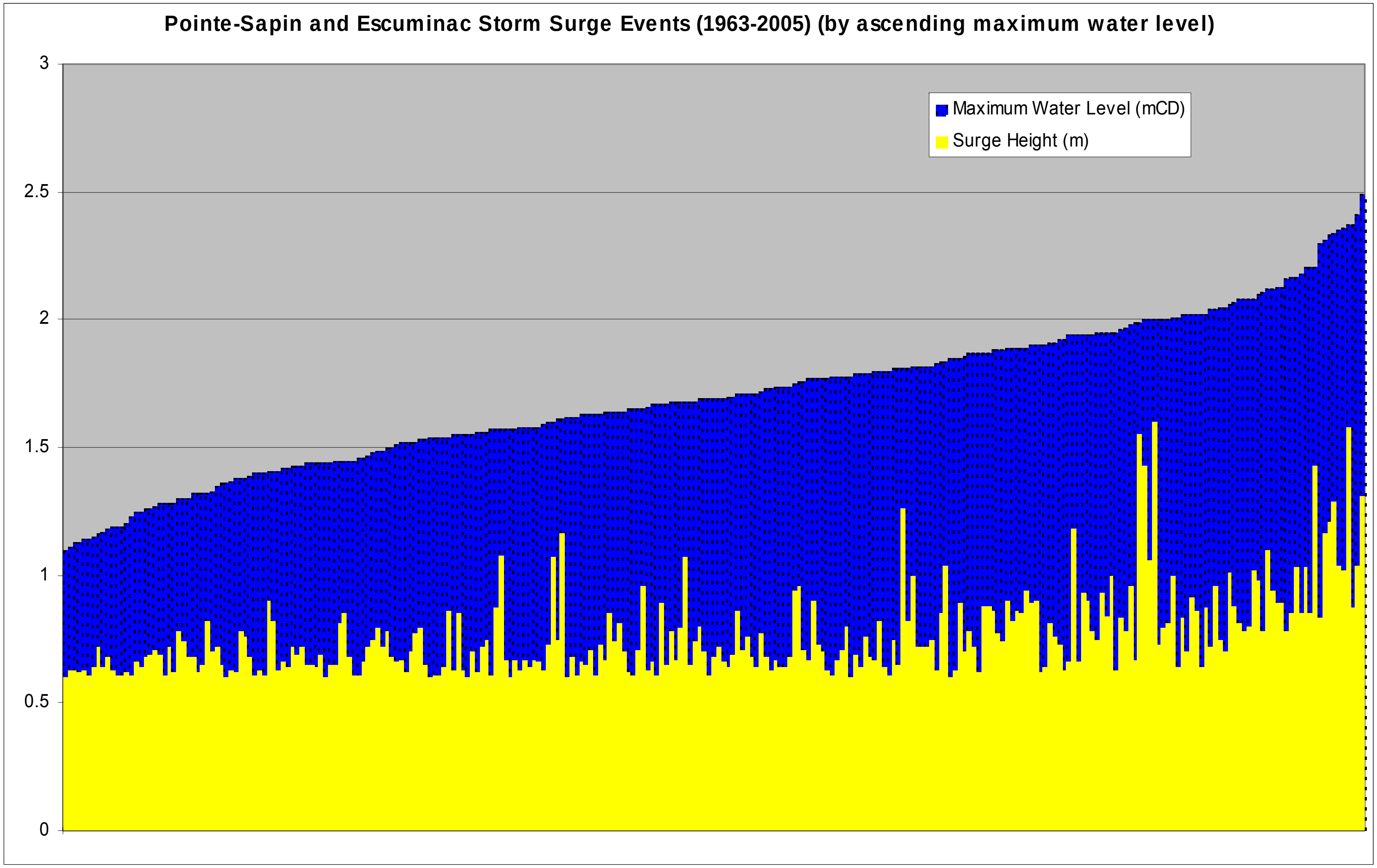


Figure 34. All observed storm-surge events >60 cm at Pointe-Sapin and Escuminac, 1963–2005, arranged by ascending water level.

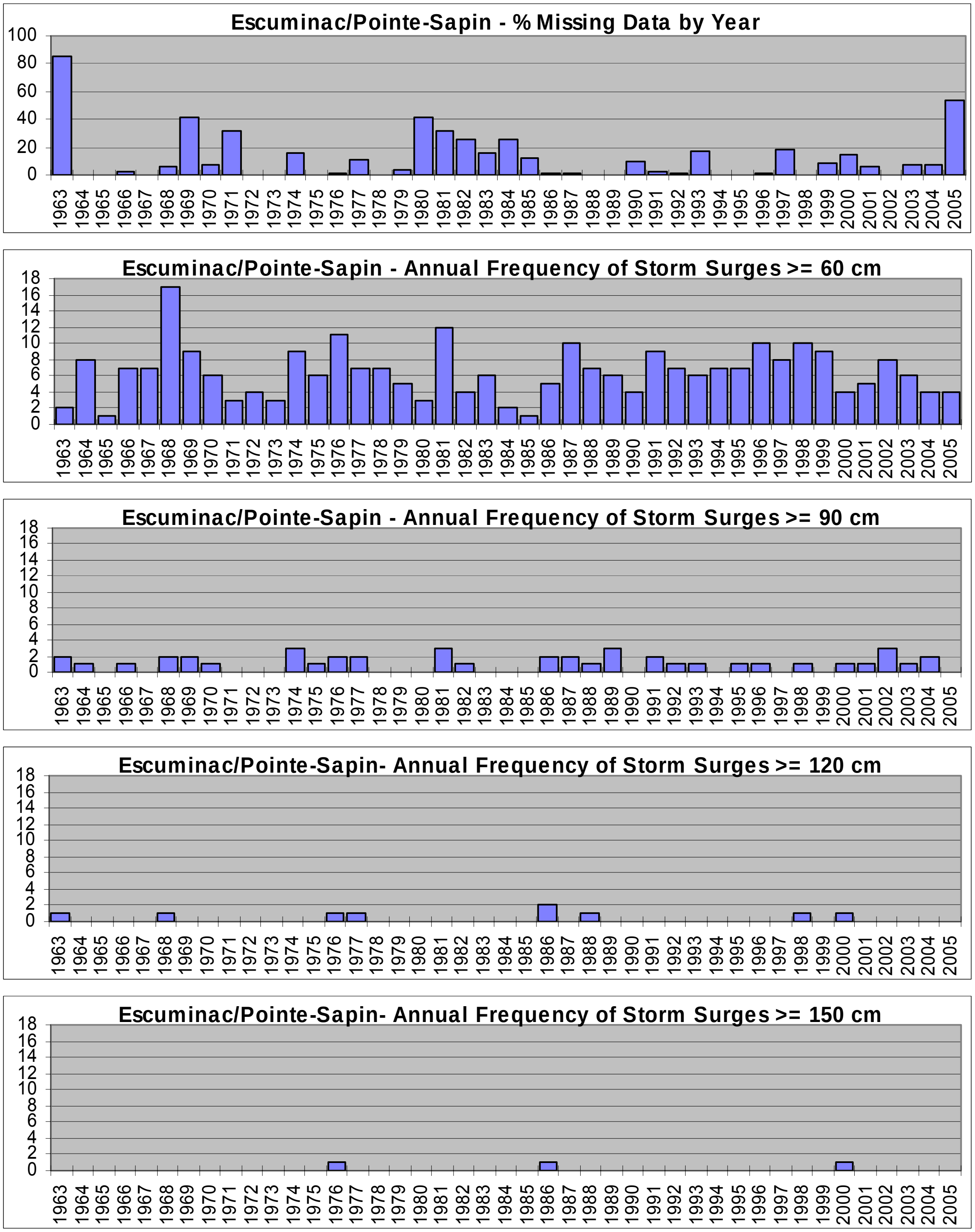


Figure 35. Escuminac/Pointe-Sapin storm surges above 60, 90, 120 and 150 cm, and plot of missing data.

4.2.6 The climatology of storm surges at Pointe-du-Chêne and Escuminac

Years with less than 20% missing data at Pointe-du-Chêne are chosen to represent the storm-surge climatology of the area. Eleven of these 15 years have less than 10% missing data. Of the four remaining years (1977, 1982, 1984 and 2004), all have the majority of their missing data during the fair-weather months rather than during the fall and winter. The average number of events per year above various thresholds is shown in Figures 36 and 37.

Years with less than 10% missing water-level data at Escuminac and Pointe-Sapin are chosen to represent the storm surge climatology of the area. Twenty of these 28 years have less than 5% missing data. The average number of events per year above various thresholds are shown below in Figure 37.

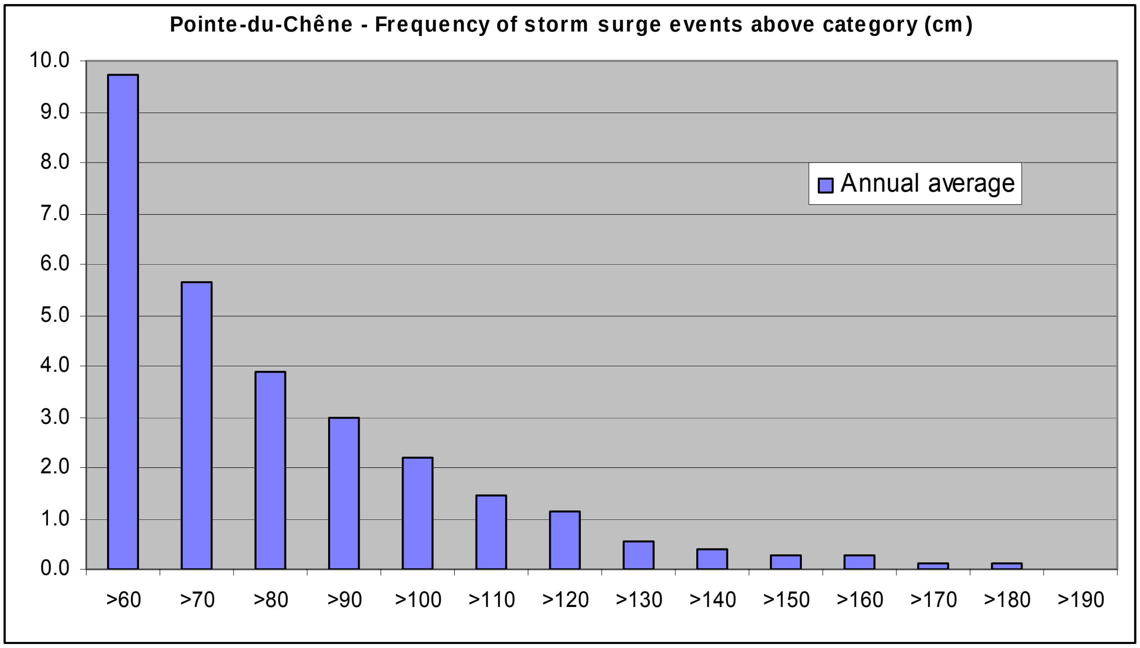


Figure 36. Average number of storm surges per year above various thresholds at Pointe-du-Chêne.

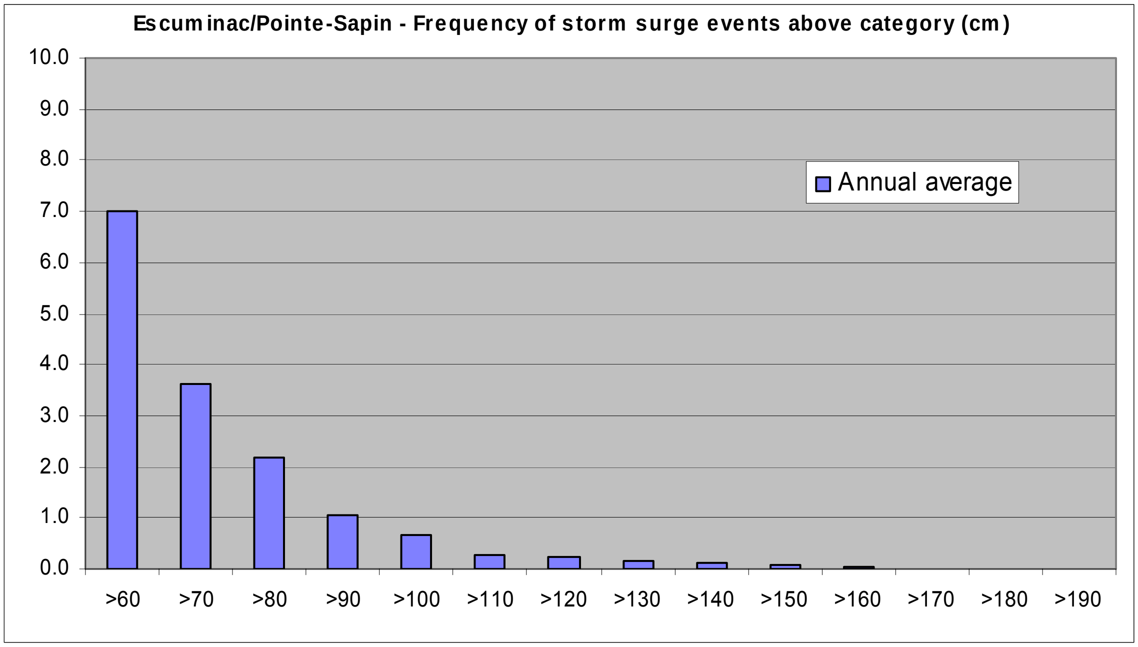


Figure 37. Average number of storm surges per year above various thresholds at Escuminac.

Storm surges at Escuminac/Pointe-Sapin (Figure 38) are similar in frequency, distribution and size to those at Charlottetown (see Figure 8 for the period 1960–2004). On average, there are about seven events each year in excess of 60 cm, with close to one event each year above 100 cm. There is great variability in frequency from one year to the next, with no obvious discernible trend. Nine storm surges above 120 cm have been identified at Escuminac/Pointe-Sapin for the period 1963–2005, compared with 13 events at Charlottetown for the period 1960–2005. The very large storm surges may, however, be a little more frequent, with three events in excess of 150 cm identified at Escuminac (even with the storm of January 21, 2000, missing), as opposed to two at Charlottetown. The largest recorded storm surge was 160 cm in height on March 17, 1976. These storm surges are mainly associated with the stormy period of the late fall and winter. The statistics show an increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there were few occurrences in the period from May to September.

Storm surges at Pointe-du-Chêne (Figure 39) are larger and more frequent than those at Escuminac or Charlottetown, although their distribution throughout the year is, of course, similar, since they are usually set up by the same storms. Ten events above 60 cm are observed per year on average, with two to three events above 100 cm per year on average. Storm surges above 150 cm occur once every two or three years, and storm surges as high as 200 cm have been recorded (198 cm on March 17, 1976, and 200 cm on January 21, 2000), representing the largest recorded storm surges in Atlantic Canada known to the present authors.

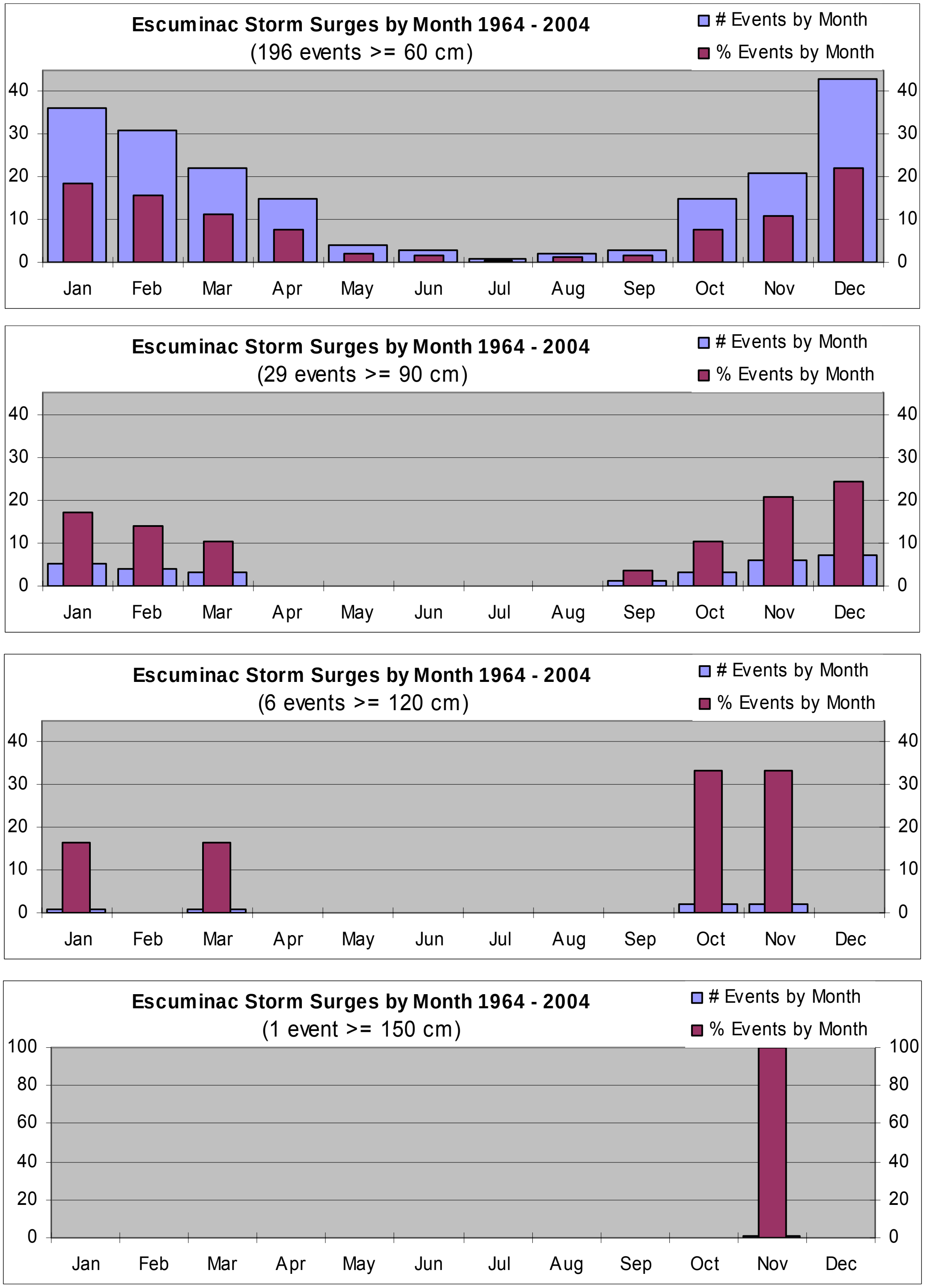


Figure 38. Escuminac/Pointe-Sapin storm surges above 60, 80, 100 and 120 cm by month.

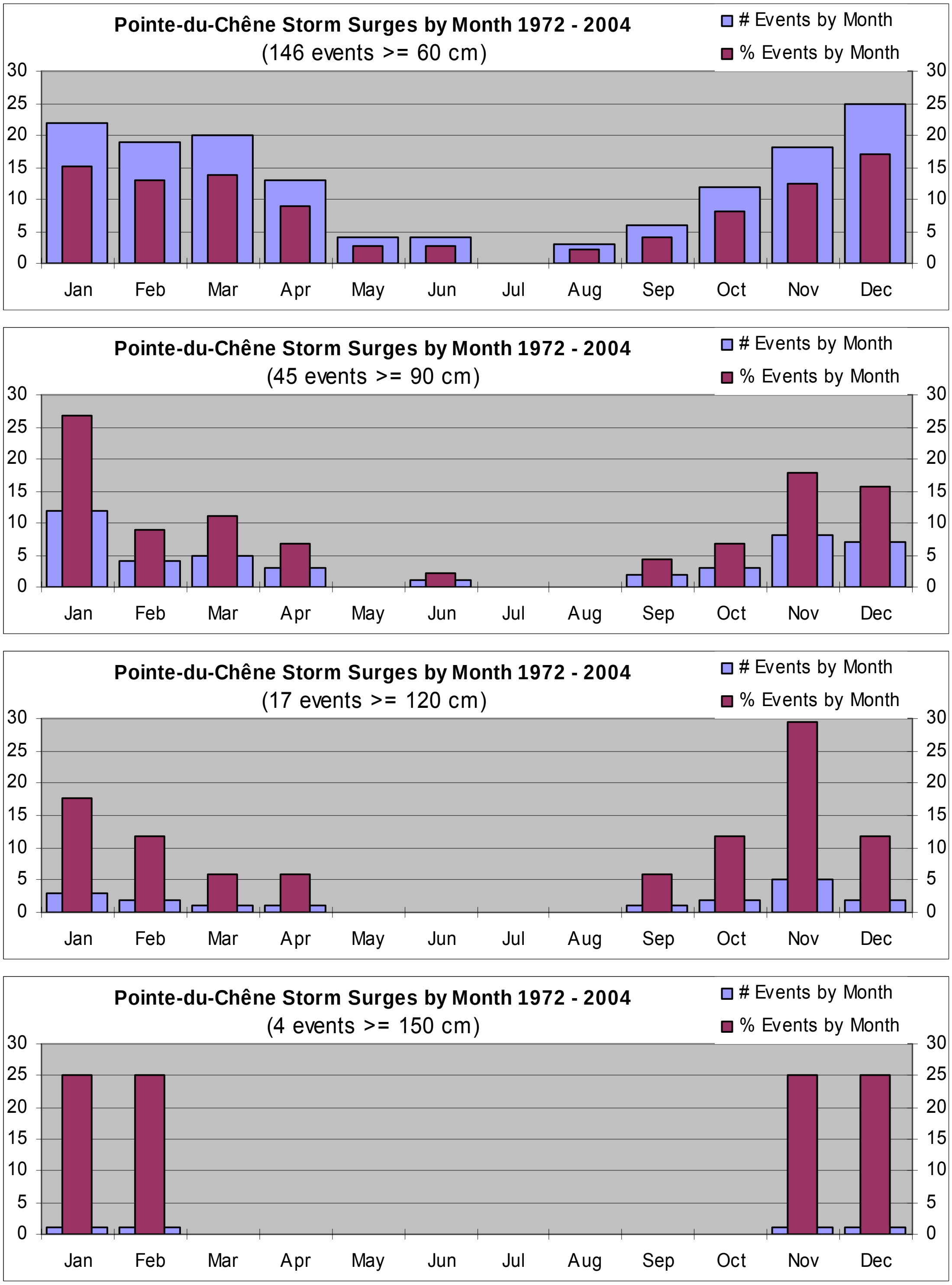


Figure 39. Pointe-du-Chêne storm surges above thresholds of 60, 90, 120 and 150 cm by month.

4.2.7 Extreme events at Pointe-du-Chêne and Escuminac

In the previous analysis, all water-level data were adjusted to the year 1977, assuming a linear sea-level rise of 20 cm/century at Escuminac and Pointe-Sapin and 25 cm/century at Pointe-du-Chêne. These data can now be adjusted to the year 2000 by adding 4.6 cm to the water-level values at Escuminac and Pointe-Sapin and 5.75 cm to the water-level values at Pointe-du-Chêne (storm-surge values are already normalized and require no further adjustment). This therefore represents the approximate water level that any storm-surge event from the past might have reached, had it had occurred in the year 2000.

Table 4 lists the top 10 storm surges recorded at Pointe-du-Chêne (1971–2005) together with the maximum observed water levels reached during the events and the water level that the events would have reached if they had occurred in the year 2000. Also listed is a qualitative description of where the storm surge peaked in the tidal cycle (i.e., near/at high tide, at low tide, at a low high tide, etc.). The same information is shown in Table 5 for Escuminac and Pointe-Sapin for the period of their water-level data (1963–2005).

Table 6 lists the top 11 observed water-level events in the water-level data at Pointe-du-Chêne and the top 11 water levels that would have been reached if all events had occurred in the year 2000. Table 7 shows the same data for Escuminac/Pointe-Sapin.

The same data are displayed graphically in Figures 40 and 41 (the top 10 storm surges), Figures 42 and 43 (the top 11 observed water levels) and Figures 44 and 45 (the top 11 water levels when adjusted to the year 2000). Prior to the recent reinstallation of the tide gauge at Pointe-du-Chêne, the record water level there from tide-gauge data was 2.90 m CD, set on March 17, 1976. Recent data have captured two events in excess of this, owing to the storm of February 19, 2004 (White Juan), and the storm of December 27, 2004 (a damaging wave and coastal erosion event in the area). Additionally, field surveys have captured the level of the definitive storm of January 21, 2000; nonetheless, other important dates and levels are missing. These include the storm of October 29, 2000, and Hurricane Gustav on September 12, 2002. Hurricane Gustav set the ninth highest water level recorded in the Charlottetown data, is a known flooding event at Pointe-du-Chêne and was probably somewhere near the level of the White Juan event. Other events that show up on the list of top 10 water levels at Charlottetown (which are likely to also have had a significant impact at Pointe-du-Chêne) include the Kennedy Inaugural Storm of January 21, 1961 (the second highest water level ever recorded at Charlottetown) and the storm of January 21, 1973 (fourth highest at Charlottetown), both of which predate the data set.

Historic levels at Escuminac do not contain the level of the storm of January 21, 2000, although the flood in those parts, somewhat diminished from farther south, was certainly also at new record water levels. Interestingly, the highest known level since 1963 comes from the appended Pointe-Sapin data and is due to the storm of October 21, 1968 (Hurricane Gladys). The highest predicted tide at Pointe-du-Chêne is about 1.7 m CD. The highest known storm surge is about 2.0 m. Combining these numbers gives a highest possible water level of 3.7 m CD, which is just a little higher than the level of the January 21, 2000, storm, suggesting that Pointe-du-Chêne has already seen something close to its worse-case scenario flood level in today’s climate. The highest predicted tide at Escuminac is about 1.6 m CD.

Table 4. Pointe-du-Chêne: Top 10 storm-surge events, 1971–2005.

Date	Storm-surge height (m CD)	Maximum observed water level (m CD)	Maximum water level (m CD) (2000)	Tide cycle
January 21, 2000	2.00	3.62	3.62	High
March 17, 1976	1.98	2.90	2.96	Mid
January 4, 1986	1.87	2.80	2.84	Low
December 7, 1977	1.85	2.66	2.72	Low
November 22, 1986	1.65	2.80	2.84	Mid
February 19, 2004	1.61	3.08	3.07	High
November 21, 1988	1.48	2.80	2.83	High
March 12, 1991	1.42	2.14	2.16	Low
February 1, 1992	1.36	2.53	2.55	Low
November 21, 1989	1.35	2.63	2.66	Low high

Table 5. Escuminac and Pointe-Sapin: Top 10 storm-surge events, 1963–2005.

Date	Storm-surge height (m CD)	Maximum observed water level (m CD)	Maximum water level (m CD) (2000)	Tide cycle
March 17, 1976	1.53	2.00	2.05	Low
October 29, 2000	1.52	2.42	2.42	Low high
November 22, 1986	1.43	2.01	2.04	Low
October 29, 1963	1.41	1.97	2.05	Low
January 4, 1986	1.37	2.23	2.26	Mid
October 21, 1968	1.35	2.47	2.54	High
December 7, 1977	1.31	2.34	2.39	Mid
October 30, 1998	1.30	1.85	1.86	Low
November 21, 1988	1.30	2.35	2.38	Nearly high
December 8, 1968	1.30	1.92	1.99	Low

Table 6. Pointe-du-Chêne: Top 10 water-level events, 1971–2005

By observed water level			By water level year 2000		
Date	Maximum observed water level (m CD)	Surge height (m CD)	Date	Maximem water level (m CD) (2000)	Surge height (m CD)
January 21, 2000	3.62	2.00	January 21, 2000	3.62	2.00
February 19, 2004	3.08	1.61	February 19, 2004	3.07	1.61
December 27, 2004	2.95	1.29	March 17, 1976	2.96	1.98
March 17, 1976	2.90	1.98	December 27, 2004	2.94	1.29
January 4, 1986	2.80	1.87	November 22, 1986	2.84	1.65
November 22, 1986	2.80	1.65	January 4, 1986	2.84	1.87
November 21, 1988	2.80	1.48	November 21, 1988	2.83	1.48
February 5, 1974	2.71	1.23	February 5, 1974	2.78	1.23
December 7, 1977	2.66	1.85	December 7, 1977	2.72	1.85
November 12, 1987	2.63	1.24	January 17, 1977	2.66	1.06
November 21, 1989	2.63	1.35	Nov 12,1987	2.66	1.24

Table 7. Escuminac and Pointe-Sapin: Top 10 water-level events, 1963–2005.

By observed water level			By water level year 2000		
Date	Maximum observed water level (m CD)	Surge height (m CD)	Date	Maximum water level (m CD) (2000)	Surge height (m CD)
October 21, 1968	2.47	1.31	October 21, 1968	2.54	1.31
October 29, 2000	2.42	1.58	December 19, 1963	2.46	1.04
December 27, 2004	2.42	0.87	October 29, 2000	2.42	1.58
February 6, 2001	2.41	1.02	December 27, 2004	2.42	0.87

By observed water level			By water level year 2000		
Date	Maximum observed water level (m CD)	Surge height (m CD)	Date	Maximum water level (m CD) (2000)	Surge height (m CD)
February 19, 2004	2.40	1.04	February 6, 2001	2.41	1.02
December 19, 1963	2.39	1.04	February 19, 2004	2.40	1.04
November 21, 1988	2.38	1.21	December 7, 1977	2.39	1.29
December 7, 1977	2.35	1.29	November 21, 1988	2.38	1.21
November 26, 1974	2.34	1.16	November 26, 1974	2.36	1.16
June 12, 1976	2.30	0.83	June 12, 1976	2.35	0.83
January 4, 1986	2.23	1.43	February 5, 1974	2.26	1.03

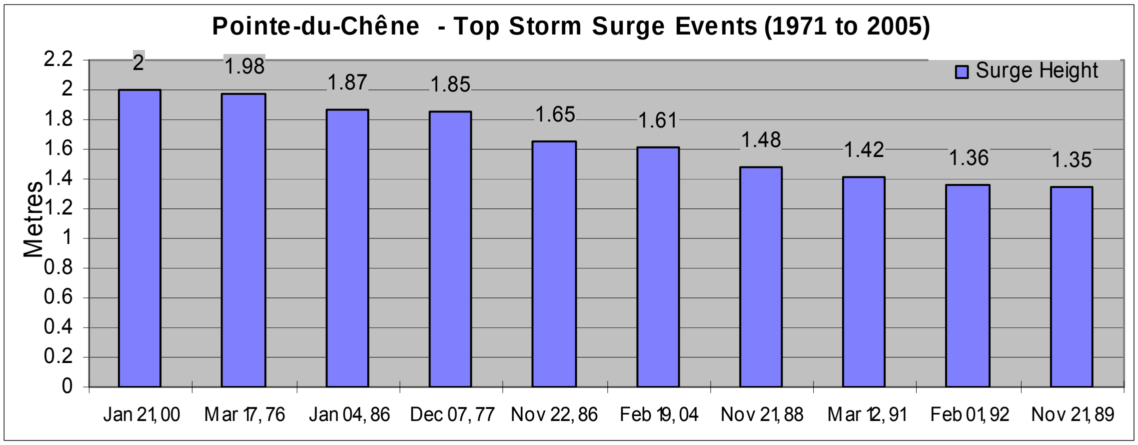


Figure 40. The top 10 storm-surge events at Pointe-du-Chêne, 1971–2005.

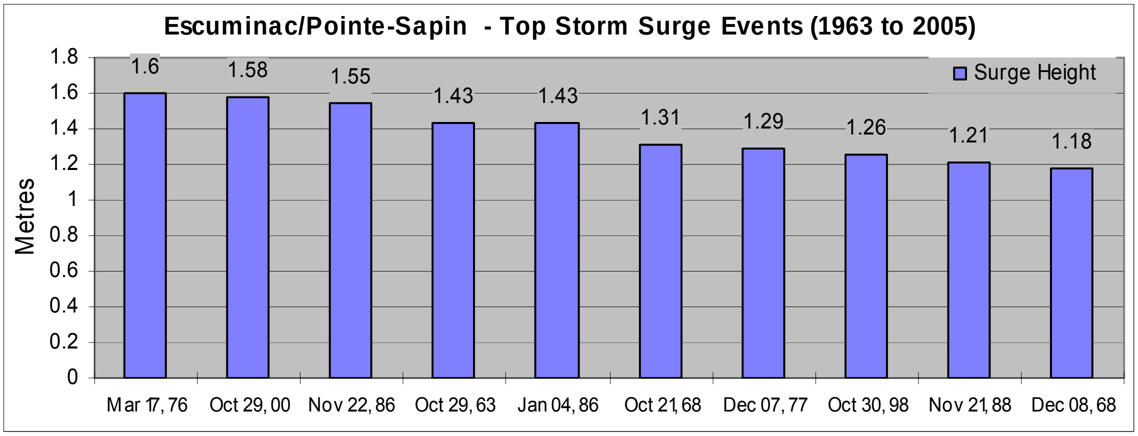


Figure 41. The top 10 storm-surge events at Escuminac/Pointe-Sapin, 1963–2005.

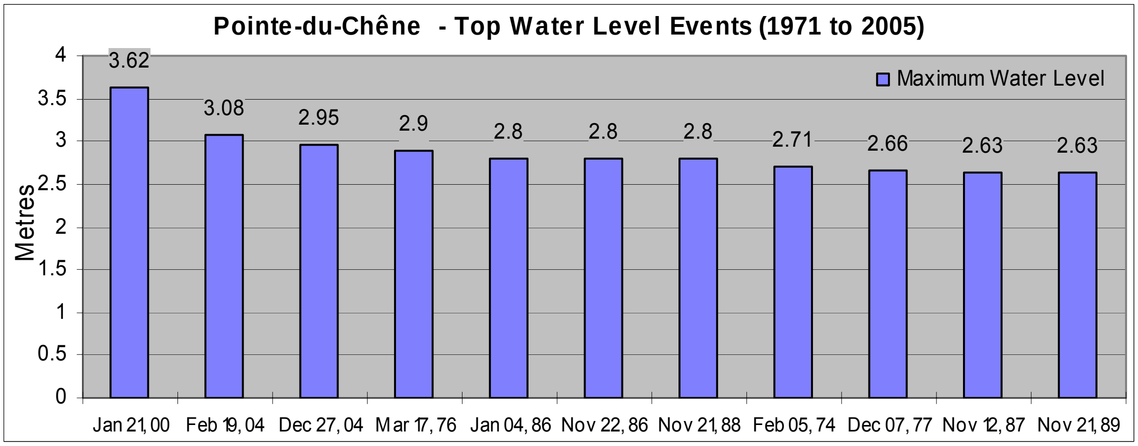


Figure 42. The top 11 recorded water levels at Pointe-du-Chêne, 1971–2005.

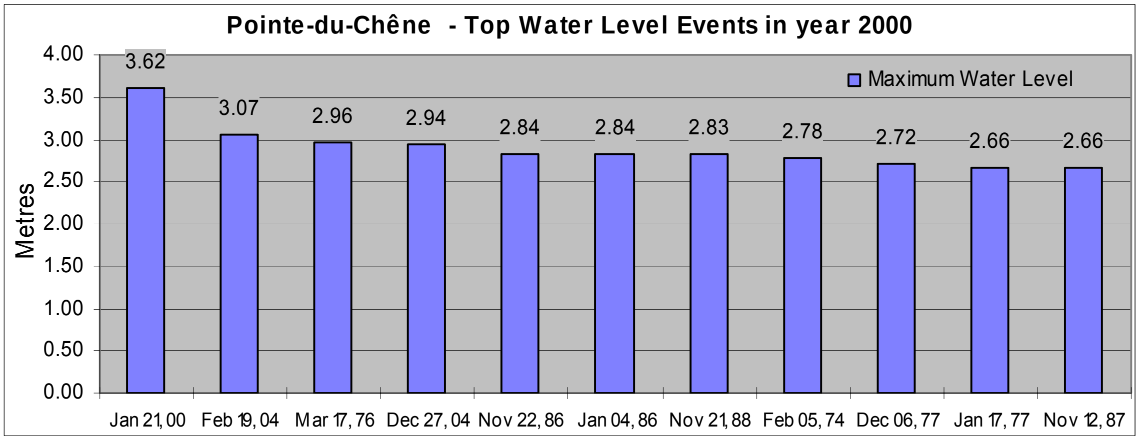


Figure 43. The top 11 water levels at Pointe-du-Chêne (adjusted to year 2000).

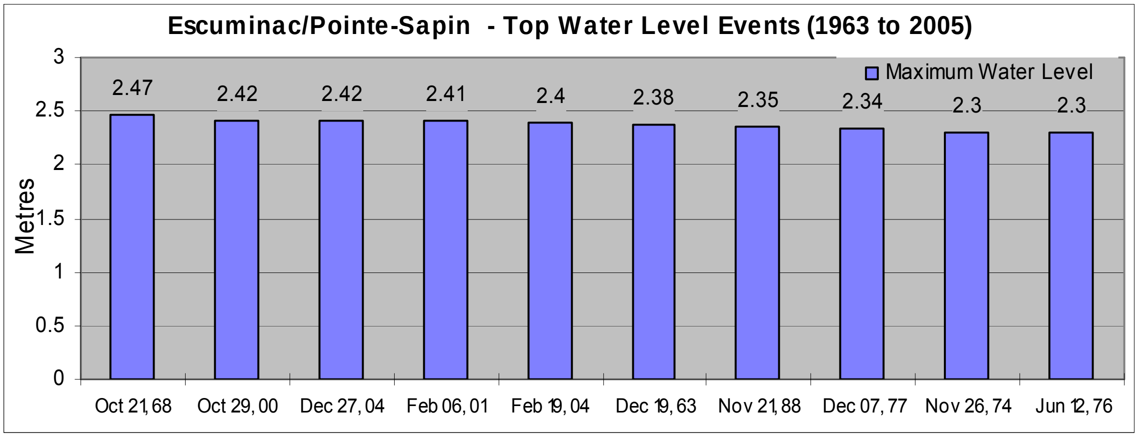


Figure 44. The top 10 recorded water levels at Escuminac/Pointe-Sapin, 1963–2005.

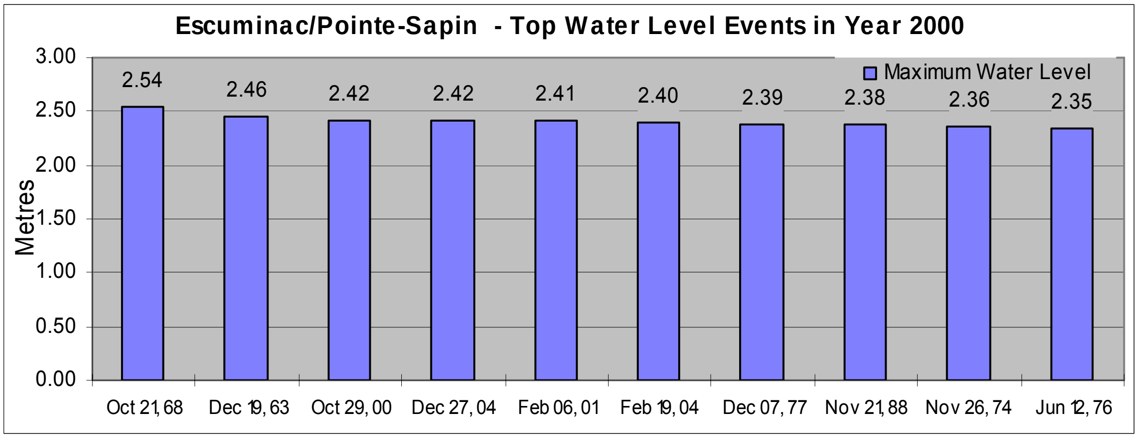


Figure 45. The top 10 water levels at Escuminac/Pointe-Sapin (adjusted to year 2000).

The highest known storm surge is about 1.6 m. Combining these numbers gives a highest possible water level of 3.2 m CD, which is 70 cm higher than the recorded level of Hurricane Gladys, suggesting that the shoreline in the northern sections of our study area has not seen its worse-case scenario flood level in today's climate. Even if the level of the January 21, 2000, storm was close to this level, the shoreline was protected by ice at the time, and the flood came with the absence of ocean waves. Our worse-case-scenario storm in the northern sections of the study area, where the shoreline is fully exposed to the brunt of waves developing in a northeasterly air flow across the Gulf of St. Lawrence, has certainly not been seen of late. This is discussed further in the case study of the storm of October 29, 2000 (Section 4.2.9.2).

According to the light detection and ranging (LiDAR) data collected in this project, seawater begins to flood the main wharf at Pointe-du-Chêne at a level of 1.2 m above the level of the digital elevation model (DEM), which is about 20 cm below mean sea level (MSL). There is, however, a low section to this wharf, and flooding in areal extent does not progress significantly there until about 1.6 m above DEM, at which time the water is encroaching on the town. At 1.8 m above DEM, the water is beginning to intrude into the town, and 50% of the wharf is under water. This level corresponds to 1.6 m above MSL and about 2.65 m above CD. Of all the storm-surge events noted in the period 1971–2005, only nine events have exceeded this level, although others have been close. If sea-level rise is taken into account, then 11 of these storms would have caused flooding at this level.

In Section 4.3 of this report, an extreme-value analysis of water levels at Pointe-du-Chêne is developed to estimate the return periods of extreme water levels under plausible climate-change scenarios. In the future, not only will flooding occur at higher levels, but flooding at any given level will increase in frequency. To demonstrate the potential increase in the frequency of flooding, we cannot just look at storm-surge events, but we must also look at water-level exceedances. Our water-level data for Pointe-du-Chêne are over 25 years (1971–1992 and 2003–2005), with 5.66 years' worth of data missing in total. The important years 2000 and 2002, however, which contain the passage of the January 21 and October 29, 2000, storms and Hurricane Gustav, are missing. These two years are therefore added into the database, assuming that they are otherwise normal apart from the big storms. The October 29, 2000, storm is assumed to be >3.1 m CD (see Attachment B in Section 4.2.15.2), and Gustav is assumed to be about the level of White Juan (i.e., >3.0 m CD). The number of observed water levels that crossed various thresholds during this (21.34-year) period is listed in Table 8 (column 2).

Table 8. Average annual frequency of water-level exceedances at Pointe-du-Chêne in the year 2000 (based on 1971–2005 water-level data) and the year 2100 (assuming present storm climatology and present rate of sea-level rise).

Column 1	Column 2	Column 3	Column 4
Level (m CD)	No. of events, 1971–2005 (data adjusted to year 2000), above threshold	No. of events on average per year above threshold (year 2000)	No. of events on average per year above threshold (year 2100)
≥2.2	74	3.47	?
≥2.3	46	2.16	?
≥2.4	31	1.45	?
≥2.5	24	1.12	3.47
≥2.6	15	0.70	2.16
≥2.7	11	0.52	1.45
≥2.8	9	0.42	1.12
≥2.9	6	0.28	0.70
≥3.0	4	0.19	0.52
≥3.1	2	0.09	0.42
≥3.2	1	0.05	0.28
≥3.3	1	0.05	0.19
≥3.4	1	0.05	0.09
≥3.5	1	0.05	0.05
≥3.6	1	0.05	0.05
≥3.7			0.05

Column 1	Column 2	Column 3	Column 4
Level (m CD)	No. of events, 1971–2005 (data adjusted to year 2000), above threshold	No. of events on average per year above threshold (year 2000)	No. of events on average per year above threshold (year 2100)
≥3.8			0.05
≥3.9			0.05

Note the large increase in exceedance frequency at the lower levels. For the sake of argument, let us assume that the climatology of storms stays the same and that relative sea level rises at 30 cm/century for the next 100 years (i.e., close to its present rate); then column 4 shows the frequency of exceedances per year around the year 2100. Whereas we can expect one exceedance of 2.7 m CD (where half the main wharf is awash and water is encroaching on the town) every two years or so at present, by the year 2100, we could expect three such exceedances every two years. The White Juan level (>3.0 m CD), which historically has occurred once every five to six years on average, will now occur once every second year, and the water level of 3.62 m CD that occurred on January 21, 2000, would come in at 3.92 m CD. Table 8 demonstrates that with sea-level rise and global warming, not only will flooding move to higher levels, but also the floods at the lower levels will become much more frequent.

4.2.8 Storms

Storm surges in the Gulf of St. Lawrence usually affect large areas and are often associated with large (synoptic)-scale weather systems. There is a very close connection between the storm surges that are recorded at Escuminac and Pointe-du-Chêne and those at Charlottetown. The surges are mainly associated with the passage of extratropical (mid-latitude) storms, mainly in the fall and winter, but can also be caused by tropical cyclones reaching our latitudes mainly in the summer and fall.

In the Prince Edward Island sea-level rise report, all storm-surge events at Charlottetown in excess of 90 cm were collated in a table, and track maps for these storms were drawn. Data in this table included the date when the storm-surge event peaked at Charlottetown, the duration of the event above 60 cm, the storm-surge peak value, the water level at the time of the peak surge, the maximum water level attained during the event, the lowest central pressure attained by the storm while it was south of latitude 50°N, the greatest rate of fall of central pressure within a 24-hour period (Δ24 Press), the time-centred latitude of this maximum fall Φ (i.e., 12 hours into the period) and the geostrophically equivalent maximum bergeron rate of fall (b, in bergerons), where 1 bergeron corresponds to a rate of fall of 24 mb over 24 hours at 60°N. Geostrophically equivalent bergeron rates of fall were calculated for lower latitudes by multiplying the maximum 24-hour rate of fall at the time-centred latitude Φ by $\sin\Phi/\sin 60$ (cf. Sanders and Gyakum, 1980).

Also included in this table were subjective estimates of the wind regime over the Gulf of St. Lawrence in the area north of Prince Edward Island, east of New Brunswick and south of Anticosti during these storm-surge events. These were obtained by assessing the synoptic weather charts for the period between 6 hours before, and between 6 and 12 hours before, the storm-surge peak. The wind regime was given by direction (N, NNE, etc.) and speed

(G = gales; S = storms; Str = strong wind, Mod = moderate wind). The data are shown in Table 9.

It can be seen from Table 9 that storms causing storm surges usually bring a period of northeasterly gale- or storm-force winds across the Gulf of St. Lawrence. Furthermore, an analysis of wind direction and speed at the Magdalen Islands at the start and finish of these storm-surge events (i.e., when the storm surge reaches 60 cm and falls below 60 cm at Charlottetown) showed that northeasterlies generally preceded the peak storm surge and that northwesterlies usually prevailed as it declines. This is consistent with a cyclone passing the latitude of Prince Edward Island and moving to the northeast.

The minimum pressures reached in Table 9 show that most of the lows that generate these intense storm surges are themselves very deep. At some point, 86% of these weather systems had central pressures of 980 mb or less, 60% had central pressures of 970 mb or less and 32% had central pressures of 960 mb or less. It was found that 82% of these systems had a bergeron deepening rate of at least one and therefore qualify as explosively deepening, with 27% of the storms deepening at a bergeron rate of two or more. One storm, the storm of January 5, 1989, had a bergeron rate of over three. More information on many of the storms listed here can be found in the Canadian Climate Centre’s catalogue of *Severe Storms off Canada’s East Coast* (Lewis and Moran, 1984).

Table 9. Wind events causing storm surges >0.9 m at Charlottetown, 1960–2000. The wind regime is given by direction (N, NNE, etc.) and speed (G = gales; S = storms; Str = strong wind, Mod = moderate wind). Storms in bold generated storm surges of 110 cm or more at pointe-du-Chêne.

Date	Duration (hours)	Surge (m)	Water level (m CD)	Maximum water level (m CD)	Minimum pressure (mb)	Δ24 pressure (mb)	ϕ	b	Wind regime (0–6 hours before)	Wind regime (6–12 hours before)
01-05-61	8	0.9	3.4	3.4	970	36	42	1.9	N, S	NE, G
01-21-61	18	1.31	3.28	3.89	962	23	39	1.3	NE, S	NE, G
03-23-62	7	1.02	1.78	2.88	968	23	38	1.4	NE, G	NE, G
02-20-63	8	1.02	2.8	2.92	970	27	42	1.5	ENE, S	ENE, G
10-30-63	4	0.94	3.07	3.19	976	13	41	0.7	NW, Str	NW, G
11-28-63	5	1.03	2.26	2.63	988	27	51	1.3	NW, G	NW, G
12-19-63	9	1.43	3	3.05	950	50	39	2.9	NNE, S	NE, G
01-28-66	17	0.96	2.15	3.01	962	22	36	1.4	NE, S	NE, S
02-08-67	7	1.07	1.93	2.64	974	18	42	1.0	NNE, S	NE, G
12-08-68	13	1.27	3.12	3.36	956	40	38	2.3	W, Str	W, Str
11-29-68	no data	1.11							NE, G	NW, Str
01-15-70	8	0.9	2.09	2.99	970	26	42	1.4	NNW, S	NNW, S
12-07-70	17	1.0	2.09	3.02	978	10	43	0.5	NNE, S	NE, G
12-25-70	14	1.03	3.17	3.17	982	20	43	1.1	NE, G	NE, G
12-27-70	8	0.99	1.6	2.63	948	38	39	2.2	NE, S	NE, G
03-05-71	9	0.91	2.55	2.7	963	21	39	1.2	N, G	NE, Str
01-21-73	**9**	**1.0**	**3.77**	**3.77**	**966**	**30**	**42**	**1.6**	**N, S**	**NNE, G**
02-05-74	**14**	**1.09**	**2.88**	**3.66**	**968**	**27**	**41**	**1.5**	**NNE, S**	**NNE, G**
02-18-74	**10**	**0.99**	**2.12**	**2.88**	**962**	**32**	**37**	**1.9**	**NNE, S**	**NE, G**
10-20-74	**6**	**0.96**	**3.42**	**3.42**	**960**	**36**	**39**	**2.1**	**NNE, S**	**NE, G**
03-17-76	**15**	**1.2**	**3.57**	**3.76**	**952**	**46**	**42**	**2.5**	**NE, S**	**NE, G**
09-15-77	**5**	**0.99**	**1.58**	**2.19**	**984**	**17**	**46**	**0.9**	**N, S**	**NE, G**
12-07-77	**22**	**1.04**	**3.24**	**3.24**	**960**	**22**	**43**	**1.2**	**NE, S**	**NE, G**
12-17-79	7	0.91		3.35	969	38	40	2.1	N, G	Var, Str
02-21-80	4	0.93	1.65	2.22	972	14	36	0.9	NW, G	NW, G
10-02-82	**5**	**1.07**	**1.85**	**2.57**	**986**	**14**	**50**	**0.7**	**N, G**	**NNE, G**
12-25-83	**16**	**1.17**	**1.92**	**3.57**	**950**	**36**	**44**	**1.9**	**N, S**	**N, G**
12-26-84	5	1.12	2.6	2.61	994	49	52	2.2	NW, G	NW, G
01-05-85	7	0.91	3.39	3.39	956	40	38	2.3	N, S	NNE, Str
01-16-85	**11**	**1.02**	**1.8**	**2.96**	**960**	**30**	**42**	**1.6**	**N, S**	**NNE, G**
02-28-85	3	0.91	2.79	2.79	978	34	44	1.8	NW, G	N, Str
01-04-86	**10**	**1.06**	**2.08**	**2.77**	**976**	**27**	**45**	**1.4**	**N, S**	**NNE, G**
01-06-86	8	1.01	1.86	2.83	974	29	43	1.5	ENE, G	ENE, Str
03-07-86	4	0.92	2.47	2.57	976	19	43	1.0	NE, G	NE, G
11-22-86	**7**	**0.92**	**2.32**	**3**	**978**	**20**	**42**	**1.1**	**NE, S**	**NE, G**
12-08-86	5	1.2	2.36	2.68	991	36	46	1.8	NW, G	NW, G
01-24-87	5	1.13	2.16	2.22	967	28	39	1.6	S, Mod	SE, S
11-12-87	**7**	**0.93**	**2.97**	**2.97**	**967**	**28**	**40**	**1.6**	**NE, G**	**NE, G**

Date	Duration (hours)	Surge (m)	Water level (m CD)	Maximum water level (m CD)	Minimum pressure (mb)	Δ24 pressure (mb)	ϕ	b	Wind regime (0–6 hours before)	Wind regime (6–12 hours before)
12-30-87	14	1.04	2.46	2.99	953	43	38	2.5	NW, S	N, G
11-22-88	**15**	**1.11**	**2.5**	**3.1**	**971**	**9**	**46**	**0.5**	**NNE, G**	**NE, S**
01-05-89	17	1.13	1.94	3.3	941	56	36	3.4	N, G	NNE, G
01-21-89	7	1.0	2.56	2.97	964	35	45	1.8	N, S	NE, G
03-12-91	**13**	**1.41**	**2.42**	**2.59**	**959**	**22**	**42**	**1.2**	**N, S**	**NE, G**
12-03-91	10	0.9	3.37	3.37	974	32	48	1.6	W, Mod	NW, Mod
02-02-92	**16**	**1.08**	**2.5**	**3.24**	**962**	**34**	**38**	**2.0**	**NE, S**	**NE, S**
12-30-93	9	1.12	3.62	3.62	956	43	39	2.5	N, S	NE, S
12-08-94	5	0.97	2.11	2.42	960	41	45	2.1	N, G	NNW, G
01-15-96	7	1.3	2.96	2.96	988	8	48	0.4	NW, G	W, Str
03-07-97	9	0.9	2.36	2.95	959	41	44	2.1	NNW, S	NE, S
04-02-97	7	0.9	1.71	2.64	978	9	38	0.5	NNE, S	NNE, G
01-21-00	**unavail.**	**1.36**			**946**	**42**	**38**	**2.5**	**NE, Mod**	**E, Mod**
10-29-00	unavail.	1.29			979	18	39	1.0	NE, S	NE, S

All storm-surge events that caused storm surges of 110 cm or more at Pointe-du-Chêne were identified from their water-level data (1971–1992 and August 2003 to October 2005). There were 30 such events in total. The track maps for these 30 storms are shown in Attachment C (in Section 4.2.15.3). Seventeen of these storms can be found in Table 9 (in bold), as well as the list of 90-cm storm-surge events at Charlottetown (for the period 1960–1998 plus the two benchmark storms of the year 2000: January 21 and October 29). Five of the remaining 13 storms occurred since this table was published (in Manson, 2002a). The other eight events all also counted as events at Charlottetown, but with storm-surge heights in the range of 60–90 cm.

A composite plot of all the storm tracks is shown in Figure 46; while there may be some exceptions to the rule (such as the storm of October 2, 1982), it emphasizes the common pattern of these storms. As discussed above, these storms are mainly extratropical marine storms that deepen explosively off the east coast and pass by to the east of the study area, usually accompanied by a period of northeasterly or northerly gale- or storm-force winds across the Gulf of St. Lawrence. The geometry of these storms is usually favourable for bringing large seas into the study area (in the absence of sea ice), and this is discussed further in Section 4.2.10.

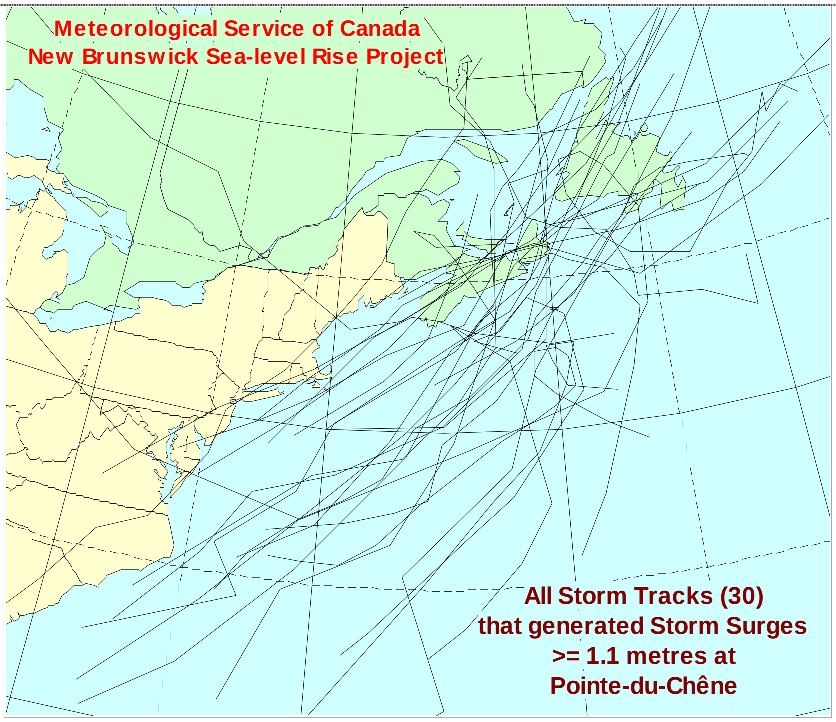


Figure 46. Composite of storm tracks.

Tropical cyclones can also affect our region when they recurve north or northeastward off the east coast of North America from more southern latitudes. These storms are often in the dying phase of their life cycle, due to passage over colder waters north of the Gulf Stream wall, and are often in the process of transitioning into extratropical or post-tropical cyclones. Nonetheless, they can make landfall in eastern Canada as true hurricanes (such as Luis in Newfoundland in 1995 or Juan in Nova Scotia in 2003) or may indeed reintensify due to mid-latitude dynamic forcing (such as the subtropical storm of October 29, 2000).

To examine the impact of tropical cyclones in our area, the U.S. National Hurricane Center's hurricane database (HURDAT), or "best tracks" (1851–2004), was interrogated. The detailed study is included as Attachment D (Section 4.2.15.4). Over the years, numerous tropical cyclones have affected the area. The tracks of those storms that generated surges of 60 cm or more at any of the tide-gauge sites (Pointe-du-Chêne, Escuminac, Pointe-Sapin, Charlottetown or Rustico) during their period of record are shown in Figure 47.

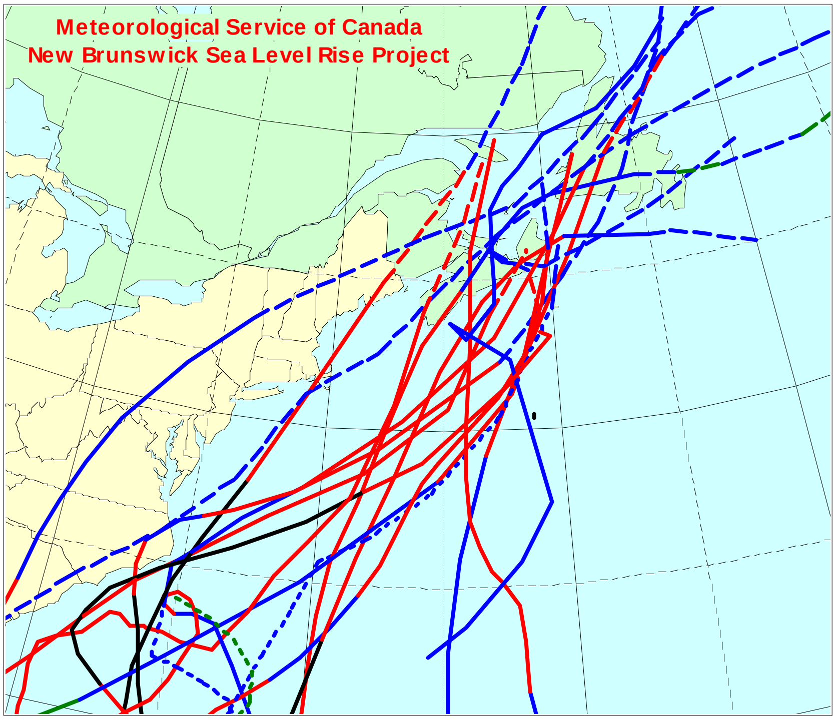


Figure 47. The tracks of tropical cyclones that have generated storm surges of 60 cm or more at any tide-gauge site (Pointe-du-Chêne, Escuminac, Pointe-Sapin, Charlottetown or Rustico).

Although less common than extratropical storm-surge events, tropical cyclones can be very powerful and occur during the tropical weather season (June to November) when there is no wave protection from sea ice. Hurricane Gladys in 1968 and the subtropical storm of October 29, 2000, are discussed further in the next section.

4.2.9 The benchmark storms

Table 10 shows the top 10 water levels recorded at Charlottetown, Pointe-du-Chêne and Escuminac/Pointe-Sapin over the history of their water-level data. Also shown is the rank of that water-level event at the other locations (the rank above 10 is not actually the true rank of the measured water level but the rank as adjusted to 1977).

Table 10. Top water-level events. Storms that are colour-coded or in bold will be discussed in detail.

	Charlottetown				Pointe-du-Chêne				Escuminac			
	Date	Maximum observed water level	Rank at Pointe-du-Chêne	Rank at Escuminac	Date	Maximum observed water level	Rank at Charlottetown	Rank at Escuminac	Date	Maximum observed water level	Rank at Charlottetown	Rank at Pointe-du-Chêne
1	**Jan 21, 2000**	**4.22**	**1**	M	**Jan 21, 2000**	**3.62**	**1**	M	**Oct 21, 1968**	**2.47**	**234**	**M**
2	Jan 21, 1961	3.84	M	M	**Feb 19, 2004**	**3.08**	**3**	**5**	**Oct 29, 2000**	**2.42**	**55**	**M**
3	**Feb 19, 2004**	**3.77**	**2**	**5**	**Dec 27, 2004**	**2.95**	**121**	**3**	**Dec 27, 2004**	**2.42**	**121**	**3**
4	Jan 21, 1973	3.76	M	17	Mar 17, 1976	2.90	5	44	**Feb 6, 2001**	**2.41**	**85**	**M**
5	Mar 17, 1976	3.76	4	44	Jan 4, 1986	2.80	377	11	**Feb 19, 2004**	**2.40**	**3**	**2**
6	Dec 30, 1993	3.67	M	22	Nov 22, 1986	2.80	200	49	Dec 19, 1963	2.39	165	M
7	Feb 5, 1974	3.65	8	12	Nov 21, 1988	2.80	126	7	Nov 21, 1988	2.38	126	7
8	Dec 25, 1983	3.59	24	M	Feb 5, 1974	2.71	7	12	Dec 7, 1977	2.35	58	9
9	Sep 12, 2002	3.49	M	27	Dec 7, 1977	2.66	58	8	Nov 26, 1974	2.34	406	15
10	Dec 1, 1943	3.44	M	M	Nov 12, 1987	2.63	219	74	Jun 12, 1976	2.30	75	12

While storm surges have continuity from one site to the next, the water levels themselves do not, but depend on the phasing of the storm surge with the tide. Large storm-surge events of long duration are the most likely to show up as significant events at all three sites. The storms listed in Table 10 are all significant events in their own right, but some are benchmark events for the issues of coastal flooding and coastal erosion. The storms that are colour-coded or in bold will be discussed in more detail.

4.2.9.1 The storm of January 21, 2000

On January 21, 2000, a very intense low-pressure system passed northward over the Maritimes and affected numerous coastal locations through the impacts of severe coastal flooding, wave damage and ice-pressure damage (Forbes et al., 2000). With a minimum central pressure of 946 mb at 1800 UTC on January 21, while located 110 km SSE of

Halifax, the storm subsequently passed 55 km east of Charlottetown at 0000 UTC on January 22 (central pressure 951 mb) and then tracked northward across the Gulf of St. Lawrence.

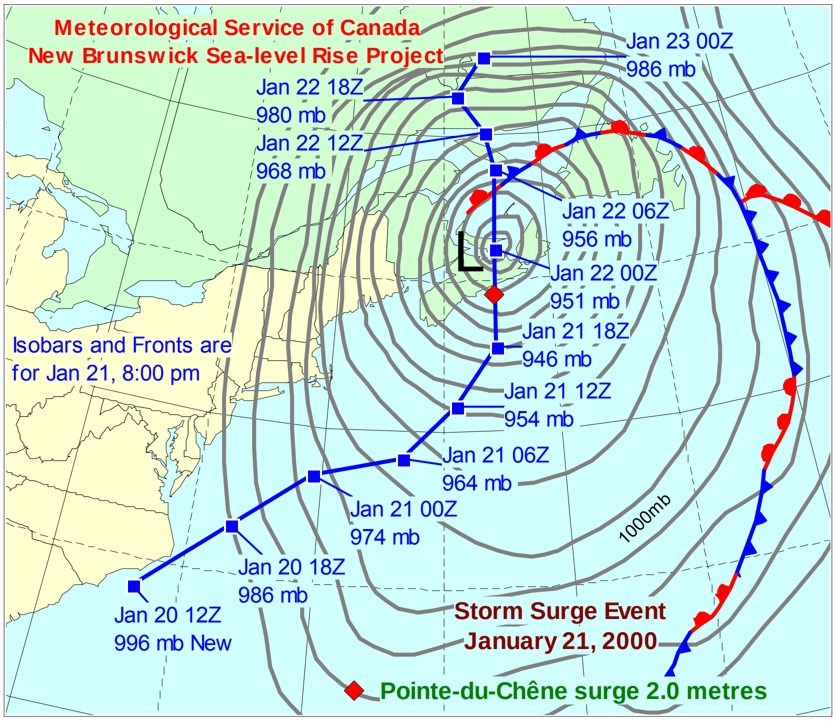


Figure 48. Weather map for January 22, 2000, at 0000 UTC.

The storm surge associated with this system coincided with high tide at many locations during a run of perigean spring tides (the moon was at perigee on January 19 and was full on January 21). The resulting coastal flooding was particularly severe in eastern New Brunswick and throughout the Northumberland Strait. This event has been studied by MacPhee et al. (2000), Forbes et al. (2000, 2001), Bobanovic et al. (2000) and Bigio et al. (2000).

Impacts from this storm were felt across the region and included wave damage along the Nova Scotian coastlines in the Bay of Fundy and in Cape Breton. The strong winds also brought very large waves and coastal infrastructure damage to the southern coast of Newfoundland. On the eastern shores of Prince Edward Island, which were mainly ice-free, high water levels covered wharves and coastal sections in many communities, and ocean waves caused serious erosion of the barrier beach at Souris. On the North Shore of Prince Edward Island, the storm surge was not at its peak during the high tides, and pack ice protected the shoreline from the ocean waves. Many coastal communities nonetheless saw their wharves overtopped and experienced minor flooding; damage, however, was not severe, and the main beaches were largely unaffected. On the western coast of Prince Edward Island, the storm surge (estimated at 1.5–2.0 m) phased with the high tide to cause severe flooding of coastal sections, affecting many communities. In these areas, ice pressure at the time of the flooding caused sea-ice ride-up and pile-up on the shoreline.

The flooding continued through Northumberland Strait on the evening of January 21, affecting all coastal locations, including parts of the downtown cores in Charlottetown and Summerside.

Impacts were felt everywhere along the Gulf coastlines of New Brunswick and especially in the study area of this project — particularly over its southern sections — and exceeded anything in the recollection of coastal residents. As the storm developed, pack ice in the western Gulf of St Lawrence (see Photo 1) was pushed towards the coastlines by the winds, elevated on extraordinarily high water levels.

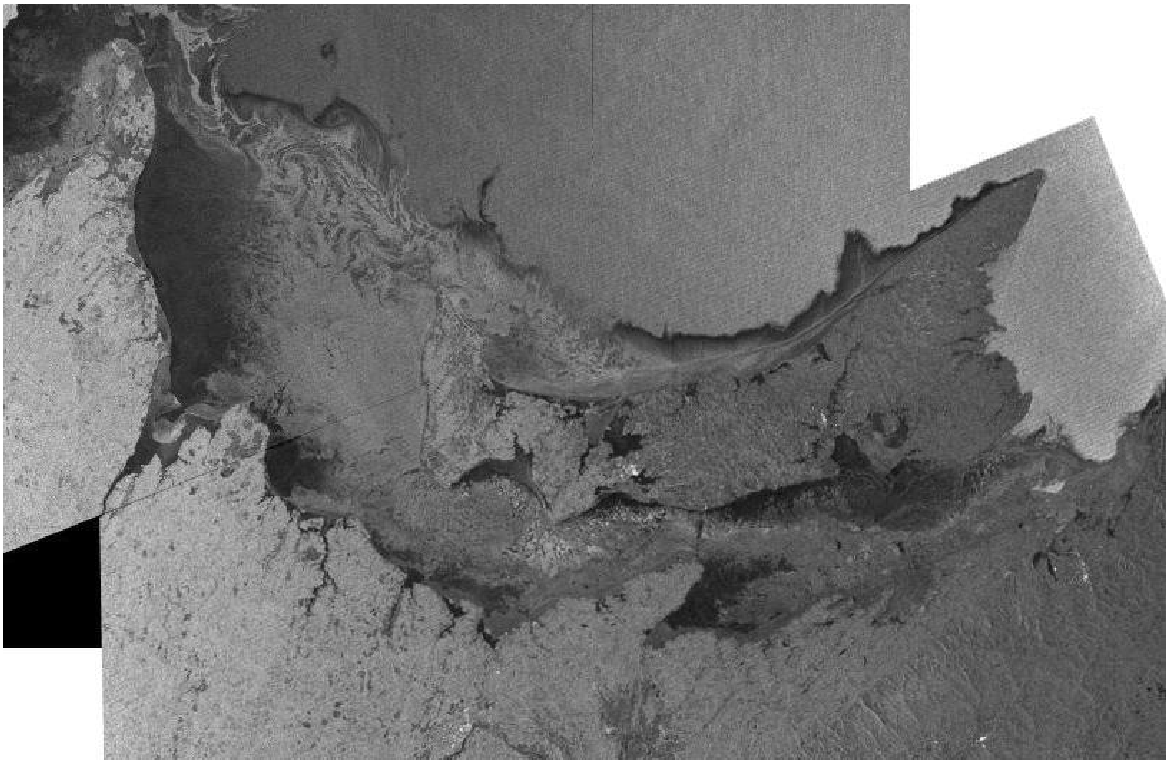


Photo 1. Radarsat image showing ice distribution on January 21, 2000, at 1030 UTC.

In most places, the ice piled up on the shorelines (see Photo 2 at L'Aboiteau), beachheads, wharves and sea defences, sometimes with severe consequences (see Photo 3 at Cap-des-Caissie wharf). The ice typically measured 50 cm in thickness (see Photo 4 of Paul Noseworthy of Environment Canada, measuring the ice at Cap-Pelé), and some ice pile-ups were 3–4 m high (see Photo 5 of Donald Forbes, nearly 2 m tall, of Natural Resources Canada [NRCan] at L'Aboiteau). Ice pile-ups in Barachois directly affected some homes and cottages (see Photo 6). Cakes of ice, however, moved inland with the floodwaters in various places and subsequently littered the landscape (see Photo 7 from near Grande-Digue). At Robichaud, the ice somehow managed to cross the wharf in a sheet (perhaps due to sufficiently elevated water levels before the onset of strong ice pressure), bending vertical structures to the ground (see Photo 8), and was subsequently left on the wharf when the water levels fell (see Photo 9), later to be removed only by heavy machinery.

Photo 2. Ice on the shorelines at L'Aboiteau.

Photo 3. Ice pile-up at Cap-des-Caissie wharf.

Photo 4. Measuring ice thickness at Cap-Pelé.

Photo 5. Ice pile-up at L'Aboiteau.

Photo 6. Ice pile-up near Barachois.

Photo 7. Ice cake on car near Grande-Digue.

 **Photo 8.** Ice damage at Robichaud.	 **Photo 9.** Ice sheet left on Robichaud wharf.
 **Photo 10.** Wetting line at Shediac Bridge.	 **Photo 11.** Wetting line at Shediac Bridge.
 **Photo 12.** Wetting line at Saint-Édouard-de-Kent.	 **Photo 13.** Wetting line at Bouctouche.

While ice impacts were mainly directly at the shoreline, the impacts of the coastal flooding were more widespread and in some areas penetrated as much as 1 km inland. Numerous homes and cottages along the shoreline were inundated, some severely. Flood levels were somewhat diminished towards the north of this study area, although coastal flooding was also reported in the Bay of Chaleur, but to a lesser degree. The tide gauge at Belledune (data courtesy of the Belledune Port Authority) recorded a storm surge of 1.3 m, which was not in phase with the high tide. The Emergency Measures Organization subsequently administered a federal disaster fund to help affected stakeholders. After the floodwaters retreated, a residual deposit of ice and snow was left on houses, power posts and trees, marking the former water levels for a short period until sunshine subsequently melted it away. These residual debris lines can be seen at the bases of properties in Shediac Bridge in Photo 10 and of properties towards the head of Bouctouche Bay in Photo 11. They can also be seen on the red building on the wharf at Saint-Edouard-de-Kent in Photo 12 and on abutments of the bridge at Bouctouche in Photo 13.

Flooding at Pointe-du-Chêne occurred during the afternoon of January 21, and many dramatic photographs subsequently came to light. Photo 14 shows flooded streets during the storm, and Photo 15 taken the next day shows a house that was removed from its cinder block foundation. At one point during the flood, some residents in the area near the Parlee Beach parking lot had to be rescued from their house, where floodwaters had become dangerously deep. The DEM built from LiDAR data collected during this project has successfully reproduced the areal extent of the flood, and confirmation of this from local residents has worked as feedback to ground-truth the LiDAR data themselves (see Section 4.4).

Photo 16 was taken on January 22 and shows the former tide-gauge building on the wharf at Pointe-du-Chêne. A wetting line is clearly evident in the brickwork, and Donald Forbes of NRCan subsequently levelled this in. Photo 17 shows a detail of the same building, with two strips of black tape on its right-hand side. The lower strip, visible between the two pieces of yellow rope, marks the former record water level at Pointe-du-Chêne (from water-level data of 1971–1992) of 2.90 m CD, recorded on March 17, 1976. This level is itself a flood level. The higher piece of black tape marks the new record flood level of the January 21 storm — 3.62 m CD (approximately 2.55 m above MSL).

After the storm, Environment Canada staff Réal Daigle and Paul Noseworthy toured the region, creating a photographic record and marking wetting lines in various locations with nails. Photo 18 shows Paul Noseworthy pointing to one such nail at Cap-Pelé. Subsequently, staff from NRCan and the Centre of Geographic Science revisited these sites and recovered the water levels using differential global positioning system (GPS) surveying techniques. Photo 19 shows David Frobel of NRCan recovering the water level from the nail at Cap-Pelé, on a survey mission in November 2003.

Figure 49 shows the water-level data for the January 21 storm at Charlottetown. Also shown is the previous record water level of 3.84 m CD, associated with the passage of the Kennedy Inaugural Storm on January 21, 1961 (so named because it disrupted preparations for the J.F. Kennedy inaugural ceremonies in Washington, D.C.; Ludlum, 1961). The predicted tide has been corrected here for sea-level rise.

It is interesting to note that the January 21, 2000, storm did not quite generate the highest storm surge on record at Charlottetown; nor did it occur at the time of highest possible astronomical tide. However, it was close in both cases, and the water level it reached is probably within 20 cm of the highest level that we could expect in today’s climate. The same is true at Pointe-du-Chêne, as discussed above. In future, as sea levels continue to rise or indeed accelerate and as storms come and go in the coastal zone, large storm surges will eventually phase with sufficiently large tides to produce new record water levels at Charlottetown and Pointe-du-Chêne. This is the premise of this project.

Photo 14. Flooded streets in Pointe-du-Chêne.

Photo 15. House off foundation in Pointe-du-Chêne.

Photo 16. Wetting line on tide-gauge building.

Photo 17. Record water levels at Pointe-du-Chêne.

Photo 18. Marking the water level at Cap-Pelé.

Photo 19. Water-level recovery at Cap-Pelé.

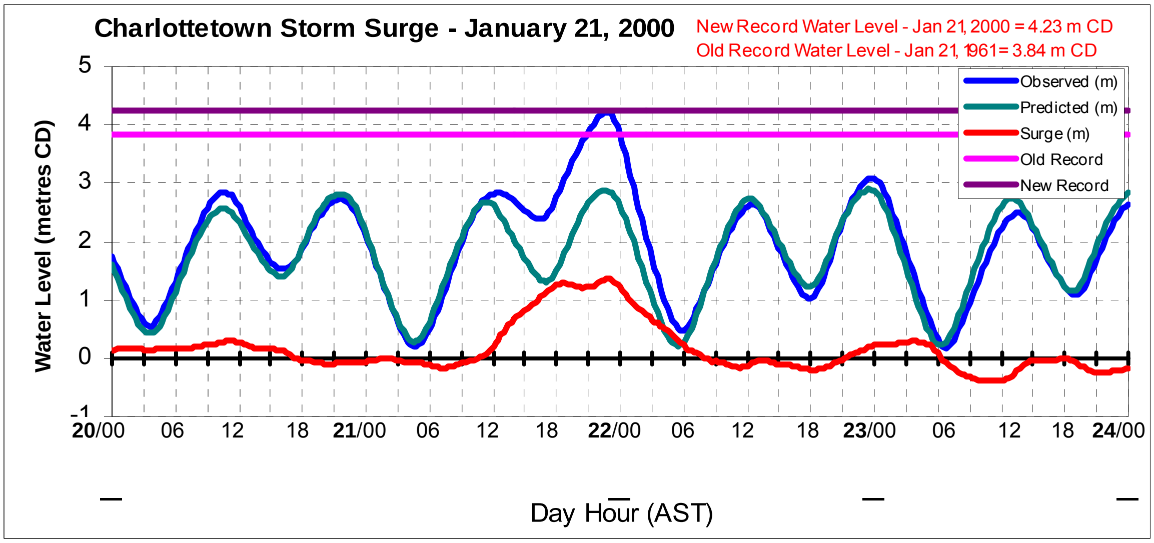


Figure 49. Water-level data at Charlottetown for the January 21, 2000, storm.

4.2.9.2 The storm of October 29, 2000

Early on October 29, 2000, a subtropical storm (Bevan, 2000) approached the Maritimes from the south–southwest and reintensified to lie south of Cape Breton Island as a 979-mb centre (Figure 50). This intense and unusual storm (Bowyer et al., 2001) brought storm-force northeasterly winds across the Gulf of St. Lawrence and extensive coastal flooding and damage to eastern New Brunswick and northern Prince Edward Island (Forbes et al., 2001, 2004).

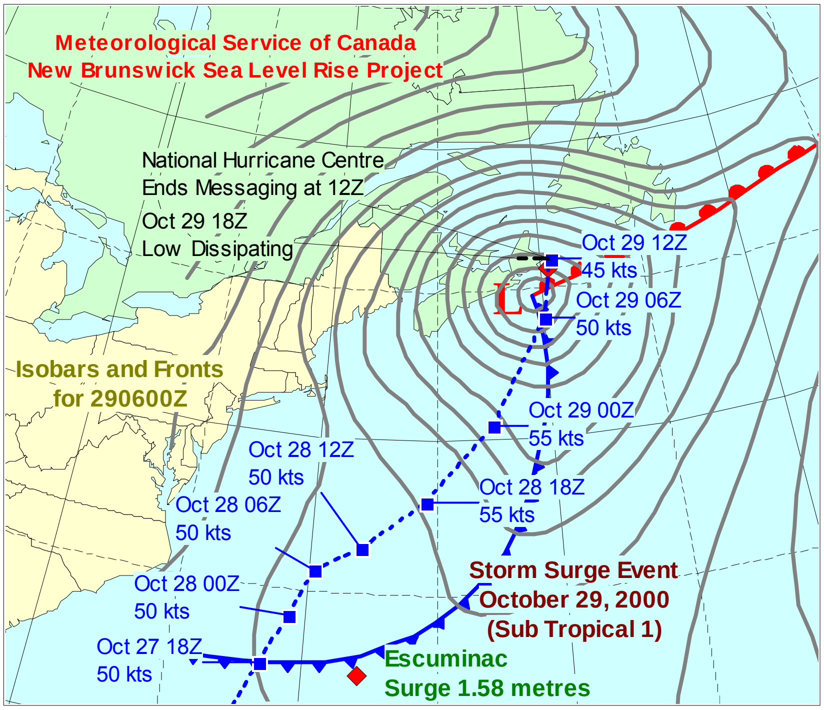


Figure 50. Weather map for October 29, 2000, at 0600 UTC.

Figure 51 shows water-level data from the Escuminac tide gauge and wave-height data from a directional waverider buoy (see Manson et al., 2002a, for instrument details) located at 46°29.2'N 63°11.2'W in 25 m of water, a position off Brackley Beach in Prince Edward Island, approximately 5 km northeast of the entrance to North Rustico Harbour. The storm-force northeasterly winds produced a very large storm surge of 1.52 m on adjusted water-level data (or 1.58 m on unadjusted data, as shown here), which is close to being the largest on record at Pointe-Sapin/Escuminac. The surge was coincident with the lower high tide of the day, producing a water-level peak of 2.42 m CD at 0600 AST. This peak is 1 cm less than the all-time record of 2.43 cm set on November 21, 1988. (This record only shows up as 2.38 cm CD in Table 7, the list of the top 10 water-level events at Escuminac, but it should be remembered that the entire water-level analysis presented here has been done with hourly data only, whereas in recent years, water-level data have been archived at 15-minute intervals. The higher value of 2.43 cm showed up at an intermediate time.) The surge was in decline during the time of the next high tide (which was the higher high tide of the day), but still produced a second water-level peak of 2.42 cm CD in the late afternoon.

These storm-force northeasterly winds also brought very large waves, which pounded exposed shorelines for hours. The waverider buoy off Brackley Beach recorded significant wave heights (average height of the highest one third of the waves) of 7 m, with many large waves of 11 m and a maximum wave of 14 m. The waves were larger during the first water-level peak in the early morning, but were still very significant (4–5 m) during the second water-level peak in the late afternoon.

Major impacts were recorded on the north shore of Prince Edward Island both to beaches and to coastal infrastructure (Parkes and Ketch, 2002b). The entire west coast of Prince Edward Island between North Cape and West Point was also very badly affected. On the Gulf coasts of New Brunswick, the combination of high water levels and high ocean waves caused widespread minor flooding along the shoreline (see Photos 20 and 21, taken during the storm towards the head of Bouctouche Bay) and extensive wave damage to the shoreline and to its beaches and coastal infrastructure. Most places from La Dune de Bouctouche northward were severely affected, since they were exposed to the full brunt of the waves running from the northeast.

There was no tide gauge at Pointe-du-Chêne to measure the water levels; however, newspapers (*Times & Transcript*, Moncton, October 30, 2000) reported that the water at its height was “one third of a metre above the wharf and about 1.5 metres above the normal high mark.” With highest astronomical tide (HAT) at ~1.7 m CD, this estimate indicates a water level of about 3.2 m CD. The storm-surge model predicted a value of 2.65 m CD, but the model was low on this storm; in Attachment B (Section 4.2.15.2), we suggest a higher value of 3.1 m CD. This is about the level of the February 19, 2004, White Juan event. Roads (including Mackenzie Road) and houses in Pointe-du-Chêne flooded or were surrounded by water, forcing many families to temporarily leave their homes. Damage was reported to the road leading to the wharf. Damage was also recorded at Parlee Beach, where waves stripped away the sand and undercut the dunes to such an extent that fencing material that had previously been on top of the dunes was subsequently found on the beach.

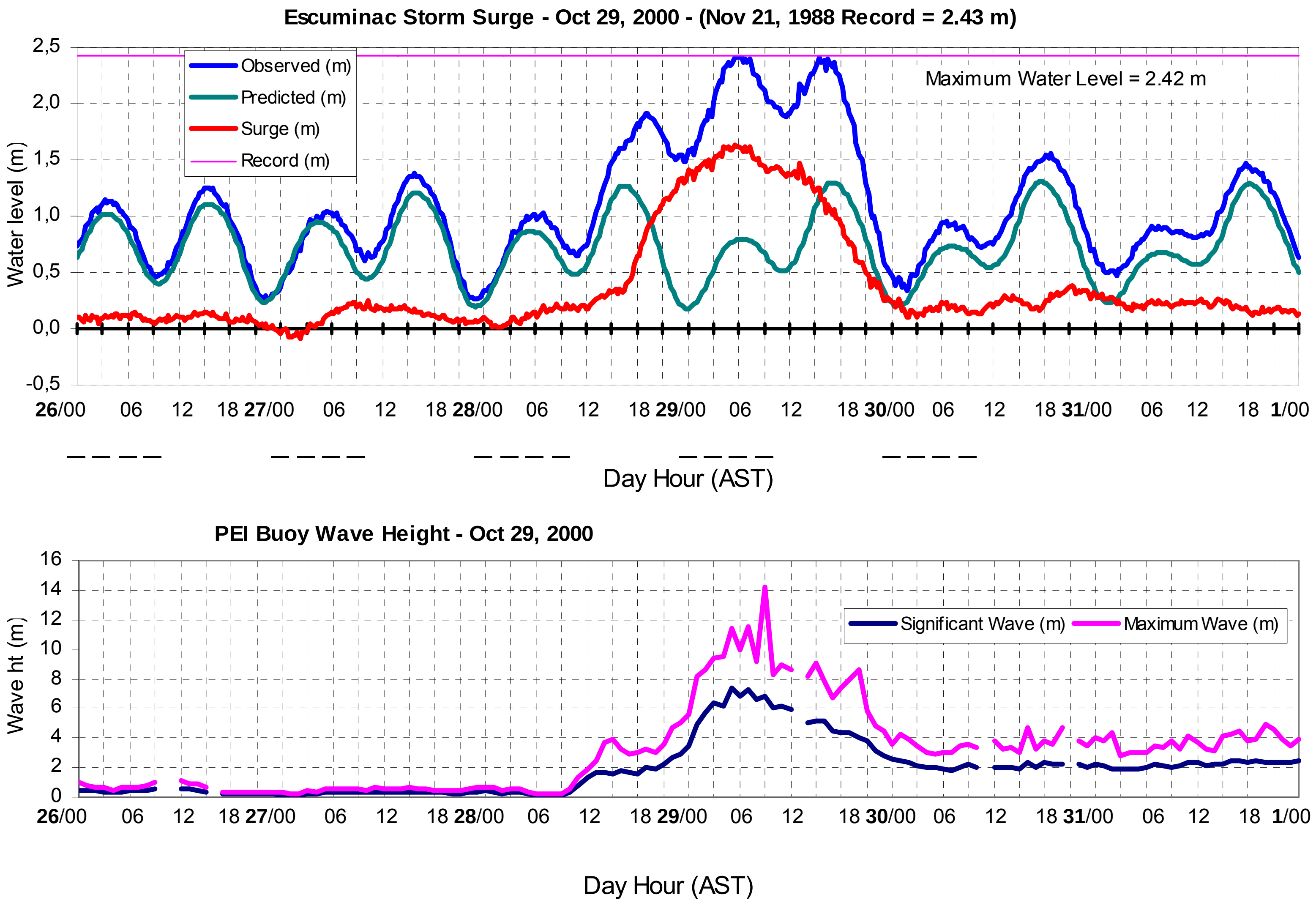


Figure 51. Escuminac, New Brunswick, water-level data (above) and Prince Edward Island wave data (below) for October 26–31, 2000 (same time scale).

Photo 20. Head of Bouctouche Bay.

Photo 21. Head of Bouctouche Bay.

Photo 22. La Dune de Bouctouche.

Photo 23. La Dune de Bouctouche.

Photo 24. Wharf damage at Escuminac.

Photo 25. Erosion on the Acadian Peninsula.

The storm had a major impact on all shorelines, including cliffs, dunes, beaches and low shores. Ocean waves entirely engulfed La Dune de Bouctouche (see Photo 22), severely eroding its sandy leading face and sweeping away significant parts of the Irving Eco-Centre boardwalk (see Photo 23). Damage to this site was so extensive that it has been suggested that the storm destabilized the dune to such an extent that other lesser storms that might otherwise not have had a big impact were subsequently also able to leave their mark (Forbes et al., 2001, 2004).

Damage was recorded to coastal infrastructure at Saint-Édouard-de-Kent, Cap-Lumière, Richibucto, Cocagne and Rexton. Luckily, most fishing boats were out of the water; however, several fishing boats and other smaller vessels around the region are known to have been swamped or damaged. Some flooding was also reported in Cocagne and in Rexton, where several families were evacuated after the Richibucto River spilled its banks.

Severe damage was recorded at Kouchibouguac National Park, where waves stripped away much of the sand and left impressive vertical dune cuts, with some sites showing potentially permanent setback. Much of the park's boardwalk was demolished. A major breach developed in the dune system at Kellys Beach, which can still be seen today (see LiDAR visualization in Figure 52).

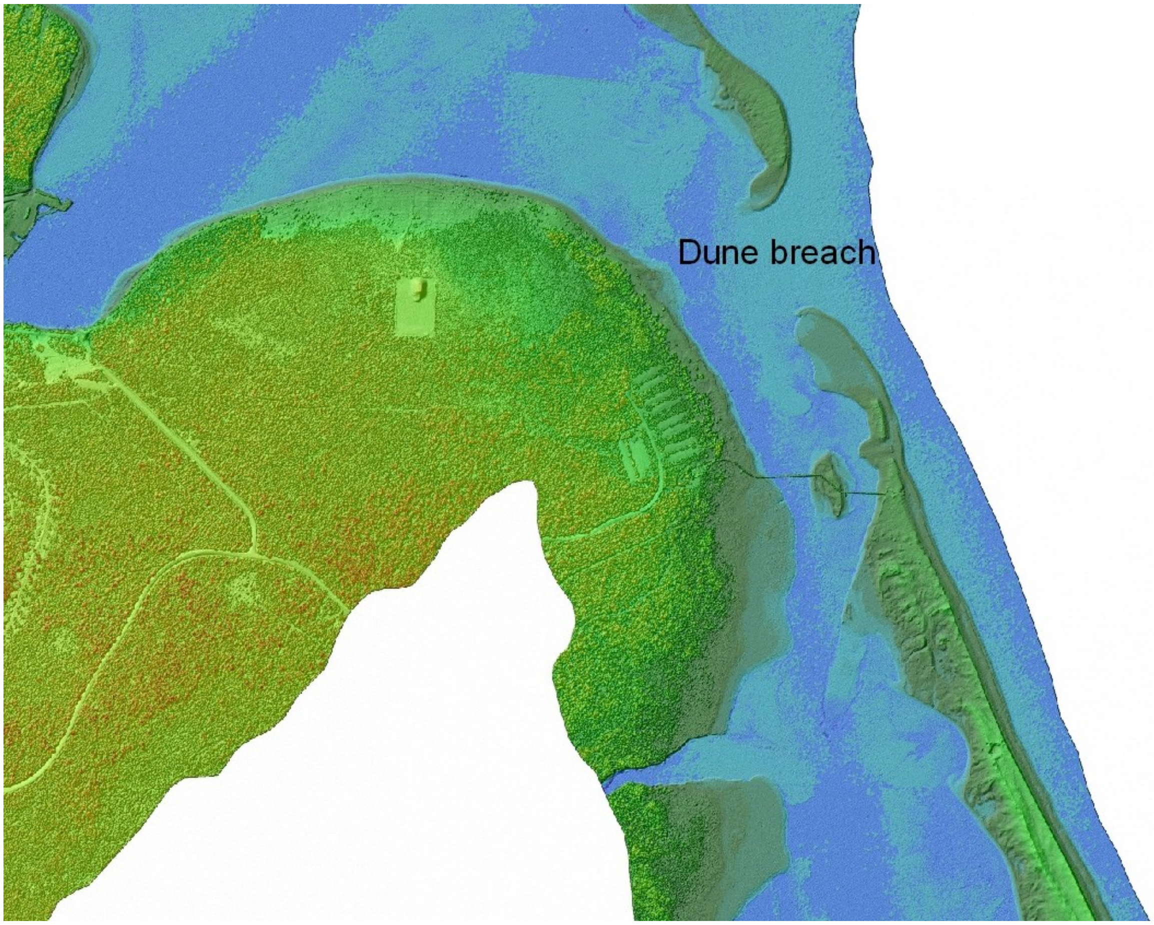


Figure 52. LiDAR image of Kellys Beach in Kouchibouguac National Park. LiDAR mapping (valid April 2004) by Applied Geomatics Research Group, Nova Scotia Community College.

The wharf system at Escuminac was highly impacted. In places, the surface of the wharf was entirely stripped away, and whole structural sections were undermined (see Photo 24). Subsequently, during repairs, the wharf geometry was redesigned.

The wide-reaching coastal impacts of this storm continued north of the study area through the Miramichi, the Acadian Peninsula (see Photo 25) and the Bay of Chaleur. In the Bay of Chaleur, the wharf at Petit-Rocher was badly damaged, and part of Beresford Beach was lost to the sea. At Charlottetown, to the south of the study area, the storm surge was out of phase with the tide, and little in the way of flooding and damage was reported in Northumberland Strait.

Bad as this storm was, it is important to remember that it would have been a lot worse if it had occurred a few hours earlier or later and had been in phase with the higher high tide of the day (as demonstrated by Figure 51). Under those circumstances, the water level would have reached approximately 2.94 m CD instead of 2.42 m CD at the Escuminac tide gauge. If the storm had caught HAT at Escuminac (approximately 1.6 m CD), then the storm would have reached approximately 3.2 m CD. MSL at Escuminac is approximately 0.75 m CD (see Section 4.1), and this maximum water level is therefore 2.45 m above MSL, or approximately the level of the January 21 storm (in fact, 10 cm less). This storm, however, came with ocean waves; during the storm of January 21, the shoreline was protected by ice.

Further information and some images of the October 29, 2000, storm and its impacts on Prince Edward Island can be found in McCulloch et al. (2002) in Supporting Document 3 (*Wind Climatology*), Supporting Document 4 (*Wave Climatology*) and Supporting Document 9 (*Coastal Geology and Shore-Zone Processes*).

4.2.9.3 The storm of February 6, 2001

On February 6, 2001, a 980-mb low tracked steadily northeastward across the spine of Nova Scotia and crossed Newfoundland on February 7. The system occurred during a run of spring tides and brought northeasterly gale to storm-force winds into the study area, which subsequently backed to northwesterly gales as the system moved away. The storm generated a 1-m storm surge at the Escuminac tide gauge, which combined with a high tide of 1.45 m to produce a water level of 2.41 m CD (see Figure 53). This water level ranks number four in the 43-year Pointe-Sapin/Escuminac water-level database and was just 1 cm lower than the water level of the October 29, 2000, storm (Section 4.2.9.2 above) that did so much damage to the shoreline.

The Dalhousie University storm-surge model run at Environment Canada predicted the storm surge well, and storm-surge warnings were issued in advance of the event by the Maritimes Weather Centre (MacAfee et al., 2001). Flooding was reported to fishermen's facilities in western Prince Edward Island, and minor flooding occurred all along the shoreline in the study area (see Photos 26 and 27 at the head of Bouctouche Bay). Although the water level was the same as during the storm of October 29, 2000 (compare Photo 28 of Bouctouche bridge taken on February 6, 2001, with Photo 29 taken on October 29, 2000), ice protected the shoreline from the impacts of ocean waves, and, once the water receded, there was little damage done. This event serves to illustrate well the protective nature of the sea ice.

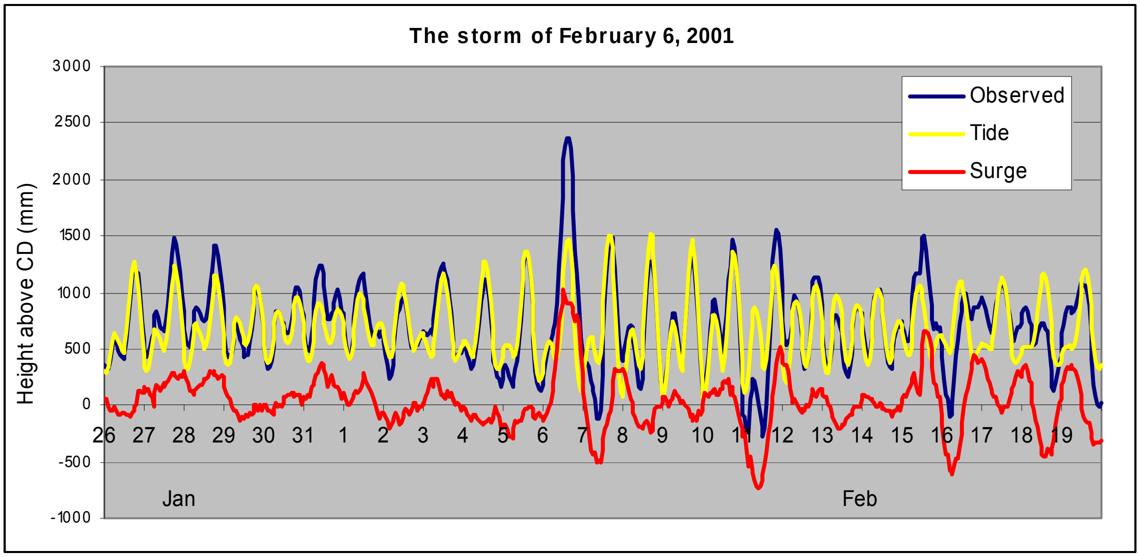


Figure 53. Water-level data at Escuminac during the storm of February 6, 2001.

Photo 26. Bouctouche Bay, February 6, 2001.

Photo 27. Bouctouche Bay, February 6, 2001.

Photo 28. Bouctouche bridge, February 6, 2001.

Photo 29. Bouctouche bridge, October 29, 2000.

4.2.9.4 White Juan, February 19, 2004

The phenomenal storm of February 19, 2004, was a paralyzing blizzard in the Maritimes. Many areas received 70–90 cm of fresh snow, and power outages were common, creating a provincial state of emergency in Nova Scotia and Prince Edward Island and a lengthy cleanup. It became known as White Juan because it followed relatively shortly after Hurricane Juan, a storm that was still fresh in many minds. The storm was relatively slow-moving to the south of Nova Scotia (Figure 54) and was very intense, producing a prolonged period of gale- and storm-force winds over the Gulf of St. Lawrence and a prolonged storm surge. The surge was 1.1 m at Escuminac but not in phase with the tide; still, it produced a water level of 2.40 m CD, the fifth highest on record (Table 10). Ice protected the shoreline from ocean waves, and in many ways impacts here were similar to those of the storm of February 6, 2001. At Pointe-du-Chêne, a 1.6-m storm surge was in near phase with the tide, producing a water level of 3.08 m CD, the highest ever recorded by a tide gauge and the second highest on record. Parts of the town flooded. At Charlottetown and throughout Northumberland Strait, the surge was in phase with the tide, and widespread flooding was reported. Charlottetown itself reported a 1.3-m storm surge, the third highest water level on record in 95 years of water-level data. Although the Charlottetown waterfront must have flooded to some degree, the Emergency Measures Organizationcould not confirm it officially at the time "because of all the snow."

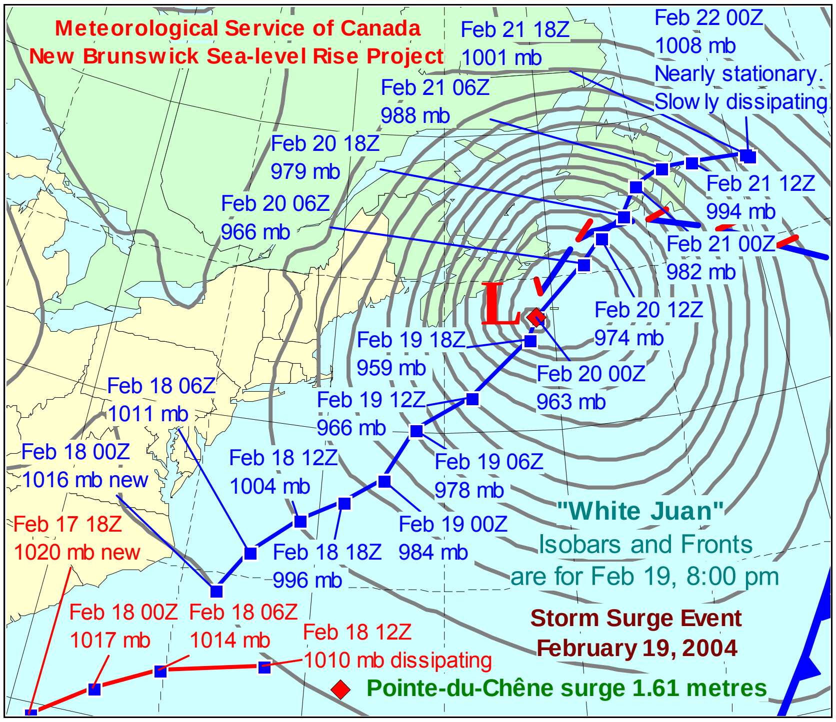


Figure 54. Weather map for February 20, 2004, at 0000 UTC.

Figure 55 shows the LiDAR visualization of Pointe-du-Chêne during the White Juan snowstorm. The red line marks the highest extent of the flood water. Much of the wharf and parts of the town are flooded. The storm-surge model predicted this event well, and storm-surge warnings had been issued the day before. New Brunswick Emergency Measures Organization officials were therefore on hand in Pointe-du-Chêne to assist in evacuations and to coordinate a response.

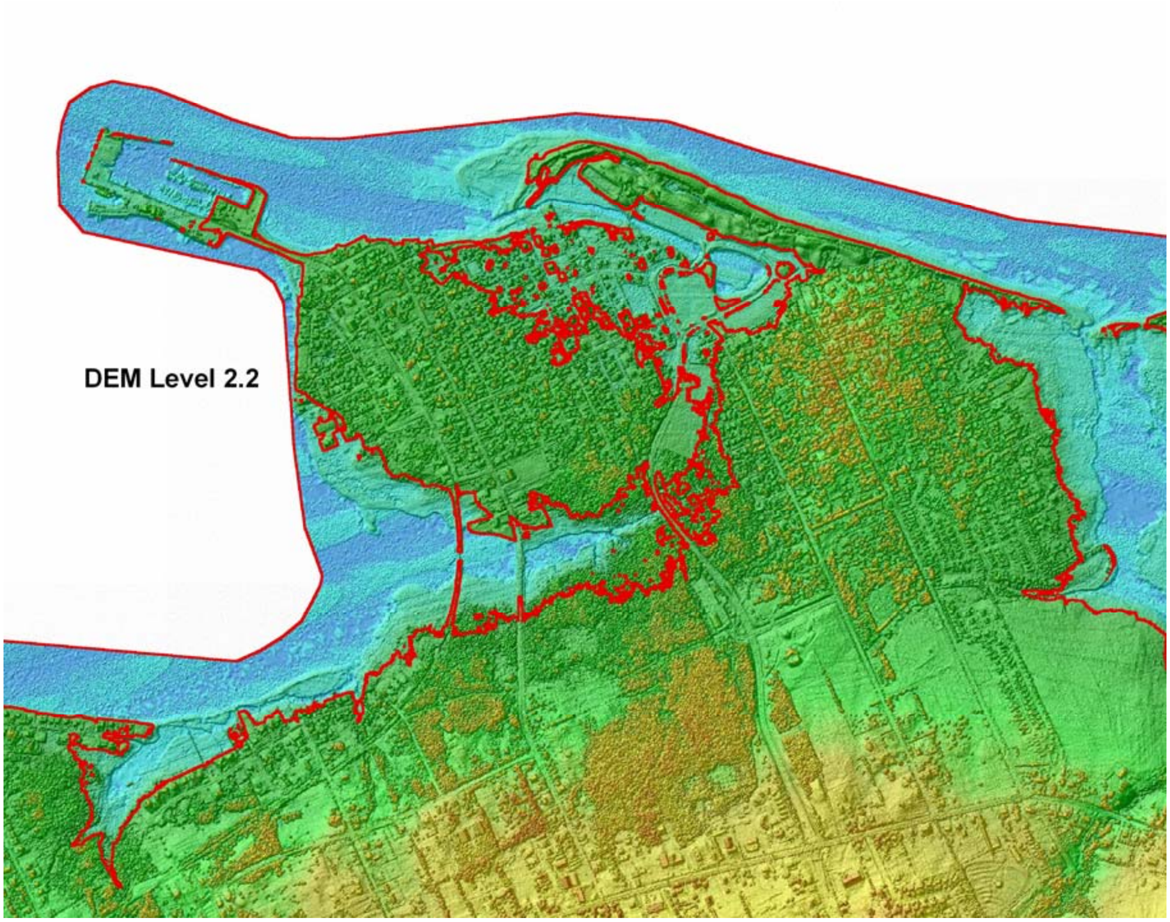


Figure 55. Aerial extent of the White Juan flood of February 19, 2004, in Pointe-du-Chêne. LiDAR mapping (valid May 2003) by Applied Geomatics Research Group, Nova Scotia Community College.

4.2.9.5 The storm of December 27, 2004

On the afternoon of December 27, 2004, a very intense 969-mb low-pressure system passed east of Cape Breton Island and subsequently moved across Newfoundland (Figure 56). This was another major snowstorm in the Maritimes. This system, combined with a ridge of high pressure over Quebec, brought a prolonged period of storm-force northeasterly, then northerly, winds across the Gulf of St. Lawrence. Power outages were common, and this blizzard had many similarities to the White Juan snowstorm discussed above. The most notable difference was that the storm occurred early in the winter when there was no ice protection from ocean waves, resulting in far-reaching coastal impacts.

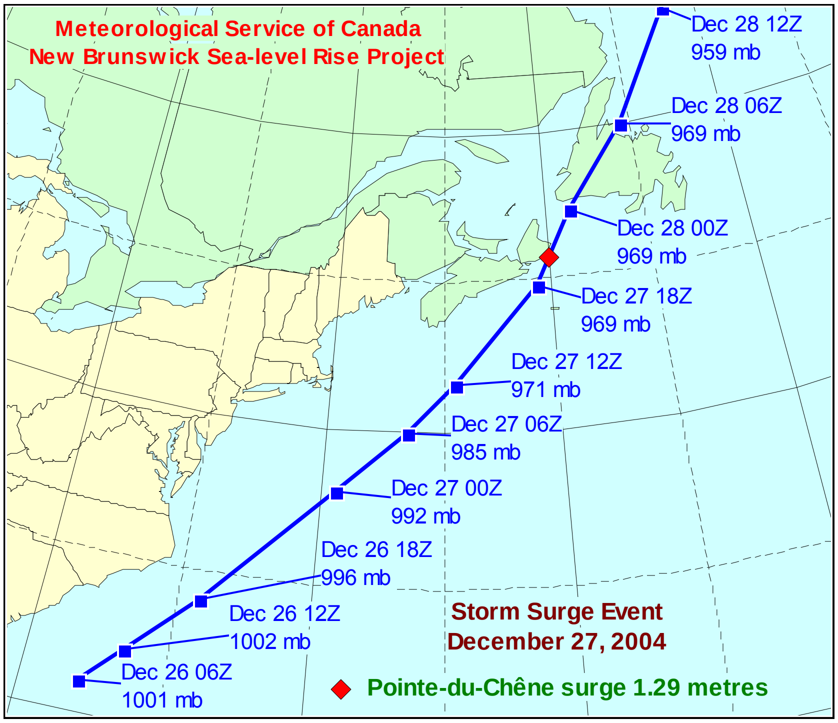


Figure 56. Track of the storm of December 27, 2004.

The storm occurred during a period of apogean spring tides (the moon was full on December 26 and at apogee on December 27). It occurred the day after the December 26 Sumatran tsunami, an event that travelled the world's oceans. The tsunami registered at the Halifax tide gauge (Rabinovich, 2005), appearing as a series of saw-toothed excursions with an amplitude of about 15 cm. Evidence for a tsunami signal at the tide gauges in the Gulf of St. Lawrence, however, is difficult to find.

Impacts from this storm were recorded in numerous areas through the southern Gulf of St. Lawrence. Flooding, shoreline erosion and coastal infrastructure damage were reported in Pictou and Antigonish counties and along shorelines of the Cape Breton Highlands. Damage of the same nature, some of it severe, was recorded along the east coast of Kings County, Prince Edward Island, and all along the North Shore, including the Prince Edward Island National Park.

At Escuminac, a storm surge of 87 cm combined with high tide to produce a water level of 2.42 m CD (2.47 m from the 15-minute data), the third highest in Table 10. This is about the level of the October 29, 2000, storm, but the contribution from the storm surge was much less; hence, the ocean waves were almost certainly smaller. At Pointe-du-Chêne, a storm surge of 1.29 m combined with high tide to produce a water level of 2.95 m CD, also the third highest in Table 10. At Charlottetown, the storm surge was coincident with low tide, and no impacts were reported there or in other central sections of Northumberland Strait, since they were protected from the larger waves.

At Kouchibouguac National Park, there was no damage to park infrastructure, but water crossed many of the dunes, which were subsequently strewn with cakes of ice. On the south side of Kellys Beach, water penetrated up to 45 m across the dunes; during the storm, a small new channel was carved, connecting the sea to the lagoon (see Photo 30). Once floodwaters subsided, this channel was left dry, but park officials were concerned that it could develop into a permanent breach in subsequent storms.

At La Dune de Bouctouche, waves moved entirely across the dune, in places leaving deposits of slushy ice and sand over previously vegetated areas. The sections of the Irving Eco-Centre boardwalk that had been destroyed during the storm of October 29, 2000, had been rebuilt farther from the shoreline, and these remained intact; now, however, two other sections of the boardwalk (closer to the interpretation centre) were undermined (see Photo 31). Notice also in Photo 31 the recent further erosion of the leading face of the dune.

Farther south, flooding was reported at various other locations, including Grand Barachois and Pointe-du-Chêne. The flooding at Pointe-du-Chêne was at DEM Level 2.1, some 10 cm or so less than the White Juan flood earlier in the year (Figure 55).

Again, the storm-surge model had forecast this system well, and storm-surge warnings had been issued in advance of the event.

Photo 30. Changes to dune at Kouchibouguac.

Photo 31. Damage at La Dune de Bouctouche.

4.2.9.6 Hurricane Gladys, October 21, 1968, and the storm of December 19, 1963

Two earlier storms (from Pointe-Sapin data) show up in Table 10, the highest observed water levels (from hourly water-level data) at Pointe-Sapin/Escuminac. Hurricane Gladys recorded the top ranking water level on October 21, 1968. The track of the storm is shown in Figure 57.

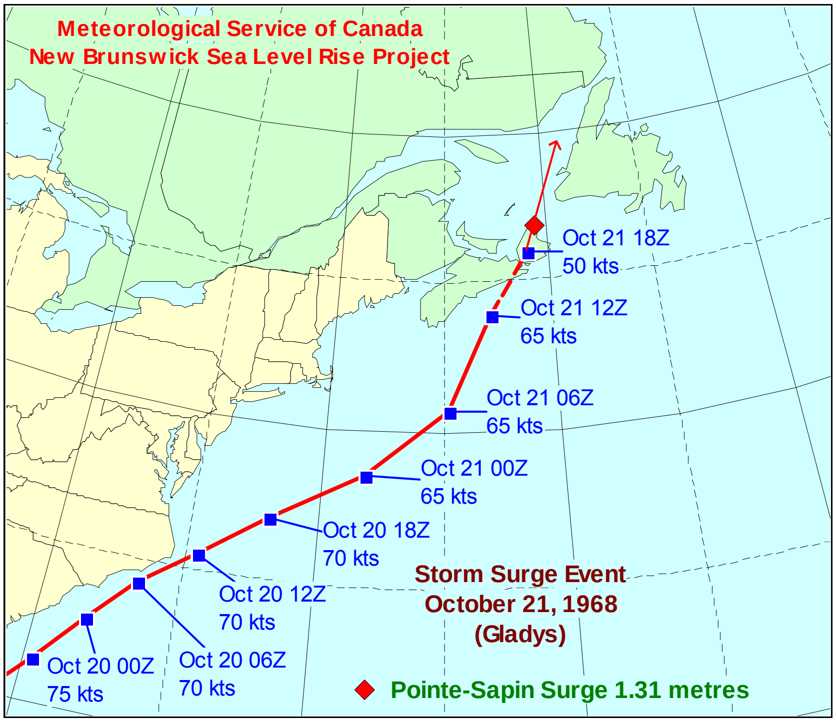


Figure 57. Track of Hurricane Gladys, October 1968.

In the U.S. National Hurricane Center's HURDAT database, the storm is declared extratropical on October 21 at 12Z. Surface weather maps at the time showed an expansive wind field in the northwest quadrant, not unlike the subtropical storm of October 29, 2000.

According to Kindervater (1984) in his report *Flooding Events in New Brunswick, An Historical Perspective*:

> In Gloucester County, Shippigan Island was severed from the mainland when the causeway bridge became inundated by the high tides. A one mile section of highway between the communities of Shippigan and Inkerman was also submerged by the tides. At Newcastle, the Miramichi River was reported to have risen about 6 feet above normal to threaten a number of buildings and overtopped the wharves. Six families in the Richibucto area were forced from their homes as heavy rains swelled the Richibucto River to eight feet above normal. The public wharf and many village streets were flooded.

The storm of December 19, 1963, ranks number 6 in the list in Table 10. This is another early winter storm, like the storm of December 27, 2004, which came when there was little or no ice to protect the shoreline from the impacts of ocean waves. The two systems attained about the same water level. The storm surge on December 19, 1963, was

1.07 m as opposed to 0.87 m on December 27, 2004. Ocean waves may therefore have been somewhat similar or larger in 1963.

4.2.9.7 Earlier major storm and flooding events

Our analysis of the two earlier storms in Section 4.2.9.6 above reminds us that flooding and coastal erosion in the study area are ongoing processes and that damage to coastal infrastructure is nothing new (Ruffman, 1999, for instance, draws attention to extensive coastal damage at Pointe-du-Chêne from a hurricane in 1873). In this section, reference is made to other reports that highlight significant coastal storm and flooding events in the study area, many of which predate the tide-gauge data.

Robichaud and Bégin (1997) collated a list of storms with severe coastal impacts in their study of coastal forest margins just east of Shediac Bay. The storm dates were compiled from various sources, including local newspaper archives and interviews with older residents. Storm classification was based on mentions of the degree of coastal infrastructure damage, coastal markers, levels of coastal immersion and records of wave height and wind velocity. Water-level data from Pointe-du-Chêne (1972–1990) were also consulted.

Kindervater (1984) compiled a history of flooding events in New Brunswick. The report mainly deals with inland flooding, but coastal flooding events are also discussed. His sources included government reports and records and newspaper archives. His reports of coastal flooding along the Gulf coast often refer to Newcastle and the Miramichi rather than to areas farther south. This is probably due more to the location and bias of newspaper publishers like the *Chatham Gazette* (Chatham) and the *North Shore Leader* (Newcastle) than to anything else, and many of the storms would also have affected our present study area.

This list of storms from Robichaud and Bégin (1997) is reproduced in Table 11, columns 2–6. Wind speeds are from Moncton meteorological observing stations. “Hurricanes” are marked with an X. We note that storm number 6 denoted by “(X)” is not in the HURDAT database and that storm numbers 4 and 9 (denoted by “xx”) are tropical cyclones in the database. Also shown in the table is the rank of that event in terms of highest water levels at the tide-gauge sites of Charlottetown (YYG), Escuminac/Pointe-Sapin (WPJ) and Pointe-du-Chêne (CHE). Ranks above 10 are not the true rank of the measured water-level data, but the rank of those data as adjusted to 1977. “M” stands for missing data. If the storms are mentioned by Kindervater (1984), then they are marked with a K in column 10. Storm number 10 on March 31, 1962, is mentioned by Kindervater (1984), but as a heavy rainfall flooding event.

Although details of storm damage are minimal in the Robichaud and Bégin (1997) paper, they do mention that storm number 8 on November 27, 1951, flooded part of the town of Shediac. They also mention that storm number 22 on November 21, 1988, caused heavy infrastructure damage along the coast.

Table 11. Major storms in the study area, from Robichaud and Bégin (1997). Wind speeds are from Moncton meteorological observing stations. "Hurricanes" are marked with an X. We note that storm number 6 denoted by "(X)" is not in the HURDAT database and that storm numbers 4 and 9 (denoted by "xx") are tropical cyclones in the database. "M" stands for missing data. If the storms are mentioned by Kindervater (1984), then they are marked with a K in column 10.

1	2	3	4	5	6	7	8	9	10
		Wind							
	Date	Direction	Maximum speed	Flood	Hurricane	YYG	WPJ	CHE	
1	1899, Sep 7	NW	High	?		M	M	M	
2	1904, Sep 15	?	High	?	X	M	M	M	
3	1917, Oct 20	?	High	?		?	M	M	
4	1923, Oct 1	?	Very high	?	xx	M	M	M	
5	1930, Oct 25	?	70	?		M	M	M	
6	1938, Nov 25	NE	Very high	Catastrophic	(X)	197	M	M	
7	1940, Sep 17	NE	130-145	?	X	174	M	M	K
8	1951, Nov 27	?	Very high	Catastrophic		35	M	M	
9	1959, Jun 19	NE	102	Severe	xx	528	M	M	K
10	1962, Mar 31	?	Very high	Severe		?	M	M	K
11	1962, Oct 8	?	128	Severe	X	400+	M	M	
12	1963, Oct 30	?	136	Severe	X	80	47	M	
13	1963, Dec 19	?	160	Moderate		165	6	M	K
14	1971, Fall	N	Very high	Severe		128?	57?	36?	
15	1974, Oct 20	NE	130	Severe		11	46	13	
16	1974, Nov 26	?	112	Severe		406	9	15	
17	1976, Mar 17	NE	?	Catastrophic		5	44	5	
18	1976, Jun 12	?	High	Severe		75	10	12	
19	1977, Dec 7	?	Very high	Severe		58	8	9	
20	1986, Nov 22	NNE	130	Catastrophic		200	49	6	
21	1987, Nov 12	NE	85	Severe		219	74	10	
22	1988, Nov 21	NE,N	101	Catastrophic		126	7	7	
23	1989, Nov 21	N	89	Severe		279	90	11	

Kindervater (1984) reported details of many historical flooding incidents along the Gulf coast of New Brunswick. These included the following:

- September 1884. Streets were flooded in Newcastle due to high tides.
- November 3–4, 1897. Streets and houses were flooded in Newcastle due, he reports, to heavy rain, high tides and strong northeasterly winds.

- May 8–9, 1926. Wharves flooded in Newcastle due, he reports, to an easterly gale and high tides.

- August 24–25, 1927 (1927 Storm A in the HURDAT database). Flooding occurred throughout Northumberland Strait from Cape Little to Shediac Cape, due, he reports, to high winds and heavy seas. In Shediac Bay, wreckage from boats, floats and wharves was reported to be strewn along the shore for kilometres. At Pointe-du-Chêne, some of this debris was reported to have been swept inland to the "ditches on Pleasant Street."

- November 20, 1937. Many basements were flooded in Newcastle and agricultural lands were flooded in Nelson-Miramichi, due, he reports, to high tides and rain.

- September 17–20, 1940. A severe gale (actually a tropical cyclone) caused coastal flooding in Bathurst and at Chatham/Newcastle and elsewhere along the Miramichi. Wharf damage was reported at Burnt Church and Oak Point, and several boats were lost along the Escuminac shore. A highway bridge was carried away at Bouctouche, and at least one home was inundated to the first floor. The main highway at Cocagne was damaged by floodwaters. At Upper Cape and Baie Verte, up to 8 m of shoreline were eroded, and several cottages were damaged.

- April 8–9, 1950. Coastal flooding was reported along the Miramichi, due to high tides and storm-force winds.

- June 20, 1959. The Escuminac Disaster (reported erroneously by Kindervater as June 26, 1959). Many boats wrecked, with much loss of life at Escuminac. Floodwaters reported over wharves at Newcastle.

- November 15–16, 1962. Gale-force winds and high tides caused minor flooding in southeastern New Brunswick, inundating wharves and highways and isolating homes. The area hardest hit was between Bouctouche and Shediac. A road near Bouctouche was flooded with as much as 1.5 m of water in some sections. The wharf at St. Edwards was submerged and damaged. Wharves at Shediac, Pointe-du-Chêne and Cape Bauld were partially inundated but largely undamaged.

- May 26–27, 1967. Heavy rains, high tides and hurricane-force northeasterly winds. Downtown areas in Newcastle were flooded, and debris was scattered along the shoreline.

Both Robichaud and Bégin (1997) and Kindervater (1984) recognized the difficulties associated with the kinds of surveys that they undertook and that their databases may be incomplete and inhomogeneous. This becomes clear when comparing the two reports, since important storms in one report — for instance, Kindervater's (1984) storms of August 26–27, 1927, and Hurricane Gladys of October 21, 1968 — are omitted from the Robichaud and Bégin (1997) report, while the so-called "catastrophic" floods of November 25, 1938, and November 27, 1951, are omitted from the Kindervater (1984) report. Nonetheless, many important storms are captured between these two reports, and some of these storms will have equalled or possibly exceeded the "benchmark" events detailed in this present study in terms of damaging waves on elevated water levels, although none is likely to have exceeded the flood levels of the storm of January 21, 2000.

4.2.10 Wind and wave climatology

4.2.10.1 Introduction

In the following sections we investigate measured and hindcast records of wind speeds and directions and wave heights and periods (with directions as available) in order to identify the winds and wind events that are most important in forming waves affecting the shorelines of the southern Gulf of St. Lawrence, develop climatologies to determine trends in past storminess, and attempt to predict future wind and wave climates and event frequencies to 2100. See Figure 58 for wind station locations.

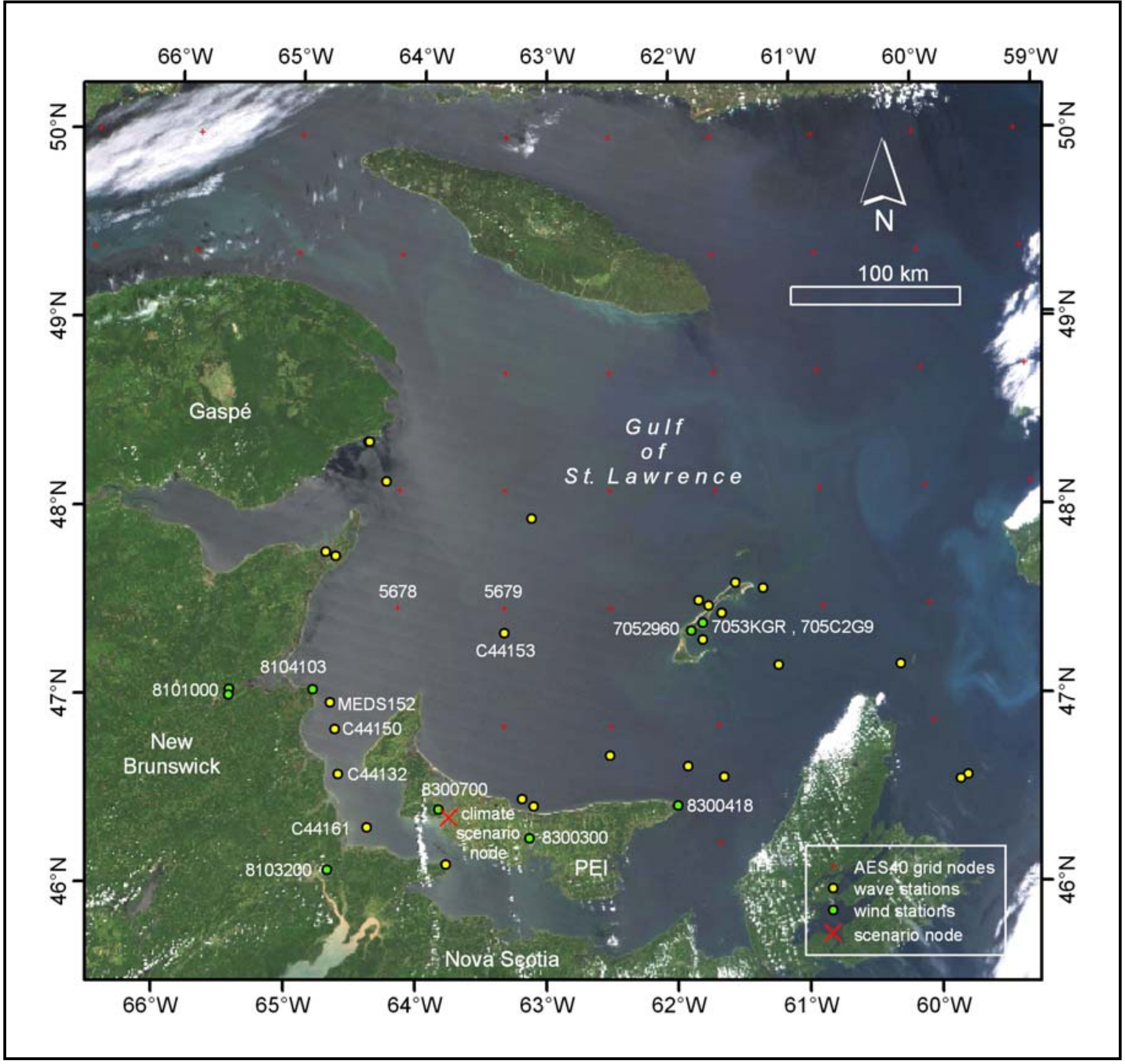


Figure 58. Locations of wind stations, wave buoys, hindcast nodes and the applicable scenario forecast node in the southern Gulf of St. Lawrence. SeaWifs image courtesy of the U.S. National Aeronautics and Space Administration.

4.2.10.2 Wind storms

4.2.10.2.1 Wind storm processes

The weather in the Gulf of St. Lawrence is generally described by cold dry air originating over the continent, which drifts eastward to meet warm moist air originating over the Caribbean Sea. Cyclogenesis occurs in troughs or at fronts where these air masses meet, resulting in the formation of extratropical cyclones in which air moves counterclockwise around low-pressure centres. The most intense extratropical cyclones form during winter and late fall, when the relative temperature difference between air masses is greatest (Sanders and Gyakum, 1980; Canavan, 1996). Extratropical cyclones that affect the Maritime provinces can form offshore of the southeastern United States, over the continent east of the Rocky Mountains or farther north in the Arctic (Gyakum et al., 1996). In winter, the most common are extratropical cyclones that form offshore of the southeastern United States and move northeastward towards the Maritimes. Some of these undergo explosive deepening and become very intense storms.

During the tropical weather season in the Atlantic (June to November), tropical cyclones (e.g., hurricanes and tropical storms) originating in the tropical and subtropical North Atlantic may also recurve northeastward along the eastern U.S. coast, passing just to the south of or over the Maritime provinces. These cyclones are usually weakening and losing their tropical characteristics at this point, due to passing over the colder shelf waters north of the Gulf Stream wall, and are often in the final stages of their life cycle. Occasionally, however, they may retain their tropical characteristics and strength and make landfall in the Maritimes. Notable recent landfalling hurricanes in Eastern Canada include Luis in Newfoundland in 1995, Hortense in Nova Scotia in 1996 and Juan in Nova Scotia in 2003.

As tropical storms transition to become post-tropical, the core of strongest winds tends to move away from a tight centre, and the systems begin to more closely resemble extratropical storms or weaker extratropical weather systems. The American National Weather Service and National Hurricane Center describe these post-tropical systems as extratropical; Canadian meteorologists use the term post-tropical to try to maintain the distinction between transitioned tropical systems and true extratropical cyclones. The most common region for transition is between 35°N and 45°N, with higher latitudes favoured towards the end of the tropical cyclone season (Hart and Evans, 2001). This fall period (October to November) is a time when such storms may also reintensify during transition (Abraham et al., 1999; Bowyer et al., 2001).

High wind speeds contribute to both storm-wave and storm-surge development. Identification of historical storms and stormy periods in wind records is important, since subsets of these events generated storm surges and waves that caused previous coastal flooding and erosion. Knowledge of the historical variability and impacts of storms provides conceptual insights into future frequencies and severities of flooding and erosion with changing climate scenarios. Therefore, the AES40 wind climatology for the node closest to southeastern New Brunswick is investigated in this section in order to identify periods in the wind record during which wind storms were more frequent and to describe wind regimes and storm events that contribute to wave and storm-surge formation.

4.2.10.2.2 Wind events since 1953

Methods and data sources

Measured wind speeds and directions were obtained from the Meteorological Service of Canada for stations near the study area, including Moncton A (8103200), Miramichi A/Chatham A (8101000), Point Escuminac Auto (8104103), Summerside A (8300700), Charlottetown A (8300300), East Point (8300418), Grindstone Island (7052960), Magdalen Islands Auto (7053KGR) and Magdalen Islands A (705C2G9) (Figure 58). Records have existed digitally since 1953 for Moncton, Miramichi/Chatham, Point Escuminac, Summerside, and Charlottetown, but they either show sudden irreconcilable “jumps” in wind speeds, presumably in response to the anemometer being moved or new structures built adjacent to it, or are considered too far removed from the coast to reflect marine winds. The record from Point Escuminac is likely most representative of marine winds, but it is too short (1986–2002) to develop a climatology. A long composite record from the Magdalen Islands stations has been developed (Manson et al., 2002b), but it is considered too far from the study area. Wind data from the Irving Whale wave buoy (C44153) were obtained from MEDS (Section 4.2.10.5).

Winds were also measured at two wave buoys over the period of this study: Pointe-Sapin (C44150) and Cap-des-Caissie (C44161). The buoys at these stations were deployed and retrieved by CCGS *Opilio* and CCGS *Terry Fox*. In 2003, the Pointe-Sapin (C44150) buoy, a Watchkeeper in 28-m water depth, operated from July through December. In 2004, a 3-m Discus buoy at Pointe-Sapin (C44150) was deployed in 28-m water depth in late May and retrieved in late December, and the Watchkeeper buoy at Cap-des-Caissie (C44161) was deployed in late May in 11-m water depth and retrieved in early January. In 2004, only the Pointe-Sapin Watchkeeper buoy was deployed in 28-m water depth, this time in early June, and was retrieved in late December. The records are given in Figure 59.

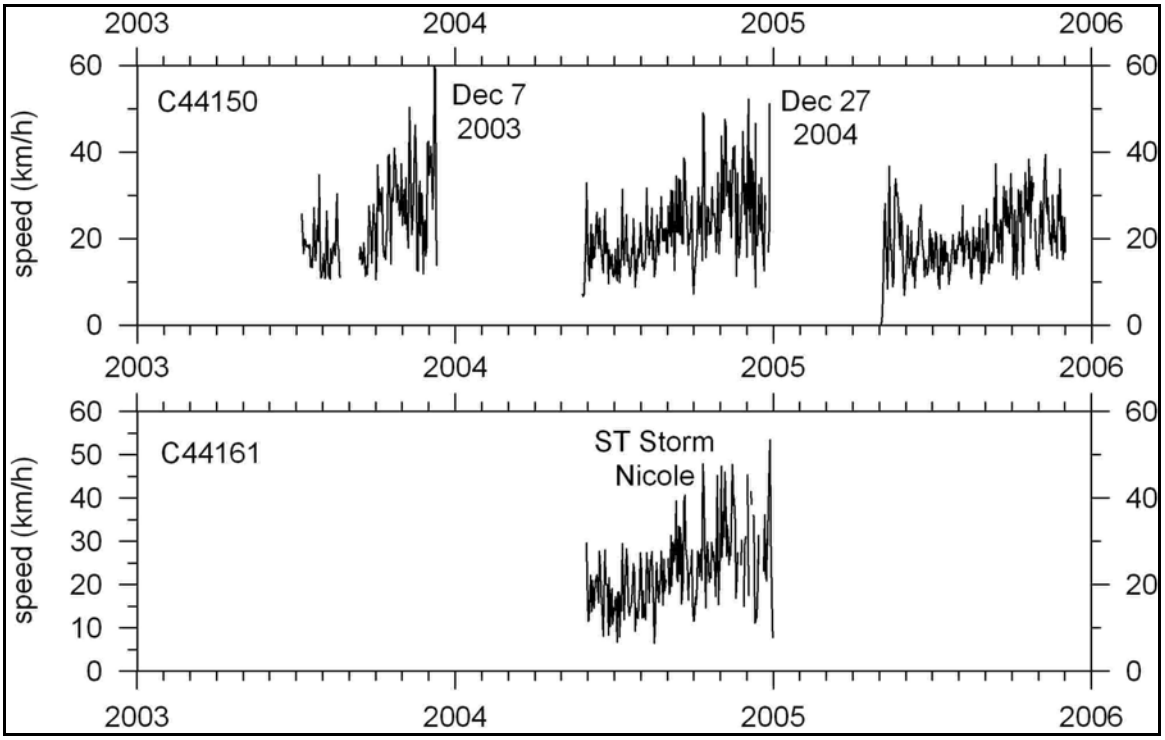


Figure 59. Winds measured at wave buoys deployed in this study.

Two AES40 hindcast nodes (Swail et al., 1998, 2000) at the western entrance to Northumberland Strait (nodes 5678 and 5679; Figure 58) may provide a better estimate of local marine winds than does the Magdalen Islands composite record; further, there are no missing data, and the hindcast measurements are regularly spaced, eliminating bias in finding storms. Our analyses will concentrate on node 5678. We will validate both nodes 5678 and 5679 by comparison with measured buoy data.

Results

Figure 59 shows several important wind events that produced storm surges and waves during the study: an event on December 7, 2003, during which winds peaked at 63 km/h from 50° at the Pointe-Sapin buoy (C44150); subtropical Storm Nicole on October 11 and 12, 2004, during which winds at the Pointe-Sapin buoy reached 63 km/h from 33° and winds at Cap-des-Caissie (C44161) reached 64 km/h from 26°; and an event that occurred as a transitioning low passed by the study area on December 27, 2004, during which winds reached 55 km/h from 45° at Pointe-Sapin and 58 km/h from 26° at Cap-des-Caissie. This event separated the Cap-des-Caissie buoy from its mooring, setting it adrift. It is noteworthy that all these events are northeasterly and occurred in the autumn. Subsequent analyses focus on autumn northeasterly events.

AES40 node 5679 hindcast data are shown in comparison with data measured at the Irving Whale buoy in Figure 60. The agreement is very good in both wind direction (r^2 = 0.76) and wind speed (r^2 = 0.97). The relatively low r^2 for direction is a result of wraparound from 0 to 360 (clusters at 360° on each axis), which affects the simple r^2 statistic.

A similar test can be conducted for node 5678 and data measured at the Pointe-Sapin buoy (C44150) (Figure 61). Owing to the greater distance between the hindcast and measurements, agreement is less good (r^2 = 0.52 for direction and 0.79 for speed). The low correlation for direction is due to southerly winds at Pointe-Sapin, for reasons not clear, correlating with westerly winds at node 5678, compounded by the wraparound through north seen in Figure 60. This means that while hindcasting is successful at nodes, the hindcasting cannot be translated geographically, just like measurements in one location cannot be translated to a distant location; subsequent analyses are therefore relevant at node 5678, not the position of the Pointe-Sapin buoy.

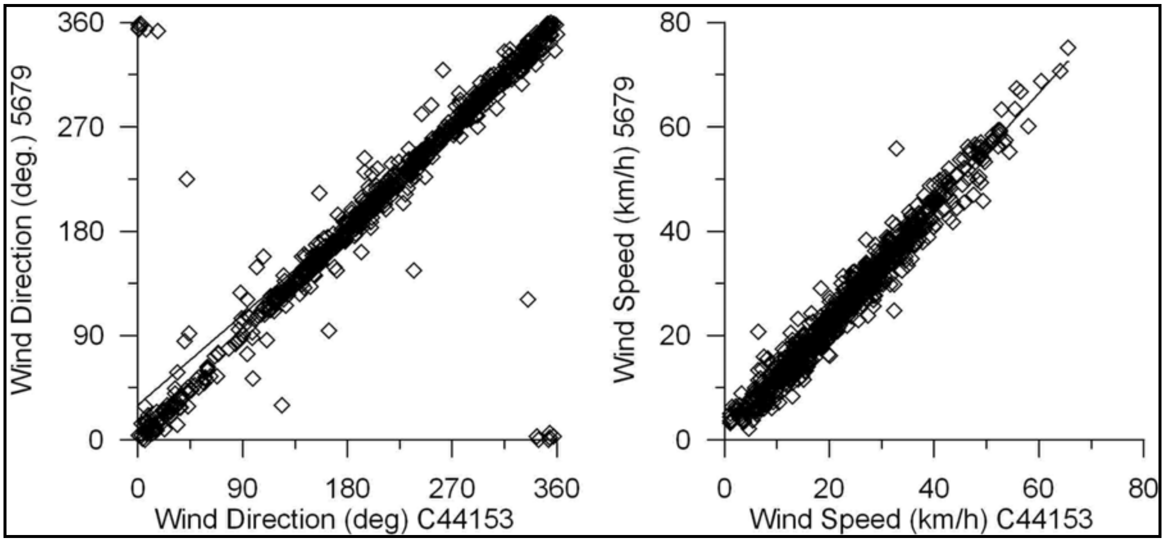


Figure 60. Wind speeds and directions at hindcast node 5679 compared with measured Irving Whale buoy data (C44153).

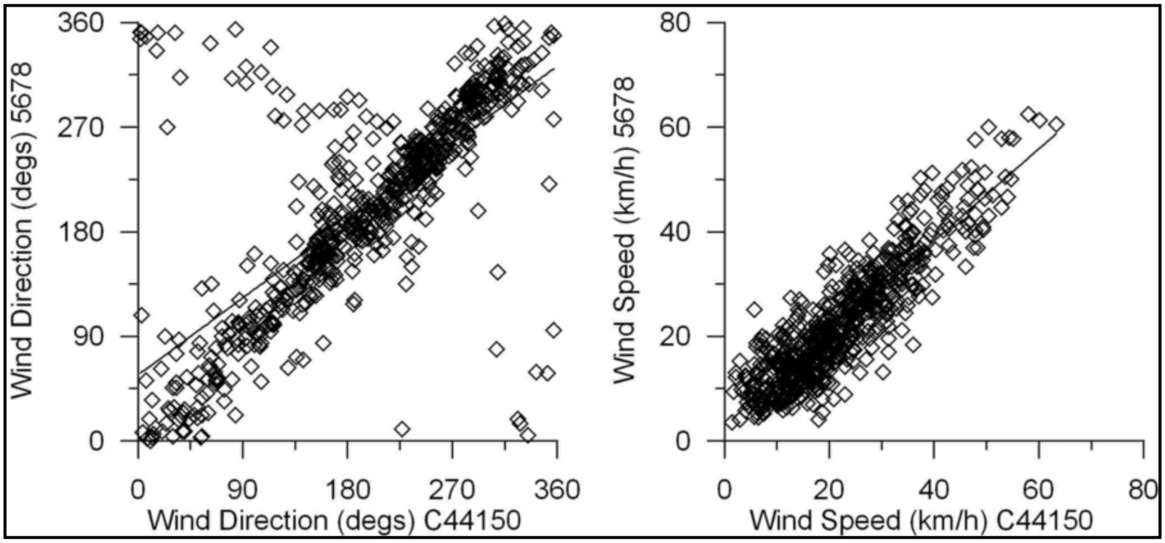


Figure 61. Wind speeds and directions at hindcast node 5678 compared with measured Pointe-Sapin buoy data (C44150).

A time–time plot of the percentage of time that winds exceed 40 km/h at hindcast node 5678 is given in Figure 62. Notable periods of exceedance by winds from the northeast during the autumn (September–December) include 1960, 1962–1966, 1967–1968, 1970, 1974–1982, 1985, 1987–1989, 1991, 1993, 1998–2001 and 2004. These periods correspond quite well to periods of high waves (Section 4.2.10.5.2), which is to be expected, as the waves are hindcast from the AES40 winds. A list of wind events greater than or equal to 40 km/h at hindcast node 5678 was compiled. The entire list of 1264 events was subdivided into 165 events with a mean northeasterly direction and further subdivided into 58 autumn (September–December) northeasterly events. The annual occurrence of these 58 events is shown in Figure 63, which demonstrates a trend towards increased occurrence (seven-year running mean r^2 = 0.65), particularly since the late 1980s. Prior to the late 1980s, events were sporadic, in many years not occurring at all, but in other years occurring often (e.g., 1970 and 1981). After the late 1980s, at least one event occurred every year, but never more than three in a single year (1996).

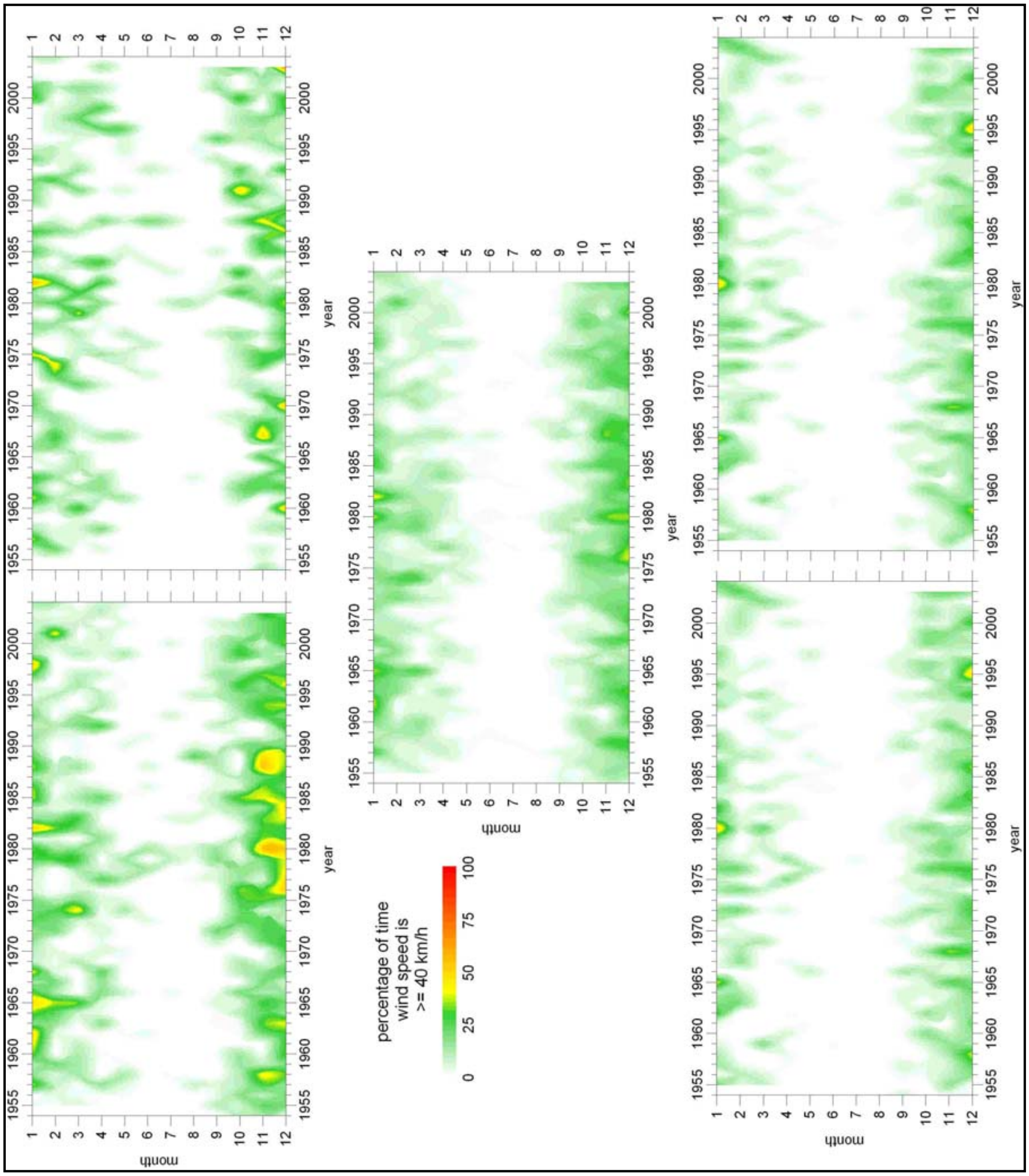


Figure 62. A time–time plot of the percentage of time, from each direction, that wind speeds exceeded 40 km/h at AES40 hindcast node 5678.

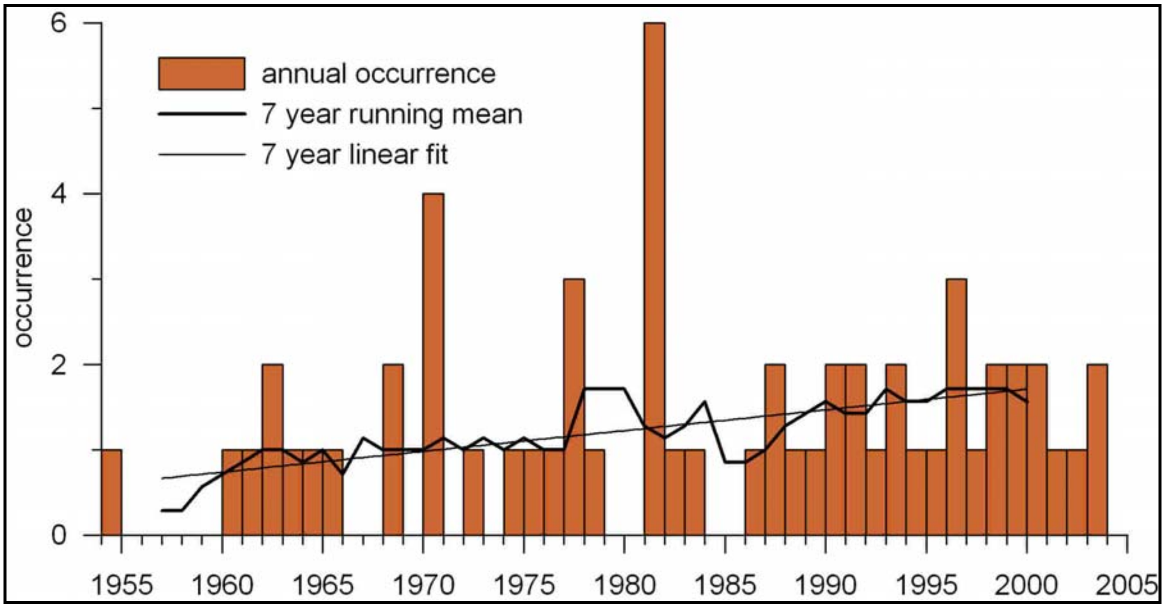


Figure 63. Annual occurrence of northeasterly autumn wind events at node 5678 greater than or equal to 40 km/h for at least six hours.

4.2.10.2.3 Wind events by year 2100

Methods and data sources

The freely available statistical downscaling model software SDSM V.3.1 (Wilby et al., 2002) was used in conjunction with CGCM1 climate scenario daily means obtained from the Canadian Institute for Climate Studies (Boer et al., 2000) to statistically downscale the daily mean AES40 wind speeds and directions at node 5678. We use scenario data from a model grid node located at 46°39'N, 63°75'W, near Summerside (Figure 58). Statistical downscaling uses change scenarios developed from climate models, in this case the CGCM1 GHG+A run. Station data, in this case semi-modelled AES40 winds at node 5678, are used to calibrate selected model variables. The CGCM1 GHG+A scenario does not cover the interval between 2000 and 2010.

Results

It was found, through correlation and multiple regression, that wind speeds were best represented by the scenario variables of surface and 800 hPa level wind speeds. Together, these account for 80% of the 1961-1990 variability at node 5678. Mean downscaled and AES40 daily mean wind speeds between 1961 and 1990 were found to be not significantly different ($\alpha = 0.05$), and the variances were similarly found to be not significantly different ($\alpha = 0.1$), although Figure 64 shows that variance is not well reflected in forecasting. Wind directions were not successfully downscaled. The best result was achieved using the scenario variables of wind direction and divergence at surface and the 800 hPa level, but only 53% of the directional variability at node 5678 is explained. Mean directions and dispersions between the modelled and AES40 wind directions were found to be different at all significance levels and, therefore, will not be further analyzed. Downscaled wind speeds between 1961 and 2100 are shown in Figure 64.

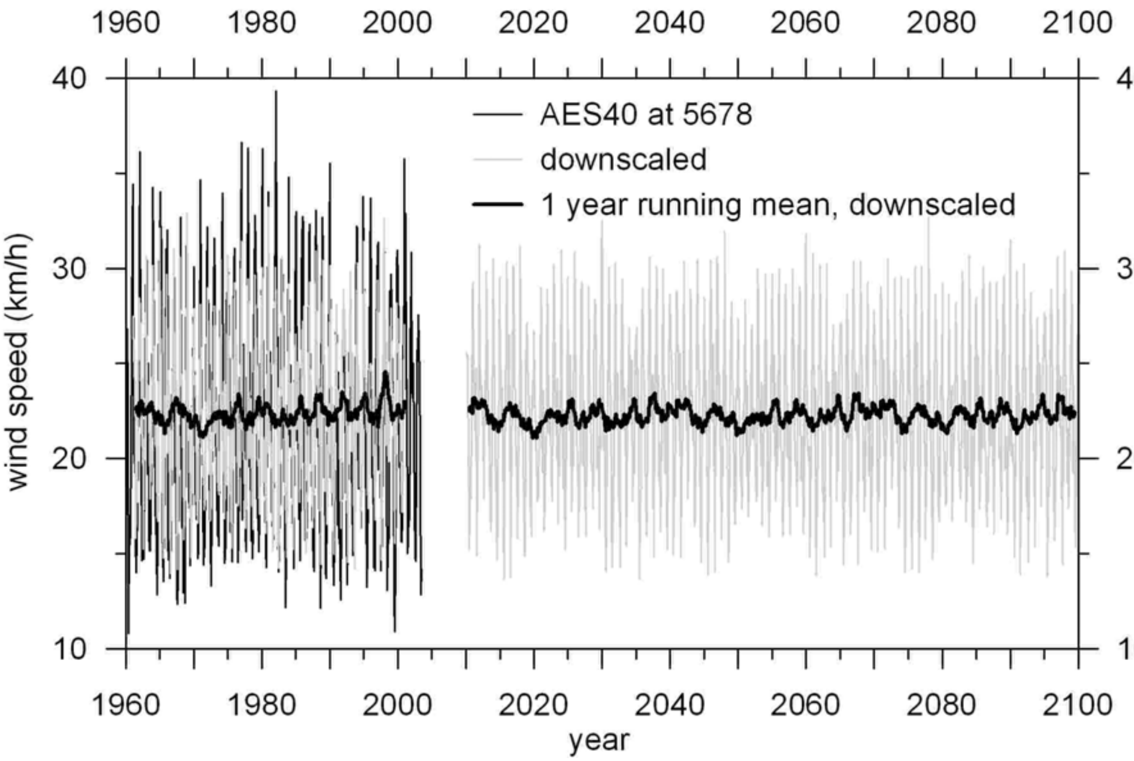


Figure 64. Downscaled monthly mean wind speeds between 1961 and 2100 with AES40 monthly mean wind speeds between 1960 and 2003. Downscaled wind speeds accurately reflect the means, but the variability is underestimated. Extreme events are therefore not well forecast.

Figure 64 shows that, in this analysis, no future changes in monthly mean wind speeds are expected. Of greater interest than monthy means, however, is the occurrence of extreme events. Because the variance is not well reflected in downscaling, the occurrence of extreme events cannot be determined. Previous research on storminess in the northern hemisphere (Lambert, 1995, 2004) has demonstrated that overall frequency of cyclones may be expected to decrease slightly, but that storm tracks are not expected to change significantly, and the strongest events (i.e., the top 5%) are expected to increase in frequency by as much as 17% by 2100. This suggests increasing frequency of occurrence of autumn northeasterly events in the southern Gulf of St. Lawrence.

4.2.10.3 Waves

4.2.10.3.1 Wave formation, shoaling and breaking

Waves are the most widely recognized causes of coastal erosion and damage to coastal infrastructure. Waves form offshore during wind storms and carry energy to the shoreline, where it is absorbed or reflected by natural coastal systems and engineered structures. Coastal erosion, increased sediment mobility and damage to infrastructure can be caused by large waves, especially when they are superimposed on higher-than-normal water levels during storm surges.

Fetch is the distance over which wind acts to form waves. It is usually the distance from land in the upwind direction, but in the southern Gulf of St. Lawrence, sea ice can also act to limit fetch. Longer fetch and longer time over which the wind acts on the water result in higher waves (vertical distance from trough to crest) with a longer wavelength (horizontal distance from one crest to the next) and a longer period (time it takes for a wave to pass). Long waves travel faster than waves of shorter length and are less attenuated; thus, they travel farther and can leave the immediate area of a storm. Long waves can precede an approaching storm in the form of swell; however, if the storm is travelling quickly, swell waves and short, locally developed waves can all be present in what is known as a fully developed sea. Long swell waves occur in the Gulf of St. Lawrence, entering through Cabot Strait, but are less common than short, locally developed waves.

As waves approach the shore, they begin to encounter the seafloor at a depth usually taken to be approximately one half the wavelength; at depths of one quarter the wavelength, substantial changes to waves occur. Storm waves in the Gulf of St. Lawrence may have wavelengths up to 200 m, suggesting that substantial wave transformation is occurring in water depths of 50 m or more. When waves are transformed, they grow in height and shorten in wavelength and period. Over an irregular bottom, different parts of the wave move more slowly in shallow water than in deeper water, the wave is refracted and diffracted, and changes in wave height, direction and sediment transport occur.

With further shoaling, as wave height increases and wavelength decreases, parts of a wave may begin to break. This is commonly taken to occur when the height of an unbroken wave reaches about 78% of the water depth (Komar, 1998). In many locations on the southeastern coast of New Brunswick, nearshore bars are present, so waves can break, reform in the deeper bar troughs and then break on another bar closer to shore, such that bands of breaking waves are often observed on barred shorelines. With each breaking episode, energy is dissipated. When a wave breaks on the beach, depending on the slope of the beach face, the breaker may take several forms. On gently sloping beaches (slope less than ~0.025), spilling breakers tend to occur, which dissipate their energy over a broad width of beach. On steeper beaches (slope greater than ~0.10), plunging breakers occur, which dissipate their energy in a very narrow width of shoreline (Galvin, 1968; Gaughan and Komar, 1975). Plunging breakers may be especially effective in causing erosion of the upper beach and dune or cliff toe and damage to coastal infrastructure when superimposed on higher-than-normal water levels accompanying storm surges.

The final stage of wave breaking is termed run-up, when the swash of a broken wave carries on up the beach. The height of wave run-up, expressed as an exceedance interval, is commonly taken as an empirical function of the deep-water wave height and wavelength, the breaking wave height and the beach slope (Battjes, 1974; Smith and Kraus, 1990; Komar, 1998). During storms, when accompanied by storm surges, run-up can cause overtopping of beaches and coastal structures, transport of debris and significant flooding inland.

4.2.10.3.2 Waves since 1954

Methods and data sources

Historical wave height and period, occasionally wave direction and sometimes associated meteorological data (e.g., wind speed and direction) from 22 different wave buoy locations in the southern Gulf of St. Lawrence (Figure 58) were obtained from MEDS of Fisheries and Oceans Canada and compiled in a database. These begin in the early 1970s, but the records from any given location are often short, rarely cover more than a single summer and rarely capture significant events. Notable historical stations include Irving Whale (C44153) and Pointe-Sapin (MEDS152) (Figure 65).

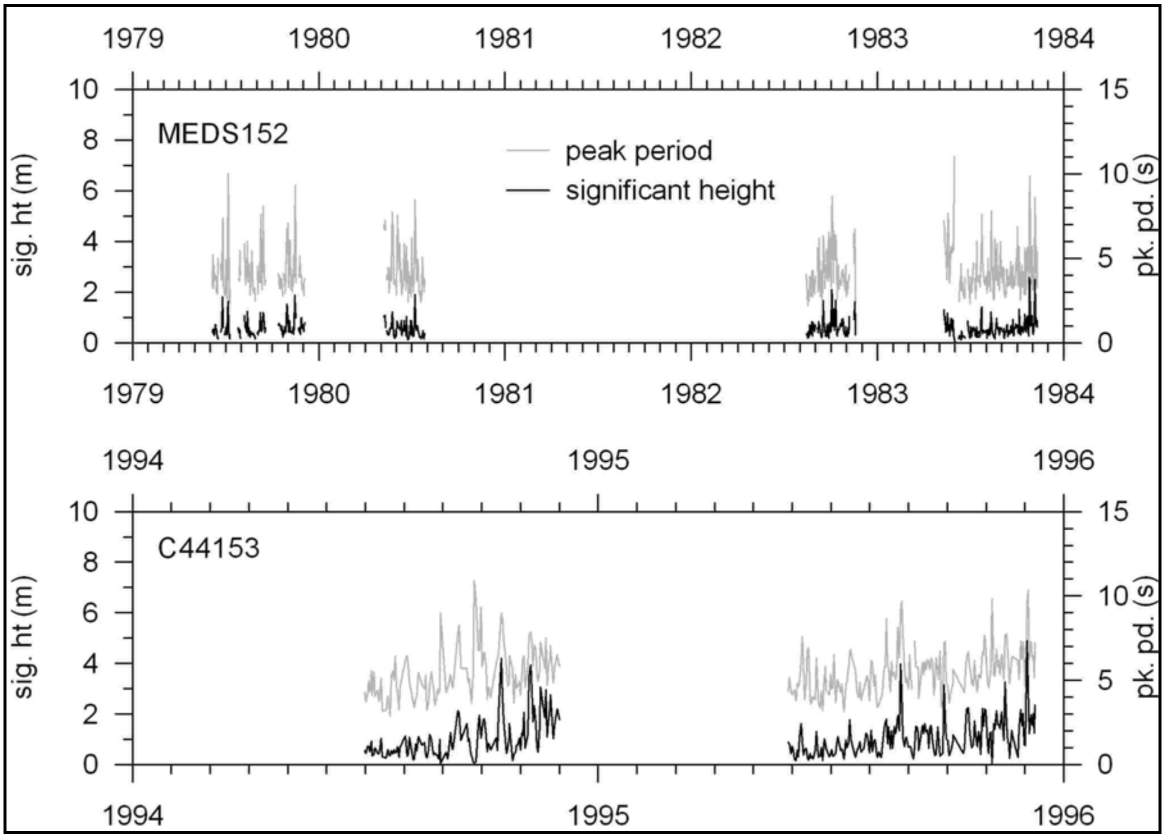


Figure 65. Daily means of waves measured at the Irving Whale (C44153) and Pointe-Sapin (MEDS152) stations.

Three stations were occupied over the course of this project: Pointe-Sapin (C44150), Gros Cap (C44132) and Cap-des-Caissie (C44161). The buoys at these stations were deployed and retrieved by CCGS *Opilio* and CCGS *Terry Fox*. In 2003, two buoys were deployed. The Pointe-Sapin (C44150) buoy, a Watchkeeper in 28-m water depth, operated from July through December, but a Triaxys Wave-rider at Gros Cap was struck by a vessel, and the data were unrecoverable. In 2004, three buoys were deployed. The 3-m Discus buoy at Pointe-Sapin (C44150) was deployed in 28-m water depth in late May and retrieved in late December, the Triaxys Wave-rider buoy at Gros Cap (C44132) was deployed in 14-m water depth in mid-September and retrieved in late December, and the Watchkeeper buoy at Cap-des-Caissie (C44161) was deployed in late May in 11-m water depth and retrieved in early January. In 2004, only the Pointe-Sapin Watchkeeper buoy was deployed in 28-m water depth, this time in early June, and was retrieved in late December. The records are given in Figure 66.

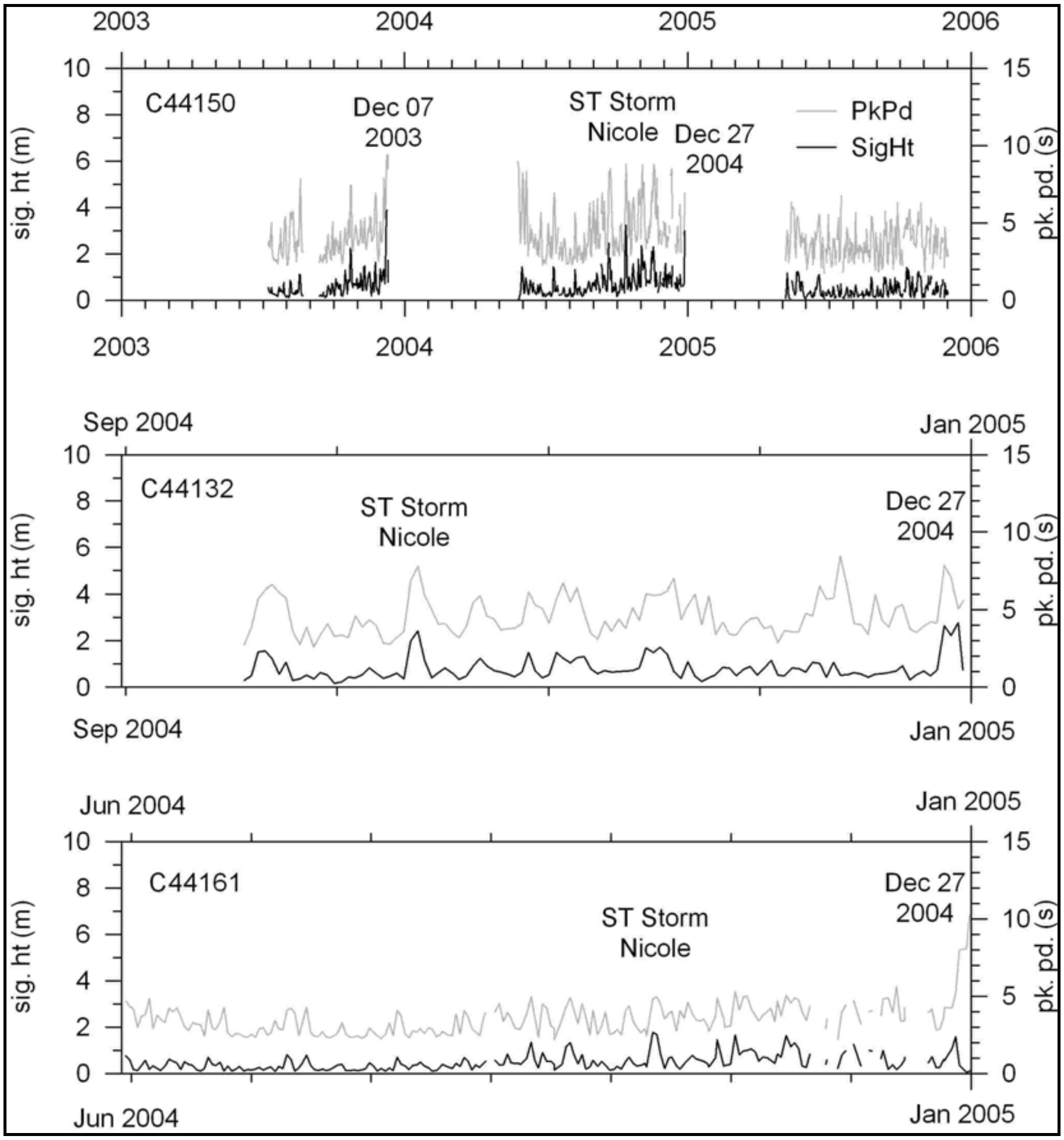


Figure 66. Daily mean significant height and peak period of waves measured in this study.

In addition to measured waves, there also exist in the southern Gulf of St. Lawrence AES40 hindcast wave data (Swail et al., 1998, 2000). This data set consists of, among other variables, six-hourly hindcast wave heights, wave periods, wave directions, wind speeds and wind directions. Sea ice was incorporated into the hindcast beginning in 1972. Because of the length and consistency of this record, much of the analyses of waves will focus on two nodes of the hindcast adjacent to the study area (5678 and 5679; Figure 58). Measured data will be used to validate the hindcast.

Results

The wave buoys deployed during this study captured several important wave events (Figure 67), particularly in 2004, when Subtropical Storm (STS) Nicole passed through the study area on October 11 and 12 and a transitioning intense low-pressure system passed through on December 27, 2004. These are summarized in Table 12. STS Nicole moved the Gros Cap buoy approximately 30 m southeast (it is uncertain whether this was a result of stretching of the mooring lines or movement of the mooring weight); the December 27 event separated the Cap-des-Caissie buoy from its mooring, setting it adrift.

The arrangement of the buoys in 2004 demonstrates the variable wave climate along the southeastern New Brunswick coast. During both STS Nicole and the December 27 event, significant wave heights were highest at Pointe-Sapin and decreased southeast to Cap-des-Caissie. Maximum wave heights and peak periods show similar trends, except that they appear to have not been comparably measured by the Gros Cap Triaxys buoy. Peak storm winds were comparable at Pointe-Sapin and Cap-des-Caissie and from similar northeasterly directions, so the differences in storm waves are most likely due to decreased northeasterly fetch in the southeastern parts of the study area. Table 12 also lists an event on December 7, 2003, which was measured only by the Pointe-Sapin buoy. No significant events occurred in the southern Gulf of St. Lawrence in 2005.

The Irving Whale buoy (C44153) and AES40 hindcast node 5679 are in close proximity (15 km) and present an opportunity to validate the AES40 hindcast. Significant wave height is well predicted (r^2 = 0.89), while peak period is poorly predicted (r^2 = 0.32). It is thought that the poor prediction lies mostly in the difficulty of measuring the period of small waves, as long period outliers in Figure 67 at C44153 are exclusively small waves.

Table 12. Statistics of wave events measured during this study.

Event	Station	Significant height(m)	Maximum height(m)	Peak period(s)	Maximum wind speed (km/h)	Peak wind direction (degrees)
December 7, 2003	C44150	4.7	11.5	9.9	63	50
STS Nicole	C44150	4.8	22.8	9.9	63	33
STS Nicole	C44132	3.3	6.9	10.0	n/a	50*
STS Nicole	C44161	3.2	15.1	6.4	64	26
December 27, 2004	C44150	4.7	19.4	7.4	55	45

Event	Station	Significant height(m)	Maximum height(m)	Peak period(s)	Maximum wind speed (km/h)	Peak wind direction (degrees)
December 27, 2004	C44132	3.6	6.7	9.5	n/a	45*
December 27, 2004	C44161	2.4	13.9	5.3	58	26

* Wave directions: Against oceanographic convention, we report, for comparison with winds, the direction from which waves come, not the direction to which they travel.

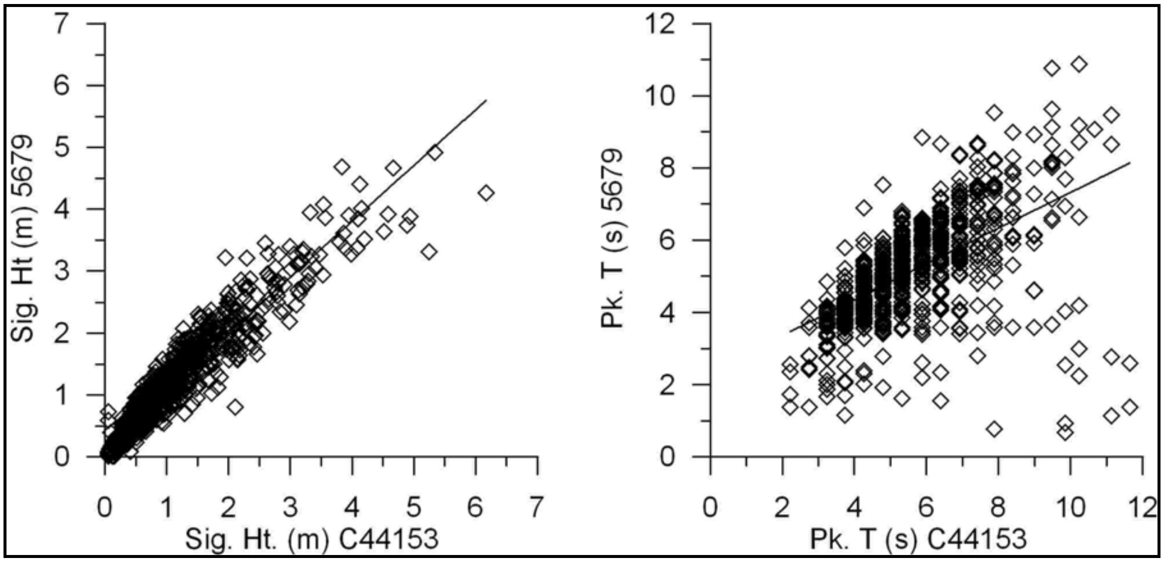


Figure 67. Corresponding measurements of significant wave height and peak period at Irving Whale (C44153) versus hindcast significant wave height and peak period at AES40 node 5679.

A similar test can be done for hindcast node 5678 and the Pointe-Sapin stations (MEDS153 and C44150); however, due to the distance between the measurements and hindcast positions (69 km), resulting in different fetch lengths and slightly different arrival times of storm waves, there is less agreement between both significant wave height (r^2 = 0.55) and peak period (r^2 = 0.23) (Figure 68). Again, peak period is particularly poorly correlated; in this case, it becomes obvious that no periods under 2 seconds were measured, further indicating that periods of small waves are either not well measured or been removed during quality-control.

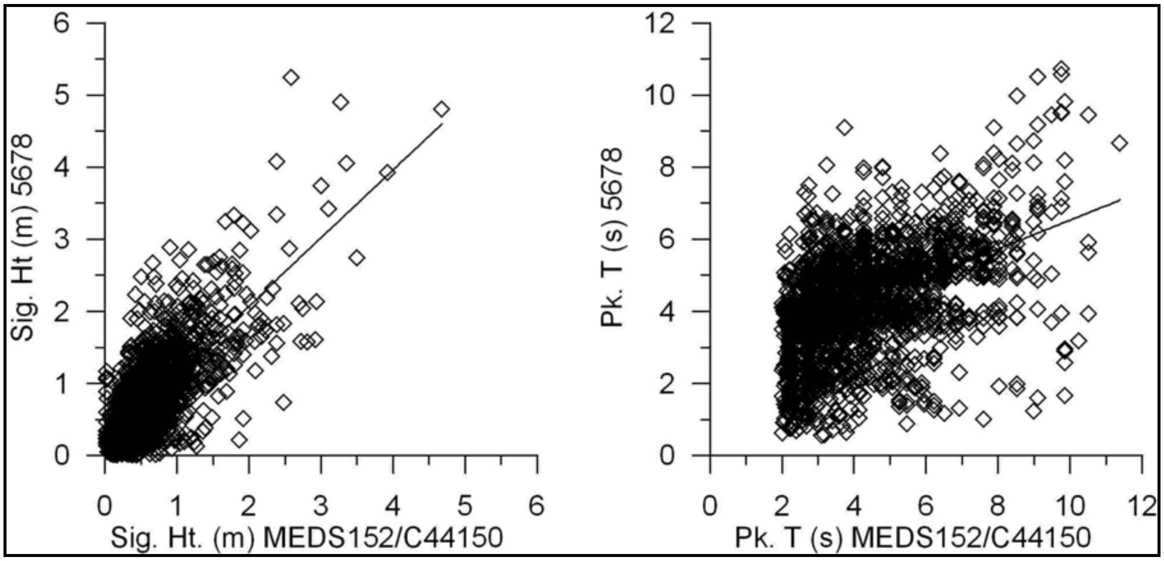


Figure 68. Corresponding measurements of significant wave height and peak period at Pointe-Sapin (MEDS152 and C44150) versus hindcast significant wave height and peak period at AES40 node 5678.

While the agreement between hindcast node 5678 and the Pointe-Sapin buoy data is low, the good agreement between node 5679 and the Irving Whale station indicates that the hindcast data are locally accurate. This is as expected, because measured wind data are used to train the AES40 wind predictions, which then drive the wave hindcast; the closer a hindcast node is to a wind measurement site, the more accurate are the predictions at that node. Assuming that node 5678 is as accurate as node 5679 in predicting local significant wave height and that the closer position of node 5678 to the study area better reflects its wave climate, and acknowledging that hourly significant wave heights at node 5678 reflect only slightly more than half the variability in significant wave heights at the Pointe-Sapin station, subsequent analyses focus on node 5678.

A time–time plot of the monthly percentage of time hindcast significant wave heights exceeding 3 m at node 5678 is shown in Figure 69. The five panels give significant wave heights gridded by month and year, thus illustrating seasonal variability through time. These are given in the centre panel for all directions (i.e., the percentage of time that waves are ≥3 m from any direction) and by each directional quadrant in the surrounding four panels (e.g., the percentage of time northeasterly waves are ≥3 m).

Figure 69 shows that waves greater than 3-m significant height occur most often from the northeast, northeasterly waves occur most often in the fall season (September through December) and there are several intervals of variable duration during which fall northeasterly waves occurred more frequently: 1960–1966, 1968, 1970, 1974, 1977–1981, 1986–1988, 1991, 1998–2000 and 2003–2004.

Hindcast waves at node 5678 were analyzed for events greater than or equal to 3 m for at least six hours. The 206 events identified were subdivided into those with mean wave directions from the northeast (90 events) and then further subdivided into those with mean northeasterly wind directions occurring in the fall (September–December). This final subset contains 53 events. A time series of annual occurrences is given in Figure 70.

Events occurred particularly often in the intervals 1960–1966, 1968, 1970, 1974, 1977–1978, 1981, 1983, 1986–1987, 1991, 1993, 1995, 1998–2000 and 2004. These intervals agree reasonably well with the intervals of increased northeasterly waves in Figure 69.

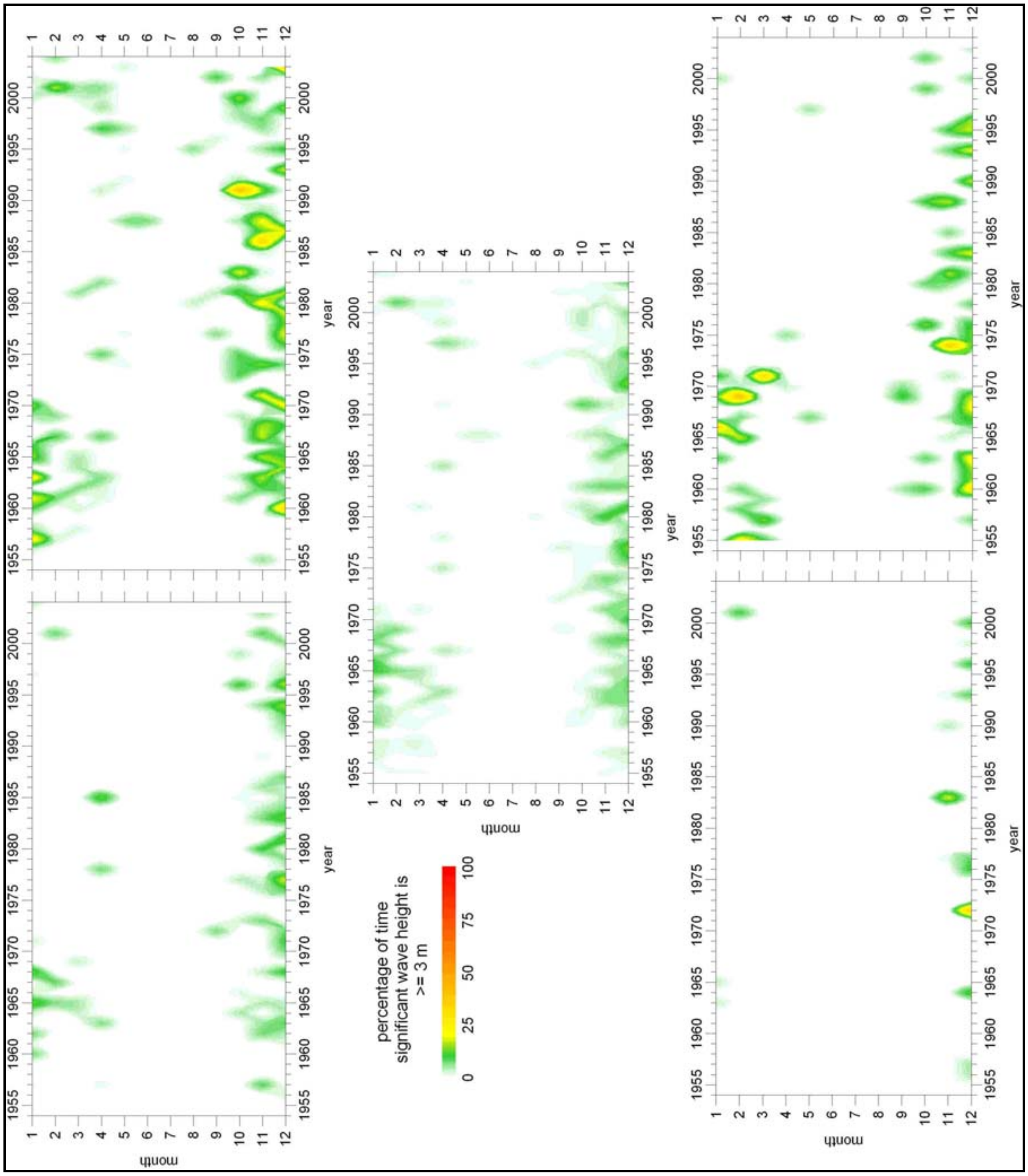


Figure 69. Time–time plots of the monthly percentage exceedance of 3-m significant wave height at AES40 hindcast node 5678. Prior to 1972, ice was not included in the hindcast.

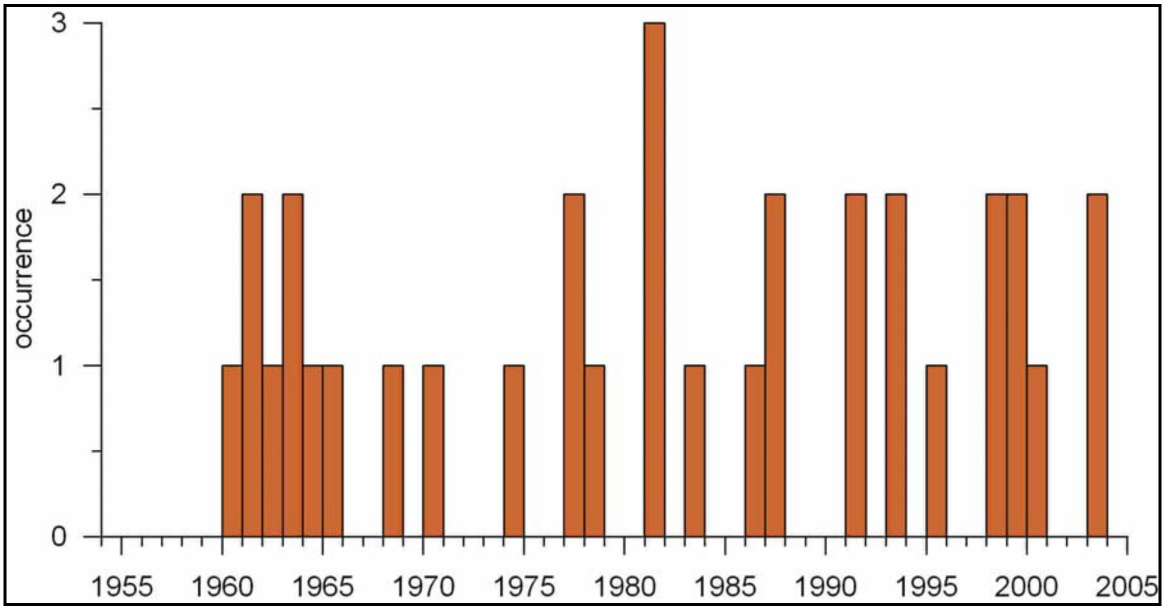


Figure 70. Autumn occurrence of wave events at node 5678 with significant heights ≥3 m for at least six hours and mean wave directions from the northeast.

4.2.10.3.3 Waves by 2100

Methods and data sources

The freely available statistical downscaling model software SDSM V.3.1 (Wilby et al., 2002) was used in conjunction with CGCM1 climate scenario daily means (Boer et al., 2000) for a grid node at 46°39'N, 63°75'W obtained from the Canadian Institute for Climate Studies to statistically downscale the AES40 winds at node 5678 (see Section 4.2.10.2.3 for more details). The relationship between wind speed and significant wave heights in the 1954–2004 hindcast (Figure 71) was then used to calculate the future wave heights for the 2000–2100 period.

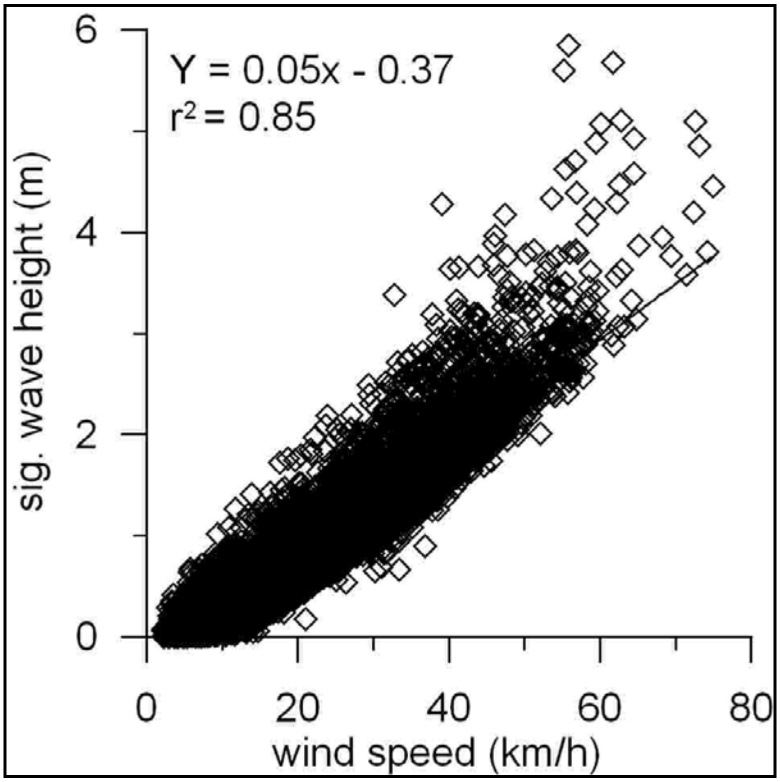


Figure 71. Daily mean significant wave height versus wind speed at node 5678, 1954–2004.

Results

Figure 72 shows that downscaled waves do not exhibit the variability of hindcast waves. This is a result of downscaled winds not reflecting the variability in hindcast winds. Like that of winds, no future trend is apparent. However, the comparison shows that in the hindcast waves after 1971, wave heights become zero in the winter season (January–April), suggesting that in the absence of ice, waves would be no different in the future than they are today.

Ice is, however, present today and restricts winter wave fetch and heights (see Figure 69). The main climate-change issue affecting southeastern New Brunswick may be an ice-free southern Gulf of St. Lawrence, wherein winter waves are able to form, thus lengthening the active erosion season.

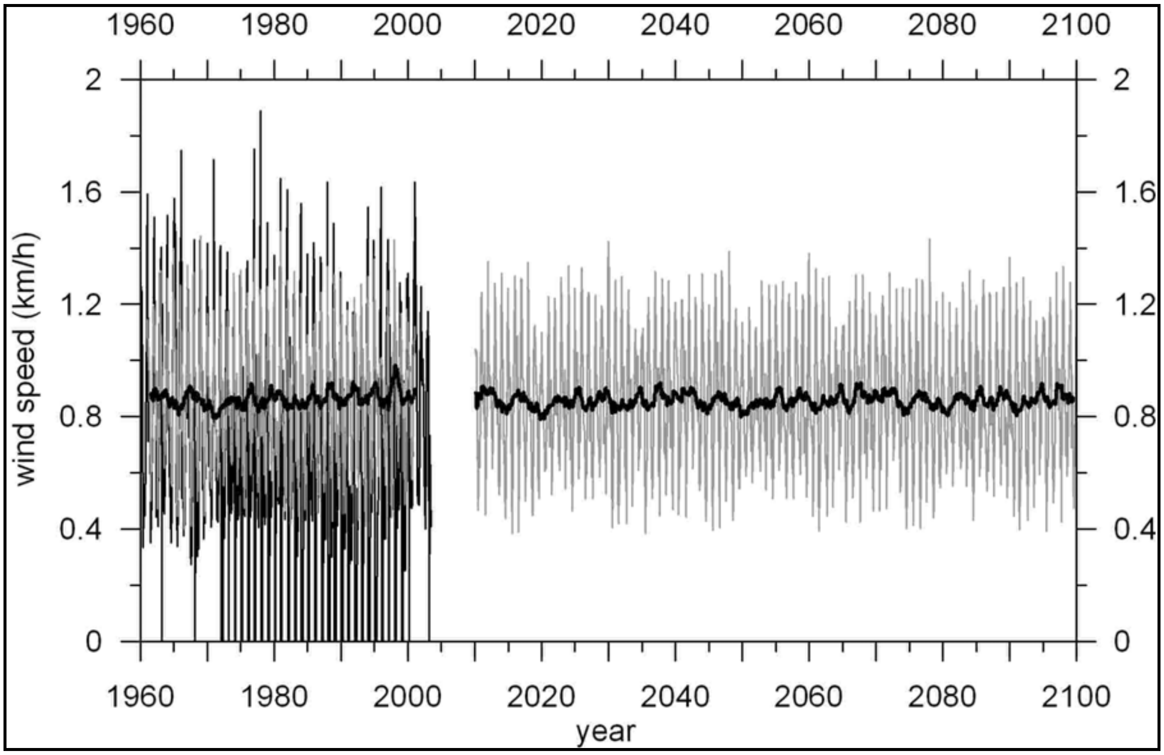


Figure 72. Downscaled monthly mean significant wave heights between 1961 and 2100 with AES40 monthly mean significant wave heights between 1960 and 2003. Similar to winds, extreme events are not well forecast. Prior to 1972, AES40 hindcasts do not include ice, nor do waves derived from downscaled winds.

4.2.11 Sea-ice climatology

Melting of sea ice and glaciers in the Arctic predicted by global climate-change scenarios will be partly responsible for the predicted future sea-level rise in the Gulf of St. Lawrence. Also, the presence of sea ice in the Gulf of St. Lawrence is known to have a dampening effect on waves and on wave-related impacts associated with storm surges. Thus, coastal erosion and wave-associated flooding are expected to increase if sea ice in the Gulf decreases, as is predicted in future global climate-change scenarios.

In 2002, for a similar study of coastal impacts of climate change and sea-level rise on Prince Edward Island, the Canadian Ice Service (CIS) provided an up-to-date climatology of sea ice in the Gulf of St. Lawrence. Interannual and interdecadal variability of the ice cover were examined, and an ice severity index was derived. This information is required for quantitative studies of the effects of sea ice on storm surges and waves.

For the current study for the southeastern coast of New Brunswick, the same sea-ice climatology for the Gulf of St. Lawrence still applies and is presented. New and up-to-date sea-ice severity indices are derived, and interannual variability for the area of interest is presented.

4.2.11.1 Current sea-ice climatology in the Gulf of St. Lawrence

Ice conditions in the Gulf of St. Lawrence have been monitored by CIS since the late 1950s to support shipping activities. Daily ice charts depicting ice concentrations and thickness are prepared using visual observations from shore and ship reports, aerial reconnaissance and (more recently) remote sensing data from airborne and space-borne sensors. Since 1968, CIS has also prepared weekly regional ice charts depicting ice conditions over the Gulf and Canadian east coast. These weekly regional ice charts for the period 1971–2000 are used in this study to describe the current climatology of ice conditions in the Gulf of St. Lawrence.

4.2.11.1.1 CIS digital charts database and climatic products

The CIS weekly regional ice charts for the period 1971–2000 were digitized in vector format, and a GIS software package was used to generate a set of weekly statistical products. A subset of these weekly products is presented here to describe the climatology of sea ice in the Gulf of St. Lawrence:

- maps of freeze-up and break-up dates (Figures 73 and 74);
- dates of ice formation from the first appearance of ice in the Gulf until maximum ice cover is reached and ice disintegration from maximum ice cover until complete disappearance of ice. Ice formation is defined to occur when the concentration is 1/10 or more (i.e., 10% or more of the area is covered by ice). Ice disintegration occurs when ice concentration starts decreasing from its maximum value;
- maps of total concentration (Figures 75A–82A);
- median concentration of ice over the Gulf for various dates from the start of the ice season to the end of the ice season;
- maps of predominant ice type (Figures 75B–82B);
- median values of the predominant ice type when ice is present in the Gulf of St. Lawrence for the same dates as above from the beginning to the end of the ice season.

A review of Figures 73–82 allows us to describe the ice climatology in the Gulf of St. Lawrence.

4.2.11.1.2 Normal ice formation

Ice starts forming in early to mid-December in the St. Lawrence River and estuary as well as coastal shallows of New Brunswick; in the second half of December, ice starts forming in coastal areas of Northumberland Strait, which becomes completely ice covered by the end of the month. By the end of December, ice also forms in the Strait of Belle Isle, as well as along the north shore of the Gulf of St. Lawrence. During January, ice formation progresses eastward across the Gulf more rapidly than it progresses southward from the north shore and covers most of the Gulf except the southern portion of the western Newfoundland coast by the end of January. The entire Gulf is affected by the end of February.

4.2.11.1.3 Normal ice concentrations and thickness

By January 1, grey ice in concentrations 9–9+ is typically found in Northumberland Strait. By January 15, the grey ice extends to the North Shore of Prince Edward Island, and the ice in Northumberland Strait has become grey-white. By the end of January, concentrations in most of the Gulf are 9–9+ (except the southern portion of the west Newfoundland coast), and the thickness has grown to grey-white in the southern half, while first-year ice appears in Northumberland Strait. Ice continues to grow in thickness during February; the entire southern half of the Gulf is first-year thickness by the end of the month, and concentrations are 9–9+ over the whole Gulf.

4.2.11.1.4 Normal melting of ice

At the beginning of March, concentrations begin to decrease, starting in the St. Lawrence River and spreading to the estuary and northwest portion of the Gulf by the middle of March. During the second half of March, concentrations decrease in the middle of the Gulf. Ice cover in Northumberland Strait decreases during the last week of March, and low concentrations are found by the beginning of April. By mid-April, most of the ice in the Gulf is cleared except for the Northern Arm, where ice will remain until the third week of May. Note that as the thinner forms of ice melt first, the remaining thicker forms are predominant, as shown in our charts.

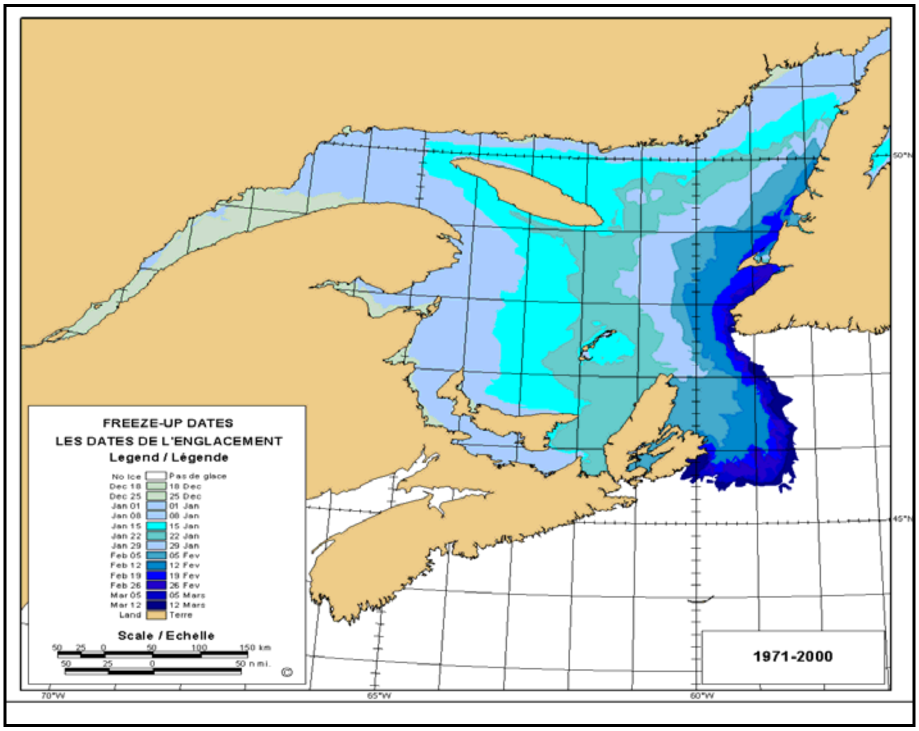


Figure 73. Normal freeze-up dates.

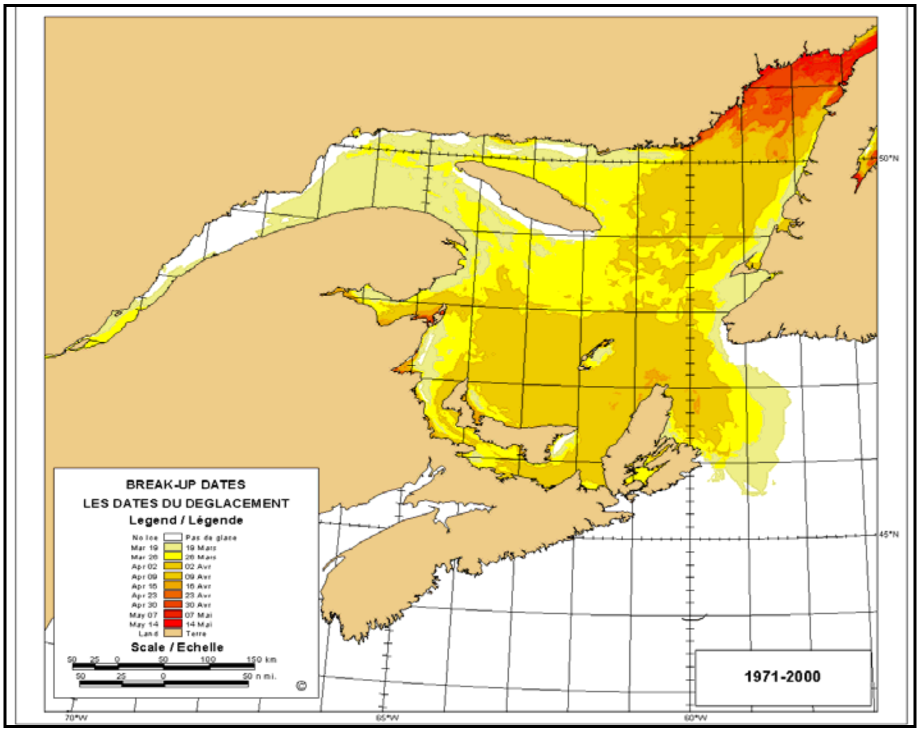


Figure 74. Normal break-up dates.

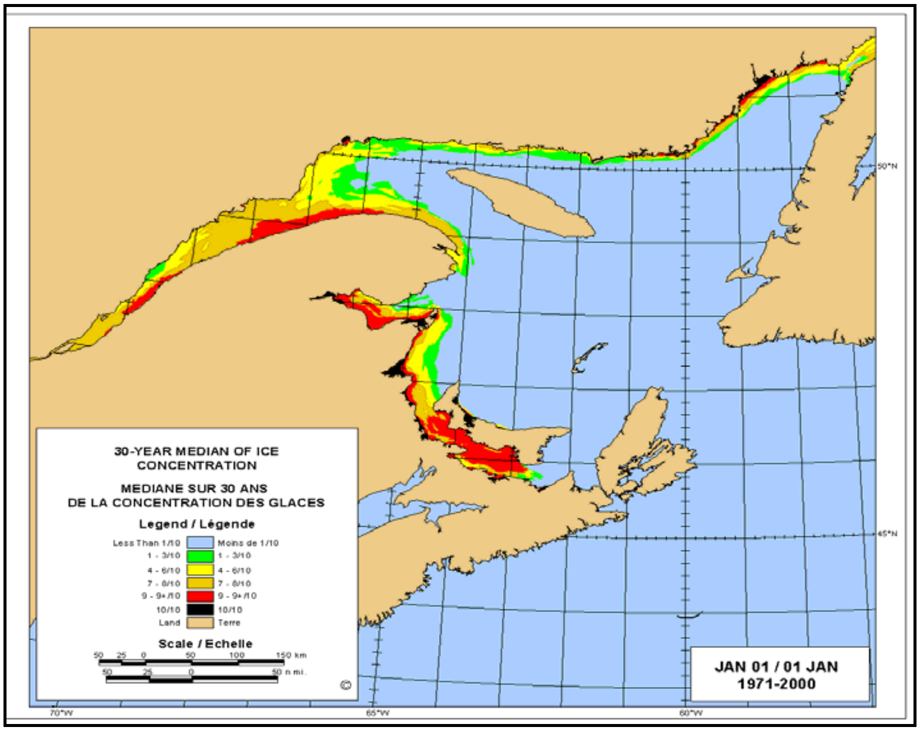


Figure 75A. 30-year median of total ice concentration (1971–2000) — January 1.

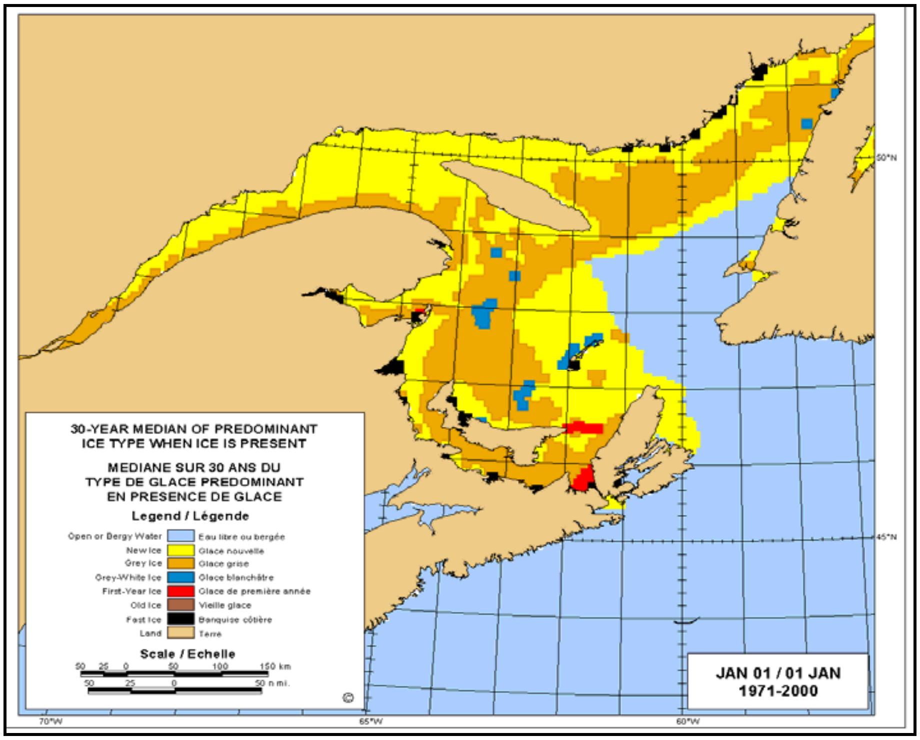


Figure 75B. 30-year median of predominant ice type when ice present (1971–2000) — January 1.

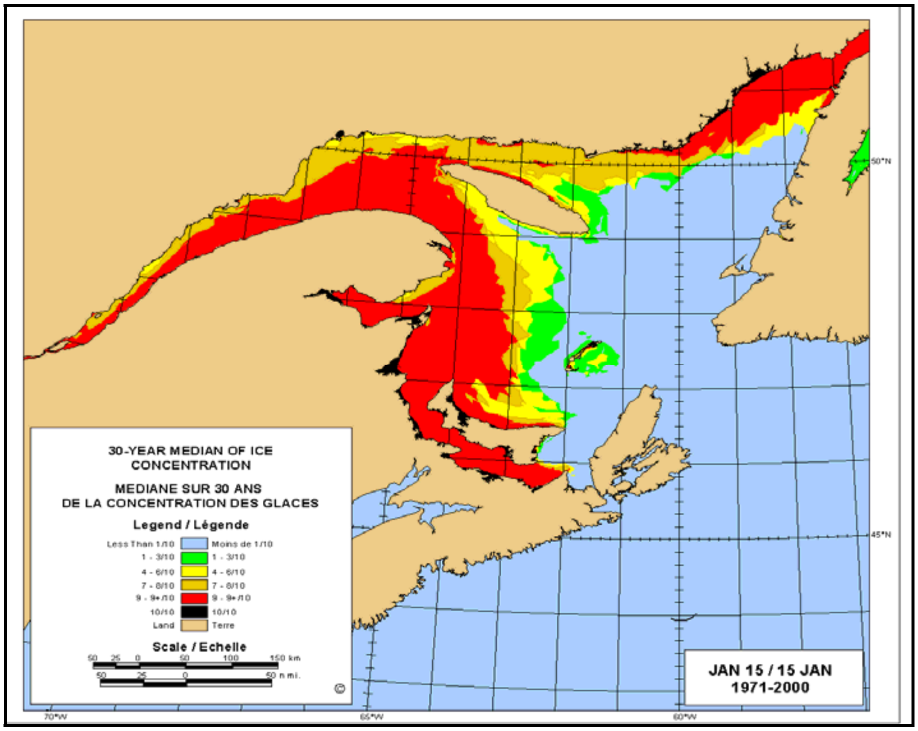


Figure 76A. 30-year median of total ice concentration (1971–2000) — January 15.

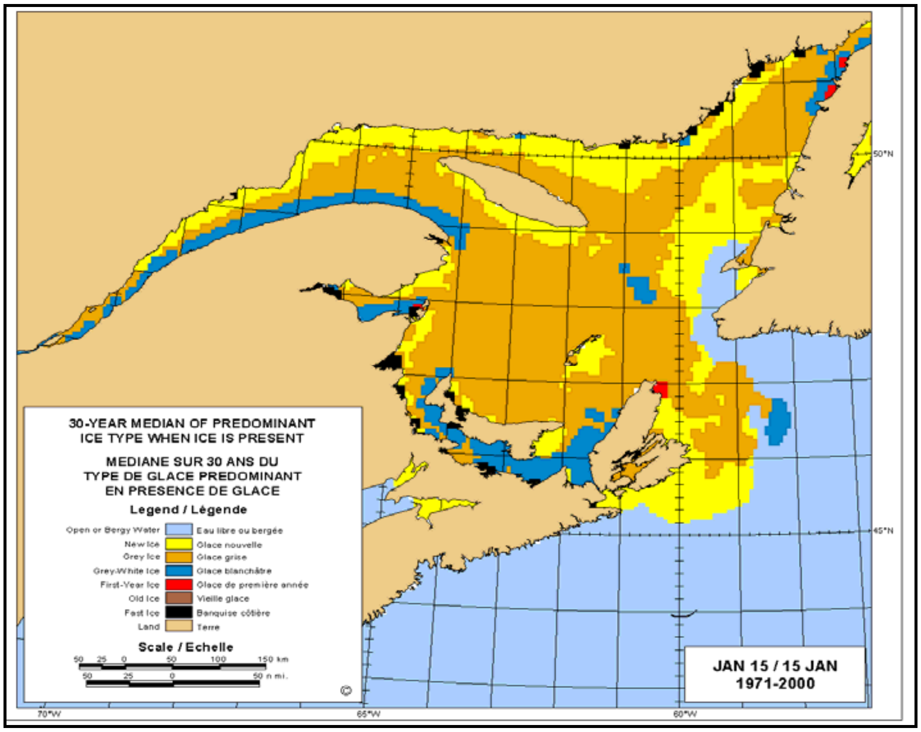


Figure 76B. 30-year median of predominant ice type when ice present (1971–2000) — January 15.

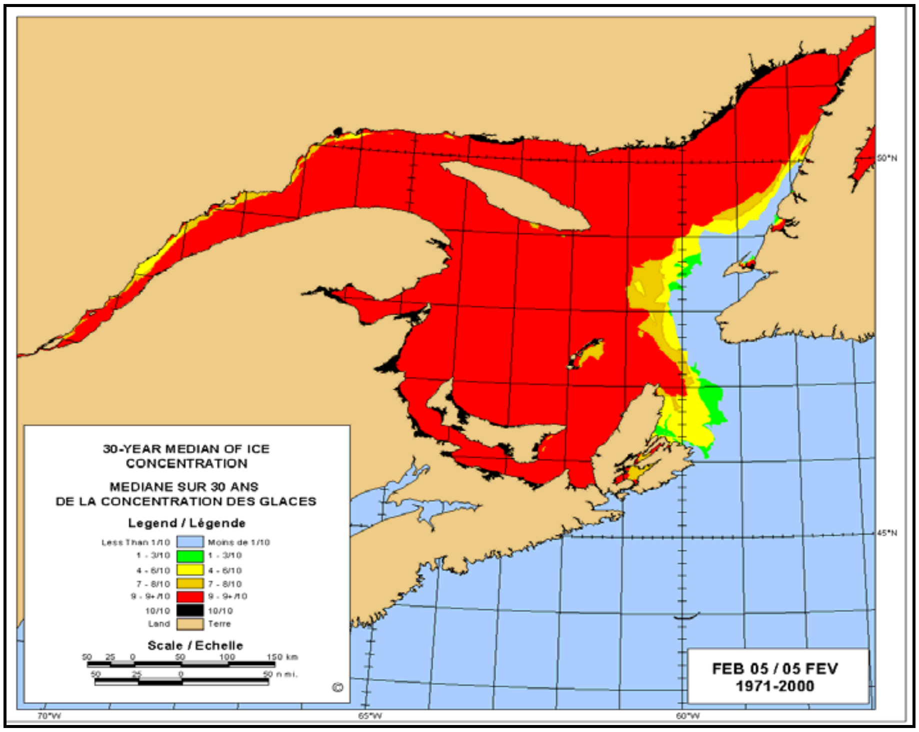


Figure 77A. 30-year median of total ice concentration (1971–2000) — February 5.

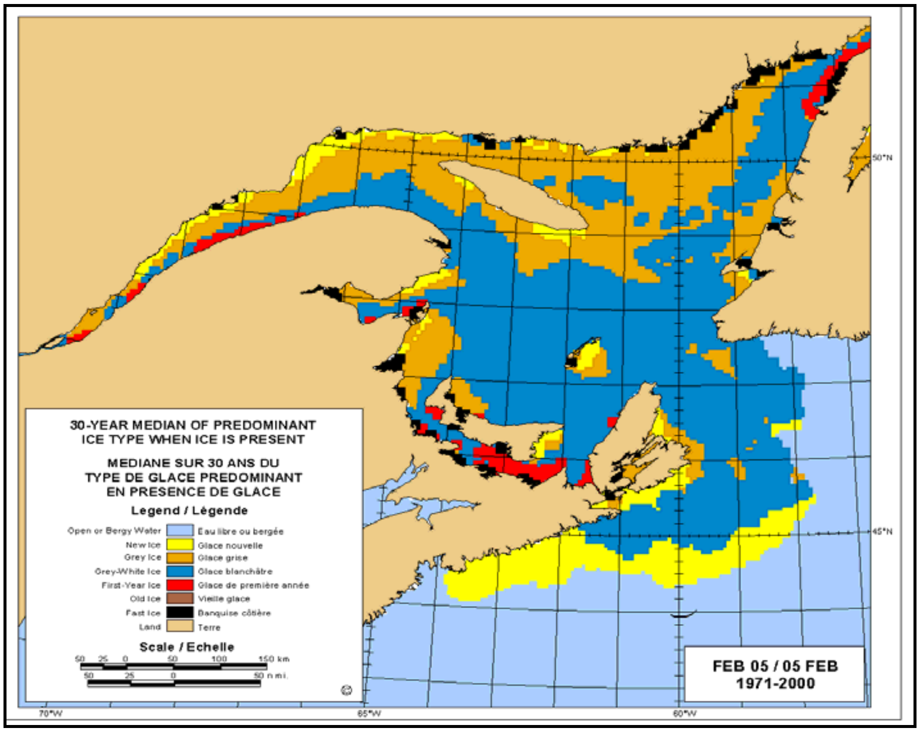


Figure 77B. 30-year median of predominant ice type when ice present (1971–2000) — February 5.

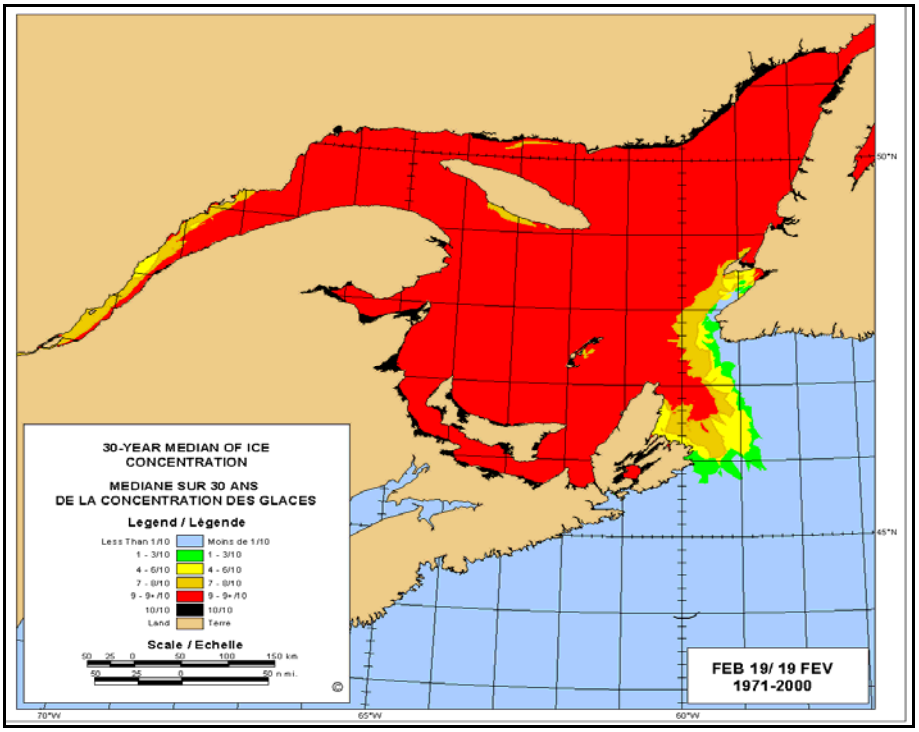


Figure 78A. 30-year median of total ice concentration (1971–2000) — February 19.

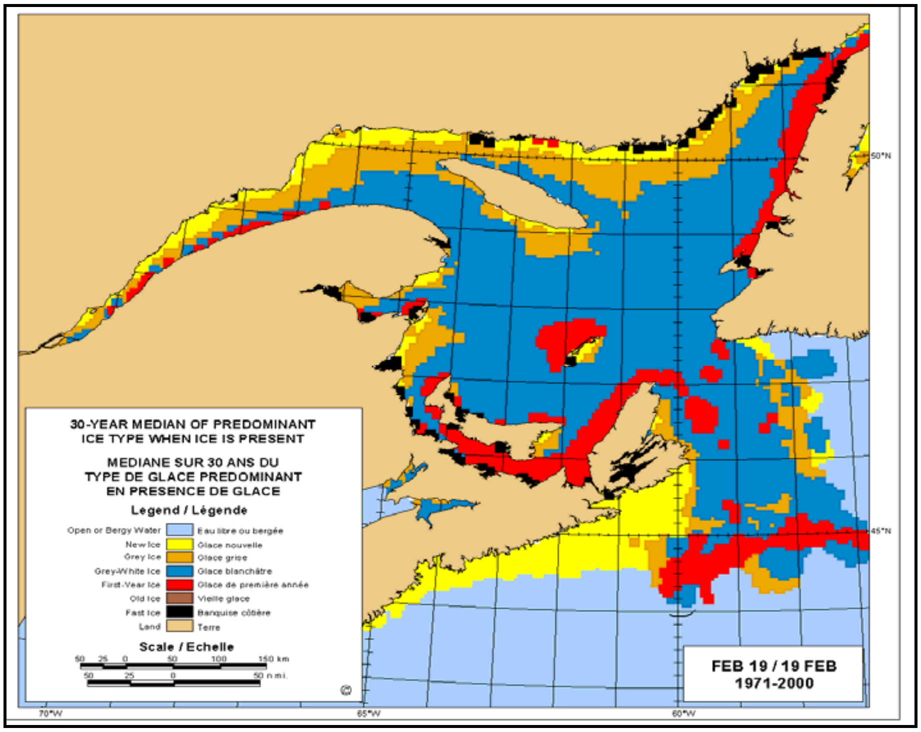


Figure 78B. 30-year median of predominant ice type when ice present (1971–2000) — February 19.

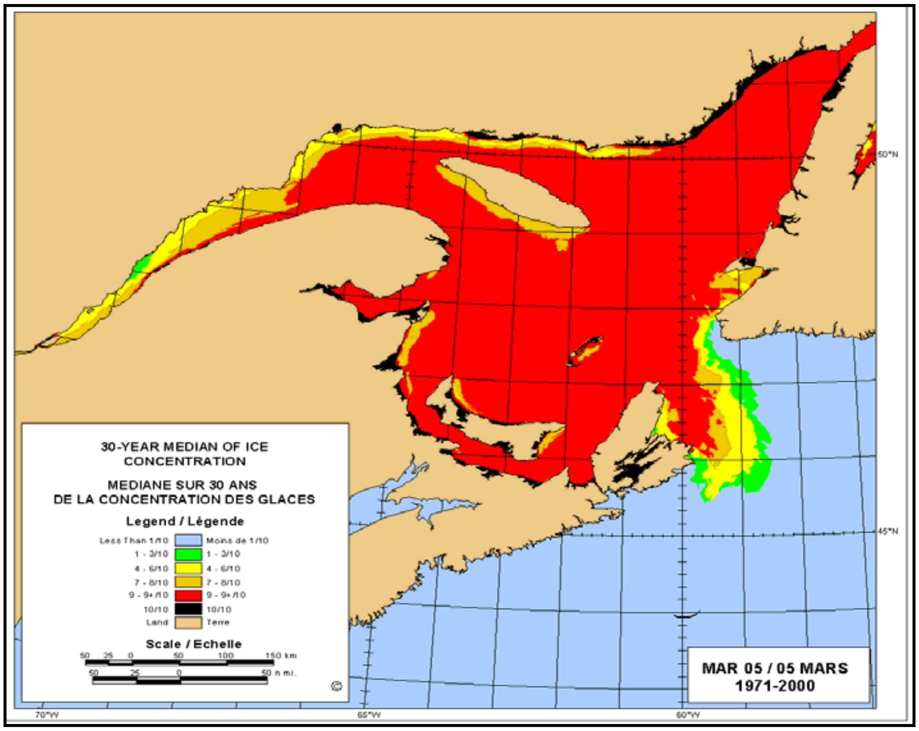


Figure 79A. 30-year median of total ice concentration (1971–2000) — March 5.

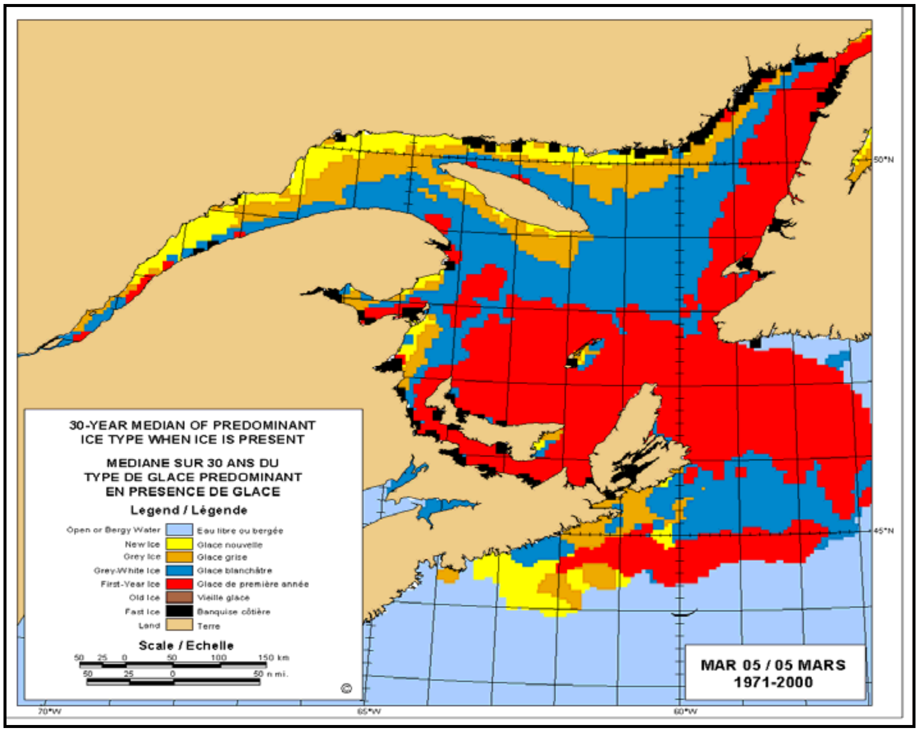


Figure 79B. 30-tear median of predominant ice type when ice present (1971–2000) — March 5.

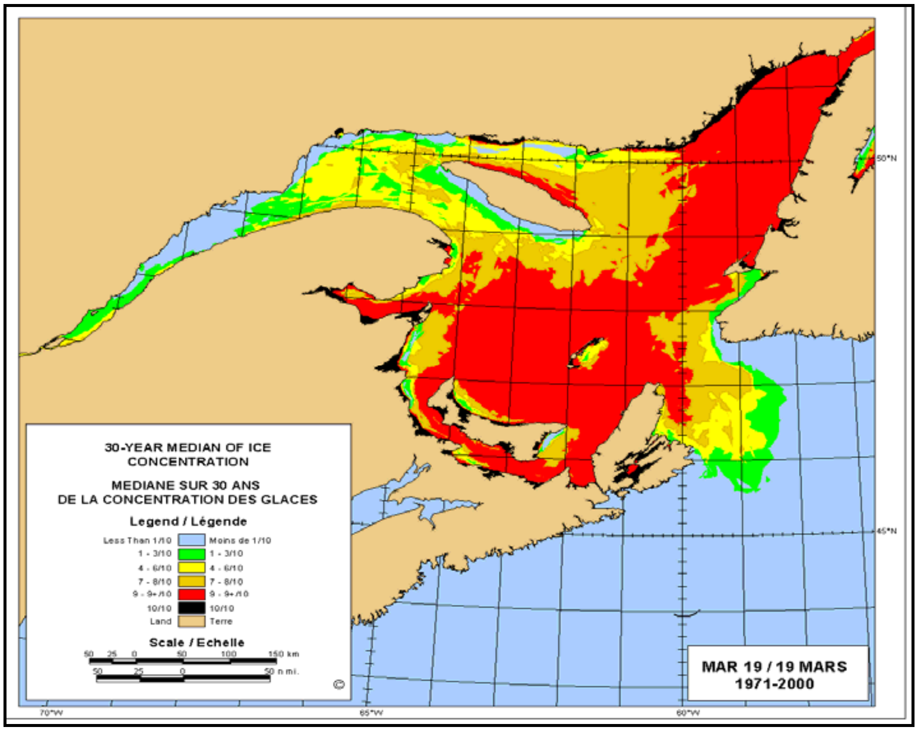


Figure 80A. 30-year median of total ice concentration (1971–2000) — March 19.

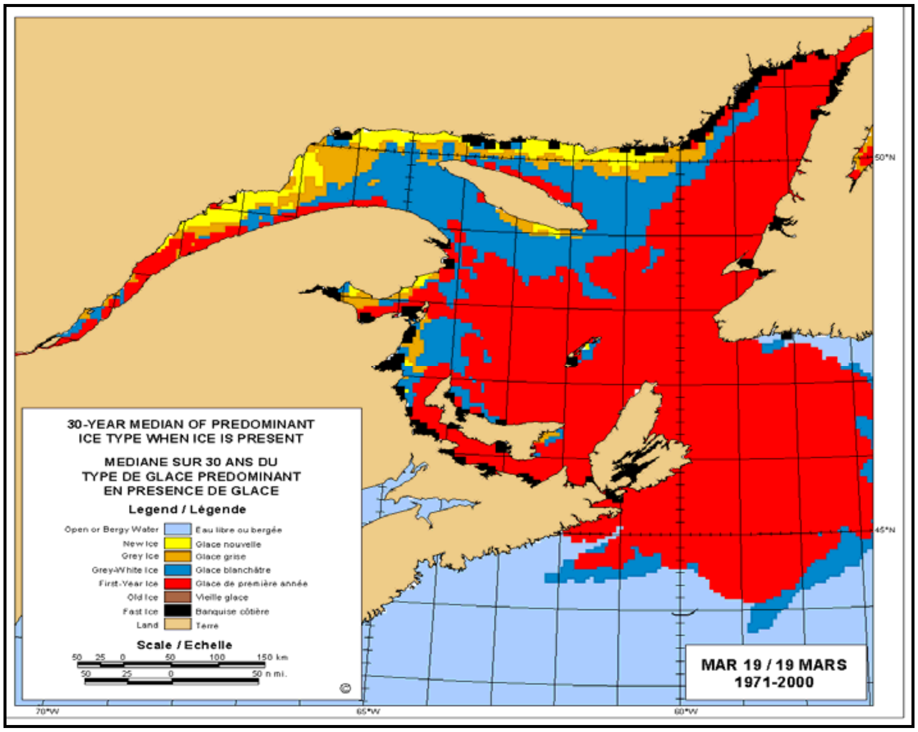


Figure 80B. 30-year median of predominant ice type when ice present (1971–2000) — March 19.

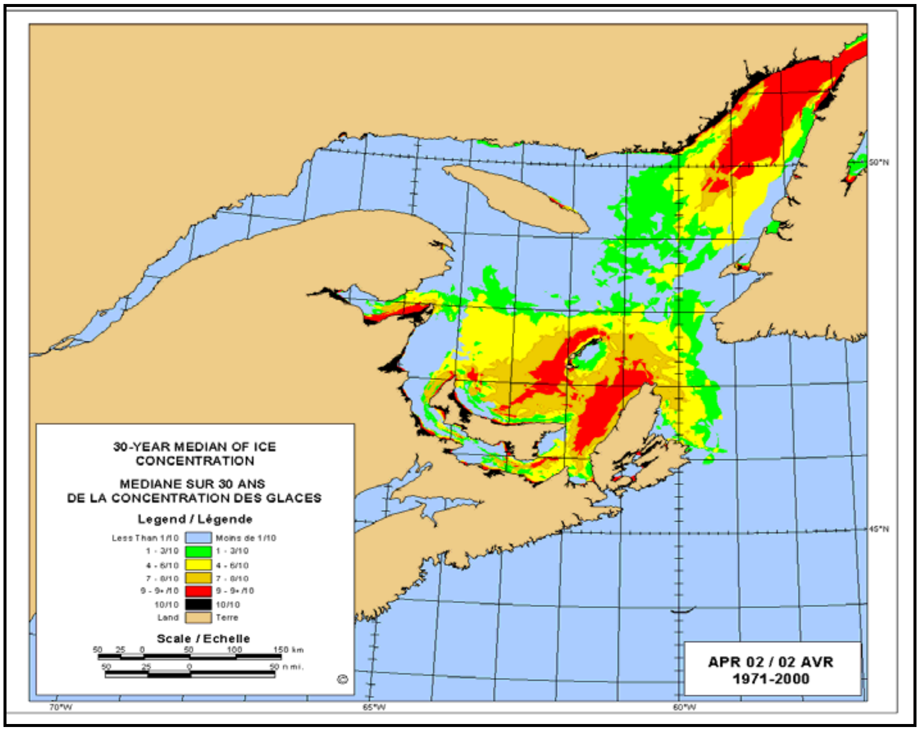


Figure 81A. 30-year median of total ice concentration (1971–2000) — April 2.

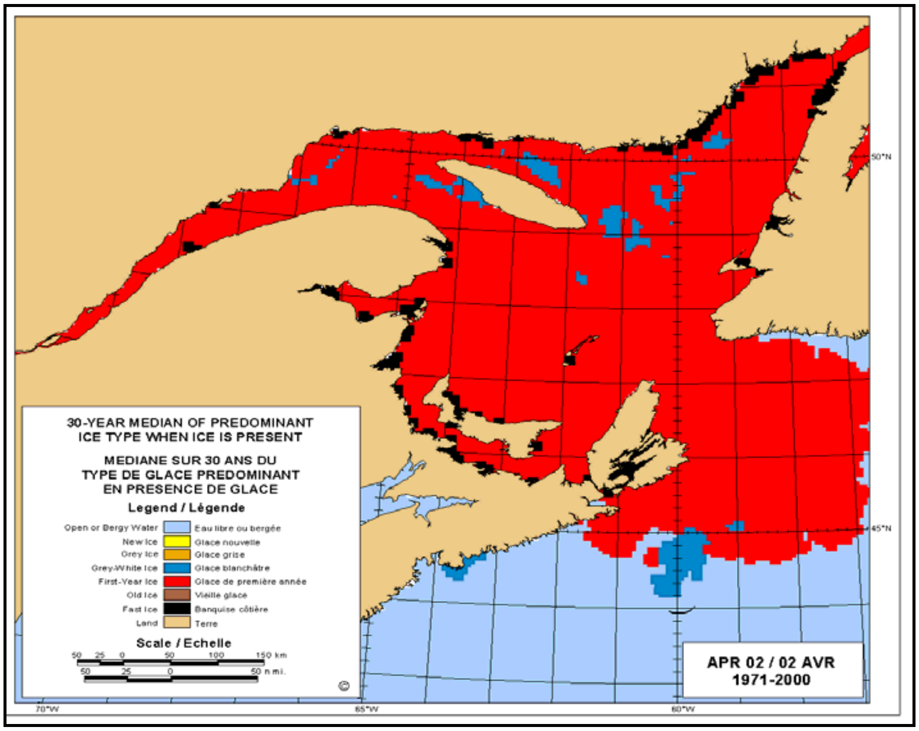


Figure 81B. 30-year median of predominant ice type when ice present (1971–2000) — April 2.

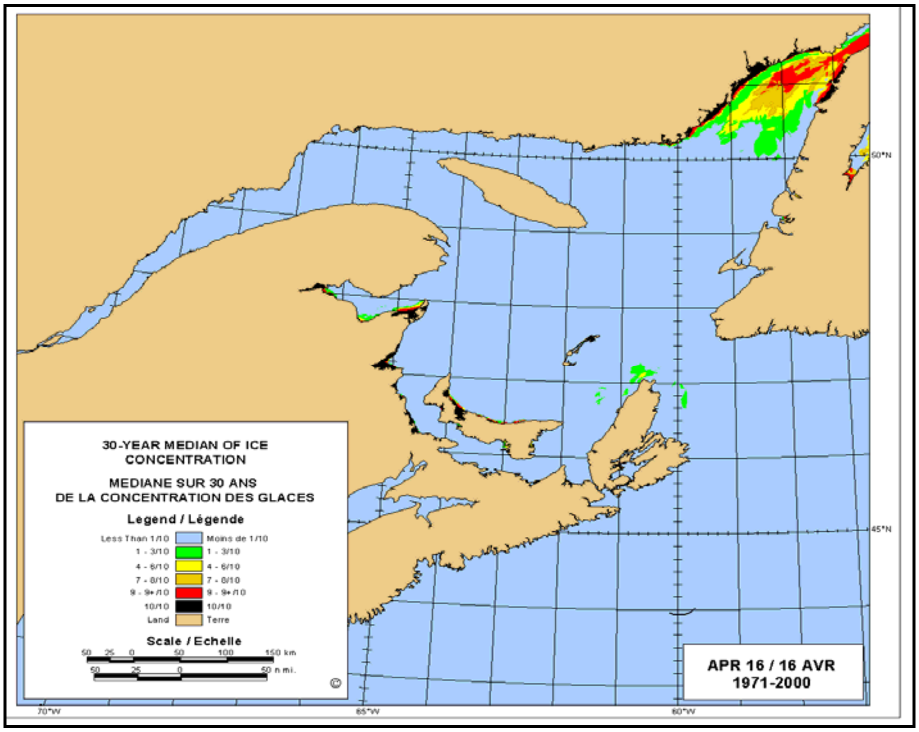


Figure 82A. 30-year median of total ice concentration (1971–2000) — April 16.

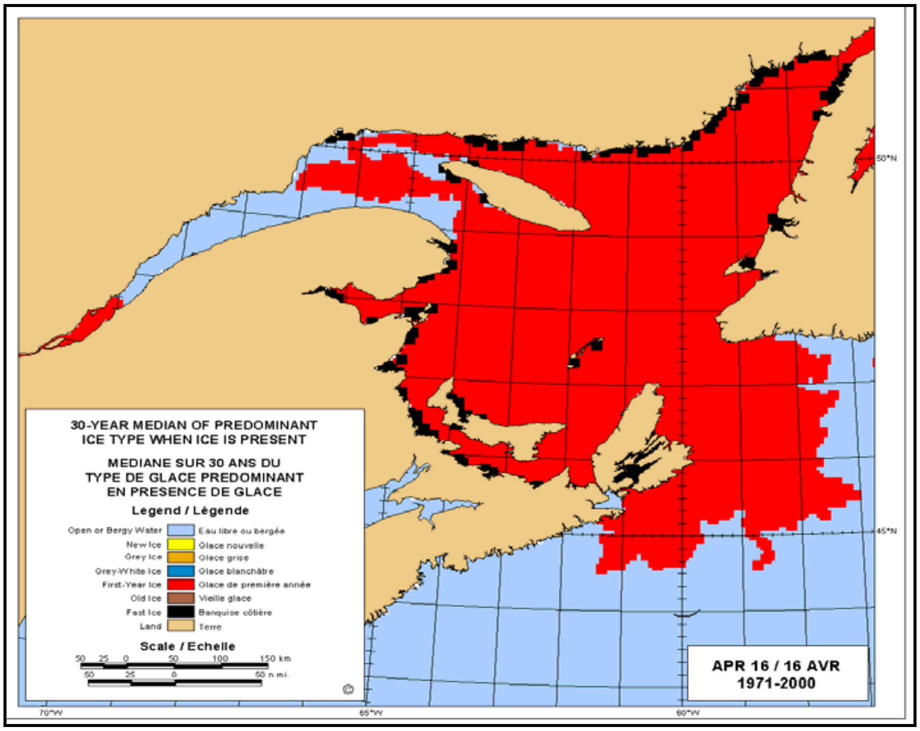


Figure 82B. 30-year median of predominant ice type when ice present (1971–2000) — April 16.

4.2.11.2 Interannual and interdecadal variability of ice cover

The ice information given above describes the median or normal conditions over the 30-year period of study, 1971–2000; however, the ice cover is highly variable from one year to another, as can be seen from Figure 83, representing the total accumulated ice coverage (TAC) over the Gulf for each individual year for the period 1971–2005. The TAC is expressed as a percentage of the area covered by ice and calculated by summing all individual weekly ice-coverage data (area in square kilometres × average concentration) from the beginning to the end of the season (November 26 to July 16 for southern areas) and normalizing.

The TAC can be used as an ice-severity index for the whole season. A quick glance at Figure 83 shows extreme values ranging from 7.5% (1999–2000) to close to 20% (1989–1990). We also see that 1998–2000 were low-ice years, but we had a similar situation in the early 1980s, and the TAC has been rising again since 2000.

Although the number of years is small, Figure 83 also seems to indicate the presence of cycles in the variability of the TAC, with approximate periods of 15–20 years and maxima in the mid-1970s and again in early 1990s. These cycles in regional ice conditions and their relationship with the North Atlantic Oscillation (NAO) and the El Niño have been examined before (Mysak et al., 1996; Prinsenberg et al., 1997). Mysak et al. (1996) observed that simultaneous NAO/El Niño events tend to be associated with above-average sea-ice extent in the Labrador Sea. CIS has investigated correlations between ice coverage in the Gulf and various environmental parameters (Ballicater, 2000). This preliminary study investigated possible links between various ice parameters and environmental parameters such as NAO, solar flux and volcanic eruptions. In this last study, some correlation was observed between the TAC in the Gulf of St. Lawrence and the NAO. A stronger correlation with NAO was observed with landfast ice, but TAC is preferred because of the uncertainty in observing landfast ice.

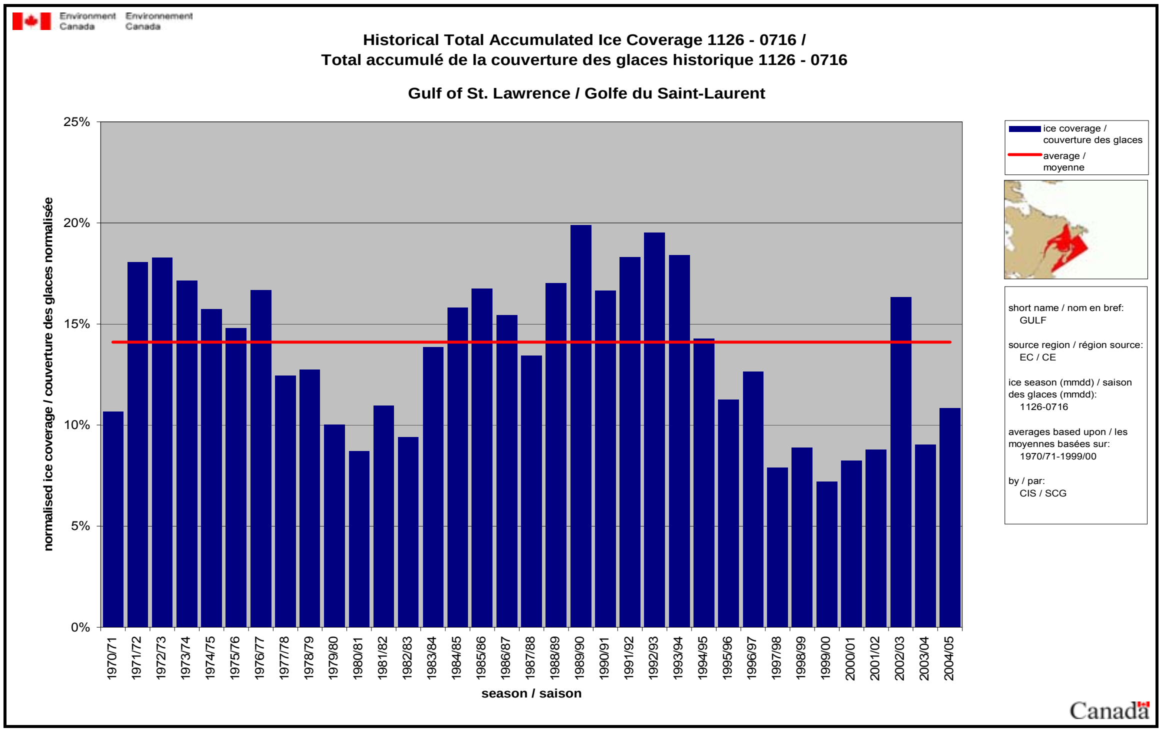


Figure 83. Total accumulated ice coverage for the Gulf of St. Lawrence, 1971–2005.

4.2.11.3 Impacts of ice on waves and storm surges

It is generally agreed that the presence of sea ice has a dampening effect on both the wave action causing erosion and wave-associated flooding during elevated water levels caused by storm surges. The exact impact that sea ice has on storm-surge magnitude is not fully known and is debated in the literature, although its impact, under most circumstances, is not thought to be large. In the 2002 study for Prince Edward Island (McCulloch et al., 2002), we attempted to investigate these relationships by calculating weekly ice coverages for the period 1971–2000 for four areas: Gulf of St. Lawrence, Magdalene shallows, North Shore of Prince Edward Island and Northumberland Strait.

In the 2002 study, the coverage was calculated by including all ice types and concentrations of 1/10 and more. It was also assumed that the dampening effect of ice could be found if only particular ice conditions were included in the coverage, such as first-year ice and/or ice with concentrations of 3/10, 5/10 or more, fast ice, ice volumes, etc. This was to be investigated in future studies. Also, it seems that not all storms of similar intensities will cause the same high water levels at a location under the same ice conditions. Further work is required to clarify the storm climatology before adequate investigations of the impacts of ice can be done.

In the present study, we have concentrated on the Northumberland Strait area and the month of January for our calculations of weekly ice coverages. Furthermore, we have also broken down the coverage by ice type because we think that not only the cover but also the thickness of the ice should play an important role in the dampening effect. Figures 84–88 show the historical ice coverages by type for the years 1969–2005 on January 1, 8, 15, 22 and 29, respectively. Great variability is observed in the ice cover during the first week of January. It is also interesting to note that even though the region is almost 100% ice covered for most years on January 29, the actual types of ice can vary greatly. Attempts to correlate storm surges with the presence of sea ice should take the ice type into account.

Even though this study did not attempt to determine the exact correlation of ice with storm surges and wave erosion, it is clear that the presence of ice has a dampening effect on wave-associated impacts and that in a future climate with reduced or no ice in the Gulf, the storm-surge impacts and rates of coastal erosion are expected to be more severe.

Other impacts of ice that were not addressed in this study include:

- direct damage caused by ice being carried onto the coast by wind stress and ice pressure; and
- the implications of a future warmer climate with little or no ice in the Gulf, leading to loss of the seasonal protective barrier against wave erosion afforded by the icefoot and nearshore landfast ice complex.

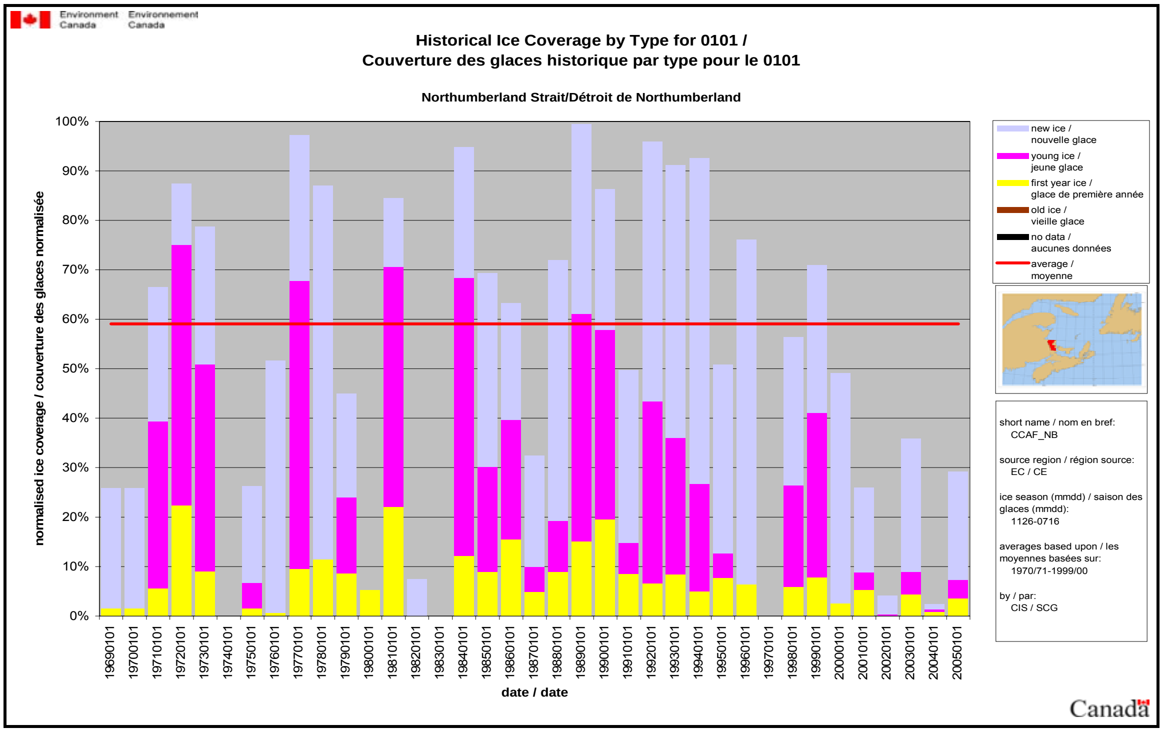


Figure 84. Historical ice coverage by type, January 1.

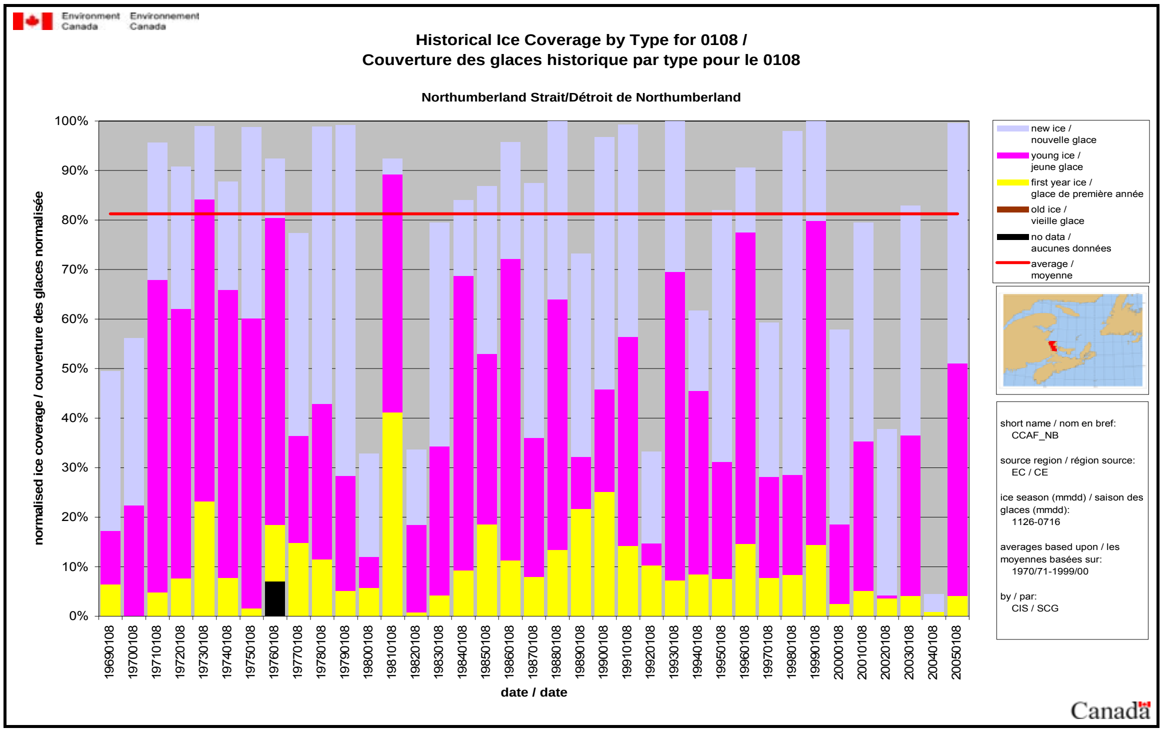


Figure 85. Historical ice coverage by type, January 8.

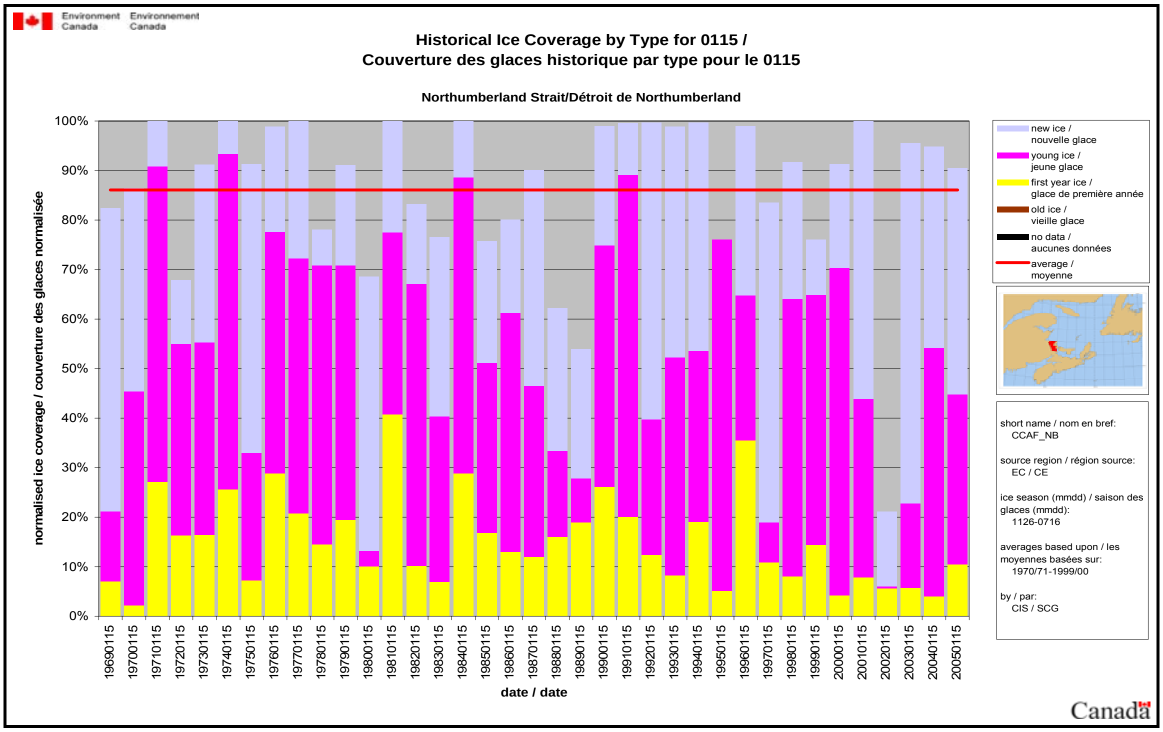


Figure 86. Historical ice coverage by type, January 15.

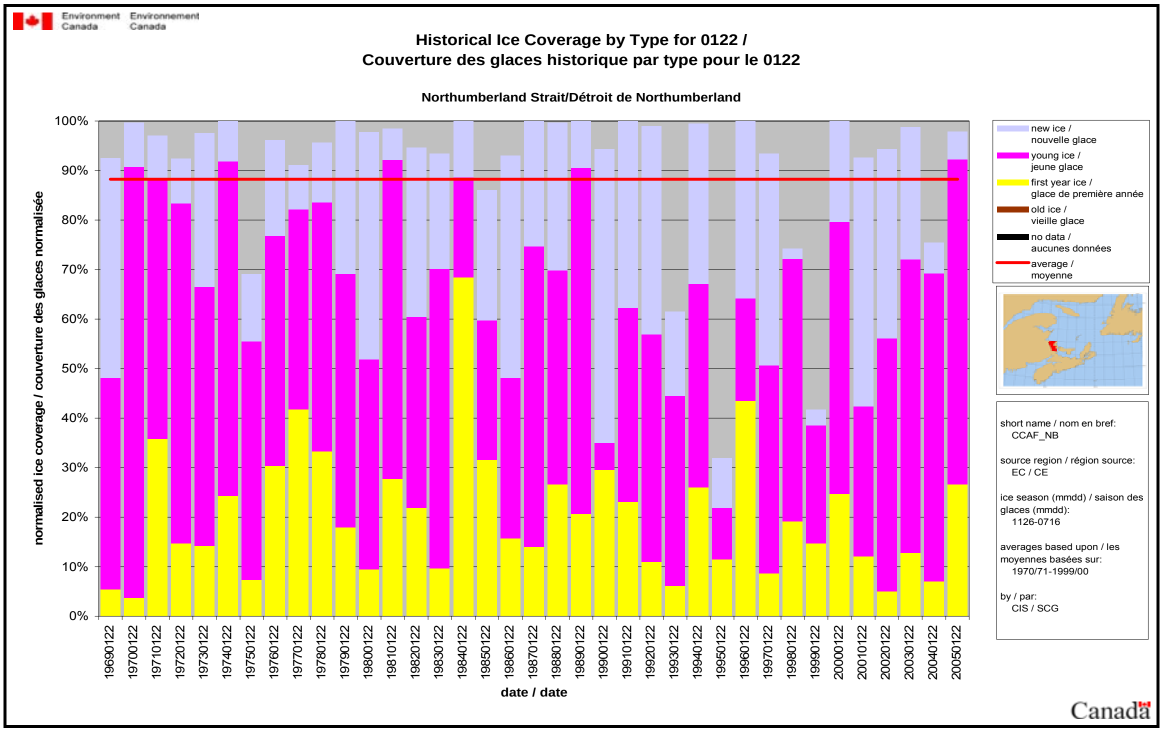


Figure 87. Historical ice coverage by type, January 22.

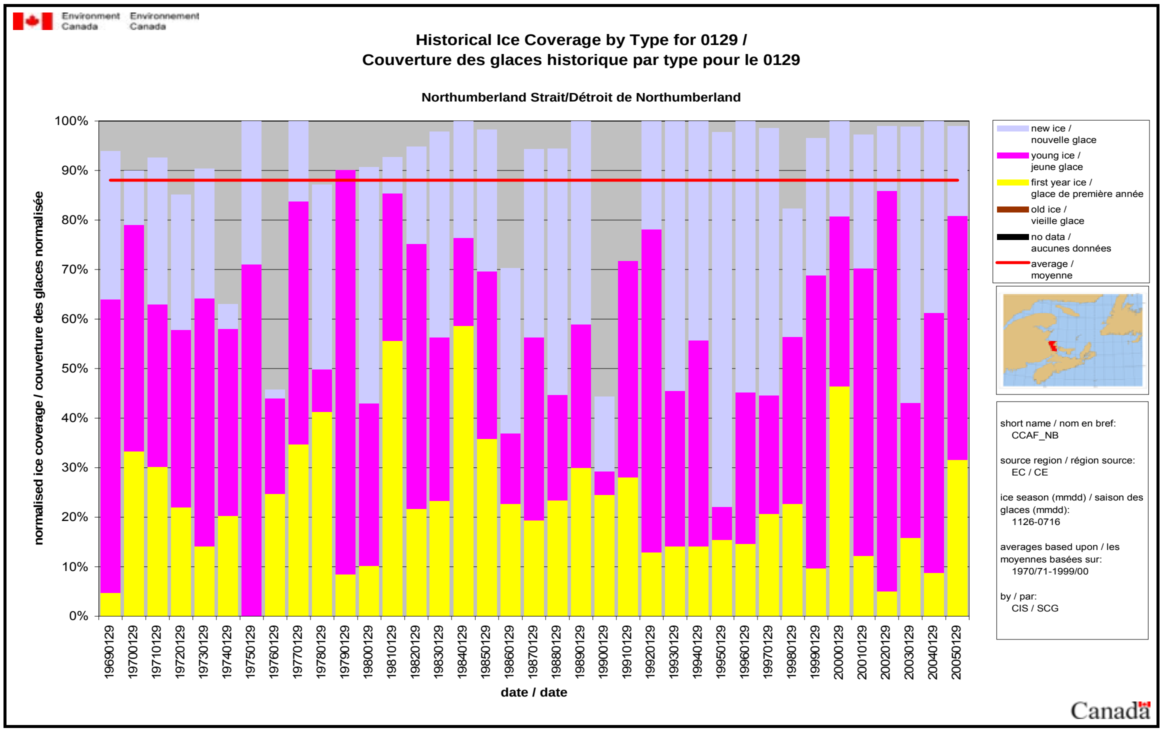


Figure 88. Historical ice coverage by type, January 29.

4.2.11.4 Trends and future ice climatology

The latest results of the Canadian Global Climate Model (GCM) indicate that by the year 2050, the ice extent in the northern hemisphere will be limited to higher latitudes and that the Gulf will be free of ice (Flato and Boer, 2001). Other researchers, however, have argued that this model may lack the necessary resolution to adequately resolve this issue in the Gulf of St. Lawrence, and more recent evidence suggests that decreases in sea ice in the Gulf of St. Lawrence will be greatest in the north and less significant in the south (Francois Saucier, pers. comm.). In the 2002 Prince Edward Island sea-level-rise study, we attempted to determine the existence of trends using the TAC and found a slight decrease in the TAC for the period 1971–2000 (which, however, is not statistically significant). The Ballicater (2000) study, using 1969–1998 data, also investigated short- and long-term trends of ice cover in the Gulf of St. Lawrence and showed a slight increase in ice conditions. These conflicting results demonstrate that the number of years of data remains statistically inadequate and the addition of just two years of data can apparently change the results.

In the present study, we have extended our period for the calculation of the TAC, and it now covers the period 1971–2005. This is shown in Figure 89, where we can still see a negative trend for the TAC.

The Ballicater (2000) study also shows that it is possible to predict ice conditions in the short term; a statistical regression model accounting for the current-year ice conditions and environmental parameters (NAO, solar flux, freezing degree-days, volcanic forcing anomaly) can be used to model the slow trend and the observed cycles in ice conditions in the short term.

We have also extended the period to 2005 in attempting to determine trends for the length of the ice season, as shown in Figure 90. The start date and end date of the season are defined as the dates at which ice coverage reaches 10% and ice coverage reduces below 10% of the total area, respectively. Figure 90 still shows a slight reduction of the length of the ice season, but, again, it is not statistically significant.

In summary, our records do show slight tendencies of decreasing ice conditions in the Gulf of St. Lawrence, but they are not as significant as the ones found in the Arctic. These tendencies cannot be used to predict long-term future ice conditions. This means that we have not yet started observing the predicted decrease in ice cover in the Gulf as we have in the Arctic. The GCM does predict the decrease to occur, and our observations indicate this decrease could just be slower than it is in the Arctic.

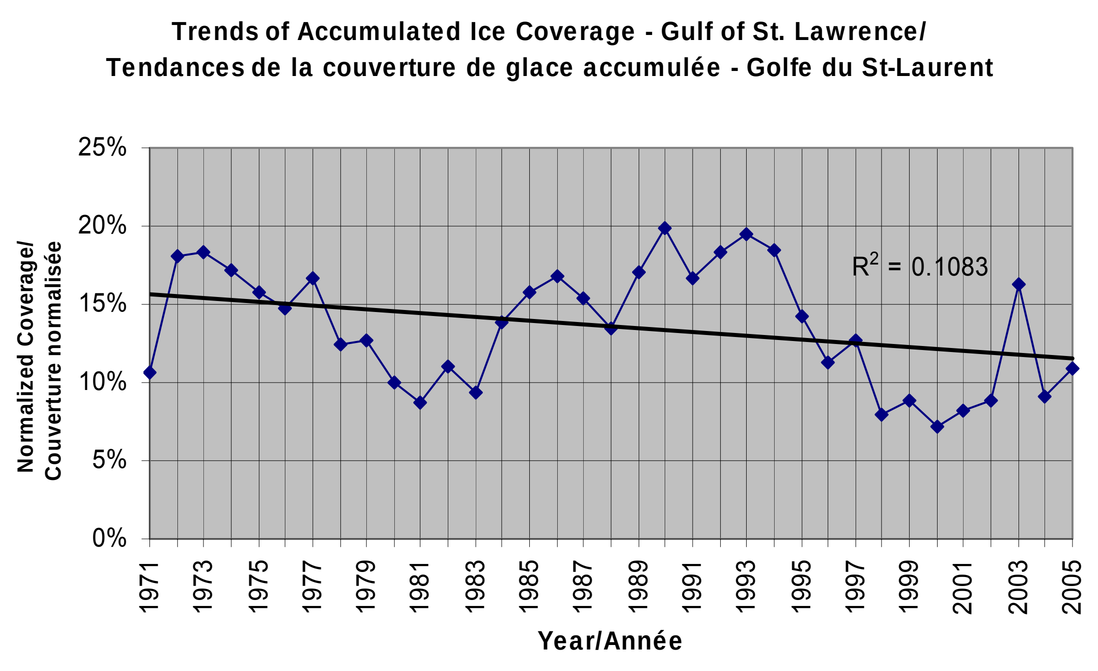


Figure 89. Trend of accumulated ice coverage, Gulf of St. Lawrence.

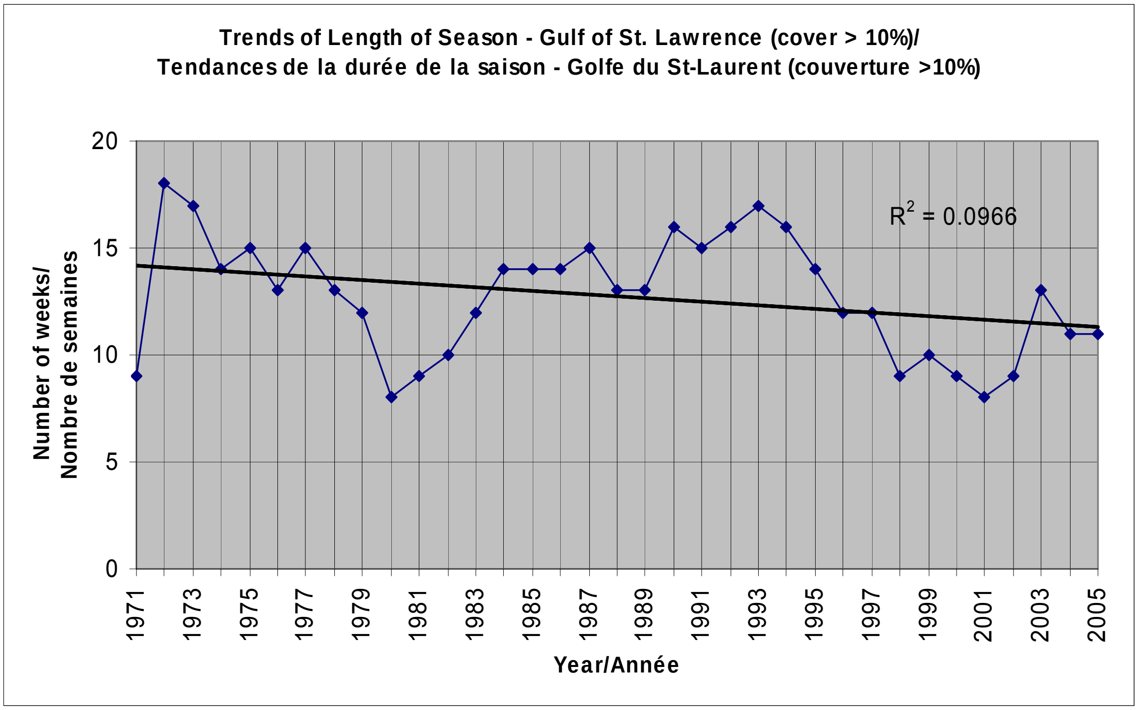


Figure 90. Trend of length of season, Gulf of St. Lawrence.

4.2.12 Summary and conclusions

The entire digital inventory of water-level data in the southern Gulf of St. Lawrence was examined in this report to establish the storm-surge climatology of the project study area and to identify extreme storm surges and water-level events. Most storms affecting the southern section of the study area have impacts elsewhere in the Northumberland Strait. The long-term Charlottetown data are therefore crucial to this study, since they allow for an assessment of storm conditions through the decades and demonstrate both the fundamental importance of the storm of January 21, 2000, and the fact that sea-level rise has already played a role in extreme water levels through the period of the data.

The tide-gauge record at Charlottetown is one of the longest available in eastern Canada; it goes back to 1911 and is very complete back to 1938. The water-level record at Escuminac goes back to 1973, but, when combined with earlier records from nearby Pointe-Sapin, goes back to 1963 (43 years). Water-level data from Pointe-du-Chêne are more limited and span the period from 1971 to 1992. The Pointe-du-Chêne tide gauge was re-established for the purpose of this project, and new data from 2003 to 2006 were collected, capturing some very important storms.

Storm-surge events in excess of 60 cm were extracted from the Charlottetown water-level record, taking sea-level rise into account and interpolating where possible for missing events from data at adjacent tide-gauge sites. These events were then collated by decade (1940s to 1990s), by half-decade, by year and by month.

Water-level data from 1960 to 1998 were chosen to represent the storm-surge climatology for Charlottetown. Generally speaking, storm surges above 60 cm are frequent events in Charlottetown, occurring about eight times a year on average (compared with, for instance, about two or three times a year on average along the Atlantic coast in Halifax). Storm surges of 100 cm or more occur on average about once a year. Storm-surge events above 120 cm are uncommon and occur on average about three times a decade. No events were found in excess of 160 cm. Storm surges at Charlottetown are mainly associated with the stormy period of the late fall and winter. Averaged statistics show an increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there are few occurrences in the period from May to September. Storm surges show great variability in frequency from one year to the next, owing to the great range in frequency, severity and track of the storms themselves. Decadal statistics indicate that the storm surges at Charlottetown appear to have become somewhat more frequent from the 1940s to the 1960s and that the larger surges (>120 cm) did not occur at all in the 1940s and 1950s (nor in the somewhat incomplete data prior to that), but show up thereafter. The 1960s, 1970s and 1980s were strong storm-surge decades, with more than two 80-cm events on average each year, and the 1980s showed more than one 100-cm event on average each year. The 1990s generally saw fewer storm surges, although there were a few particularly big events. Many large storm-surge events have shown up since the year 2000. Half-decade statistics draw attention to the fact that some periods are more active than others, particularly the early 1960s and the late 1980s, which were periods of climatologically more frequent northeasterly gales. The period since 2000 has also been very active.

On January 21, 2000, a fierce winter storm caused extensive flooding of coastal areas in southeastern New Brunswick and all along Northumberland Strait, including Pointe-du-Chêne and the downtown waterfront areas of Summerside and Charlottetown in Prince Edward Island. In Charlottetown, this storm brought a new record water level of 4.22 m above CD, which exceeded the previous record (set exactly 39 years earlier) by 39 cm. This storm (and the flood levels it reached through the region) is the definitive benchmark flooding event for this project. Other extreme storm-surge and water-level events have been identified at Charlottetown, and the water-level data have been systematically adjusted to the year 2000 to demonstrate the impacts that sea-level rise, through the period of the existing data, has already had on extremes of water level and on coastal flooding. When sea-level rise is taken into account, the difference between the new and old record water levels at Charlottetown is reduced to 27 cm.

A storm-surge climatology has also been developed for the Escuminac/Pointe-Sapin area just to the north of the present study area (using 28 years of data) and for Pointe-du-Chêne (using 15 years of data). Storm surges at Escuminac/Pointe-Sapin are similar in frequency, timing and size to those at Charlottetown for the period 1960–2004. On average, there are about seven events each year in excess of 60 cm, with close to one event each year above 100 cm. There is great variability in frequency from one year to the next, with no obvious trend. Nine storm surges above 120 cm have been identified at Escuminac/Pointe-Sapin for the period 1963–2005, compared with 13 events at Charlottetown for the period 1960–2005. The very large storm surges were a little more frequent at Escuminac, with three events in excess of 150 cm identified (not including the storm of January 21, 2000), as opposed to two at Charlottetown. The largest recorded storm surge was 160 cm in height on March 17, 1976. These storm surges are mainly associated with the stormy period of the late fall and winter. As at Charlottetown, there was an observed increase in frequency in October and November, with peak activity in December and January. Frequency declines significantly in April, and there were few occurrences in the period from May to September.

Storm surges at Pointe-du-Chêne are larger and more frequent than those at Escuminac or Charlottetown, although their distribution through the year is, of course, similar, since they are usually caused by the same storms. Ten events above 60 cm are observed per year on average, with two to three events above 100 cm per year on average. Storm surges above 150 cm occur once every two or three years, and storm surges as high as 200 cm have been recorded (198 cm on March 17, 1976, and 200 cm on January 21, 2000), representing the largest recorded storm surges in Atlantic Canada known to the authors of the present report.

With global warming, sea-level rise is forecast to accelerate. As storms come and go in the coastal zone, large storm surges will eventually phase with sufficiently large tides to produce new record water levels in the study area and at Charlottetown. Additionally, with time, flooding at any given lower level will increase dramatically in frequency, and this point is demonstrated quantitatively at Charlottetown and Pointe-du-Chêne through an exceedance count of the existing data (adjusted for sea-level rise) above various thresholds.

Synoptic weather maps were examined for storms that have given rise to storm surges of 90 cm or more at Charlottetown and 110 cm or more at Pointe-du-Chêne, and track maps were produced. These storms are mainly extratropical marine storms that deepen explosively off the east coast and pass to the east of the study area, usually accompanied by a period of northeasterly or northerly gale- or storm-force winds across the Gulf of St. Lawrence. The geometry of these storms is usually favourable for bringing large seas into the study area (in the absence of sea ice). The history of tropical cyclones in the study area has been examined using the U.S. National Hurricane Center's hurricane database (HURDAT) or "best tracks" (1851–2004). Although less common than extratropical storm events, tropical cyclones can be very powerful and occur during the tropical weather season (June to November). when there is no wave protection from sea ice. Historically, tropical storms have been an important contributor to the ongoing process of coastal erosion in the region.

The highest water levels at the tide-gauge sites of Charlottetown, Escuminac/Pointe-Sapin and Pointe-du-Chêne were used to identify the benchmark storms of the last 40 years, and these are presented as case studies, with emphasis on storm impacts. The case studies illustrate, among other things, the important protective role that sea ice plays during the winter months and draw attention to the enhanced rates of coastal erosion that are probable with a shorter ice season in a future warmer climate. The case studies also illustrate the importance of the storm-surge forecasting program to emergency response and short-term mitigation and the value of LiDAR data in real-time flood mapping.

A brief literature survey of flooding events in the area serves to highlight other important storms that predate the tide-gauge data and reminds us that flooding and coastal erosion in the study area are ongoing processes and that damage to coastal infrastructure is nothing new.

It is clear that the flood levels observed during the storm of January 21, 2000, are close to the maximum levels that can be reached in today's climate. However, this storm occurred at a time when the shoreline was protected by sea ice. The storm of October 29, 2000, in comparison, was accompanied by very large waves on elevated water levels and was very damaging to shorelines and coastal infrastructure. It is the worst storm that we know of in the last 40 years in terms of wave damage and coastal erosion. Conditions would have been considerably worse if the storm had been in phase with the higher high tide of the day. Worse circumstances in terms of wave damage can therefore occur today and may indeed have occurred in the past, and we do not need the addition of sea-level rise due to climate change to achieve this.

Measured and hindcast records of wind speeds and directions and of wave heights and periods (with directions, as available) were investigated to identify the winds and wind events that are most important in forming waves affecting the shorelines of the southern Gulf of St. Lawrence, to identify any trends in past storminess and forcing of coastal erosion in the study area and to attempt to predict future forcing to 2100.

Winds that appear most effective at generating waves impacting the study area are from the northeast and are associated with the passage of tropical, transitioning or extratropical low-pressure systems typically tracking to the north and northeast. These tend to occur during the autumn and winter months, but they are effective at generating waves only during the ice-free months, when effective fetch is longest. We investigated the AES40 wind data set for a node at the entrance to western Northumberland Strait.

Notable periods of high frequency of occurrence of northeasterly autumn winds greater than 40 km/h include 1960, 1962–1966, 1967–1968, 1970, 1974–1982, 1985, 1987–1989, 1991, 1993, 1998–2001 and 2004. We identified 58 wind events with winds over 40 km/h for at least six hours, occurring in the autumn and with mean northeasterly directions. The annual occurrence of these events shows an apparent increasing trend.

Wave buoys deployed as part of this study captured three important wave events affecting the study area: December 7, 2003; Sub-tropical Storm Nicole (October 11–12, 2004); and December 27, 2004. These northeasterly wind events brought waves up to 4.8 m significant height and 10.0-second peak period. The arrangement of the buoys allows demonstration that waves entering western Northumberland Strait decrease in height towards the south and east.

A wave hindcast record near the western entrance to the Strait indicates that periods of increased occurrence of waves greater than 3 m from the northeast in the autumn occurred in 1960–1966, 1968, 1970, 1974, 1977–1981, 1986–1988, 1991, 1998–2000 and 2003–2004. A list of 53 autumn events with waves greater than 3 m for at least six hours and mean northeasterly directions was developed and shows no meaningful trend in annual event frequency since 1960.

Daily mean AES40 wind speeds were used to statistically downscale general circulation model scenario variables and predict wind speeds to 2100. Wind directions were not successfully downscaled. The results suggest that no significant change in wind speeds is expected to occur; however, as the variance in wind speed was underpredicted, this is not indicative of extreme events. An overall decrease in event frequency is suggested, but this is expected to be accompanied by an increase in frequency of the most extreme events. Using the downscaled wind speeds and the correlation of wind speed to wave height in the hindcast data set, we determined that wave heights are also not expected to change significantly to 2100. Similarly to winds, however, wave height variance was not well predicted, and extreme wave events are not represented. Wave events will likely follow a scenario similar to that for winds, with an added complication.

Wave formation is currently dampened in the winter months by sea ice. We describe a scenario in which sea ice is expected to decrease in the southern Gulf of St. Lawrence. This will allow winter storms to generate waves, thus increasing the overall frequency of wave events and the frequency of severe events.

Based on the ice charts from CIS, we developed an accurate climatology of sea ice in the Gulf of St. Lawrence. Examination of the TAC in the Gulf shows high interannual variability, as well as some cycles that can be associated with the NAO and other environmental parameters.

Our records also indicate a decreasing trend in ice cover and duration of the ice season, which, however, is not statistically significant. It is believed that the presence of ice has a dampening effect on storm surges and waves that cause flooding and erosion. Ice severity indices have been calculated and should be used in studies attempting to demonstrate this relationship quantitatively.

Even though this study did not attempt to determine the exact correlation of ice with storm surges and wave erosion, it is still a qualitative observation that the presence of ice has a dampening effect. We therefore surmise that in a future warmer climate with reduced ice concentration and thickness in the Gulf of St. Lawrence, storm surges and wave erosion may be more severe.

Other issues that were not addressed in this study include direct damage caused by ice being carried onshore by wind stress and ice pressure, as observed in the January 21, 2000, storm; and implications of the potential loss of the seasonal protective barrier of landfast ice in a future warmer climate.

4.2.13 References

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4.2.15 Attachments

4.2.15.1 Attachment A: Charlottetown monthly missing data in percent

1960–2005

1960–1974 (quality controlled)

%	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Jan	0.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	99.9	0.0	0.0	0.0	0.0
Apr	0.0	0.0	13.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	0.0	0.0	0.0	0.0
May	0.0	0.0	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jun	41.3	9.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	4.8	3.4	0.0	0.0	29.0	0.0	0.0	0.0	0.0	0.0	99.9	0.0	0.0	0.0	0.0
Aug	0.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.1	35.5	0.0	0.0	0.0
Sep	0.0	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7	29.9	36.7	0.0	0.0
Oct	2.8	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	0.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	99.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1975–1989 (quality controlled)

%	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Jan	0.0	33.9	53.6	41.0	61.8	0.0	0.0	15.1	0.0	99.9	0.0	0.0	0.0	0.0	0.0
Feb	0.0	30.7	26.6	0.0	84.4	0.0	2.7	9.8	0.0	0.7	0.0	0.0	0.0	0.0	0.0
Mar	0.0	37.9	10.6	0.0	2.3	0.0	8.1	0.1	0.0	2.7	0.0	0.0	0.0	0.0	28.4
Apr	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	36.9
May	0.0	0.0	9.5	0.0	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.6
Jun	0.0	0.0	22.1	24.0	99.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	16.9	0.3	56.9	49.7	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	100.0	56.2	16.3	0.1	27.7	0.0	0.0	37.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	75.6	0.0	42.8	17.9	6.7	0.0	0.1	49.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	0.0	3.6	62.5	0.0	0.0	0.0	0.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	73.2	27.6	0.7	99.9	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	27.2	69.9	15.2	100.0	3.6	0.0	99.9	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0

1990–2005 (quality controlled)

%	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Jan	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Feb	0.0	0.0	0.0	46.3	0.0	0.0	11.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	79.6	0.0	0.0	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.9	0.4	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0	28.4	0.0	14.4	0.0	0.0	8.1	0.0	0.0	1.2	0.3	0.0
Jun	0.0	0.0	0.0	0.0	0.0	35.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	0.0
Jul	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	99.9
Aug	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	100.0
Sep	0.0	0.0	0.0	0.0	0.0	43.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Oct	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.3	0.0	100.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.9	4.4	0.0	15.8	1.7	0.0	100.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	100.0

1911–1959

1911–1923

%	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923
Jan	100	3.2	0.0	0.0	0.0	100	1.6	0.0	99.9	0.1	100	100	0.0
Feb	100	0.0	0.0	0.0	0.0	100	0.0	0.0	100	0.0	100	100	0.0
Mar	100	4.8	0.0	0.0	0.0	100	0.0	0.0	100	0.0	100	100	0.0
Apr	0.1	0.0	0.0	0.0	0.0	100	1.7	0.0	100	0.0	100	100	0.0
May	0.0	0.0	0.0	0.0	99.9	100	0.0	0.0	100	0.0	100	45.3	0.0
Jun	0.0	0.0	0.0	0.0	100	3.5	0.0	0.0	100	49.9	100	0.0	99.9
Jul	0.0	0.0	0.0	0.0	100	0.0	0.0	0.0	100	100	100	0.0	100
Aug	0.0	1.7	0.0	0.0	100	0.0	0.0	0.0	100	100	100	0.0	100
Sep	0.0	0.0	0.0	0.0	100	0.0	0.0	0.0	100	100	100	0.0	100
Oct	0.0	0.0	22.4	0.0	100	0.0	0.0	0.0	100	100	100	0.0	100
Nov	6.5	0.0	5.4	0.0	100	3.3	0.0	0.0	100	100	100	0.0	100
Dec	0.1	0.0	3.2	0.0	100	0.0	0.0	0.0	100	100	100	0.0	100

1924–1936

%	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936
Jan	100	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100
Feb	100	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100
Mar	100	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100
Apr	100	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100
May	100	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100
Jun	100	0.1	99.9	100	100	99.9	100	100	0.0	100	100	100	100

%	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936
Jul	100	0.0	100	100	0.1	100	100	0.1	93.4	100	100	100	100
Aug	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100	100
Sep	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100	100
Oct	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100	100
Nov	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100	100
Dec	100	0.0	100	100	0.0	100	100	0.0	100	100	100	100	100

1937–1949

%	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Jan	100	0.1	0.0	1.6	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jun	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
Sep	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1950–1959

%	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0
Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.0	0.0	0.0	0.0	23.2	0.0	0.0	0.0	0.0	0.0
Oct	0.0	0.0	0.0	0.0	3.4	0.0	0.0	0.0	0.0	0.0
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4.2.15.2 Attachment B: Estimating the water level of October 29, 2000, at Pointe-du-Chêne

Figure B1 shows verification of the Dalhousie storm-surge model as run by Environment Canada for the October 29, 2000, storm at Escuminac. Three model runs are shown beginning on October 27, 28 and 29 at 0000 UTC. The storm surge (although forecast to be significant) was somewhat underpredicted by the model (perhaps due to the strength of the predicted wind), with the most accurate run being on October 29. The predicted water level for the second water-level peak on the afternoon of October 29 (which was when water levels were highest at Pointe-du-Chêne) was out by about 35 cm.

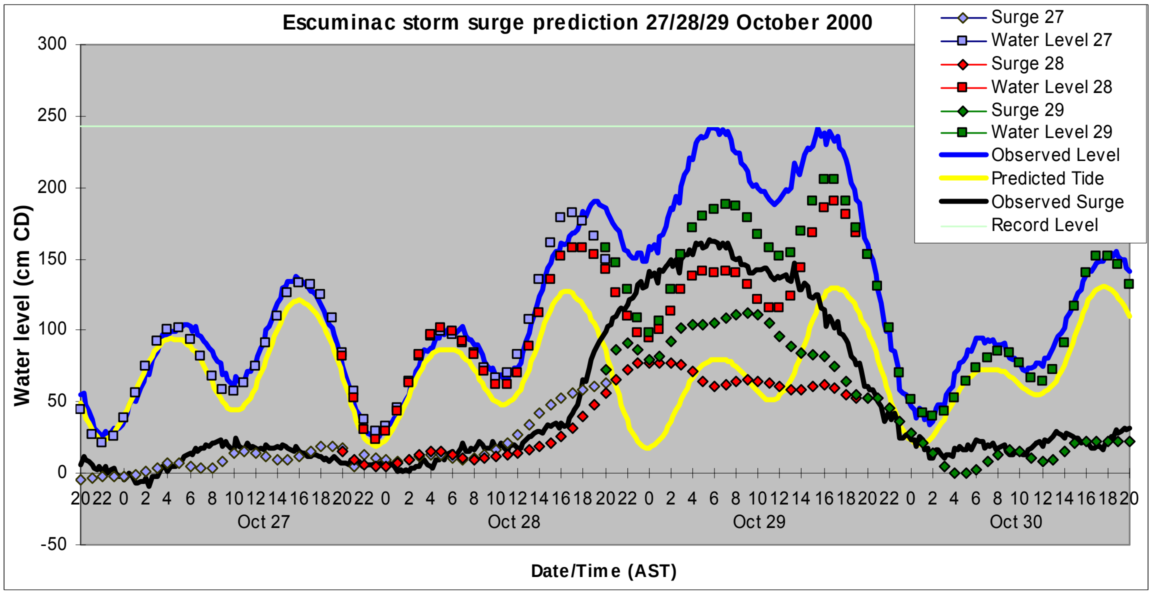


Figure B1. Water-level data and storm-surge model predictions for Escuminac for October 29, 2000.

Figure B2 shows the storm-surge model prediction for Pointe-du-Chêne from the model run of October 29, 2000. Also shown is an adjusted surge, computed by adding the error (the difference between the observed and predicted) in the surge at Escuminac to the Pointe-du-Chêne predicted surge and water level. The storm-surge model prediction gives a maximum surge of 1.43 m and a water level of 2.65 m CD. The adjusted values give a storm surge of 1.91 m and a water level of 3.11 m CD.

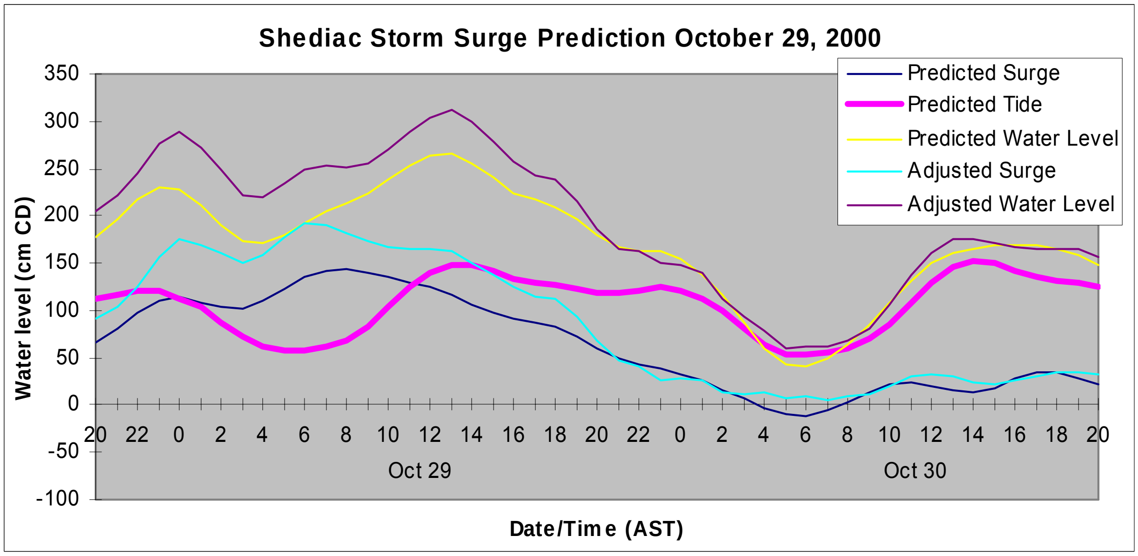
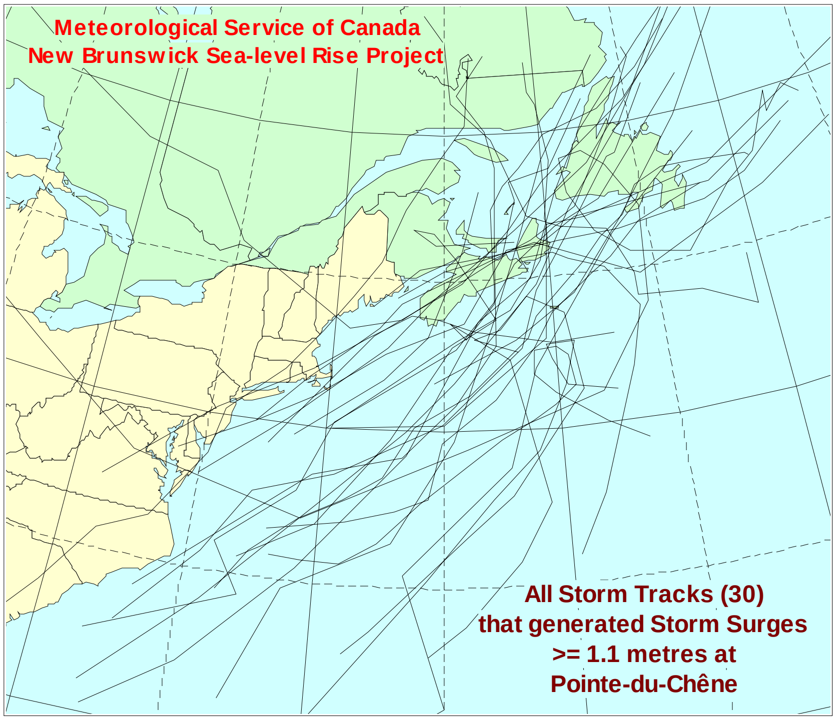
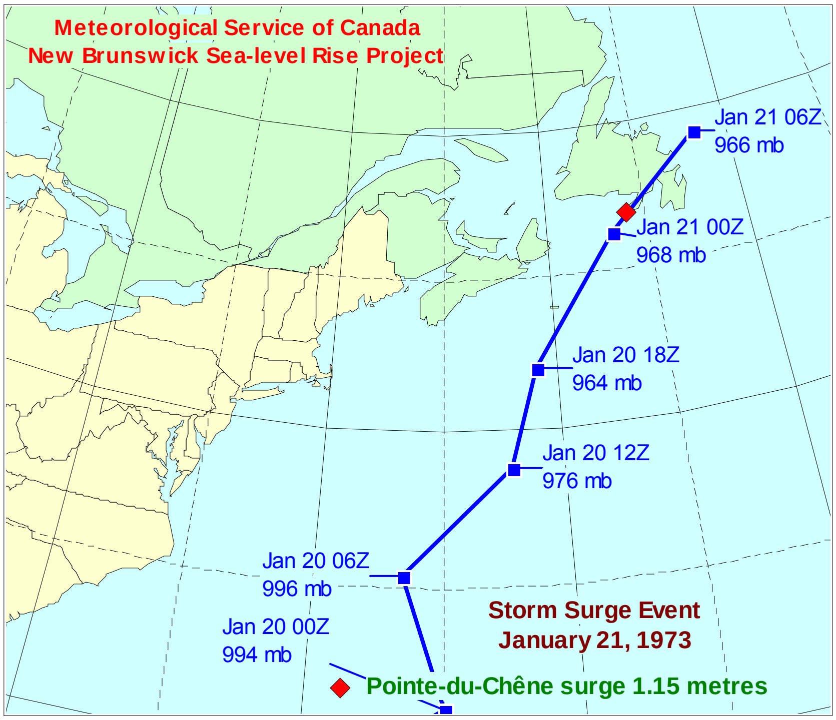
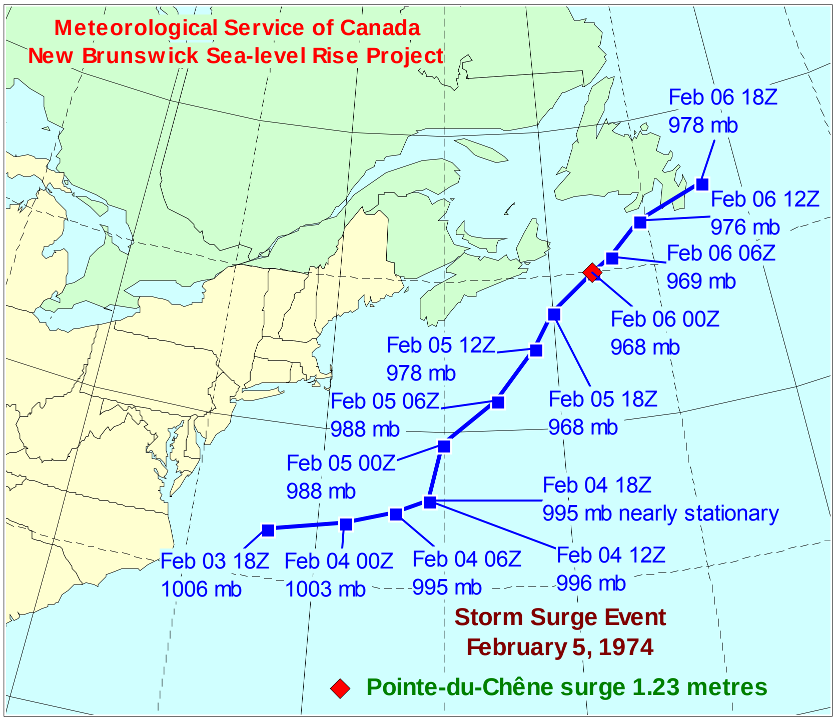


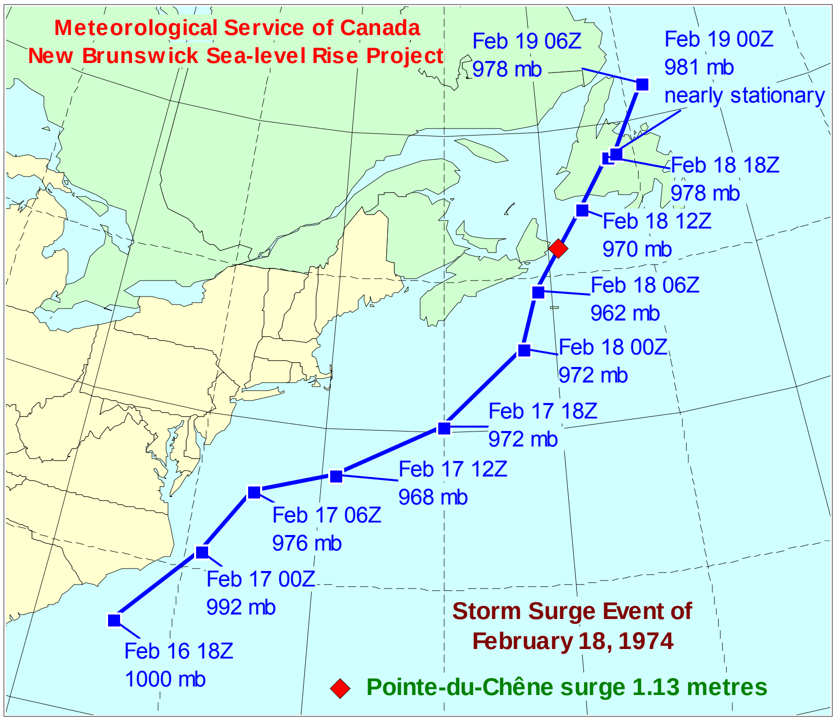
Figure B2. Storm-surge model predictions for Pointe-du-Chêne for October 29, 2000.

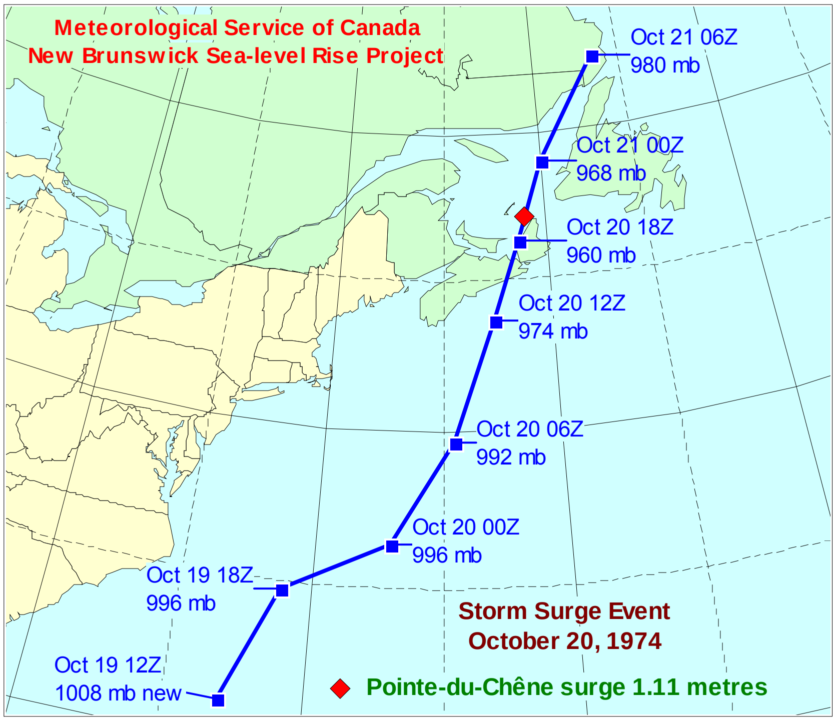
4.2.15.3 Attachment C: Storm-track maps

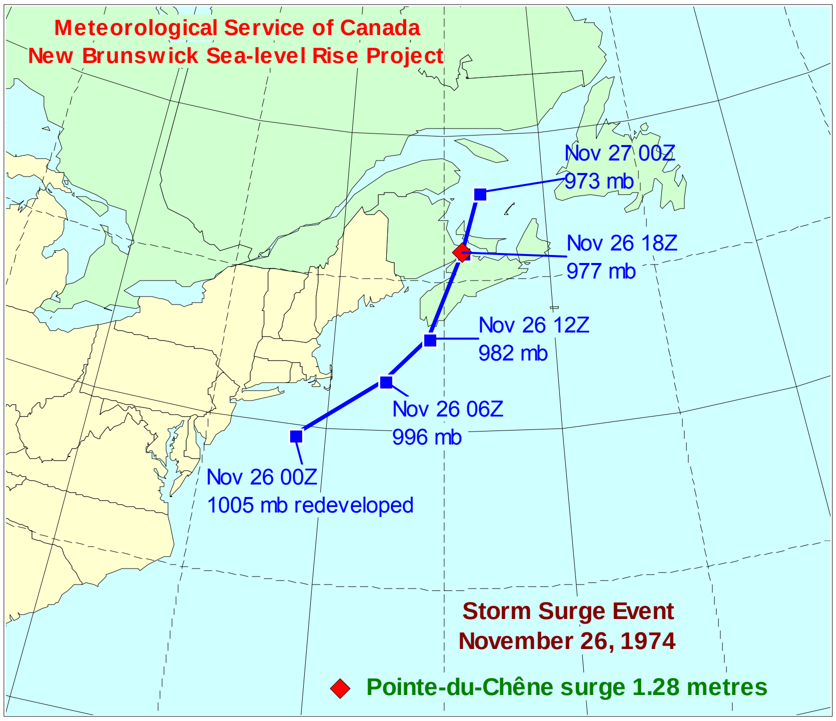


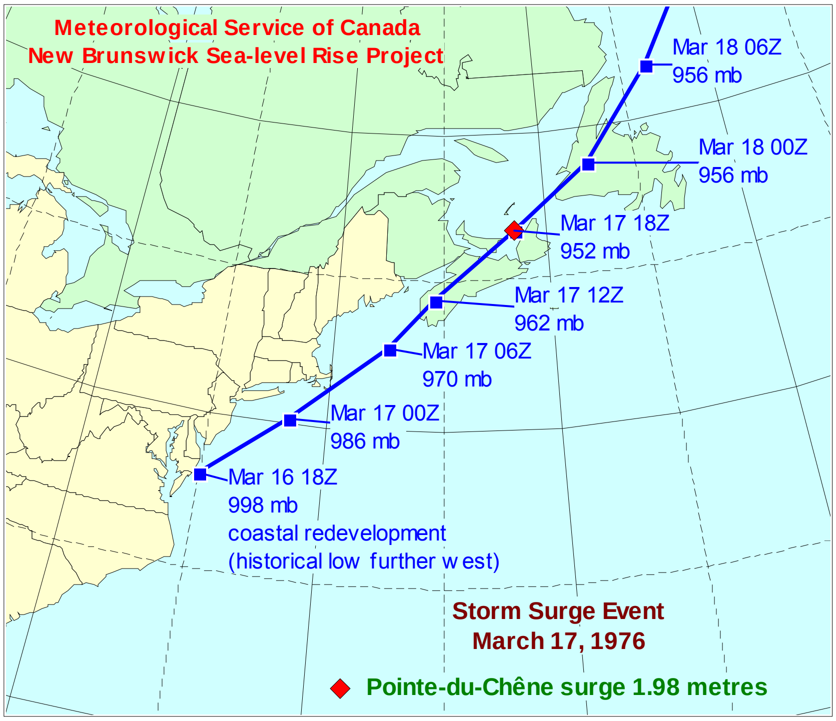


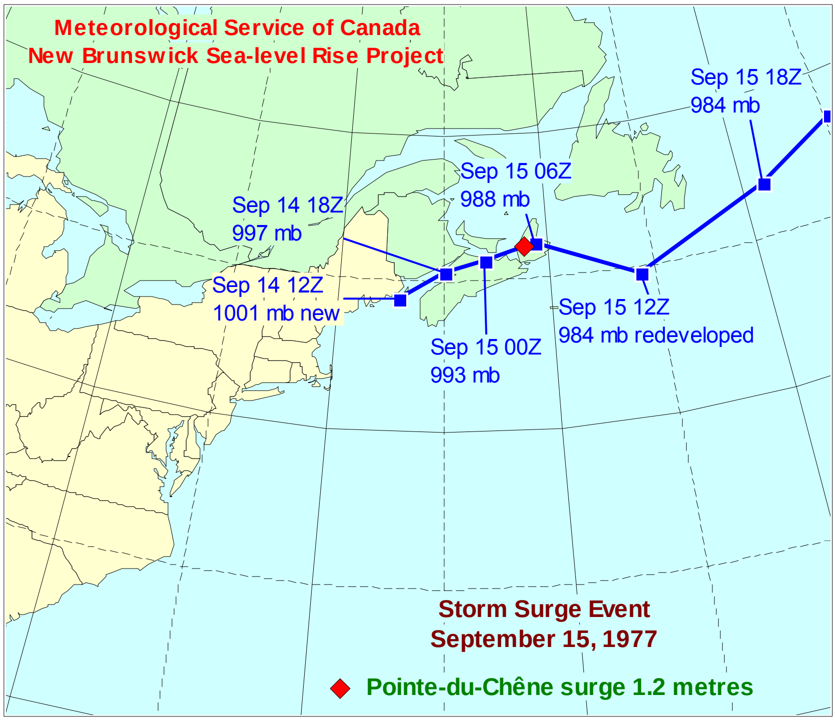

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Feb 06 18Z
978 mb
Feb 06 12Z
976 mb
Feb 06 06Z
969 mb
Feb 06 00Z
968 mb
Feb 05 12Z
978 mb
Feb 05 06Z
988 mb
Feb 05 18Z
968 mb
Feb 05 00Z
988 mb
Feb 04 18Z
995 mb nearly stationary
Feb 03 18Z
1006 mb
Feb 04 00Z
1003 mb
Feb 04 06Z
995 mb
Feb 04 12Z
996 mb
Storm Surge Event
February 5, 1974
◆ Pointe-du-Chêne surge 1.23 metres

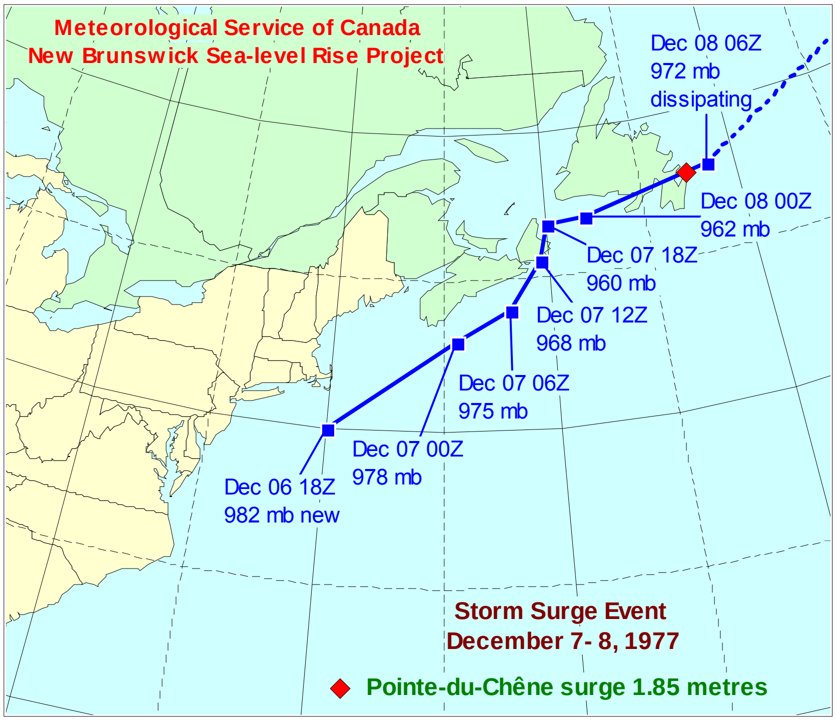

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Feb 19 06Z
978 mb
Feb 19 00Z
981 mb
nearly stationary
Feb 18 18Z
978 mb
Feb 18 12Z
970 mb
Feb 18 06Z
962 mb
Feb 18 00Z
972 mb
Feb 17 18Z
972 mb
Feb 17 12Z
968 mb
Feb 17 06Z
976 mb
Feb 17 00Z
992 mb
Feb 16 18Z
1000 mb
Storm Surge Event of
February 18, 1974
◆ Pointe-du-Chêne surge 1.13 metres

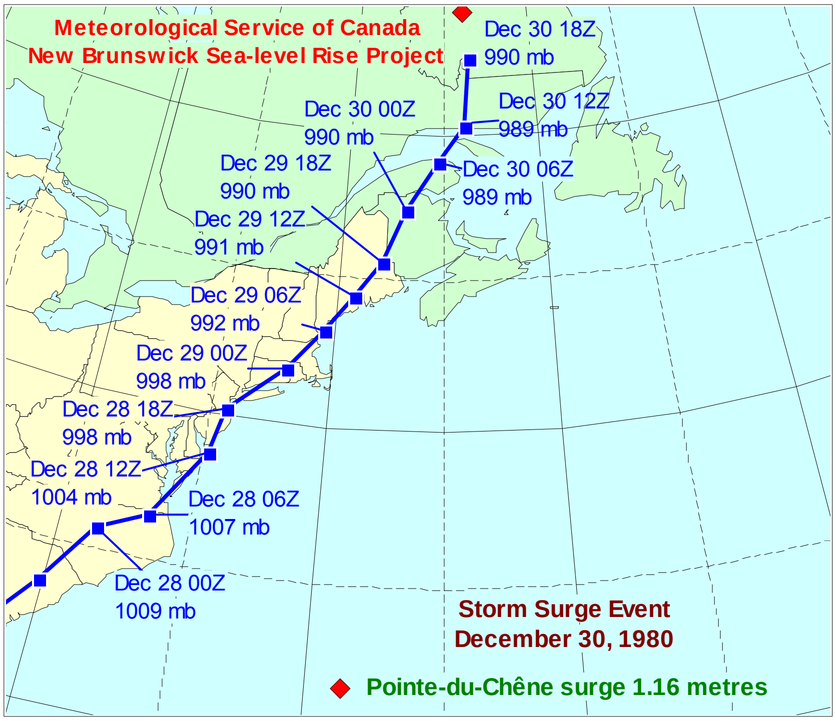

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Oct 21 06Z
980 mb
Oct 21 00Z
968 mb
Oct 20 18Z
960 mb
Oct 20 12Z
974 mb
Oct 20 06Z
992 mb
Oct 20 00Z
996 mb
Oct 19 18Z
996 mb
Oct 19 12Z
1008 mb new
Storm Surge Event
October 20, 1974
◆ Pointe-du-Chêne surge 1.11 metres

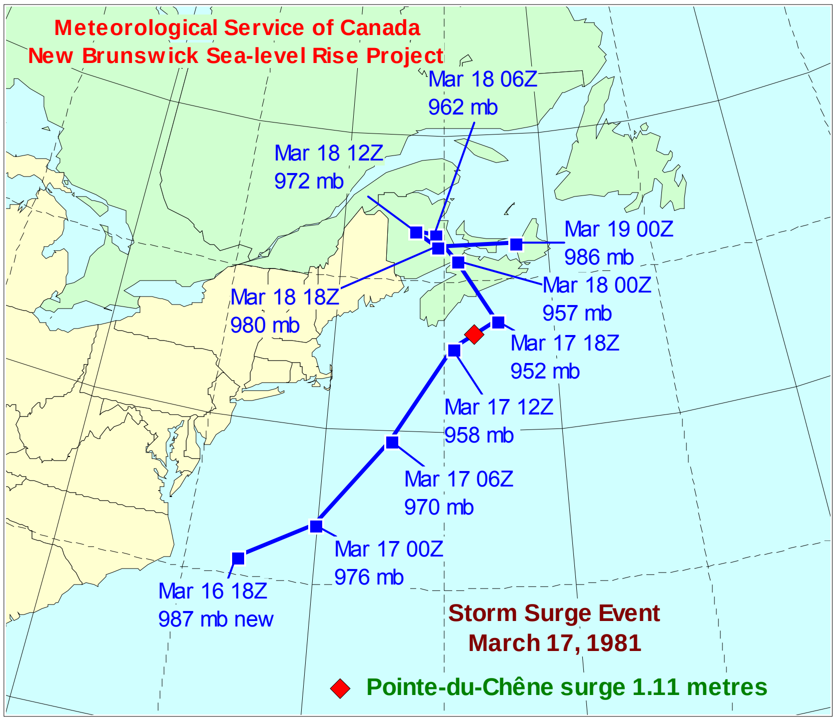

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Nov 27 00Z
973 mb
Nov 26 18Z
977 mb
Nov 26 12Z
982 mb
Nov 26 06Z
996 mb
Nov 26 00Z
1005 mb redeveloped
Storm Surge Event
November 26, 1974
◆ Pointe-du-Chêne surge 1.28 metres

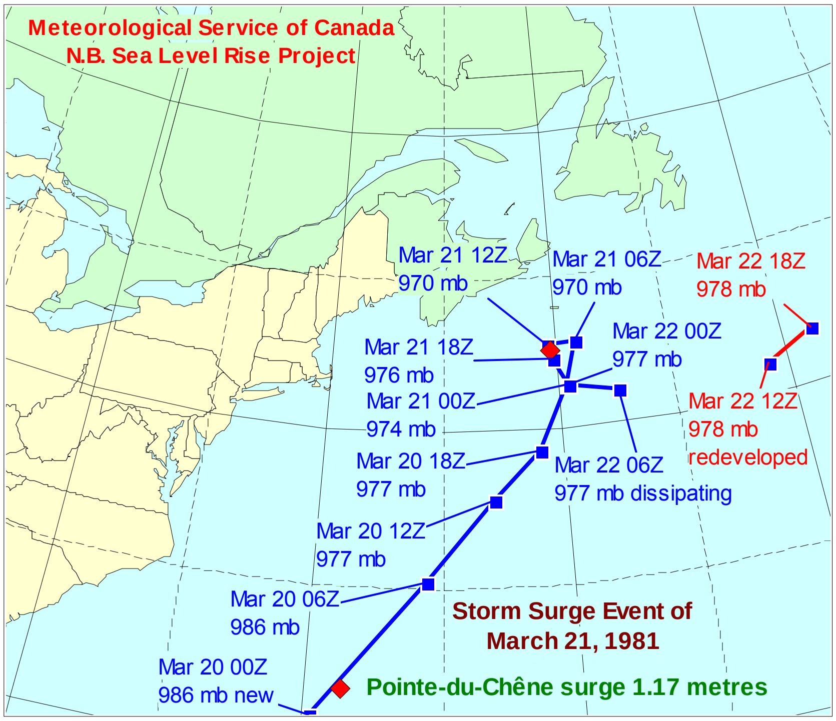

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Mar 18 06Z
956 mb
Mar 18 00Z
956 mb
Mar 17 18Z
952 mb
Mar 17 12Z
962 mb
Mar 17 06Z
970 mb
Mar 17 00Z
986 mb
Mar 16 18Z
998 mb
coastal redevelopment
(historical low further west)
Storm Surge Event
March 17, 1976
◆ Pointe-du-Chêne surge 1.98 metres

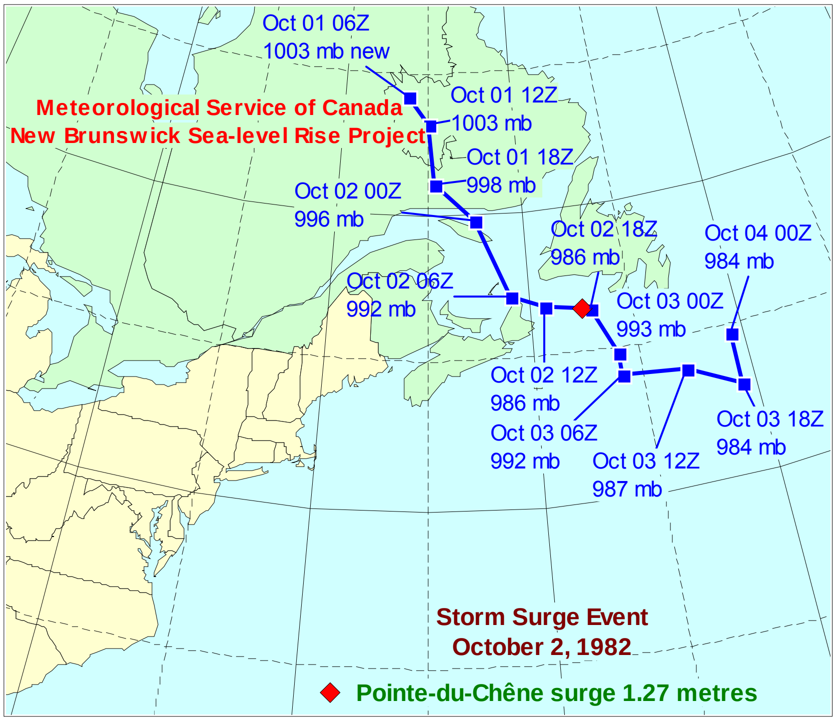

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Sep 15 18Z
984 mb
Sep 15 06Z
988 mb
Sep 14 18Z
997 mb
Sep 14 12Z
1001 mb new
Sep 15 00Z
993 mb
Sep 15 12Z
984 mb redeveloped
Storm Surge Event
September 15, 1977
◆ Pointe-du-Chêne surge 1.2 metres

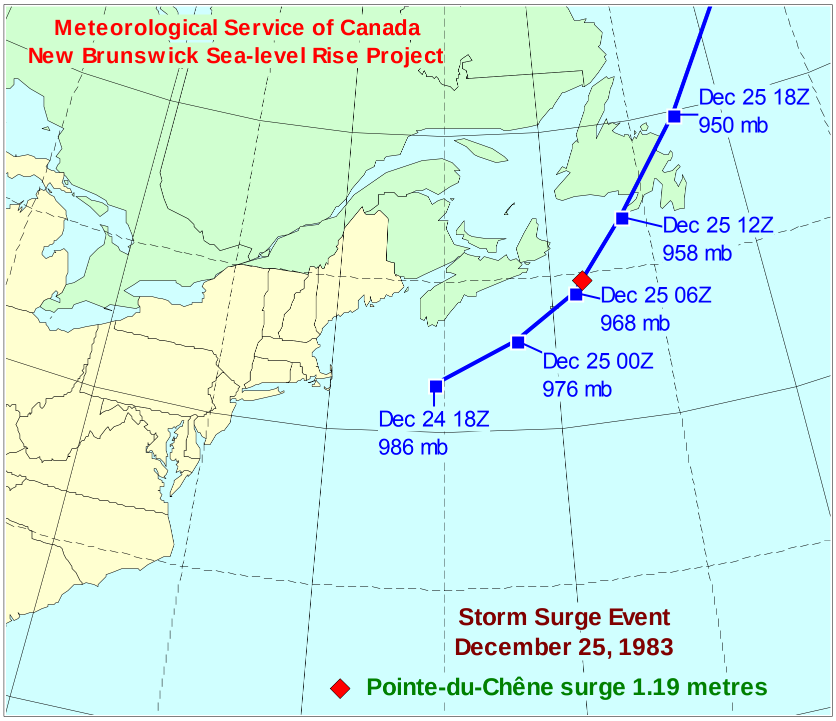

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Dec 08 06Z
972 mb
dissipating
Dec 08 00Z
962 mb
Dec 07 18Z
960 mb
Dec 07 12Z
968 mb
Dec 07 06Z
975 mb
Dec 07 00Z
978 mb
Dec 06 18Z
982 mb new
Storm Surge Event
December 7- 8, 1977
◆ Pointe-du-Chêne surge 1.85 metres

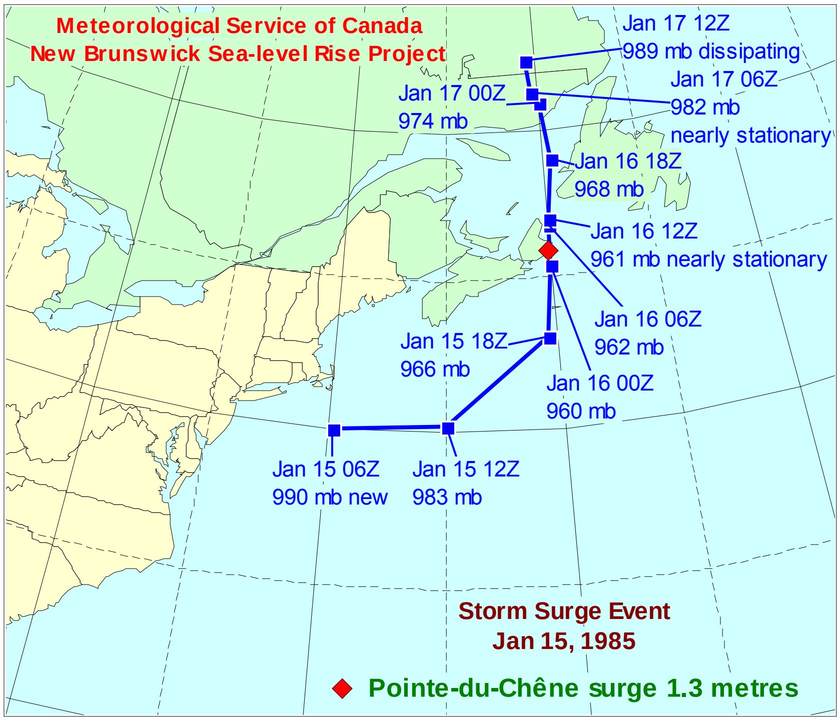

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Dec 30 18Z
990 mb
Dec 30 12Z
989 mb
Dec 30 06Z
989 mb
Dec 30 00Z
990 mb
Dec 29 18Z
990 mb
Dec 29 12Z
991 mb
Dec 29 06Z
992 mb
Dec 29 00Z
998 mb
Dec 28 18Z
998 mb
Dec 28 12Z
1004 mb
Dec 28 06Z
1007 mb
Dec 28 00Z
1009 mb
Storm Surge Event
December 30, 1980
◆ Pointe-du-Chêne surge 1.16 metres

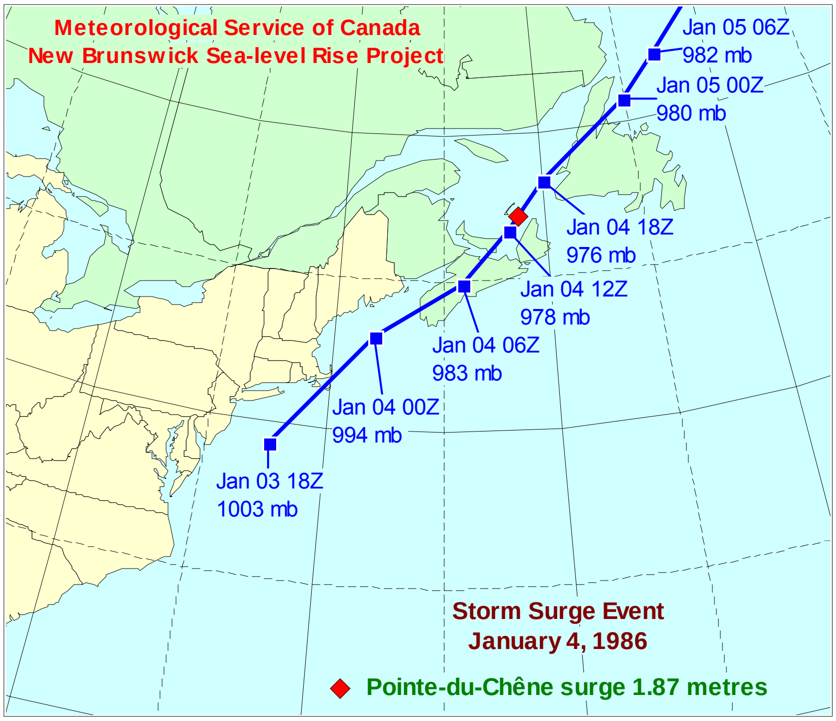

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Mar 18 06Z
962 mb
Mar 18 12Z
972 mb
Mar 19 00Z
986 mb
Mar 18 00Z
957 mb
Mar 18 18Z
980 mb
Mar 17 18Z
952 mb
Mar 17 12Z
958 mb
Mar 17 06Z
970 mb
Mar 17 00Z
976 mb
Mar 16 18Z
987 mb new
Storm Surge Event
March 17, 1981
◆ Pointe-du-Chêne surge 1.11 metres

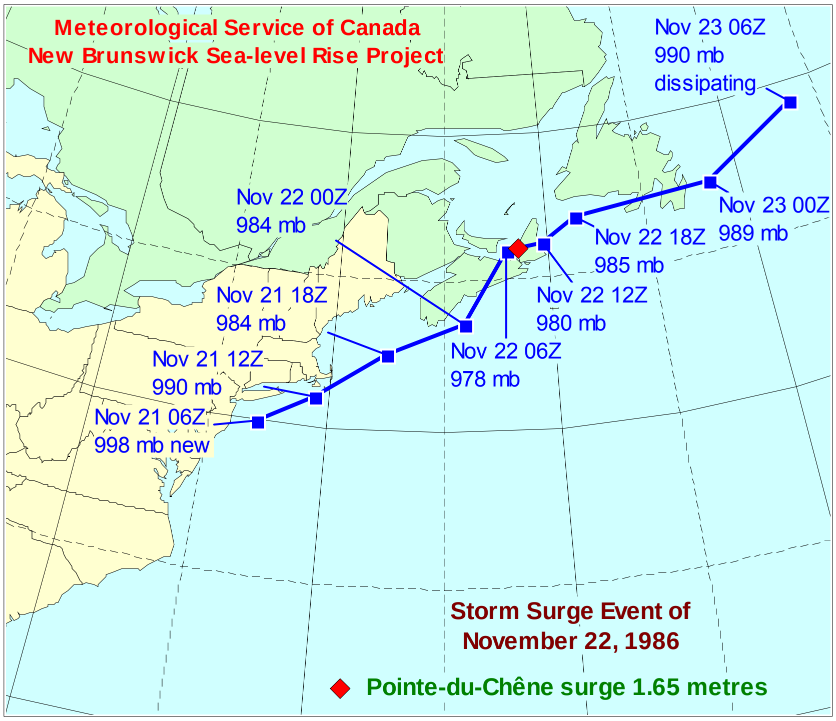

Meteorological Service of Canada
N.B. Sea Level Rise Project
Mar 21 12Z
970 mb
Mar 21 06Z
970 mb
Mar 22 18Z
978 mb
Mar 22 00Z
977 mb
Mar 21 18Z
976 mb
Mar 21 00Z
974 mb
Mar 22 12Z
978 mb
redeveloped
Mar 20 18Z
977 mb
Mar 22 06Z
977 mb dissipating
Mar 20 12Z
977 mb
Mar 20 06Z
986 mb
Storm Surge Event of
March 21, 1981
Mar 20 00Z
986 mb new
◆ Pointe-du-Chêne surge 1.17 metres

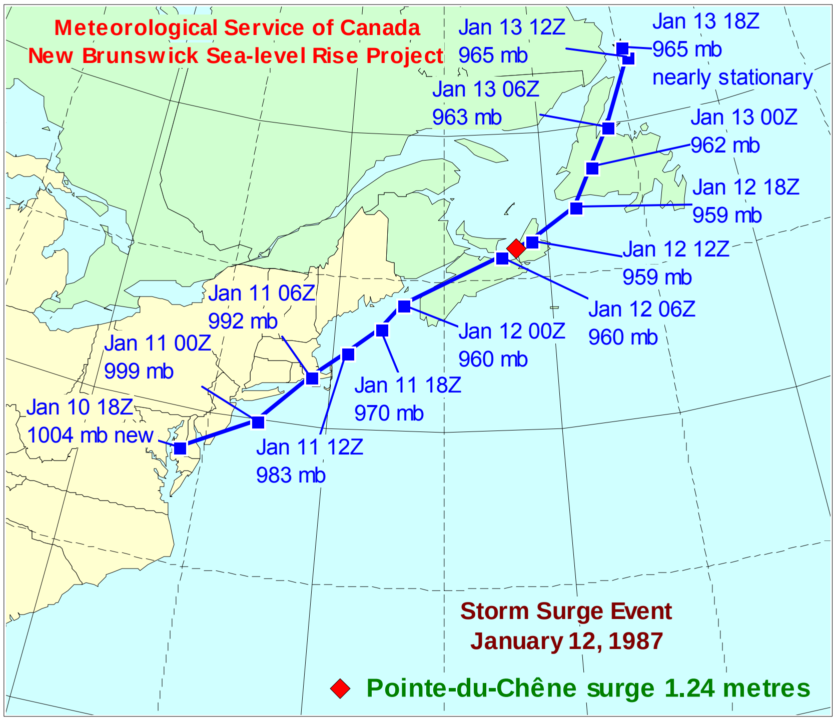

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Oct 01 06Z
1003 mb new
Oct 01 12Z
1003 mb
Oct 01 18Z
998 mb
Oct 02 00Z
996 mb
Oct 02 06Z
992 mb
Oct 02 12Z
986 mb
Oct 02 18Z
986 mb
Oct 03 00Z
993 mb
Oct 03 06Z
992 mb
Oct 03 12Z
987 mb
Oct 03 18Z
984 mb
Oct 04 00Z
984 mb
Storm Surge Event
October 2, 1982
◆ Pointe-du-Chêne surge 1.27 metres

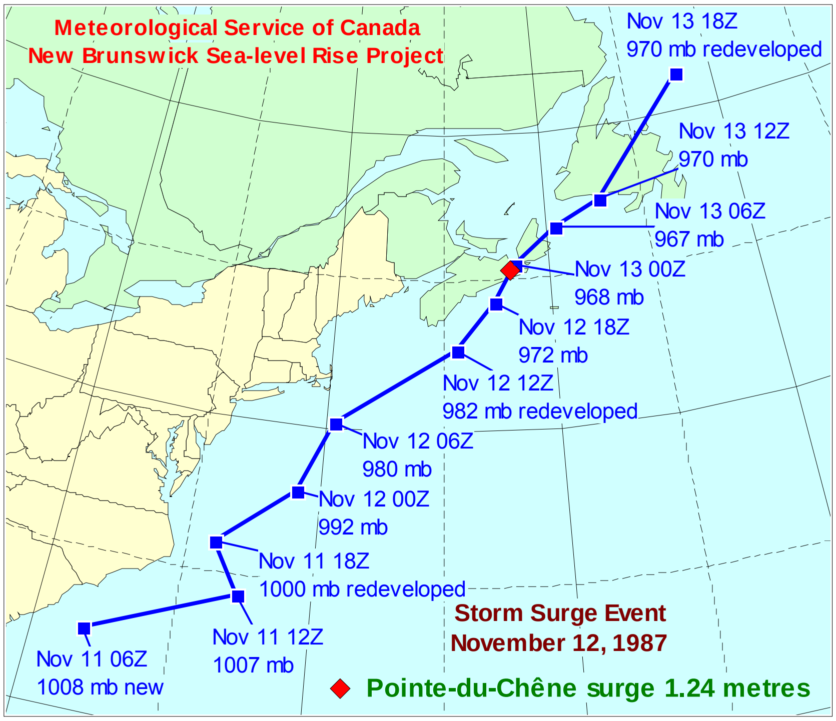

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Dec 25 18Z
950 mb
Dec 25 12Z
958 mb
Dec 25 06Z
968 mb
Dec 25 00Z
976 mb
Dec 24 18Z
986 mb
Storm Surge Event
December 25, 1983
◆ Pointe-du-Chêne surge 1.19 metres

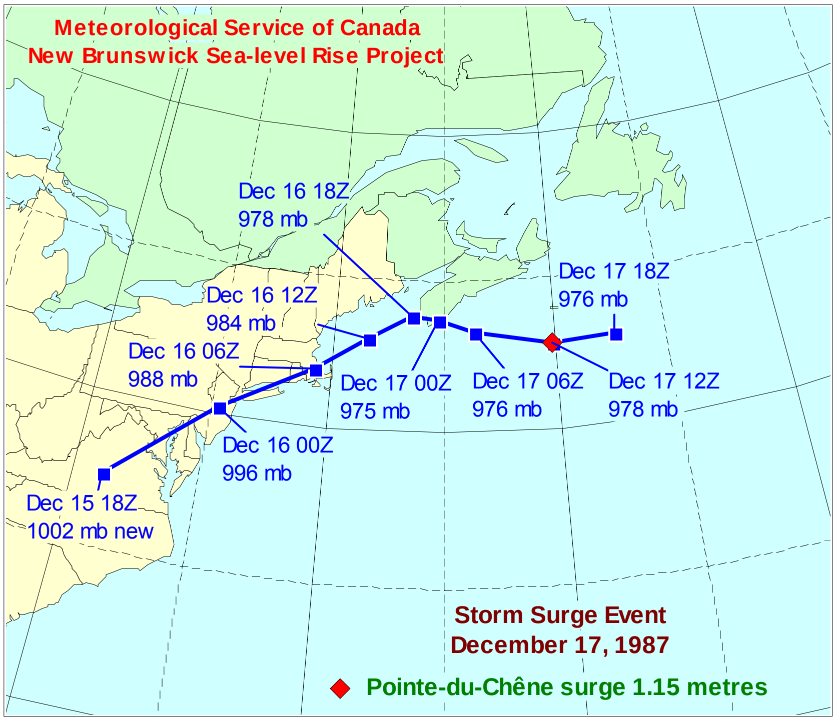

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Jan 17 12Z
989 mb dissipating
Jan 17 06Z
982 mb
nearly stationary
Jan 17 00Z
974 mb
Jan 16 18Z
968 mb
Jan 16 12Z
961 mb nearly stationary
Jan 16 06Z
962 mb
Jan 15 18Z
966 mb
Jan 16 00Z
960 mb
Jan 15 06Z
990 mb new
Jan 15 12Z
983 mb
Storm Surge Event
Jan 15, 1985
◆ Pointe-du-Chêne surge 1.3 metres

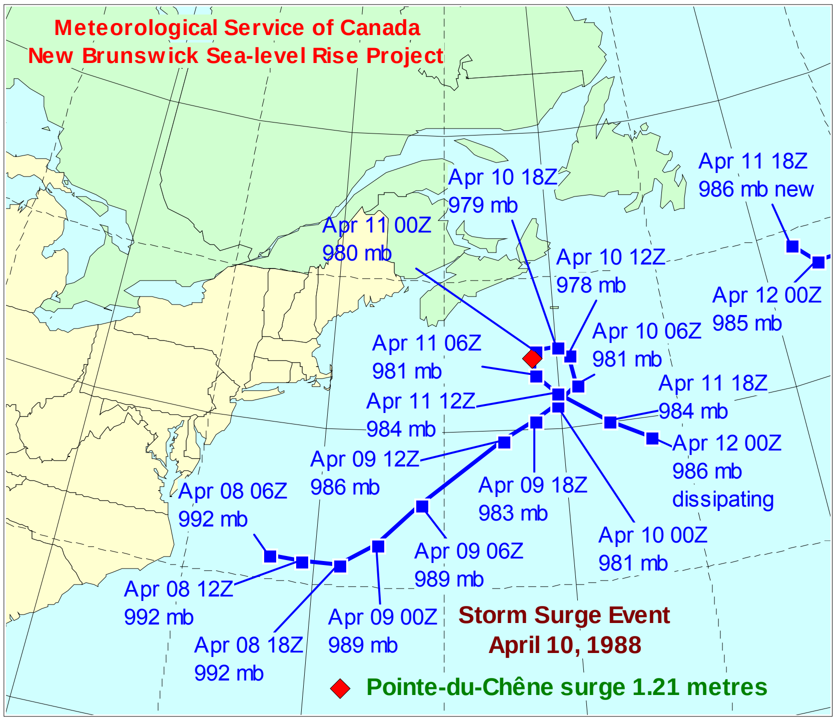

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Jan 05 06Z
982 mb
Jan 05 00Z
980 mb
Jan 04 18Z
976 mb
Jan 04 12Z
978 mb
Jan 04 06Z
983 mb
Jan 04 00Z
994 mb
Jan 03 18Z
1003 mb
Storm Surge Event
January 4, 1986
◆ Pointe-du-Chêne surge 1.87 metres

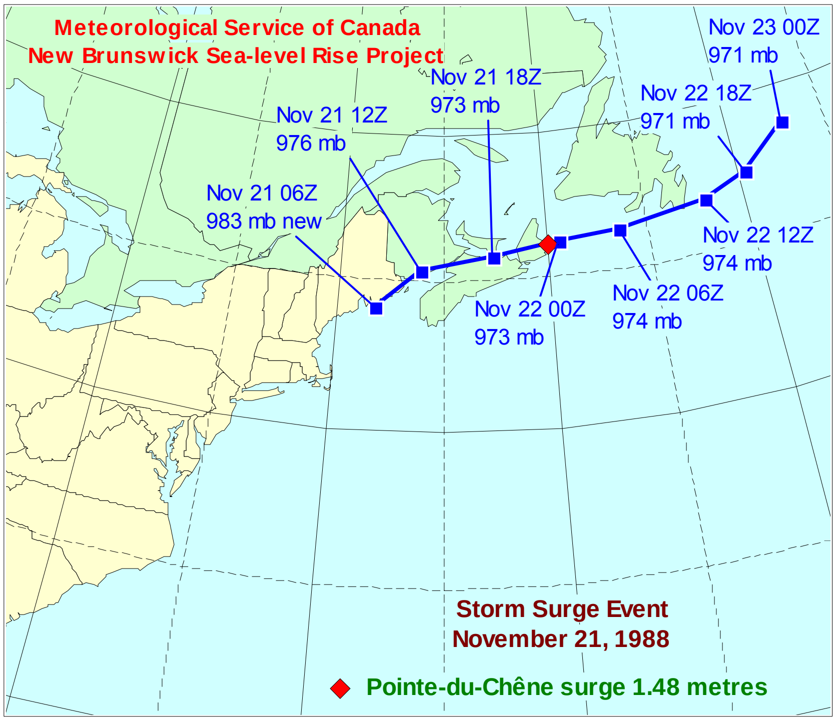

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Nov 23 06Z
990 mb
dissipating
Nov 22 00Z
984 mb
Nov 23 00Z
989 mb
Nov 22 18Z
985 mb
Nov 22 12Z
980 mb
Nov 21 18Z
984 mb
Nov 22 06Z
978 mb
Nov 21 12Z
990 mb
Nov 21 06Z
998 mb new
Storm Surge Event of
November 22, 1986
◆ Pointe-du-Chêne surge 1.65 metres

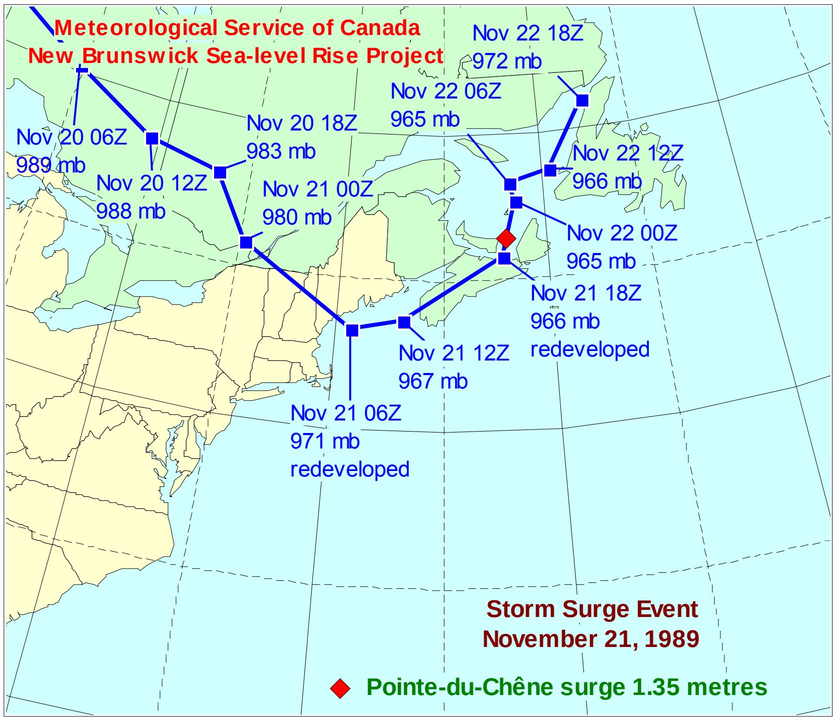

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Jan 13 12Z
965 mb
Jan 13 18Z
965 mb
nearly stationary
Jan 13 06Z
963 mb
Jan 13 00Z
962 mb
Jan 12 18Z
959 mb
Jan 12 12Z
959 mb
Jan 12 06Z
960 mb
Jan 11 06Z
992 mb
Jan 12 00Z
960 mb
Jan 11 00Z
999 mb
Jan 11 18Z
970 mb
Jan 10 18Z
1004 mb new
Jan 11 12Z
983 mb
Storm Surge Event
January 12, 1987
◆ Pointe-du-Chêne surge 1.24 metres

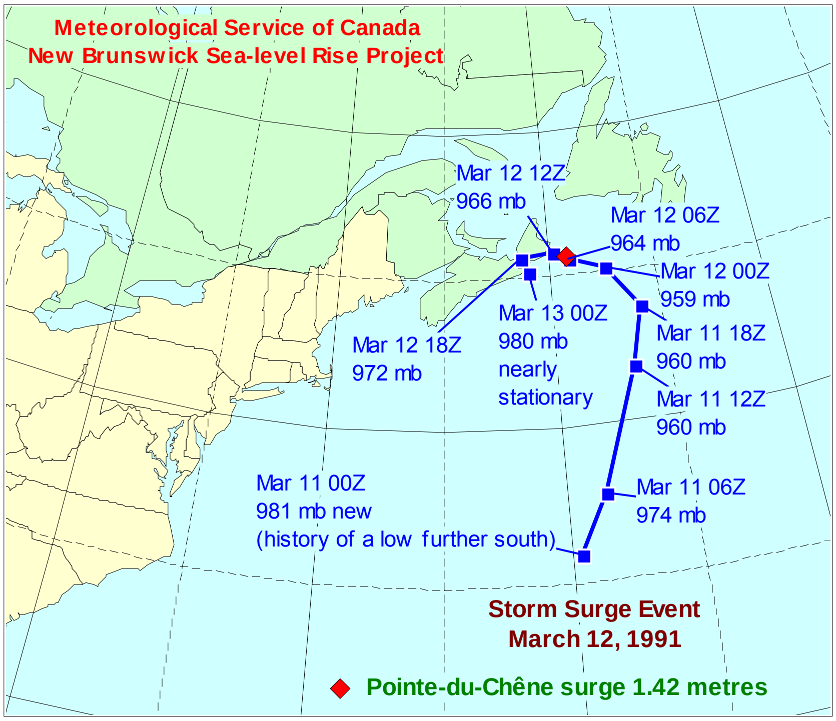

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Nov 13 18Z
970 mb redeveloped
Nov 13 12Z
970 mb
Nov 13 06Z
967 mb
Nov 13 00Z
968 mb
Nov 12 18Z
972 mb
Nov 12 12Z
982 mb redeveloped
Nov 12 06Z
980 mb
Nov 12 00Z
992 mb
Nov 11 18Z
1000 mb redeveloped
Nov 11 12Z
1007 mb
Nov 11 06Z
1008 mb new
Storm Surge Event
November 12, 1987
◆ Pointe-du-Chêne surge 1.24 metres

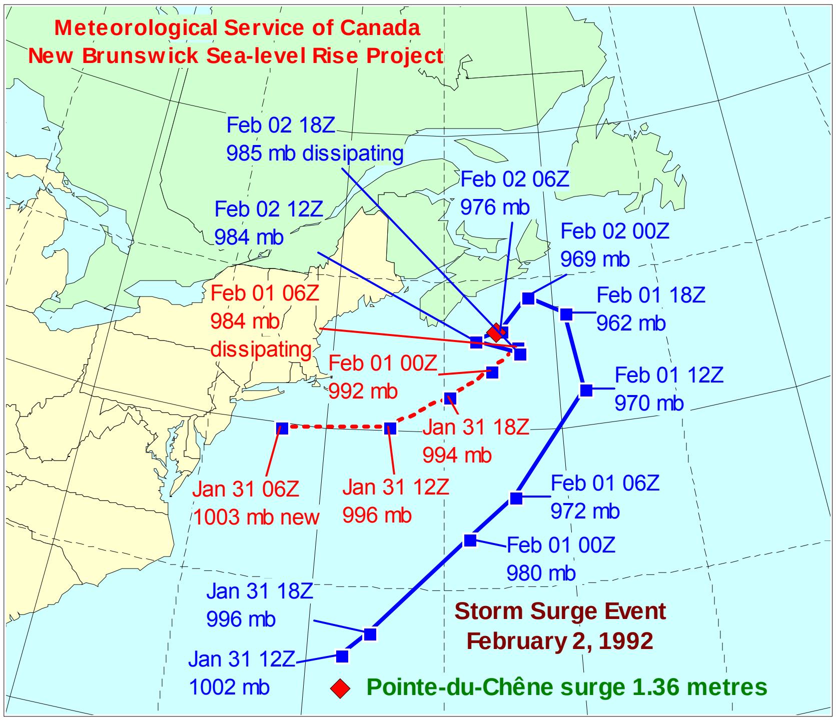

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Dec 16 18Z
978 mb
Dec 16 12Z
984 mb
Dec 16 06Z
988 mb
Dec 16 00Z
996 mb
Dec 15 18Z
1002 mb new
Dec 17 00Z
975 mb
Dec 17 06Z
976 mb
Dec 17 12Z
978 mb
Dec 17 18Z
976 mb
Storm Surge Event
December 17, 1987
◆ Pointe-du-Chêne surge 1.15 metres

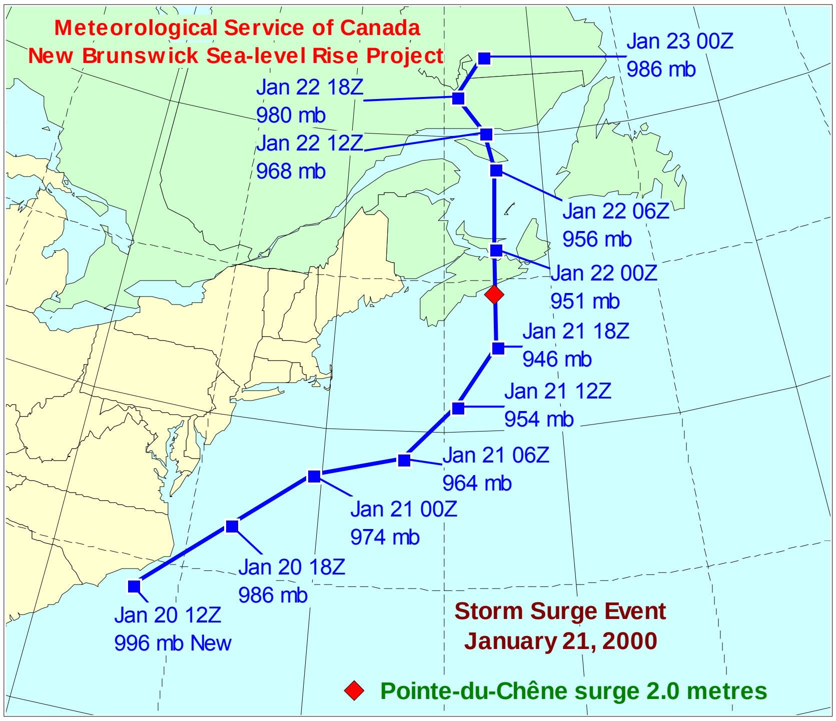

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Apr 10 18Z
979 mb
Apr 11 00Z
980 mb
Apr 10 12Z
978 mb
Apr 11 18Z
986 mb new
Apr 12 00Z
985 mb
Apr 10 06Z
981 mb
Apr 11 06Z
981 mb
Apr 11 12Z
984 mb
Apr 11 18Z
984 mb
Apr 12 00Z
986 mb
dissipating
Apr 09 12Z
986 mb
Apr 08 06Z
992 mb
Apr 09 18Z
983 mb
Apr 10 00Z
981 mb
Apr 09 06Z
989 mb
Apr 08 12Z
992 mb
Apr 09 00Z
989 mb
Apr 08 18Z
992 mb
Storm Surge Event
April 10, 1988
◆ Pointe-du-Chêne surge 1.21 metres

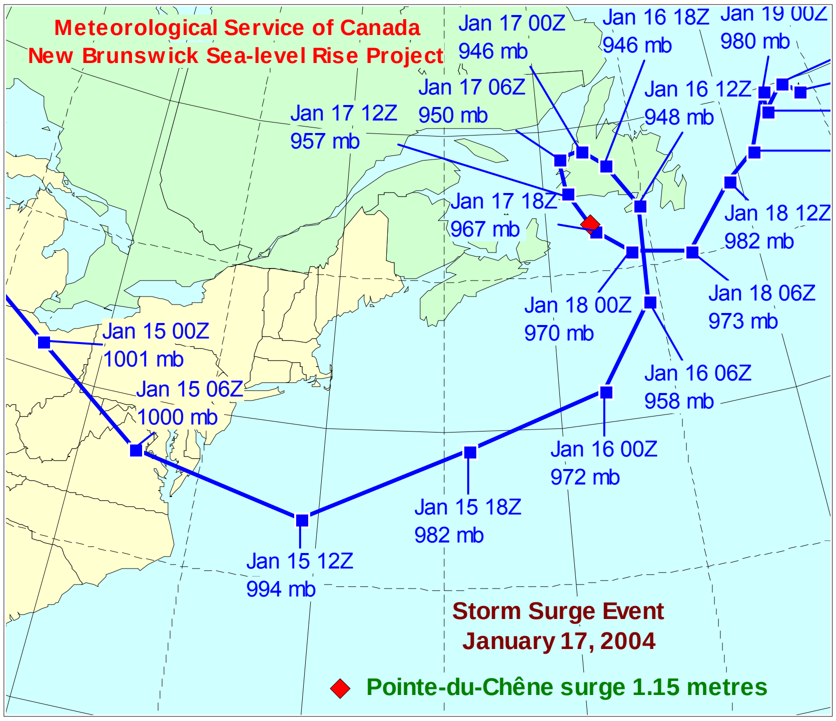

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Nov 23 00Z
971 mb
Nov 21 18Z
973 mb
Nov 22 18Z
971 mb
Nov 21 12Z
976 mb
Nov 21 06Z
983 mb new
Nov 22 12Z
974 mb
Nov 22 00Z
973 mb
Nov 22 06Z
974 mb
Storm Surge Event
November 21, 1988
◆ Pointe-du-Chêne surge 1.48 metres


Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Nov 20 06Z
989 mb
Nov 20 12Z
988 mb
Nov 20 18Z
983 mb
Nov 21 00Z
980 mb
Nov 21 06Z
971 mb
redeveloped
Nov 21 12Z
967 mb
Nov 21 18Z
966 mb
redeveloped
Nov 22 00Z
965 mb
Nov 22 06Z
965 mb
Nov 22 12Z
966 mb
Nov 22 18Z
972 mb
Storm Surge Event
November 21, 1989
◆ Pointe-du-Chêne surge 1.35 metres


Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Mar 11 00Z
981 mb new
(history of a low further south)
Mar 11 06Z
974 mb
Mar 11 12Z
960 mb
Mar 11 18Z
960 mb
Mar 12 00Z
959 mb
Mar 12 06Z
964 mb
Mar 12 12Z
966 mb
Mar 12 18Z
972 mb
Mar 13 00Z
980 mb
nearly
stationary
Storm Surge Event
March 12, 1991
◆ Pointe-du-Chêne surge 1.42 metres

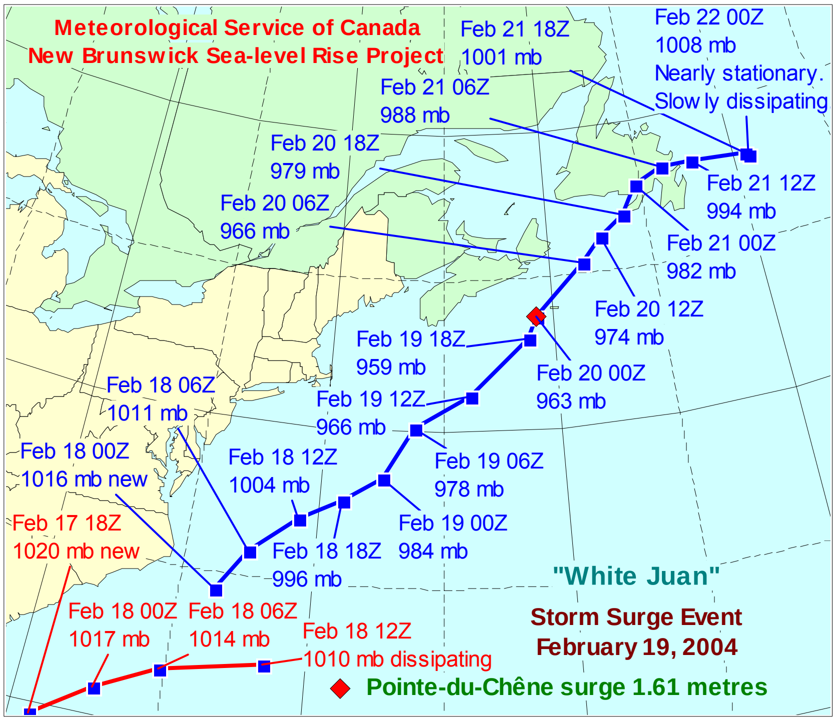

Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Feb 02 18Z
985 mb dissipating
Feb 02 06Z
976 mb
Feb 02 12Z
984 mb
Feb 02 00Z
969 mb
Feb 01 06Z
984 mb
dissipating
Feb 01 18Z
962 mb
Feb 01 00Z
992 mb
Feb 01 12Z
970 mb
Jan 31 18Z
994 mb
Jan 31 06Z
1003 mb new
Jan 31 12Z
996 mb
Feb 01 06Z
972 mb
Feb 01 00Z
980 mb
Jan 31 18Z
996 mb
Storm Surge Event
February 2, 1992
Jan 31 12Z
1002 mb
◆ Pointe-du-Chêne surge 1.36 metres


Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Jan 23 00Z
986 mb
Jan 22 18Z
980 mb
Jan 22 12Z
968 mb
Jan 22 06Z
956 mb
Jan 22 00Z
951 mb
Jan 21 18Z
946 mb
Jan 21 12Z
954 mb
Jan 21 06Z
964 mb
Jan 21 00Z
974 mb
Jan 20 18Z
986 mb
Jan 20 12Z
996 mb New
Storm Surge Event
January 21, 2000
◆ Pointe-du-Chêne surge 2.0 metres



Storm Surge Event
January 17, 2004

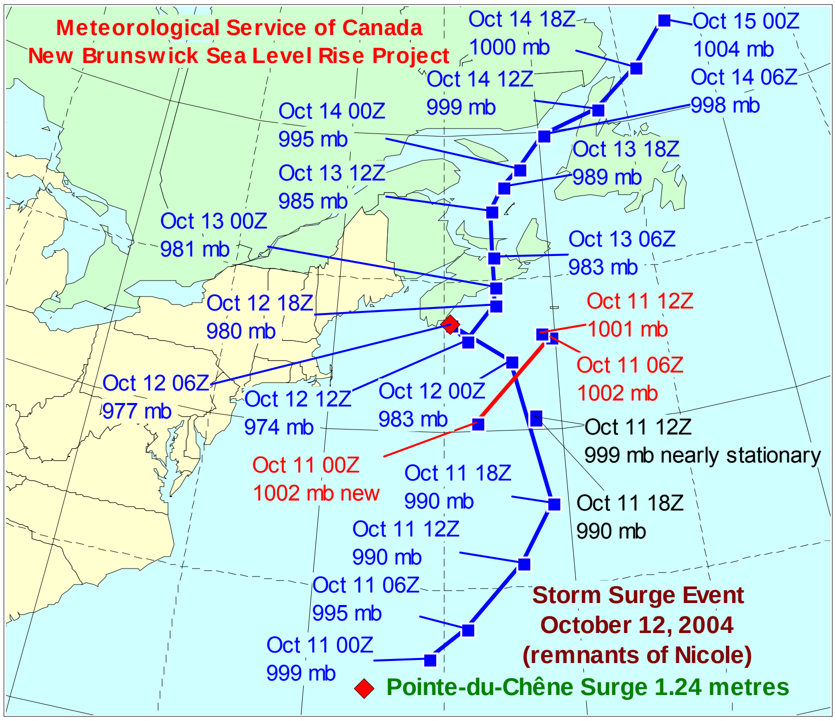
◆ **Pointe-du-Chêne surge 1.15 metres**

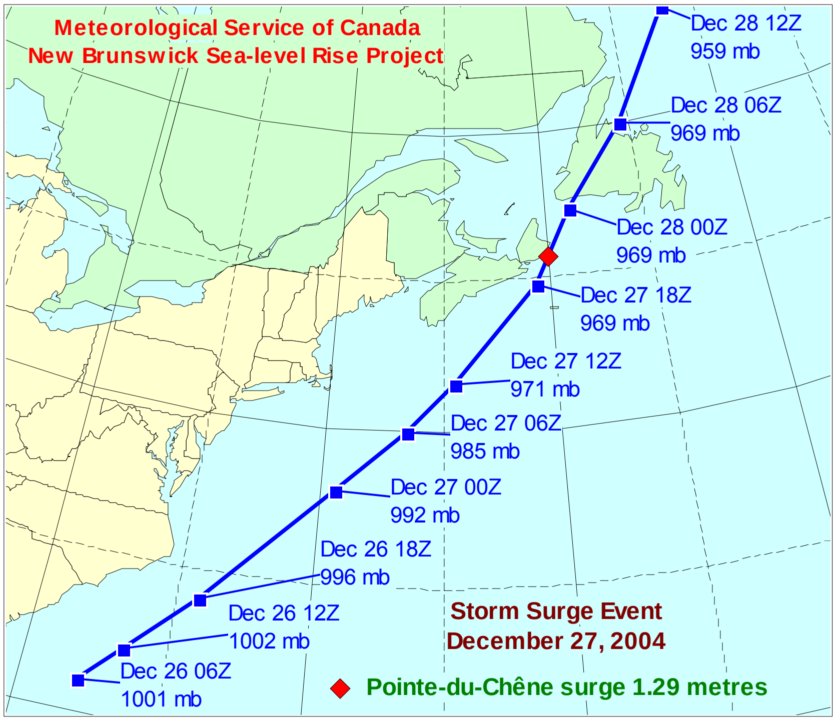


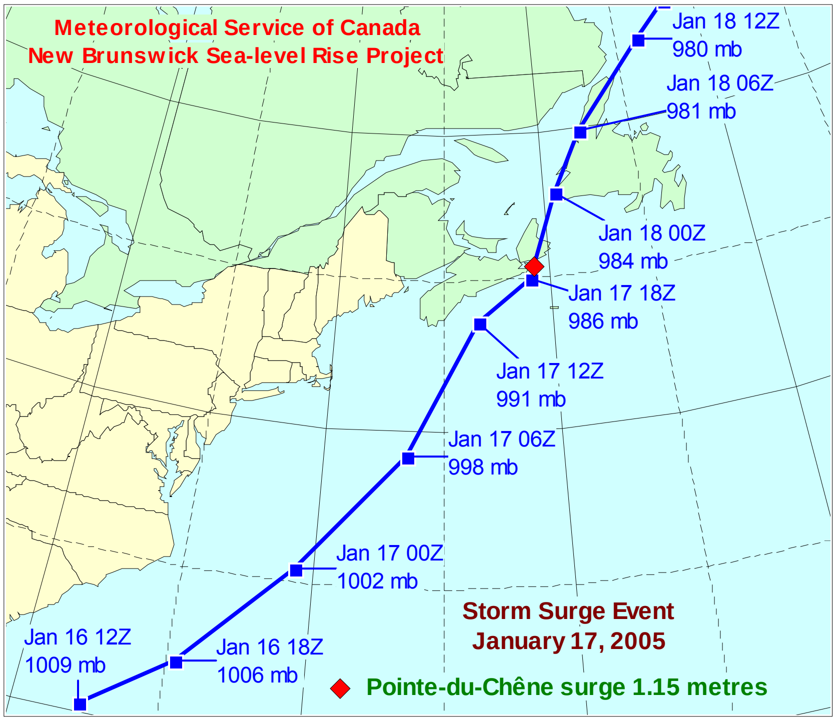
"White Juan"

Storm Surge Event
February 19, 2004

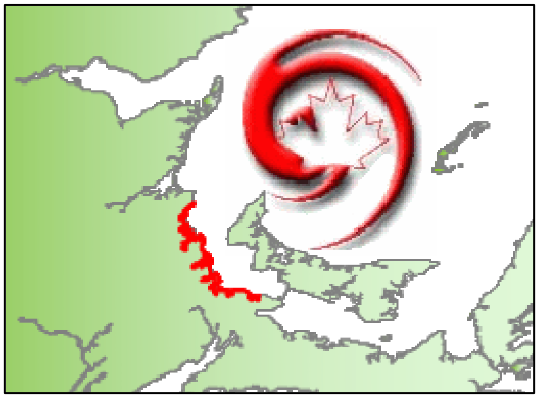
◆ **Pointe-du-Chêne surge 1.61 metres**


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 14 18Z
1000 mb
Oct 15 00Z
1004 mb
Oct 14 12Z
999 mb
Oct 14 06Z
998 mb
Oct 14 00Z
995 mb
Oct 13 18Z
989 mb
Oct 13 12Z
985 mb
Oct 13 00Z
981 mb
Oct 13 06Z
983 mb
Oct 12 18Z
980 mb
Oct 11 12Z
1001 mb
Oct 11 06Z
1002 mb
Oct 12 06Z
977 mb
Oct 12 12Z
974 mb
Oct 12 00Z
983 mb
Oct 11 12Z
999 mb nearly stationary
Oct 11 00Z
1002 mb new
Oct 11 18Z
990 mb
Oct 11 18Z
990 mb
Oct 11 12Z
990 mb
Oct 11 06Z
995 mb
Oct 11 00Z
999 mb
Storm Surge Event
October 12, 2004
(remnants of Nicole)
◆ Pointe-du-Chêne Surge 1.24 metres


Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Dec 28 12Z
959 mb
Dec 28 06Z
969 mb
Dec 28 00Z
969 mb
Dec 27 18Z
969 mb
Dec 27 12Z
971 mb
Dec 27 06Z
985 mb
Dec 27 00Z
992 mb
Dec 26 18Z
996 mb
Dec 26 12Z
1002 mb
Dec 26 06Z
1001 mb
Storm Surge Event
December 27, 2004
◆ Pointe-du-Chêne surge 1.29 metres


Meteorological Service of Canada
New Brunswick Sea-level Rise Project
Jan 18 12Z
980 mb
Jan 18 06Z
981 mb
Jan 18 00Z
984 mb
Jan 17 18Z
986 mb
Jan 17 12Z
991 mb
Jan 17 06Z
998 mb
Jan 17 00Z
1002 mb
Jan 16 12Z
1009 mb
Jan 16 18Z
1006 mb
Storm Surge Event
January 17, 2005
◆ Pointe-du-Chêne surge 1.15 metres

4.2.15.4 Attachment D: Storm-surge events associated with tropical cyclone passages



Data sources

- The U.S National Hurricane Center's HURDAT or "best tracks" database (1851–2003) The 1851–2004 archive was used for the 2004 cyclones.

> The latest version of these data can be downloaded from:
> http://www.nhc.noaa.gov/tracks1851to2004_atl.txt
>
> Background information relating to the database can be found in the following document: Jarvinen, B.R., Neumann, C.J. & Davis, M.A.S. 1984. NOAA Technical Memorandum NWS NHC 22.
> http://www.aoml.noaa.gov/hrd/hurdat/noaatechmemo.html

- Marine Environmental Data Service (MEDS) hourly tide-gauge observations for Point-du-Chêne, Escuminac, Charlottetown, etc.

Methodology and results

The U.S. National Hurricane Center's database was used to extract all tropical cyclones that crossed a rectangular search area centred over the northeastern Maritimes (see figures below). One hundred and twenty-five cyclones touched or crossed the search area. Cyclones ranged from fairly minor events with winds as low as 20 knots to major tropical or extratropical events with winds as high as 95 knots (Gerda, September 10, 1969). A full tabular listing of the 125 cyclones is provided below.

Forty-six of the 125 events crossed the search rectangle with hurricane-force winds near the centre (≥63 knots). See the tabular listing below.

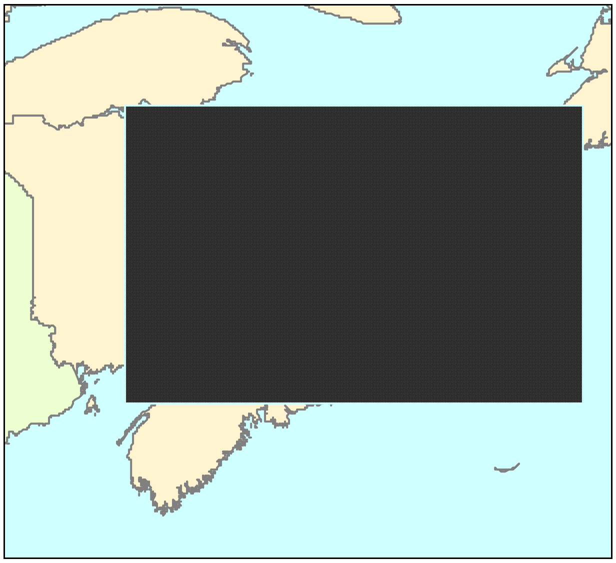
The MEDS hourly tide-gauge observations for Pointe-du-Chêne, Escuminac, Pointe-Sapin, Charlottetown and Rustico were examined for storm surges associated with tropical cyclone passages. The period of record for these sites is limited to a small subset of the U.S. National Hurricane Center track database, with details below:

Tide-Gauge Period of Record

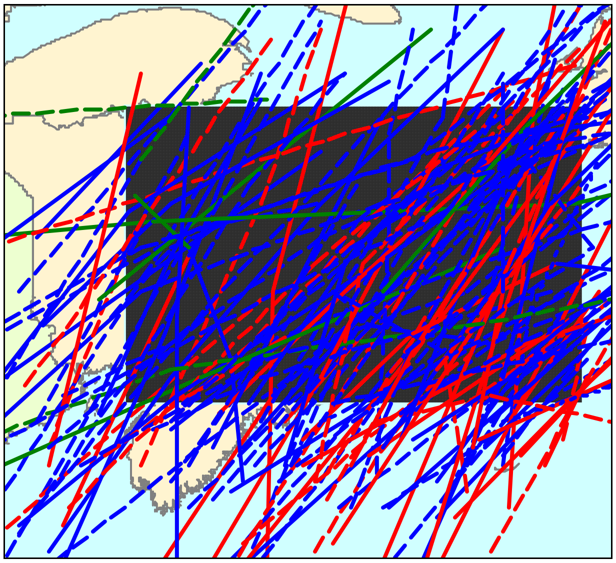
Pointe-du-Chêne	Late 1971 to early 1992 Late 2003 to 2005	
Escuminac	1973 to 2005	
Pointe-Sapin	1963 to 1975	
Charlottetown	1911 to 2003	(large blocks of missing data before 1938)
Rustico	1972 to 1996	

Only 16 cyclones of tropical origin actually resulted in storm surges of 60 cm or more at the various stations along the New Brunswick Gulf coast and Prince Edward Island. Again, a tabular listing of these cyclones is attached.

Cyclone track maps are provided for the 16 surge events.



Rectangular search area extending from the Bay of Chaleur to southwest Newfoundland to south to the vicinity of Halifax.



Storms of tropical origin that passed within the rectangular search area.

Comments

Only 16 tropical cyclones resulted in significant storm surges. The relatively low number of surge events is likely due to the fact that pure tropical cyclones have limited areas of high winds, and, in most cases, tracks directly over the New Brunswick Gulf coast would be required to force a storm surge. Cyclones undergoing extratropical[3] transition would see expanding areas of high winds on the west side of the track. This could occasionally allow a surge to develop with a track well east of Prince Edward Island (hurricane Ione, September 1955). The most significant storm surge by far was the recent October 29, 2000, event, which resulted in a surge of 1.58 m at Escuminac. This cyclone moved through the waters southeast of Nova Scotia, eventually lying east of Cape Breton on the morning of October 29. The hybrid storm, exhibiting characteristics of both tropical and mid-latitude cyclones, had a wide wind field that encompassed the Gulf of St. Lawrence.

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[3] A term used to indicate that a cyclone has lost or is losing its “tropical” characteristics. Cyclones can become extratropical and still retain winds of hurricane or tropical storm force strength (see http://www.nhc.noaa.gov/aboutgloss.html).

Tabular listing of all tropical cyclones passing between Bay of Chaleur and southwestern Newfoundland, 1851–2003

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Aug 27, 1851	missing						missing		40	
Not Named	Oct 17, 1862	missing						missing		50	E
Not Named	Aug 23, 1863	missing						missing		70	
Not Named	Sep 23, 1866	missing						missing		80	
Not Named	Oct 5, 1869	missing						missing		70	
Not Named	Sep 4, 1870	missing						missing		80	
Not Named	Oct 13, 1871	missing						missing		70	
Not Named	Sep 2, 1872	missing						missing		60	E
Not Named	Aug 7, 1874	missing						missing		70	
Not Named	Sep 7, 1874	missing						missing		70	E
Not Named	Sep 30, 1874	missing						missing		60	E
Not Named	Oct 16, 1875	missing						missing		50	
Not Named	Aug 5, 1877	missing						missing		50	
Not Named	Sep 22, 1877	missing						missing		60	
Not Named	Nov 30, 1877	missing						missing		40	E
Not Named	Aug 20, 1878	missing						missing		80	
Not Named	Aug 19, 1879	missing						missing		70	

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Oct 29, 1879	missing						missing		60	
Not Named	Nov 20, 1879	missing						missing		80	
Not Named	Sep 11, 1880	missing						missing		60	E
Not Named	Sep 9, 1880	missing						missing		60	
Not Named	Sep 12, 1882	missing						missing		50	
Not Named	Sep 23, 1885	missing						missing		70	E
Not Named	Aug 23, 1886	missing						missing		75	*
Not Named	May 19, 1887	missing						missing		35	E
Not Named	Oct 21, 1887	missing						missing		45	E
Not Named	Aug 23, 1888	missing						missing		35	
Not Named	Sep 13, 1888	missing						missing		35	
Not Named	Sep 27, 1888	missing						missing		40	
Not Named	Nov 28, 1888	missing						missing		80	
Not Named	Sep 26, 1889	missing						missing		35	
Not Named	Oct 8, 1889	missing						missing		50	
Not Named	Sep 8, 1891	missing						missing		80	
Not Named	Oct 6, 1891	missing						missing		85	
Not Named	Oct 15, 1891	missing						missing		80	

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Aug 22, 1893	missing						missing		100	
Not Named	Aug 17, 1893	missing						missing		85	
Not Named	Aug 30, 1893	missing						missing		60	
Not Named	Oct 14, 1896	missing						missing		85	
Not Named	Sep 25, 1897	missing						missing		30	
Not Named	Oct 6, 1898	missing						missing		25	
Not Named	Oct 7, 1899	missing						missing		35	E
Not Named	Nov 2, 1899	missing						missing		40	E
Not Named	Sep 13, 1900	missing						missing		45	E
Not Named	Oct 12, 1900	missing						missing		40	E
Not Named	Oct 29, 1900	missing						missing		45	E
Not Named	Sep 30, 1901	missing						missing		25	E
Not Named	Jun 17, 1902	missing						missing		35	E
Not Named	Sep 15, 1904	missing						missing		65	E
Not Named	Aug 2, 1908	missing						missing		75	E
Not Named	Nov 24, 1912	0.29						missing		60	E
Not Named	Jul 22, 1916	0.27						missing		55	
Not Named	Sep 7, 1918	0.39						missing		50	E

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Oct 2, 1923	missing						missing		75	E
Not Named	Aug 27, 1924	missing						missing		85	E
Not Named	Sep 4, 1924	missing						missing		70	E
Not Named	Aug 8, 1926	missing						missing		70	E
Not Named	Aug 25, 1927	missing						missing		90	E
Not Named	Sep 17, 1932	missing						missing		35	E
Not Named	Sep 18, 1933	missing						missing		60	E
Not Named	Oct 8, 1933	missing						missing		75	E
Not Named	Oct 29, 1933	missing						missing		60	E
Not Named	Jun 20, 1934	missing						missing		40	E
Not Named	Oct 2, 1935	missing						missing		65	E
Not Named	Aug 2, 1937	missing						missing		40	
Not Named	Sep 14, 1937	missing						missing		55	
Not Named	Sep 26, 1937	missing						missing		75	E
Not Named	Sep 30, 1937	missing						missing		35	E
Not Named	Sep 3, 1940	0.23						missing		55	
Not Named	Sep 17, 1940	0.77	3.04					missing		55	
Not Named	Sep 9, 1943	0.27						missing		60	

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Sep 16, 1943	0.43						missing		40	E
Not Named	Sep 15, 1944	0.49						missing		35	E
Not Named	Oct 22, 1944	0.56						missing		45	E
Not Named	Jun 29, 1945	0.17						missing		40	E
Not Named	Sep 20, 1945	0.32						missing		25	E
Not Named	Sep 15, 1946	0.27						missing		60	E
Able	Aug 21, 1950	0.29						missing		35	
Barbara	Aug 15, 1953	data problem						missing		70	E
Carol	Sep 7, 1953	0.49	3.03					missing		65	
Not Named	Oct 8, 1953	0.43	2.91					missing		60	E
Edna	Sep 12, 1954	0.75	2.59					missing		65	E
Ione	Sep 21, 1955	0.62	3.05					missing		60	E
Helene	Sep 29, 1958	0.97	3.16					missing		70	
Not Named	Jun 20, 1959	0.63	2.28					missing		70	E
Cindy	Jul 11, 1959	0						missing		50	E
Not Named	Sep 15, 1961	0.22						missing		35	
Frances	Oct 9, 1961	data problem						missing		40	E
Daisy	Oct 8, 1962	0.49						missing		55	E
Ginny	Oct 29, 1963	0.73	3.05	1.39	2.00			missing		90	E
Dora	Sep 15,	0.38		0.31				missing		55	E

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
	1964										
Gladys	Sep 24, 1964	0.28		0.24				missing		60	E
Celia	Jul 21, 1966	0.25		0.09				missing		65	E
Gladys	Oct 21, 1968	0.74	2.96	1.31	2.67			missing		65	E
Blanche	Aug 12, 1969	0		0.16				missing		65	
Gerda	Sep 10, 1969	0.33		0.51				missing		95	
Beth	Aug 16, 1971	missing		0.28				missing		65	
Carrie	Sep 4, 1972	missing		0.31				0.1		45	E
Alice	Jul 6, 1973	0.22		0.18		0.24		0.29		60	
Blanche	Jul 28, 1975	missing		0.41		0.48		0.25		60	E
Evelyn	Oct 15, 1977	missing		0.60	1.63	0.38		0.15		70	
David	Sep 7, 1979	0.75	2.13	0.60	1.44	0.81	1.48	0.62	1.14	50	E
Subtrop 1	Oct 25, 1979	0.25		0.42		0.31		0.31		60	S
Subtrop 1	Jun 20, 1982	0.46		0.33		0.28		0.38		60	S
Diana	Sep 16, 1984	0.51		0.47		0.57		missing		60	
Ana	Jul 19, 1985	0		0.36		0.17		0.2		60	
Alberto	Aug 8, 1988	0.1		0.22		0.11		0.17		35	
Chris	Aug 30, 1988	0.1		0.15		0.05		0.21		25	
Dean	Aug 8, 1989	0.17		0.11		0.23		0.17		65	
Bertha	Aug 2, 1990	0.58		Missing		0.65	1.95	0.69	1.53	70	
Lili	Oct 14, 1990	0.12		0.23		0.21		0.17		45	
Bob	Aug 20,	0.13		0.37		0.37		0.2		50	

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
	1991										
Unnamed	Nov 2, 1991	0.27		0.20		0.05		0.23		50	
Allison	Jun 8, 1995	0.24		0.39		missing		0.5	0.94	50	E
Barry	Jul 9, 1995	missing		0.10		missing		0.18		50	
Bertha	Jul 14, 1996	0.37		0.42		missing		missing		55	
Hortense	Sep 15, 1996	0.76	2.82	0.54		missing		missing		70	
Josephine	Oct 10, 1996	0.77	2.8	0.57		missing		missing		45	E
Floyd	Sep 18, 1999	missing		0.53		missing		missing		40	E
Subtrop	Oct 29, 2000	1.29	3.25	1.58	2.37	missing		missing		50	E
Karen	Oct 15, 2001	0.31		0.12		missing		missing		40	
Gustav	Sep 12, 2002	1.35	3.41	1.02	2.08	missing		missing		80	
Juan	Sep 29, 2003	1.10	2.85	0.50		0.50		missing		85	
Francis	Sep 10,2004	0.12		0.41		missing		missing		20	E
Nicole*	Oct 12, 2004	0.36		0.94	1.89	missing		missing			

* This storm was a post-tropical redevelopment that crossed the Maritimes. The U.S. National Hurricane Center stopped tracking Nicole at 38.5°N.

Tabular listing of tropical cyclones — hurricane strength only (≥63 knots)

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Aug 23, 1863	missing						missing		70	
Not Named	Sep 23, 1866	missing						missing		80	
Not Named	Oct 5, 1869	missing						missing		70	
Not Named	Sep 4, 1870	missing						missing		80	
Not Named	Oct 13, 1871	missing						missing		70	
Not Named	Aug 7, 1874	missing						missing		70	
Not Named	Sep 7, 1874	missing						missing		70	E
Not Named	Aug 20, 1878	missing						missing		80	
Not Named	Aug 19, 1879	missing						missing		70	
Not Named	Nov 20, 1879	missing						missing		80	
Not Named	Sep 23, 1885	missing						missing		70	E
Not Named	Aug 23, 1886	missing						missing		75	*
Not Named	Nov 28, 1888	missing						missing		80	
Not Named	Sep 8, 1891	missing						missing		80	
Not Named	Oct 6, 1891	missing						missing		85	
Not Named	Oct 15, 1891	missing						missing		80	
Not Named	Aug 22, 1893	missing						missing		100	
Not	Aug 17,	missing						missing		85	

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Named	1893										
Not Named	Oct 14, 1896	missing						missing		85	
Not Named	Sep 15, 1904	missing						missing		65	E
Not Named	Aug 2, 1908	missing						missing		75	E
Not Named	Oct 2, 1923	missing						missing		75	E
Not Named	Aug 27, 1924	missing						missing		85	E
Not Named	Sep 4, 1924	missing						missing		70	E
Not Named	Aug 8, 1926	missing						missing		70	E
Not Named	Aug 25, 1927	missing						missing		90	E
Not Named	Oct 8, 1933	missing						missing		75	E
Not Named	Oct 2, 1935	missing						missing		65	E
Not Named	Sep 26, 1937	missing						missing		75	E
Barbara	Aug 15, 1953	phase problem						missing		70	E
Carol	Sep 7, 1953	0.49	3.03					missing		65	
Edna	Sep 12, 1954	0.75	2.59					missing		65	E
Helene	Sep 29, 1958	0.97	3.16					missing		70	
Not Named	Jun 20, 1959	0.63	2.28					missing		70	E
Ginny	Oct 29, 1963	0.73	3.05	1.39	2.00			missing		90	E
Celia	Jul 21, 1966	0.25		0.09				missing		65	E
Gladys	Oct 21,	0.74	2.96	1.31	2.67			missing		65	E

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
	1968										
Blanche	Aug 12, 1969	0		0.16				missing		65	
Gerda	Sep 10, 1969	0.33		0.51				missing		95	
Beth	Aug 16, 1971	missing		0.28				missing		65	
Evelyn	Oct 15, 1977	missing		0.60	1.63	0.38		0.15		70	
Dean	Aug 8, 1989	0.17		0.11		0.23		0.17		65	
Bertha	Aug 2, 1990	0.58		missing		0.65	1.95	0.69	1.53	70	
Hortense	Sep 15, 1996	0.76	2.82	0.54		missing		missing		70	
Gustav	Sep 12, 2002	1.35	3.41	1.02		missing		missing		80	
Juan	Sep 29, 2003	1.10	2.85	0.50		0.50		missing		85	

Tabular listing of storms of tropical origin that resulted in a storm surge ≥0.6 m (shown in red) at Pointe-du-Chêne, Escuminac, Pointe-Sapin, Charlottetown or Rustico

Name	Date	Charlottetown Surge (m)	Charlottetown Water Level (m)	Pointe-Sapin and Escuminac Surge (m)	Pointe-Sapin and Escuminac Water Level (m)	Pointe-du-Chêne Surge (m)	Pointe-du-Chêne Water Level (m)	Rustico Surge (m)	Rustico Water Level (m)	Max Winds (knots)	Extra-Tropical (E)
Not Named	Sep 17, 1940	**0.77**	3.04					missing		55	
Edna	Sep 12, 1954	**0.75**	2.59					missing		65	E
Ione	Sep 21, 1955	**0.62**	3.05					missing		60	E
Helene	Sep 29, 1958	**0.97**	3.16					missing		70	
Not Named	Jun 20, 1959	**0.63**	2.28					missing		70	E
Ginny	Oct 29, 1963	**0.73**	3.05	**1.39**	2.00			missing		90	E
Gladys	Oct 21, 1968	**0.74**	2.96	**1.31**	2.67			missing		65	E
Evelyn	Oct 15, 1977	missing		**0.60**	1.63	0.38		0.15		70	
David	Sep 7, 1979	**0.75**	2.13	**0.60**	1.44	**0.81**		**0.62**	1.14	50	E
Bertha	Aug 2, 1990	**0.58**		Missing		**0.65**	1.95	**0.69**	1.53	70	
Hortense	Sep 15, 1996	**0.76**	2.82	0.54		missing		missing		70	
Josephine	Oct 10, 1996	**0.77**	2.8	0.57		missing		missing		45	E
Subtrop	Oct 29, 2000	**1.29**	3.25	**1.58**	2.37	missing		missing		50	E
Gustav	Sep 12, 2002	**1.35**	3.41	**1.02**		missing		missing		80	
Juan	Sep 29, 2003	**1.10**	2.85	0.50		0.50		missing		85	
Nicole*	Oct 12, 2004	0.36		**0.94**	1.89	missing		missing			

* This storm was a post-tropical redevelopment that crossed the Maritimes. The National Hurricane Center stopped tracking Nicole at 38.5°N.

Tropical Cyclone Track Maps

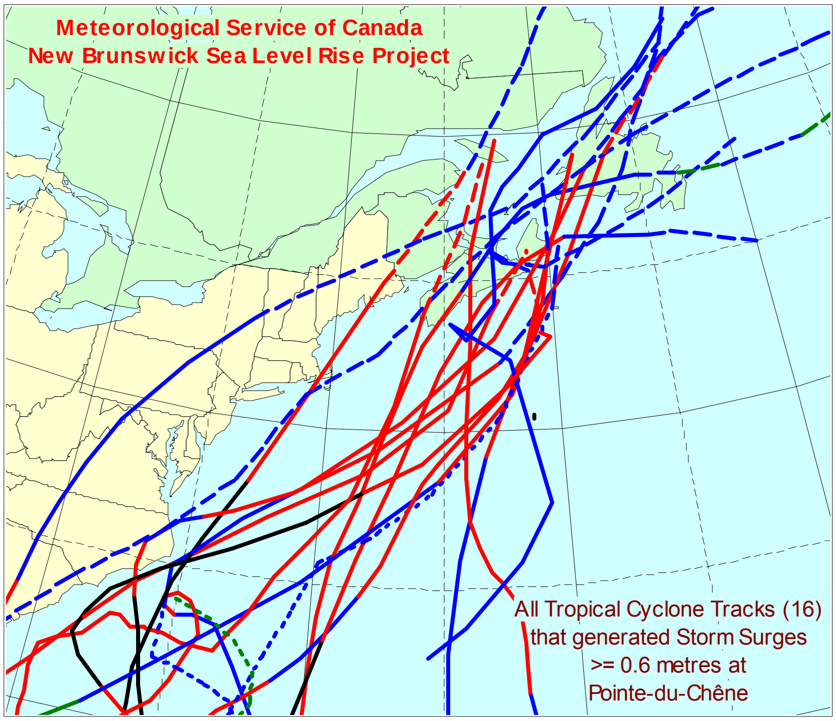
Tropical cyclone tracks that resulted in a storm surge ≥0.6 m are mapped in this section. The following colour-coding applies to all tracks with the exception of Nicole.

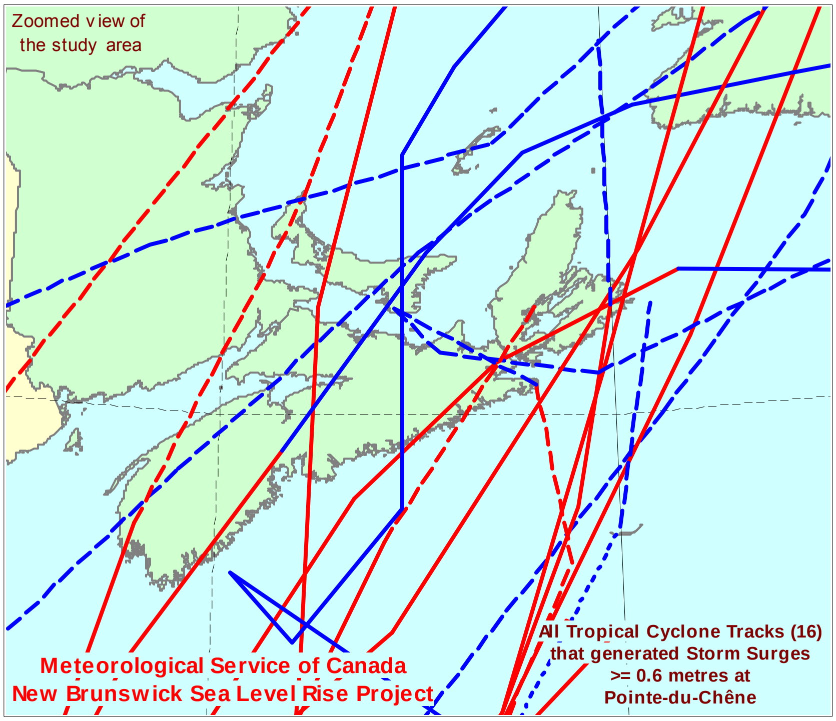
Wind Speed Range and Track Map Colour-Coding

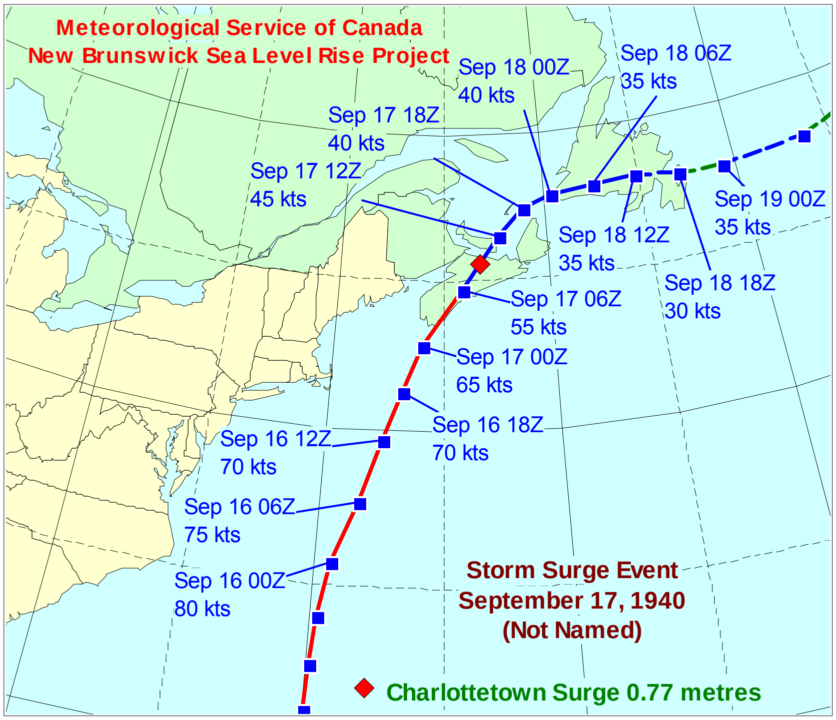
Definition	Colour	Winds (knots)	Winds (km/h)	Winds (mph)
Tropical Depression	Green [*]	<34	<63	<39
Tropical Storm	Blue [*]	34–63	63–118	39–73
Saffir-Simpson 1	Red [*]	64–82	119–153	74–95
Saffir-Simpson 2	Red [*]	83–95	154–177	96–110
Saffir-Simpson 3 (intense hurricane)	Black [*]	96–113	178–209	111–130
Saffir-Simpson 4 (intense hurricane)	Black [*]	114–135	210–251	131–155
Saffir-Simpson 5 (intense hurricane)	Black [*]	>135	>251	>155

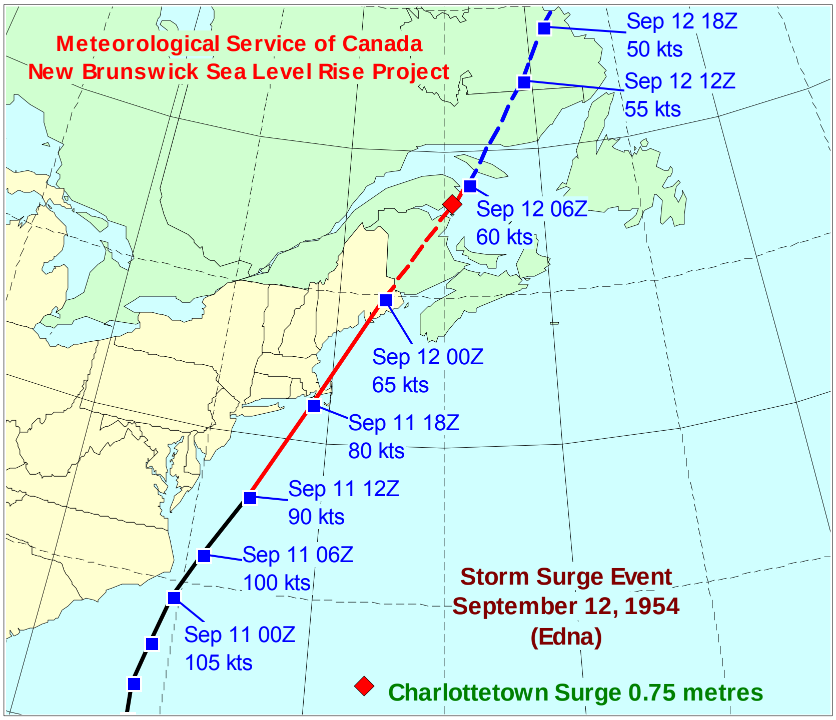
[*] Dashed lines indicate that the storm is subtropical or extratropical.

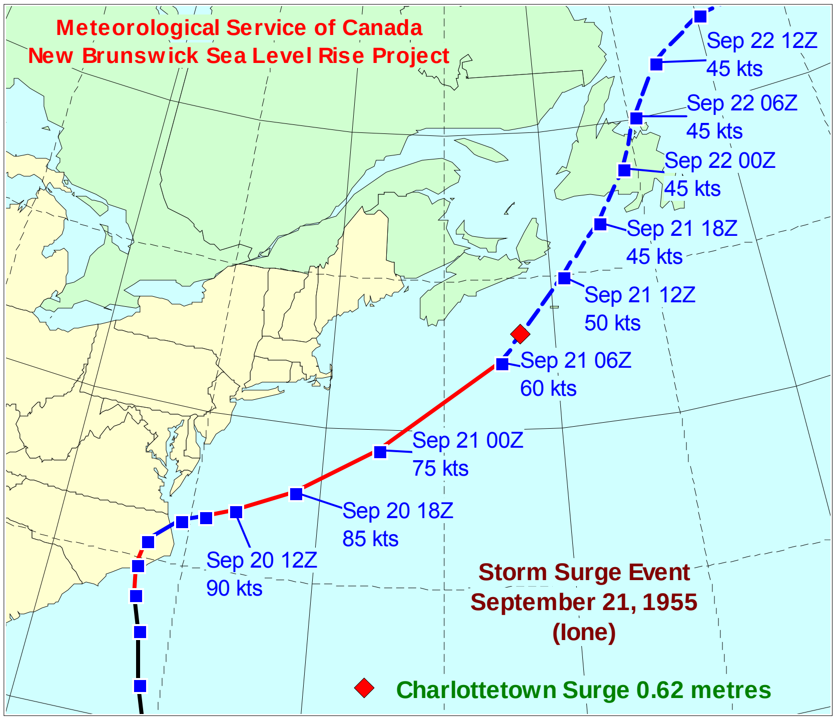
The following two maps provide a summary or spaghetti plot of the tracks that resulted in storm surges.

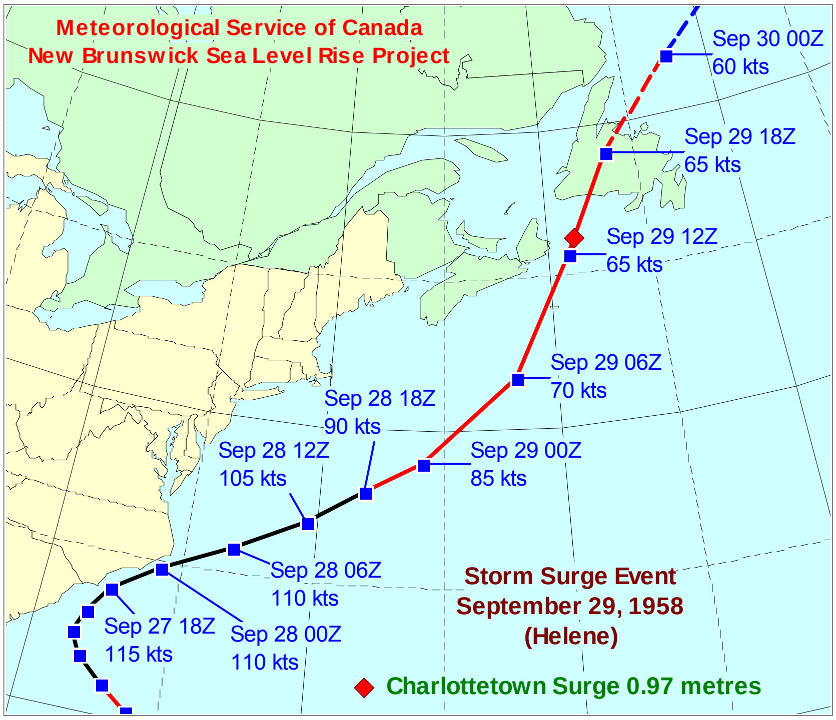


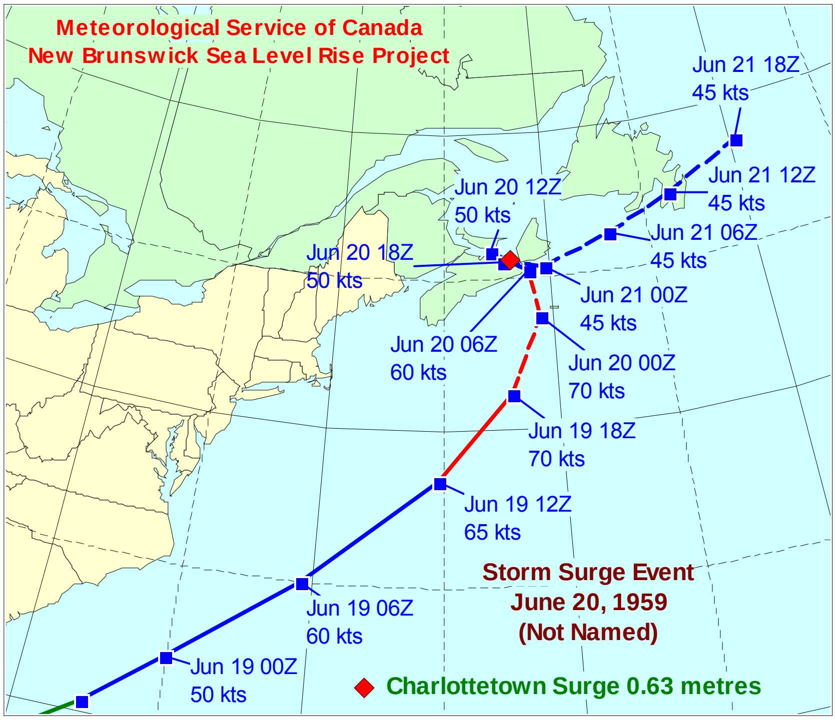


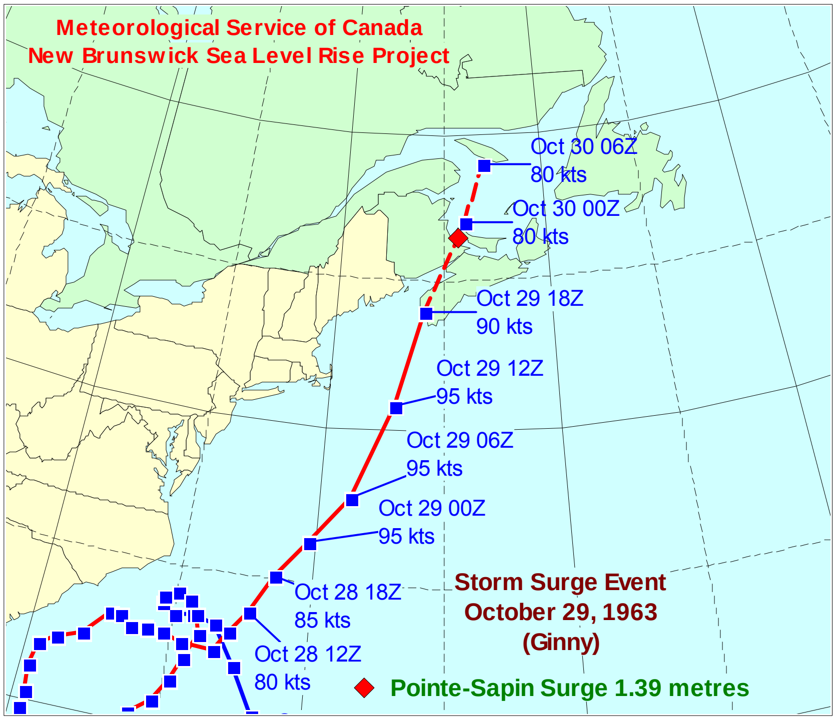

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 18 00Z
40 kts
Sep 18 06Z
35 kts
Sep 17 18Z
40 kts
Sep 17 12Z
45 kts
Sep 19 00Z
35 kts
Sep 18 12Z
35 kts
Sep 18 18Z
30 kts
Sep 17 06Z
55 kts
Sep 17 00Z
65 kts
Sep 16 18Z
70 kts
Sep 16 12Z
70 kts
Sep 16 06Z
75 kts
Sep 16 00Z
80 kts
Storm Surge Event
September 17, 1940
(Not Named)
Charlottetown Surge 0.77 metres

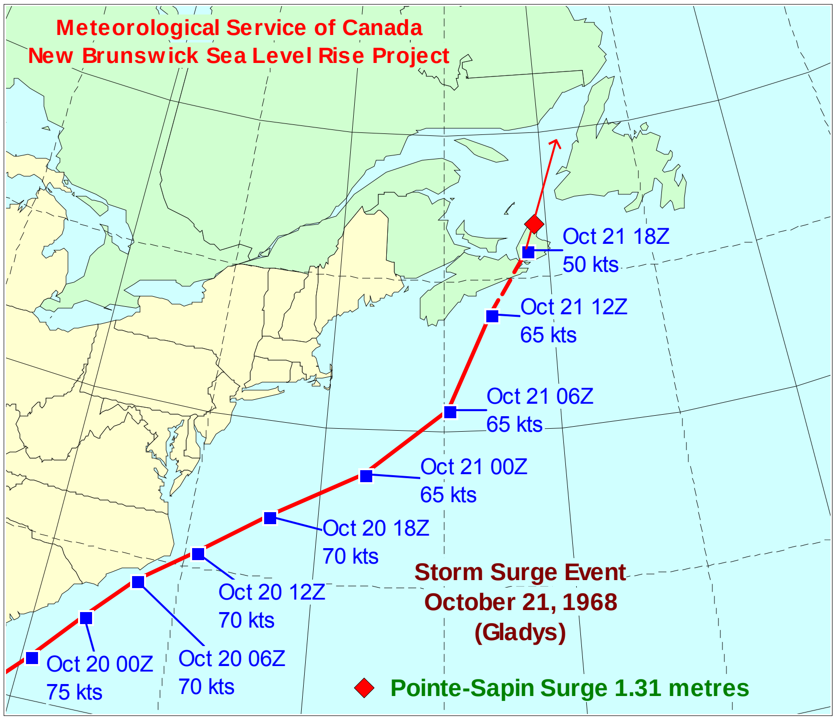

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 12 18Z
50 kts
Sep 12 12Z
55 kts
Sep 12 06Z
60 kts
Sep 12 00Z
65 kts
Sep 11 18Z
80 kts
Sep 11 12Z
90 kts
Sep 11 06Z
100 kts
Sep 11 00Z
105 kts
Storm Surge Event
September 12, 1954
(Edna)
Charlottetown Surge 0.75 metres

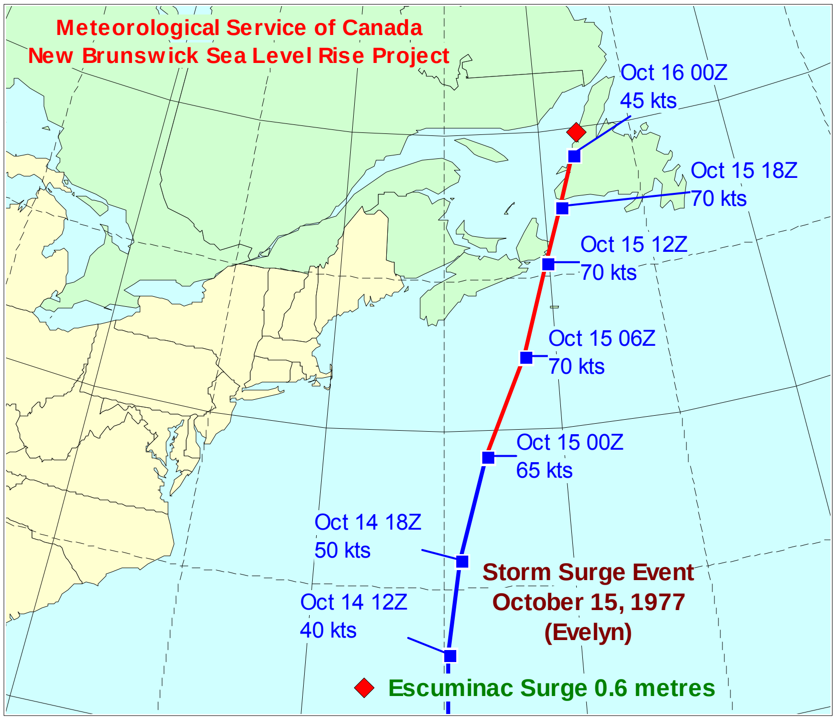

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 22 12Z
45 kts
Sep 22 06Z
45 kts
Sep 22 00Z
45 kts
Sep 21 18Z
45 kts
Sep 21 12Z
50 kts
Sep 21 06Z
60 kts
Sep 21 00Z
75 kts
Sep 20 18Z
85 kts
Sep 20 12Z
90 kts
Storm Surge Event
September 21, 1955
(Ione)
◆ Charlottetown Surge 0.62 metres

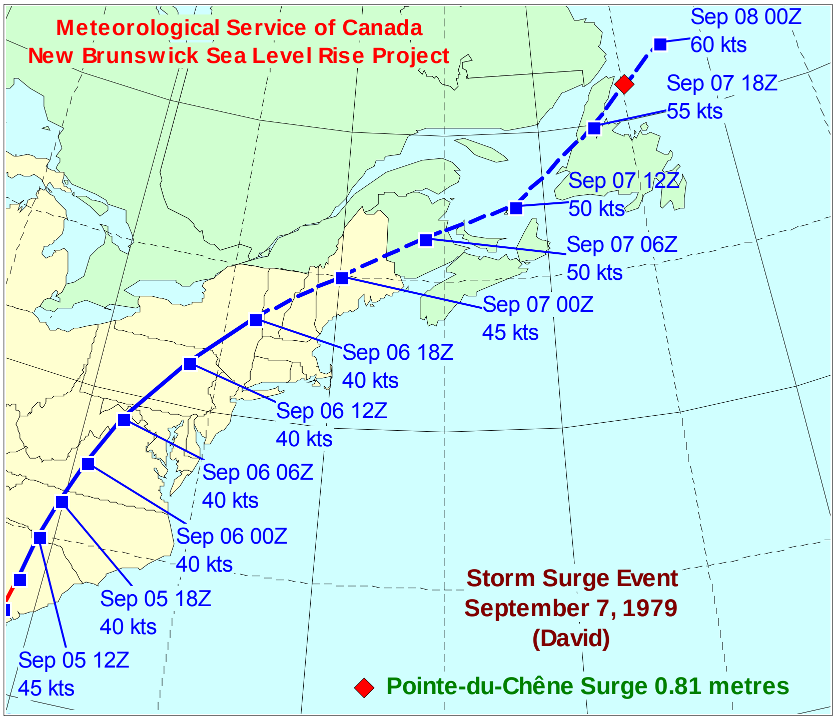

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 30 00Z
60 kts
Sep 29 18Z
65 kts
Sep 29 12Z
65 kts
Sep 29 06Z
70 kts
Sep 28 18Z
90 kts
Sep 28 12Z
105 kts
Sep 29 00Z
85 kts
Sep 28 06Z
110 kts
Sep 27 18Z
115 kts
Sep 28 00Z
110 kts
Storm Surge Event
September 29, 1958
(Helene)
◆ Charlottetown Surge 0.97 metres

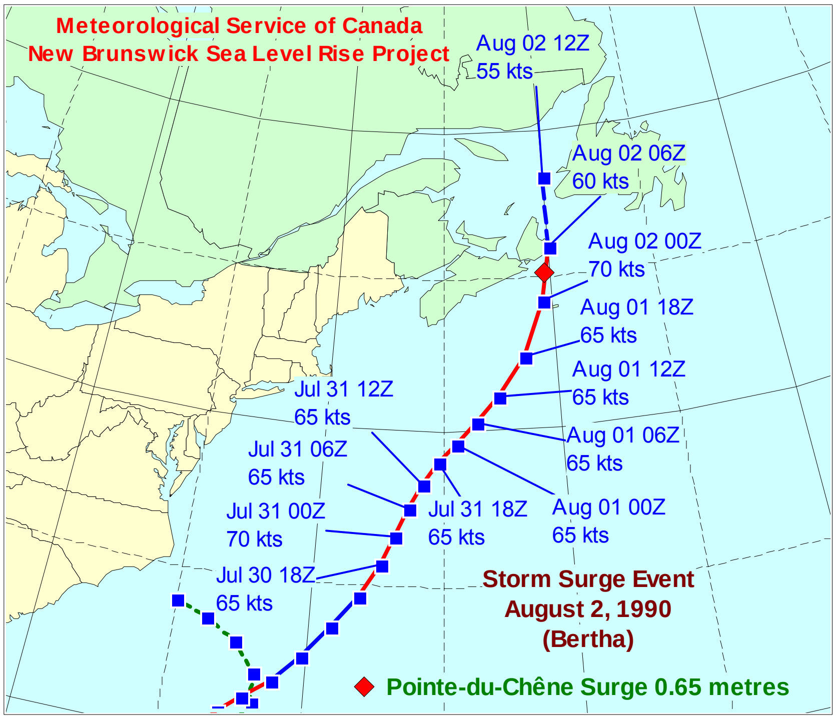

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Jun 21 18Z
45 kts
Jun 21 12Z
45 kts
Jun 20 12Z
50 kts
Jun 21 06Z
45 kts
Jun 20 18Z
50 kts
Jun 21 00Z
45 kts
Jun 20 06Z
60 kts
Jun 20 00Z
70 kts
Jun 19 18Z
70 kts
Jun 19 12Z
65 kts
Storm Surge Event
June 20, 1959
(Not Named)
Jun 19 06Z
60 kts
Jun 19 00Z
50 kts
◆ Charlottetown Surge 0.63 metres

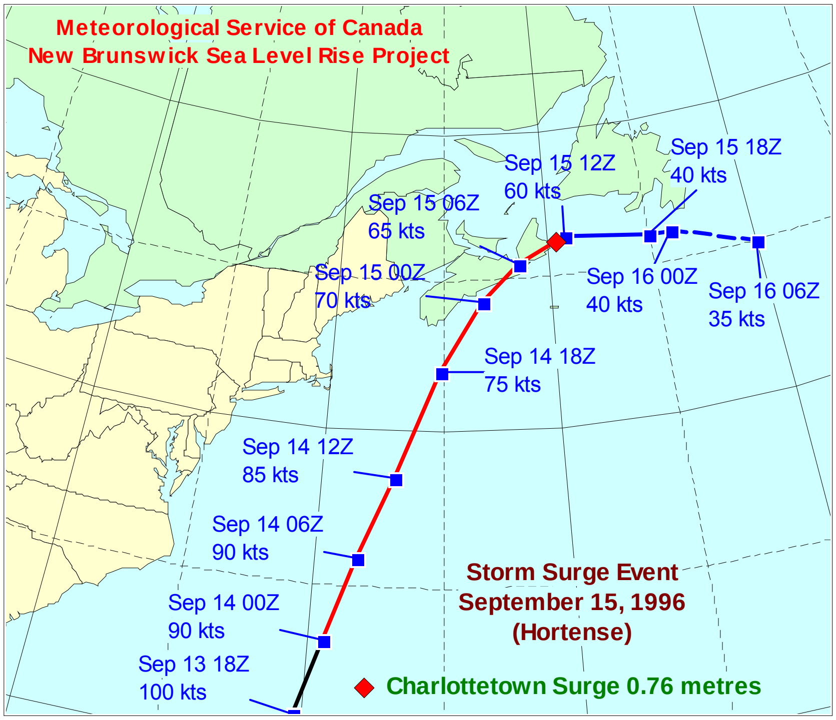

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 30 06Z
80 kts
Oct 30 00Z
80 kts
Oct 29 18Z
90 kts
Oct 29 12Z
95 kts
Oct 29 06Z
95 kts
Oct 29 00Z
95 kts
Oct 28 18Z
85 kts
Oct 28 12Z
80 kts
Storm Surge Event
October 29, 1963
(Ginny)
◆ Pointe-Sapin Surge 1.39 metres

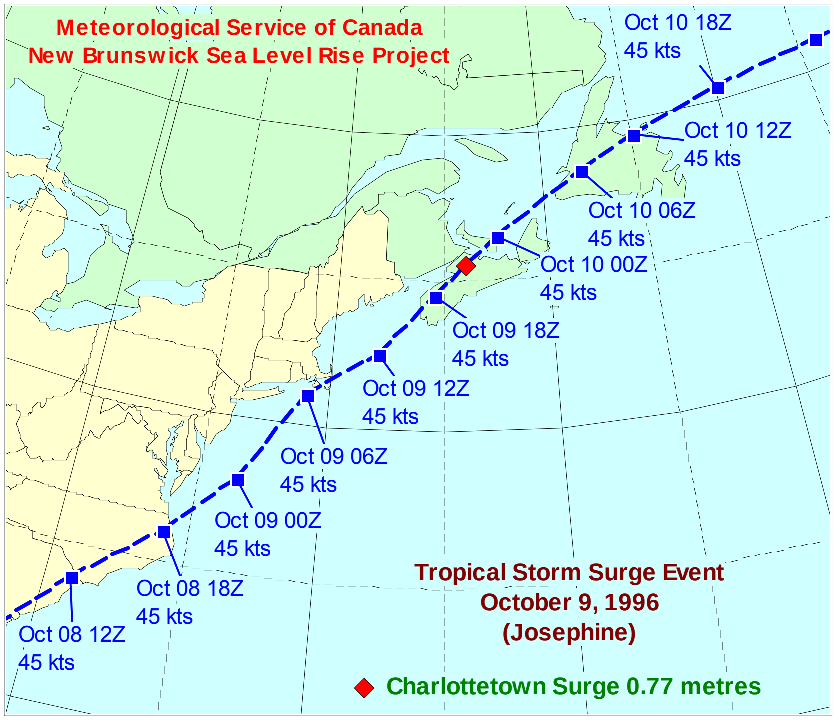

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 21 18Z
50 kts
Oct 21 12Z
65 kts
Oct 21 06Z
65 kts
Oct 21 00Z
65 kts
Oct 20 18Z
70 kts
Oct 20 12Z
70 kts
Oct 20 06Z
70 kts
Oct 20 00Z
75 kts
Storm Surge Event
October 21, 1968
(Gladys)
◆ Pointe-Sapin Surge 1.31 metres

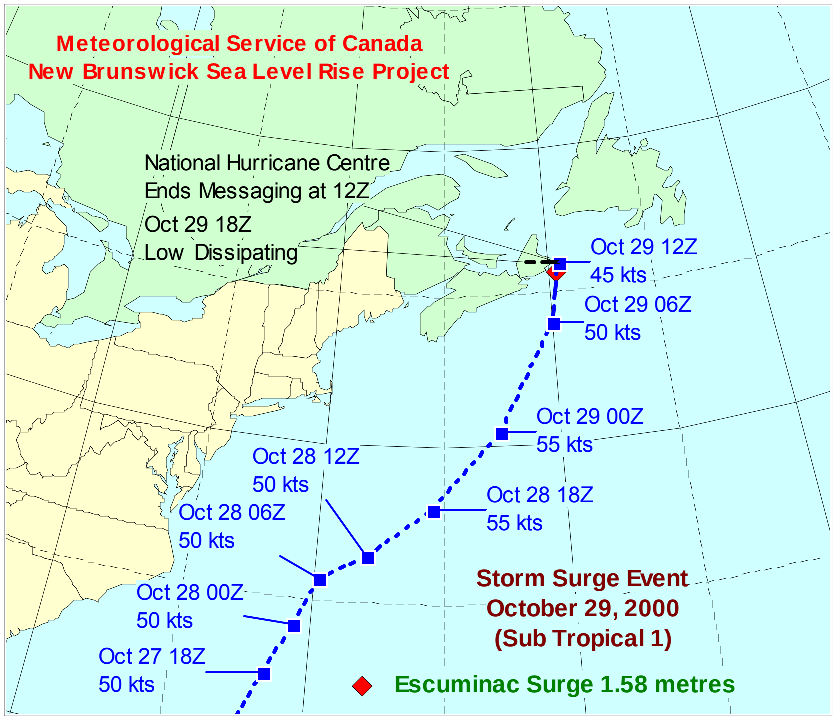

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 16 00Z
45 kts
Oct 15 18Z
70 kts
Oct 15 12Z
70 kts
Oct 15 06Z
70 kts
Oct 15 00Z
65 kts
Oct 14 18Z
50 kts
Oct 14 12Z
40 kts
Storm Surge Event
October 15, 1977
(Evelyn)
◆ Escuminac Surge 0.6 metres

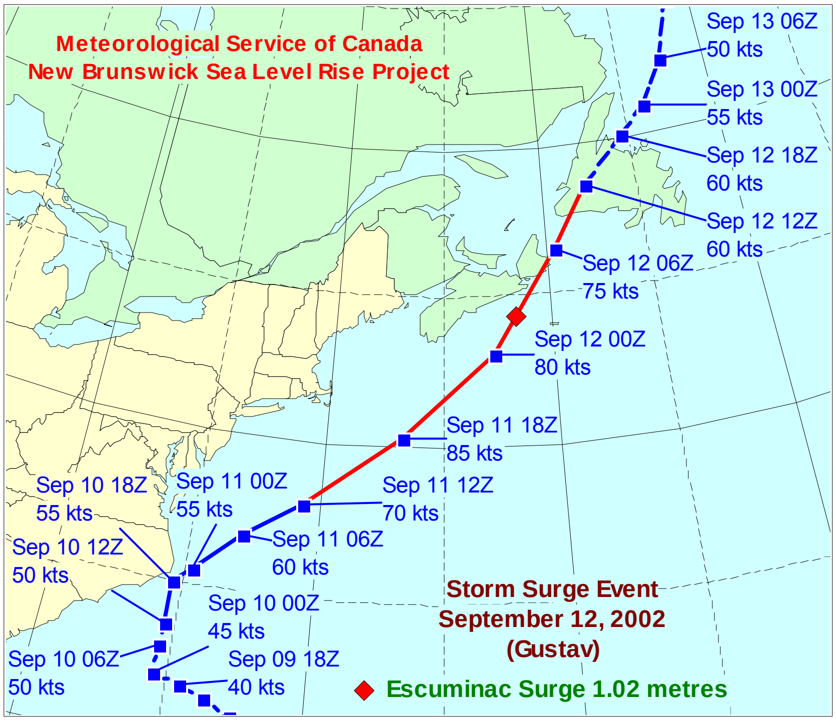

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 08 00Z
60 kts
Sep 07 18Z
55 kts
Sep 07 12Z
50 kts
Sep 07 06Z
50 kts
Sep 07 00Z
45 kts
Sep 06 18Z
40 kts
Sep 06 12Z
40 kts
Sep 06 06Z
40 kts
Sep 06 00Z
40 kts
Sep 05 18Z
40 kts
Sep 05 12Z
45 kts
Storm Surge Event
September 7, 1979
(David)
◆ Pointe-du-Chêne Surge 0.81 metres

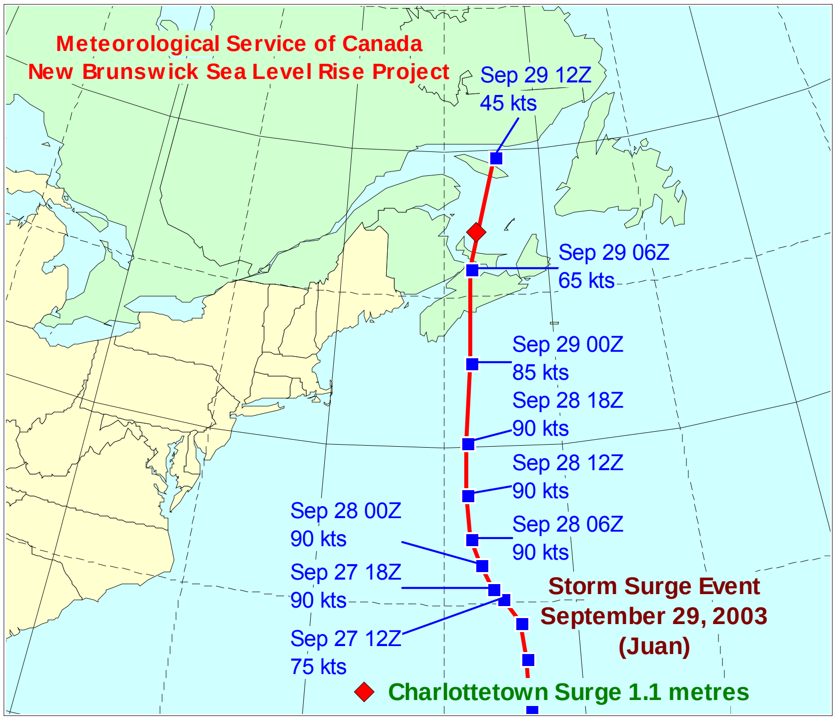

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Aug 02 12Z
55 kts
Aug 02 06Z
60 kts
Aug 02 00Z
70 kts
Aug 01 18Z
65 kts
Aug 01 12Z
65 kts
Aug 01 06Z
65 kts
Aug 01 00Z
65 kts
Jul 31 18Z
65 kts
Jul 31 12Z
65 kts
Jul 31 06Z
65 kts
Jul 31 00Z
70 kts
Jul 30 18Z
65 kts
Storm Surge Event
August 2, 1990
(Bertha)
◆ Pointe-du-Chêne Surge 0.65 metres

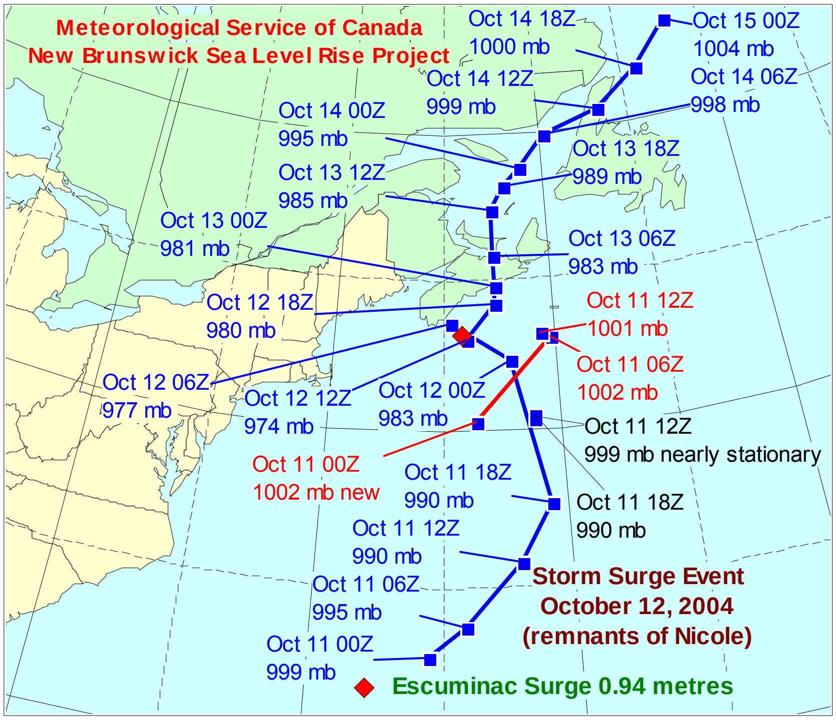

Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 15 12Z
60 kts
Sep 15 18Z
40 kts
Sep 15 06Z
65 kts
Sep 15 00Z
70 kts
Sep 16 00Z
40 kts
Sep 16 06Z
35 kts
Sep 14 18Z
75 kts
Sep 14 12Z
85 kts
Sep 14 06Z
90 kts
Sep 14 00Z
90 kts
Sep 13 18Z
100 kts
Storm Surge Event
September 15, 1996
(Hortense)
◆ Charlottetown Surge 0.76 metres


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 10 18Z
45 kts
Oct 10 12Z
45 kts
Oct 10 06Z
45 kts
Oct 10 00Z
45 kts
Oct 09 18Z
45 kts
Oct 09 12Z
45 kts
Oct 09 06Z
45 kts
Oct 09 00Z
45 kts
Oct 08 18Z
45 kts
Oct 08 12Z
45 kts
Tropical Storm Surge Event
October 9, 1996
(Josephine)
◆ Charlottetown Surge 0.77 metres


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
National Hurricane Centre
Ends Messaging at 12Z
Oct 29 18Z
Low Dissipating
Oct 29 12Z
45 kts
Oct 29 06Z
50 kts
Oct 29 00Z
55 kts
Oct 28 18Z
55 kts
Oct 28 12Z
50 kts
Oct 28 06Z
50 kts
Oct 28 00Z
50 kts
Oct 27 18Z
50 kts
Storm Surge Event
October 29, 2000
(Sub Tropical 1)
Escuminac Surge 1.58 metres


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 13 06Z
50 kts
Sep 13 00Z
55 kts
Sep 12 18Z
60 kts
Sep 12 12Z
60 kts
Sep 12 06Z
75 kts
Sep 12 00Z
80 kts
Sep 11 18Z
85 kts
Sep 11 12Z
70 kts
Sep 11 06Z
60 kts
Sep 11 00Z
55 kts
Sep 10 18Z
55 kts
Sep 10 12Z
50 kts
Sep 10 00Z
45 kts
Sep 10 06Z
50 kts
Sep 09 18Z
40 kts
Storm Surge Event
September 12, 2002
(Gustav)
Escuminac Surge 1.02 metres


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Sep 29 12Z
45 kts
Sep 29 06Z
65 kts
Sep 29 00Z
85 kts
Sep 28 18Z
90 kts
Sep 28 12Z
90 kts
Sep 28 00Z
90 kts
Sep 28 06Z
90 kts
Sep 27 18Z
90 kts
Storm Surge Event
September 29, 2003
(Juan)
Sep 27 12Z
75 kts
◆ Charlottetown Surge 1.1 metres


Meteorological Service of Canada
New Brunswick Sea Level Rise Project
Oct 14 18Z
1000 mb
Oct 15 00Z
1004 mb
Oct 14 12Z
999 mb
Oct 14 06Z
998 mb
Oct 14 00Z
995 mb
Oct 13 18Z
989 mb
Oct 13 12Z
985 mb
Oct 13 00Z
981 mb
Oct 13 06Z
983 mb
Oct 12 18Z
980 mb
Oct 11 12Z
1001 mb
Oct 11 06Z
1002 mb
Oct 12 06Z
977 mb
Oct 12 12Z
974 mb
Oct 12 00Z
983 mb
Oct 11 12Z
999 mb nearly stationary
Oct 11 00Z
1002 mb new
Oct 11 18Z
990 mb
Oct 11 18Z
990 mb
Oct 11 12Z
990 mb
Storm Surge Event
October 12, 2004
(remnants of Nicole)
Oct 11 06Z
995 mb
Oct 11 00Z
999 mb
◆ Escuminac Surge 0.94 metres

4.3 Storm-surge and meteorological modelling

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4.3.1 Background

The coastlines of the southern Gulf of St. Lawrence are highly vulnerable to flooding. This has been clearly demonstrated by recent flooding events in southern New Brunswick and Prince Edward Island that have attracted much media attention. This vulnerability has led to concern over possible climate-change scenarios that predict an accelerating rate of rise of global sea level from the present value of 1–2 mm/year to a probable value of 5 mm/year over the next century. Such an acceleration will exacerbate the problem of coastal flooding and increase the need for more effective mitigation and adaptation strategies.

The objectives of this component of the project were to conduct storm-surge, meteorological and statistical modelling in order to quantify the impacts of climate change — more specifically, sea-level rise and storm intensity — for the Gulf of St. Lawrence coastal zone of southeastern New Brunswick.

The project involved three main types of activity:

- modelling of storm surges and their validation by direct comparison against independent sea-level observations in the study region;
- analysis of trends and extremes of all long sea-level records for the region; and
- upgrades to near real-time, web-based display of storm-surge forecasts and their validation against observed sea level in the study area.

In Section 4.3.2, we describe the installation of two new tide gauges that provided the independent sea-level observations used to test the forecast skill of the Dalhousie storm-surge model used in this study. In Section 4.3.3, we define critical flood levels for Shediac, and in Section 4.3.4, we describe the storm-surge model and give an indication of the skill of its one- and two-day forecasts of water levels. In Section 4.3.5, the surge model is used to reconstruct storm surges for the last 40 years for the whole of the eastern seaboard of Canada. In Section 4.3.6, the return periods of total water levels (tide plus surge) are calculated from observed hourly sea-level data and compared with corresponding results based on the 40-year reconstruction of surges and predicted tides. We also make projections about how such return levels might change under plausible climate-change scenarios; this type of information is critical for the design of sensible strategies for adapting to climate change. In Section 4.3.7, we discuss the improvement of the web-based display of short-term sea-level forecasts; this type of information is needed to mitigate the effect of flooding by a particular storm. In Section 4.3.8, we show how flood-risk probabilities from observed sea-level records, or results from the surge model, can be visualized at the municipal level using a digital elevation model (DEM). Conclusions are offered in Section 4.3.9.

4.3.2 Sea-level observations: installation of coastal tide gauges

Dalhousie University has developed a storm-surge model that is used operationally by Environment Canada to forecast coastal flooding (see Section 4.3.4). The model has shown significant skill, with lead times of up to 48 hours, and the resulting storm-surge advisories and warnings have proved to be extremely useful to provincial emergency measures offices in their disaster management activities.

To further improve the storm-surge model's forecasts and also develop a realistic set of risk scenarios under a changing climate, it is first necessary to rigorously assess the quality of the forecasts using independent sea-level observations. Results from a well-validated model can then allow an analysis of the threats to critical infrastructure by global sea-level rise using a geographic information system (GIS). This, in turn, leads to a better understanding of the implications of current and future flooding for disaster-management activities (e.g., mitigation through land use or structural reinforcement, evacuation routes and first-responder activities).

To collect the independent sea-level data required for model validation, new tide gauges were installed in 2003 at Pointe-du-Chêne and Wood Islands by the Canadian Hydrographic Service (CHS) (contact Charles O'Reilly) specifically for the purposes of this study. The tide gauges and data loggers were supplied by Dr. K. Thompson (with support from the Canadian Foundation for Innovation). Funding for the installation, testing and operation of the gauges was provided by Environment Canada (contact Jim Abraham). Hourly sea-level data from these gauges, along with additional data from the permanent tide-gauge network of Atlantic Canada, have been used to test the forecast skill of the storm-surge model, as described in Section 4.3.4.

The Pointe-du-Chêne location was chosen because of its direct relevance to this project. The Wood Islands location was chosen for two reasons. First, it is sufficiently close to Pointe-du-Chêne to provide an indication, along with the Charlottetown tide gauge, of the spatial variability of the surge distribution on scales of the order of 100 km. Second, this gauge is located at the Wood Islands Ferry terminal. It has been clear from recent news reports that the safe operation of this ferry service can be compromised by negative storm surges — i.e., anomalously low water levels caused by the anomalous meteorological forcing. The forecast skill of the surge model in this region is thus relevant for safe navigation in the Northumberland Strait. Figures 1 and 2 show the tide gauge hut at Wood Islands and its location on the wharf.

Figure 1. Tide-gauge hut, tide-gauge recorder and logger at the Wood Islands site. Photograph kindly provided by Fred Carmichael (CHS).

Figure 2. Tide-gauge hut on the side of the wharf at the Wood Islands site. Photograph kindly provided by Fred Carmichael (CHS).

4.3.3 Flooding levels for southeastern New Brunswick

Early in the project, Don Forbes, George Parkes, Hal Ritchie and Keith Thompson developed a set of recommended flooding levels for the Centre of Geographic Sciences (COGS) to use with the DEM for southeastern New Brunswick. Similar to the earlier analysis for Charlottetown, it was recommended that there be two main levels considered for illustration purposes at Pointe-du-Chêne:

1. *Extreme observed value*: 3.6 m above Chart Datum (CD). This is the current best estimate of the high-water-level value for the January 21, 2000, storm, which was clearly the highest flooding event observed in the region.

2. *Moderate climate-change scenario*: 4.2 m above CD. This would correspond to a moderate 100-year rise of 50 cm global sea level plus 10 cm of crustal subsidence.

4.3.4 Storm-surge model and its validation

The initial storm-surge model was developed at Dalhousie University (Bobanovic and Thompson, 2001) and passed to Environment Canada for operational use. In research mode, we are also using an equivalent modified version of the Princeton Ocean Model (Mellor, 1998). It is based on the depth-averaged, barotropic momentum and continuity equations, which are not repeated here but can be found in these references. The model predicts depth-averaged, horizontal ocean currents and the change in sea level, or surge, due to storms. It is forced by variations in surface air pressure and the surface wind stress computed from the atmospheric winds at a height of 10 m. It is also forced by the bottom stress that depends on the depth-averaged horizontal ocean current and a prescribed bottom drag coefficient. The model domain extends from 38°N to 60°N and from 72°W to 42°W (see Figure 7 below). It therefore includes the Labrador and Newfoundland shelves, Gulf of St. Lawrence, Scotian Shelf, Bay of Fundy and Gulf of Maine. The model resolution is 1/12°, which corresponds to a latitudinal resolution of about 9 km. A radiation boundary condition is applied to the model's open boundaries. More detail is available in the previously mentioned references.

For operational forecasting, the atmospheric surface pressure and surface winds (required to calculate the wind stress) are provided by the operational Meteorological Service of Canada atmospheric forecast model. For the 40-year reconstruction presented in Section 4.3.5, the atmospheric driving fields are the AES40 surface wind data (Swail and Cox, 2000) and deduced surface pressures (see same section).

In the next section, we present results of the validation of the storm-surge modelling system, based on the observations from the new gauges installed at Pointe-du-Chêne and Wood Islands. The two new gauges internally record sea-level observations every 15 minutes on a Sutron data logger. The Marine Environmental Data Service (MEDS) automatically downloads the new stored data for each day, carries out quality control, places data in its archive and forwards the observations to the Centre for Marine Environmental Prediction at Dalhousie University. The data are also made available to the general public. After reaching Dalhousie University, the sea-level data from MEDS are further error-checked, and the predicted tide is removed to leave the so-called "residual" (i.e., the part left behind after subtraction of the tide). The hourly sea levels and residuals are then plotted and compared against the 48-hour forecasts made by the Dalhousie storm-surge model, which runs every day, driven by forecast surface winds and pressures provided routinely by Environment Canada.

A typical plot of the observed sea level for Shediac (for the month of October 2004) is shown in Figure 3. (The complete record can be seen at http://www.cmep.ca.) The black line in the top panel shows the observed hourly sea level. It is clearly a mixture of diurnal and semi-diurnal tides with a range of about 2 m. (The tide is due to the gravitational pull of the sun and moon and can be readily calculated using a standard tidal analysis package of an observed hourly sea-level record.) The blue line in the top panel shows the residual — i.e., the difference between the observed sea level and the predicted tide. The hourly changes of the residual are due primarily to changes in air pressure and wind stress acting over the shelf seas of Atlantic Canada and are forecast with the surge model. The red line in the top panel shows the 0- to 24-hour forecasts from the surge model. Note the close agreement between the red and blue lines: this demonstrates that the surge model has useful skill in predicting surges 24 hours into the future.

The bottom panel of Figure 3 shows the observed hourly water level for Shediac (same as top panel) and the 24-hour forecast of total water level (red line) based on summing the surge forecast and the predicted tide. The blue line is the error in forecasting the total level one day into the future. (A statistical model is used to forecast errors in the local mean and remnant tidal energy left in the residuals.)

The 24-hour forecast skill of the model at Pointe-du-Chêne is generally reasonable (the standard deviation of the forecast error is less than about 10 cm). It is similar to the skill of the model at Charlottetown, the site of a gauge from the permanent tide-gauge network of Atlantic Canada.

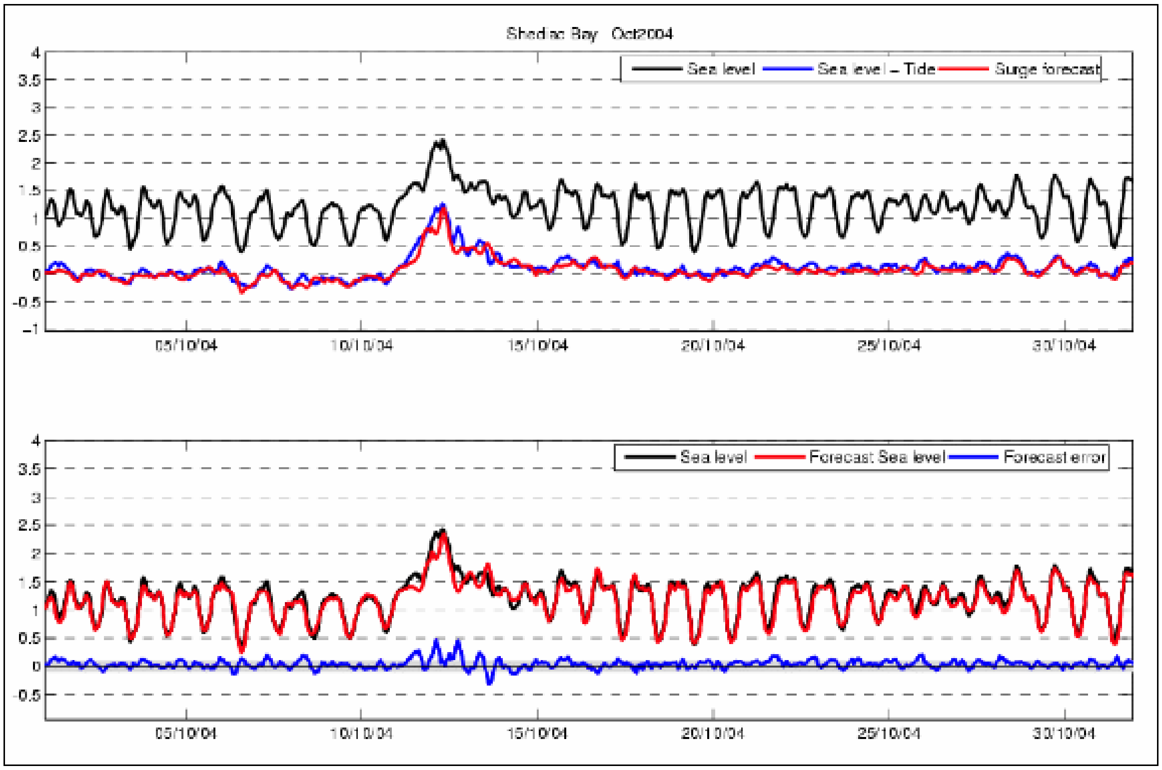

Figure 3. Observed sea level, and the forecasts from the storm-surge model, for Shediac for October 2004. Top panel: Black line (observed sea level), blue line (residual, i.e., observed sea level — predicted tide), red line (0- to 24-hour forecast from the storm-surge model). Bottom panel: Black line (observed sea level), red line (0- to 24-hour forecast of the total water level), blue line (0- to 24-hour forecast error.

Figure 4 shows the forecast skill of the model in December 2004 when a strong storm hit the Atlantic provinces. The agreement between observed and predicted models is quite good for the times for which we have reliable data. Note that it appears that the Pointe-du-Chêne gauge malfunctioned just after the peak of the storm surge in late December. This is confirmed by Figure 5, which shows the forecast skill of the model for the same period but at Wood Islands, a nearby gauge.

Overall, results of the validation using independent sea-level data show that the performance of the surge model in the southern Gulf of St. Lawrence is quite good, with forecast error standard deviation less than 10 cm.

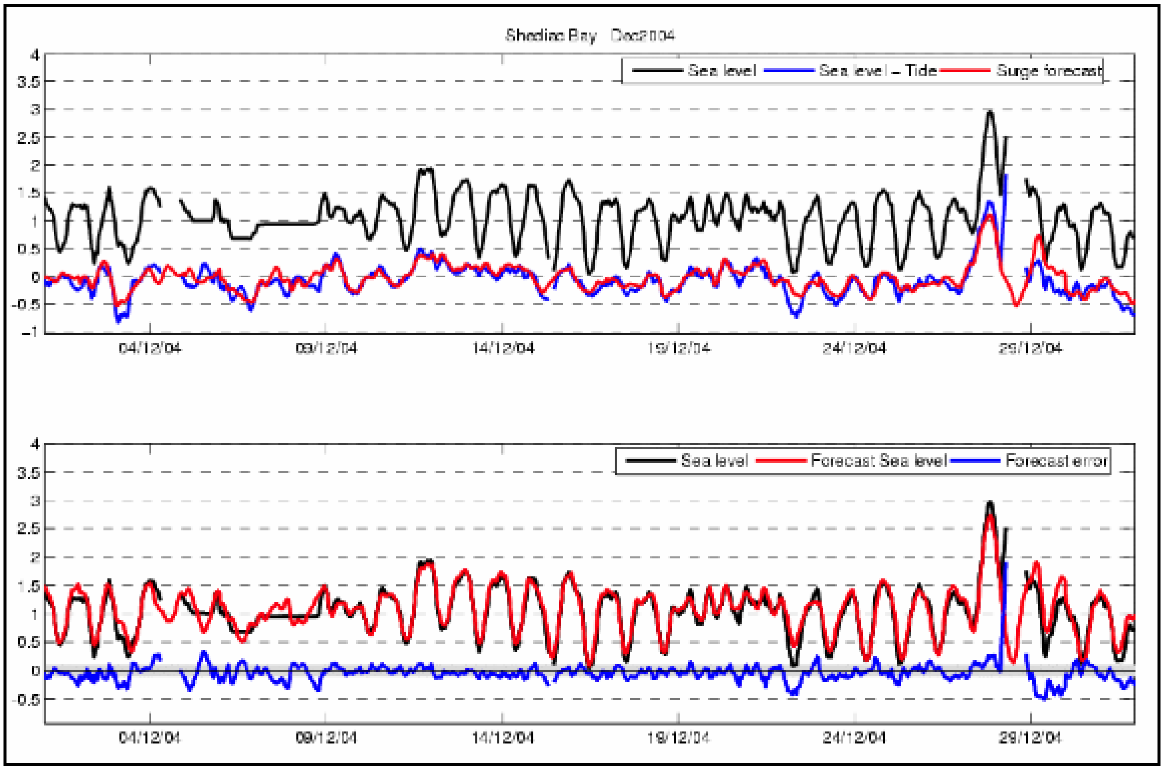

Figure 4. Same as for Figure 3, but for Shediac, December 2004.

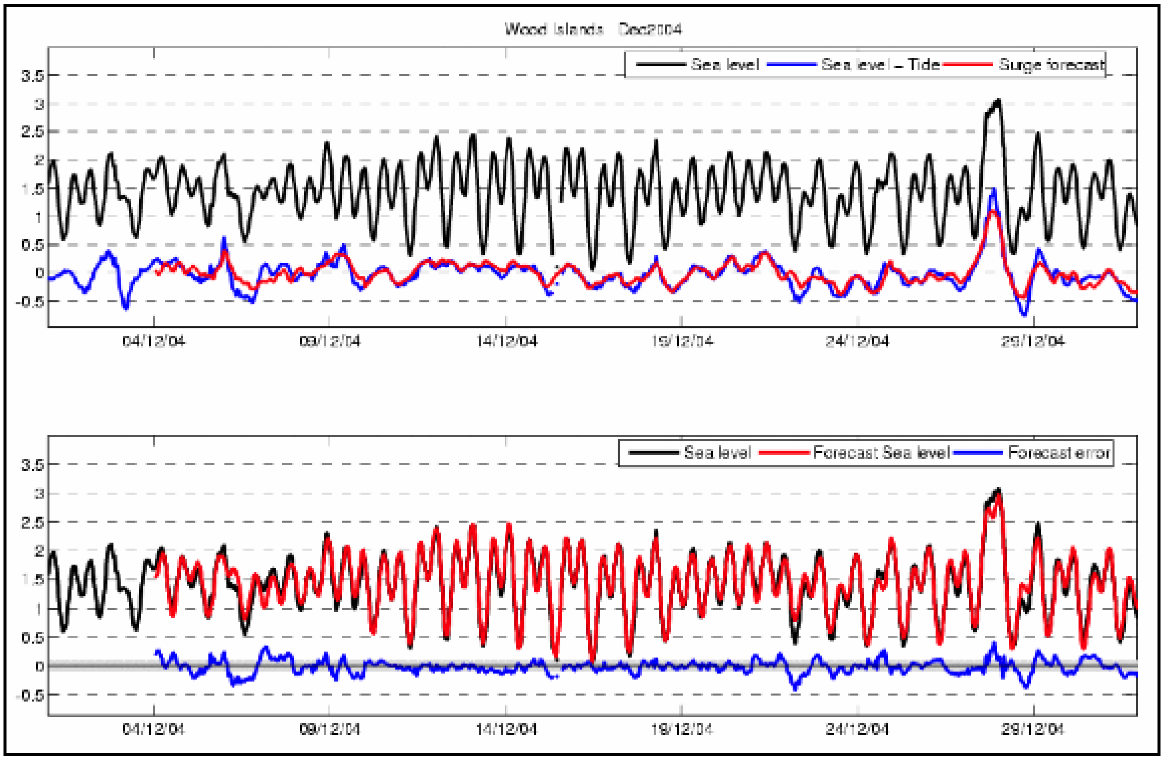

Figure 5. Same as for Figure 3, but for Wood Islands, December 2004.

4.3.5 Forty-year storm-surge reconstruction

In this section, we describe the use of the validated surge model to reconstruct sea-level changes over the last 40 years at every point in the Northwest Atlantic model domain. These simulated data are then used to identify areas that are currently at risk and how that risk might change over the next century.

Long time series of gridded fields of surface wind and air pressure are necessary to produce storm-surge reconstructions. In recent years, atmospheric reanalyses have made these fields available. However, most multidecadal surface winds and pressure fields are available only at low resolution and are therefore not suitable for a study ultimately focused on extreme sea-level events. The AES40 wind fields are an exception.

AES40 wind fields are available for more than four decades and at a relatively high resolution. They are, therefore, the most suitable winds for this study at this time. Unfortunately, AES40 was produced to perform wave hindcasts and therefore does not contain pressure fields. The pressure fields must therefore be inferred from the wind fields. The winds used to drive the model were obtained from the AES40 data set (Swail and Cox, 2000). The fields cover the North Atlantic (0°N to 75°N, 83°W to 20°E) and are available every six hours from 1958 to 2000 with a horizontal resolution of 0.625° in latitude and 0.833° in longitude. The generation of the AES40 winds by Swail et al. (2000) started with first-guess fields from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996). These fields were first evaluated and adjusted by trained meteorologists based on comparison with wind observations. The adjusted fields were then further modified after assessing the performance of a wave model driven by the adjusted winds. In total, over 10 000 hours were spent by trained meteorologists subjectively improving the NCEP reanalysis winds. Validation studies suggest that the AES40 winds have a bias of about 0.3 m/s and an error standard deviation of about 1.2 m/s (Swail et al., 2000).

As mentioned above, the AES40 wind fields were produced with the ultimate goal of reconstructing North Atlantic waves, and no attention was paid to the calculation of the pressure fields. Pressure fields are, however, essential to storm-surge modelling. Pressure fields from other reanalyses (e.g., NCEP/NCAR) are available, but are too coarse for the study of extreme events. We therefore decided to dynamically retrieve (infer) the pressure fields from the AES40 wind fields.

The theory for dynamic retrieval was first implemented by Gal-Chen (1978) and has since been used to generate pressure fields from Doppler radar observations (e.g., Gal-Chen and Kropfli, 1984; Parsons et al., 1987; Liou, 2001). In the present case, we assume that the horizontal pressure gradient above the planetary boundary layer is given by:

$$-\frac{1}{\rho}\nabla p_a = \frac{\partial \vec{u}}{\partial t} + (\zeta + f)\vec{k} \times \vec{u} + \frac{1}{2}\nabla |\vec{u}|^2 \tag{1}$$

where p_a is the atmospheric pressure, $\vec{u}$ represents the gradient wind, f is the Coriolis parameter, ζ is the vorticity and $\vec{k}$ is the upward-pointing vector. The basic idea is to use the AES40 winds to calculate the right-hand side of (1) and thus to retrieve the pressure fields. This is done by first taking the divergence of the equation to obtain an elliptical equation for pressure. All terms containing $\vec{u}$ are evaluated using AES40 surface winds. The elliptical equation is then solved about some arbitrary constant using successive over-relaxation. Details of such numerical methods are readily available (e.g., Press et al., 1986).

The difficulty in using AES40 winds to estimate the divergence of the right-hand side of (1) is that it does not represent the winds just above the planetary boundary layer. The AES40 winds are 10-m winds. These surface winds must therefore be brought up through the planetary boundary layer before they can be used to solve the elliptic equation.

In order to compute the most accurate transfer function (i.e., the cross-isobar angles and amplitude factors between surface winds and winds just above the planetary boundary layer), the NCEP/NCAR six-hourly reanalyzed surface wind and pressure fields were used (Kalnay et al., 1996). First, six-hourly geostrophic winds were derived from the NCEP/NCAR pressure fields for the 1990–1999 period. All six-hourly 10-m surface and calculated geostrophic winds were then gathered for a 10-year period (1990–1999 inclusively), and a transfer function was calculated to obtain the cross-isobar angle and scaling factor that best minimized the errors over the period of one month. The relationships thus obtained vary smoothly from month to month and between years. The 10-yearly values obtained for each month were therefore averaged to provide the cross-isobar angle and amplitude scaling factor for each month of the year.

The transfer functions were used to bring the AES40 surface wind fields out of the planetary boundary layer, providing the winds necessary to solve for the pressure fields. Twenty-nine land stations (all not used in the retrieval process) and 23 Coastal-Marine Automated Network (C-MAN) and buoy records were used to validate the pressure fields. This is illustrated in Figure 6. The standard deviation of the error of the predicted pressure field is 2.65 mb, thereby validating the method used here.

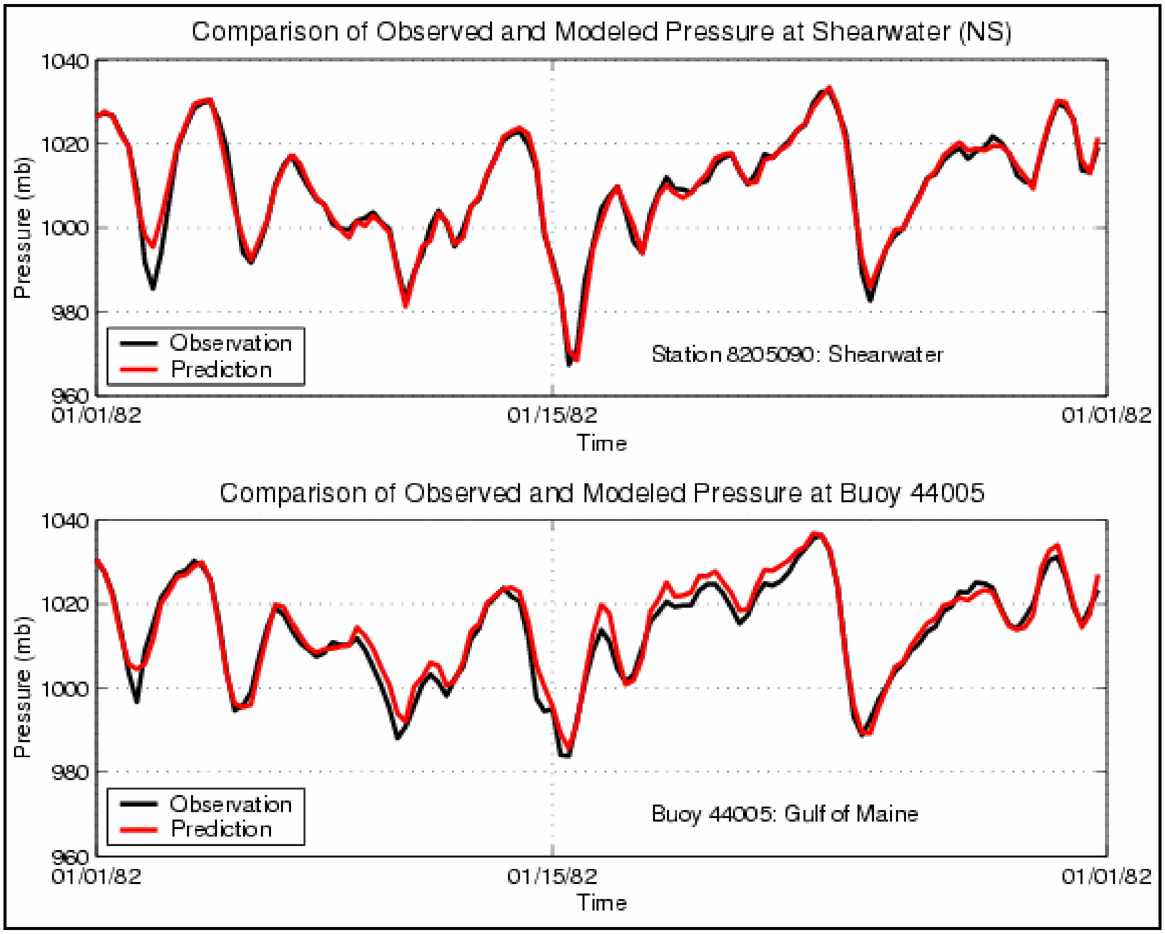

Figure 6. Time series of observed (black) and inferred (red) surface pressures for January 1982. The top panel shows the time series at Shearwater. The bottom panel shows the time series at Buoy 44005 (located in the Gulf of Maine) for the same period.

4.3.5.1 Reconstructed surges and their accuracy

The storm-surge model was run for the Northwest Atlantic (Figure 7) for the period 1960–1999, driven by the AES40 winds and inferred air pressures. The results are hourly maps of sea levels. This is illustrated in the top two rows of Figure 8. To validate the 40-year hindcast, the model surges were compared with observed residuals (observed sea levels minus tides) filtered to remove high-frequency signals not resolved by the model (i.e., periods shorter than 12 hours are not resolved due to Nyquist frequency of 12 hours associated with the 6-hourly wind and pressure forcings). Overall, there was generally good agreement between the surge hindcasts and the observed sea-level residuals, as illustrated in the bottom panel of Figure 8. Clearly, the model reproduces well the amplitude of the large storm event. The frequency-dependent structure of the hindcast surges also generally compares well with that of the observed residuals (compare the black and red lines).

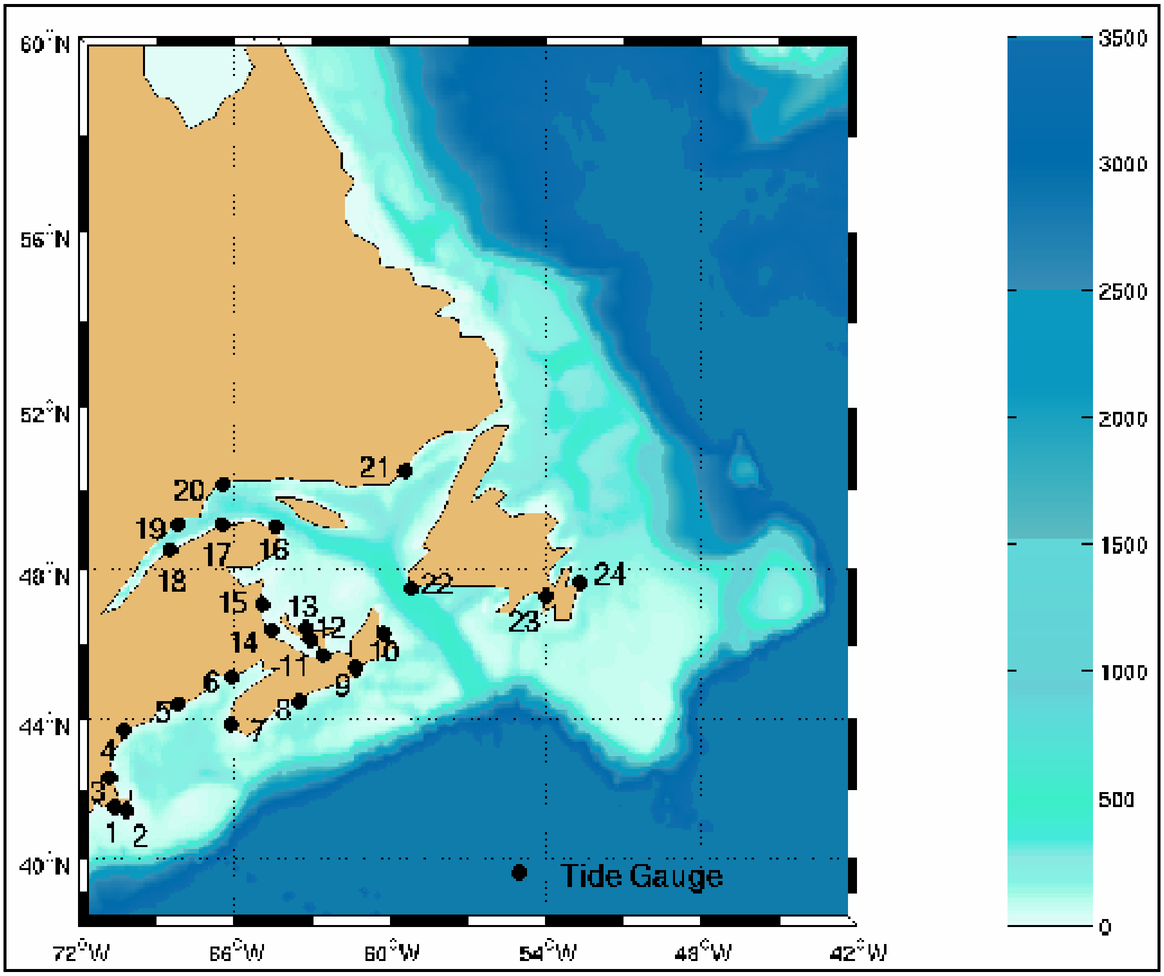

Figure 7. Domain of the storm-surge model and location of tide gauges. The colours indicate the model depth in metres. The dots mark the location of the tide gauges providing hourly sea-level data for validation of the storm-surge hindcasts (see Table 1 below). The numbers are station codes used for this study.

The comparison of the hindcast surges and observed residuals presented in Figure 8 is typical. We were also encouraged to find that the hindcast error remained relatively constant when calculated separately for each year of the 40-year reconstruction. The standard deviation of the forecast error is typically less than 10 cm. As sea level is an integrator of wind and pressure forcing, a fairly constant hindcast error implies that the accuracy of AES40 winds and the inferred air pressures is fairly stable over the study period.

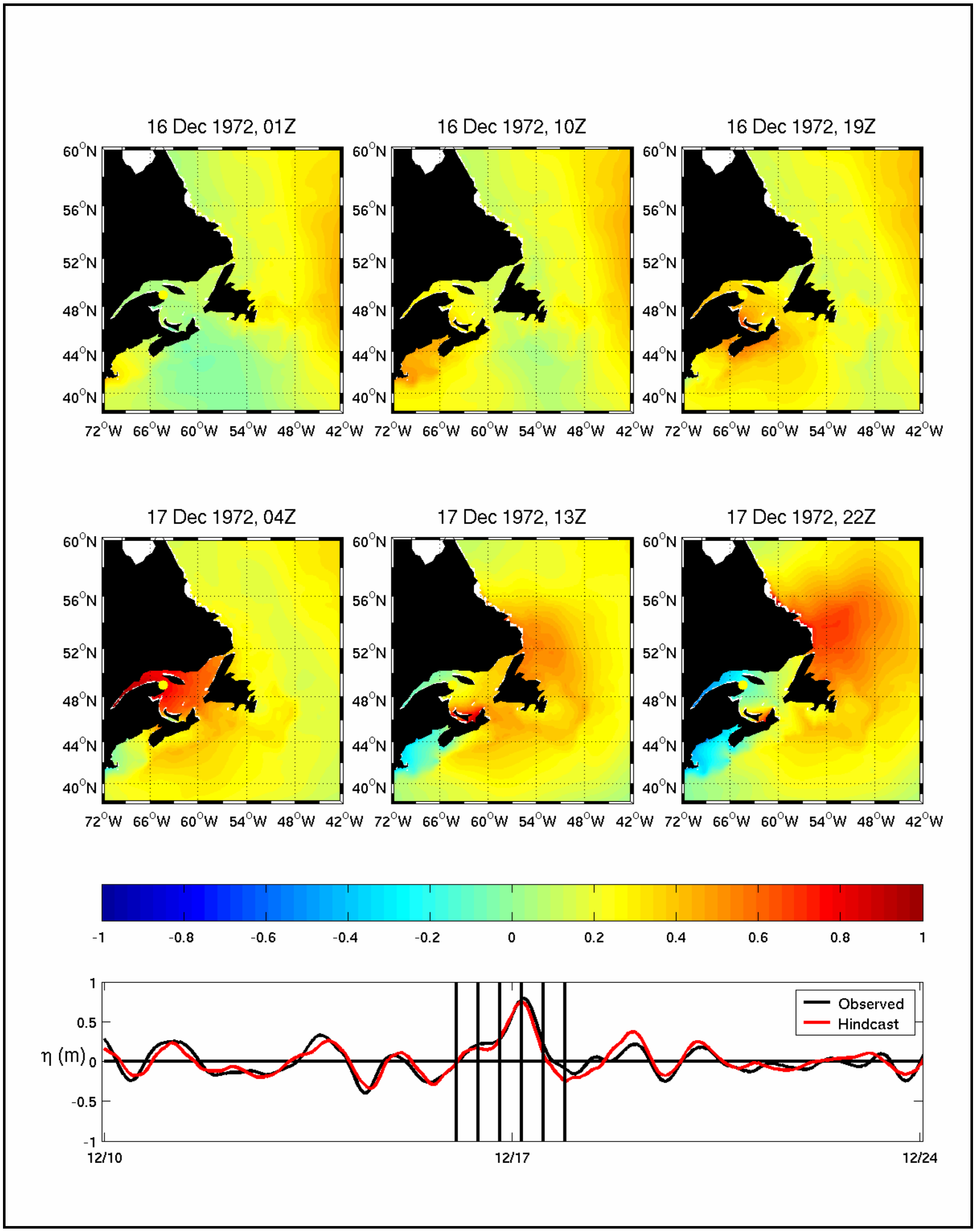

Figure 8. Evolution of the surge event of December 1972. The top six panels are snapshots of the hindcast surges taken nine hours apart. The colourbar is surge levels in metres. The bottom panel shows the observed filtered residuals (black) and the hindcast surges (red) at the gauge location marked by the yellow dot. The series cover two weeks surrounding the surge event of December 17, 1972. The vertical lines mark the times at which the snapshots are taken.

4.3.5.2 Extremal analysis of observed and reconstructed surges

The focus of the present study is the distribution of extreme surges and sea levels. This means that although small errors in the timing of hindcast surges may lead to large hindcast errors, such timing errors will have little effect on the extreme surges. The return periods of observed residuals and hindcast surges were therefore calculated for all stations. This is illustrated in Figure 9 using the observation records of Charlottetown and Saint John. Extreme residual maxima and minima can be compared using Figure 9. At first glance, it is obvious that the slope of the maxima (or, alternatively, the difference between the 2-year and the 40-year return level) is often more pronounced for the maxima than for the minima. At most stations, the absolute values of the smallest annual maxima are larger than those of the annual minima. The slopes also differ, with the slope of the maxima exceeding the slope of the minima (minus sign put aside) at 18 of the 24 stations. Note that five of the six stations with larger minima range are located along the St. Lawrence River. The largest differences in range of maxima to minima are found at the southernmost stations, where hurricanes are known to lead to extreme positive residuals. The larger range in maxima is in general agreement with skewness in the forcing fields (Bernier, 2005). Other factors, such as an increase in apparent bed friction associated with decrease in water depth during large negative surge events, can act to limit the amplitude of surges and lead to larger positive than negative surges.

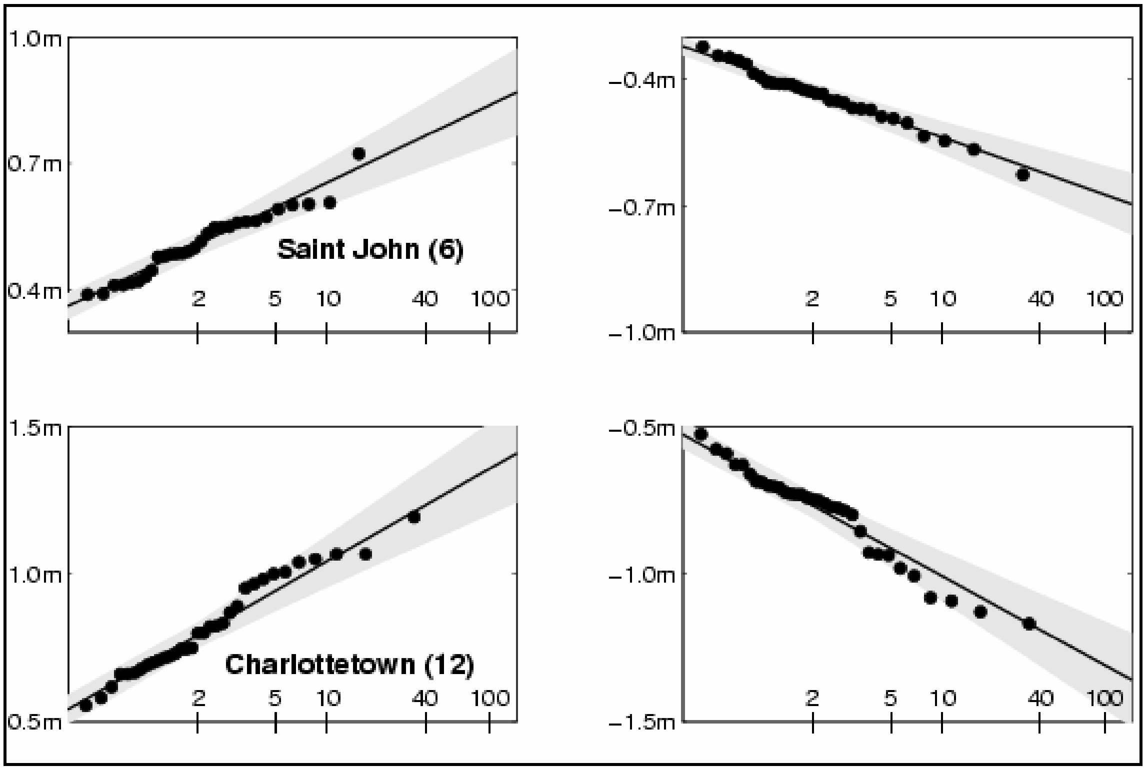

Figure 9. Return period of observed extreme residuals. The x-axis is the return period in years. The y-axis is the critical return level in metres. The dots are the ordered observed residual annual maxima (left column) and annual minima (right column), available between 1960 and 1999. The lines were fit using maximum likelihood. Shaded areas mark the 95% confidence intervals obtained using the delta method. Note the difference in the range of maxima and minima.

To validate the model with respect to extreme surges, we compared the 40-year return level of hindcast surges (bottom panels of Figure 10), calculated from a Type I extremal analysis, with the 40-year return level of the filtered residuals (top panels of Figure 10).

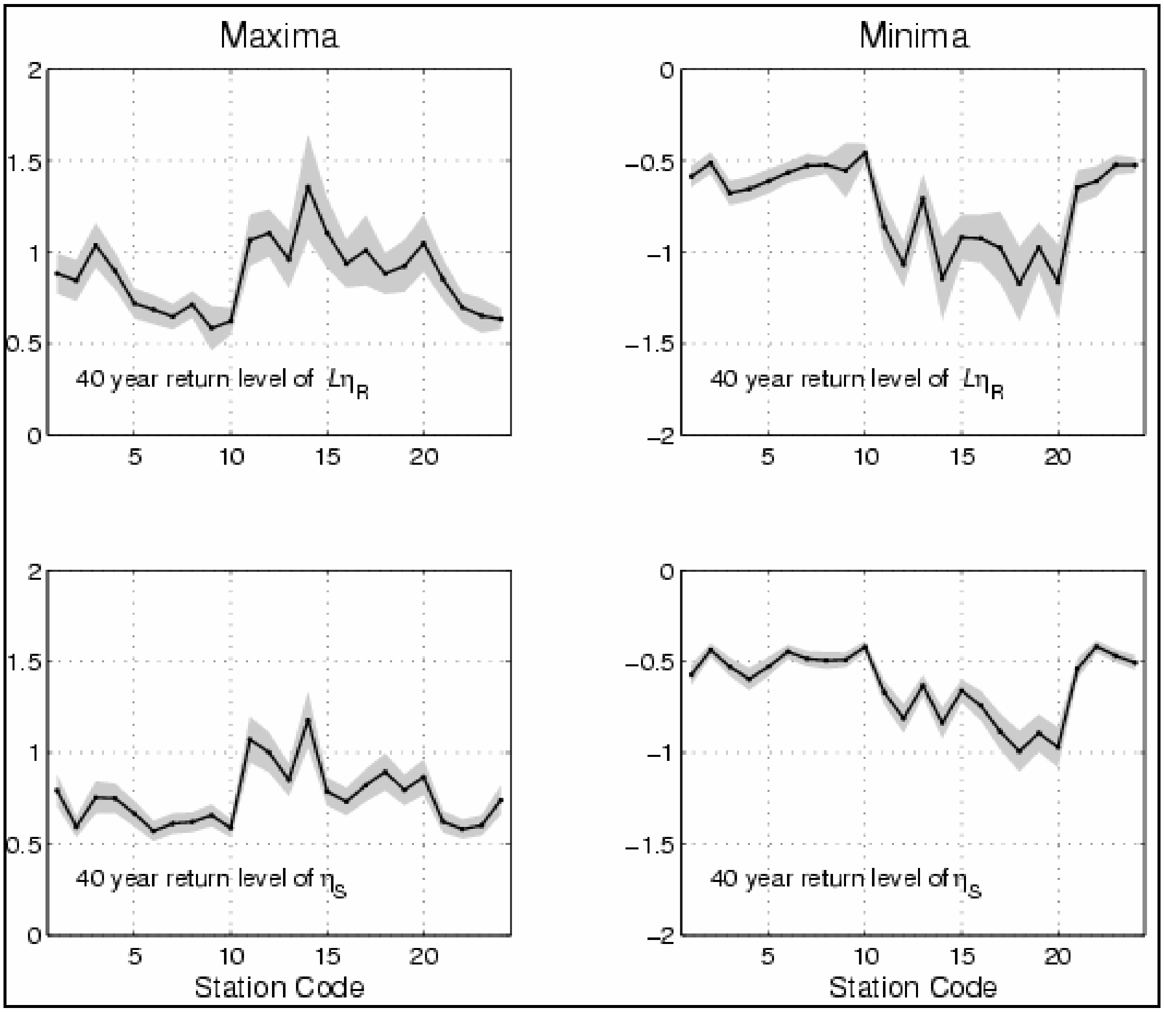

Figure 10. Forty-year return level of positive and negative residuals. The x-axis shows the station code (Figure 7). The y-axis is the 40-year return level in metres calculated from the Type I extremal distribution fit to the adjusted annual maxima (left) and minima (right), as shown in Figure 9. The shaded areas mark the 95% confidence intervals at return period of 40 years. The top left panel shows the observed positive return levels. The bottom left panel shows the hindcast positive return levels. The top right panel shows the observed negative return levels. The bottom right panel shows the hindcast negative return levels. The largest return levels are observed in the Gulf of St. Lawrence region. In general, the bottom panels exhibit the same station-to-station variability as the top panels. At some stations, the model underestimates the 40-year return level; overall, however, the model captures the spatial signal and leads to return levels that are within the confidence intervals of the observed return levels for both maxima and minima.

The predicted return levels have a spatial pattern that is similar to the observed return levels. There is a slight tendency to underestimate the 40-year return level; however, we were encouraged to find that our estimates are usually within the confidence interval of the observed return levels. The differences are most evident at Boston, Saint John and Shediac Bay (compare right panels of Figure 10). At Boston, two of the largest events are associated with hurricanes (in general, the resolution of our forcing fields is too coarse to resolve hurricanes, and we therefore underestimate such events). At Boston and Saint John, differences may also be due to horizontal model resolution and the difficulty associated with modelling harbour effects. At Shediac Bay, the difference in return periods is likely primarily the result of comparing an extremal analysis based on a 12-year record with an extremal analysis based on a 40-year record.

Given the overall reasonable agreement between the return periods of the observed residuals and model hindcasts, we made a map of the 40-year return level for the study area (Figure 11). It is the first time such a map has been generated. This map was obtained by fitting a Type I distribution to the 40-annual maxima at every grid point. Figure 11 highlights the spatial variability in the 40-year return levels.

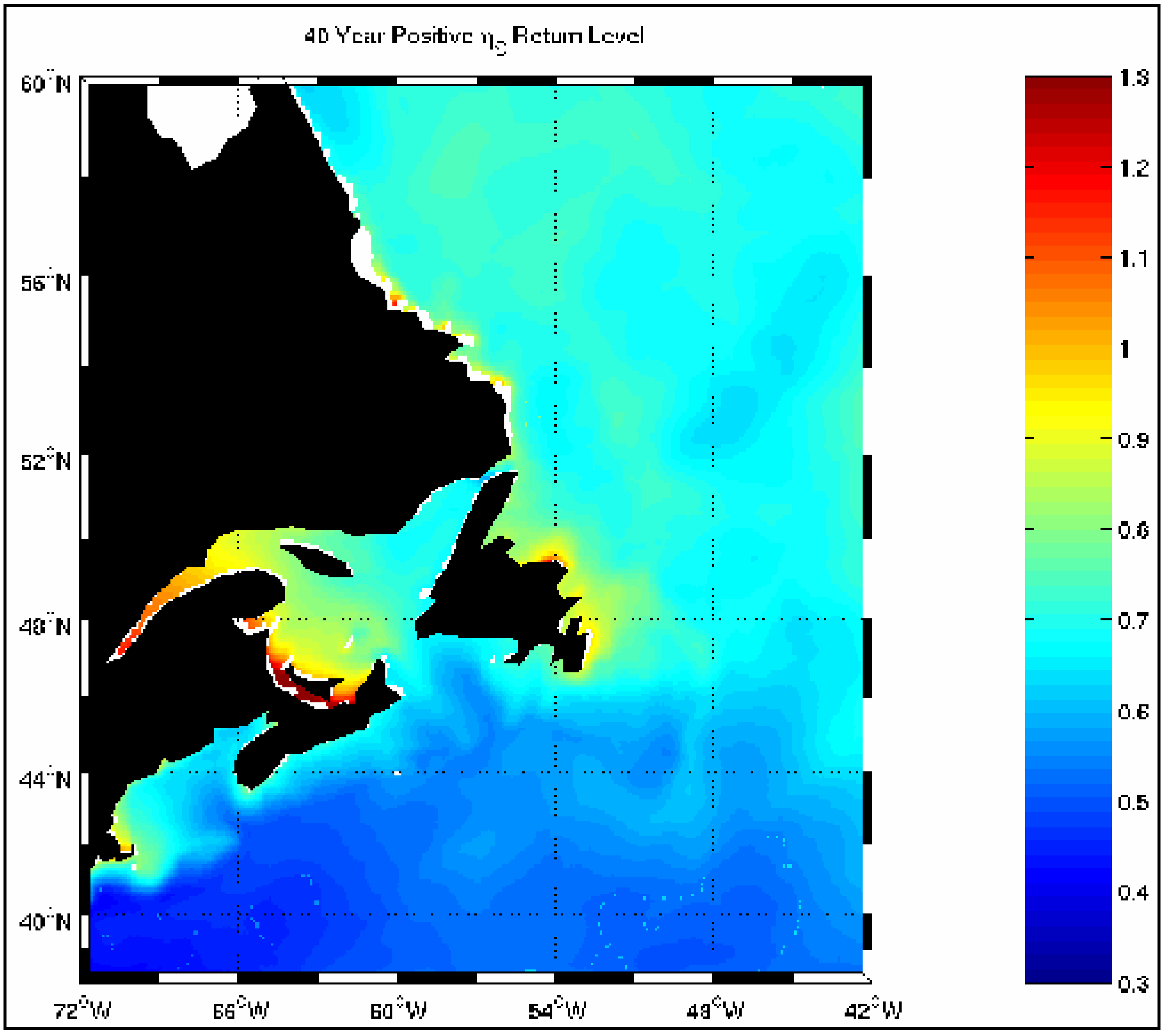

Figure 11. Forty-year hindcast-surge maxima return level based on the 40-year hindcast. The colourbar indicates the 40-year positive surge return levels in metres. The graph shows significant

spatial variability. The most extreme surge events are expected to occur in the coastal regions highlighted by the warmest colours.

4.3.5.3 Multidecadal trends in extreme surges

In this section, the presence of trends in the annual maxima and minima is investigated.

The Type I extremal distribution is commonly used in the study of sea-level records (e.g., Dixon and Tawn, 1999; Lowe et al, 2001; Woodworth and Blackman, 2002; Bernier and Thompson, submitted; Bernier et al., submitted). It has the following form:

$$\Pr(M_n < \eta_c) = \exp\{-\exp[-(\eta_c - a_n)/b_n]\} \tag{2}$$

where $\Pr$ is a probability, M_n is the maxima of a sequence of *n* independent, identically distributed random variables, η_c is the critical level, a_n is a location parameter and b_n is a scale parameter. There are two parameters in (2) that can be allowed to vary with time: the location parameter a_n, a measure of the mean, and the scale parameter b_n, a measure of the spread (Coles, 2001).

Trends in the location parameter $a_n = a_{n0} + a_{n1}t$, where t denotes time and a_{n0}, a_{n1} are parameters estimated from the observed annual maxima or minima (see Coles, 2001, or Bernier, 2005, for details), were calculated at every grid point of the hindcast for both maxima and minima. The trends in residual maxima are significantly different from 0 at only 3 of 24 stations, with a median rate of −0.4 mm/year. The trend in hindcast maxima a_{n1}^{+} is negative over the region except over the Labrador Shelf and Labrador Sea and in the northeastern Gulf of St. Lawrence (top left panel of Figure 12). Few points have trends significantly different from 0 (bottom left panel of Figure 12). Together, however, they suggest that there has been a slight, but large spatial scale, decrease in extreme positive surges over the period 1960–1999.

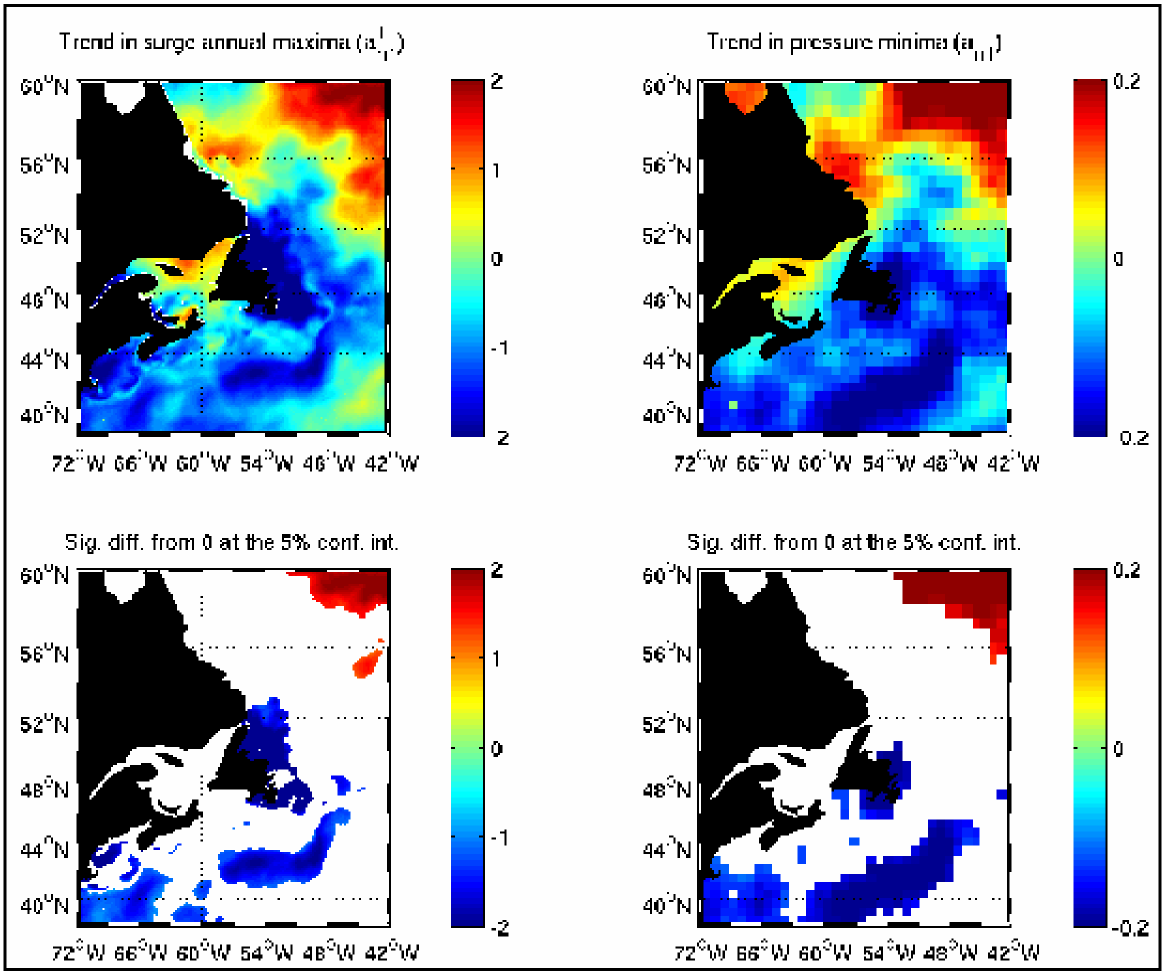

Figure 12. Trends in hindcast-surge annual maxima and pressure annual minima. The colourbar indicates the trends in location parameter (in mm/year for the left column and in mb/year for the right column), with negative values indicating that extremes are becoming less extreme. The left panels are the trends in hindcast-surge maxima, with the bottom panel showing only trends that are significantly different from 0 at the 5% significance level. The right panels are the same, but for the trends in pressure annual minima (which lead to surge maxima through the inverted barometer effect). Note how the spatial variability in the trends of surge maxima matches that of the pressure minima. Note also that the range in trends is similar, predominantly negative and significant over the same regions for both surges and pressures. The factor of 10 difference between the left and right columns is due to the inverted barometer effect.

The trends in residual minima are significantly different from zero at only 4 of 24 stations, with a median rate of 0.1 mm/year. Note here that a positive trend implies that negative surges are becoming more negative. Trends in minima a^{-}_{n1} were also calculated at every grid point of the hindcast (not shown). As for the maxima, few points have trends significantly different from zero. The generally positive trends in surge annual minima therefore indicate that the amplitudes of the minima are increasing with time.

To further explore the origin of the trends in surge annual maxima and minima, trends were also fitted to the annual pressure minima and maxima (e.g., right column of Figure 12). The trends in minima are based on departure from a fixed pressure value such that a negative trend indicates a decrease in the occurrence of low-pressure systems. Note how the region of positive trend in annual minima (bottom right panel of Figure 12) covers the same region, and has the same magnitude, as the trend in surge maxima (bottom left panel). The trends in pressure maxima (associated with anticyclones) are positive, indicating an increase in high-pressure systems. The trends in surge minima are significant and also positive over the same region (not shown). This implies that the trends in both sea-level minima and maxima not only are present in the pressure fields, but also have the same temporal and spatial signals. Thus, it appears that the trends in surge maxima and minima are primarily driven by changes in the pressure fields. More precisely, it is likely that a tendency to higher highs and less intense lows is causing the trends in surge maxima and minima.

4.3.6 Trend and extremal analyses of total water levels

The observed hourly sea-level records for the 24 locations were subject to thorough quality control prior to analysis, including visual inspection of all large recorded values. All records used in this study have a minimum of 10 years of observations between 1960 and 1999. The long-term means were removed from all records prior to analysis.

Estimates of the frequency of coastal flooding are typically based on the analysis of annual maxima. The application of the theory is illustrated for Charlottetown, one of the few locations in the study region with a long (1938 to present) and fairly complete observation record. The annual maxima and minima (about the annual mean) were first extracted from the record (top panel of Figure 13). Note the difference in the interannual variability of the maxima and the minima and the offset between the mean sea level and the extremes. The latter reflects the effect of the tides at Charlottetown.

The maxima and minima were ordered and plotted on Type I probability paper. The dots show the annual maxima (bottom left panel of Figure 13) and annual minima (bottom right panel of Figure 13). The lines were fitted using maximum likelihood. The shaded areas mark the 95% confidence intervals obtained using the delta method (e.g., Coles, 2001). Note the difference in the slope of the return-level line (e.g., the difference between the 2-year and the 40-year return period) of the maxima and minima. The largest differences in the slopes of maxima to minima are found at the southernmost stations, where hurricanes are known to lead to extreme positive residuals. Other factors, such as an increase in apparent bed friction associated with a decrease in water depth during large negative residual events, can limit the amplitude of residuals (e.g., Grant and Madsen, 1979) and lead to larger positive than negative residuals.

The annual maxima about the corresponding annual mean for Charlottetown are also shown in Figure 13. The linear trend in location parameter, based on 1960–1999 annual maxima, is −2.0 mm/year. Linear trends in the location parameter of the Type I extremal distribution, calculated for all remaining stations, reveal that only one station has a trend that is significantly different from zero. However, it is noticeable that 18 out of 24 stations have negative trends, with a median rate of −1.8 mm/year. This suggests that for this region, there has been a slight, but large spatial scale, decrease in the maxima over the period 1960–1999.

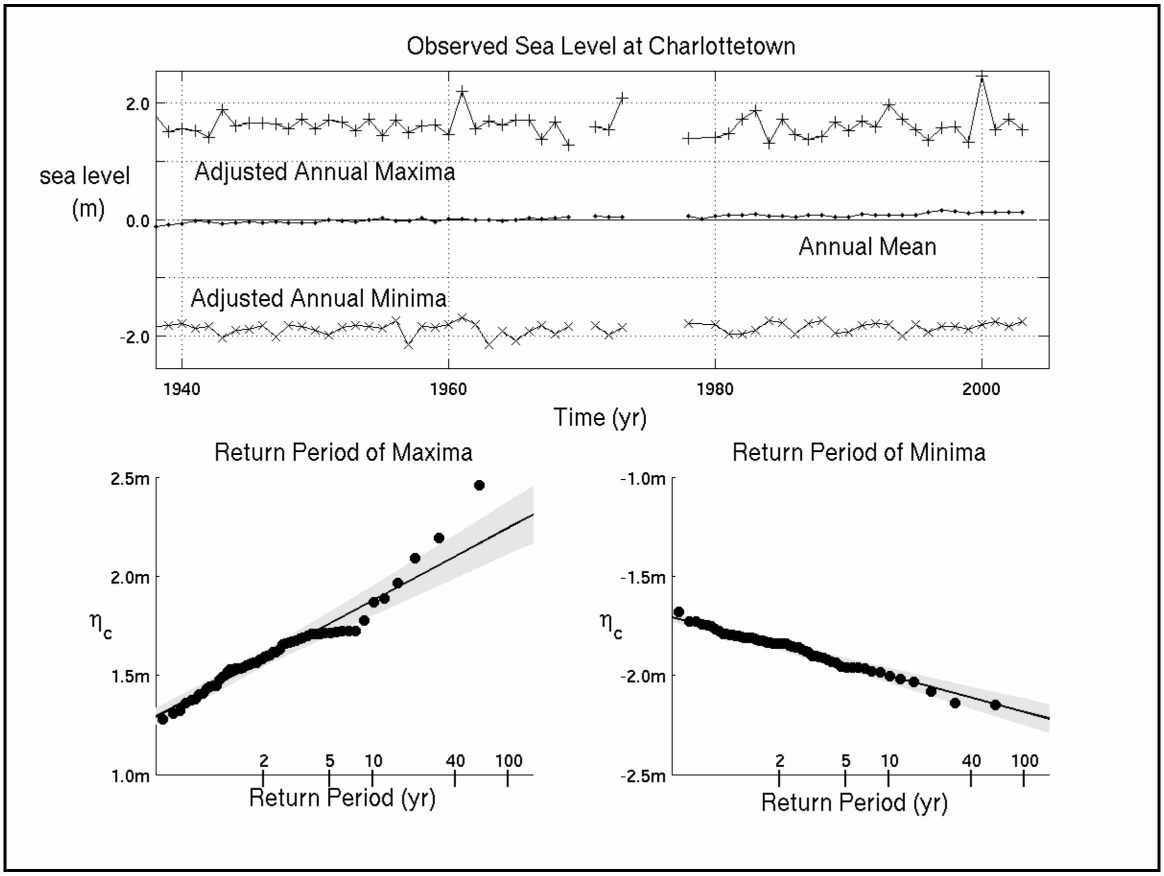

Figure 13. Observed sea level at Charlottetown. The top panel shows the annual mean about the long-term mean in metres. Note the trend in annual means. The adjusted annual maxima and annual minima are also plotted. The average difference between the means and maxima and minima is due in large part to the tides. The bottom two panels are Type I plots of the maxima and minima about the annual means. The x-axes are the return period in years, and the y-axes are the return level in metres. The dots are the ordered, observed adjusted annual maxima (bottom left panel) and observed annual minima (bottom right panel) from 1938 to 2004.

The annual minima about the corresponding annual mean for Charlottetown are also presented in Figure 13. The linear trend in location parameter, based on 1960–1999 annual minima, is 0.7 mm/year. The trend is not significantly different from zero at the 5% significance level. A similar analysis for the remaining stations reveals that only two stations have a trend that is significantly different from zero, with a median rate of −0.9 mm/year.

The trends in location parameter for the adjusted annual maxima and minima show somewhat similar spatial patterns, although they differ from those found for the residual maxima and minima. Such differences were expected. One reason is that the timing of surges' annual maxima and minima with the tides is such that it is rarely the largest surges that lead to extreme total sea levels. It is rather the mid-range to large surges that occur at or near high tide that lead to extreme sea levels. The modulation of the tidal cycle can also considerably affect the amplitude of extreme sea levels. This signal is smallest and least evident around the Northumberland Strait, where the dominant tide is diurnal instead of semi-diurnal.

4.3.6.1 Trends and extremes of the 40-year reconstruction

An important limitation of standard extremal theory is that it requires the hourly sea-level records to exceed about 30 years in length. Unfortunately, this is rarely the case (Table 1). In Atlantic Canada, only a small number of such records are available. In the Gulf of St. Lawrence, a region that regularly sustains damage due to large flood events, only one such record is available. Another problem is that the distribution of both tides and surges varies considerably over the region. Knowledge of the distribution of extremes at one location is therefore not a good estimate of the distribution of extremes at other locations. Our solution to this problem is to use a validated storm-surge model to reconstruct long sea-level records in data-poor regions. The return periods of seasonal extreme sea level are then calculated from the seasonal maxima of the reconstructed records.

Table 1. Description of the tide gauges used in this study. The columns are (i) Station name, (ii) Station code, (iii) Location in degrees of latitude, (iv) Location in degrees of longitude, (v) Years of operation, and (vi) Coverage (percentage of record containing observations).

Station name	Code	Latitude	Longitude	Record	Coverage
Woods Hole, RI	1	41.52	70.67	1958–	91.98
Nantucket Island, RI	2	41.29	70.10	1965–	96.39
Boston, MA	3	42.36	71.05	1921–	99.11
Portland, ME	4	43.66	70.25	1910–	97.23
Bar Harbor, ME	5	44.39	68.21	1950–	91.05
Saint John, NB	6	45.25	66.06	1896–	77.13
Yarmouth, NS	7	43.84	66.12	1900–	34.87
Halifax, NS	8	44.66	63.58	1898–	78.56
Point Tupper, NS	9	45.60	61.37	1971–1992	81.82
North Sydney, NS	10	46.22	60.25	1970–	96.62
Pictou, NS	11	45.68	62.70	1957–1996	29.52
Charlottetown, PEI	12	46.23	63.11	1911–	80.32
Rustico, PEI	13	46.47	63.58	1972–1996	84.55
Pointe-du-Chêne, NB	14	46.23	64.55	1971–	56.27
Lower Escuminac, NB	15	47.08	64.88	1963–	70.02
Rivière-au-Renard, QC	16	49.00	64.38	1969–	87.49
Ste-Anne-des-Monts, QC	17	49.13	66.48	1967–	80.73
Pointe-au-Père, QC	18	48.52	68.47	1897–1989	74.80
Sept-Iles, QC	19	50.22	66.40	1972–	85.67
Baie-Comeau, QC	20	49.23	68.13	1962–1991	71.27
Harrington Harbour, QC	21	50.50	59.48	1939–1989	58.57

Station name	Code	Latitude	Longitude	Record	Coverage
Port-aux-Basques, NL	22	47.57	59.13	1935–	62.29
Argentia, NL	23	47.30	53.98	1971–	91.65
St. John’s, NL	24	47.57	52.72	1935–	69.20

The basic idea behind our approach is simple: add the multidecadal storm-surge hindcast to tidal predictions for the hindcast period (calculated using tidal constants from the short record) and subject the reconstructed total sea-level record to a standard extremal analysis based on its annual maxima. We stress that modelling the exact occurrence of a given extreme is not the goal; rather, we focus on our ability to reproduce the distribution of the annual maxima and thus the return period of extreme sea levels.

The focus of the present study is not the hindcasting of particular storm surges; it is the estimation of flooding probabilities at particular times of the year. The steps in the calculation of seasonal return periods for a location with, say, only five years of data are as follows:

- Step 1: The tides, η_T, are predicted for four years using a tidal package (e.g., Pawlowicz et al., 2002) based on tidal constants fitted to the fifth year of observations.
- Step 2: The observed sea levels, for the four years not used for the tidal analysis, are written in the form $\eta = \eta_T + \eta_S + \eta_R^{'}$, where η is the observed sea level, η_S is the hindcast surge and $\eta_R^{'}$ is a hindcast error that includes the effect of seiches and baroclinic effects not captured by the storm-surge model as well as errors in predicting the tide based on data from another year.
- Step 3: The $\eta_R^{'}$ can be binned by time of year to reflect seasonality in the distribution of $\eta_R^{'}$ when reconstructing seasonal records instead of annual records. We used two seasonal bins in this study: spring–summer and fall–winter.
- Step 4: We predict the tides for 40 years using the constants previously fitted to one year of observations. (Note that the tidal package of Pawlowicz et al. [2002] does have the option of allowing for the 18.6-year nodal modulation. We have verified that it is recovered in the predicted tides.) We then add, for the season of interest, the 40-year predicted record of tides, surge hindcast and a synthetic $\eta_R^{'}$ record obtained by randomly sampling with replacement from the binned $\eta_R^{'}$ record (see Bernier, 2005, and Bernier and Thompson, 2006, for details). To allow for sampling variability, 10 realizations are generated each 40 seasons in length.
    - Step 5: The median of the seasonal maxima of the 10 realizations is used in the standard extremal analysis.

The extremal analysis of the reconstructed seasonal maxima is shown in Figure 14 for Pointe-du-Chêne’s (Figure 7, station 14) winter and spring return periods. There is an offset between the stormy season of winter and the quieter season of spring and a difference in the slope of the two lines. Both are primarily associated with weaker cyclone activity during the spring season (e.g., Koutitonsky and Budgen, 1991), which results in both smaller a_n (due to generally less intense storms) and b_n (due to a smaller variability in the distribution of surges at that time of year).

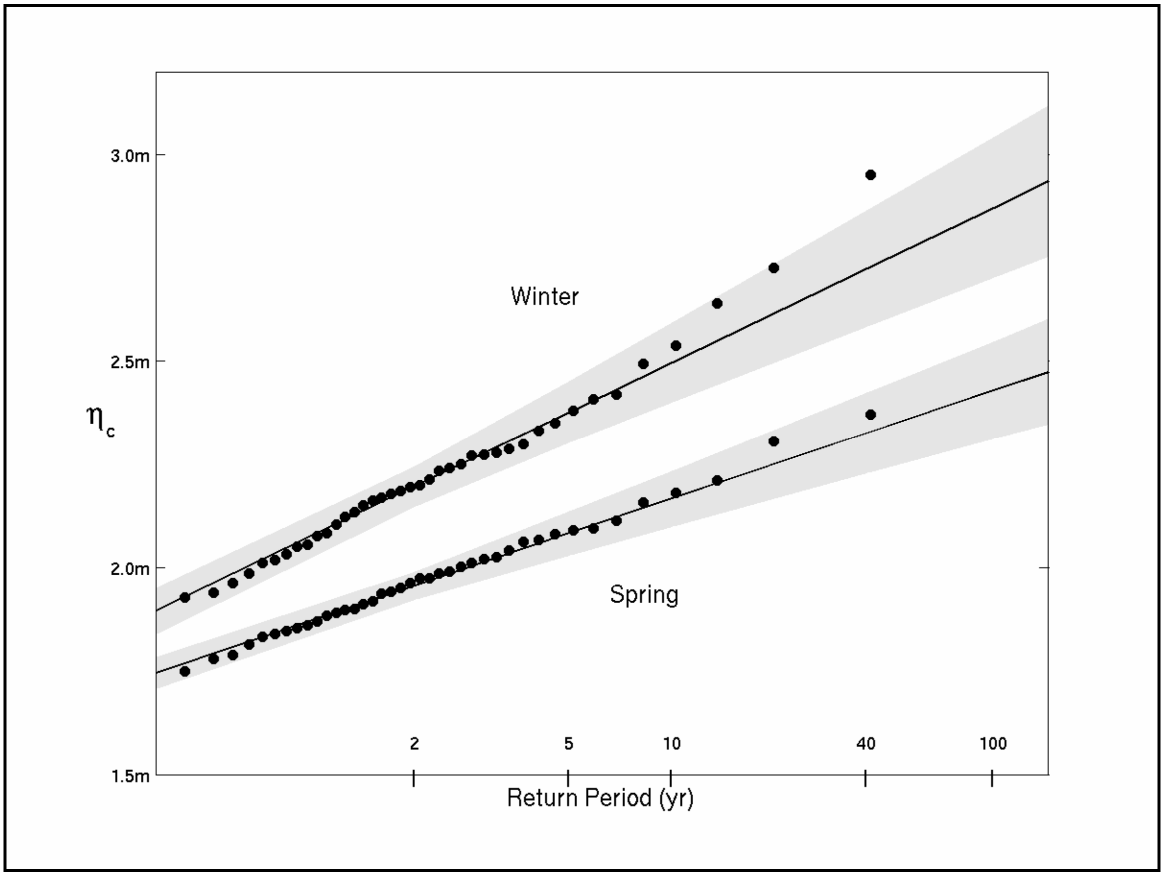

Figure 14. Seasonal return period of extreme total sea levels at Shediac calculated under current conditions using the seasonal reconstructed records. The x-axis is the return period of the seasonal maxima in years. The y-axis is the seasonal return level in metres. Note both the offset and the change in the slope of the return-level line between the stormier winter period (January to March) compared with the quieter spring period (April to June).

The ability of our approach to estimate annual and seasonal return periods at all locations was evaluated by comparing the reconstructed return levels with the observed return levels. Results showed good agreement between the observed and reconstructed annual and seasonal sea levels. As expected, the largest return levels (for a given return period) are observed at stations with large tidal amplitudes (e.g., Saint John in the Bay of Fundy). This is illustrated in Figure 15, where maximum observed tidal amplitude is plotted along with the 40-year return level of observed sea levels for each station (Table 2). The large difference in the spatial structure of the extreme total sea levels is not only due to differences in surge amplitude; it is primarily due to large spatial differences in tidal amplitudes. Figure 15 also illustrates that the tide alone is not a good approximation of the return levels of extreme total sea levels. At return periods of 40 years, the maximum observed tide is typically more than 0.5 m below the return level line. As the return periods increase, the maximum tidal amplitude remains the same and becomes a progressively worse estimate of the return level of extreme total sea levels. In general, the 40-year annual return levels based on the reconstructed records are within about 10 cm of the observed annual return levels (Table 2). The 40-year reconstructed seasonal return levels also show the same station-to-station variability as the 40-year observed seasonal return levels. Thus, we can generate annual and seasonal extremes with only 5-year records and our 40-year surge hindcast.

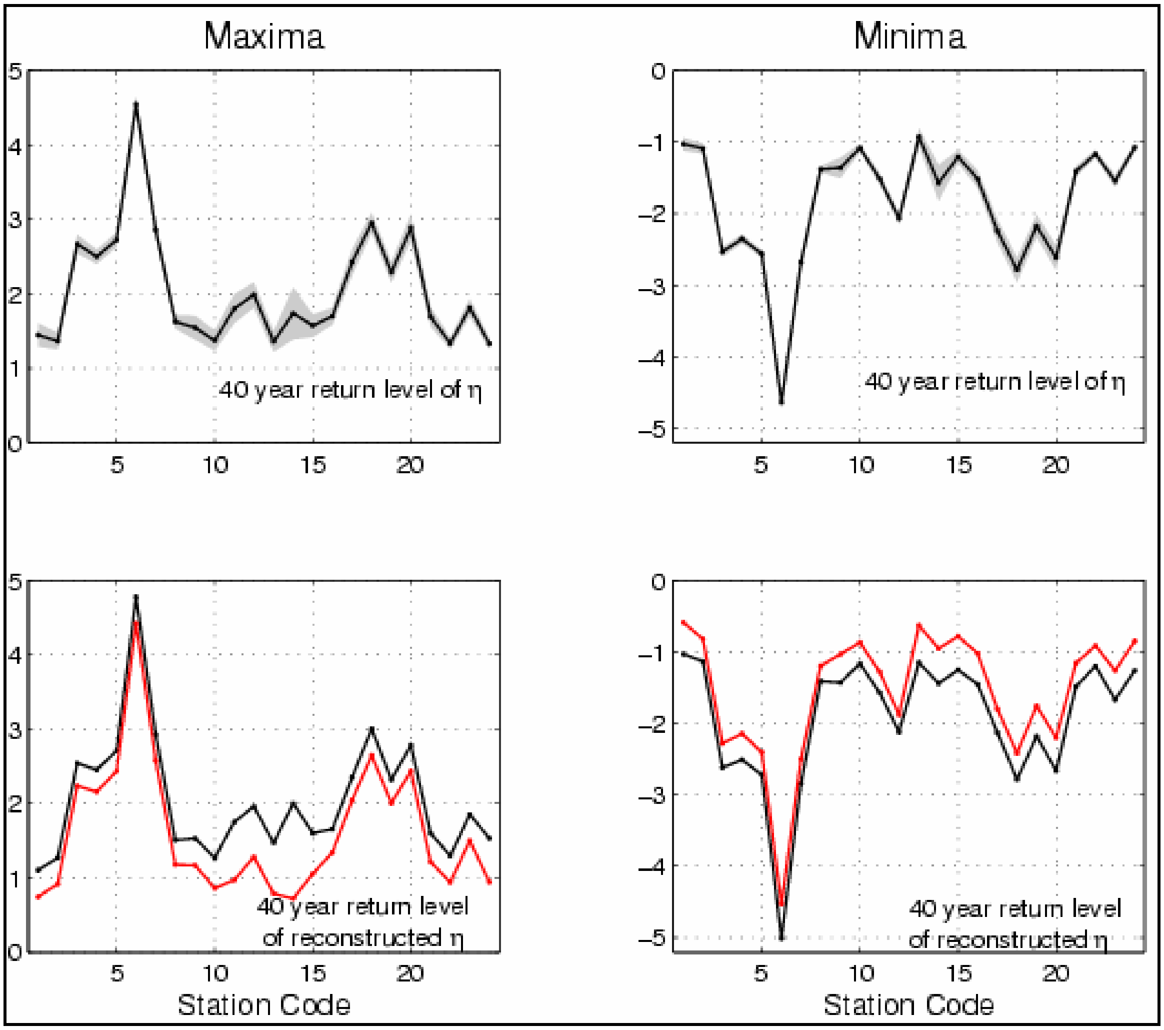

Figure 15. Forty-year return level of positive and negative total sea levels. The x-axis shows the station code. The y-axis is the 40-year return level in metres calculated from the Type I distribution fitted to the adjusted annual maxima (left) and minima (right), as shown in Figure 9. The shaded areas mark the 95% confidence intervals at return periods of 40 years. The top left panel shows the observed positive return levels. The bottom left panel shows the positive 40-year reconstructed return levels (in black) obtained using five years of hourly sea-level observations and the 40-year surge hindcast and the largest tide on record (in red). The top right panel shows the 40-year return level of the negative total sea levels. The bottom right panel is the negative 40-year reconstructed return levels (in black; also obtained using only five years of hourly sea-level observations) and the

largest negative tide on record (in red). Note how the bottom panels exhibit the same station-to-station variability as the top panels, showing that only five years of data and the surge hindcast are needed to obtain reasonable 40-year return levels.

Table 2. Observed and reconstructed 40-year return levels at the 24 tide gauge locations. The columns are defined as follows: (i) Station name, (ii) Station code, (iii) 40-year observed positive return level (in metres) with the ± marking the 95% confidence interval, (iv) 40-year positive reconstructed return level (in metres) based on the 40-year hindcast and five years of data, (v) 40-year negative return level (in metres) with the ± marking the 95% confidence interval, (vi) 40-year negative reconstructed levels (in metres) based on the 40-year hindcast and five years of data.

Station name	Code	Maxima observed (m)	Maxima reconstructed (m)	Minima observed (m)	Minima reconstructed (m)
Woods Hole	1	1.45 ± 0.16	1.10	−1.02 ± 0.09	−1.03
Nantucket Island	2	1.36 ± 0.11	1.25	−1.09 ± 0.07	−1.14
Boston	3	2.67 ± 0.13	2.53	−2.53 ± 0.07	−2.62
Portland	4	2.50 ± 0.10	2.45	−2.35 ± 0.06	−2.51
Bar Harbor	5	2.73 ± 0.10	2.72	−2.56 ± 0.05	−2.72
Saint John	6	4.55 ± 0.11	4.78	−4.64 ± 0.08	−5.00
Yarmouth	7	2.86 ± 0.10	2.93	−2.68 ± 0.07	−2.84
Halifax	8	1.63 ± 0.09	1.52	−1.38 ± 0.05	−1.41
Point Tupper	9	1.54 ± 0.16	1.53	−1.36 ± 0.14	−1.43
North Sydney	10	1.37 ± 0.13	1.27	−1.08 ± 0.06	−1.17
Pictou	11	1.80 ± 0.20	1.76	−1.51 ± 0.08	−1.57
Charlottetown	12	1.99 ± 0.17	1.92	−2.07 ± 0.08	−2.12
Rustico	13	1.36 ± 0.14	1.47	−0.92 ± 0.12	−1.15
Pointe-du-Chêne	14	1.74 ± 0.35	1.91	−1.57 ± 0.25	−1.45
Lower Escuminac	15	1.57 ± 0.15	1.55	−1.20 ± 0.09	−1.26
Rivière-au-Renard	16	1.70 ± 0.11	1.65	−1.51 ± 0.12	−1.46
Ste-Anne-des-Monts	17	2.43 ± 0.18	2.35	−2.24 ± 0.16	−2.13
Pointe-au-Père	18	2.96 ± 0.13	3.01	−2.79 ± 0.17	−2.79
Sept-Iles	19	2.29 ± 0.14	2.30	−2.17 ± 0.16	−2.18
Baie-Comeau	20	2.89 ± 0.18	2.77	−2.61 ± 0.17	−2.66
Harrington Harbour	21	1.69 ± 0.13	1.61	−1.40 ± 0.07	−1.49
Port-aux-Basques	22	1.33 ± 0.08	1.28	−1.16 ± 0.06	−1.20
Argentia	23	1.81 ± 0.12	1.87	−1.54 ± 0.08	−1.67
St. John’s	24	1.33 ± 0.08	1.55	−1.07 ± 0.06	−1.26

4.3.6.2 Extremes under realistic climate-change scenarios

This section briefly explores how climate change may modify the return period of extreme sea levels. The return levels presented thus far are based on a hindcast for a fixed observation period. It is possible to extend our approach to allow for some elements of climate change. For example, it is straightforward to approximate the effect of sea-level rise by simply adding a constant height to the return levels, as was done in the previous section. However, in the region studied here, it is not possible to add a spatially uniform rate of sea-level rise, as the effect of vertical crustal movements is spatially variable (Peltier, 2004) and of the same order as the generally accepted rate of global sea-level rise of 1–2 mm/year (Church et al., 2001). Rates of sea-level rise must therefore be station dependent. At Pointe-du-Chêne, close to the location of the DEM, relative sea level is expected to have risen 0.8 m by 2100, whereas it is expected to have risen 0.7 m at Halifax. In terms of changes in storminess, the consensus seems to point towards an increase in the number of strong wind events associated with an increase in the number of deep lows, although the overall number of low-pressure events is expected to decrease (e.g., Lambert, 2004). The impacts of sea-level rise and increased storminess on the return period of extreme sea levels are investigated next.

Three climate-change scenarios are discussed. They are illustrative rather than definitive and focus on annual rather than seasonal extremes. We also focus on Halifax, an important east-coast Canadian city with a long sea-level record. The extension of the method to other locations and from annual to seasonal extremes is straightforward.

For the purpose of this exercise, it is assumed that the filtered residuals recorded at Halifax between 1960 and 1999 represent the current conditions and are denoted by η_{pres}. Hence, the observed sea-level record at Halifax is given exactly by $\eta = \eta_T + \eta_{pres} + \eta_R^{'}$, where $\eta_R^{'}$ includes, as before, the effects of seiche and baroclinicity. It is further assumed that the the impact of climate change can be expressed simply through a mathematical transformation of η_{pres}. The transformed η_{pres} will be referred to as $\eta_{c\lim}$, the climate-modified residuals.

4.3.6.2.1 Scenario 1

It is assumed that atmospheric conditions (i.e., winds and pressure forcing) remain unchanged as we progress into the next century. It is further assumed that sea level at Halifax, the representative station, will have risen 0.7 m by 2100. This sea-level rise is imposed on the present observed residuals η_{pres} to obtain $\eta_{c\lim}$, the climate-modified residuals. The effect on the residuals is illustrated in the left panel of Figure 16. The black line shows η_{pres} plotted against itself as a reference. The blue line shows $\eta_{c\lim} = 0.7 + \eta_{pres}$ — hence, the present residuals plus sea-level rise plotted against η_{pres}. In terms of the probability density function (or similarly the histogram), applying sea-level rise shifts the probability density function of $\eta_{c\lim}$ to the right by 0.7 m (not shown).

The shift in the probability density function increases the annual maxima by 0.7 m (and also a_n, the location parameter of the Type I distribution fit to the annual maxima). This is illustrated in the Type I plot (right panel of Figure 16). The plot is produced by fitting a line through the ordered annual maxima of $\eta = \eta_T + \eta_{pres} + \eta_R^{'}$ (black line) and $\eta = \eta_T + \eta_{c\lim} + \eta_R^{'}$ (blue line). The return-period plot shows that the impact of sea-level rise is so important that extreme sea levels with a current return period of 100 years are expected to have become regular events by 2100.

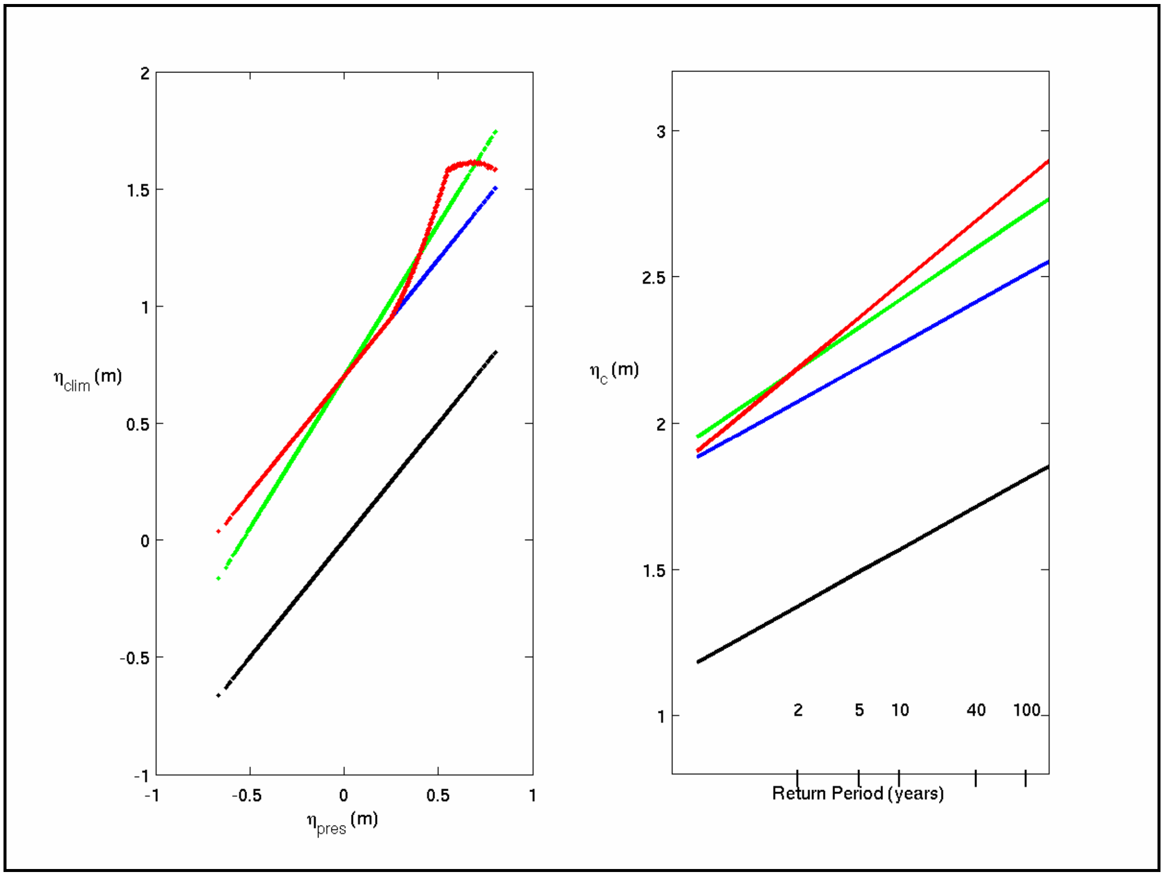

Figure 16. Return period of extreme total sea levels into the next century for Halifax. The left panel shows the climate-modified residuals, $\eta_{c\lim}$, against the present residuals, η_{pres}. η_{pres} is plotted against itself in black as a reference. Residuals resulting from sea-level rise (blue line) and the combined effect of sea-level rise and changes in storminess (green and red lines) are also plotted. The right panel is the return-period plot of extreme total sea levels associated with each climate-change scenario. Each line is based on an extremal analysis of the annual maxima of each climate-modified total sea level, $\eta = \eta_T + \eta_{c\lim} + \eta_R^{'}$. The return levels shown are for (i) current conditions (black line), (ii) sea-level rise (blue line), (iii) sea-level rise and linear increase of residuals amplitude (green line) and (iv) sea-level rise and inflation of mid-range surge amplitude (red line).

4.3.6.2.2 Scenario 2

It is assumed that in combination with sea-level rise, increased storminess will lead to a linear increase of the climate-modified residuals. Hence, $\eta_{c\lim} = 0.7 + \alpha\eta_{pres}$, where α is an arbitrarily chosen scaling factor ($\alpha = 1.3$ was chosen). The resulting climate residuals are plotted against η_{pres} (in green) in the left panel of Figure 16. The linear increase in surge intensity has shifted and stretched the probability density function of η_{pres}. The location parameter, α_n, is increased via the inflation of the annual maxima. The shape parameter b_n, a measure of the spread, is also increased. The return-period plot of ordered annual maxima of $\eta = \eta_T + \eta_{c\lim} + \eta_R^{'}$ is shown in green in the right panel of Figure 16. The impact of the linear increase in surge amplitude on the return-period plot is twofold: the return-level line is lifted, and the slope of the return-level line is accentuated. The overall effect is to further reduce the return periods of extreme total sea levels.

4.3.6.2.3 Scenario 3

It is assumed that in combination with sea-level rise, weak cyclones will have a tendency to deepen more, while intense cyclones will remain relatively unchanged. The effect on the amplitude of surges is assumed to be as follows: mid-amplitude residuals are inflated, while the largest residuals are left untouched. This is illustrated in the left panel of Figure 16 (red line). The effect of the chosen triangular scaling is to fatten the probability density function at the mid-range amplitudes (i.e., in the positive tail of the distribution), while keeping the range fixed.

The impact of increasing mid-amplitude surges appears more important than that of a linear increase in surge amplitude (compare the red and green lines of the right panel of Figure 16). This result underlines that it is rarely the most extreme residuals that lead to annual maxima. Extreme sea levels are, in fact, typically the result of a large (but not unusual) residual coinciding with high tide.

The results shown in Figure 16 suggest that over the next century, the continued increase in flooding risk will primarily be brought about by sea-level rise (assuming that the increase in sea level is comparable with what is expected for Halifax). The simple sensitivity study presented here also shows that changes in storminess should not be overlooked when forecasting flooding risk into the next century.

4.3.7 Web-based display

Hourly sea-level data from Pointe-du-Chêne, Wood Islands and 12 other Atlantic Canadian gauges are sent daily by MEDS to Dalhousie. These data are error-checked, processed and posted on the web along with forecasts from the storm-surge model. The results can be viewed at http://www.cmep.ca/. It is necessary to click on “Projects and Online Data,” then “Shelf,” then “Flooding Forecasts.” It is then possible to select a gauge and time period using an interactive map (Figure 17).

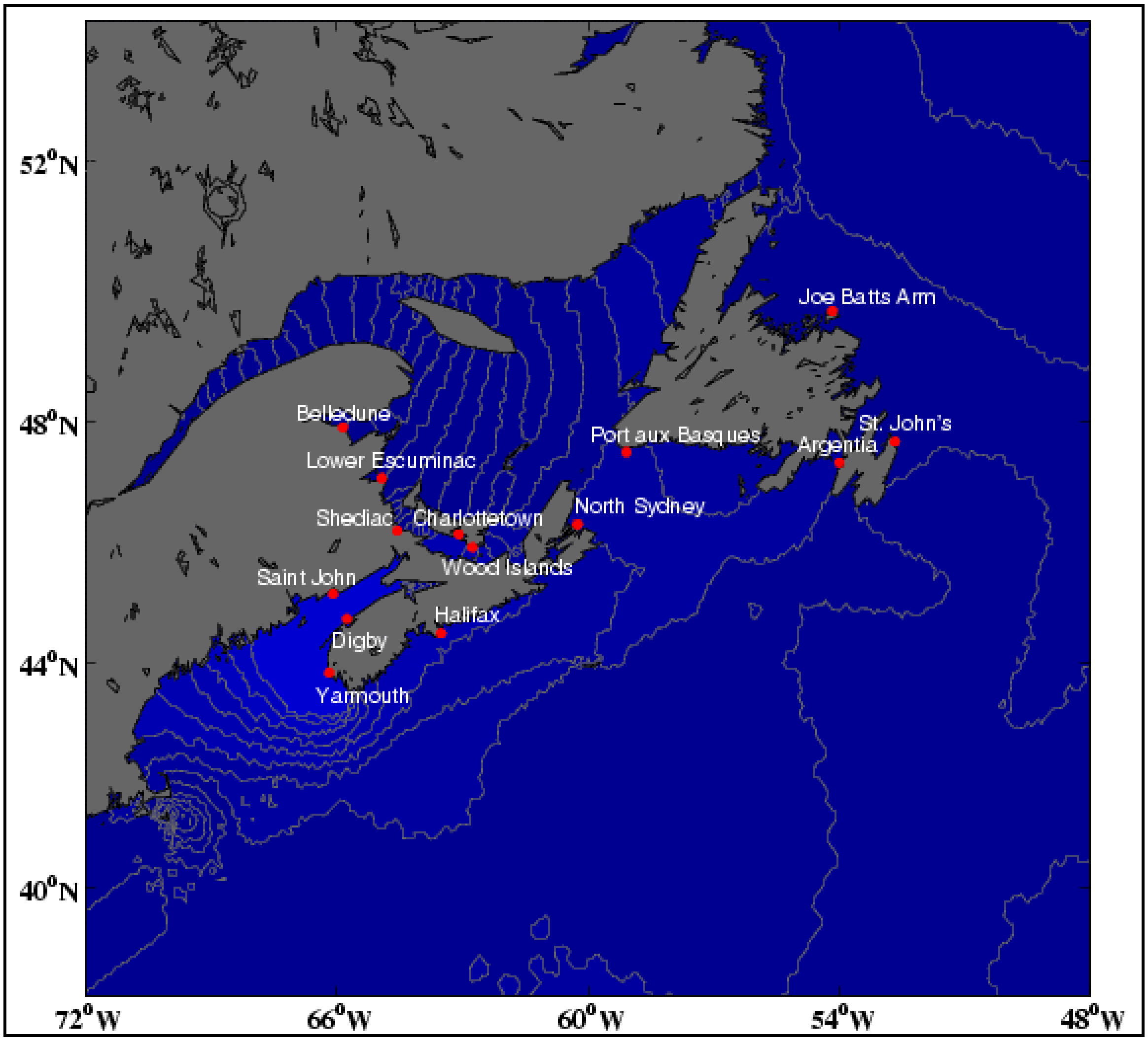

Figure 17. Map taken from the near-real-time web display of tide-gauge data and storm-surge forecasts for Atlantic Canada. The map shows the locations of the tide gauges. After clicking on a red dot, the viewer is prompted to specify a time period of interest, following which time-series plots (similar to Figure 3) are displayed. It should be noted that the Shediac tide gauge is actually in Pointe-du-Chêne.

The following upgrades were made to the web site during this project:

- The format of the time-series plots was improved through the addition of horizontal grid lines to facilitate comparison with specified flood levels. We also automated the selection of the optimum plotting position for the legends on the time-series plots. This overcomes an over-plotting problem identified earlier.

- An image gallery showing the tide-gauge sites and the aftermath of important floods was added (click under Images).

- An archive of old storm-surge movies was added. This is useful if a graphical summary of a past storm surge is required.

- A zoom of flooding forecasts in the southern Gulf of St. Lawrence was added.

In addition to the time-series plots of hourly sea levels and comparison with one-day forecasts, it is possible to view "movies" of the sea-level distribution for Atlantic Canada for the next two days. It is necessary to click on "Movies of Atlantic Canada" on the left-hand control panel. Three options are then made available: Tide (the predicted tide based on WebTide tidal constituents, kindly provided by Charles Hannah of the Bedford Institute of Oceanography); Storm Surge (forecasts from the Dalhousie storm-surge model, Figure 18); and Total Sea Level (sum of Tide and Storm Surge, Figure 19).

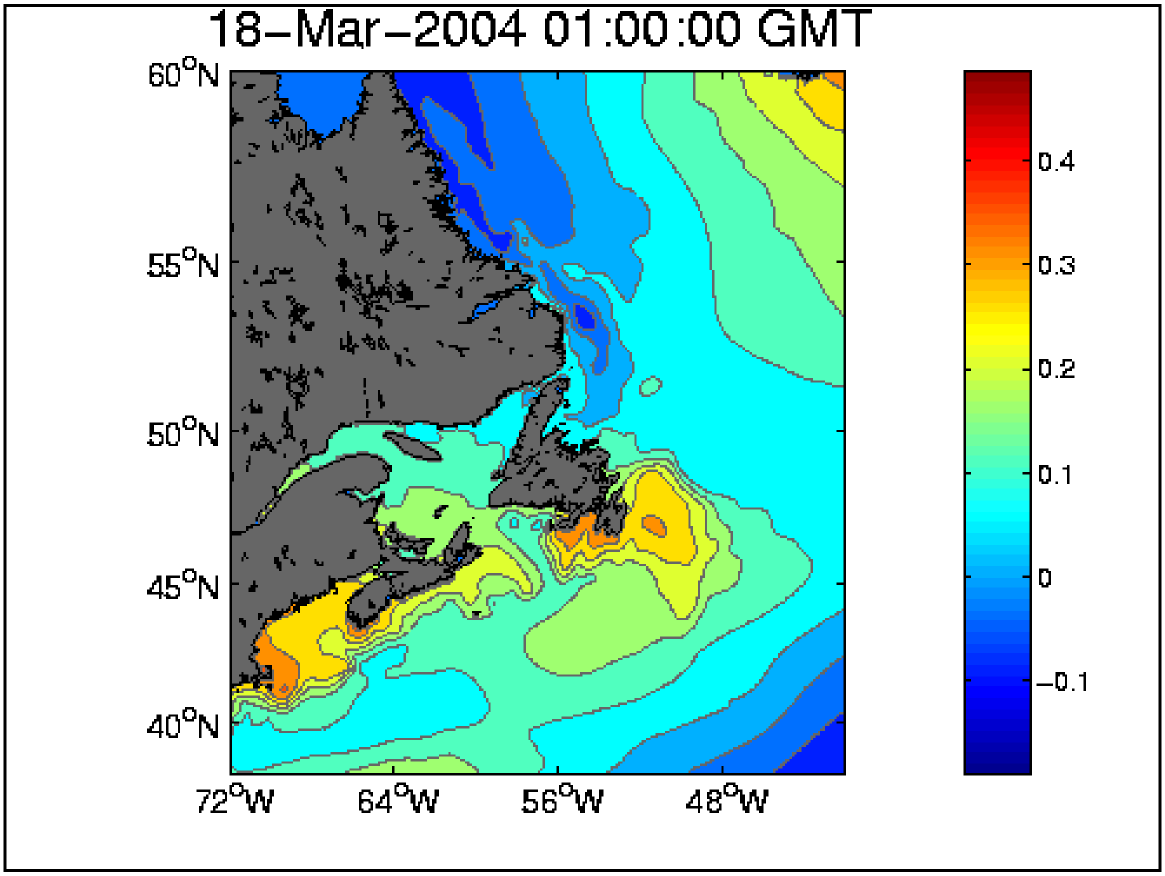

Figure 18. Snapshot of the storm-surge forecast for March 18, 2004. Heights are in metres (as shown by the colour bar to the right).

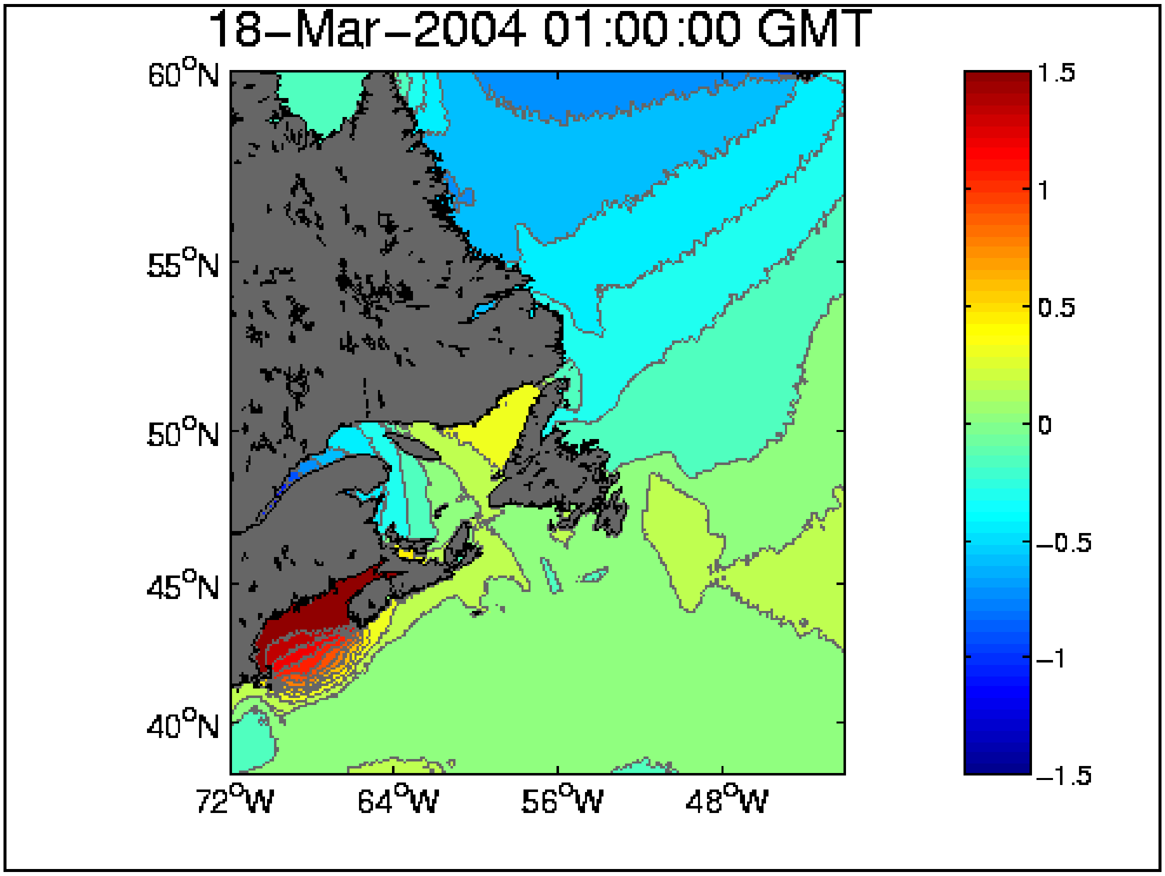

Figure 19. As for Figure 18, but for the total water level (surge and tide combined). Note the different scale.

4.3.8 Municipal downscaling of flooding risk

In this section, we describe how we downscale the flooding statistics to the community level (i.e., downscale the results of the extremal analysis to a horizontal resolution of metres). The goal is therefore the calculation of location and time-specific extreme statistics, essential information for the development of any sensible adaptation strategy in response to climate change.

In this section, a DEM for the Shediac Bay area, which covers an important Piping Plover nesting ground (top panel of Figure -20), is used to downscale the return period of extreme sea levels for the nesting season (spring). The Piping Plover is a species at risk. It is found on the shorelines of the Northumberland Strait, the Magdalen Islands and some beaches of Nova Scotia, Prince Edward Island and Newfoundland. In 2001, there were about 220 pairs of plovers and some 43 single birds left (Environment Canada Species at Risk: http://www.speciesatrisk.gc.ca/). Piping Plovers begin arriving at their nesting grounds in Atlantic Canada in late April. Other than predators and human disturbance, loss of habitat due to storm surges and sea-level rise is considered a threat to the species. In this section, a DEM for an important Piping Plover nesting ground (top panel of Figure 20) is used to downscale the return period of extreme sea levels for the nesting season (spring). Return periods for the winter season are also downscaled for comparison.

The approach is to flood the DEM to a specific level (η_c), or equivalently return periods, to identify areas at risk. The DEM can therefore be used to evaluate the extent of any hindcast or forecast flood event. One subtlety is that flooding must be path dependent — e.g., a small valley can be flooded only if the land separating it from the adjacent ocean is also flooded. Another subtlety is that allowance had to be made for culverts that can affect the extent of flooding but are not detected by the light detection and ranging (LiDAR) system that was used to make the DEM. It is also noted that the DEM is flooded naively, in the sense that no delay is allowed for a flood to propagate through a culvert or to retire from a flooded region. Models are available for this purpose and could be used in future studies.

The flooding frequencies are obtained by performing an extremal analysis on annual or seasonal maxima. At Shediac, the analysis must be performed using the reconstructed sea levels due to the poor data coverage at the Pointe-du-Chêne tide gauge. The winter and spring return periods are shown in Figure 14. The sea level at which each point in the DEM becomes flooded is then associated with a return period. The result is a map of the return period of flood events for the winter and spring seasons (middle and bottom panels of Figure 20, respectively). Figure 20 shows the different extent of the return period of flooding for the winter (middle panel) and spring (bottom panel) months. Note how the vulnerable area differs between the seasons. Note also how slowly the spatial extent of area at risk grows with increasing return period in the spring compared with the winter. In fact, the 100-year spring return level barely exceeds the 5-year winter return level. This is the first time that maps of the seasonal return periods have been produced. They have the advantage of simplicity and show the areas most vulnerable to flooding for targeted time periods.

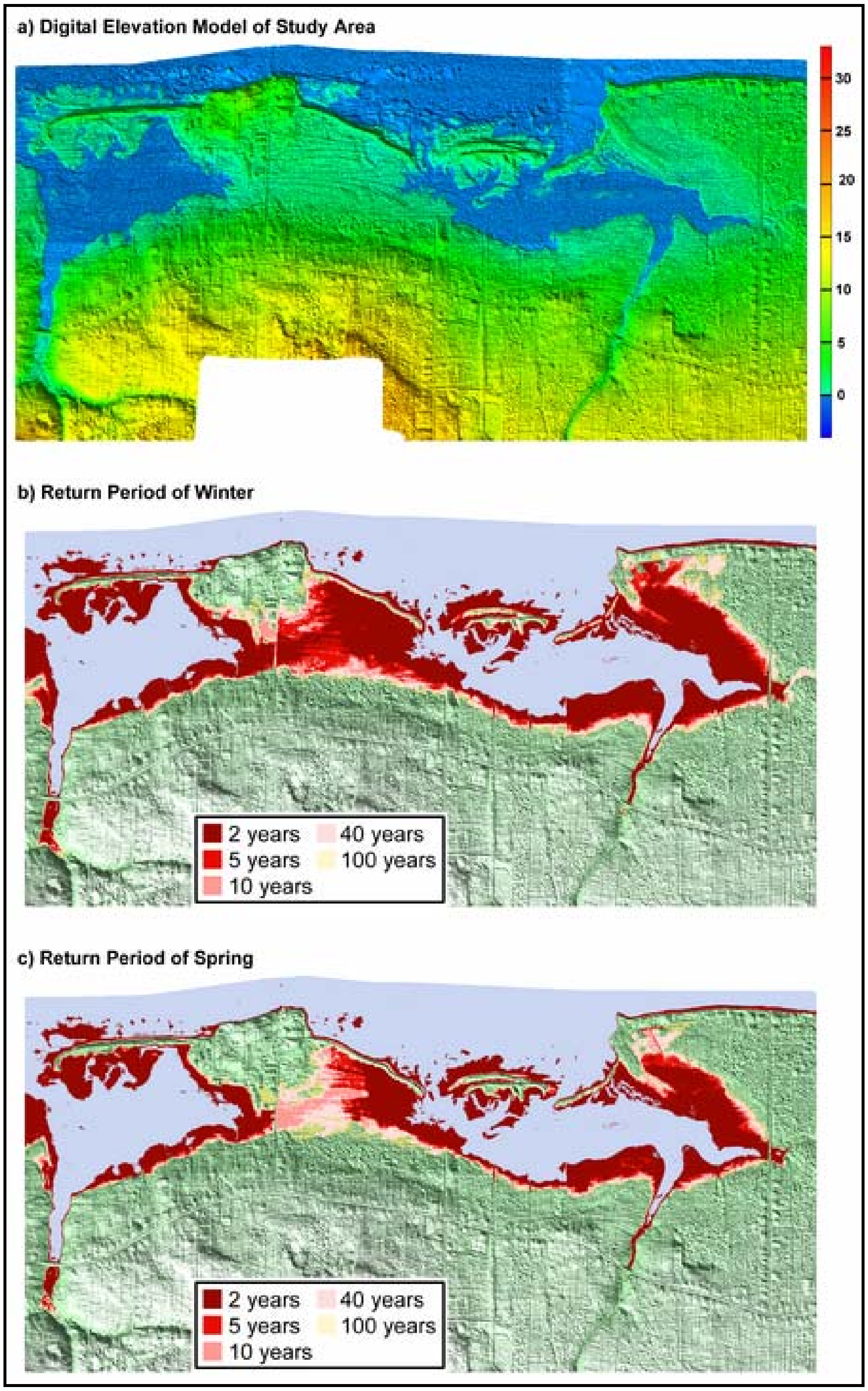

Figure 20. Spatial mapping of the seasonal return period of floods at Shediac. The top panel is the DEM for an area located near station 14 (Figure 7). The colourbar of the top panel indicates elevation above the DEM datum, which is located 21 cm below mean sea level. The horizontal resolution is 1 ± 0.30 m, and the vertical resolution is 1 ± 0.11 m (Tim Webster, COGS, pers. comm.). The middle panel is a return-period map of winter extreme events. The return periods are based on the extremal analysis of the reconstructed winter maxima (Figure 14). The bottom panel is a return-period map of spring extreme events.

4.3.8.1 Visualization of flooding risk under a changing climate

Allowing for changes in the severity of storms is difficult, and ultimately such changes should be based on reliable high-resolution forcing from global climate models. These are currently not available. We therefore performed preliminary sensitivity studies by modifying the shape of the distribution of observed surges. Changes in storminess represented by large increases in the amplitude of large or mid-range residuals were found to have less impact on the return period of extreme sea levels than the realistic sea-level rise predicted for some areas of the study region (e.g., Scotian Shelf) over the next century. This does not imply that changes in storm severity have little impact on the return period of extreme events. Rather, this sensitivity study highlights that in regions where sea-level rise is considerable (order of 1 m), it alone will result in a dramatic reduction in the return period of extreme events over the next century.

Sea-level rise in this region is expected to contribute, over the next 25 years, about 0.2 m to the Shediac area where the DEM is available. On the return-period plot (Figure 14), the rise in sea level will raise the current spring return-level line to roughly the current winter line. It is therefore expected that the risk of flooding will increase sufficiently during the nesting period so that in 25 years, the spring return-period plot and vulnerability map should resemble the current winter return-period plot and vulnerability map (middle panel of Figure 20). The impact on the bird population is discussed in Section 4.6 of this report.

An additional set of return-period maps, covering regions close to Shediac Bay, is presented in Section 5 (Annex A). The methodology used to calculate the additional maps is identical to that used in the present section and is based on extreme return levels calculated from the Pointe-du-Chêne sea-level record. Given that the tidal amplitude and phase can change rapidly in this region on spatial scales of tens of kilometres, we have restricted the spatial coverage of these additional maps to the immediate vicinity of Shediac Bay. The maps (see Figure 21 for an example) depict flooding extents with present sea levels (blue line) and with a 60-cm sea-level-rise scenario (red line).

For the remaining regions, maps (see Figure 22 for an example) have been produced to depict flooding extents that resulted from the January 21, 2000, storm with present sea levels (blue line) and with a 60-cm sea-level-rise scenario (red line). These maps are also presented in Section 5 (Annex B).

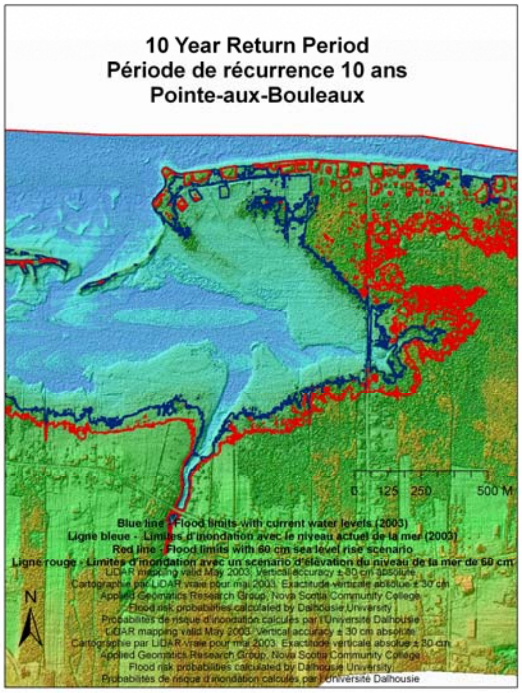

Figure 21. Return-period map.

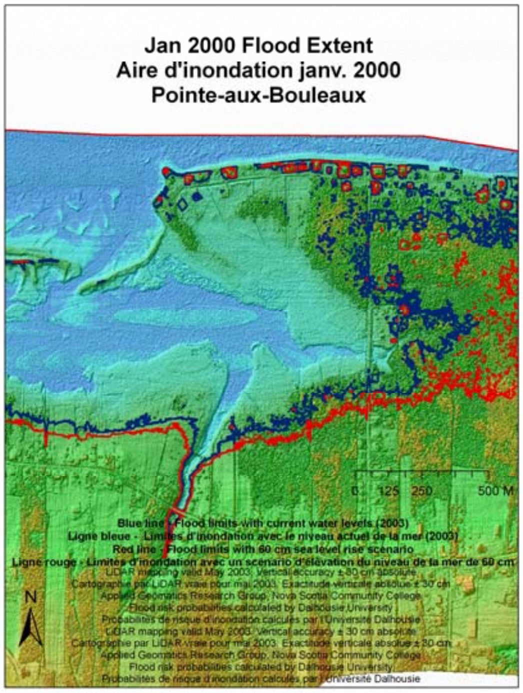

Figure 22. January 21, 2000, storm-surge map.

4.3.9 Summary and conclusions

In this study, we developed an approach to evaluate flooding risk along the New Brunswick coast of the Gulf of St. Lawrence that is based on sea-level observations, extremal analysis and a storm-surge model developed by Dalhousie University. The approach included the installation of two new tide gauges to provide independent sea-level data to test the model, as well as the analysis of historical sea-level observations made over the last century. Considerable effort was expended to make the information useful to non-scientists. For example, an open-access web site was developed to provide daily flood forecasts to the general public. We also developed new ways of visualizing flooding risk that could be readily understood by concerned members of the community.

The two new tide gauges were installed at Pointe-du-Chêne and Wood Islands. These locations were chosen in order to obtain data in areas where too few observations were available to allow the skill of our storm-surge model to be accurately evaluated. Subsequent analysis suggests that the one-day forecasts of the storm-surge model at these gauges have an accuracy better than 10 cm.

A 40-year hindcast of storm surges was performed for the Northwest Atlantic to quantify the return period of extreme sea levels. We were encouraged to find that the standard deviation of the hindcast error (the difference between the observed tidal residuals and the surges reconstructed by the model) is typically 8 cm and compares well with the typical operational forecast error. The surge hindcasts also exhibited the same seasonal and interannual variations in standard deviation as the observed residuals. Having demonstrated the quality of the hindcast, we produced maps of the standard deviation of surges for the Northwest Atlantic by season. As expected, the surge variance was highest during the fall and winter. We also showed that the regions with the highest surge variance were in the southern Gulf of St. Lawrence and along the eastern shore of Newfoundland.

To estimate the frequency of extreme total sea levels (in contrast to extreme surges), we added the tide and other physical processes not resolved by the storm-surge model. An important point to note is that the approach in this study requires only a few years of hourly sea-level observations to estimate multidecadal return levels of total sea level. Overall, the predicted 40-year return levels of total sea level (tide plus surge) are within about 10 cm of the observed 40-year return levels. The method was also adapted to calculate the return period of extreme events over any season of interest.

Allowing for changes in the frequency and severity of storms (based on climate-change scenarios) is difficult, and ultimately such changes should be based on reliable climate-change scenarios from global climate models. Given that such downscaled forcing fields were not available, we carried out some sensitivity studies of the effect of changes in the surge distribution on the frequency of extreme total sea levels and compared the impacts with those of sea-level rise. The effect of significant changes in storminess, represented by large changes in the distribution of the surges, on the return period of extreme sea levels was found to be less than the effect of the large sea-level rise predicted for some areas of the study region (e.g., Scotian Shelf). This does not imply that changes in storm severity have little impact on the return period of extreme events. Rather, this sensitivity study suggests that in regions where sea-level rise over the next century is considerable (in the order of 1 m), it alone will result in a dramatic reduction in the return period of extreme events.

With the availability of a DEM, it was possible to downscale the results of an extremal analysis to produce maps of the return period of flood extent. The return-period maps presented in this study have the advantage of simplicity. They are easy to understand and allow rapid visual identification of areas most at risk of flooding. They can therefore be used by planners and policy-makers to identify zones where development should be limited, adaptation measures put in place or ecosystem management considered. The seasonal return period of negative sea levels can also be estimated from short records. The results of the extremal analysis of minima can also be downscaled using DEMs and high-resolution bathymetries. In areas where maritime traffic requires a minimum water depth for ships to enter ports or navigate safely, maps of the return period and extent of low water levels can thus be produced.

A set of return-period maps, covering regions close to Shediac Bay, is presented in Section 5 (Annex A). The methodology used to calculate the maps is based on extreme return levels calculated from the Pointe-du-Chêne sea-level record. For the remaining regions, maps have been produced to depict flooding extents that resulted from the January 21, 2000, storm with present sea levels and with a 60-cm sea-level-rise scenario. These maps are also presented in Section 5 (Annex B).

It should be noted that in Shediac Bay, the current 40-year storm-surge return level is expected to become closer to a 5-year return level with a 60-cm sea-level-rise scenario, expected by 2100.

4.3.10 Acknowledgements

We thank the Climate Change Impacts and Adaptation Program and Public Safety and Emergency Preparedness Canada for financial support of the work reported here. We also acknowledge the support of the Canadian Hydrographic Service (Charles O'Reilly and Fred Carmichael) and Environment Canada (Jim Abraham) in connection with the tide-gauge installations. WebTide tidal constituents were generously provided by Charles Hannah of the Bedford Institute of Oceanography. We also thank Tim Webster for giving us access to the DEM and providing useful advice.

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4.4 LiDAR digital elevation models and flood-risk mapping

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4.4.1 Introduction

Storm surges are typically 0.6–2 m in height for this region (Parkes et al., 1997); thus, technologies with vertical precision significantly finer than these values must be employed to generate flood-risk maps of sufficient resolution. Airborne light detection and ranging (LiDAR) is an emerging technology that offers the vertical accuracy and high spatial sampling density required for this purpose. Many LiDAR systems have vertical accuracies on the order of 30 cm or better. LiDAR technology has been employed for shallow bathymetric charting (e.g., Guenther et al., 2000), although cost remains an impediment to widespread acceptance for the latter purpose. The technology can also be used to image the land and water surface (Hwang et al., 2000), as in the study presented here. A general overview of airborne laser scanning technology and principles is provided by Wehr and Lohr (1999). Applications to coastal process studies in the United States have been reported by Sallenger et al. (1999), Krabill et al. (1999) and Stockdon et al. (2002), among others. Preliminary trials in Atlantic Canada were reported by O'Reilly (2000), and subsequent experience was described by Webster et al. (2004b, in press). Most of the coast of the conterminous United States has now been mapped using this technology (Brock et al., 2002).

In this section, we describe the methods and results of utilizing two LiDAR systems to generate high-resolution digital elevation models (DEMs) and associated flood-risk maps for the coast of New Brunswick along the Northumberland Strait (Figure 1) (MacKinnon, 2004). This project builds on the experience gained from the successful application of LiDAR technology to storm-surge flood-risk mapping on Prince Edward Island (Dickie, 2001; McCulloch et al., 2002; Webster et al., 2002, 2004a; Webster and Forbes, 2006).

4.4.2 Methods

4.4.2.1 LiDAR systems

LiDAR mapping involves an aircraft emitting laser pulses towards the ground and measuring the return time of the pulse (see Webster et al., 2004a). The laser scan is acquired by rapid repetition of the laser-pulse transmitter and cross-track deflection of the beam using an oscillating mirror to produce a zigzag pattern of laser hits on exposed surfaces below the aircraft (Figure 2). A time interval meter (TIM) records the mirror scan angle, the time when the pulse is transmitted from the sensor, the time of the returning reflected pulse and, in some cases, the intensity of the return. The configuration of the TIM is what determines if the sensor captures the first or last reflected returns. New-generation LiDARs are capable of capturing first, last and intermediate returns, along with multiple intensities. The data volume with such sensors is a potential problem, and the information content of the intermediate returns is an area of active research. Using precise differential global positioning system (GPS) technology to determine the location of the aircraft (Krabill and Martin, 1987) and an inertial measurement unit (IMU) to measure the aircraft attitude (pitch, yaw and roll), the location of individual laser returns measured by the TIM can be determined (Figure 2). In this study, two LiDAR systems were employed to survey the area: the Mark I system was used for the 2003 survey, and the Mark II system was used for the 2004 survey.

The nominal accuracy of the systems used in this study is ±30 cm both horizontally and vertically. The preliminary data output includes geographic coordinates (longitude and latitude) and elevation (in metres) for each laser point reflection, all referenced to the World Geodetic System ellipsoid of 1984 (WGS 84), the ellipsoid employed in the GPS system. If the data are to be used for geographic information system (GIS) applications such as flood-risk mapping, the horizontal coordinates are converted to an appropriate map projection, in this case using the Universal Transverse Mercator (UTM) grid. Elevations on most land-based topographic maps are measured relative to a geodetic vertical datum. For Canada, this is known as the Canadian Geodetic Vertical Datum of 1928 (CGVD28). Thus, for many applications, including flood-risk mapping, the LiDAR elevations are transformed from ellipsoid heights to orthometric heights. Orthometric heights are based on the geoid, an equipotential surface defined by the earth's gravity field, approximately equal to mean sea level. To obtain orthometric heights, an adjustment must be made for the local vertical separation between the ellipsoid and the geoid. The difference between the WGS84 ellipsoid and the CGVD28 geoid is obtained by using the HT1_01E model, since replaced by HTv2.0, with an accuracy of ±5 cm with 95% confidence in southern Canada (Geodetic Survey Division, Natural Resources Canada, http://www.geod.nrcan.gc.ca/products_e.php#software)

4.4.2.2 Terra Remote Sensing Mark I and Mark II LiDAR systems

Terra Remote Sensing Inc. of Sidney, British Columbia, was contracted to acquire the LiDAR survey data for the study areas. The requested LiDAR point density on open ground was a posting every 60 cm. The absolute accuracy of the LiDAR data for this study was specified to be ±30 cm in the vertical. Two LiDAR systems were used to acquire data during leaf-off conditions following snowmelt in the spring of 2003 and 2004. In 2003, the Mark I system (Figure 2A) was used to acquire data over four of the seven survey polygons (Figure 1). In 2004, the more sophisticated Mark II system (Figure 2B) was used to acquire data over the remaining three polygons (Figure 1). Surveys were acquired near low-tide conditions where possible, and GPS baselines were kept below 50 km to minimize aircraft trajectory errors.

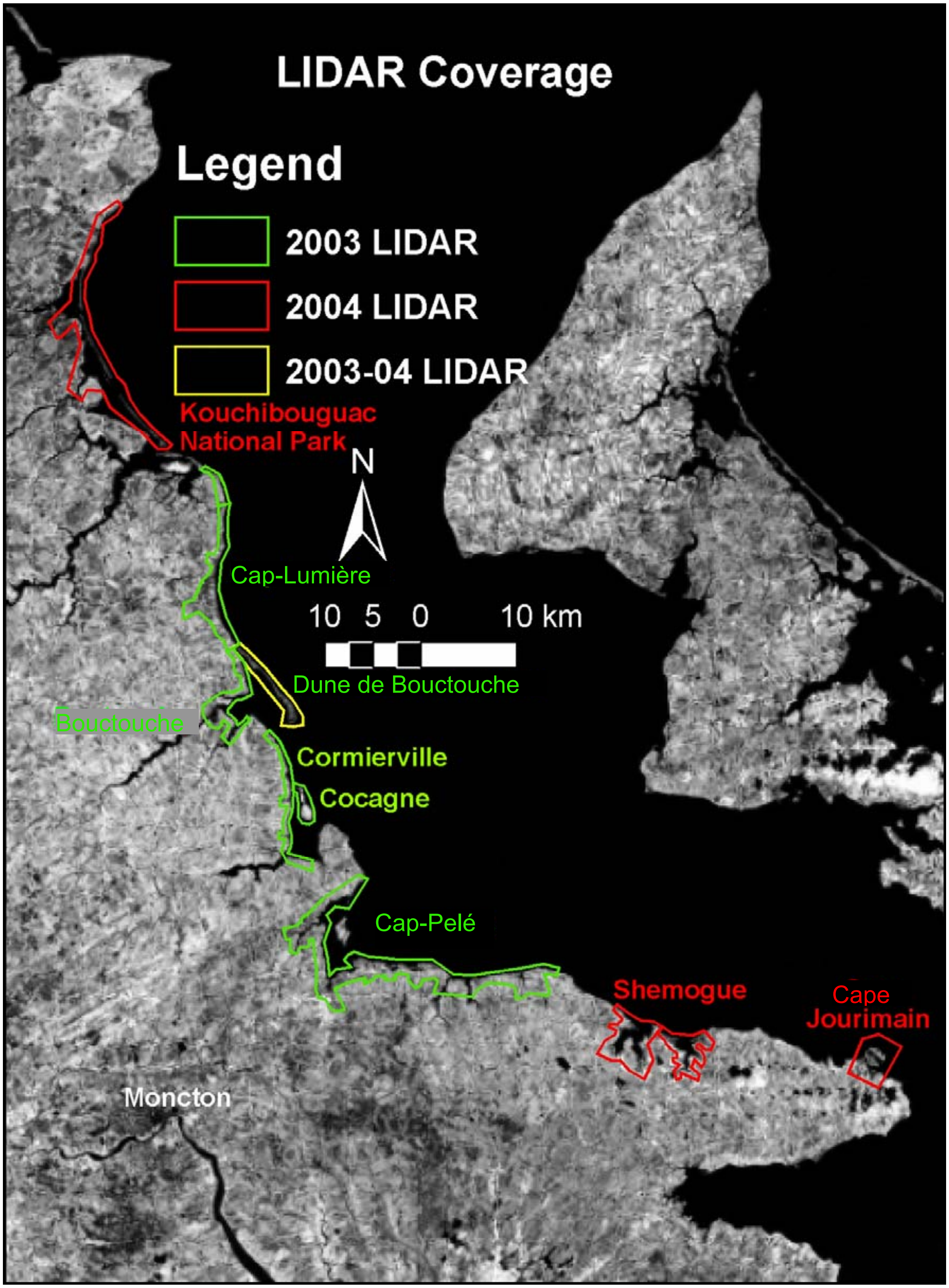

Figure 1. LiDAR survey polygons acquired in 2003 and 2004, Northumberland Strait coastal zone of New Brunswick.

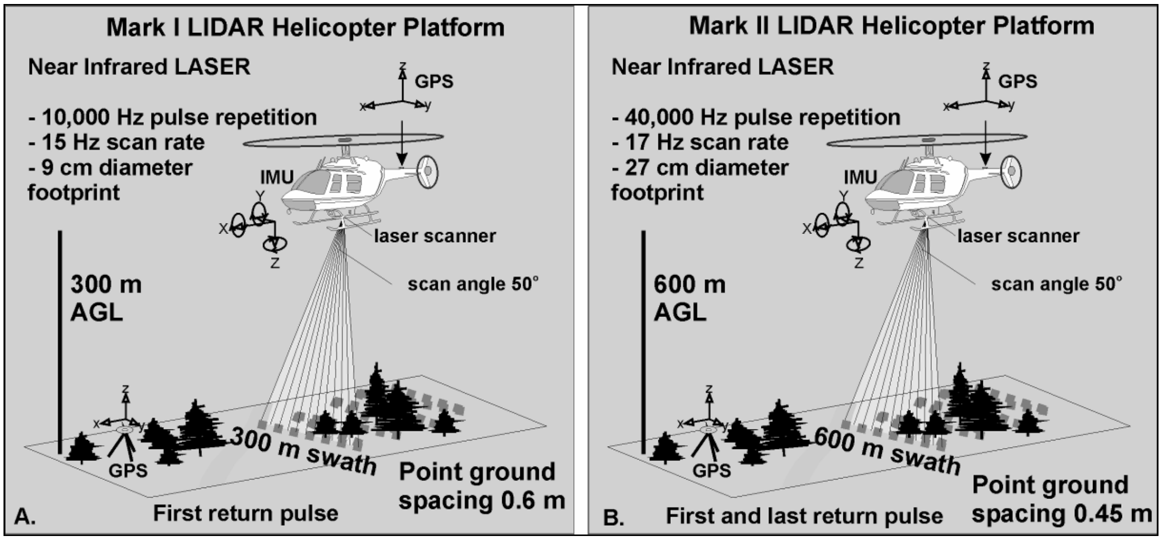

Figure 2. LiDAR configuration. A. Mark I system used for the 2003 acquisitions. B. Mark II system used for the 2004 acquisitions.

The Mark I is a first-return LiDAR system that was originally designed for corridor mapping and was mounted on a pod fixed to the underside of a Bell 206L helicopter (Figure 2A). The laser beam had a ground footprint diameter of 9 cm with an average point spacing of 60 cm (Figure 2A). The narrow laser beam facilitated penetration to the ground in vegetated terrain. The survey was conducted from May 23 to June 3, 2003 (Figure 3).

The Mark II system is capable of recording the first and last returns and the intensity of one of the returns and was mounted on a pod that was fixed to the underside of a Bell 206L helicopter (Figure 2B). It was decided to acquire the intensity on alternating returns; thus, every other first and last return would record the intensity. The laser beam had a ground footprint diameter of 27 cm with an average point spacing of 45 cm (Figure 2B). Because the Mark II sensor is capable of recording the first and last returns, the wider laser beam could still partially penetrate the vegetation canopy and reflect off the ground or near-ground surface and be measured as the last returning pulse. The survey was conducted from April 27 to April 29, 2004 (Figure 4). The Mark II has improved precision to better than ±15 cm in the vertical as a result of the higher-precision laser ranging system and IMU. The technical specifications required the horizontal and vertical accuracy to be within 30 cm of measured GPS points.

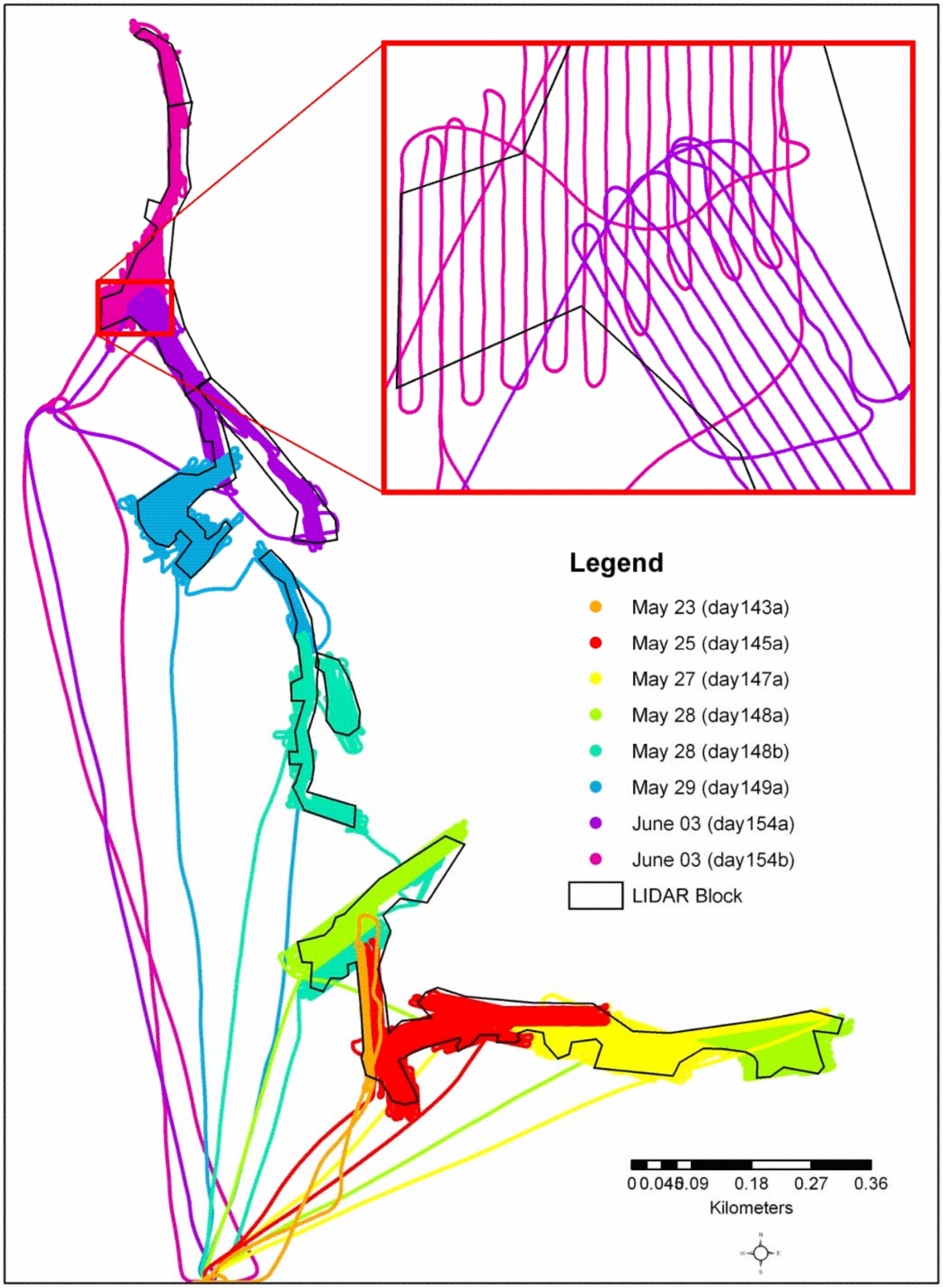

Figure 3. LiDAR acquisition dates and flight lines acquired during 2003 surveys (from MacKinnon, 2004).

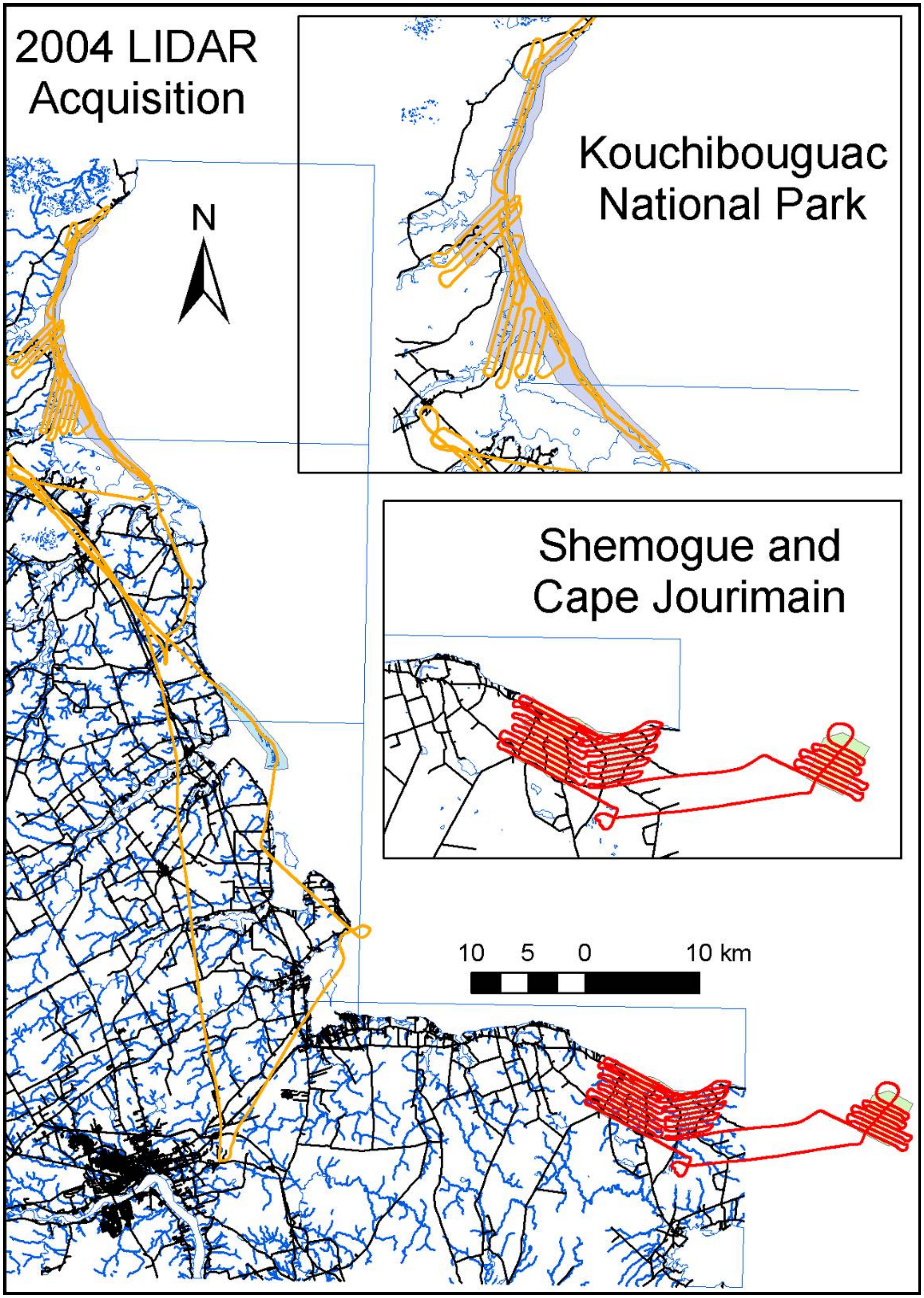

Figure 4. LiDAR acquisition dates and flight lines acquired during 2004 surveys. Red areas flown April 26, orange areas flown April 29.

4.4.2.3 LiDAR point attributes

In this study, the data were delivered as ASCII files separated into 2-km by 2-km tiles based on the UTM grid. The 2003 data files have data fields for each LiDAR point, including easting and northing position based on UTM zone 20 NAD83, ellipsoidal and orthometric heights, the GPS time for every laser shot and the flight line number. The last two fields facilitated testing for systematic errors between adjacent flight lines or strips (e.g., Maas, 2000, 2002). The 2004 data have the same fields as the 2003 data, with additional fields including echo number and the intensity of alternating returns. The echo number is an integer code that defines whether the return was the first or last of multiple returns or a single return (Table 1).

Table 1. Mark II return-pulse echo-coding scheme.

Echo code	Explanation
0	Only one return pulse
1	First of many returning pulses
2	Last of two returning pulses
3	Last of multiple (greater than two) returning pulses

4.4.2.4 Digital elevation models

DEMs are used for a variety of geoscience applications at scales ranging from 10^{-1} to 10^6 m. Some DEMs have been compiled from contours or spot heights derived from traditional photogrammetry. These methods for determining elevations have degraded accuracies in vegetated terrains, where ground elevations are inferred from canopy heights. The best regional DEMs available for this study area are 1:10 000 scale with a vertical accuracy of ±2.5 m, which have been derived from traditional photogrammetry available from Service New Brunswick (https://www.web11.snb.ca/snb7001/e/2000/2900e_1c_i.asp). Other high-resolution (m to cm scale) DEMs can be built with ground-based GPS survey equipment, but the coverage area is limited (e.g., individual beaches or coastal structures).

In this study, LiDAR surveys were conducted along the coastal zone in order to derive high-resolution DEMs that were used to generate flood-risk maps from raised sea levels. The result of a LiDAR survey is a point cloud, which represents the reflected laser pulses as a cluster of points in space. The points are classified into targets representing “ground” features and “non-ground” features, typically vegetation or buildings. The LiDAR point data acquired for this project were analyzed and used to construct surface models in a GIS. All of the LiDAR points (“ground” and “non-ground”) were used to construct digital surface models (DSMs). However, for flood-risk mapping, a “bald earth” DEM was constructed by interpolating only the “ground” LiDAR points. Data from the Mark II LiDAR sensor also included the intensity of alternating returning pulses. Grey-scale intensity maps were interpolated from some of the Mark II data utilizing both classes of LiDAR points to generate a LiDAR “backscatter” map equivalent of the DSM. The intensity map resembles a black and white near-infrared photograph.

4.4.2.5 LiDAR surface models (DEM, DSM, intensity maps)

Various terrain surfaces were constructed from the LiDAR points. The DSM surface was linearly interpolated to a 1-m grid from a triangular irregular network (TIN) that was constructed from all the LiDAR points. The “ground” points were used to construct a DEM using the same method. Although other interpolating methods were evaluated (e.g., inverse distance weighting), the TIN method was found to be the most effective at representing the intensity values for all the LiDAR returns (“ground” and “non-ground”). Although the LiDAR intensity surfaces were not extensively used in this projection, Brennan and Webster (2006) demonstrated that accurate land-cover classification could be obtained by using the intensity maps with the DSM, DEM, normalized height grid (DSM − DEM) and echo information.

Colour-shaded relief models were generated for the DSM and DEM surfaces by falsely illuminating the surfaces from the northwest at a zenith angle of 45° and applying a five times vertical exaggeration. To ensure that the LiDAR surfaces between adjacent coastal polygons (Figure 1) matched, the maximum elevation range of the surveyed region was determined and used to colorize all of the surfaces. The maximum elevation used for the DEM was 38 m and for the DSM was 58 m.

4.4.2.6 Validation of LiDAR DEM

In this study, the absolute accuracy of the LiDAR DEMs was required for accurate flood-risk modelling and mapping; therefore, extensive ground control using GPS and traditional survey methods were used in the LiDAR validation analysis (Figure 5).

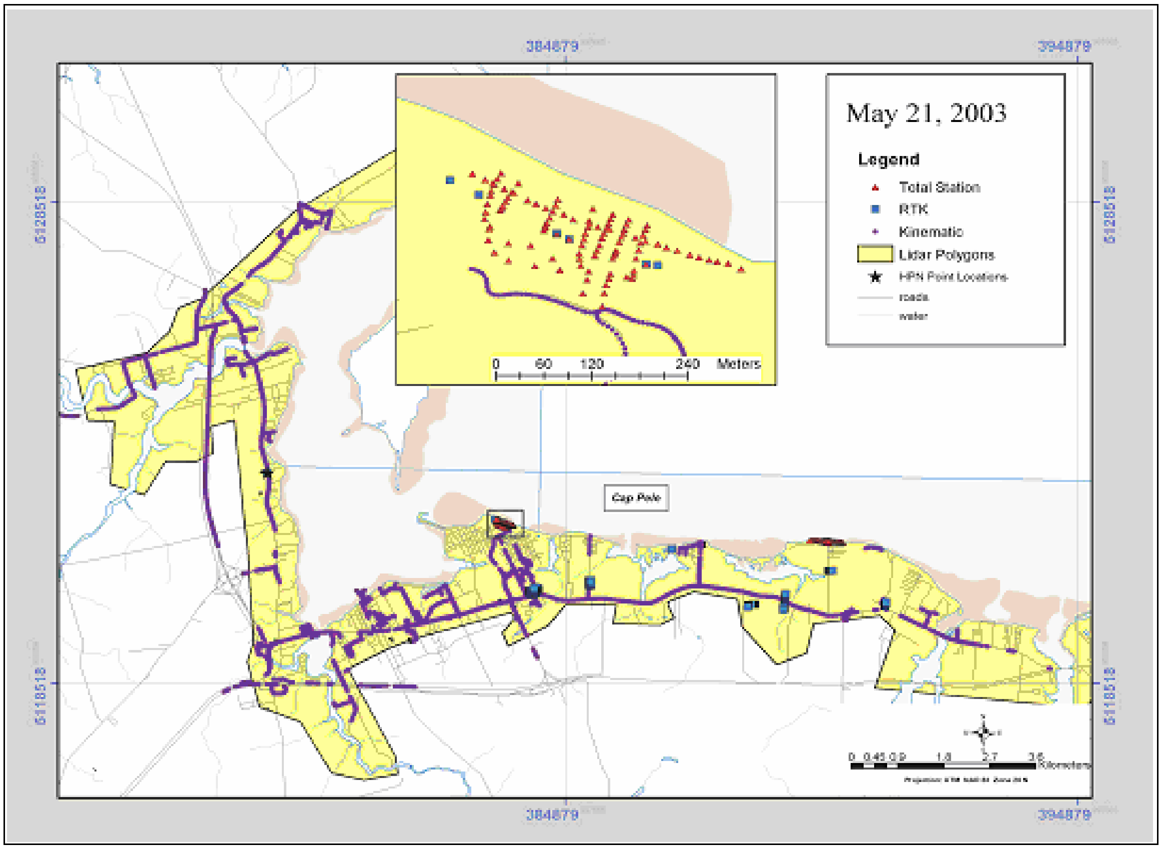

Figure 5. Example of LiDAR validation survey points for the Cap-Pelé survey block (from MacKinnon, 2004).

A methodology described in Webster (2005) and Webster and Dias (2006) was used for comparing the checkpoint validation data with the LiDAR ground points and derived DEMs. Coastal features (e.g., wharves) in the DEM were compared with digital orthophotos to ensure an accurate representation. The validation checkpoints consisted of real-time kinematic (RTK) GPS surveys of roads, wharves and beaches and traditional surveys utilizing a total station for dune transects and under the forest canopy (Webster et al., 2006).

4.4.2.7 Sea levels for flooding

The January 21–22, 2000, storm produced one of the highest storm-surge water levels on record for the Northumberland Strait region (Parkes and Ketch, 2002; Forbes et al., 2004). The tide gauge at Escuminac did not capture this event, having frozen prior to the highest water level during the storm. However, staff from Environment Canada marked the high-water position using nails in power poles and other wooden structures in many of the coastal communities affected by the storm surge. These high-water marks were surveyed with RTK GPS in 2002 with a precision of 2–5 cm in the vertical and used to estimate the water level associated with the January 2000 storm-surge event (Webster et al., in press). It is estimated that the water level associated with the January 2000 storm reached 2.55 m above CGVD28 vertical datum. Mean sea level is approximately 19 cm above CGVD28 for this region. Three water levels were selected for initial flood-risk modelling. These were the January 2000 storm level (2.55 m above CGVD28) and 50 cm and 70 cm above that level, representing the same storm in the next century using two sea-level-rise predictions (50 and 70 cm/century) (Church et al., 2001). Owing to the uncertainties in the estimates of future sea-level rise, it was decided to construct additional flood-risk maps using water levels at 10-cm increments up to a maximum of 4 m above CGVD28.

4.4.2.8 Flood-risk modelling and mapping

Standard GIS and image-processing capabilities were combined with the LiDAR DEM to model the potential areas of flooding at sea levels from 0 to 4 m (CGVD28). Galy and Sanders (2002) presented a similar approach where they used a DEM to map flood risk along the River Thames in the United Kingdom. Our method assumes that a given water level from the storm-surge event would form a horizontal flood plane extending landward from the open ocean. Thus, hydraulic effects, associated time lags and flood expansion or dampening were not considered in the modelling effort.

Webster et al. (2004a) discussed the requirement to ensure that areas on the DEM below a given flood level are included only if they have free connection to the ocean. In this study, a combination of 1:10 000 topographic map layers and the DEM colour-shaded relief maps was used to interpret where culverts or bridges existed. These areas would typically be represented by an embankment on the DEM and would prevent free connection of the low-lying areas upstream with the ocean. For these areas where culverts and bridges existed, the DEM was notched across the roadbed and assigned an elevation equal to that of the nearest upstream part of the channel. An automated GIS routine made use of this modified DEM with “hydraulic pathways” to determine the flood extent inland. The GIS processing involved applying a threshold to the modified DEM at a given flood level, resulting in a binary raster that was then converted to a vector polygon, and computing the perimeter and area attributes. The largest polygon (area) generated was then selected that would represent the inland flooded area with connection to the ocean, and smaller low-lying inland polygons not having connection with the ocean would be discarded during this process. In addition to the flood-extent maps, Webster and Forbes (2006) highlighted the importance of flood depth for the assessment of potential damage associated with storm-surge flooding. Once the flood extent was determined for the three water levels, flood-depth maps were generated for each water level by subtracting the DEM from the water level over the area of inundation.

4.4.2.9 Change detection along La Dune de Bouctouche (2003–2004)

La Dune de Bouctouche is one of the largest natural dune systems along the coast of New Brunswick and hosts several endangered flora and fauna. The entire dune was surveyed with LiDAR in 2003, and a section was resurveyed in 2004 to evaluate changes in the dune morphology using LiDAR. A significant storm-surge event that occurred in February 2004 caused coastal erosion and flooding in the region. Although the LiDAR surveys were acquired during similar seasons, the tidal conditions during the surveys and the precision of the two systems were different. The LiDAR surfaces of La Dune de Bouctouche were gridded at 1-m resolution and subtracted from one another (2004 − 2003 DEM) to highlight areas of significant change in dune morphology. Because of the limited range precision in the 2003 surveys, any change between the DEMs of less than 0.3 m was considered noise and ignored. The change surface was classified into 0.5-m vertical increments and examined for areas of significant change. Once areas of change were identified, topographic profiles were extracted from the two LiDAR DEMs and used to quantify the type of change (i.e., dune crest lowering or setback of the dune).

4.4.3 Results

4.4.3.1 Surface model examples of 2003 LiDAR campaign (DEM, DSM)

The LiDAR data from 2003 were inspected to ensure that all of the coastal polygons were surveyed and accurate DEMs were constructed. LiDAR point classification errors were observed in the 2003 data that were associated with coastal features that have abrupt vertical relief relative to the surrounding terrain. For example, the edges of wharves were classified as “non-ground”; therefore, the initial DEM did not accurately represent these features. The “non-ground” points that were incorrectly classified for these areas were used to construct DEMs that more accurately represented the coastal features following a method described in Webster et al. (2004a). The DSM and DEM were compared with the information that can be interpreted from Service New Brunswick’s digital orthophoto series of map products to ensure accurate LiDAR point classifications (Figure 6). A systematic pattern was observed in the LiDAR data over flat areas, such as water. This pattern, also found in LiDAR data from other systems and data providers (D. Whalen, Geological Survey of Canada, pers. comm., 2005), has been termed the “wood-grain effect.” It is caused by a combination of the limited precision of the laser ranging system and the motion of the aircraft. The variance of the pattern is within the specifications of the survey, but the pattern detracts from the fidelity of the colour-shaded relief maps of the DEM and DSM.

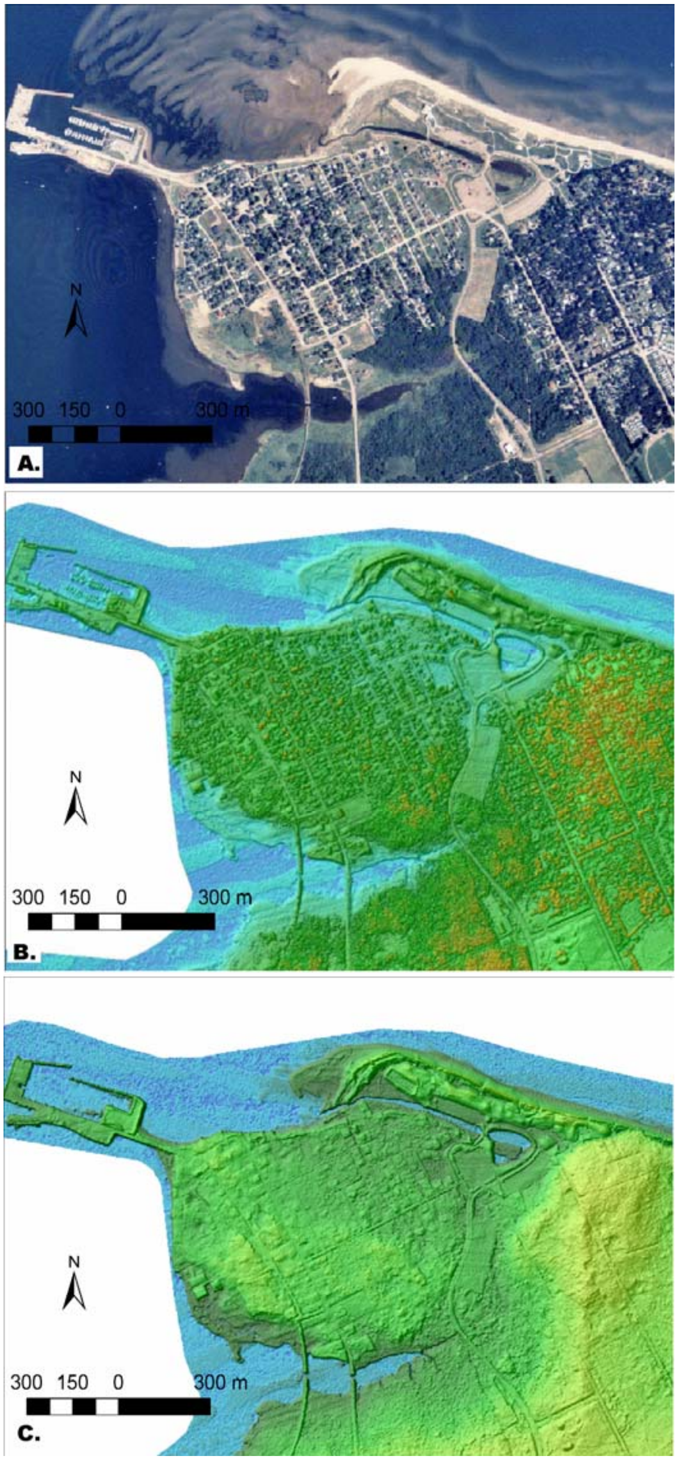

Figure 6. Example of orthophoto and LiDAR surface models for Pointe-du-Chêne. A. Colour orthophoto (source: Service New Brunswick). B. LiDAR digital surface model (DSM). C. LiDAR digital elevation model (DEM).

4.4.3.2 Surface model examples of 2004 LiDAR campaign (DEM, DSM, intensity maps)

The LiDAR data from 2004 were inspected to ensure that all of the coastal polygons were surveyed and accurate DEMs were constructed. Coastal features that were incorrectly classified as “non-ground” in the 2003 LiDAR data were correctly classified in most of the 2004 data. The DSM and DEM maps do not show any signs of the systematic “wood grain” effect (Figure 7). The absence of this artifact is a result of the increased precision of the laser ranging system used in the Mark II system for the 2004 surveys. In addition to constructing DSM and DEM maps, the intensity of the LiDAR returns was used to construct maps of the Kouchibouguac National Park area (Figure 7). Although the intensity of the reflected laser pulses near the edge of the scan tends to be lower than nadir pulse for some LiDAR systems, the intensity values for these data are very consistent across the swath, with the exception of nadir scans over flat water, thus allowing intensity mosaics to be constructed without significant artifacts between flight lines (Figure 7).

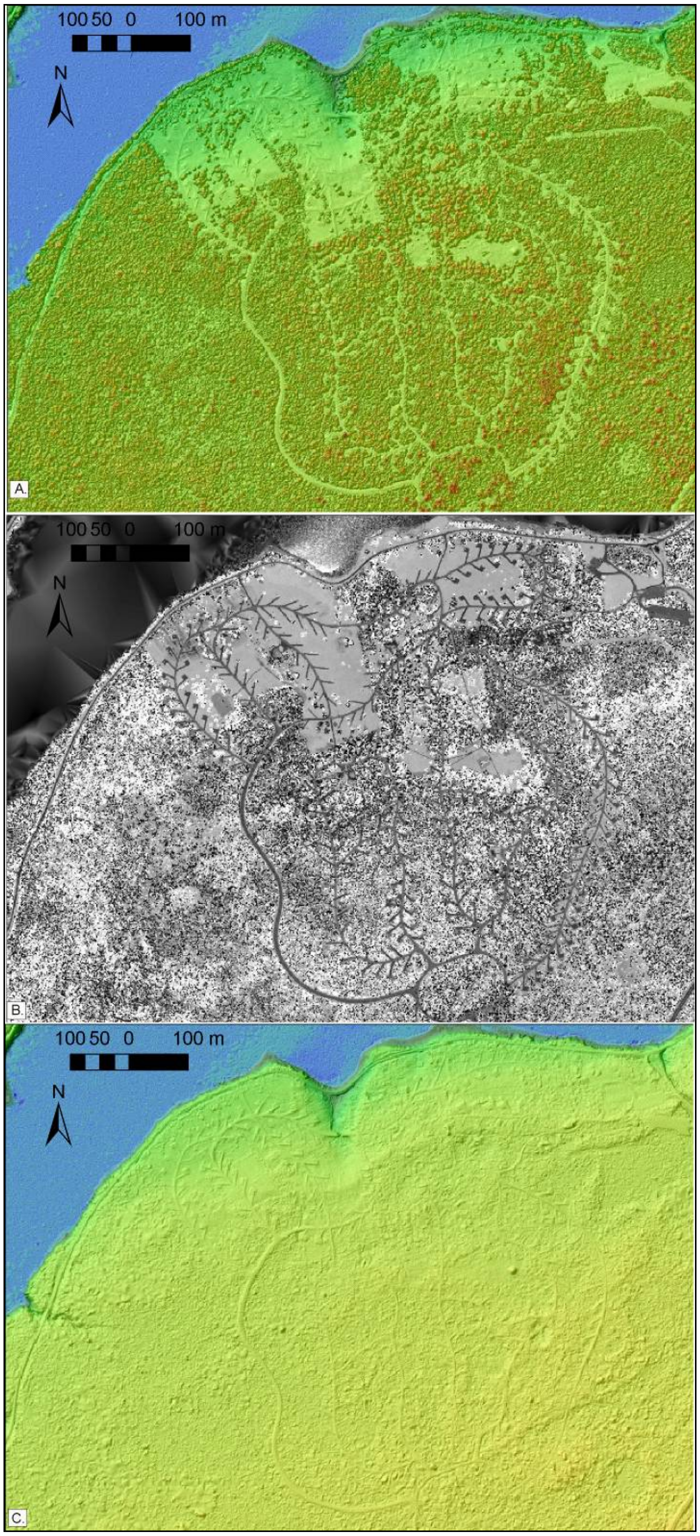

Figure 7. Examples of surfaces derived from the Mark II LiDAR sensor used in the 2004 surveys. The surfaces show the Kouchibouguac National Park campground area. A. DSM. B. Intensity of all the reflected laser pulses. C. DEM.

4.4.3.3 LiDAR height validation (2003, 2004 data)

The 2003 and 2004 LiDAR data met the specifications based on the comparison with the GPS and total-station survey data with the LiDAR points and derived DEMs. The summary statistics for the LiDAR 2003 DEMs compared with GPS surveys are presented in Table 2 and Figure 8A. The mean difference in height between the GPS and LiDAR DEMs for the 2003 survey polygons is 0.11 m, with a mean standard deviation of 0.11 m and a mean root-mean-square (RMS) error of 0.16 m.

The summary statistics for the LiDAR 2004 DEMs compared with GPS surveys are presented in Table 3 and Figure 8B. The mean difference in height between the GPS and LiDAR DEMs for the 2004 survey polygons is 0.11 m, with a mean standard deviation of 0.08 m and a mean RMS error of 0.12 m.

In general, the 2004 DEMs are more accurate than the 2003 DEMs, with slightly lower mean offsets and lower standard deviation values. The 2004 DEM data are more accurate because of the increased precision of the laser scanner and the increased accuracy of the IMU of the Mark II system.

Table 2. Validation results of 2003 DEMs.

LiDAR polygon	Mean difference (m) GPS − DEM	Standard deviation (m) GPS − DEM	RMS error (m) GPS − DEM	Number of GPS points
Cap-Pelé	0.04	0.11	0.11	20 748
Cormierville	0.21	0.12	0.24	2 426
Bouctouche	0.12	0.10	0.16	3 125
Cap-Lumière	0.07	0.12	0.14	810

Table 3. Validation results of 2004 DEMs.

LiDAR polygon	Mean difference (m) GPS–DEM	Standard deviation (m) GPS–DEM	RMS error (m) GPS–DEM	Number of GPS points
Cap Jourimain	0.10	0.09	0.14	1645
Shemogue	0.11	0.07	0.10	3333

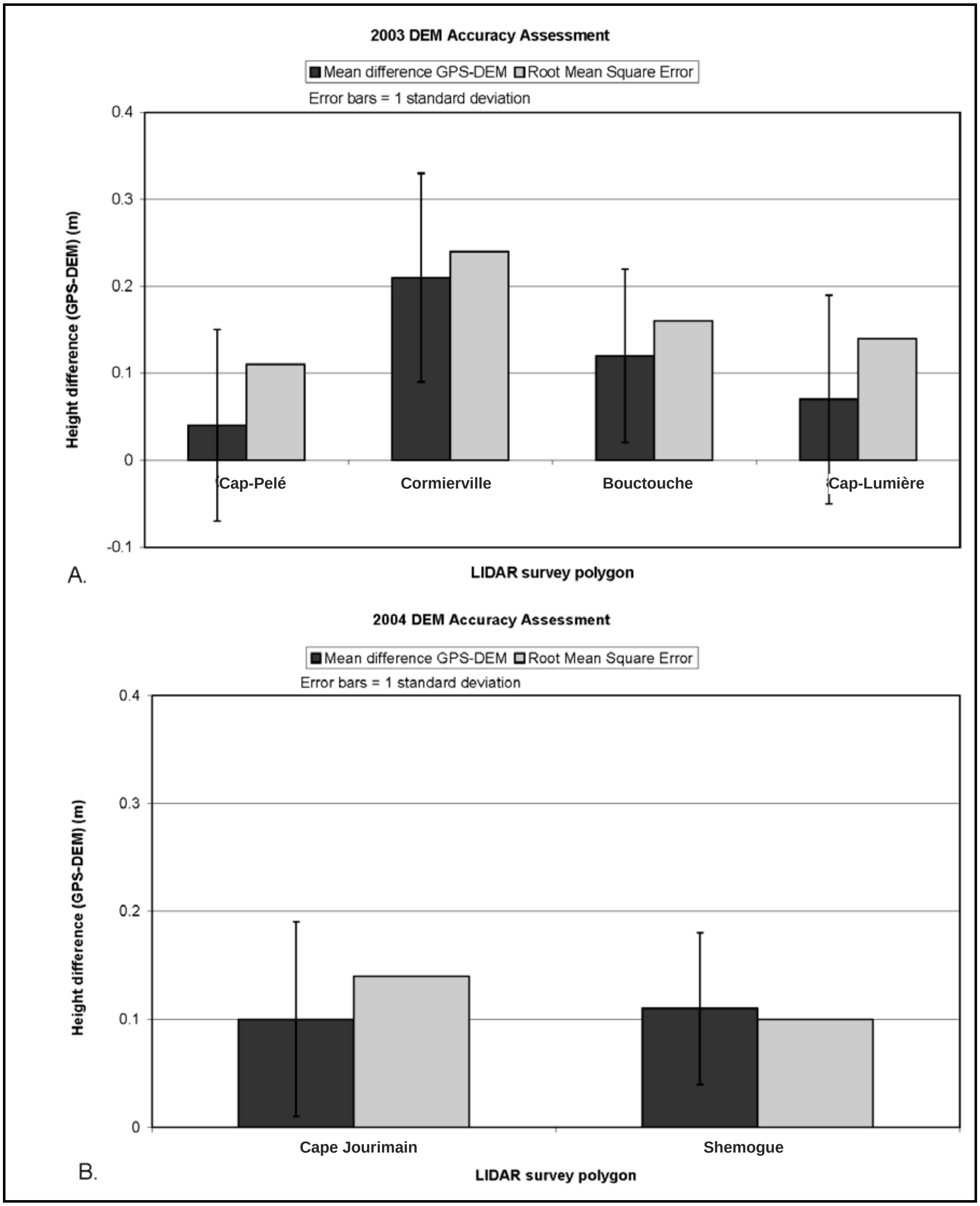

Figure 8. Graphical representation of LiDAR DEM height differences compared with GPS field measurements. A. GPS–DEM differences for the 2003 survey polygons. B. GPS–DEM differences for the 2004 survey polygons.

4.4.3.4 Flood-risk map examples (January 2000 storm, plus sea-level rise)

The notched LiDAR DEMs were used to construct flood-risk maps for three water levels. The levels are based on the January 2000 storm, determined to be 2.5 m above the level of the DEM, and the same storm superimposed on increased relative sea level in 100 years of 50 cm and 70 cm. The flood-risk maps represent the areas of inundation from the ocean for a given water level. Only low-lying areas that have free connection with the ocean were flooded. An example of the three flood extents (January 2000 storm, January storm in 100 years with 50 cm and 70 cm of relative sea-level rise) is shown in Figure 9A for the Petit-Cap area near Shemogue.

Flood-depth maps were constructed in order to better estimate the potential economic and ecosystem impacts of coastal flooding events. The flood depth was calculated for the three above-mentioned water levels (Figure 9B). The flood-depth maps of the January 2000 flooding event were used for validating the results of the flood modelling. Staff from Environment Canada visited several communities throughout the larger study area to evaluate the flood-extent and flood-depth maps. They reported a general agreement of within 10 cm in the vertical between the flood-depth maps for the January 2000 storm and water depths measured in the field (R. Daigle, Environment Canada, pers. comm., 2005).

Additional flood-risk maps were generated for 10-cm increments in water level, to allow for a more precise estimate of the areas potentially affected by future sea-level rise and storm-surge events. The 10-cm-increment flood extents are available as vector polygons that denote the area of flood inundation.

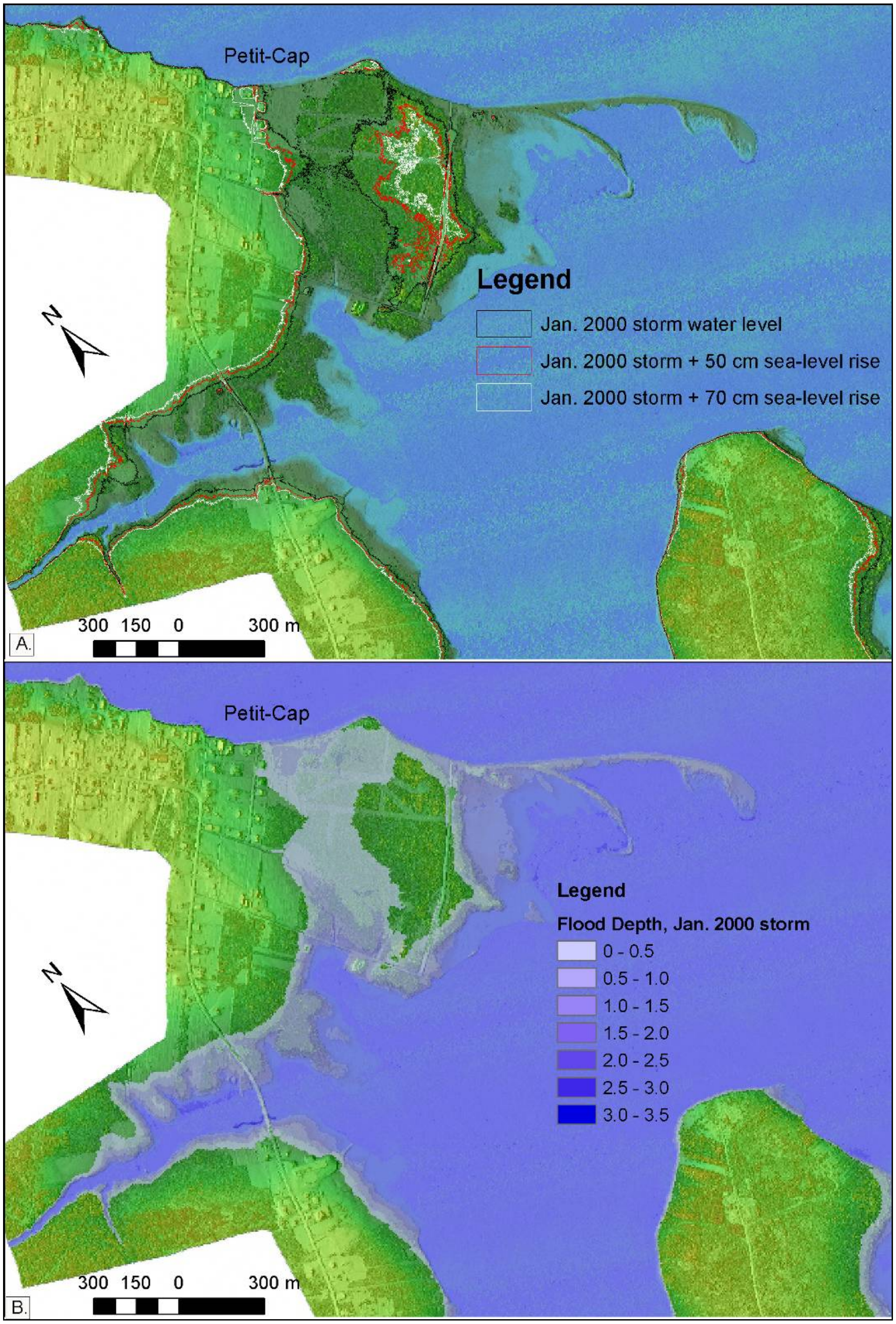

Figure 9. Examples of flood-risk maps for Petit-Cap. A. Flood-risk extents for the January 2000 storm and the same storm in 100 years with relative sea-level rise of 50 and 70 cm. B. Flood depth associated with the January 2000 storm.

4.4.3.5 Visualization of elevation models and flood-risk maps

To visualize flooding as a result of a storm-surge event superimposed on sea-level rise, animation sequences have been constructed for some areas. These have a background image consisting of a a LiDAR colour shaded relief (CSR) or satellite image draped over the DSM to simulate a perspective view of the landscape. The water level associated with a storm-surge or sea-level rise is then increased and flows over the landscape. The water levels for the flood-risk animation sequences increase by 10-cm increments to a maximum of 4 m above CGVD28. This is a very effective way to present the flood-risk modelling results in a way that is readily understood by the general public. An example of the visual effect of these animations is demonstrated in Figure 10 for the Shemogue Harbour area. A high-resolution Quickbird satellite image (DigitalGlobe) is draped over the LiDAR DSM at normal water levels (Figure 10A), and the water level is increased to that of the January 2000 storm-surge event (Figure 10B).

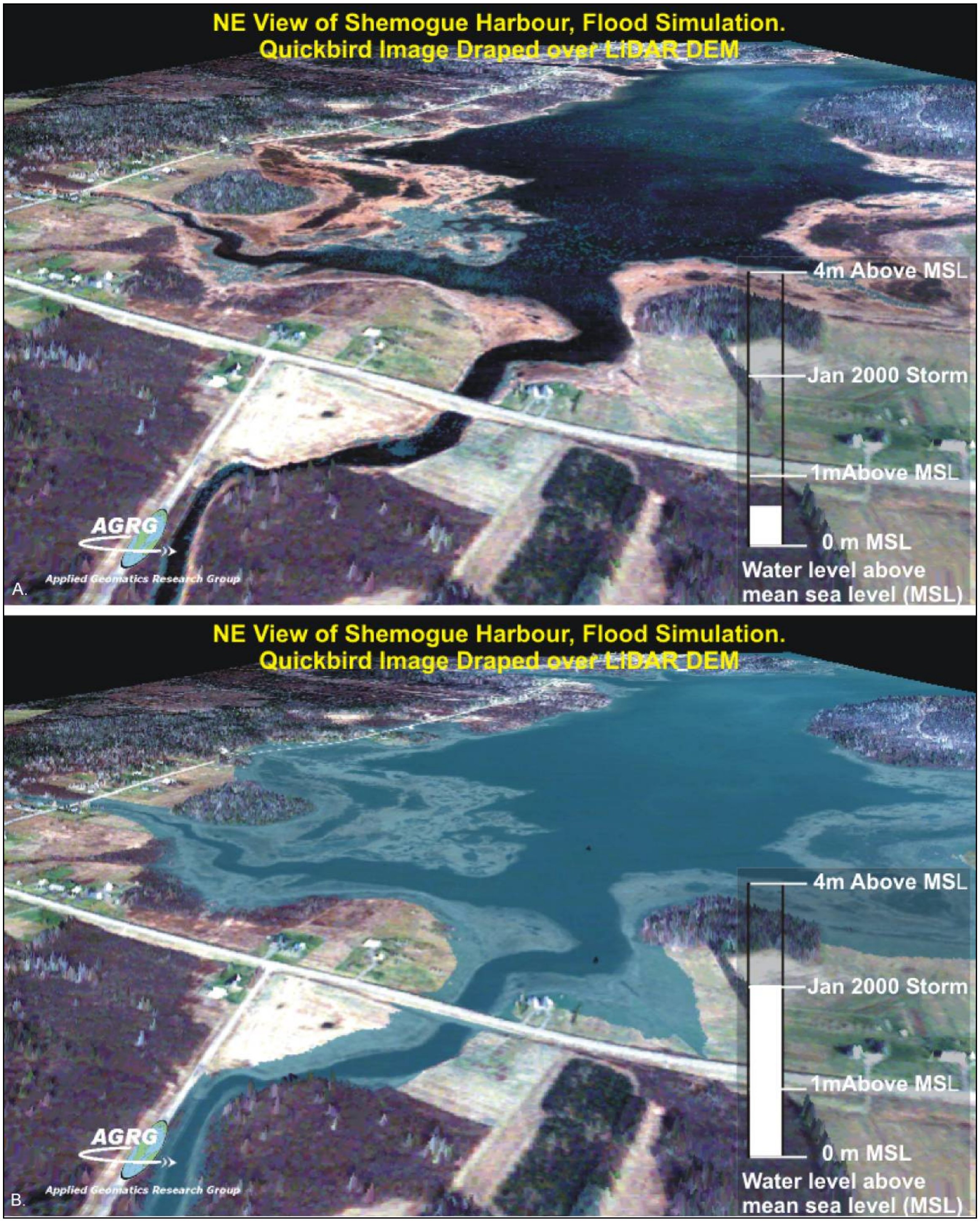

Figure 10. Example of flood-risk map visualization. A. Quickbird satellite true colour image draped over LiDAR DSM, normal water level within the tidal range. B. Simulated water level associated with the January 2000 storm-surge event. Includes material (2004) © DigitalGlobe, Inc. all rights reserved.

4.4.3.6 Change detection along La Dune de Bouctouche (2003–2004)

The results of subtracting the 2003 DEM from the 2004 DEM for La Dune de Bouctouche have highlighted areas of change along the dune system (Figure 11). The change surface map was classified into 0.5-m vertical increments and examined for areas of significant change. The maximum amount of change in the elevation of the dune between surveys was a lowering of 3.2 m. The most significant areas of change occurred on the eastern ocean-facing side of the dune, as would be expected from a storm-surge event. Two areas were examined in detail based on the occurrence of significant change in the two DEMs (Figure 11). The most change occurred on the eastern flank of the dune, and a less significant area of change occurred at the southern tip of the dune (Figure 11A). The dune was reduced by more than 3 m, and the beach seaward of the foot of the dune was lowered by 0.5 m from the storm (Figure 11B, C). The change at the southern end of the dune is less dramatic where the dune has been lowered by 1 m and the crest has been set back more than 15 m (Figure 11D, E).

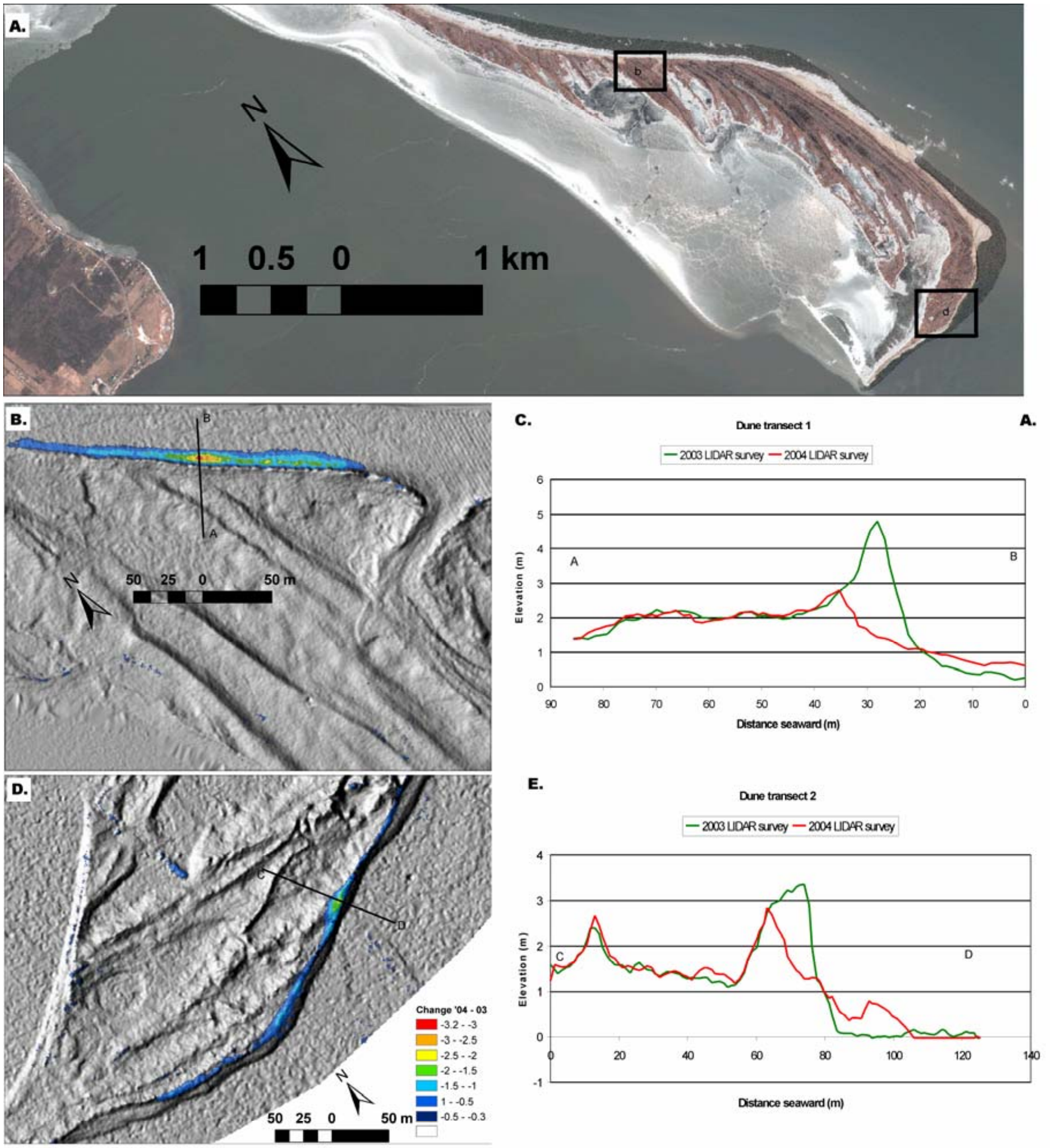

Figure 11. Change detection from 2003 to 2004, La Dune de Bouctouche. A. Quickbird satellite colour infrared image of the dune system with the location of detailed changes (b and d). Includes material (2004) © DigitalGlobe, Inc. all rights reserved. B. Vertical change (colours) in the dune between 2003 and 2004 over a greyscale shaded relief LiDAR DEM. C. Profile of the dune in 2003 (green) and 2004 (red). D. Vertical change (colours) in the dune between 2003 and 2004 over a greyscale shaded relief LiDAR DEM. E. Profile of the dune in 2003 (green) and 2004 (red).

4.4.4 Summary and conclusions

LiDAR mapping involves an aircraft emitting laser pulses towards the ground and measuring the travel time of the pulse to and from the point of reflection. The laser scan is acquired by rapid repetition of the laser-pulse transmitter and cross-track deflection of the beam using an oscillating mirror to produce a zigzag pattern of laser hits on exposed surfaces below the aircraft.

LiDAR surveys in southeastern New Brunswick were carried out in 2003 and 2004 in order to build a high-resolution DEM of flood-prone areas along the coast for most of the study area. Additional LiDAR products in the form of DSMs (showing buildings and trees) and intensity backscatter maps were also constructed for the survey areas. These surveys met the accuracy specifications and provided the high-resolution point sampling along the coast required to construct the DEM as a basis for flood-risk and flood-depth mapping. The flood extents and flood depths associated with the January 2000 storm surge have been qualitatively validated by field visits to sites where the water levels are known. The extents of the flooding associated with the January 2000 storm generally agree, and the flood depths are typically within 10 cm of observed water depths. The elevation datum for the LiDAR DEM was taken to be CGVD28 or orthometric zero. This is about 20 cm below mean water level as determined at the Pointe-du-Chêne tide gauge.

Using innovative methods to model hydraulic pathways to low-lying areas landward of causeways and other barriers, it was possible to determine potential flood extents at 10-cm intervals up to a water level of 4 m above mean sea level for the survey areas. This allowed near-continuous flooding simulations and animations to be constructed. The ability to generate a full sequence of water levels allows emergency measures and planning officials to access more information for use in designing disaster-mitigation and climate-change adaptation plans.

Repetitive LiDAR surveys at La Dune de Bouctouche demonstrated the utility of this technology to measure change in dune systems. A significant amount of change was mapped between the 2003 and 2004 DEMs. The modifications of the dune morphology are attributed to a significant storm event that occurred on February 19–20, 2004. The precision of the technology enables the detection of vertical changes on the order of decimetres in the elevation of coastal features, as demonstrated by erosion of the dune crests observed in this study.

In summary, the airborne LiDAR topographic mapping provided the high-resolution DEM required as an essential foundation for assessment of flooding and erosion hazards in all other components of the project.

4.4.5 Acknowledgements

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4.5 Coastal erosion

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4.5.1 Introduction

One potential impact of climate change is the rapid sea-level rise and the subsequent erosion of ecologically, economically or culturally valuable land. In southeastern New Brunswick, coastal communities are concerned about this possibility, since erosion and rising sea levels have already resulted in major land loss, and methods of counteracting these phenomena are limited and often expensive. Communities are also concerned with knowing exactly when the coastal retreat in the region will begin to accelerate as anticipated by the scientists.

According to a number of various erosion studies published for southeastern New Brunswick, coastal-retreat rates have not increased significantly during the second half of the 20th century. However, the situation may have changed over the last few years as storms have become more frequent and more intense, leading to extensive coastal retreat in a number of sectors within the region. Thus, the next challenge for scientists will be to determine whether the recent increase in coastal-retreat rate represents a genuine, lasting long-term erosion-rate increase and, if so, whether it can be directly related to climate change.

4.5.1.1 Component objectives

For scientists involved in this component of the project, the first objective was to collect the results of a number of coastal-erosion studies published for southeastern New Brunswick (Section 4.5.2) and to produce new studies for sectors where the trends and impacts of erosion were not well documented (Section 4.5.3). The second objective was to develop scenarios concerning the potential coastal-erosion situation over the next 100 years. The final objective was to familiarize coastal communities (knowledge transfer) with the concepts of coastal erosion and migration via public workshops and to make available previous coastal-erosion rates, as well as new data acquired from this project.

The first and third objectives have been met. The second has been met only in part, owing to the lack of geoscientific data for the region, particularly with respect to the status of sediment inventories in the coastal zone. However, scientists involved in this component are satisfied with the expertise that has been gained from the study and hopeful that the information presented in the following sections will provide all users with additional and, occasionally, new insight into the recent and future evolution of the southeastern coast of New Brunswick.

4.5.1.2 Erosion versus accumulation

An increase in the onshore wind speeds over short periods of time (from a few hours to a few dozen hours) produces high-energy waves that break against the coast. This combination of factors is considered the most important cause of coastal erosion. Another significant factor in coastal retreat is the relative sea-level rise, which enables waves to reach land previously beyond their range. It is generally acknowledged that the phenomenon of coastal erosion is neither new nor isolated. Coastal erosion probably first occurred during the formation of the first oceans, about four billion years ago. However, coastal erosion probably first caused “problems” a short time after the development of the first permanent coastal communities, about 3500 years ago. The occupation of an environment as dynamic and changing as a coastal zone inevitably leads to a conflict between the natural mobility of the coastal environment and the desire to take advantage of economic, strategic, social and cultural opportunities offered by the coast — and, especially, to ensure that these opportunities endure.

In southeastern New Brunswick, a number of erosion problems could have been averted during the 20th century had the proponents or managers of coastal development better understood coastal dynamics and underlying processes. Coastal erosion involves not only the removal of sediments and the destruction of coastal forms, but also a reorganization of that material elsewhere along the coast, with transport and accumulation often leading to the creation of new coastal forms. This is an important concept, as it implies that the impacts of erosion are not limited to those sites marked by this process and that the consequences of erosion are not always negative. In a context of climate change and rapid sea-level rise, the erosion process may even help preserve coastal forms, as outlined in the following examples:

- In sectors characterized by cliffs, coastal erosion and retreat inevitably lead to the destruction and gradual disappearance of coastal land. On the other hand, sediments removed from that land generally accumulate on the shore and contribute to the maintenance, movement and, indeed, formation of new beaches. Retreating cliffs also create the necessary space for landward movement of beaches, a process essential for their conservation in the context of sea-level rise. By limiting sediment transfer and the creation of new spaces, the development of coastal protection structures along the cliffs is, in a number of regions, the primary cause of the disappearance of beaches and their habitats.

- In sectors characterized by coastal dunes, the coastal-erosion and -retreat process leads sometimes to complete destruction of the dunes, but more often to their relocation. In fact, during erosion phases, part of the sediments removed from the dunes may be transferred to the shore, contributing to the formation of beaches. These beaches in turn supply the sediment necessary for their reconstruction.

> Another part of the sediment removed from the dunes may be transferred to the back of the dunes, contributing to their widening and landward migration. As in the case of cliffs, fixed structures developed on the dunes (e.g., buildings, roads) interfere with the transfer of sediment and are, in a number of regions, the primary cause of the disappearance of those coastal forms and their habitats.

Both of the above cases clearly illustrate the extent and complexity of coastal-zone interactions, in particular those caused by erosion and accumulation processes. While it is tempting to describe coastal erosion and retreat as “problems” calling for a solution, in a number of cases these processes are necessary for the maintenance and evolution of a number of coastal environments.

4.5.1.3 Erosion sensitivity index

Coastal sensitivity to erosion from storm waves varies between regions, depending on geological, geomorphological, oceanographic and human factors. In order to assess this sensitivity, the Geological Surveys Branch of the New Brunswick Department of Natural Resources developed in 1996 an index to weight the relative contribution of six factors in stormy weather: fetch length and breaker-zone width; orientation, composition and height of coastal relief; and distribution of protection structures. Two hundred and seventy-three coastal sectors, corresponding to the 1:10 000-scale digital topographical maps from Service New Brunswick, were included in the study (O’Carroll, 1996; O’Carroll and Bérubé, 1997). The methodology and results are summarized in a figure in Annex C (Section 5).

This study showed that fetch length and water depth at the coast appear to play a decisive role in determining coastal sensitivity to storm waves. Thus, the southeastern coast of the province (Northumberland Strait) is probably less sensitive to storm waves than the northeastern coast (Gulf of St. Lawrence), but more sensitive than the northern coast (Chaleur Bay); the protective effect of Prince Edward Island significantly reduces fetch length, and water depth is rather shallow along the Strait. In the southeastern region, sensitivity increases significantly north of Cocagne, primarily because of the longer fetch length, but also because of the reduced width of the breaker zone. Thus, 10 of the 14 regional coastal sectors characterized by strong to very strong sensitivity are located north of Cocagne. The majority (five of eight) of the sectors characterized by low sensitivity are also located north of Cocagne but associated with long estuaries that are protected from high-energy waves during storms.

Despite its obvious limitations, the index is a useful decision-making tool, as it offers an overview of coastal sensitivity to storm waves.

4.5.1.4 Erosion database

A number of coastal erosion studies have been produced for New Brunswick over the last 50 years. In order to make this information available to the public, managers and other stakeholders in coastal matters, the New Brunswick Department of Natural Resources (Geological Surveys Branch) created the New Brunswick Coastal Erosion Database (NBCEDB) in 1998. Developed using Microsoft-Access software, the NBCEDB contains details on study sites (location, geomorphology and sensitivity), evolutionary trends (rates, periods and margins of error) and measurement sources (year, author and publication). Although the NBCEDB was developed primarily to identify and monitor erosion sites, it also provides information on sites that are accumulating sediment or apparently stable.

Before the results obtained under this component were entered, the NBCEDB for southeastern New Brunswick (Pointe-Sapin to Port Elgin) contained a total of 968 coastal displacement rates (expressed in m/year), including 716 (74%) associated with sites undergoing erosion, 224 (23%) with sites accumulating sediment and 28 (3%) with apparently stable sites. When the study is complete (Kouchibouguac to Shemogue), 1654 new rates will be added to the NBCEDB, including 1207 (73%) associated with eroding sites, 428 (26%) with sites accumulating sediment and 19 (1%) with apparently stable sites. This simple, first-order categorization (erosion – accumulation – apparent stability) already illustrates the comprehensive nature of the recent evolution of New Brunswick's coasts: the number of sectors undergoing erosion is considerably greater than the number of sectors affected by other types of change.

When consulted in conjunction with the multiyear digital maps produced as part of this work, the NBCEDB is a useful decision-making tool, especially as the erosion maps allow readers to visualize the rates of retreat or advance in context with coastal zone landforms.

4.5.2 Earlier work on erosion trends and impacts

The measured coastal-retreat and -advance rates presented in this section were obtained using techniques frequently used in the past by scientists and researchers. The results of the various studies are presented here in order to show the area covered and process followed by the various disciplines working on managing and understanding New Brunswick's coastal zone. Focus is placed on photogrammetric studies, as this technique has greatly improved over the years. A number of measurements and rates obtained by those studies differ from our results and sometimes appear erroneous. However, the earlier works are valuable in that they have piqued the interest of a number of our scientists and offer a glimpse into how our understanding of this field is evolving, while allowing us, in several cases, to contribute additional information on specific sites where detailed studies have been conducted.

4.5.2.1 Regional studies

4.5.2.1.1 Causeway-bridge construction

In the late 1950s, the Geographic Division of the Department of Mines and Technical Services of Canada conducted a mapping project to assess the potential impact of a change in high-tide levels anticipated from the construction of a causeway-bridge between Prince Edward Island and New Brunswick (Forward et al., 1959; Forward and Raymond, 1960). One objective of the project was to measure historic coastal-retreat rates using surveying and photogrammetry in order to predict more accurately potential damage to coastal properties. At the end of the project, the authors set the total value of compensation to be paid to landowners along the Northumberland Strait at $2,924,000. Additional amounts were also anticipated to cover expenses related to potential repair work to bridges and wharves and to build the coastal-protection structures recommended in the case of some communities.

The surveying and photogrammetric work completed during the project produced roughly 30 coastal-retreat rates for southeastern New Brunswick (Pointe-Sapin to Port Elgin). These data show a cliff-retreat rate of 1.12 m/year between the mid-1930s and the late 1950s. Among the highest coastal-retreat rates measured in the region, the edge of a property located along Rayworth Beach in Baie Verte retreated by 113 m between 1935 and 1958. Apparently, the property line retreated especially quickly in 1938, a year marked by one of the most severe coastal storms (November 25) in the history of the province.

4.5.2.1.2 Industrial sand extraction

During the 1970s, the Mineral Resources Division of the New Brunswick Department of Natural Resources hired a consultant to conduct a mapping project to document the impact of industrial sand extraction on the north and east coasts of the province (Hunter, 1975). The consultant determined that, although sand extraction was not the only cause of beach and dune erosion, the practice nevertheless led to extensive damage to those environments. For example, in southeast New Brunswick (Cap-Lumière to Petit-Cap), the consultant calculated that close to 170 000 m^3 of sand had been extracted from the coast between 1968 and 1974; these data did not consider illegal extraction activities (i.e., those lacking a permit from the province), which were relatively common during the period.

As a result of submission of the study, the *Quarriable Substances Act* was amended to limit and supervise extraction activities throughout the coastal zone (public and private lands). One positive result of the new regulations was to eliminate all coastal quarries and sand pits and require that any uncontaminated dredged sand be placed along the shore adjacent to harbour infrastructures, in order to reduce erosion problems. In addition to generating the data necessary in order to amend the Act, this project provided the province with an enormous number of data (nearly 600 rates) on coastal-retreat trends. These data showed that, between the mid-1940s and the early 1970s, the beaches, dunes and cliffs in the province's southeast migrated landward at a rate of 0.79, 1.15 and 0.78 m/year, respectively.

4.5.2.1.3 Installation of protection walls

In the early 1990s, the Minerals and Energy Division of the New Brunswick Department of Natural Resources and Energy conducted a field-mapping project in order to describe the geomorphology of the coast between Cap-Lumière and Port Elgin (Bérubé and Thibault, 1996, 1998). One of the project's objectives was to update Hunter's (1975) geomorphological maps to include estuarine coasts. The project showed that the region's shoreline was formed of not only beaches (49%) and shore platforms (rocky) (6%), but also salt marshes (45%).

The project also revealed that, in order to protect buildings, roads and wharves from erosion, nearly 10% of the region's coast had been fortified using rock embankments or retaining walls (Bérubé, 1993). In fact, nearly 600 coastal-protection structures, of various lengths and types, were catalogued as part of this field-mapping project. The highest-density sectors (greater than 2.5 km of protection structures per 10 km of coast) were identified along the coast between Bouctouche and Barachois; the Shediac sector turned out to be the most heavily fortified. The lowest-density sectors (less than 1 km of protection structures per 10 km of coast) were identified along the coast between Petit-Cap and Port Elgin and north of Saint-Édouard-de-Kent. However, the author concluded that the distribution of protection structures was mainly a function of coastal-development density and not of more severe coastal erosion.

Another objective of the project was to update coastal-retreat rates for the region under study. This work was based on photogrammetric analyses conducted in cooperation with students from the Department of History and Geography of the Université de Moncton. On the basis of 60 erosion measurements taken between Cap-Lumière and Port Elgin, the study by Tremblay (1993) showed that, between 1945 and 1983, the dunes, cliffs and salt marshes of the region retreated at a rate of 1.21, 0.43 and 0.31 m/year, respectively. The study by Roberge (1994), based on 14 erosion measurements taken in the eastern part of Cape Jourimain, indicated that, between 1933 and 1993, both unconsolidated and rocky cliffs, as well as the sandy barriers (dunes and sand spits) in that sector, retreated at a rate of 0.60, 0.28 and 2.51 m/year, respectively.

4.5.2.2 Local studies

4.5.2.2.1 Sand-barrier evolution

A number of studies were produced on the evolution of the large sand spits along the southeastern coast of New Brunswick that form the barrier-island system of Kouchibouguac National Park and the Bouctouche sand spit. In the case of the dunified sand barriers of Kouchibouguac, the Master's and Ph.D. work by Dagneau (1996, 2002) indicates that the barrier-island system as a whole is moving landward, while the central zone of the system shows a fluctuating balance between sediment deposition, dune reconstruction, tidal-inlet infilling and the erosive effect of coastal storms. In fact, several sections of the coastal dunes from the central zone are apparently experiencing a trend contrary to that normally observed elsewhere along the New Brunswick coast — i.e., they are advancing seaward. Other information concerning the evolution of the barrier-island system of Kouchibouguac is presented in Section 4.5.3.1 of this report.

Three major works discuss how the Bouctouche sand spit and adjacent coast have evolved: a Ph.D. thesis by Ollerhead (1993) and three articles based on it (Ollerhead et al., 1994; Ollerhead and Davidson-Arnott, 1995a,b); a Master's thesis by Chiasson (2000); and a Master's thesis by Giangioppi (2004). The work by Ollerhead, based on ^{14}C dating of sediment from salt marshes and optical dating of dune sediments, indicates that the coastal system is probably 2200 years old and that the oldest dune was probably established 800 years ago. Chiasson's Master's thesis stresses the importance of developing an environmental monitoring plan for the sand spit, in order to obtain a better understanding of how it is currently evolving and protect its habitats from human activities that could threaten its integrity. Finally, the work by Giangioppi deals with the sediment budget of the sand spit, provides a description and monitoring of breaches and other landforms associated with storm events and describes recent coastline change trends (1945–2001). The primary maps produced from her work were published by the New Brunswick Department of Natural Resources (Giangioppi et al., 2002a,b) and are presented in Annex C3 of this report (Section 5). Other information concerning the evolution of the barrier-island system of Kouchibouguac is presented in Section 4.5.3.1 of this report.

Cocagne Bar

The Cocagne Bar is a former sand spit located along the Cormierville coast, about 8 km north of Cocagne. Owing to its dynamic nature, this sand system is an ideal site for the study of short-term variations in coastal retreat (periods of 5–15 years). Information from very short time scales is valuable because it helps, among other things, to pinpoint periods during which the impacts of coastal storms were most severe or in which insufficient sediment was deposited to maintain the stability or promote the growth of sand systems. The Cocagne Bar was first studied by Hunter (1975), who suggested, after conducting a detailed examination of the shore platform, that the spit was most likely a remnant of a much longer sand spit (formerly 3 km in length, compared with 1 km today). His photogrammetric study showed that the proximal section of the spit was rapidly moving inland (1945–1971: −2.23 m/year) and that its median section had on occasion been used as a sand-extraction site (in 1968 and 1969: 1280 m^3/year).

In the early 2000s, in order to understand the historical evolution of the Cocagne Bar, the Geological Surveys Branch of the New Brunswick Department of Natural Resources and the Environmental Technology Department of New Brunswick Community College conducted photogrammetric analyses based on an old bathymetric map (1839) and eight series of aerial photos (1945, 1954, 1963, 1973, 1976, 1983, 1995 and 2001) (Bérubé et al., 2002). The study established that, in 1839, the sand spit was relatively short (1.2 km), and its distal section was connected to a small island called Dickson Point. Traces of this small island are still visible today at the edge of the shore platform; they form a reef. These observations therefore suggest that the former spit described by Hunter (1975) (3 km) was not a single segment; rather, it was formed by a series of two or more tombolos. The coastal-retreat rates produced by the study show that the landward spit migration rate was extremely rapid: 4.06 m/year between 1839 and 1945 and 4.43 m/year between 1945 and 2001. However, the spit migration rate was well below average between 1954 and 1963, when the retreat rate was only 0.76 m/year. This slower regressive evolution could be indicative of a period of calm in terms of coastal storm frequency or a period in which larger amounts of sediment were deposited. The full results of the study are presented in Annex C (Section 5). Other information concerning the recent evolution of the Cocagne Bar is presented in Section 4.5.3.2.3 of this report.

Grande-Digue Point

The Grande-Digue Point is a small sand spit located south of Cap-des-Caissie, on the northwestern shore of Shediac Bay. The spit was eroded in the second half of the 20th century and could, over the next few decades, disintegrate completely. Aquaculturists, whose equipment is located in the shallow waters behind the spit (which offers protection against storm waves), are concerned that it may disappear. In response to their concern, the Geological Surveys Branch of the New Brunswick Department of Natural Resources conducted a study in the early 2000s to gain a better understanding of the causes and trends of erosion along the spit (Bérubé and Evans, 2003). This work revealed that the spit had been one of the most heavily used sand-extraction sites in southeastern New Brunswick. Between 1968 and 1974, approximately 4880 m^3 of sand were extracted annually (Hunter, 1975). The photogrammetric data produced by the project show that the rate of retreat between 1945 and 2001 was particularly high in the middle section of the spit (4.39 m/year), relatively high in the proximal section (1.74 m/year) and much lower in the distal section (0.58 m/year). However, a breach formed in the middle section of the spit in the early 1990s and has since evolved into a tidal inlet, which could deprive the distal section of the necessary supply of sand to remain in equilibrium over the next few years. The results of the study are presented in Annex C4 (Section 5).

Dupuis Corner Spit

In the late 1980s, a student in the Department of History and Geography of the Université de Moncton completed a project to map the evolution of the small sand spit at Dupuis Corner, located on the east bank of the mouth of the Kouchibouguac River (Robichaud, 1989). As in the case of the Cocagne Bar, the Dupuis Corner Spit is a highly dynamic sand system and an ideal site from which to study short-term (periods of 5–15 years) coastal-retreat variations. For the study, an old bathymetric map (1806), five series of aerial photographs (1945, 1954, 1963, 1971, 1982) and field observations (1988) were used to characterize the principal spit movements. The student began by determining that the length of the spit had diminished considerably over the last few centuries, from 2900 to 1400 m between 1806 and 1945 and from 1400 to 650 m between 1945 and 1988. He subsequently determined that the average spit retreat rate between 1945 and 1982 was 3.07 m/year and, as in the case of the Cocagne Bar, that the retreat rate was less significant between 1954 and 1963 (1.97 m/year). Finally, the spit itself was also affected by sand-extraction operations: approximately 1620 m^3 of sand were extracted annually between 1968 and 1972 (Hunter, 1975).

4.5.2.2.2 Coastal forest evolution

Pointe-Sapin peatlands

Although peatlands are not coastal landforms, they may still be found on the coast and, as such, are an important element of southeastern New Brunswick's coastal landscape. In the late 1980s, the Department of Geography and the Centre d'études nordiques of Université Laval, in cooperation with the Department of History and Geography of the Université de Moncton, conducted a study of the evolution of the coastal peatlands located between Escuminac and Pointe-Sapin (Bégin et al., 1989). The purpose of the study was to pinpoint the relationship between coastal retreat and the degradation of the spruce trees living at the edge of peatlands. The authors began by using photogrammetric studies to show that the coastal-retreat rate (1954–1983) was rapid in the region: 1.40 m/year in the peat cliffs, 0.84 m/year in rock cliffs, 1.25 m/year in salt marshes and 0.82 m/year along the sandy barriers (dunes and sand spits). The authors also conducted dendrochronological analyses to determine that sand-spit migration towards the peatlands had limited substratum drainage and inhibited spruce growth. Finally, the work revealed that peat-cliff erosion and retreat could have two opposite outcomes: substratum drainage and improved spruce growth or substratum destabilization and reduced spruce growth.

Cocagne Island cliffs

In the mid-1990s, the Geological Surveys Branch of New Brunswick's Department of Natural Resources and the Department of History and Geography of the Université de Moncton conducted dendrochronological and photogrammetric studies to assess the role of coastal erosion in the degradation of a spruce forest located in the northeastern section of Cocagne Island (Bérubé et al., 2006). Their work demonstrated that the history of the forest was marked by three phases: substratum colonization, population consolidation and forest-edge degradation. The colonization phase occurred in the early 1940s and 1950s. During this period, Acadian families then living on the island abandoned their farms, which set in motion a process of field colonization by spruce and other forest species. During the consolidation phase, between 1950 and 1970, the high density of pioneer populations reduced exposure to storm winds, which contributed to improved spruce growth. Furthermore, although the cliffs retreated at a rate of 0.43 m/year during the period, the majority of the spruce trees were located more than 5 m from the coast at the time and were thus sheltered from storm waves and salt spray. Finally, during the forest-degradation phase, which began in the 1970s, increased cliff erosion and retreat resulted in the toppling of spruce trees located at the cliff edge; their mortality rate was especially high in storms during the period 1986–1988. The results of this study are summarized in Annex C5 (Section 5).

Cap-Pelé marsh

In the early 1990s, a student in the Department of Geography who was also affiliated with the Centre d'études nordiques of Université Laval applied dendrochronology and photogrammetry to document the effects of storms and sea-level rise on the coastal forests of a sector of Cap-Pelé (Robichaud, 1993; Robichaud and Bégin, 1997). The study showed that, given significant coastal retreat (1.10 m/year between 1945 and 1982), the strong winds accompanying storm events have a significant impact on this type of coastal environment: the forest adjoining and colonizing the cliff top is characterized by a number of trees that are bent over and even show exposed roots. A correspondence was noted between the storm years, in particular those between 1986 and 1989, and increased mortality or reduced growth of trees. Storm winds apparently even caused mechanical breakage (e.g., loss of branches) in trees located 20 m from the cliff. Where the forest borders on a salt marsh, the studies show that, in addition to being concurrent with the major storms, tree mortality is initially observed in the low-lying parts of the coastal land and subsequently appears in the higher parts. The progression rate of the mortality front at the site between 1985 and 1991 was assessed at 3 m/year. Thus, it appears that long-term sea-level rise allows storm floods to gradually reach parts of the forest that were previously beyond their range.

4.5.3 Studies produced under this component

4.5.3.1 Kouchibouguac to Bouctouche

4.5.3.1.1 Introduction

The coast of the Kouchibouguac embayment extends some 40 km from Pointe de Pruches (just north of Pointe-Sapin) in the north to Pointe des Mares (just north of Cap-Lumière) in the south (Figure 1). The straight-line distance across the bay on a baseline between these two headlands is 32.5 km. The coast is inset 10.5 km from the baseline in the vicinity of Kellys Beach, showing a subtle spiral form opening to the south, consistent with net southward longshore drift. As in other parts of the study area, the low coastal plain has little relief and limited sediment cover (Rampton et al., 1984). The bay opens to the east–northeast and is exposed to wave approach from the open gulf to the north and northeast, the direction from which the largest storm waves approach (Hale and Greenwood, 1980; Forbes et al., 2004). Sandy barrier islands with nearshore bars and coastal dunes form the coast in the central part of the Kouchibouguac embayment (McCann, 1982) and protect a number of shallow bays and estuaries formed by the drowning of several river valleys (notably the Kouchibouguac, Kouchibouguacis, Saint-Charles and Richibucto rivers) by rising sea level (Johnson, 1925).

At present (New Brunswick, 2002), there are three main barrier islands: from north to south, these are North Kouchibouguac Beach (NKB), South Kouchibouguac Beach (SKB) and North Richibucto Dune (or Beach) (NRB), with a large spit to the south known as South Richibucto Beach (SRB). Another small barrier island is present between SKB and NRB, set in behind the south end of SKB. The number of barrier islands may vary over the years as inlets close or are opened in storm events. At present, NKB is effectively welded to the coast at Pré à Germain in the north. On the north side of the Pré à Germain headland, the north end of NKB combines with a small spit extending south from the opposite point to form a barrier with a central inlet across a small lagoon; another narrow barrier exists across the small drowned valley north of that (south of Rivière-au-Portage). From Pré à Germain north towards Pointe-Sapin, low cliffs up to 4 m high occur on the headlands, and somewhat higher cliffs are found on the south side of Pointe-Sapin, but otherwise the coast is low. The volume of beach sand is very limited to the north, despite historical problems of harbour shoaling at Pointe-Sapin. Southward longshore transport of sand from the Escuminac embayment to the north is diverted seaward at Pointe de Pruches and moves alongshore seaward of a rock platform, to come ashore again in the vicinity of the harbour (Forbes, 1982).

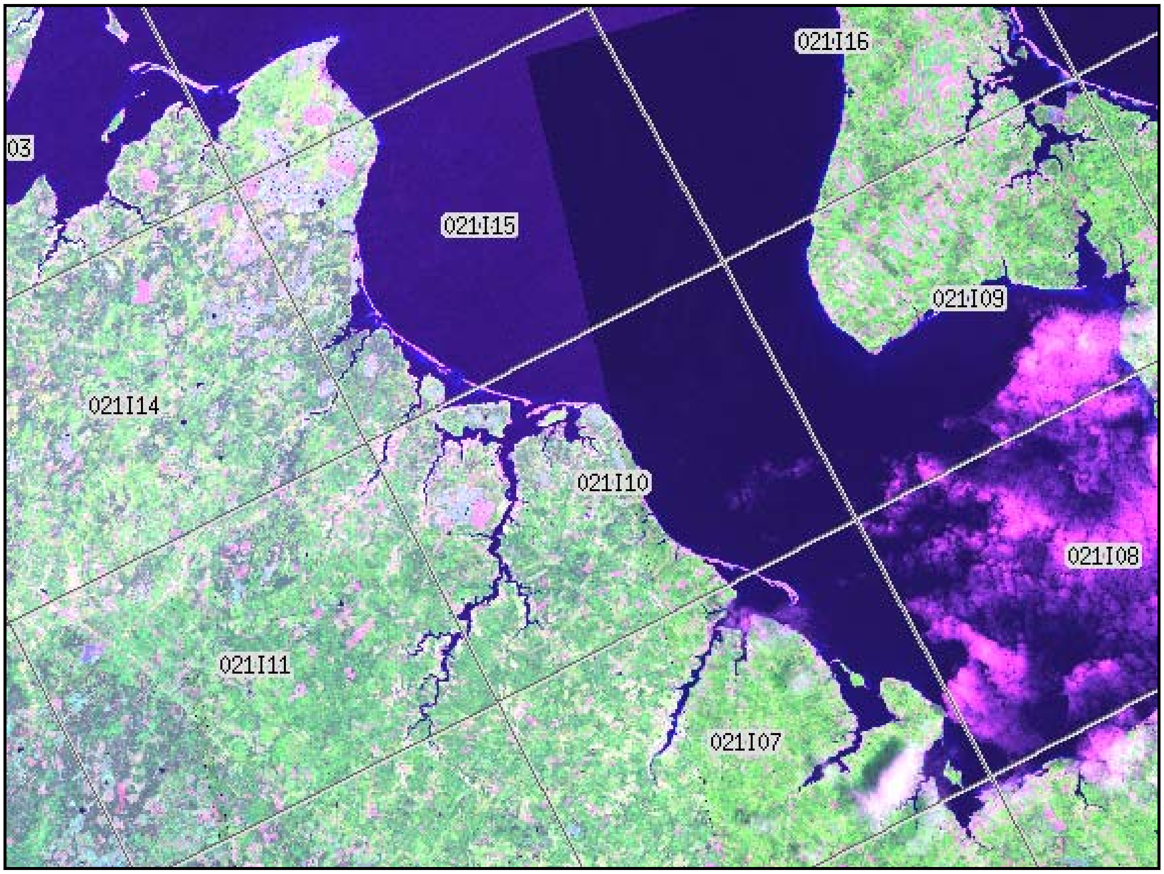


Figure 1. Landsat 7 mosaic showing the coast from Kouchibouguac to Bouctouche (courtesy of GeoBase).

Most of the shallow inner shelf in the area of Pointe-Sapin is floored with lag gravel, except for a low, linear, shore-parallel sand ridge 600–900 m wide and up to about 2.2 m high, in 8- to 10-m water depth 2.5 km offshore, interpreted as an abandoned (overstepped) barrier-beach ridge (Forbes, 1987). Kranck (1967, 1971) described the seabed sediments of Kouchibouguac Bay and showed that the conditions off Pointe-Sapin extend south into the bay, where most of the seafloor has a veneer of coarse lag gravel, presumably developed by erosion of underlying till as the shoreline migrated across the shelf (Kranck, 1972). Sand is largely confined to the present shore zone in the Kouchibouguac embayment, forming a multiple nearshore linear and crescentic bar system along much of the barrier-island shoreline (Davidson-Arnott and Greenwood, 1974; Greenwood and Davidson-Arnott, 1975, 1977, 1979; Greenwood and Hale, 1980). Away from the barrier systems in the central part of the bay, the beaches are narrow, and the volume of beach and nearshore sand is extremely limited (Forbes, 1982, 1987).

South of Pointe des Mares, the southern headland of the Kouchibouguac embayment, a relatively straight section of coast extends directly south approximately 7.5 km to Gros Cap. Except on the north side of the harbour at Cap-Lumière, where southward sediment transport is trapped and the beach and dunes are prograding, the rest of this section is largely erosional, with sandstone cliffs up to about 6 m high (Figure 2). On the south side of Gros Cap, substantial shore protection has been installed in front of newly developed properties. From this point south, the coast extends in another broad embayment about 22 km to the harbour of Saint-Édouard-de-Kent and the start of Bouctouche Spit (La Dune de Bouctouche). Over much of this distance, the coast is a sand beach backed by a single foredune ridge. Two small barriers backed by shallow lagoons are present between Gros Cap and Côte-Sainte-Anne. A beach and dune ridge also extends across the front of stream outlets with wetlands between Chockpish and Saint-Édouard-de-Kent.

Figure 2. Foundation of an abandoned fish plant south of Cap Lumière, partially destroyed by erosion of low sandstone cliff (D.L. Forbes/GSC, May 2005).

Bouctouche Spit, known locally as La Dune de Bouctouche (Figure 3), is a spectacular flying spit, one of the finest in eastern Canada, and extends about 12 km across the front of Bouctouche Bay (Ganong, 1908; Johnson, 1925; Ollerhead and Davidson-Arnott, 1995a,b). It terminates in a wide recurved dune-ridge complex opposite Saint-Thomas-de-Kent. Based on digital rectification of the 1839 Bayfield chart, Ollerhead and Davidson-Arnott (1995b) demonstrated that the last recurve was added since that time. However, they also concluded that spit extension is now limited by constrained sediment supply and by sediment bypassing under strong ebb currents across the mouth of Bouctouche Bay. The spit can be subdivided into three sections (Ollerhead and Davidson-Arnott, 1995b):

- a narrow proximal section, subject to erosion and more frequent overwash;
- a transitional zone with preserved recurved dune ridges behind the foredune, but where occasional breaching still occurs; and
- a distal depositional section with multiple recurved dune ridges building onto a shallow spit platform.

Figure 3 shows the contrasting morphology of these three sections and the area of recent washover development in the updrift portion near the Irving Eco-Centre. This is the area where major infrastructure damage was sustained in the great storms of October 2000 and December 2004.

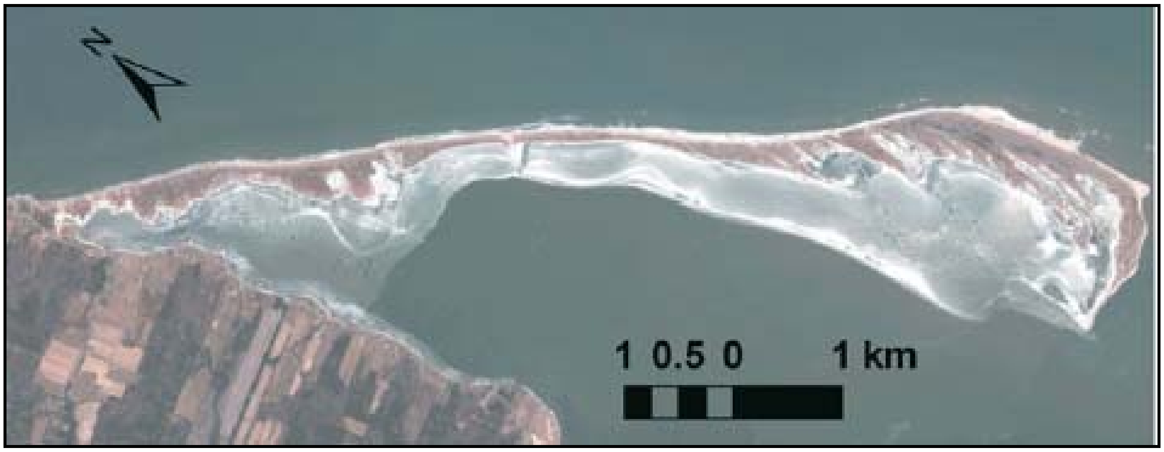


Figure 3. QuickBird image of Bouctouche Spit in 2005 (contains data copyright Digital Globe Inc.).

4.5.3.1.2 Methodology

This section of the coast was investigated using published and unpublished results from previous workers, direct field observations and surveys, air photographs and digital aerial photogrammetry, airborne light detection and ranging (LiDAR) surveys, airborne polarimetric synthetic aperture radar (PSAR) (Radarsat-2 simulation) and high-resolution satellite imagery (QuickBird).

4.5.3.1.3 Results

Kouchibouguac National Park

The barrier islands of Kouchibouguac Bay support large coastal dunes and contain the largest volume of sand anywhere along the southeastern coast of New Brunswick (Figure 4). This figure shows an alongshore profile of cliff-top and dune-crest elevation on profiles at 50-m intervals from a starting point south of Rivière-au-Portage. The data were derived from the 2004 LiDAR digital elevation model (DEM) (see Section 4.4). Also shown is the elevation of the toe-of-dune (top of beach) or the barrier crest (where no dunes are present), representing the minimum limit of wave runup. Note that dune-face collapse and aeolian ramp development during the winter preceding the LiDAR survey in April 2004 may have obscured the toe-of-dune in some places, so that the morphological expression of the runup limit may be biased low.

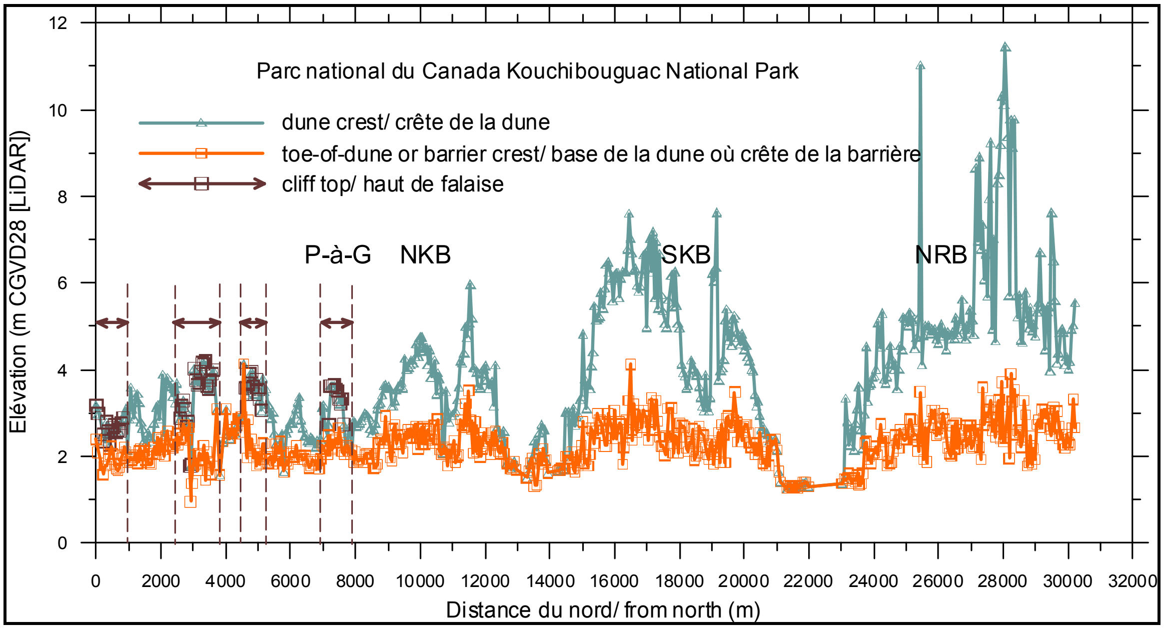


Figure 4. Dune crest, toe-of-dune or barrier crest (runup limit) and top of cliff in Kouchibouguac National Park, from 2004 LiDAR DEM: North Kouchibouguac Beach (NKB), South Kouchibouguac Beach (SKB) and North Richibucto Beach (NRB). X-axis is distance alongshore from origin near northern park boundary to southern tip of NRB (about 30 km). P-à-G = Pré à Germain.

Four small headlands separated by beaches or small barriers with low dunes are present in the northern 8 km (Figure 4), the southernmost headland being Pré à Germain. The cliffs in this area are up to 4.2 m high (CGVD28), and dune crests range from 2.5 m to almost 4 m. With one exception, the wave runup limit ranges from <2 m to a maximum of about 3 m. Farther south on NKB, the dunes rise to maximum heights of almost 5 m near the 10-km mark and 6 m near 11.5 km. The toe-of-dune marking the minimum height of wave runup in this area ranges from 1.7 to 2.9 m (3.5 m in one location) and is typically about 2.5 m (CGVD28). Beyond the Little Gully inlet near Kellys Beach, the dunes on SKB are higher, with maximum elevations of >7.5 m (>6 m for at least 2 km alongshore). The toe-of-dune elevations average slightly higher than on NKB, reaching 3.0 m in many places (two outliers, in one case up to 4 m, like the single outlier on NKB, may be bad picks of the toe-of-dune on the LiDAR profiles). As on NKB, the highest dunes and highest runup elevations are in the middle of the barrier island, dropping off towards the inlets at the north and south ends. Continuing south, the LiDAR coverage also includes NRB, where the highest dune-crest elevations were observed, up to 11.5 m in one location, with many >9 m. The modal crest elevation on NRB is between 5 and 6 m, a little lower than on SKB. On the other hand, the toe-of-dune elevation is very similar to that on SKB, although a little more variable.

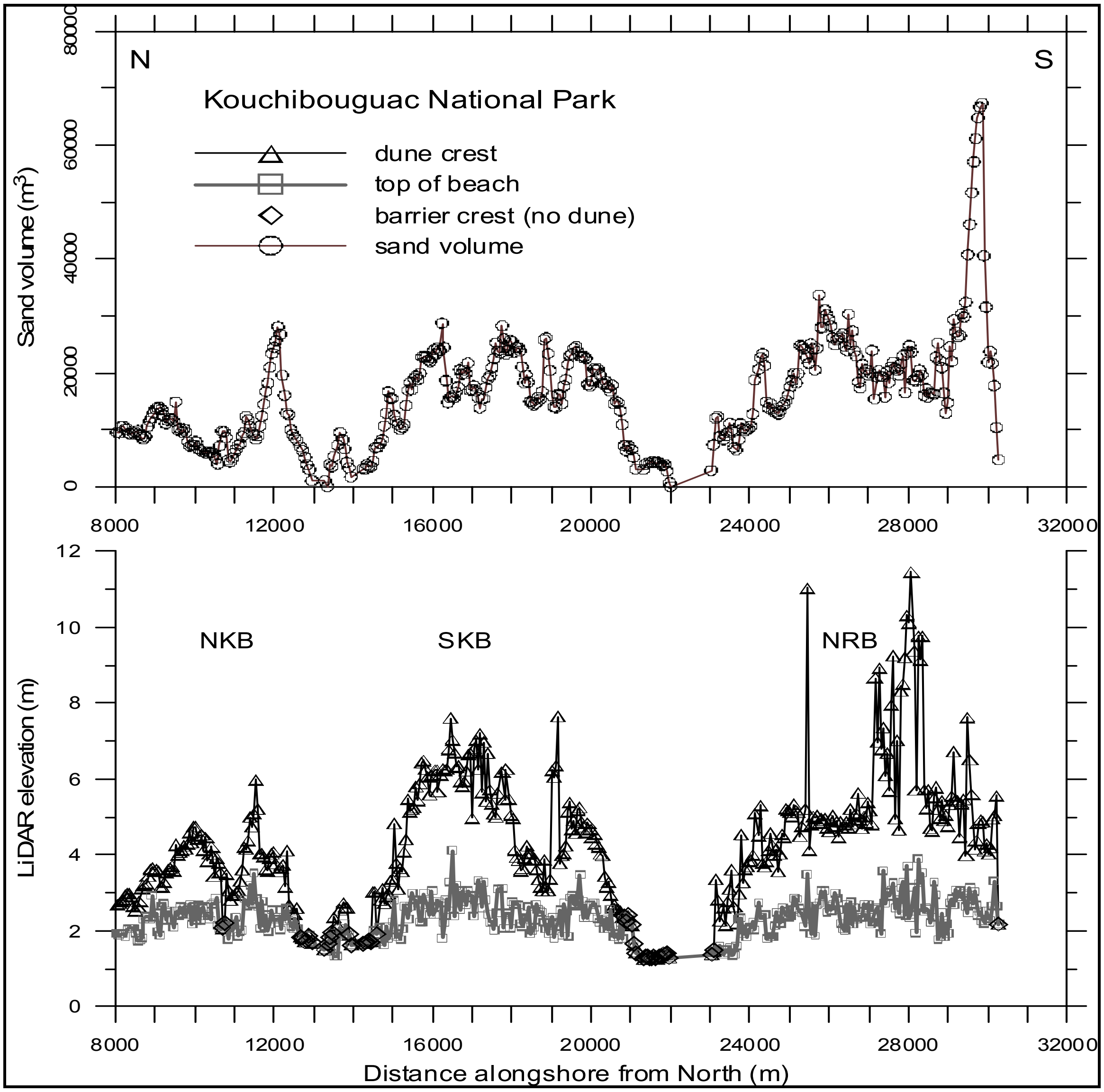


Figure 5. Dune crest, toe-of-dune (top of beach) and barrier crest (runup limit), as in Figure 4, and sand volume for three barrier islands in Kouchibouguac National Park, from 2004 LiDAR DEM: North Kouchibouguac Beach (NKB), South Kouchibouguac Beach (SKB) and North Richibucto Beach (NRB).

The combined beach and dune sand volumes in the Kouchibouguac barrier islands, from Pré à Germain to Richibucto inlet, were computed from the LiDAR DEM, taking the volume beneath the ground surface in polygons delimited by the 50-m transects (Figure 5). The base surface was taken to be approximately 0.9 m CGVD28, so the volume totals underestimate the total sand volume in the system. The overall sand storage volume estimated for the three barriers (North and South Kouchibouguac and North Richibucto) was 6.52 × 10^6 m^3. The individual island volumes were as follows:

North Kouchibouguac Beach (NKB):	0.991 × 10^6 m^3
South Kouchibouguac Beach (SKB):	2.467 × 10^6 m^3

- North Richibucto Beach (NRB): 3.061×10^6 m^3

These volumes are broadly proportional to island length and mean dune height. However, lack of correlation with dune height in Figure 5 demonstrates the importance of island width in determining the total volume. This is particularly evident at the south end of NRB (between 29 and 31 km in Figure 5).

Barrier islands such as those in Kouchibouguac National Park are dynamic features moulded by waves and wind (Greenwood and Davidson-Arnott, 1977). As noted above, the barrier system in Kouchibouguac Bay is highly dynamic, with a history of inlets opening and closing over time. Storm-wave runup can lead to washover channels that may be eroded to evolve into tidal inlets. The inlets may survive for many years but may close or open again depending on the sequence of storms, sediment supply and inlet dynamics. In the late 1970s, Richibucto Inlet (between SRB and NRB) and Blacklands Gully (between NRB and SKB) opposite Cap-de-Saint-Louis were present with much the same configuration they have today (Greenwood and Hale, 1980). Little Gully (between SKB and NKB) near Kellys Beach was also present, but subsequently closed. North Inlet (at the north end of NKB) was open south of Pré à Germain, but is sealed today. Little Gully was further widened closer to Kellys Beach in the storm of October 2000, having been reopened in a previous storm.

Future adjustments to climate change, including continued and possibly accelerated sea-level rise, can be expected to include repeated storm-wave overtopping and breaching, leading to opening and closing of tidal inlets. Examination of Figure 4 shows that under present conditions, there are several locations on NKB and SKB where dune height is lower than runup, as follows:

- immediately south of Pré à Germain on NKB (~8 km), in the vicinity of the former North Inlet;
- midway along NKB at a narrow between 10.8 and 11.2 km;
- low areas where the dunes have not recovered in the vicinity of Little Gully on SKB; and
- an extensive low section on SKB between 18.0 and 18.9 km.

The north end of NRB is also low and vulnerable, but otherwise the dune crest and width of this barrier island make it relatively resistant to breaching.

Dune-face erosion is the other mechanism that may contribute to slow landward migration of the barrier islands under rising sea level. Preliminary digital photogrammetry by A. Fréchette (Kouchibouguac National Park, see Annex C2 of section 5) confirms this trend in some areas, but shows that other parts of the barrier system, particularly on NKB, have experienced some progradation. This is to be expected as a function of longshore cell development and migration under a net southward regime of longshore drift (Carter, 1988).

Pointe des Mares (Cap-Lumière) to Saint-Édouard-de-Kent

Giangioppi (2004) undertook digital rectification of air photographs and digitization of the 1944 and 2000 shoreline from Cap-Lumière (see Annex C3) to the distal end of Bouctouche Spit. Additional shoreline vectors were digitized for intervening years along the spit. For the present study, her shoreline vectors were combined with shore-normal transects in ArcMap and used to determine shoreline advance or retreat at 50-m intervals along the entire coast from north of Cap-Lumière to Saint-Édouard-de-Kent and continuing the full length of La Dune de Bouctouche.

Figure 6 shows results for this section of the coast as mean rates of advance (positive) or retreat (negative) over 56 years from 1944 to 2000/2001. Rapid progradation is evident north of Cap-Lumière, north of the harbour structure at Côte-Sainte-Anne and at two locations north of Saint-Édouard-de-Kent. Slow persistent erosion at rates predominantly less than 0.2 m/year is evident along the sandstone cliffs between Cap-Lumière and Gros Cap (3.1–7.5 km). South of Gros Cap, the coast is retreating more rapidly in the area of the small barriers extending almost to Côte-Sainte-Anne. Rates of retreat average more than 1 m/year at two locations, amounting to about 60 m over the 57 years. South of Côte-Sainte-Anne, there is an area with erosion rates amounting to 0.5 m/year and other isolated erosional “hotspots” between there and La Dune de Bouctouche (beyond 19 km).

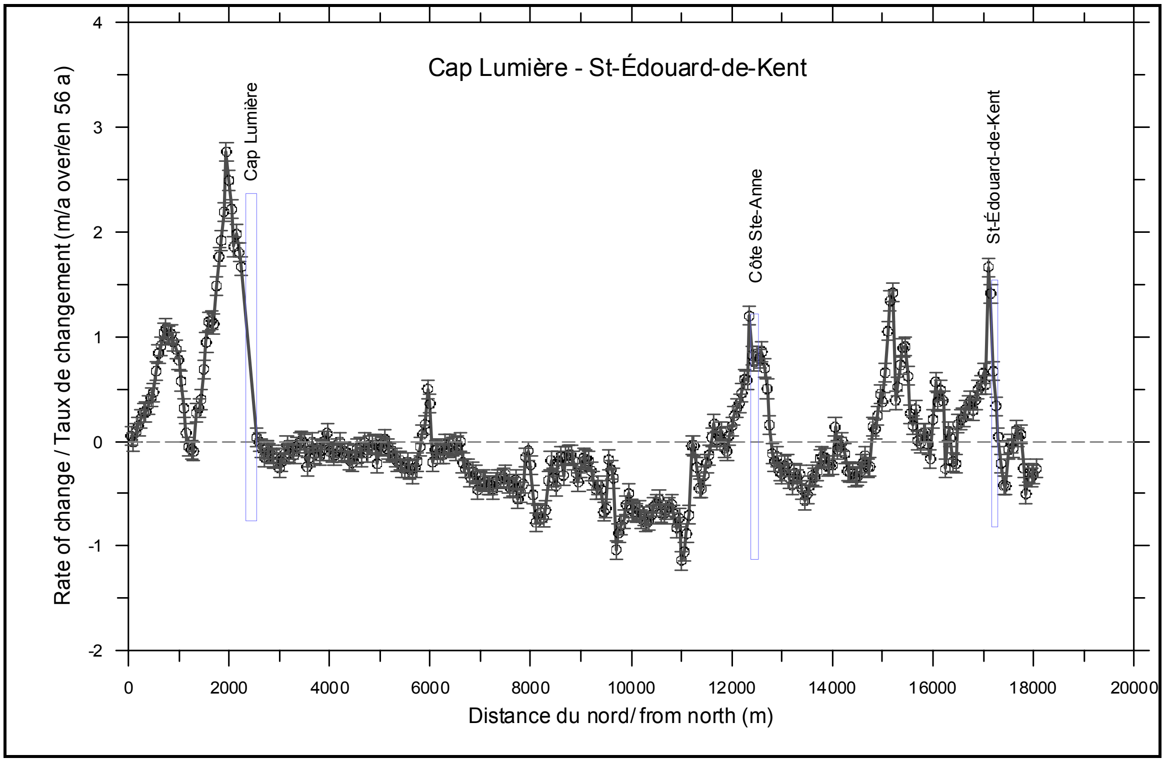


Figure 6. Erosion (negative) and accretion (positive) and error estimates at 50-m intervals alongshore from Cap-Lumière to Saint-Édouard-de-Kent at Irving Eco-Centre, derived from geographic information system (GIS) differencing of cliff and dune-line vectors courtesy of Martine Giangioppi. Mean rates in m/year over 56 years, 1944–2000/2001.

La Dune de Bouctouche

Figure 7 shows a similar plot of mean rate of coastal advance or retreat over 55 years (1945–2000/2001) on La Dune de Bouctouche. The entire dune line from the proximal end at the Irving Eco-Centre to about 8.3 km downdrift is retreating landward. Beyond that point, deposition and dune-line advance are evident for the next 2 km, followed by another erosional section, and finally the accumulation zone at the distal end (beyond 11 km). The plot of barrier and dune-crest elevation in the same figure shows an intriguing correlation with the long-term rate of retreat over the first 8 km of the spit. Beyond that, in the depositional region, there is no correlation, and none would be expected. The long-term mean retreat rate is more than 1 m/year at the proximal end of the spit and approaches 2 m/year in the vicinity of 7.5 km downspit. Progradation rates reach 2 m/year near the 10-km mark and >3.5 m/a beyond 11 km.

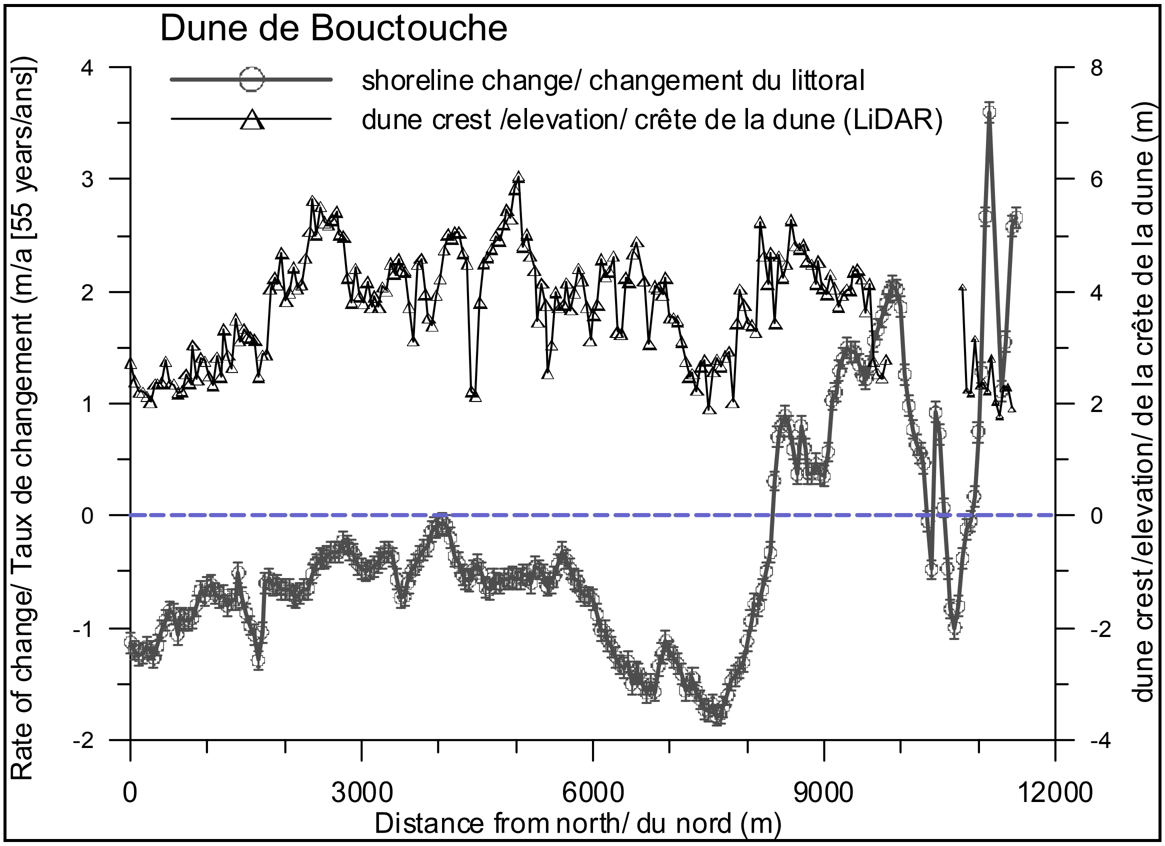


Figure 7. Erosion (negative) and accretion (positive) and error estimates at 50-m intervals alongshore from the north end of La Dune de Bouctouche, derived from GIS differencing of cliff- or dune-line vectors courtesy of Martine Giangioppi. Mean rates in m/year over 55 years, 1945–2000/2001. Also shows the barrier or dune-crest elevation from DEM derived from 2004 LiDAR.

Figure 8 shows the dune crest, barrier crest (where dunes are absent) and toe-of-dune (approximate runup limit) for La Dune de Bouctouche in greater detail, as derived from the 2004 LiDAR DEM. The crest elevation is less than 3 m CGVD28 at the proximal end and again between 7 and 8 km (the area of most rapid erosion) and in the vicinity of 10 km downspit. The maximum dune-crest elevation exceeds 6 m, and crest elevations above 5 m occur in several places. Toe-of-dune elevations are quite variable, ranging from <1.5 m to >3 m, and locally even higher. Some of the highest elevations are associated with minor peaks in the long-term retreat rate.

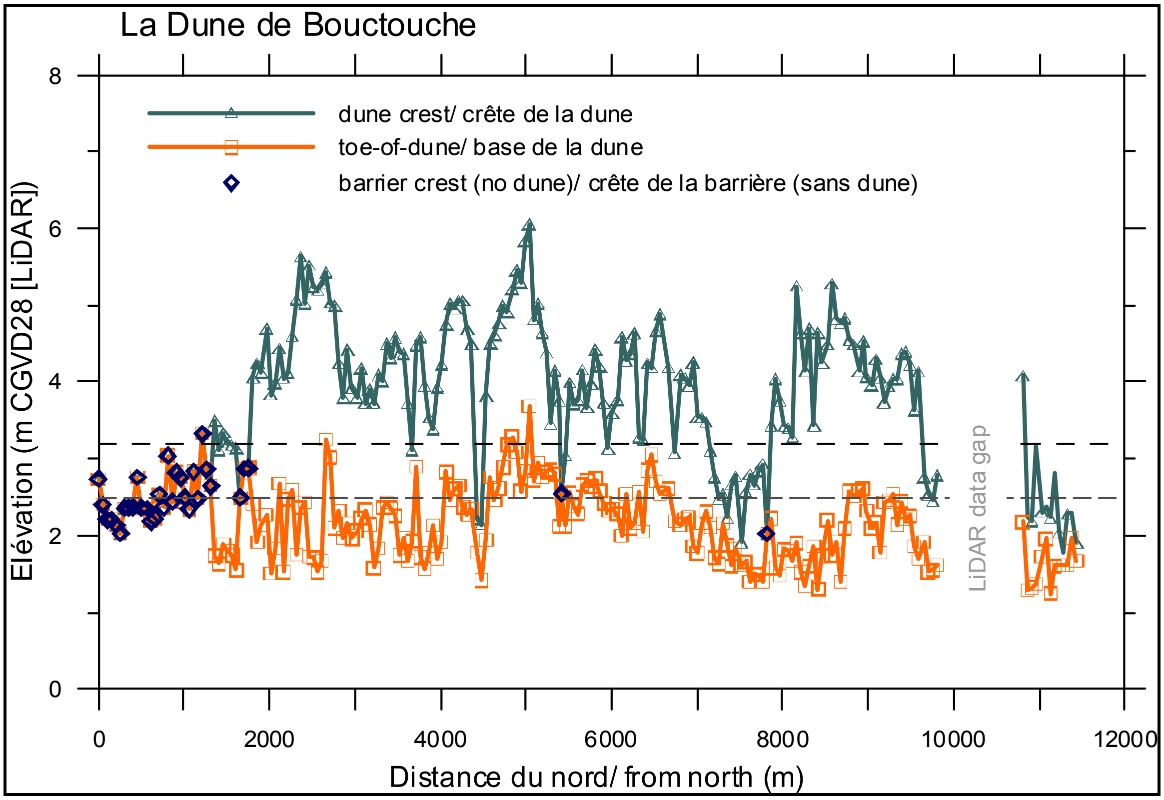


Figure 8. Dune crest, toe-of-dune and barrier crest (no dune) for La Dune de Bouctouche, from 2004 LiDAR DEM, with distance alongshore from the north, beginning at the cliff by the Irving Eco-Centre. Lower broken line is approximate maximum water level of the January 21, 2000, storm surge. Upper broken line is a conservative upper runup limit (note that this is at or below the upper runup limit derived from morphological evidence such as the toe-of-dune and barrier-crest elevation).

As for the Kouchibouguac barriers, sand storage volume was computed for La Dune de Bouctouche (Figure 9). The segment volumes shown in the figure are typically lower than in the Kouchibouguac system (Figure 4). The pattern of low storage on the narrow proximal part of La Dune de Bouctouche and higher volumes in the wide distal section mimics the longshore distribution on NRB (see Figure 4).

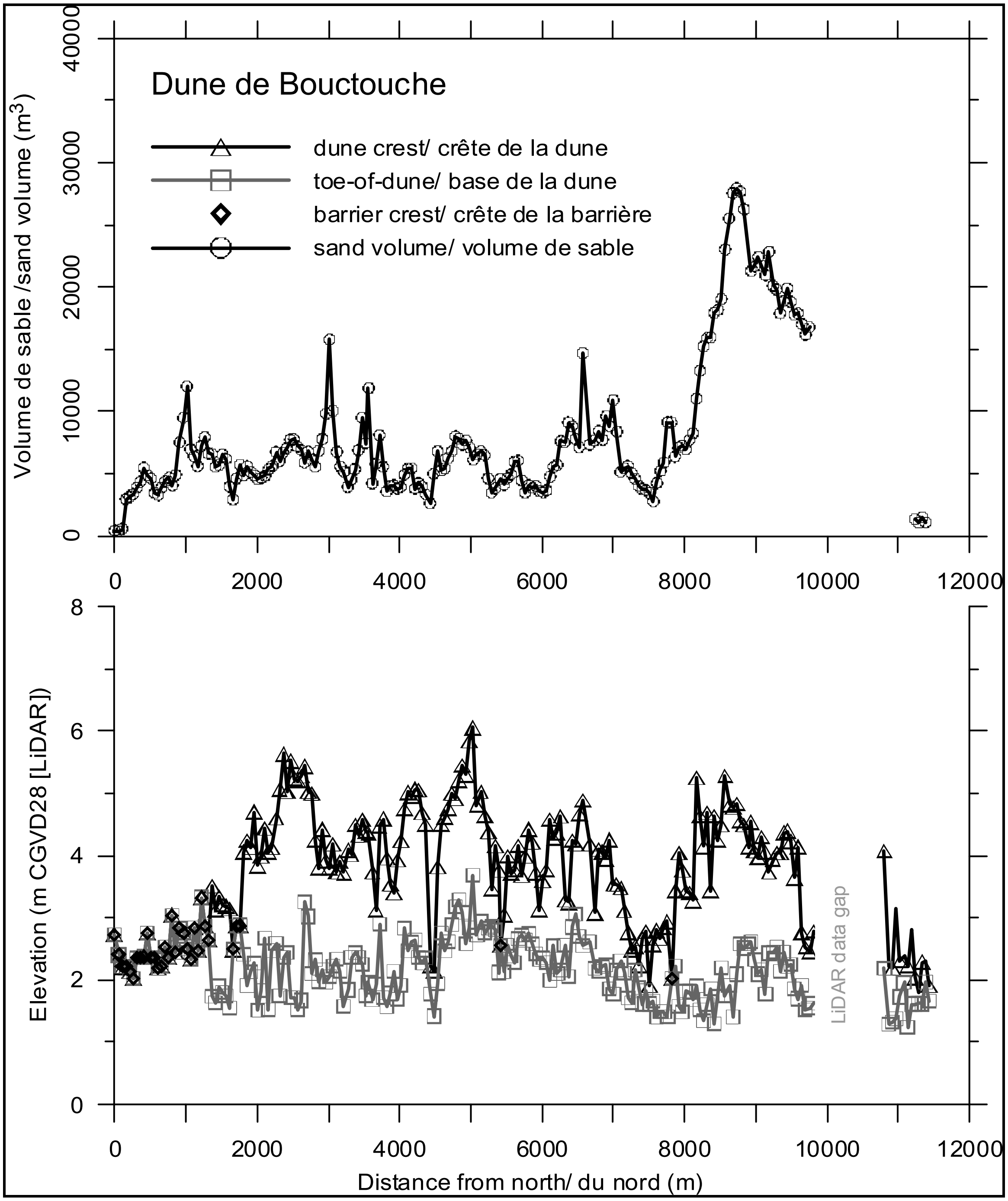


Figure 9. Dune crest, toe-of-dune and barrier crest (runup limit) and sand volume for La Dune de Bouctouche, from 2004 LiDAR DEM, with distance alongshore from the north, beginning at the cliff by the Irving Eco-Centre. Note differences in vertical scales from Figure 5.

The total storage volume computed for La Dune de Bouctouche was 1.73×10^6 m^3. At 27%, this is just over one quarter of the volume in the Kouchibouguac barriers and dunes (without considering SRB, which may hold as much as La Dune de Bouctouche). A gap in the LiDAR DEM for part of the distal section was filled by using the average value between 8.0 and 9.7 km downspit. A breakdown of storage volume between the proximal 8-km and the remaining distal section shows volumes of 0.92 × 10^6 m^3 and 0.81 × 10^6 m^3, respectively.

Surveys of the inner shelf off La Dune de Bouctouche and Saint-Édouard-de-Kent were carried out in May 2004 from CCGS *Matthew* (Forbes et al., in preparation). As in the Kouchibouguac embayment, extensive parts of the shoreface and inner shelf off La Dune de Bouctouche are covered with a lag deposit of gravel. Although there are thin patches of sand on the shoreface, the volume of this sand is a small fraction of that stored in the barrier and dune system. A ridge of sand somewhat like the one documented off Pointe-Sapin was encountered in 9 m water depth off La Dune de Bouctouche (Figure 10) and may represent an overstepped barrier deposit.

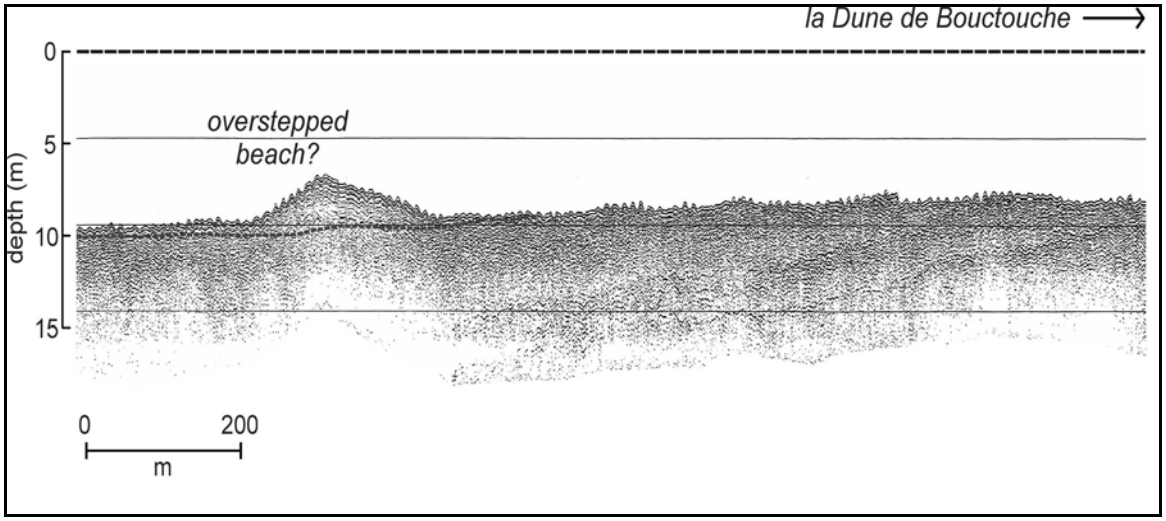


Figure 10. Section through sand ridge resting on seabed in about 9 m water depth off La Dune de Bouctouche. Land towards right. Dotted line shows base of sand.

4.5.3.1.4 Discussion

Forbes et al. (2004) presented data on dune erosion and washover events on the proximal part of La Dune de Bouctouche, showing how a sequence of storms from 2000 to 2003 resulted in removal of the foredune and extensive sand transport across the barrier. As presented in Section 4.2 of this report, several important wave events were observed during the present study at locations seaward of Pointe-Sapin (station C44150) and Gros Cap (C44132). While 2005 was an uneventful year, important storms during the preceding two years included December 7, 2003, October 11–12, 2004 (Subtropical Storm Nicole), and December 27, 2004. Significant and maximum wave heights and peak period during these events off Pointe-Sapin (and Gros Cap, in parentheses) were:

- December 2003: 4.7 m, 11.5 m, 9.9 s
- October 2004: 4.8 m (3.3 m), 22.8 m (6.9 m), 9.9 s (10 s)
- December 2004: 4.7 m (3.6 m), 19.4 m (6.7 m), 7.4 s (9.5 s).

In addition, the major storm in late October 2000 had two peak water levels above 2.4 m Chart Datum (CD) at Escuminac and significant wave height north of Prince Edward Island exceeding 7.5 m (Forbes et al., 2004). Allowing for wave shoaling, wave setup and runup on top of elevated storm-surge water levels, these events clearly had the potential to overtop extensive sections of the Kouchibouguac barrier islands and La Dune de Bouctouche, as indeed occurred, with extensive damage to the boardwalk in October 2000 and again in December 2004 (Figure 11). Although the record storm of January 21, 2000, caused extensive flooding and ice-impact damage, it was not accompanied by damaging waves. Nevertheless, the stillwater level of about 2.5 m was sufficient to overtop the small barriers north of Pré à Germain, a location in the middle of NKB, the proximal end of La Dune de Bouctouche (since the foredune was subsequently destroyed), La Grande Brèche on La Dune and an area in the transition zone. Allowing for runup to 3.5 m CGVD28 on the Kouchibouguac barriers (within the range of observed toe-of-dune elevations), cliffs and barriers at the north end of the system would be overtopped, as would the north end of NKB south of Pré à Germain, a central part of NKB, both ends and a middle section of SKB and the north end of NRB. There is a high potential, therefore, for reopening of North Inlet and for breaches in the middle of NKB and SKB. On La Dune de Bouctouche, allowing for a more modest runup limit of 3.25 m, again within the range of toe-of-dune elevations observed on the LiDAR DEM, the first 1.2 km of the barrier would be entirely overtopped, as well as two other locations within the first 2 km; overtopping (possible breaching) would also occur at La Grand Brèche (4.5 km), at about 5.3 km, on a large section of almost 700 m between 7 and 8 km, and around 9.7 km and would be possible or probable at five other locations between 3.5 and 11 km downspit (Figure 7). The occurrence of major wave events in December and projections of a reduced ice season in future, coupled with ongoing rising sea levels, raise the spectre of more frequent and damaging overtopping and breaching of the Kouchibouguac and Bouctouche barriers in future, as well as more rapid erosion and landward migration of the northern (proximal) end of the spit.

Figure 11. Damaged boardwalk and frozen slush at La Dune de Bouctouche, following storm of December 27, 2004 (Photo: R. Daigle).

As noted above, shoreline progradation is occurring updrift of harbour structures at Cap-Lumière, Côte-Sainte-Anne and Saint-Édouard-de-Kent. Along the rest of the coast between Cap des Mares and Bouctouche, accelerated erosion can be expected, threatening waterfront properties, roads and other infrastructure. Past erosion along this coast has forced the relocation of roads and abandonment of buildings (Figure 2). This pattern will continue with greater economic impact, resulting from accelerated erosion rates and increased investment.

Ollerhead and Davidson-Arnott (1995b) developed a preliminary sediment budget for Bouctouche Spit (La Dune). They concluded that the proximal section is becoming narrower with rising sea level and has been migrating landward for many centuries. This has caused the truncation of older recurved ridges in the back part of the transition zone and in the first part of the distal section (Figure 12). Giangioppi (2004) developed a revised sediment budget and demonstrated that most landward transfer of sediment has been associated with dune breaches during large storms, particularly in 1938, 1971 and 2000. She concluded, however, that the landward margin of the spit had not migrated landward during this time, as washover fans were largely confined to the existing back-barrier slope. Forbes et al. (2004) demonstrated that the major storm of October 2000 destabilized the dunes of the proximal section, resulting in extensive washover sedimentation in that storm and succeeding lesser storms in 2001 and later. This has initiated a new phase of landward migration. At the same time, the short, narrow, gravel storm ridge below the Irving Eco-Centre at the very proximal end of the spit has migrated onshore and extended beneath the boardwalk, as shown by sequential photography from the Eco-Centre tower (Figure 13).

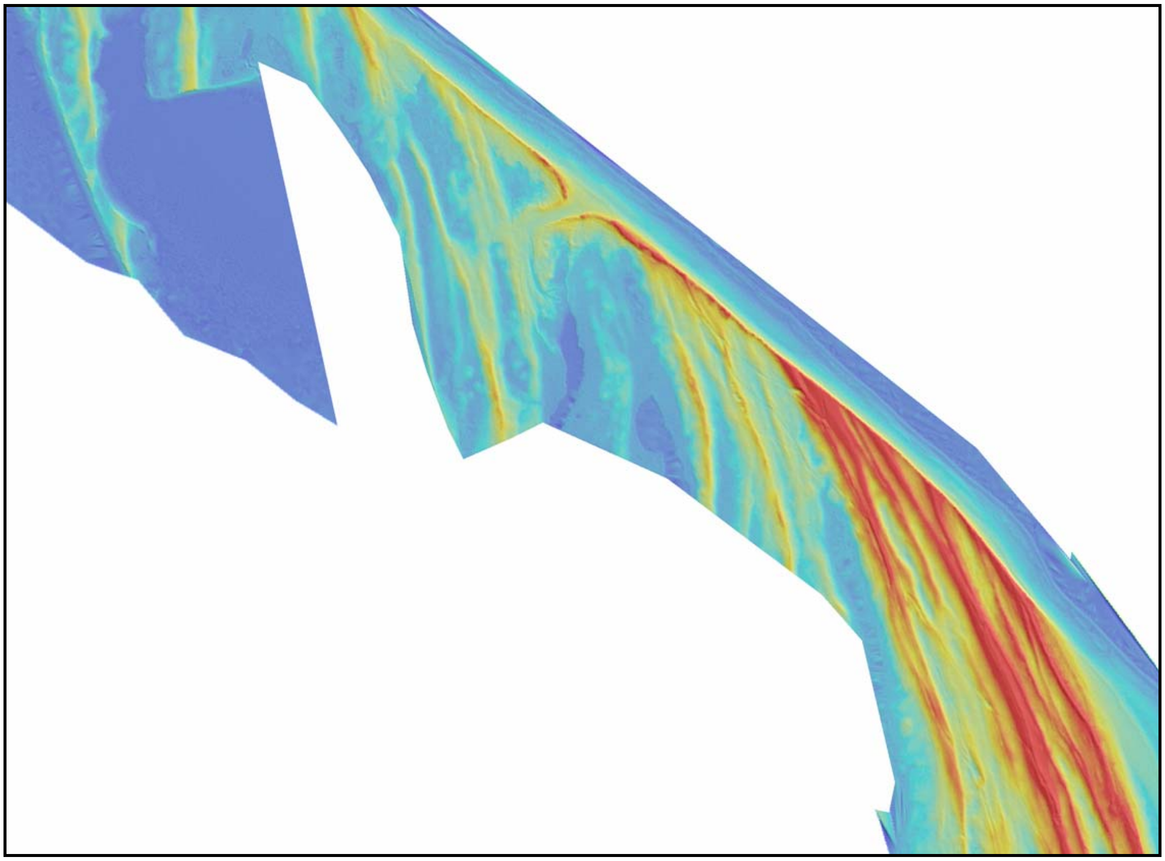


Figure 12. LiDAR image of section of La Dune de Bouctouche, prepared by Applied Geomatics Research Group, Nova Scotia Community College.

Figure 13. Onshore migration at La Dune de Bouctouche between 1999 (left photo: B. Taylor) and 2004 (right photo: G. Manson).

Peat exposed in the beach below the Irving Eco-Centre at the proximal end of the spit has been radiocarbon dated with a calibrated age of 985 ± 70 calendar years before 2000, i.e., 1015 AD ± 70 (Ollerhead and Davidson-Arnott, 1995b). These authors concluded reasonably that the peat formed behind the spit and that it was probably at least equivalent in width to the present day (300 m), from which they deduced an average landward migration rate of ≥0.3 m/year (30 m/century) over the past 1000 years and commensurate migration of the attachment point towards the southeast. This can be expected to continue at an increased pace with accelerated relative sea-level rise under climate change. It is also reasonable to assume that more frequent breaching will occur with an extended open-water storm season, possibly more intense storms and rising relative sea level in the future. Under this scenario, large breaches such as La Grande Brèche may be maintained and expanded, leading eventually to separation of the distal end of the spit, as postulated by Ollerhead and Davidson-Arnott (1995a), as observed on a similar large flying spit system in St. George's Bay, Newfoundland and Labrador (Shaw and Forbes, 1987, 1992) and as we believe may have led to the creation of Cocagne Island (see Section 4.5.3.2).

4.5.3.2 Cocagne to Shemogue

In order to obtain new data on coastal retreat and the evolution of coastal habitats, detailed geomorphological mapping of four sites of the southeastern coast of New Brunswick was carried out. The areas studied were, from north to south, the greater Cocagne, l'Aboiteau and Shemogue sectors. A fourth, smaller site was also mapped — namely, that of Parlee Beach.

4.5.3.2.1 Description of the study sites

Greater Cocagne

The greater Cocagne study site is located 15 km north of Shediac. The area around the Saint-Thomas-de-Kent wharf constitutes its northern limit, while the area around the Grande-Digue wharf forms its southern limit (Figure 14). The approximate length of the coast of this study site is 66 km, and the area covered by coastal lands (beaches, dunes, marshes) is approximately 178 ha.

Land use in the greater Cocagne sector is predominantly rural. The villages of Cocagne and Grande-Digue have 2423 and 2109 inhabitants, respectively (Statistics Canada, 2001 Census). The main commercial activities of greater Cocagne's communities are related to agriculture, fishing (lobster and herring) and tourism. In the area surrounding the village of Cocagne, the land is used to cultivate apples, vegetables and berries. Because of its proximity to highly publicized tourist sites, the greater Cocagne region benefits from the economic spin-offs related to beach and cultural tourism. It is located less than 20 km from the Parlee Beach Provincial Park, from the Pays de la Sagouine and from the Irving Eco-Centre: La Dune de Bouctouche. There are numerous campgrounds along the coast in this sector.

The greater Cocagne coastal zone includes two distinct coastal environments: the coast directly exposed to the Northumberland Strait, which is more subject to wave action, and the coast of the Cocagne Harbour and the Cocagne River, less subject to wave action. The coastal zone studied within the context of this work includes all of the coast exposed to the Strait as well as the harbour coast; only the coast of the Cocagne River was excluded from the study.

From a geomorphological perspective, the greater Cocagne study site is mainly characterized by the presence of rocky cliffs (soft sandstone), found in the area around Saint-Thomas-de-Kent and Cocagne Cape. Elsewhere, bluffs (unconsolidated till deposits and other sediments) are predominant. All along the Cocagne Harbour coast, sheltered from the waves of the Strait by the presence of Cocagne Island and the Cocagne Cape peninsula, salt marshes have developed, particularly in the southeastern part of the harbour. The best-developed sandy beaches and coastal dunes are found around Cocagne Island, which is one of the least human-altered areas of this sector. Elsewhere, the natural landscape has been affected by a strong human presence, mainly due to real-estate development (campgrounds, homes, summer cottages) and the installation of protection structures along the coast (rock embankments, rubble mounds, walls made of wood or concrete).

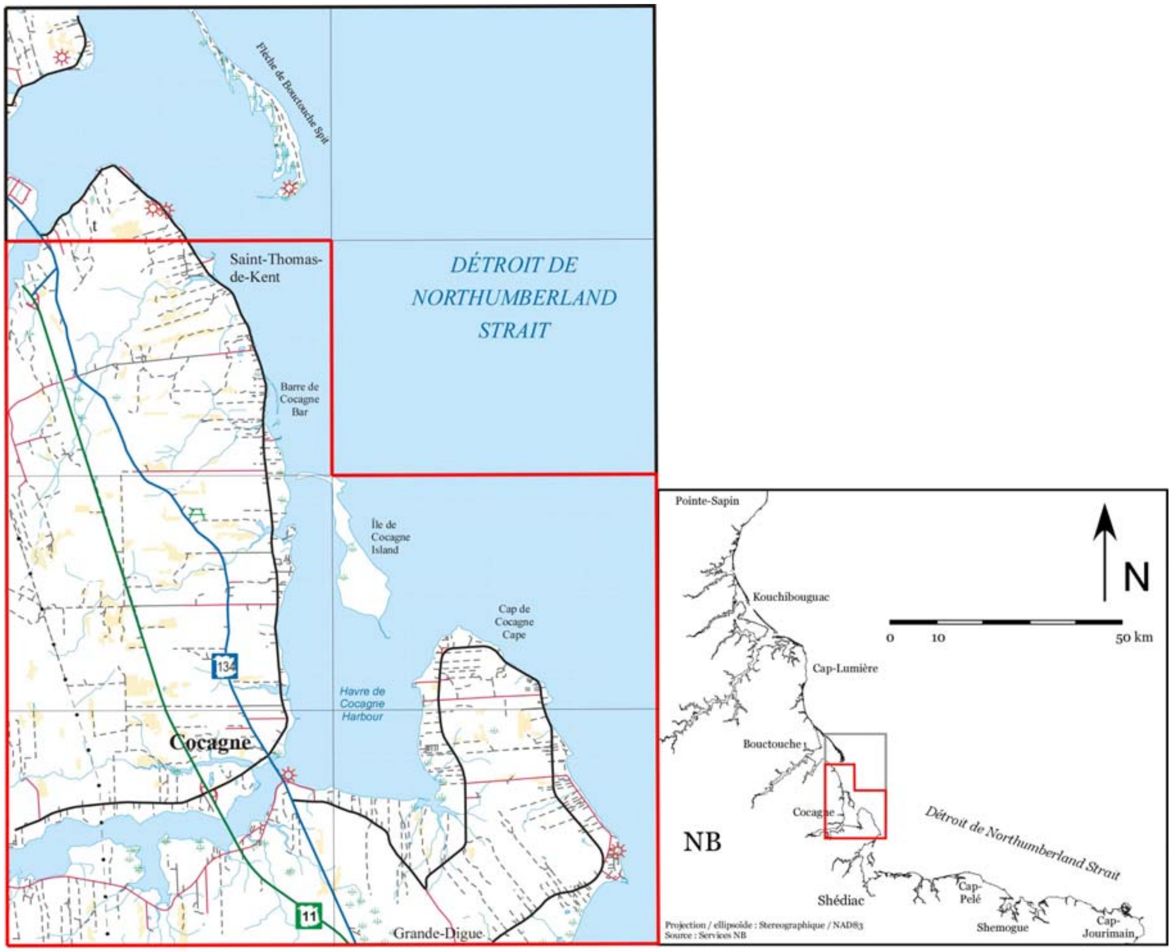


Figure 14. Location of the greater Cocagne (New Brunswick) study site.

Thus, the greater Cocagne coast was targeted as a study site for the following reasons:

- the “artificial” or very anthropogenic character of the landscape makes it a reference point for the study of coastal evolution along the Northumberland Strait; and
- the paucity of data available on the recent history of coastline-position change (rate of retreat or advance).

L’Aboiteau

The l’Aboiteau study site is located approximately 15 km east of Shediac. The Cap-Bimet community constitutes its western limit, while that of Trois-Ruisseaux forms its eastern limit (Figure 15). The approximate length of the coast of this study site is 60 km, and the area covered by coastal lands (beaches, dunes, marshes) is approximately 363 ha.

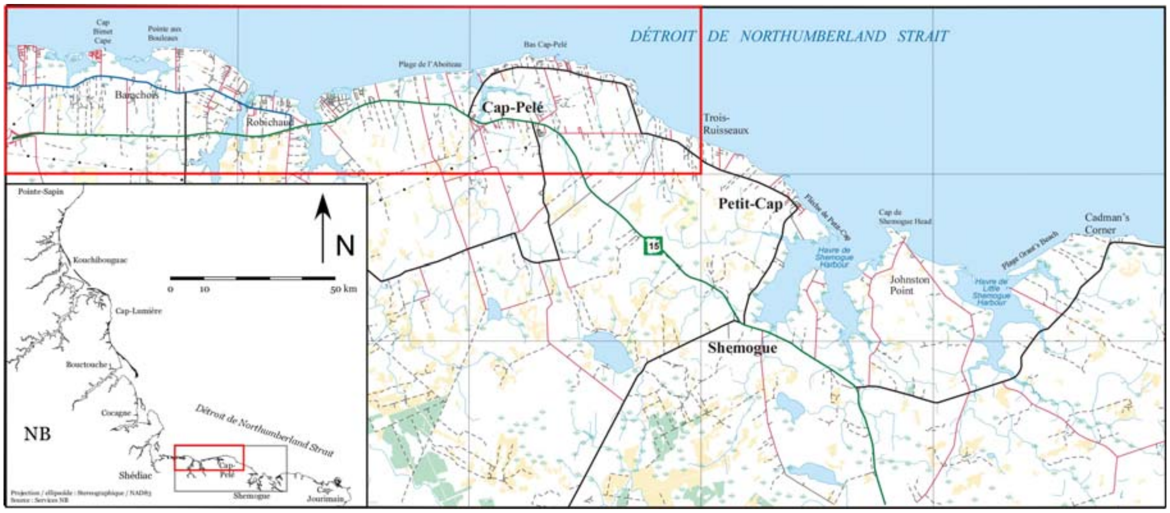


Figure 15. Location of l’Aboiteau (New Brunswick) study site.

Land use in the l’Aboiteau sector is predominantly rural. The village of Cap-Pelé has 2266 inhabitants, while Grand-Barachois, a division that includes the other communities in the study site, has 2521 inhabitants (Statistics Canada, 2001 Census). The main commercial activities of these communities are related to the fishing industry (lobster and herring) and tourism. The area surrounding the village of Cap-Pelé includes many “smoke houses” (facilities for smoking fish, particularly herring); the land is mainly dedicated to the cultivation of potatoes. The l’Aboiteau sector benefits from the economic spin-offs linked to beach tourism. There are numerous campgrounds and resort areas, the Aboiteau Park beach being the most well-known.

The l’Aboiteau coastal zone includes two distinct coastal environments: the coast directly exposed to the Northumberland Strait, which is more subject to wave action, and the coast of the Aboujagane and Kouchibouguac rivers, which is less subject to wave action. The coastal zone studied within the context of this work includes all of the coast exposed to the Strait and the coast forming the mouth of the two rivers, downstream from the bridges.

From a geomorphological perspective, the l'Aboiteau study site is characterized by the presence of rock cliffs (soft sandstone) and sand spits. The largest rocky headlands are located at Cap-Pelé and Bas-Cap-Pelé, while the sector's main sand spit is the l'Aboiteau dune, located between Cap-Pelé and Robichaud. The latter is approximately 5.6 km long and is aligned along an east–west axis. Small sand spits, less than a kilometre long, are also present in the sector; they are located at the mouths of estuaries, including notably those of Barachois and the Aboujagane River (Figure 15). The coastal zones of the estuaries are characterized by bluffs (unconsolidated till deposits and other sediments), but mainly by salt marshes, which generally cover their upstream portions. Marshes are also present, covering a smaller area along the edges of the wide coves of the estuaries (concave portions of the coast). The l'Aboiteau study site also possesses a distinct coastal environment, composed of barachois marshes. These are wet coastal environments located behind the coastal dunes, wedged between the latter and the upland. Owing to the episodic formation and closure of breaches in the dune front, the water of the barachois marshes is at times more brackish, and at times fresher.

Thus, the l'Aboiteau coast was targeted as a study site for the following reasons:

- the presence of barachois marshes, a rare landform along the coast of the Northumberland Strait; and
- the paucity of data available on the recent history of coastline-position change (rate of retreat or advance).

Shemogue

The Shemogue study site is located approximately 25 km east of Shediac. The Trois-Ruisseaux community constitutes its western limit, while the place known as Cadman's Corner forms its eastern limit; this sector is contiguous with that of l'Aboiteau (Figure 16). The approximate length of the coast of this study site is 105 km, and the area covered by coastal lands (beaches, dunes, marshes) is approximately 844 ha.

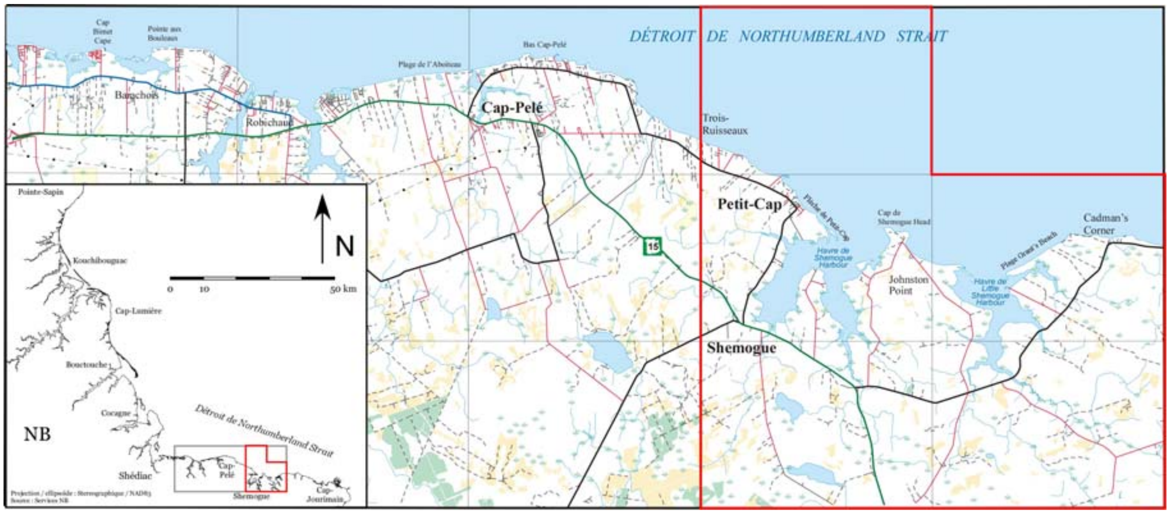


Figure 16. Location of the Shemogue (New Brunswick) study site.

Land use in the Shemogue sector is predominantly rural. It is estimated that the communities of Petit-Cap and Trois-Ruisseaux have approximately 400 inhabitants and that of Shemogue has 150 inhabitants. The main commercial activities of these communities are related to the fishing industry (lobster and herring), and many “smoke houses” are found here. Petit-Cap and Shemogue also have important fishing-boat building companies. Chapman’s Corner, Johnson Point Road and Cadman’s Corner are small communities of fewer than 100 inhabitants whose commercial activity is primarily of an agricultural nature (potatoes, market gardens, livestock), but which are also, to a small degree, involved in fishing and oyster farming. Because of adjacent tourist destinations, such as Shediac and the Murray Beach Provincial Park, the Shemogue region also benefits from economic spin-offs related to tourism.

The Shemogue coastal zone includes two distinct coastal environments: the coast directly exposed to the Northumberland Strait, which is more subject to wave action, and the coast of the Shemogue and Little Shemogue harbours, estuaries less subject to wave action. The coastal zone studied within the context of this work includes all of the coast exposed to the Strait as well as the coast of the two estuaries.

From a geomorphological perspective, the coast exposed to the Strait is characterized by the presence of rock cliffs (soft sandstone) and bluffs (unconsolidated till deposits and other sediments), as well as sand spits (Figure 17). These spits are located on both shores of the mouths of the two estuaries (Shemogue and Little Shemogue). Thus, the beaches and their associated sand dunes partially enclose the estuaries and thereby help to create a calmer environment, sheltered from the Strait’s more powerful waves. For its part, the coastal zone of the estuaries is characterized by bluffs, but the predominant environment is that of salt marshes. Salt marshes generally occupy the back of the spits and the upstream portion of the estuaries.

Although the Shemogue sector has been inhabited for a very long time, the main coastal environments found here show little or no signs of human disturbance. Apart from the Petit-Cap and Amos Point wharves and the drainage ditches dug in some salt marshes, human interventions with respect to the natural environment are very few and far between.

Thus, the Shemogue coast was targeted as a study site for the following reasons:

- the “natural” or barely anthropogenic character of the landscape makes it a reference point for the study of coastal evolution along the Northumberland Strait; and
- the paucity of data available on the recent history of coastline-position change (rate of retreat or advance).

Figure 17. Some environments and coastal characteristics of the Shemogue coastal zone (excerpt from 2001 provincial aerial photograph: DNRE01512-150).

Parlee Beach

A fourth study site was added to the project later on — namely, that of Parlee Beach and its neighbouring beaches, located northeast of Shediac (Figure 18). The Pointe-du-Chêne wharf forms the western limit of the sector, while the Cap-Brûlé community forms its eastern limit. The approximate length of the coast of this study site is 2.8 km, and the area covered by coastal lands (beaches, dunes, marshes) is approximately 50 ha (Figure 18).

Parlee Beach is at the centre of the development of the province’s beach tourism strategy. It has enjoyed international renown for almost a century and welcomes more than 500 000 visitors each year. The reasons for adding the Parlee Beach study sector stem from the fact that it has been the subject of an important beach nourishment program since the end of the 1980s and that the Province of New Brunswick would like to ensure the site’s continued existence in the context of the potential impacts of rapid sea-level rise and climate change.

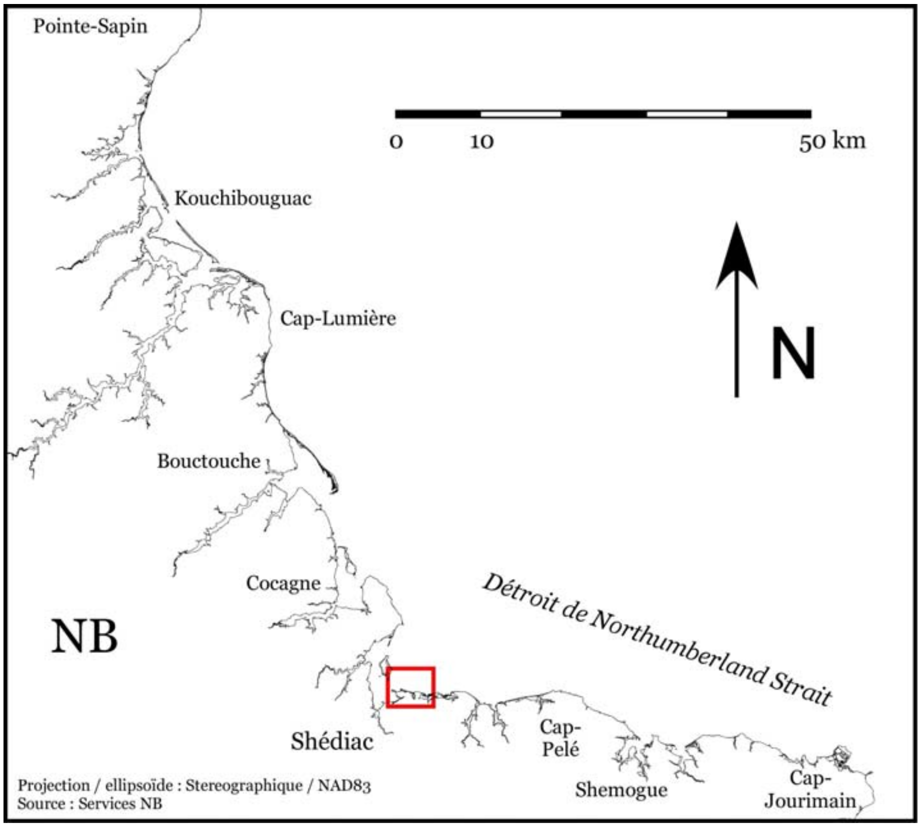


Figure 18. Location of the Parlee Beach (New Brunswick) study site.

<u>4.5.3.2.2 Production of the multiyear georeferenced maps</u>

The main objectives of the coastal-erosion component of this project are to determine the physical impacts of climate change and of the rapid rise in relative sea level on the coast of the Northumberland Strait and to determine the rate of coastline-position change in the recent past in order to better predict future displacement. To do this, multiyear georeferenced mapping, using three sets of aerial photographs, those of 1944, 1971/1973 and 2001, is used. Other series were used based on specific needs (1938, 1953, 1963, 1967, 1970, 1982 and 1995). These aerial photographs were used to digitize the landforms of the coastal zone and ultimately to calculate the coastline-position change during the period studied.

Preparatory phase

Aiming to increase the accuracy of the multiyear maps produced, the Coastal Erosion Unit colleagues agreed to proceed according to a recognized methodology used by the New Brunswick Department of Natural Resources (Geological Surveys Branch) and by geomorphologists (Ruggiero et al., 2003; Zuzek et al., 2003; Hughes et al., 2006; Pierre, 2006). One of the critical elements in this process is to make sure the size of the pixels in the digitized aerial photographs is known and that it is comparable from photograph to photograph of the same series (or year) and also from one series to another (from one year to another).

The aerial photographs were digitized using a Microtek 6800 XP optical scanner in the Environment Canada office (Sackville, New Brunswick). All impurities were cleaned from the glass surface of the scanner as well as from each of the aerial photographs prior to the digitization phase. The aerial photographs were all digitized so that each pixel represents a ground surface of approximately 50 cm by 50 cm. A total of 187 aerial photographs were digitized within the framework of this study (Table 1).

Once the aerial photographs were digitized, control points were identified. These control points or “reference points” represent elements of the landscape that are recognizable from one year to the next and that have not changed position. These can be the corners of houses, road intersections, drainage ditches and even the boundaries of cultivated fields. In the sectors where there is limited human presence, as, for example, in the heart of salt marshes or at the end of a sand spit, the control points are more difficult to identify. In such cases, natural elements were used: bayberry groves, dune ponds or other small bodies of water whose limits have not changed perceptibly.

Table 1. Year and number of aerial photographs digitized to produce the multiyear georeferenced maps of the four study sites.

Année *Year*	Échelle approx. *Approx. scale*	**Grand Cocagne**	**L'Aboiteau**	**Shemogue**	**Plage Parlee**	
1938	10 000	n.c.	n.c.	n.c.	n.c.	
1944	17 454	13 (34)	11 (21)	17 (41)	n.c.	
1953	16 500	n.c.	n.c.	9 (37)	3	
1963	17 240	n.c.	n.c.	6 (25)	3	
1967	16 500	n.c.	n.c.	n.c.	1	
1970	11 038	n.c.	n.c.	n.c.	n.c.	
1971	11 038	n.c.	15 (29)	25 (62)	n.c.	
1973	10 200	20 (65)	n.c.	n.c.	3	
1982	13 024	n.c.	n.c.	10 (59)	2	
1995	35 000	n.c.	n.c.	n.c.	1	
2001	12 500	18 (48)	13 (26)	18 (48)	2	
	Total	**51** (147)	**39** (76)	**84** (272)	**14**	**187** (509)

n.c.: series not mapped.
(): number of photographs used.

The control points identified on one series of aerial photographs in particular must also be found on the digital orthophotographs (1996) of Service New Brunswick. During the georeferencing of a photograph, the software positions the control points of the ungeoreferenced aerial photograph with respect to the same control points of the 1996 digital orthophotograph and assigns it the same geospatial longitude and latitude coordinates (Figure 19). The aerial photograph and the mapped elements are thus positioned in space. The georeferencing process was carried out using the CARIS 4.4a geographic information system (GIS) in offices loaned by the Department of History and Geography at the Université de Moncton (Physical Geography Laboratory).

The process of identifying the control points is crucial to the project. Not only is an adequate number of control points recommended, but their location must also be certain.

The points must also be well distributed over the aerial photograph, in proximity to the mapped elements (Hughes et al., 2006). Thus, control points located too far from the coastal zone were not used, even though they may have been very reliable. During the georeferencing of the photographs, the position of a 1996 control point and the same control point on the georeferencing aerial photograph had to be, ideally, less than 5 m apart for the georeferencing process to be considered successful (valid). In cases where the margin of error was too great, other control points were identified, whenever possible.

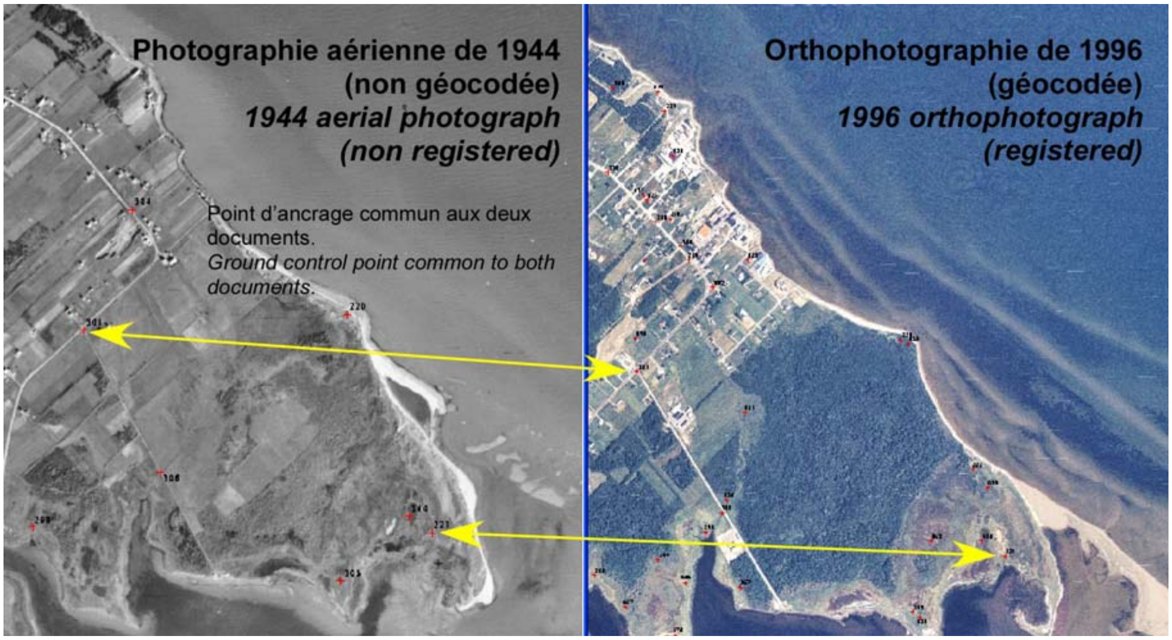


Figure 19. Example of the georeferencing of an aerial photograph using control points.

To georeference the 187 aerial photographs needed to cover all of the study sites, 1140 control points were used, it being possible to use the same control point to georeference adjacent photographs. The minimum margin of error obtained during the superimposition process of the control points was 0.010 m, and the maximum margin of error obtained was 5.899 m. Table 2 provides an order of magnitude regarding the superimposition of the control points, allowing for assessment of the quality of the georeferencing process for the various series of aerial photographs used.

Table 2. Average margin of error (m) of control points used for georeferencing the various sets of aerial photographs (in relation to the 1996 digital orthophotograph).

Grand Cocagne			L'Aboiteau			Shemogue		
1944	1973	2001	1944	1971	2001	1944	1971	2001
1,678	1,151	1,263	2,212	1,468	1,431	1,730	1,204	1,378

Digital mapping of the coastal zone

The digital mapping of the landforms of the coastal zone of the study sites was also performed using the CARIS 4.4a GIS in offices loaned by the Department of History and Geography at the Université de Moncton (Physical Geography Laboratory). In addition to consulting scientific works (local, regional and international) and the Coastal Erosion Unit colleagues, a few reconnaissance field trips were carried out in 2003, 2004 and 2005, but essentially the mapping work is based on interpretation of the aerial photographs using a Topcon (model A700) binocular stereoscope.

The multiyear georeferenced maps were designed with the goal of identifying two geomorphological limits corresponding to levels reached by the sea (Figure 20), namely:

- the coastline, which is the higher high-water line — that is, the upper limit of high-tide or storm-wave levels; and
- the shoreline, which is the ordinary high-water line — that is, the normal level of high tides.

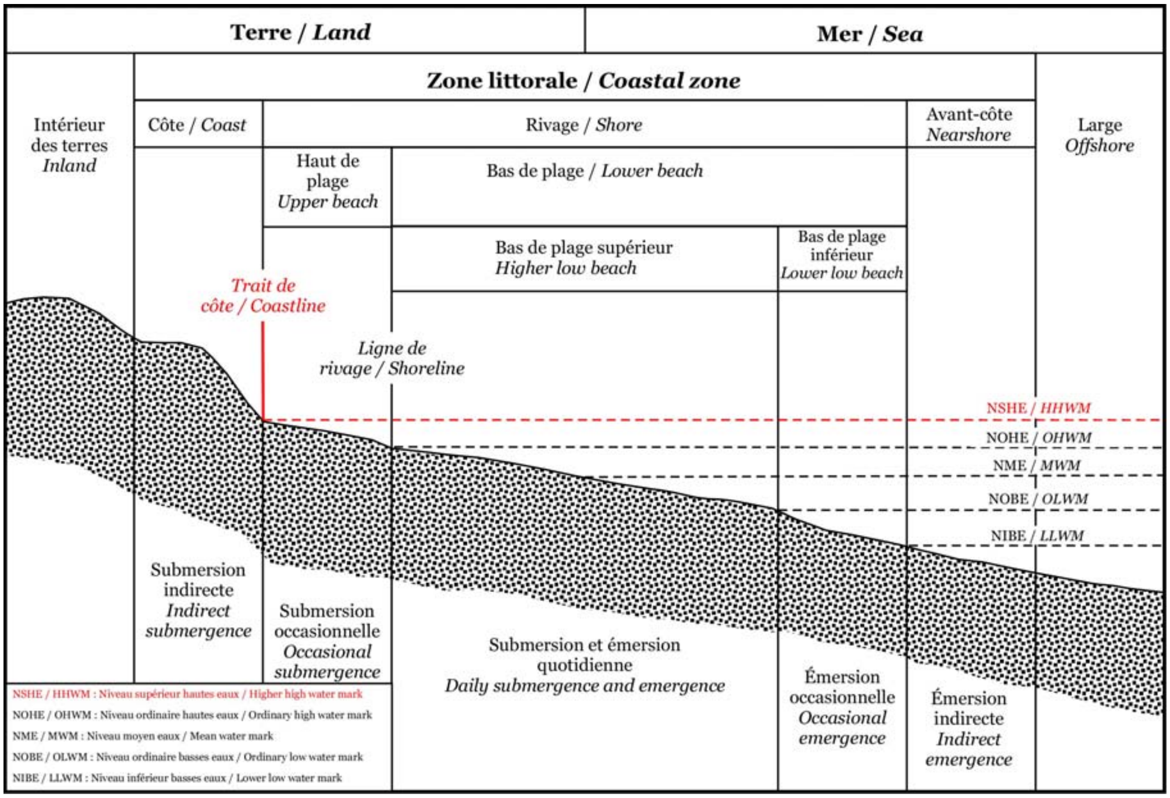
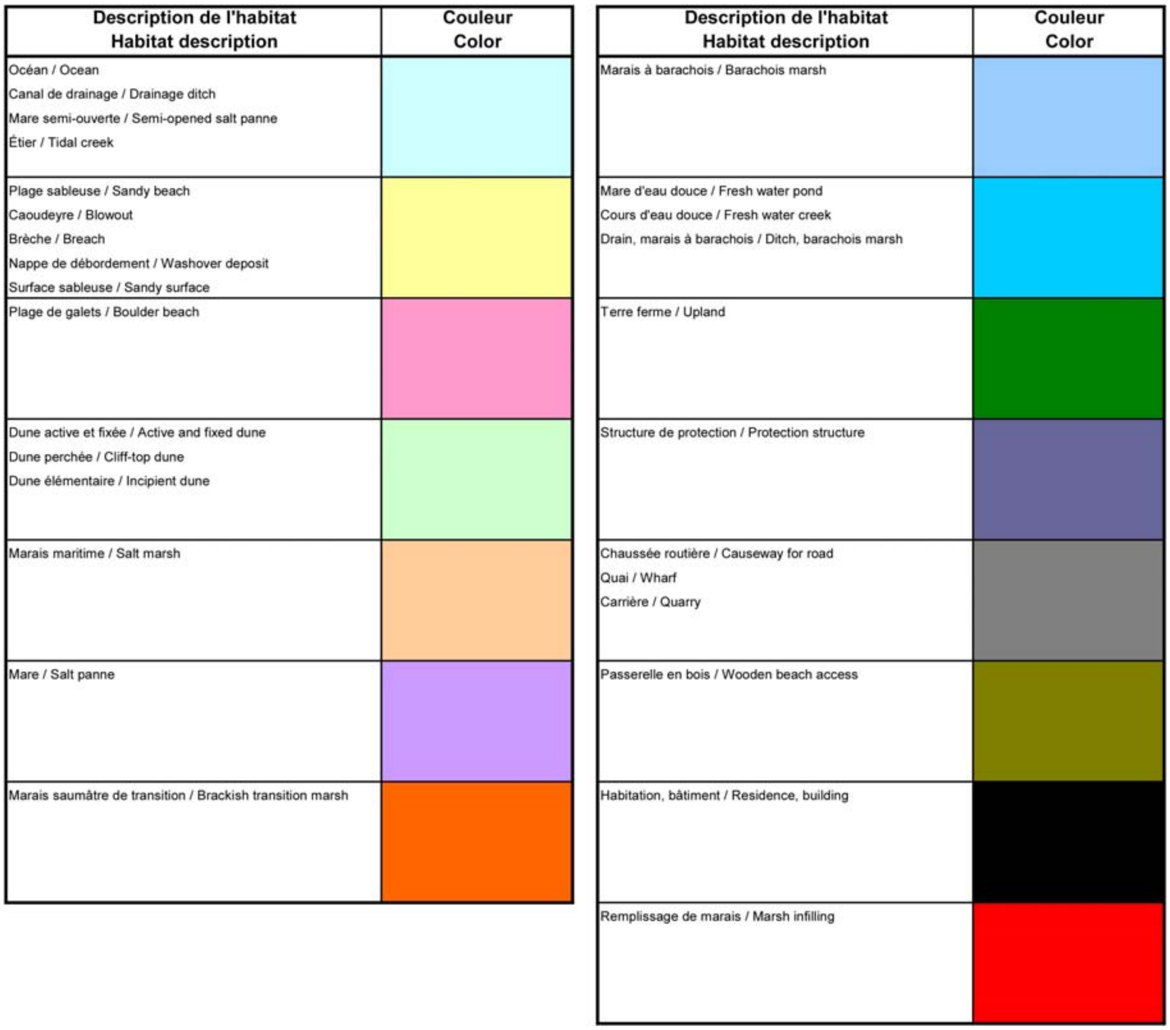


Figure 20. Delineation of the coastal zone (modified from Bérubé and Thibault, 1996).

The landform reached by these two water levels was also specified. For example, the coastline may be the limit of a dune or a cliff, whereas the shoreline may be the limit of a beach or a marsh. In addition to these limits, the mapping of the coastal zone was also designed to allow identification of the surfaces of specific habitats, including, among others, sandy or boulder beaches, dune environments, salt marshes, brackish transition marshes, bodies of water, etc., as well as zones bearing traces of human development. Table 3 presents the various habitats and developments mapped.

Table 3. Habitats and developments and their corresponding colour (as it appears on the georeferenced maps, in Annex D, Section 5).



Description de l'habitat Habitat description	Couleur Color
Océan / Ocean Canal de drainage / Drainage ditch Mare semi-ouverte / Semi-opened salt panne Étier / Tidal creek	🟦
Plage sableuse / Sandy beach Caoudeyre / Blowout Brèche / Breach Nappe de débordement / Washover deposit Surface sableuse / Sandy surface	🟨
Plage de galets / Boulder beach	🩷
Dune active et fixée / Active and fixed dune Dune perchée / Cliff-top dune Dune élémentaire / Incipient dune	🟩
Marais maritime / Salt marsh	🟧
Mare / Salt panne	🟪
Marais saumâtre de transition / Brackish transition marsh	🟧
Marais à barachois / Barachois marsh	🟦
Mare d'eau douce / Fresh water pond Cours d'eau douce / Fresh water creek Drain, marais à barachois / Ditch, barachois marsh	🟦
Terre ferme / Upland	🟩
Structure de protection / Protection structure	🟪
Chaussée routière / Causeway for road Quai / Wharf Carrière / Quarry	◼
Passerelle en bois / Wooden beach access	🟫
Habitation, bâtiment / Residence, building	⬛
Remplissage de marais / Marsh infilling	🟥

Coastline

In the case of a spit or a coastal dune, the coastline mapped corresponds either to the limit of the perennial vegetation (i.e., the edge of the beach grass [*Ammophila breviligulata*] on the upper beach) or, in the absence of vegetation, to the dune scarp (Figure 21).

In the case of cliffs, the coastline normally corresponds to the base of the cliff. However, given that several series of aerial photographs do not allow the base of the cliff to be properly identified (e.g., shaded zones due to the presence of trees or significant relief), the top of the cliff was therefore used as the coastline (Figures 21 and 22).

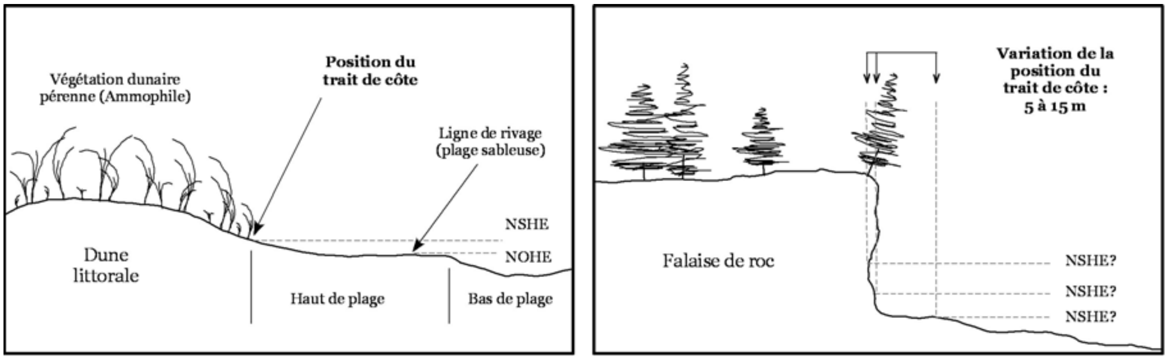


Figure 21. Examples of coastline positioning and problems encountered in interpreting the coastline using aerial photography.

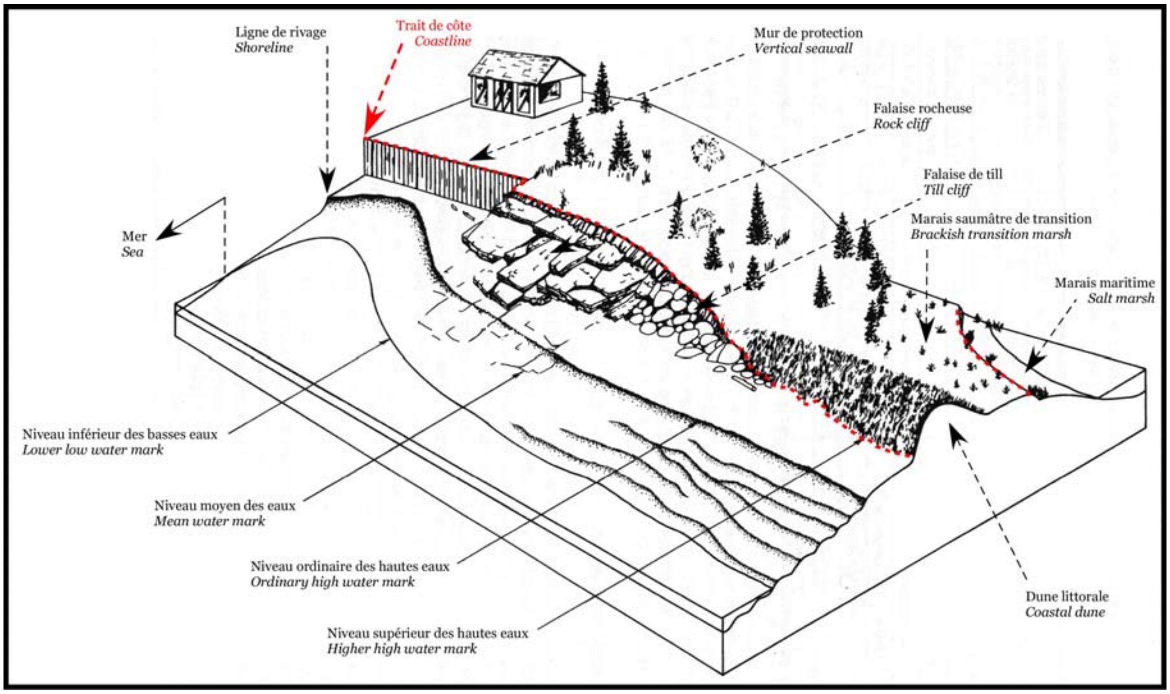


Figure 22. Examples of coastline positioning along some coastal features (modified from Bérubé and Thibault, 1996).

The coastline associated with a salt marsh corresponds to the limit between two groups of vegetation, one dominated by a combination of smooth cordgrass (*Spartina alterniflora*), samphire (*Salicornia europaea*) and salt meadow grass (*Spartina patens*) and the other by a combination of prairie cordgrass (*Spartina pectinata*), blackgrass rush (*Juncus gerardii*) and Baltic rush (*Juncus balticus*). On the aerial photographs, the zone dominated by the first combination is a rather light hue, compared with the second combination of plants, which appears as a darker hue. The area occupied by *S. alterniflora*, *S. europaea* and *S. patens* is the salt marsh, strictly speaking (or low marsh), and is punctuated by distinct or semi-open, highly salinated pannes. For its part, the area occupied by *S. pectinata, J. gerardii* and *J. balticus* is slightly elevated and situated in contact with the upland; thus, it forms the upper part of the marsh (referred to as the “brackish transition marsh” in this study). Within the brackish transition marsh, water bodies varying between salt and fresh water can exist. The salt marsh is submerged during high tide on a monthly basis, whereas the brackish transition marsh is only occasionally submerged by seawater.

Shoreline

In the case of a sandy beach, the shoreline mapped corresponds to the point of contact between dry sand and wet sand (Figure 22). In general, wet sand is darker in colour, while dry sand is lighter in colour. Thus, on sandy beaches, the shoreline marks the division between the upper beach (dry sand) and the lower beach (wet sand). However, it is understood that the position of the shoreline (dry sand / wet sand boundary) can vary depending on recent phenomena occurring just prior to when the aerial photographs were taken, such as heavy rain or a high monthly tide. Many coastal geomorphologists nevertheless use these ephemeral limits to represent the shoreline (Boak and Turner, 2005).

The shoreline associated with salt marshes usually corresponds to the limit of vegetation. If there is a microcliff in the marsh, its top corresponds to the shoreline.

No shoreline was mapped in front of rocky cliffs or bluffs. Indeed, the resolution or clarity of the aerial photographs did not always allow the presence of a beach at the cliff base to be confirmed. It must be noted that the beaches bordering these cliffs are often very narrow (less than 5 m) or not very thick (less than 50 cm), making it very difficult to distinguish the limit between dry sand and wet sand through photo-interpretation. Thus, in many cases, the position of the shoreline simply corresponds to the cliff base (Figure 22); that is why it has not been mapped.

Map quality and data accuracy

Multiyear digital maps created from a series of aerial photographs have a position error inherent in the method used, and this is despite the fact that many measures were taken to control quality and increase accuracy. The margin of error is an expression of the uncertainty associated with the position of mapped elements in relation to their actual position on the ground.

All sources of uncertainty have been taken into account and incorporated into the calculation of the margin of error. Thus, a measure of distance (i.e., the width of a beach) made using the maps will be associated with a margin of error, expressed in metres. For example, the calculation of the margin of error associated with a measurement of coastline-position change between 1944 and 1971 corresponds to the sum of the following elements:

$$\text{Margin of error} = G_1 + G_2 + P_1 + P_2 + R$$

where:

G_1 = average margin of error of control points subsequent to the georeferencing of the 1944 aerial photograph;

G_2 = average margin of error of control points subsequent to the georeferencing of the 1971 aerial photograph;
P_1 = margin of error associated with the accuracy of positioning during mapping, relating to the quality of the 1944 photograph (resolution and clarity of print) and the ability of the cartographer;
P_2 = margin of error associated with the accuracy of positioning during mapping, relating to the quality of the 1971 photograph (resolution and clarity of print) and the ability of the cartographer;
R = margin of error inherent in the resolution of the 1996 orthophotograph (document used to carry out the georeferencing of the 1944 and 1971 photographs based on the control points).

To obtain the average annual margin of error, one has only to divide the margin of error by the number of years included in the period studied. In the above example, the average annual margin of error (expressed in m/year) would correspond to this value divided by 27 (years):

$$\text{Annual margin of error} = \frac{G_1 + G_2 + P_1 + P_2 + R}{27}$$

On the multiyear georeferenced maps, 1595 transects were drawn at 50-m intervals, perpendicular to the coastline of the most recent year, which is 2001. The displacement measurements were taken at the intersections formed by the positions of the coastline in 1944, 1971/1973 and 2001 on a given transect.

Within the context of this work, a rate of coastline-position change greater than the margin of error is considered to be significant — that is, a retreat, in the case of a negative value, and an advance, in the case of a positive value. A coastline-displacement rate equal to or smaller than the margin of error is considered to represent “relative stability.”

Analysis phase

The recent evolution of the coastal zone was studied using qualitative and quantitative analyses of the multiyear georeferenced maps. The qualitative analysis mainly involves visual observation of changes to the coastal zone, through a comparison of the three main maps of a given sector (1944, 1971/1973 and 2001). The quantitative analysis relies on measurements of coastline displacement made using the multiyear maps on which appear the coastlines for the three main years mapped. The quantitative analysis also relies on the extraction of data on areas showing variation over time of the space covered by certain coastal habitats. The data relating to the area of coastal habitats are presented in the section of this report dealing with the impact of sea-level rise and climate change on ecosystems (Section 4.6).

The various figures presented in this section show specific changes and are extracted from the multiyear georeferenced maps.

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitat).

4.5.3.2.3 Recent evolution of the sand spits

Analysis of the evolution of the sandy coasts is based on the evolution types recognized by McBride et al. (1995) along the barrier islands of Louisiana, Georgia and Florida. The model proposed by these authors was adapted to the context of southeastern New Brunswick's coastal zone.

For the period of 1944–2001, the dunes and sand spits of the three study sites (greater Cocagne, l'Aboiteau and Shemogue) show five distinct evolutions: A) maintenance of a relatively stable position for the proximal and medial sections of the spit; B) lateral seaward advance of the distal section of the spit; C) landward retreat of the entire spit; D) segmentation and retreat of the spit; and E) retreat and destruction of the entire spit.

Case A: Maintenance of a relatively stable position for the proximal and medial sections of the spit[4]

The Grants Beach sand spit (Shemogue study site) is representative of the first type of evolution observed — that is, the maintenance of a relatively stable position over the last 60 years. This evolution is considered to represent a dynamic equilibrium; that is, the long-term migration of the coastline fluctuates around zero (the total advances and retreats cancel each other out over a long period of time).

The Grants Beach spit is located on the eastern shore of the mouth of the Little Shemogue estuary (Figure 16). It is approximately 1.7 km long and 230 m wide and is aligned along a southwest–northeast axis. A sandy beach 10–30 m wide borders the Grants Beach spit along the Northumberland Strait, while a large salt marsh is located behind. Some field trips allowed complementary information to be gathered: the maximum height of the dune crest is approximately 5.5 m, and its minimum height is 1 m, in relation to the adjacent sandy beach. The dune front is cliffed along the entire proximal and medial sections (Figure 23A), whereas the contact between the beach and the dune in the distal section of the spit forms a gentle regular slope.

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[4] Type "3" (*Dynamic equilibrium*): McBride et al. (1995).

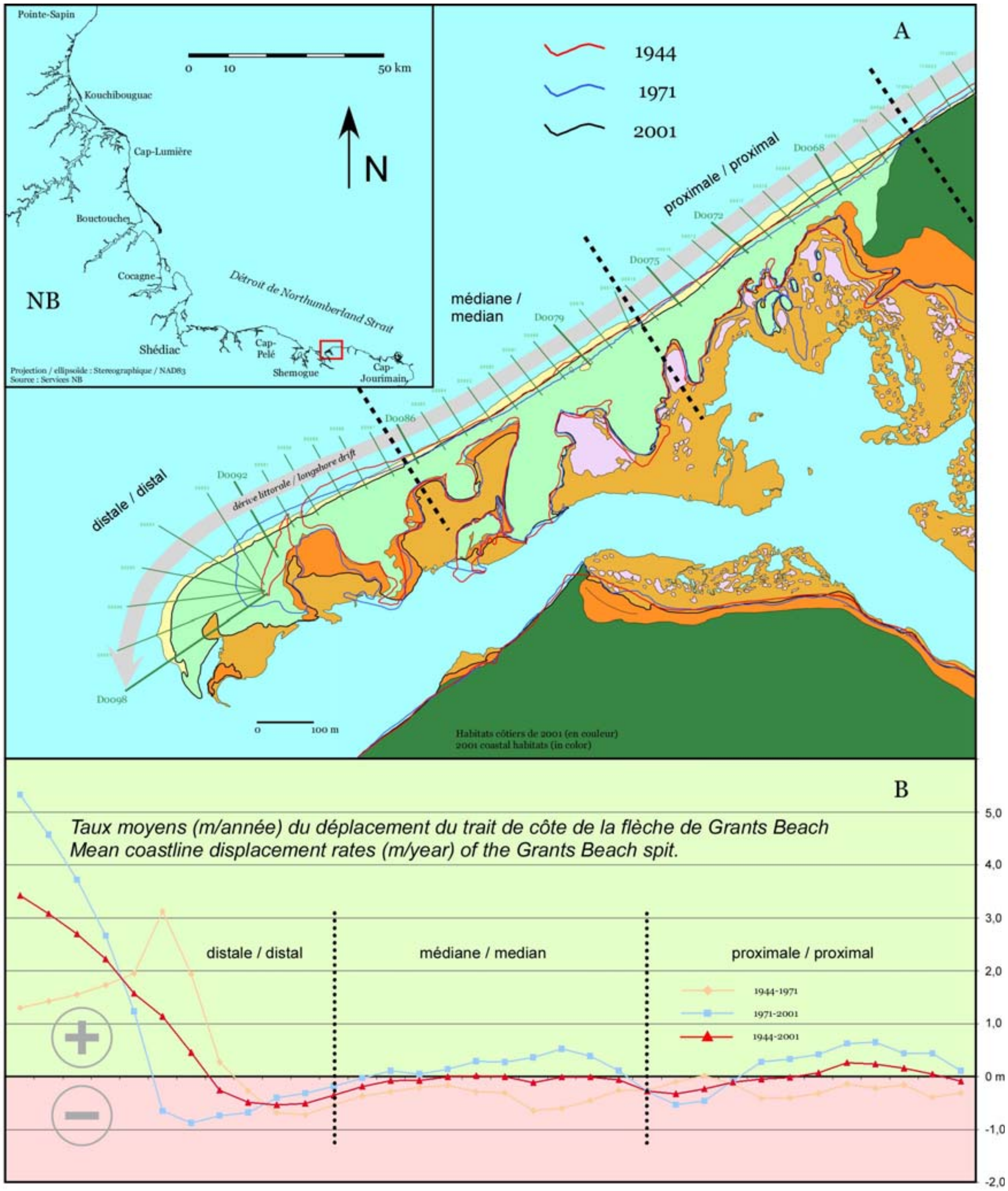

Figure 23. Coastline position of the Grants Beach sand spit in 1944, 1971 and 2001 (A) and annual rate of change (m/year) of the coastline, by section (B).

Taking into account the rates of retreat and advance over the 1944–2001 period, the entire shore of the Grants Beach spit exposed to the Strait was stable,[5] judging from the

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[5] Note: A coastline displacement rate greater than the margin of error is considered to be significant — that is, a retreat, in the case of a negative value, and an advance, in the case of a positive value. A coastline

variation in the coastline's position, which is −5.07 ± 7.27 m (corresponding to a rate of −0.09 ± 0.13 m/year).

In the proximal section (Figure 23A), the values for the 1944–1971 and 1971–2001 periods, respectively −6.32 ± 7.68 m (−0.23 ± 0.28 m/year) and 4.87 ± 6.88 m (0.16 ± 0.23 m/year), also fall within the margin of error. These figures, however, obscure the fact that, during these periods, parts of the proximal section of Grants Beach may have advanced and others may have retreated; thus, between 1971 and 2001, great variations in the coastline's position, of −15.85 ± 6.88 m and 19.5 m ± 6.88 m (Table 4), can be observed.

The medial section of the Grants Beach spit retreated between 1944 and 2001. The 1944–1971 period accounts mainly for this erosion trend, the average retreat at that time being 9.58 ± 7.68 m (0.36 ± 0.28 m/year) (Figure 23B). The most significant retreat was 17.27 ± 7.68 m. The 1971–2001 period was, for its part, characterized by relative stability (average variation of 6.67 ± 6.88 m; rate of 0.22 ± 0.28 m/year). During this second period, the extreme values were 15.69 ± 6.88 m and −0.81 ± 6.88 m, respectively.

The distal section of the Grants Beach spit can be divided into two subsections: the coast exposed to the Northumberland Strait and the tip of the spit facing the estuary. Over the period of 1944–2001, the coast of the Strait saw an average retreat of 15.91 ± 8.07 m (0.28 ± 0.14 m/year), while the tip of the spit advanced 134.17 ± 8.07 m, an average rate of 2.35 ± 0.14 m/year. During the periods 1944–1971 and 1971–2001, the greatest values for erosion along the coast exposed to the Strait were 19.44 ± 7.68 m and 26.28 ± 7.68 m, respectively. During these two periods, the tip of the spit advanced seaward; the highest rates of advance were 84.28 ± 7.68 m and 159.79 ± 7.68 m, respectively.

Based on the information from the multiyear georeferenced mapping, it can be concluded that the dominant longshore drift along Grants Beach goes from the northeast towards the southwest and that the volume of sediment it transports seems sufficiently great to keep the beach and the dune in a relatively stable position, while contributing to some lateral advancement of the distal section of the spit.

Another example of the evolution of a sand spit whose position has remained relatively stable during the last 60 years is the spit located in the northwestern portion of Cocagne Island (Figure 14).

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitats).

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displacement rate equal to or smaller than the margin of error is considered to represent "relative stability" of the coastline's position.

Table 4. Change (m) and annual rate of change (m/year) of the Grants Beach coastline from 1944 to 2001.

Section	Transect	Déplacement (m) *Displacement (m)*			Déplacement moyen annuel (m) *Mean annual displacement (m)*		
		1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
proximal	D0065	-8,24	3,36	-4,88	-0,31	0,11	-0,09
	D0066	-10,54	13,16	2,62	-0,39	0,44	0,05
	D0067	-4,12	13,10	8,98	-0,15	0,44	0,16
	D0068	-5,96	19,50	13,54	-0,22	0,65	0,24
	D0069	-3,71	18,71	14,99	-0,14	0,62	0,26
	D0070	-8,49	12,59	4,10	-0,31	0,42	0,07
	D0071	-10,86	10,04	-0,82	-0,40	0,33	-0,01
	D0072	-11,00	8,39	-2,62	-0,41	0,28	-0,05
	D0073	-3,65	-2,37	-6,02	-0,14	-0,08	-0,11
	D0074	0,47	-13,78	-13,31	0,02	-0,46	-0,23
	D0075	-2,59	-15,85	-18,45	-0,10	-0,53	-0,32
	D0076	-7,11	-8,42	-15,53	-0,26	-0,28	-0,27
médian	D0077	-6,88	3,34	-3,54	-0,25	0,11	-0,06
	D0078	-12,17	11,75	-0,42	-0,45	0,39	-0,01
	D0079	-16,16	15,69	-0,47	-0,60	0,52	-0,01
	D0080	-17,27	10,87	-6,40	-0,64	0,36	-0,11
	D0081	-8,32	8,21	-0,11	-0,31	0,27	0,00
	D0082	-7,63	8,70	1,07	-0,28	0,29	0,02
	D0083	-4,41	4,23	-0,18	-0,16	0,14	0,00
	D0084	-5,45	1,37	-4,08	-0,20	0,05	-0,07
	D0085	-7,67	3,33	-4,34	-0,28	0,11	-0,08
	D0086	-9,85	-0,81	-10,66	-0,36	-0,03	-0,19
distal (Détroit)	D0087	-14,47	-5,50	-19,98	-0,54	-0,18	-0,35
	D0088	-19,44	-9,46	-28,90	-0,72	-0,32	-0,51
	D0089	-18,43	-11,92	-30,36	-0,68	-0,40	-0,53
	D0090	-7,19	-20,37	-27,56	-0,27	-0,68	-0,48
	D0091	7,43	-22,16	-14,73	0,28	-0,74	-0,26
	D0092	52,33	-26,28	26,05	1,94	-0,88	0,46
distal (pointe)	D0093	84,28	-19,39	64,89	3,12	-0,65	1,14
	D0094	52,69	36,90	89,59	1,95	1,23	1,57
	D0095	46,75	79,92	126,66	1,73	2,66	2,22
	D0096	41,88	111,70	153,59	1,55	3,72	2,69
	D0097	38,45	136,99	175,44	1,42	4,57	3,08
	D0098	35,09	159,79	194,88	1,30	5,33	3,42

Case B: Lateral seaward advance of the distal section of the spit[6]

The second type of evolution observed during the study period is the lateral seaward advance of the distal section of the spit. The Petit-Cap spit, located on the western shore of the mouth of the Shemogue estuary, is a typical example (Figure 16). The main or dominant characteristic of this type of evolution is the advance of the coast, parallel to the shoreline. This evolution involves an influx of sand from the longshore drift, towards the distal portion (the tip) of the spit.

The Petit-Cap sand spit exposed to the Northumberland Strait was mapped for all the available years of aerial photography coverage — namely, 1944, 1953, 1963, 1971,

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[6] Type "2" (*Advance*): McBride et al. (1995).

1982, 1996 and 2001. Figure 24 shows the coastline positions of this spit for the 1944–2001 period. In 1944, the Petit-Cap spit had only a single dune crest (Figure 24A). Since 1953, a second crest has developed on the Strait side. This new dune has extended towards the southeast over the years (Figure 24B, C, D, E), and its total advance, from 1953 to 2001, was 869.40 ± 7.18 m, which represents a rate of elongation of 18.10 ± 0.13 m/year. While lengthening towards the southeast, the coastline of this new dune front simultaneously retreated landward, an average of 26.37 ± 7.18 m from 1944 to 2001 (rate of retreat of 0.46 ± 0.13 m/year). Because of this retreat, the anchoring point of the Petit-Cap spit, located in the proximal section in 1953, is now located in the medial section of the spit (Figure 24E). In 2001, the Petit-Cap sand spit was approximately 1.3 km long and a maximum of 130 m wide and was oriented along a northwest–southeast axis. Another example showing the advance of the coast seaward during the last 60 years is the case of the sand spit in the southern part of Cocagne Island (see Figure 28B below).

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitats).

Case C: Landward retreat of the entire spit[7]

The l'Aboiteau dune is representative of a transgressive evolution (Figure 25). With the advance of the ocean, this evolution is characterized by a retreat of the coast and migration landward of the entire system. The development of breaches in the dune front and the subsequent buildup of sandy deposits in back (overwash deposits) during storms contribute to the retreat and landward migration of all the coastal landforms.

Since 1944, the l'Aboiteau beach and dune have migrated landward (Figure 25A), but the magnitude measured is not the same over the entire length of the dune. Over the 1944–1971 period, the western portion retreated an average of 35.72 ± 8.04 m (rate of 1.32 ±0.30 m/year), while the eastern portion, which corresponds to the l'Aboiteau beach site, was stable, the retreat there being 3.14 ± 6.91 m (0.12 ± 0.26 m/year) (Figure 25B and Table 5). Between 1971 and 2001, these trends were maintained: average retreat of the western portion of 29.81 ± 6.02 m (0.99 ±0.20 m/year) and insignificant variation of the eastern coastline (2.08 ± 6.69 m; 0.07 ± 0.22 m/year).

The significant retreat of the western portion of the coast is partially due to the development of breaches in the dune front. Figure 25A provides a good view of the configuration of the coast: semicircular re-entrants, in the area of Chemin Emery and Gagnon Beach, are present in 1944, 1971 and in 2001; they testify to the existence of breaches in the dune front. In places, the backdune rests directly on the barachois marsh; elsewhere, it encroaches on the marsh's pools and water bodies (Figure 25A). This sand transfer, through overwash deposits, contributes to the landward migration of the coastal dune.

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[7] Type "6" (*Landward rollover*): McBride et al. (1995).

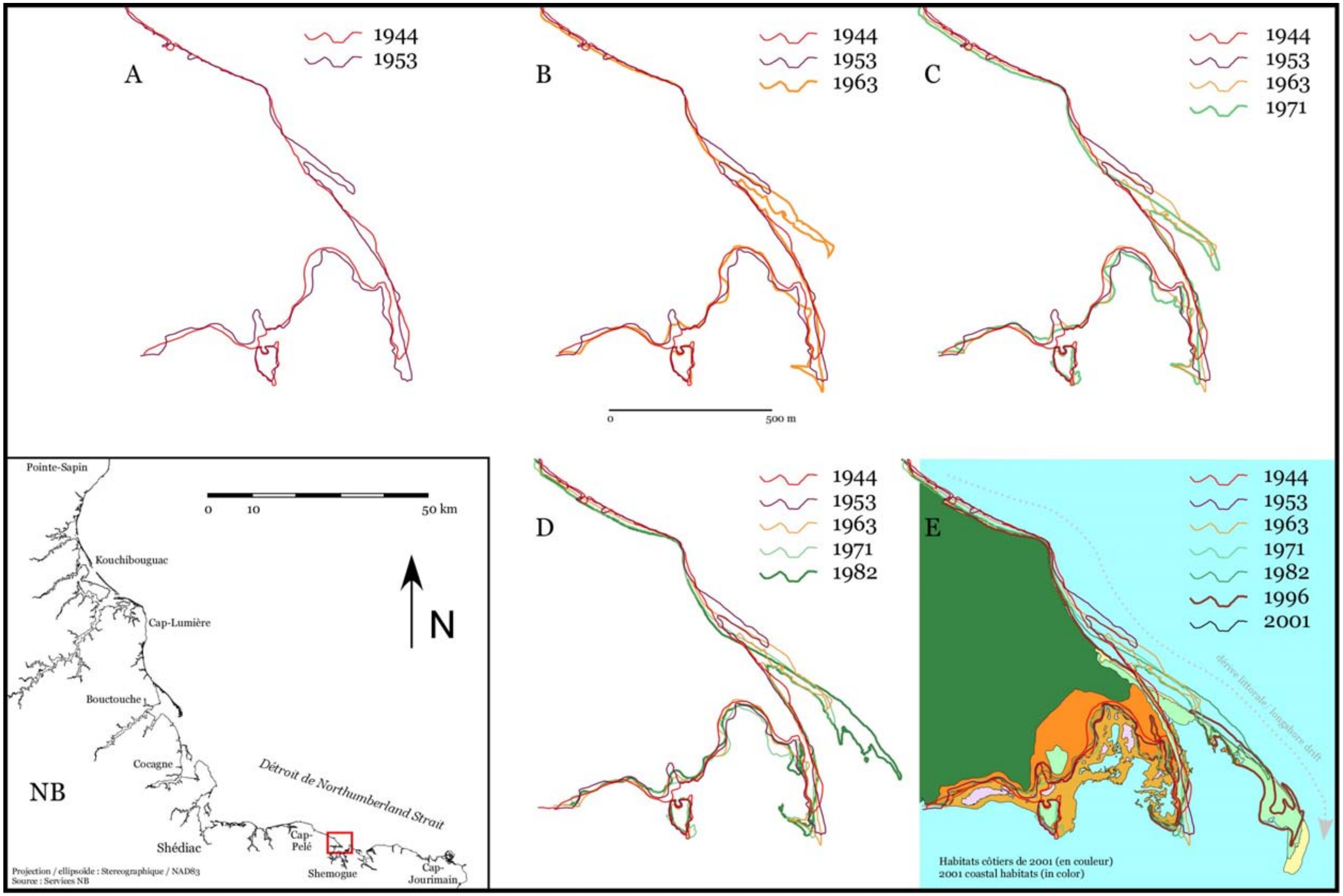

Figure 24. Coastline evolution of the Petit-Cap sand spit from 1944 to 2001.

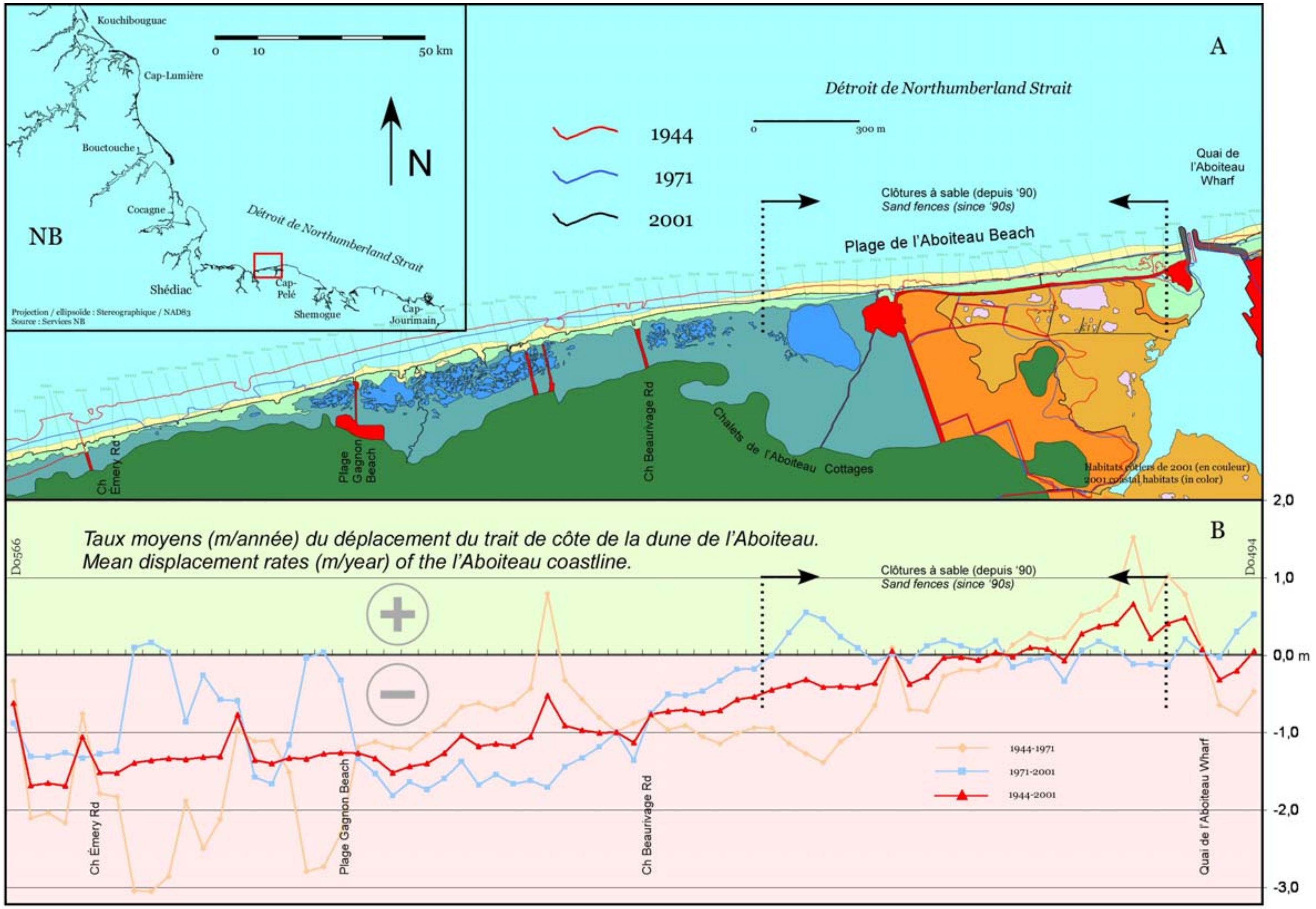

Figure 25. Coastline position of the l'Aboiteau dune in 1944, 1971 and 2001 (A) and annual rate of change (m/year) of the coastline, by section (B).

Table 5. Average change (m) and annual rate of change (m/year) of the east and west areas of the l'Aboiteau dune from 1944 to 2001.

	Transect	Déplacement moyen (m) *Average displacement (m)*			Déplacement moyen annuel (m/an) *Mean annual displacement (m/yr)*		
		1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
est *east*	D0498 à / *to* D0522	-3,14 ±6,91	2,08 ±6,69	-1,07 ±7,77	-0,12 ±0,26	0,07 ±0,22	-0,02 ±0,14
ouest *west*	D0523 à / *to* D0566	-35,72 ±8,04	-29,81 ±6,02	-65,54 ±7,36	-1,32 ±0,30	-0,99 ±0,20	-1,15 ±0,13

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitats).

Case D: Segmentation and retreat of the spit[8]

Another type of evolution observed during the study period was the segmentation of a sand spit following the development of a breach and the formation of a tidal inlet; this is the case for the Shemogue cape spit, located on the eastern shore of the mouth of the Shemogue estuary (Figure 16). This type of evolution occurs mainly along narrow and low-lying coastal dunes and spits, which are susceptible to inundation by storm waves. If they are not filled in more or less rapidly with an influx of sand from the longshore drift, the tidal inlets that develop can get larger and become deeper, resulting in the formation of a series of sandy islets.

Figure 26 shows the coastal habitats of the Shemogue cape spit for the three main years of 1944, 1971 and 2001. In 1944, the presence of a sand spit typical of the Northumberland Strait coast can be observed: that is, a sandy beach on which a dune environment has developed, behind which a salt marsh and its associated habitats can be noted. The Shemogue cape spit is neither long nor wide (approximately 1.2 km long and 240 m wide), and the dune crest is generally low (less than a metre high); it is aligned along a southwest–northeast axis.

In 1971, the proximal section of the spit was cut by the development of a breach. The dune front disappears for a length of 562.59 m, and only the sandy beach remains in this location. There is a small tidal inlet (34.25 m wide) that allows for an exchange of water between the Strait and the estuary. The formation of a breach and the opening of the tidal inlet contributed to the erosion of portions of the salt marsh located behind the dune. Landward sand transfers from the beach also contribute to marsh burial (represented by the letter "a" on Figure 26).

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[8] This type of evolution is not among the types put forth by McBride et al. (1995).

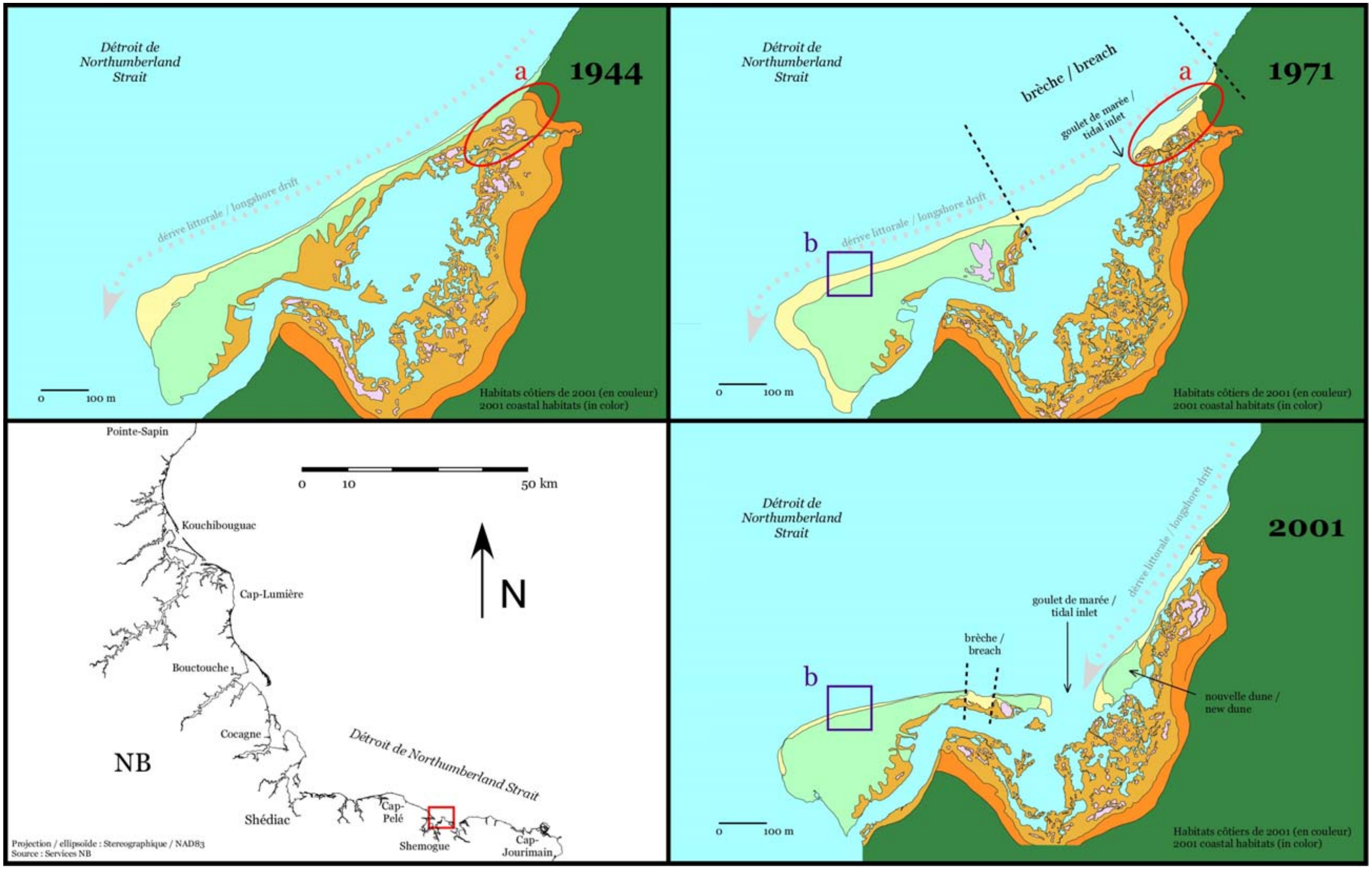

Figure 26. Coastal habitats and evolution of the Shemogue Cape sand spit in 1944, 1971 and 2001 (a: erosion and marsh sand burial; b: beach narrowing).

In 2001, the tidal inlet grew and migrated slightly towards the southwest with respect to its 1971 position, its total width being 95.61 m. The distal section of the spit is now cut off and forms a sandy islet. Because of the new hydrodynamic conditions associated with the formation and migration of the tidal inlet, the coastal configuration of the distal section has changed. The most striking aspect of the evolution of this section of the spit between 1971 and 2001 is the spectacular reduction in the width of the sandy beach. In 1971, at transect D0197 (represented by the letter “b” on Figure 26), the beach was 23.03 m wide, whereas in 2001, it was only 8.75 m. The creation of the tidal inlet seems to have stopped the influx of sand from longshore drift originating from the northeast.

Another example of an evolution showing the segmentation of a sand spit following the development of a breach during the last 60 years is that of the Cap-Bimet and Pointe-aux-Bouleaux spits (Figure 15). This section of the coast includes two sandy spits anchored to the Cap-Bimet and Pointe-aux-Bouleaux headlands. These spits enclose the Petit Barachois estuary and shelter large salt-marsh areas (Figure 27).

In 1944, the two sand spits, which are approximately 500 m long, were separated by a tidal inlet about 10 m wide (Figure 27c). In 1971, the dune front of the two spits was eroded by the formation of breaches, which led to the creation of tidal inlets. The old inlet was filled in by an influx of sand, and a coastal dune developed over it, slightly back from the old position of the dune front, forming a sandy islet. During this same period, the development of a salt marsh behind the sandy islet can also be noted (Figure 27c). From 1944 to 1971, the anchor point of the Pointe-aux-Bouleaux spit retreated an average of 63.95 ± 7.06 m (2.37 ± 0.26 m/year). This significant retreat led to the erosion and sand burial of the salt marsh located behind the spit (Figure 27a). In 2001, in the area around the sandy islet, the presence of numerous sand shoals can be noted about 100 m seaward (along the Northumberland Strait). These sand shoals must contribute to the islet’s influx of sediment, since, over the 1971–2001 period, the coastline advanced seaward an average of 23.46 ± 6.66 m (rate of advance of 0.78 ± 0.12 m/year). Over the 1944–2001 period, the distal portion of the Cap-Bimet spit was, for its part, completely eroded.

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitats).

Case E: Retreat and destruction of the entire spit[9]

This type of evolution of sandy coasts is transgressive and leads ultimately to the destruction of original landforms and to a new configuration of the coast. The conditions that led to the creation of the coastal landforms are different and differ to the point where the latter are no longer in equilibrium with the environment, but are instead in disequilibrium. In general, the coast is retreating landward, while at the same time losing its main elements (narrower beaches, less significant dune environments); this is the erosion and subsequent destruction of the coastal forms as they have existed up until now.

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[9] Type “7” (*Breakup*): McBride et al. (1995).

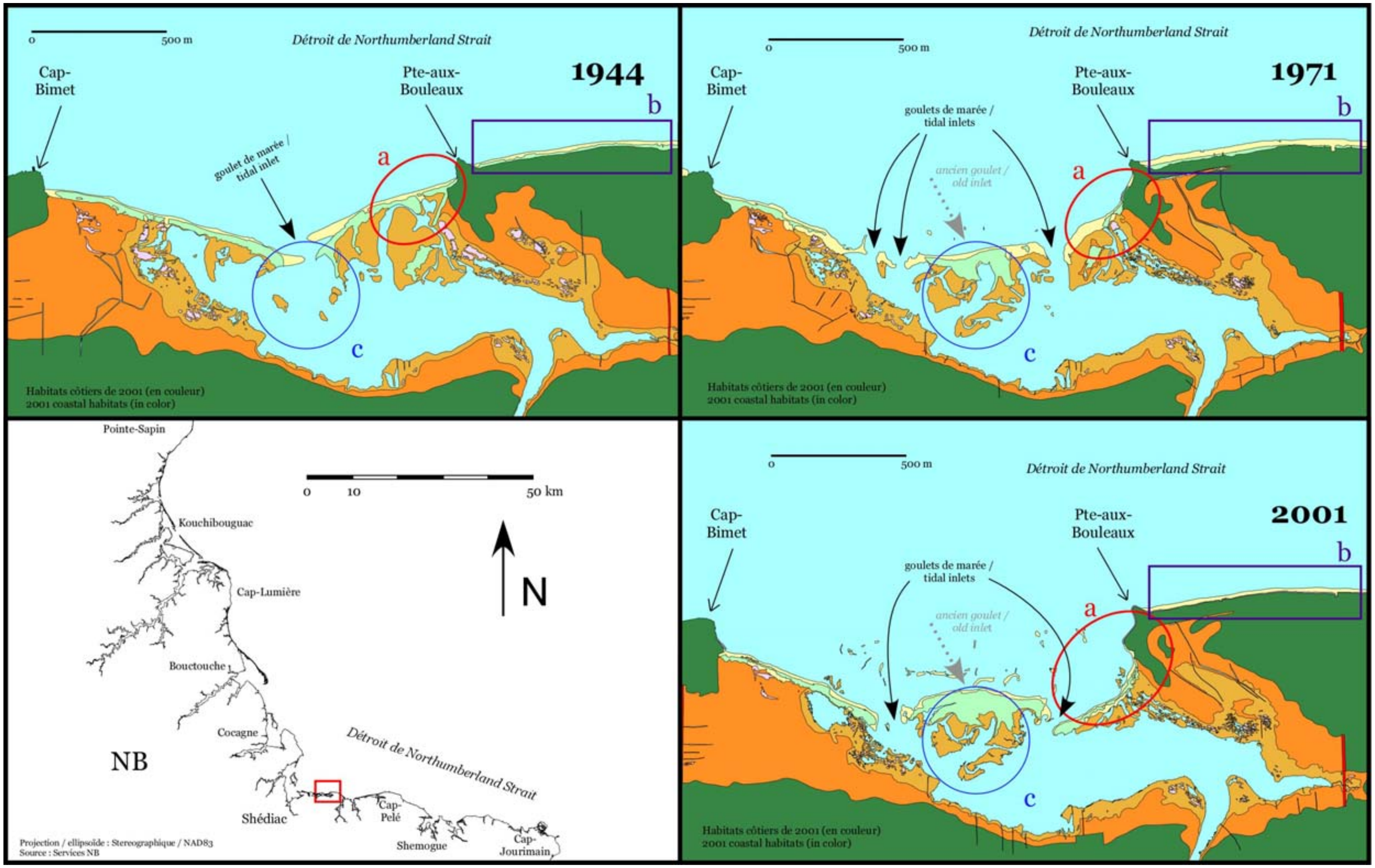

Figure 27. Evolution of the coast and habitats between two headlands, Cap-Bimet and Pointe-aux-Bouleaux (a: retreat of a spit, sand burial and erosion of a salt marsh; b: destruction of a coastal dune subsequent to property development and introduction of rock embankments; c: tidal inlet closure, formation of a dune and salt marsh).

Bérubé et al. (2002) studied the historical evolution of the Cocagne bar (sand spit) based on historical documents, in particular a bathymetric chart dating back to 1839. At that time (167 years ago), the Cocagne bar formed a tombolo; that is, it linked the shoal known as Dickson Point to the mainland (Figure 28A). The authors discuss the rapid erosion of the system and present rates of coastline retreat since 1839. Thus, the present analysis consists of a qualitative description of the recent evolution of the Cocagne bar.

In 1944, our data show that the Cocagne bar was 1.4 km long and 90 m wide and was located about 650 m from Dickson Point (Figure 28A). In 1973, it was 1.3 km long, and its widest portion was 75 m. The entire bar was located 144 m farther inland from its 1944 position, and its anchor point to the mainland had migrated 186 m farther south. The dune, which covered a good portion of the Cocagne bar in 1944, had practically disappeared by 1973; all that remained of the bar was an elongated sandy beach, slightly recurved towards the mainland. In 2001, the Cocagne bar, which had taken the shape of a typical sand spit since 1944 (a beach and a coastal dune anchored to the mainland and freely extending seaward), now comprised only a small sandy system, located in front of a salt marsh and lying right alongside the mainland. The Cocagne bar is gone; the sandy system that remains is no more than 629 m long and 60 m wide.

The Robichaud sand spit and the dune southeast of Cocagne Island are two other examples of the same type of evolution (Figure 28B and C). It should be noted that the retreat and destruction of the dune southeast of Cocagne Island also led to the complete erosion of the salt marsh that was located behind it (Figure 28B).

Readers are invited to consult the maps, attached, for further details on the subject (Section 5, Annex C, Rates of coastline-position change; Annex D, Coastal habitat distribution).

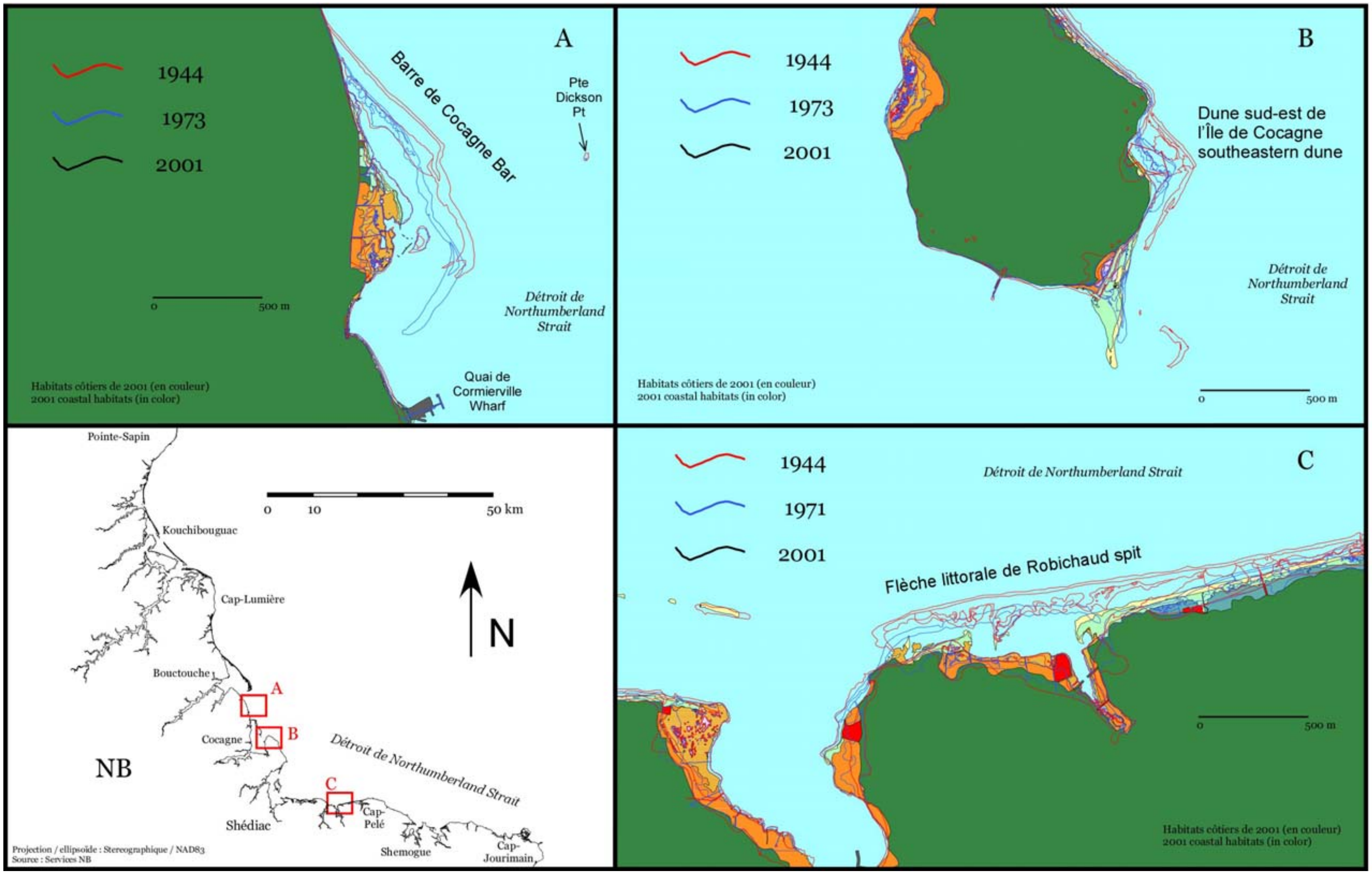

Figure 28. Destruction, over the 1944–2001 period, of the Cocagne bar (A), of the dune southeast of Cocagne Island (B) and of the Robichaud sand spit (C).

4.5.3.2.4 Recent evolution of the cliffs[10]

In general, coastline retreat along bluffs, and particularly rock cliffs, is not as significant as the retreat along dunes and sand spits. In fact, the cliffs erode so slowly that the data collected from multiyear maps do not allow us to confirm the retreat for all cliffs in the study sites. A number of the rates measured are below the margin of error for multiyear georeferenced maps. This type of coastline evolution is interpreted as representing "relative stability" or bearing little significance. The relative stability of rocky cliffs and bluffs applies mainly to the shorter periods studied, i.e., 27 years (1944–1971) and 30 years (1971–2001). However, reported over the longest study period (57 years: 1944–2001), coastline-position changes are often larger than the margin of error, meaning that there is a substantial ("real") retreat of the cliffs. We illustrate this situation by taking the rocky cliffs of Trois-Ruisseaux and the bluffs of Shemogue Cape as examples. The cliff study points to the limits of the method used; the values obtained over short periods may therefore be less reliable than those that cover long periods.

Rocky cliffs

The Trois-Ruisseaux coast faces the Northumberland Strait and is dominated by low-lying bluffs (less than 4 m high, in general) alternating with low rocky cliffs (mainly sandstone). Two rock outcrops, located 250 m apart, demonstrate the difficulties of interpreting data on slow evolutions. The first rock outcrop (outcrop 1, Figure 29A) is 200 m long. Between 1944 and 1971, as well as between 1971 and 2001, the coastline's variation appears to have been stable, with retreat values of 6.67 ± 7.40 m/year and 5.99 ± 5.96 m/year, respectively (Table 6). However, two sections of the same outcrop registered a retreat of about 10 m during the 1944–1971 period (at transects TF0272 and TF0274). Moreover, the values of the retreat for the entire outcrop during the 1944–2001 period indicate a true retreat, not relative stability: over the longer period, the average retreat of 12.66 m is large enough to distinguish it from the margin of error, ±7.47 m (0.22 ± 0.13 m/year). The second rock outcrop (outcrop 2, Figure 29A) is 400 m long. Over the three study periods (1944–1971, 1971–2001 and 1944–2001), the variation in the coastline remained stable (Table 6). Only three places along the outcrop posted significant erosion in the study period — that is, transects TF0282 and TF0283, where, between 1971 and 2001, the retreat was 7.58 ± 5.96 and 8.07 ± 5.96 m, respectively, and at transect TF0280, where, between 1944 and 2001, the retreat was 8.70 ± 7.47 m.

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[10] The word bluff here refers to the cliffs that have been shaped from a variety of heterogeneous unconsolidated deposits, of varying ages, that line the coast. In general, the bluffs in southeastern New Brunswick present, from base to summit: a silt clay layer, called mudstone, coloured ochre to red, from the Carboniferous age; glacial deposits (also called "till"), containing boulders, cobbles and pebbles in a sand–clay matrix; towards the top of the cliffs, a layer of post-glacial marine sediment, dominated by fine sediment (sand, silt, clay). The case of dune cliffs, also unconsolidated material, is dealt with in Section 4.5.3.2.3 ("Recent evolution of the sand spits"). Cliffs that develop in salt marshes are also unconsolidated cliffs, but they are not included in this category.

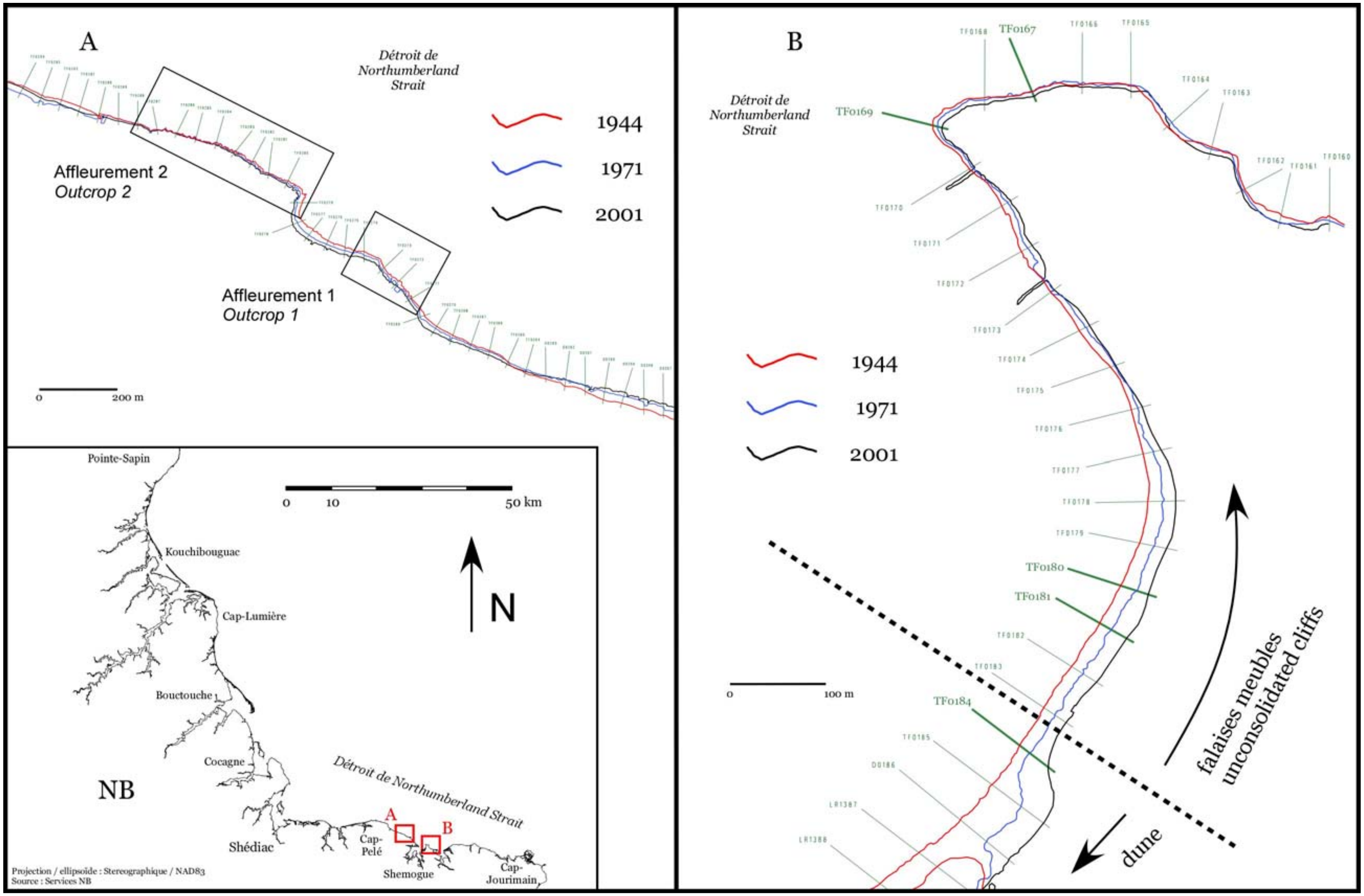


Figure 29. Coastline position in 1944, 1971 and 2001 of the Trois-Ruisseaux rocky cliffs (A) and the Shemogue Head bluffs (B).

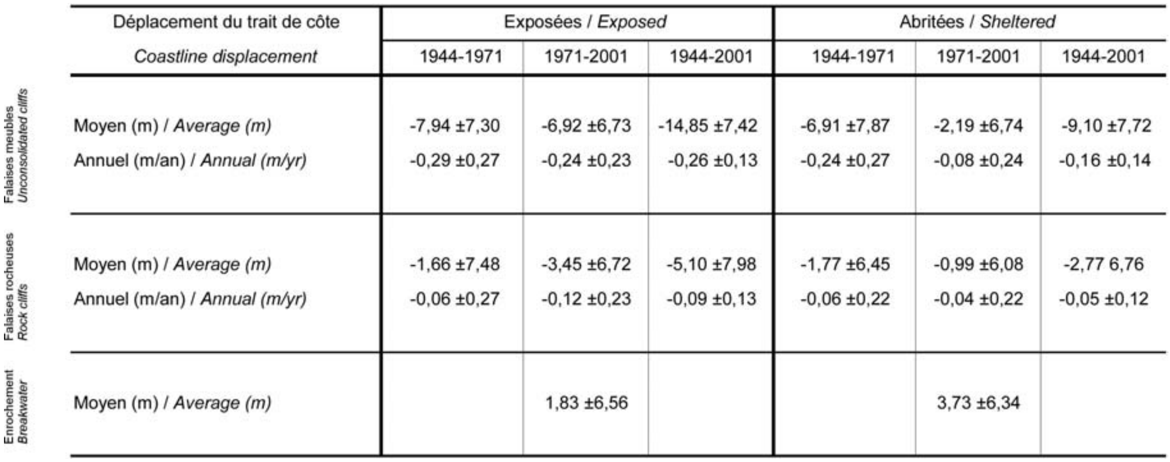
Table 6. Average change (m) and annual rate of change (m/year) of the coastline of two rock outcrops near Trois-Ruisseaux from 1944 to 2001.

	Transect	Déplacement (m) *Displacement (m)*			Déplacement moyen annuel (m/an) *Mean annual displacement (m/yr)*		
		1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
Affleurement 1 *Outcrop 1*	TF0271	-0,76	-7,07	-7,83	-0,03	-0,24	-0,14
	TF0272	-10,18	-3,36	-13,54	-0,38	-0,11	-0,24
	TF0273	-6,15	-4,07	-10,22	-0,23	-0,14	-0,18
	TF0274	-9,60	-9,45	-19,05	-0,36	-0,32	-0,33
	Moyenne / *Average*	-6,67 ±7,40	-5,99 ±5,96	-12,66 ±7,47	-0,25 ±0,27	-0,20 ±0,20	-0,22 ±0,13

	Transect	Déplacement (m) *Displacement (m)*			Déplacement moyen annuel (m/an) *Mean annual displacement (m/yr)*		
		1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
Affleurement 2 *Outcrop 2*	TF0280	-4,79	-3,91	-8,70	-0,18	-0,13	-0,15
	TF0281	-1,31	-3,27	-4,58	-0,05	-0,11	-0,08
	TF0282	0,78	-7,58	-6,80	0,03	-0,25	-0,12
	TF0283	0,32	-8,07	-7,75	0,01	-0,27	-0,14
	TF0284	-2,75	-3,43	-6,19	-0,10	-0,11	-0,11
	TF0285	1,60	-3,25	-1,65	0,06	-0,11	-0,03
	TF0286	-1,57	-1,16	-2,73	-0,06	-0,04	-0,05
	TF2087	0,26	-1,42	-1,17	0,01	-0,05	-0,02
	TF0288	-0,15	-3,05	-3,20	-0,01	-0,10	-0,06
	Moyenne / *Average*	-0,84 ±7,40	-3,91 ±5,96	-4,75 ±7,47	-0,03 ±0,27	-0,13 ±0,20	-0,08 ±0,13

The average annual rates at outcrop 2 are close to the average annual rates calculated for all rocky cliffs exposed to the Strait's waves, while those for outcrop 1 are higher. In fact, the latter are closer to the average annual rates of retreat for unconsolidated cliffs exposed to the Strait (Table 7). This notable difference in the pace of retreat of the two rock outcrops with the same exposure, and located near to each other, could be due to various factors, such as cliff height, the nature of the outcrop (sandstone composition and structure) or the presence of a (rocky) shore platform in front of the cliffs that would dissipate the energy of waves reaching the shore. These examples are a good demonstration of the complexity of rocky cliff response to marine action and the need for field studies to better explain the evolutions noted by our photo-interpretation and photogrammetric analysis work.

Table 7. Average change (m) and annual rate of change (m/year) of the coastline of bluffs and rocky cliffs from the greater Cocagne, l'Aboiteau and Shemogue study sites for three periods, according to two types of scenarios: coasts exposed to waves from the Strait and sheltered coasts.



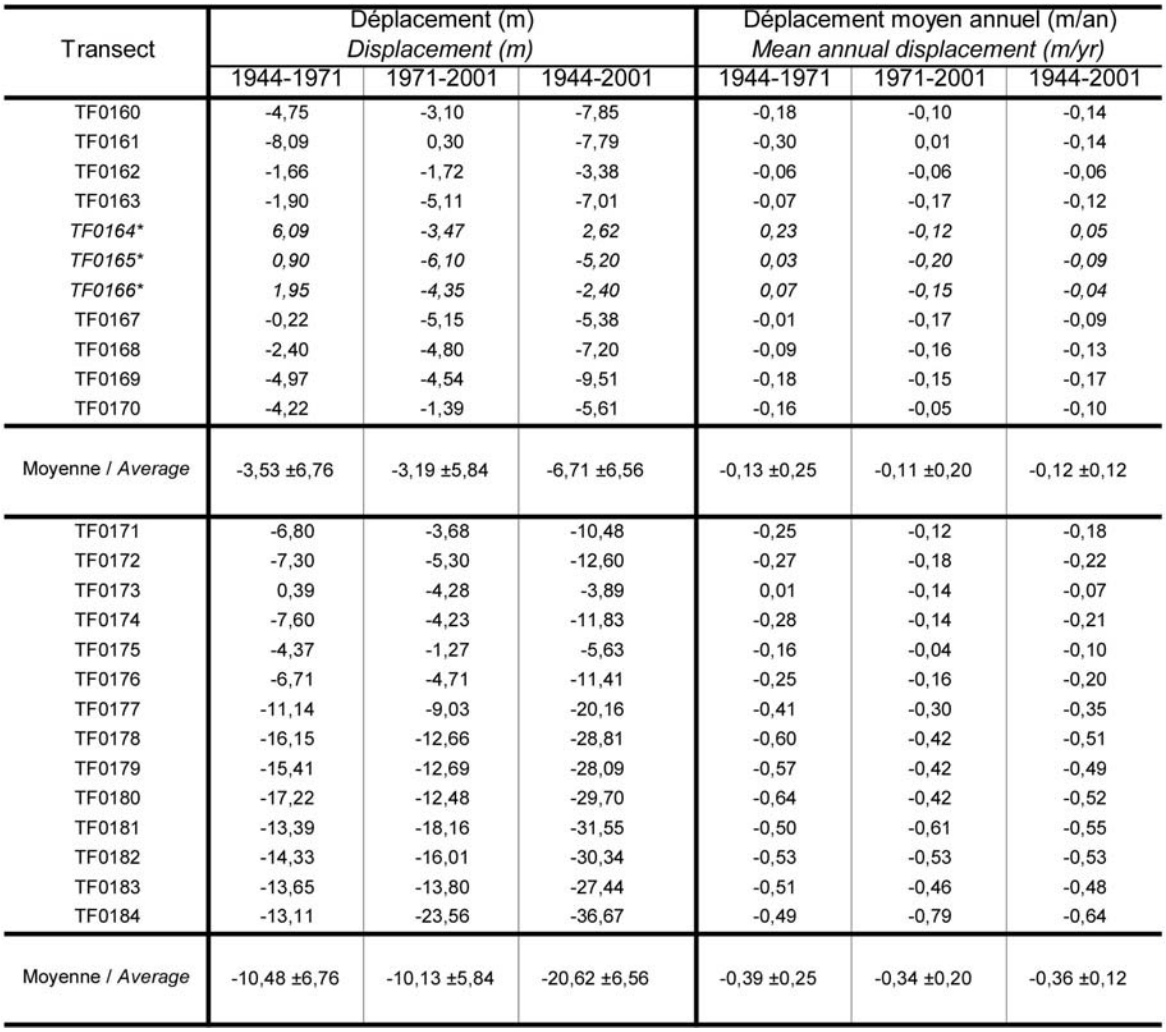
	Déplacement du trait de côte	Exposées / *Exposed*			Abritées / *Sheltered*		
	Coastline displacement	1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
Falaises meubles *Unconsolidated cliffs*	Moyen (m) / *Average (m)*	-7,94 ±7,30	-6,92 ±6,73	-14,85 ±7,42	-6,91 ±7,87	-2,19 ±6,74	-9,10 ±7,72
	Annuel (m/an) / *Annual (m/yr)*	-0,29 ±0,27	-0,24 ±0,23	-0,26 ±0,13	-0,24 ±0,27	-0,08 ±0,24	-0,16 ±0,14
Falaises rocheuses *Rock cliffs*	Moyen (m) / *Average (m)*	-1,66 ±7,48	-3,45 ±6,72	-5,10 ±7,98	-1,77 ±6,45	-0,99 ±6,08	-2,77 6,76
	Annuel (m/an) / *Annual (m/yr)*	-0,06 ±0,27	-0,12 ±0,23	-0,09 ±0,13	-0,06 ±0,22	-0,04 ±0,22	-0,05 ±0,12
Enrochement *Breakwater*	Moyen (m) / *Average (m)*		1,83 ±6,56			3,73 ±6,34	

Bluffs (unconsolidated cliffs)

The Shemogue Cape faces the Northumberland Strait and forms the eastern shore of Shemogue Harbour (Figure 16). All around the cape, the cliffs are about 4 m high; the relief fades gradually towards the south up to the anchor point of the Shemogue Cape sand spit (Figures 26 and 29B), where the cliffs are no higher than 1.5 m.

During the 1944–2001 period, the cape's cliffs (transects TF0160 to TF0170, Table 8) underwent slight erosion; the average retreat was 6.71 ± 6.56 m (an annual retreat of 0.12 ± 0.12 m/year). The rate of coastline change represents only half of the average retreat calculated for all the bluffs exposed to the Strait in the three sectors studied (Table 7). In fact, the extent of the Shemogue Cape cliffs' retreat is closer to the values calculated for the rocky cliffs exposed to the Strait. This situation is surprising at first, since the unconsolidated materials forming the bluffs are much less sturdy (offer much less resistance to wave energy). However, it is explained by the fact that, at the base of the bluffs at Shemogue Cape, fractured sandstone is exposed, forming a (rocky) shore platform. The fieldwork that developed the geomorphological cartography of New Brunswick's southeastern coasts, done in the early 1990s by Bérubé and Thibault (1996), confirms the presence of a shore platform at the base of and in front of Shemogue Cape's cliffs. The unconsolidated deposits in which the cliffs are retreating are thus resting on a stronger structure, which mitigates the waves' energy and therefore their erosion potential.

Table 8. Change (m) and annual rate of change (m/year) of the coastline of the bluffs near Shemogue Cape from 1944 to 2001.



Transect	Déplacement (m) *Displacement (m)*			Déplacement moyen annuel (m/an) *Mean annual displacement (m/yr)*		
	1944-1971	1971-2001	1944-2001	1944-1971	1971-2001	1944-2001
TF0160	-4,75	-3,10	-7,85	-0,18	-0,10	-0,14
TF0161	-8,09	0,30	-7,79	-0,30	0,01	-0,14
TF0162	-1,66	-1,72	-3,38	-0,06	-0,06	-0,06
TF0163	-1,90	-5,11	-7,01	-0,07	-0,17	-0,12
*TF0164**	*6,09*	*-3,47*	*2,62*	*0,23*	*-0,12*	*0,05*
*TF0165**	*0,90*	*-6,10*	*-5,20*	*0,03*	*-0,20*	*-0,09*
*TF0166**	*1,95*	*-4,35*	*-2,40*	*0,07*	*-0,15*	*-0,04*
TF0167	-0,22	-5,15	-5,38	-0,01	-0,17	-0,09
TF0168	-2,40	-4,80	-7,20	-0,09	-0,16	-0,13
TF0169	-4,97	-4,54	-9,51	-0,18	-0,15	-0,17
TF0170	-4,22	-1,39	-5,61	-0,16	-0,05	-0,10
Moyenne / *Average*	-3,53 ±6,76	-3,19 ±5,84	-6,71 ±6,56	-0,13 ±0,25	-0,11 ±0,20	-0,12 ±0,12
TF0171	-6,80	-3,68	-10,48	-0,25	-0,12	-0,18
TF0172	-7,30	-5,30	-12,60	-0,27	-0,18	-0,22
TF0173	0,39	-4,28	-3,89	0,01	-0,14	-0,07
TF0174	-7,60	-4,23	-11,83	-0,28	-0,14	-0,21
TF0175	-4,37	-1,27	-5,63	-0,16	-0,04	-0,10
TF0176	-6,71	-4,71	-11,41	-0,25	-0,16	-0,20
TF0177	-11,14	-9,03	-20,16	-0,41	-0,30	-0,35
TF0178	-16,15	-12,66	-28,81	-0,60	-0,42	-0,51
TF0179	-15,41	-12,69	-28,09	-0,57	-0,42	-0,49
TF0180	-17,22	-12,48	-29,70	-0,64	-0,42	-0,52
TF0181	-13,39	-18,16	-31,55	-0,50	-0,61	-0,55
TF0182	-14,33	-16,01	-30,34	-0,53	-0,53	-0,53
TF0183	-13,65	-13,80	-27,44	-0,51	-0,46	-0,48
TF0184	-13,11	-23,56	-36,67	-0,49	-0,79	-0,64
Moyenne / *Average*	-10,48 ±6,76	-10,13 ±5,84	-20,62 ±6,56	-0,39 ±0,25	-0,34 ±0,20	-0,36 ±0,12

* A quarry was operated along the cliffs and in the immediate area for some time between 1945 and 1971. The positive values of the coastline's change for the transects TF0164 to TF0166 were not included in the average (even if they were below the margin of error).

Two hundred metres to the south of Shemogue Cape, the bluffs are eroding at a much faster pace. From 1944 to 2001, the coastline retreated an average of 20.62 ± 6.56 m, for a rate of 0.36 ± 0.12 m/year (transects TF0171 to TF0184, Table 8). Some parts of the coast have retreated further, particularly at transects TF0181 and TF0184, where, over a period of 30 years (1971–2001), the coastline has retreated by 18.16 ± 5.84 m and 23.56 ± 5.84 m, respectively. The cliffs' retreat rate is similar to that seen elsewhere along coastlines exposed to the Northumberland Strait.

Study of the recent evolution of rocky cliffs and bluffs shows that simply classifying cliffs based on composition does not explain rates of change that are sometimes very different; other factors are at play. **Readers are invited to consult the maps, attached, for**

further details on the subject (Section 5, Annexes C4-C6, Rates of dune and cliff retreat; Section 5, Annex D, Distribution of coastal habitats.

4.5.3.2.5 Recent evolution of Parlee Beach

Eleven sets of aerial photographs were used to track the recent evolution of the study site: those from 1938, 1944, 1953, 1963, 1967, 1971, 1973, 1982, 1995, 1996 and 2001.

A description of Parlee Beach and its surroundings is presented below. It is mainly a survey of human interventions and construction as well as a general assessment of the shape of the spit, as observed in the various sets of aerial photographs (1938–2001). The goal of this exercise was to document the evolution of the landscape in the area's coastal zone at exact points in time. It is our hope that this background on the Parlee Beach site will contextualize the results and discussion that follow. Figure 30 should help in locating some of the information described.

Photographs from 1938, 1944 and 1953

- The three sets of photos show two (gravel?) access roads built on the salt marsh leading to sections 3 and 5 of the spit, vehicular traffic tracks on the salt marsh in section 5, as well as on the dune (1944 and 1953) in sections 4 and 5, and by-roads (additional routes) to the access road leading to section 5, located on the salt marsh (1944 and 1953).

- The three sets of photos show a large building on the upper beach in section 5, two large buildings on the upper beach in section 3, two small buildings on the salt marsh behind the dune in section 4 (1938 and 1944), and a lighthouse on the dune at the boundary of sections 4 and 5 (1953).

- The photos from 1938 show the presence of a seawall along the length of the dune in section 3.

- The dune front is absent by two breaches in sections 3 and 5 on all three sets of photos, and the dune front is fragmented into a string of several small dune islands in section 5 (1953).

Photographs from 1963 and 1967

- The two sets of photos show the same two access roads seen in the three preceding series, built on the salt marsh leading to sections 3 and 5 of the spit, along with a third access road (gravel?) built on the salt marsh in section 3 (1967). On the salt marsh, the same by-roads to the access road leading to section 5 are also visible (1963 and 1967), and the same vehicular traffic tracks seen in the three preceding series of photographs are visible on the dune and the salt marsh in sections 4 and 5, as well as other tracks in section 3 (1967).

- The two sets of photos show the same two large buildings seen in the three preceding series on the edge of the upper beach and the dune in section 3, the same lighthouse at the boundary of sections 4 and 5, a large building on the upper beach in section 5 and, in 1963 and 1967, two small subordinate buildings on the upper beach, at the boundary of sections 4 and 5.

- The two sets of photos show a seawall in front of the dune in section 5 and another seawall in front of the dune in section 4 (1967).

- Both sets of photos show that the dune front is heavily scored by access trails to the beach in section 3, discontinuity and fragmentation on the dune front, obliterated by many breaches along the length of sections 4 and 5, and partial localized sand burial of the salt marsh behind the small breaches in sections 4 and 5.

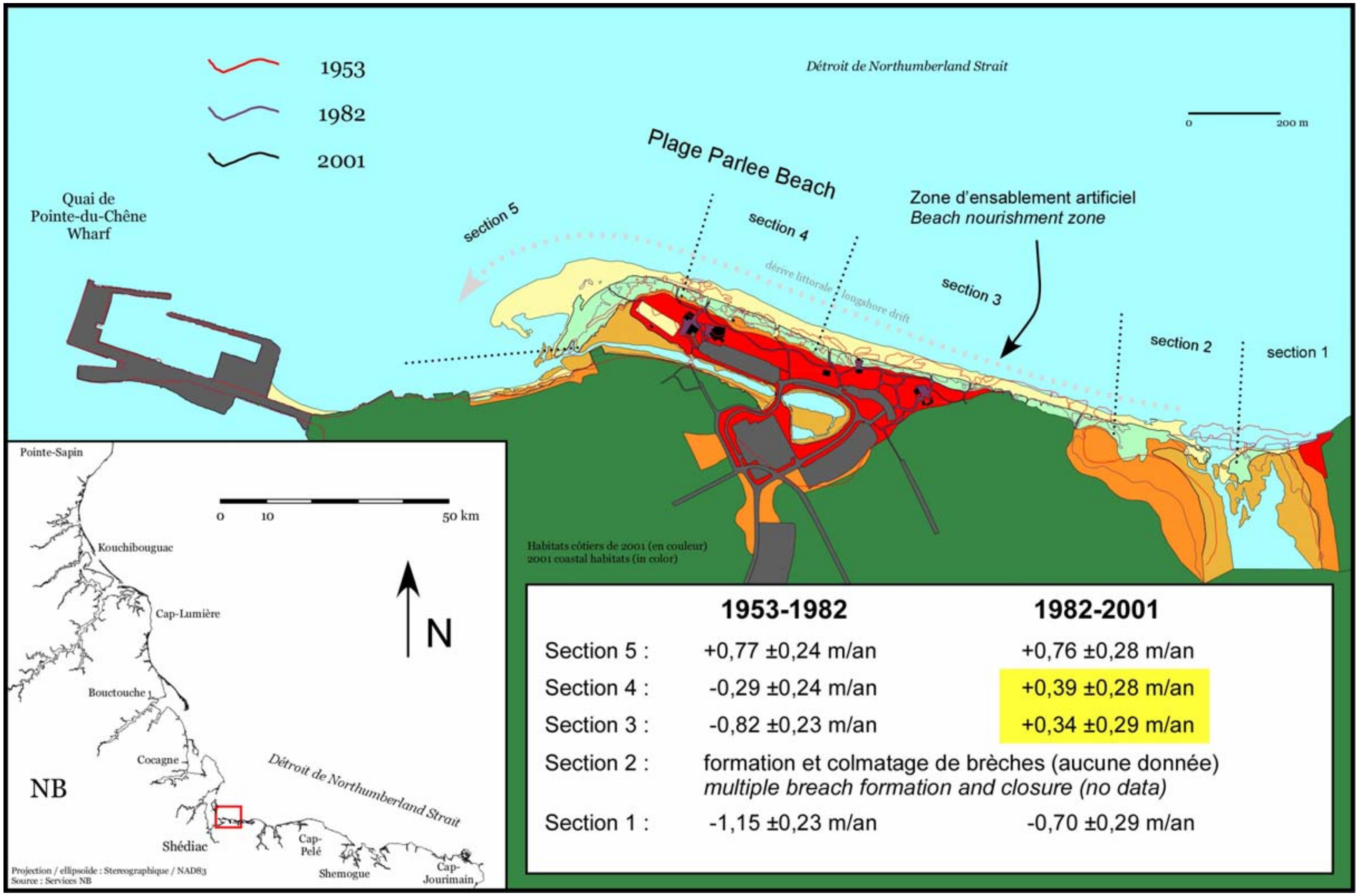
Photographs from 1971 and 1973

- On the coastal marsh, both sets of photos show the same three access roads leading to sections 3 and 5 of the spit that were seen on the two preceding series. Also on the coastal marsh, the same junctions to the access road leading to section 5 observed in the two preceding series are also visible, as well as a parking lot built on the coastal marsh behind the dune in section 3 (1973).

- Both sets of photos show a large building on the upper beach in section 5, two large buildings on the upper beach in section 3, a lighthouse and two small subordinate buildings on the beach, at the boundary of sections 4 and 5.

- The two sets of photos show a seawall on the upper beach in sections 4 and 5, as observed in the 1967 photographs.

- Both sets of photos show heavy scoring in the dune front due to access trails to the beach in the eastern part of section 3, discontinuity and fragmentation of the dune front all along section 4, also obliterated by many breaches, the absence of the dune front in section 5 and near-complete sand burial of the coastal marsh.



	1953-1982	1982-2001
Section 5 :	+0,77 ±0,24 m/an	+0,76 ±0,28 m/an
Section 4 :	-0,29 ±0,24 m/an	+0,39 ±0,28 m/an
Section 3 :	-0,82 ±0,23 m/an	+0,34 ±0,29 m/an
Section 2 :	formation et colmatage de brèches (aucune donnée) *multiple breach formation and closure (no data)*	
Section 1 :	-1,15 ±0,23 m/an	-0,70 ±0,29 m/an

Figure 30. Position of the Parlee Beach coastline in 1953, 1982 and 2001 and coastline rates of change (m/year) during two periods: 1953–1982 and 1982–2001.

Photographs from 1982, 1995, 1996 and 2001

- The 1982 set of photos shows a large building on the beach in section 3, a large building on the beach in section 5 and a lighthouse on the lower beach at the boundary of sections 3 and 4, all of which were present in the two preceding series of aerial photographs.

- All four sets of photos show the presence of asphalt parking lots, concrete pedestrian pathways and various public service facilities built on the coastal marsh fill in sections 3, 4 and 5.

- The 1982 photos show a seawall on the upper beach in section 5, already visible in the two preceding series of photos.

- The dune front along section 3 has disappeared (1982); the dune front in sections 3 and 4 is heavily scored by the access trails to the beach (1995, 1996 and 2001); the dune front is continuous along section 5 in all four sets of photos; and the coastal marsh behind the dune in sections 3, 4 and 5 is infilled.

Although it could not be confirmed during our analysis of the aerial photographs, the practice of sand extraction for aggregates undoubtedly took place in the Parlee Beach area. In the early 1970s, Hunter (1975) showed the extent and importance of the operation of sand pits along New Brunswick's sandy coasts. A number of beaches and dunes, the Parlee Beach sand spit in particular, were subjected to sand extraction until 1974. According to Hunter (1975), the province did not issue any sand extraction permits for the Parlee Beach area, and therefore no data (volume of sand extracted annually) are presented in his report. His maps nonetheless indicate the presence of extraction sites in the area, in particular the anchor point of the spit and the longshore bars facing the distal end of the spit. These extraction sites would have been documented through aerial photographs or through interviews carried out with people in the area.

Of the 11 series of aerial photographs, 7 were georeferenced to produce maps of the evolution of the Parlee Beach study site (1953, 1963, 1967, 1973, 1982, 1996 and 2001). From 1953 to 1982, these maps show that the coastline exposed to the Northumberland Strait retreated, while the distal section of the spit (section 5, Figure 30) migrated slightly towards the west. However, from 1982 to 2001, the exposed coastline advanced seaward, while its distal part continued to migrate towards the west. This change in evolution is the result of sand artificially added to the coastal system as part of the park's beach nourishment program, which began in 1988 (Table 9). This program was implemented in order to close the breaches created in the dune front, stabilize the coastline and raise the dune crest. Owing to this interference in the system's natural dynamics, the study of the coastline-position change in the Parlee Beach area must distinguish between two time periods — one before work began (1953–1982) and one for the period of beach nourishment (1982–2001).

Table 9. Statistics on beach nourishment at the Parlee Beach Provincial Park since 1988.

Année *Year*	Camion *Truck*	Verge cube *Cubic yard*	Mètre cube *Cubic metre*	Tonne métrique *Metric ton*
1988	1264	18960	14496	26093
1989	1134	17010	13005	23409
1990	368	5520	4220	7597
1991	959	14385	10998	19797
1992	1308	19620	15001	27001
1993	1371	20565	15723	28302
1994	669	10035	7672	13810
1995	538	8070	6170	11106
1996	983	14745	11273	20292
1997	0	0	0	0
1998	1240	18600	14221	25597
1999	0	0	0	0
2000	1755	26325	20127	36229
2001	1395	20925	15998	28797
2002	1200	18000	13762	24772
2003	927	13905	10631	19136
2004	3500	52500	40139	72251
2005	812	12180	9312	16762
Total	19423	291345	222751	400951
Moy. / *Ave.*	1079	16186	12375	22275

Conversion table:
1 truck load = 15 cubic yards
1 cubic yard = 0.764 56 cubic metre
1 cubic metre = 1.8 tonnes (metric tons)

Measurements of coastline change show that, between 1953 and 1982, the part of the spit exposed to the Northumberland Strait (sections 1–4, Figure 30) receded at a rate of 0.75 ± 0.23 m/year. This retreat is slightly higher than that observed along the other sand spits in the greater Cocagne, l'Aboiteau and Shemogue areas (0.60 ± 0.27 m/year on average between 1944 and 1971, Table 10). During this retreat, the area of the three primary habitats of the coastal zone did not diminish (Table 11). The area covered by sandy beaches fluctuated around 3.9 ha (3.34 ha in 1967 and 4.19 ha in 1963); the area covered by dunes fluctuated around 3.1 ha (2.97 ha in 1953 and 3.22 ha in 1967); the area of coastal marsh also remained stable until the end of the 1970s (28.6 ha). These surface-area data clearly show that between 1953 and 1982, the whole spit moved landward and that this evolution corresponds to a migration of coastal forms rather than strictly erosion. Under these conditions and during this period (1953–1982), the Parlee Beach spit corresponded to case "C" ("Landward retreat of the entire spit") referred to in Section 4.5.3.2.3.

Table 10. Average annual rate of coastline displacement, retreat and advance (m/year) of dunes and sand spits, exposed to the Strait, of the greater Cocagne, l'Aboiteau and Shemogue study sites for three periods.

Grand Cocagne, l'Aboiteau, Shemogue	1944-1971	1971-2001	1944-2001
Déplacement global / *Global displacement*	-0,60 ±0,27	-0,32 ±0,23	-0,59 ±0,13
Retrait total / *Total retreat*	-0,99 ±0,27	-0,83 ±0,23	-0,78 ±0,13
Avancée totale / *Total advance*	0,47 ±0,27	0,59 ±0,23	0,39 ±0,13

Table 11. Surface-area variation (ha) of some coastal habitats in the Parlee Beach study site between 1953 and 2001.

Tempête début 1970
Storm early 1970s

Ensablement artificiel 1988
Beach nourishment 1988

Habitat	1953	1963	1967	1973	1982	1996	2001	1953-2001	1953-1982
Plage sableuse / *Sand beach*	*3,83*	*4,19*	*3,34*	*5,85*	*4,04*	*6,72*	*6,74*	43% ↑	stable
Dune / *Dune*	*2,97*	*3,13*	*3,22*	*0,69*	*3,07*	*4,54*	*4,42*	33% ↑	stable
Marais côtier / *Coastal marsh*	*29,65*	*28,08*	*28,13*	*28,37*	*13,83*	*14,28*	*13,96*	53% ↓	

Remblaiement de marais fin 1970
Wetland infilling late 1970s

It should be noted that the areas covered by the beach and the dune in 1973 were not taken into account in calculating the average value presented above. Two major storms battered the coasts just before the photographs in this series were taken — Hurricane Beth (August 1971) and the extratropical storm Carrie (September 1972). The small area covered by the dune (0.69 ha) and the large area covered by the beach (5.85 ha) following these events are extreme cases and are not representative of the general trend, although they are valuable and interesting in and of themselves. They show the impact a series of storms can have on the coast when they come one after another, with no chance for the coastal system to recover. On the other hand, 10 years after these major weather events took place, the beach and the dune had recovered, covering areas close to their historic averages — that is, approximately 4 and 3 ha, respectively.

Our multiyear mapping has also shown that from 1982 to 2001, sections 3 and 4 of the spit registered coastline advance (0.34 ± 0.29 m/year and 0.39 ± 0.28 m/year, respectively; Figure 30). This seaward migration was the result of the beach nourishment program. Under such conditions, this evolution would correspond to Type "2" (*Advance*), according to McBride et al. (1995), which translates into the coastline advancing into the sea as a result of a surplus of sediment in the coastal system. Since 1982, the surface area occupied by the beach and the dune increased significantly, whereas it had remained largely stable since 1953 (Table 11).

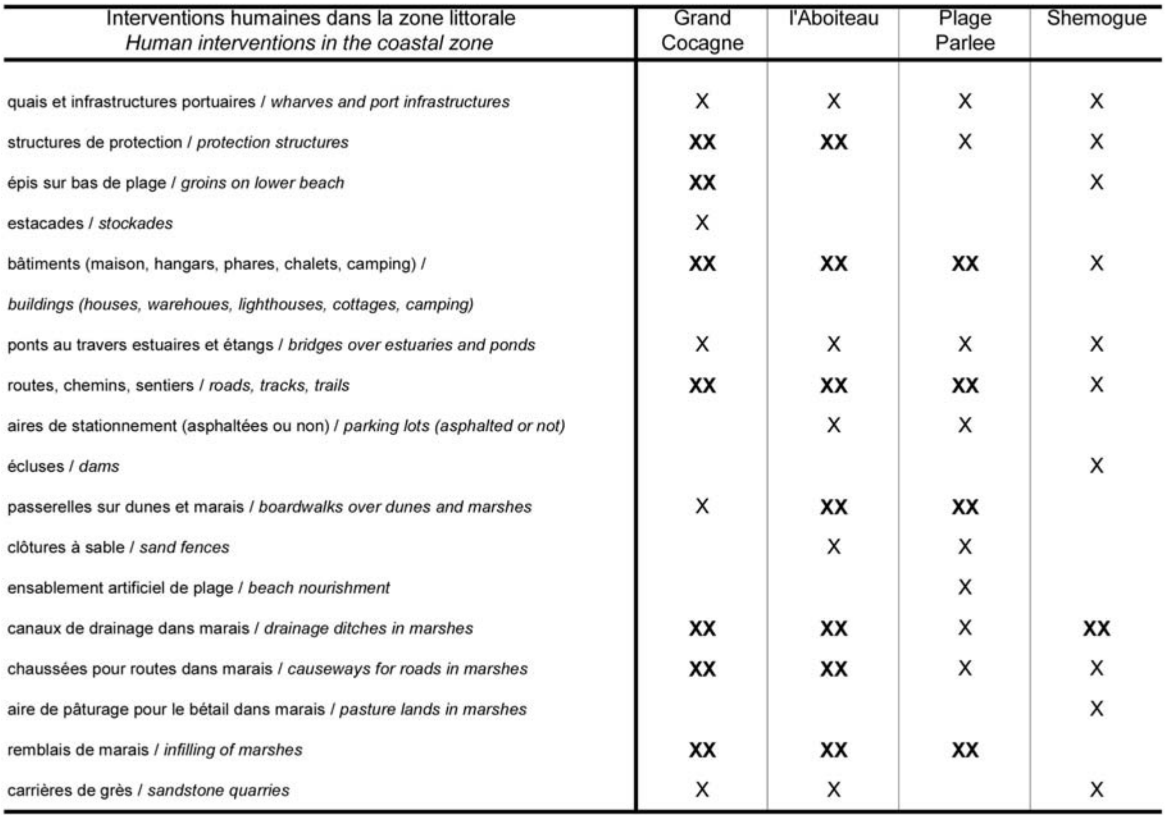
The contribution that the beach nourishment program represents for the coastal sediment system is enormous. Its evolution and its width are maintained artificially thanks to the addition of significant volumes of sand to the coastal system. This external contribution seems to be fundamental to maintaining the precarious artificial evolution supporting the beach's capacity for use. Without the nourishment program at Parlee Beach, the coastline would probably tend to readjust and return to its "natural" position — i.e., its position if no outside or anthropogenic perturbation had modified its original conditions. In the long run, this would correspond to a retreat of approximately 20 m from the coastline's position in 2001, or approximately 11.6 m back from the 1982 coastline. Today, Parlee Beach is no longer in harmony with the "natural" conditions of the environment.

4.5.3.2.6 Human intervention at the coast

The four sectors studied are affected by pressure exerted by human occupation of the coastal zone. The nature of interventions is diverse, and the extent of this pressure varies from one sector to another. In each of the study sites, coastal developments were surveyed using the oldest set of aerial photographs (1938 and 1944) up to the most recent (1996 and 2001). The list of human interventions inventoried and an assessment of their relative abundance are presented in Table 12. The following section deals exclusively with one type of construction seen in all the study sites — that is, protection structures.

The protection structures (rock embankments, rubble mounds, walls made of concrete, steel or wood) documented are mainly installed in front of bluffs, which retreat faster than rocky cliffs (Table 7). Although protection structures were identified in all the years of aerial-photography coverage, only the Shemogue coastal-zone sector did not have this type of construction in 1944. However, the series from 1971–1973 and 2001 all show the presence of walls or other types of protection at the coast. The study sites of greater Cocagne and l'Aboiteau are experiencing the most significant increases in this construction (Table 13). Figure 31 shows the expansion and scope reached by seawalls in the greater Cocagne sector from 1944 to 2001. In this sector, barring the shores of Cocagne Island, very few of the bluffs today are "natural." In some places, as in the area of Anse-de-Cocagne (eastern shore of Cocagne Harbour) and the Grande-Digue wharf, the density is so high that seawalls represent 75% and 83% of the coast, respectively (Figure 32A and B). This situation involving rock embankments and protection of the coast from erosion and retreat is also observed in the l'Aboiteau sector.

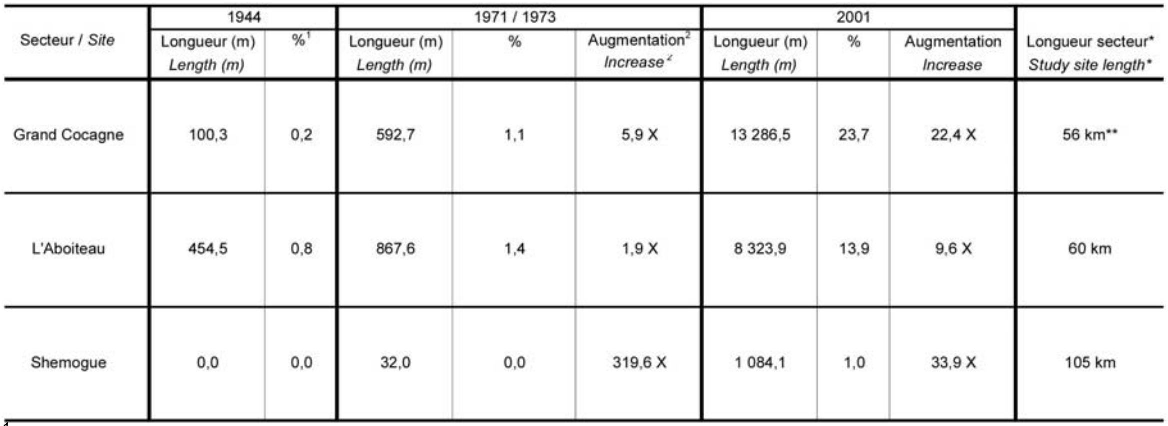
Table 12. Human interventions inventoried in the coastal zone of the four study sites based on the observation of all available aerial-photograph series.



Interventions humaines dans la zone littorale *Human interventions in the coastal zone*	Grand Cocagne	l'Aboiteau	Plage Parlee	Shemogue
quais et infrastructures portuaires / *wharves and port infrastructures*	X	X	X	X
structures de protection / *protection structures*	**XX**	**XX**	X	X
épis sur bas de plage / *groins on lower beach*	**XX**			X
estacades / *stockades*	X			
bâtiments (maison, hangars, phares, chalets, camping) / *buildings (houses, warehoues, lighthouses, cottages, camping)*	**XX**	**XX**	**XX**	X
ponts au travers estuaires et étangs / *bridges over estuaries and ponds*	X	X	X	X
routes, chemins, sentiers / *roads, tracks, trails*	**XX**	**XX**	**XX**	X
aires de stationnement (asphaltées ou non) / *parking lots (asphalted or not)*		X	X	
écluses / *dams*				X
passerelles sur dunes et marais / *boardwalks over dunes and marshes*	X	**XX**	**XX**	
clôtures à sable / *sand fences*		X	X	
ensablement artificiel de plage / *beach nourishment*			X	
canaux de drainage dans marais / *drainage ditches in marshes*	**XX**	**XX**	X	**XX**
chaussées pour routes dans marais / *causeways for roads in marshes*	**XX**	**XX**	X	X
aire de pâturage pour le bétail dans marais / *pasture lands in marshes*				X
remblais de marais / *infilling of marshes*	**XX**	**XX**	**XX**	
carrières de grès / *sandstone quarries*	X	X		X

X: occurrence of the intervention.
XX: significant occurrence of the intervention.

Table 13. Length (m) of protection walls along the coasts of the greater Cocagne, l'Aboiteau and Shemogue study sites for the three main years mapped.



Secteur / *Site*	1944		1971 / 1973			2001			
	Longueur (m) *Length (m)*	%[1]	Longueur (m) *Length (m)*	%	Augmentation[2] *Increase*[2]	Longueur (m) *Length (m)*	%	Augmentation *Increase*	Longueur secteur* *Study site length**
Grand Cocagne	100,3	0,2	592,7	1,1	5,9 X	13 286,5	23,7	22,4 X	56 km**
L'Aboiteau	454,5	0,8	867,6	1,4	1,9 X	8 323,9	13,9	9,6 X	60 km
Shemogue	0,0	0,0	32,0	0,0	319,6 X	1 084,1	1,0	33,9 X	105 km

[1] Percentage of total length of study site.
[2] Armoured coast compared with previous year.
* Estimated length based on 2001 digital maps.
** Cocagne Island perimeter (approximately 10 km) not included.

Impeding or preventing the coastal zone from retreating landward is known as "coastal squeeze"; it can be either natural or anthropogenic. A situation in which there is a natural obstacle to the migration of coastal landforms occurs when the mainland, at the contact of the coastal landform, is too high. For example, in such a context, the migration of a salt marsh landward is impeded; the surface occupied by the marsh progressively diminishes: the marsh can be submerged and eventually be doomed to disappear. A coastal-squeeze situation can also be provoked by poorly planned coastal development that does not allow room for movement by coastal landforms. Installation of seawalls falls into this category and is often responsible for coastal squeeze. For example, in the Pointe-aux-Bouleaux area between 1971 and 2001, a coastal dune completely disappeared after the installation of a series of seawalls in front of a housing development along the coast (Figure 27b).

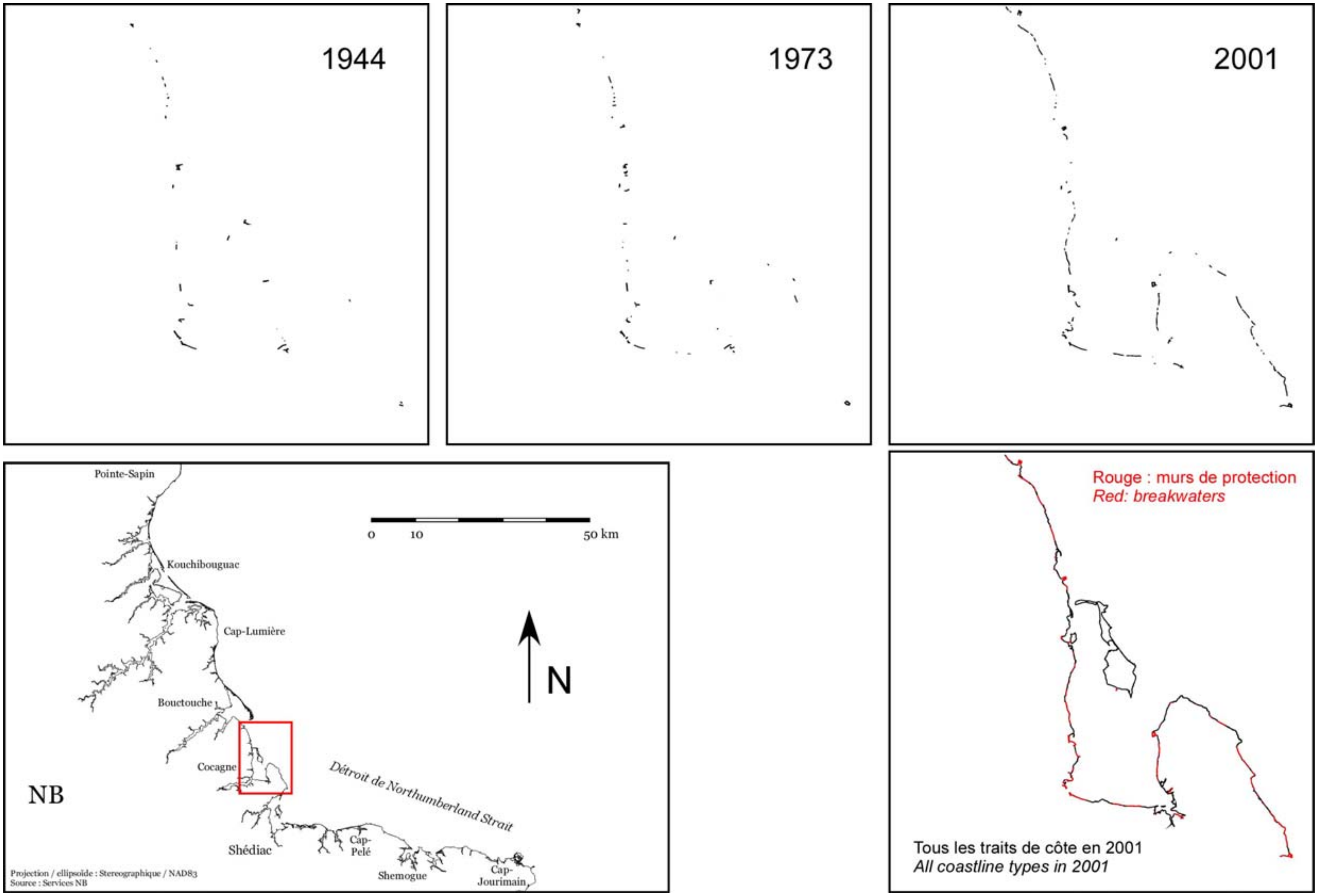


Figure 31. Distribution of protection structures along the coasts of the greater Cocagne study site in 1944, 1973 and 2001.

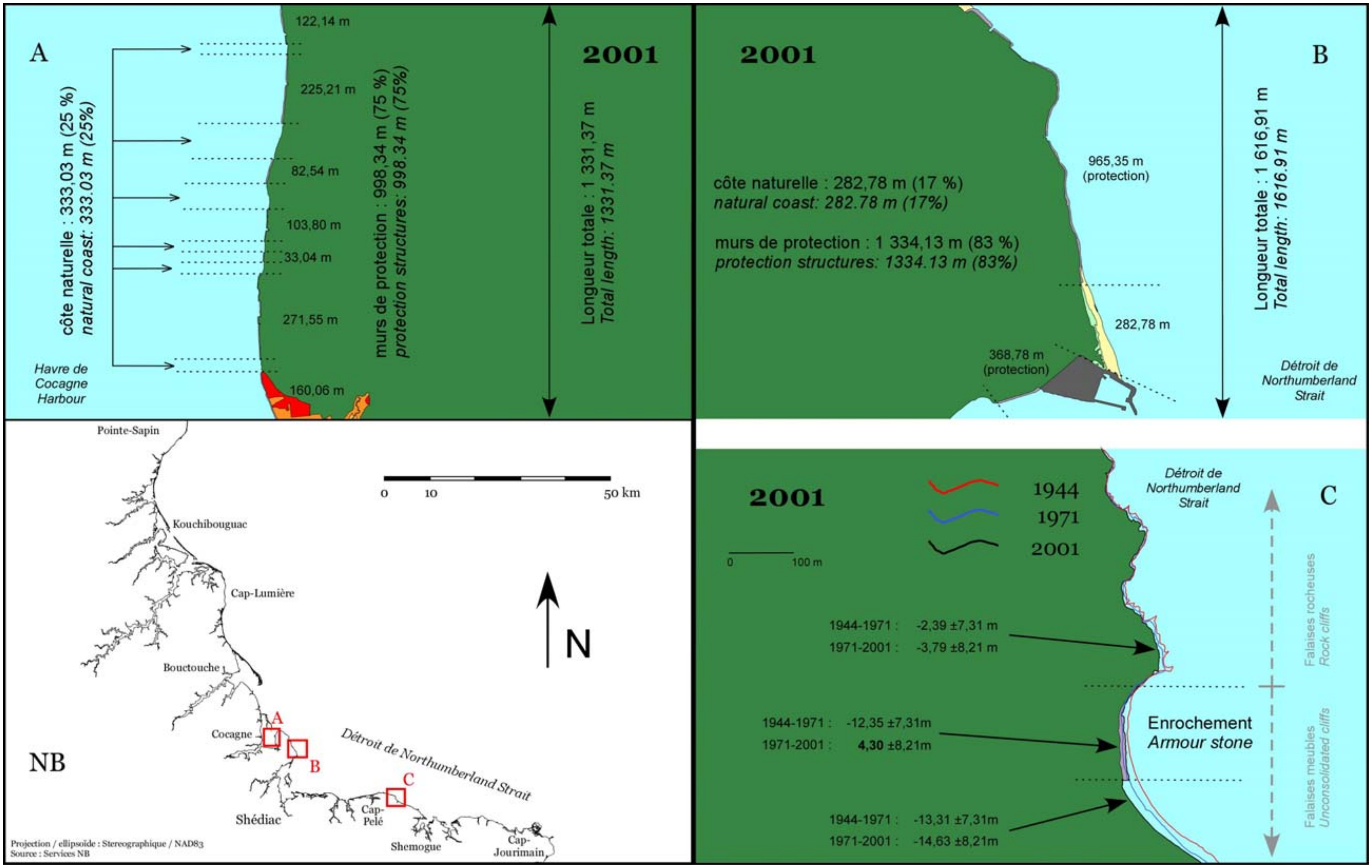


Figure 32. Density of protection structures along the coast of Anse-de-Cocagne (A), Cap-des-Caissie (B) and Fagan Point (C).

Another effect of protection structures is the erosion of the beach fronting the installation (Paskoff, 1998; French, 2001; Cormier, 2006). Although protection structures absorb most of the energy of storm waves that hit the rocks or seawall, some of the energy is reflected out to sea and generates a return wave, which accelerates the erosion of the beach face in front of the structure. During successive storms, rock blocks, even entire walls, can be knocked over and collapse. Generally speaking, the deeper the water in front of the protection structure, the more intense the wave energy reaching the structure, and the greater the potential for erosion (see Table 14).

Table 14. Relationship between water depth, wave energy and coastal impacts

In addition to stabilizing the position of the coast, the extension of seawalls often occurs beyond the previous position of the coastline. Table 7 shows that along the Northumberland Strait, seawall construction has been done so that the position of the coastline in 2001 is, on average, 1.83 ± 6.78 m farther seaward than in 1971, whereas along coastline sheltered from the Strait's waves, the coastline associated with seawalls is 3.70 ± 6.78 m farther seaward. An example of this coastline "advance" is presented in Figure 32C.

Given a scenario of accelerated relative sea-level rise over the next century, it is expected that the water depth along the coast and in front of the seawalls will increase, which could eventually translate into accelerated erosion close to structures and increased potential for damage to the structures themselves.

In short, we could therefore expect that, in all likelihood, the sandy beach located in front of the seawalls at Pointe-aux-Bouleaux (Figure 27b) will erode and disappear in the near future; similar changes have been observed elsewhere in the study sites. Constructing seawalls too far seaward could accelerate the erosion process that the property owners are attempting to impede: the water is deeper, the waves hitting the structure are stronger and the potential for erosion is therefore higher.

4.5.4 Summary and conclusions

Southeastern New Brunswick is an area of low relief developed on flat-lying, friable, sandstone bedrock. As described in Section 4.1, the area was flooded by the sea immediately after deglaciation, after which the land rose and relative sea level fell to expose large parts of the floor of Northumberland Strait. For the past 8500 years, the sea level has been rising against the land, gradually pushing back the shoreline in a process of long-term flooding and coastal erosion. There is, thus, nothing new in the trend of coastal retreat observed over recent decades, but the impact on human habitation and infrastructure is increasing as the rate of waterfront development accelerates.

The rate of coastal erosion is primarily a function of mean water level (driven by relative sea-level rise), storm and wave forcing, sediment supply, and the form and response of the shore zone (coastal morphodynamics). Where there is no excess sand supply, other factors being equal, the rate of coastal retreat is likely to be correlated with the rate of relative sea-level rise.

Although large quantities of sand are present along the New Brunswick coast, much of it is stored in coastal dunes (largest in the north) or in large tidal bedforms (largest in the southeast). The volumes of sand in the immediate shore zone are limited. Some sites, such as the mouth of Shemogue and Little Shemogue harbours, have extensive multiple bar and tidal bedform complexes of sand on the inner shoreface, but these are thin, and the beaches themselves are invariably thin. For this reason, despite the limited wave energy, rapid changes in the shoreline can occur when beaches and low barriers, particularly in the southeast, are overtopped and breached in storms. Evidence from old maps shows that former barrier beaches or spits, such as in the Robichaud and Cocagne areas, have disappeared, leaving only hints of their former presence in shoals on the shoreface. A low sand ridge mapped in 8- to 10-m water depth off Pointe-Sapin is believed to be a similar relict barrier beach abandoned on the inner shelf.

The present study has shown that rapid changes have occurred in the form and extent of some spits in the Shemogue area during the past 60 years of the airphoto record (since 1944), while others in the same area (Grants Beach) have remained stable. The large spit and barrier-island system in Kouchibouguac National Park has high dunes that prevent overtopping and act as a buffer against storm-wave attack. However, there are a number of low areas where inlets have opened or closed at various times over the past century, causing abrupt changes that affect coastal stability and habitat conditions, both on the barrier itself and in the adjacent lagoons, marshes and other coastal habitats. Despite the high dunes in this area, large sections of the Kouchibouguac barrier system are low enough to be overtopped in a major storm with high surge and waves. However, the sand volumes are high enough to limit the rate of coastal retreat. The large flying spit at Bouctouche (La Dune de Bouctouche) has moderately high dunes and multiple dune ridges, particularly in its distal part. Other parts of this system have narrow dunes or none at all. In these areas, particularly the proximal (updrift) part, overtopping, breaching and landward barrier migration have occurred in response to major storms or storm intervals since the earliest airphotos in the 1940s, and long before that.

Some sections of the coast consist of low sandstone or till cliffs, up to a few metres in height, typically showing long-term (multidecadal) erosion rates between 0.1 and 0.4 m/year. Although these rates are slow, some roads and buildings have been partially destroyed and abandoned (e.g., in the area of Cap Lumière). Erosion impacts on infrastructure and buildings, including homes, are locally important. Homes and other buildings have been damaged or destroyed by storm waves and storm-driven sea ice in several locations within the past decade. Large sections of the coast are now protected by seawalls, rubble mounds or other structures, and this hardening of the coast has accelerated over the past 20 years. However, the long-term efficacy of these adaptation measures is questionable, and many will require substantial investment in maintenance, reconstruction or replacement to maintain their protective function.

Rates of coastline change on beaches, spits and barriers range from negative to positive. Erosion rates greater than 0.5 m/year are common on many beaches, and some sites show even higher rates. The point of attachment of the Pointe-aux-Bouleaux spit retreated at an average rate of 2.4 m/year between 1944 and 2001. In other cases, local sand supply is sufficient to maintain the shoreline position or prograde seaward. Some spits have extended in length, showing typical patterns of deposition and growth in the distal (downdrift) area, while erosion, overtopping and rollover, or bypassing have occurred in the narrow proximal section (near the point of attachment to the coast). In very general terms, this is the pattern observed at La Dune de Bouctouche. Other systems, such as Grants Beach (east side of Little Shemogue Harbour), have maintained a dynamic equilibrium between intervals of dune cut and intervening deposition. Such systems may be continuing to accumulate sand from updrift sources in the bay mouth or on the inner shelf. In other cases, where sand volumes are low, spit truncation or breaching has occurred. At Cap Bimet, the end of the spit has completely disappeared. The spit on the east side of Shemogue Harbour (Shemogue Head spit) was breached prior to 1971 and eventually split in two by 2001, exposing the large salt marsh behind to wave erosion and washover. The vulnerability of this spit to overtopping and breaching was enhanced by its northwesterly exposure, low crest elevation, narrow width and limited sand volume. Major changes in the morphology and extent of the spit opposite (on the west side of the estuary) may also have been a factor. These observations underscore the importance of changes in coastal morphology (which may change wave shoaling and energy at particular sites), of waves and storm surges associated with individual large storms or groups of storms, and of preconditioning by erosion of dunes or other changes in the shore zone. Combinations of these factors may trigger rapid change. If sand is available and supplied to the site, breaches can be repaired (infilling of the former dredged channel through La Dune de Bouctouche is an example), but morphological changes sometimes lead to positive feedback, increasing susceptibility to storm damage. The Petit-Cap spit in Shemogue Harbour has built an entirely new and realigned spit ridge seaward of the 1944 spit, fed by erosion of the updrift beaches at rates between 0.2 and 0.8 m/year.

These results demonstrate the highly variable nature of coastal response to storm forcing as well as gradual changes associated with sea-level rise and climate change. It is unrealistic to attempt a common projection of future response over the entire study area. On the other hand, there are several common points of understanding that can be applied to analysis of individual sites.

Most sites currently experiencing erosion can be expected to show continuing erosion in the future, and rates are likely to increase. Therefore, planning and development should not be based simply on historical rates of erosion, but should add an appropriate additional setback to account for more rapid erosion over the life of a structure or other development.

The rate of regional subsidence declines from the southeast to the northwest. As a result, the most rapid rates of relative sea-level change will be in the southeast. This is also the area where the barriers and dune volumes are smallest, making them more sensitive to rapid change. Systems in this area with higher dunes (such as Grants Beach) will be more stable, but accelerating sea-level rise, reduced sea ice or other climate-related changes may increase the sensitivity even at these sites. Some increase in the rate of cliff erosion can be expected, but the rates are likely to remain less than 0.5 m/year in most places.

Farther north, from Bouctouche to Kouchibouguac, much larger dune volumes and higher crest elevations will partly offset the higher wave energy in this region. Nevertheless, some areas are extremely sensitive to erosion or overtopping, including the proximal part of La Dune de Bouctouche, where a sequence of storms beginning in 2000 removed the dune ridge and led to successive washover events, which deposited sand sheets across the barrier crest and the marsh behind. A large breach also developed halfway out the spit. Similar extensive breaching has occurred in the past, notably in the early 1940s, and storm grouping (successive large storms within a few years) is an important factor. However, accelerating rates of relative sea-level rise and possible increases in storm intensity may lead to more frequent and severe impacts in the future. There is no immediate likelihood of spit detachment at Bouctouche, but the highest average rates of shoreline erosion along the spit since 1944 (almost 2 m/year in one section) are between 6.0 and 8.5 km down-spit, just before the downdrift transition to long-term progradation. We conclude that the possibility of detachment within 30–50 years cannot be ruled out.

Losses of coastal salt marsh have occurred in the region from excessive infilling for development. Coastal squeeze is already a concern at a number of sites in the study area, where roads and fill present hard boundaries to marsh expansion. These observations suggest that some salt marshes in the area may experience loss of area through erosion of the seaward margin, degradation of the marsh surface and gradual expansion of low marsh at the expense of high marsh. Impacts for many coastal habitats are discussed in greater detail in the following section.

Management of coastal erosion in a changing climate will be most successful if it considers all aspects of the coastal system in the area of concern. This involves analysis of the relevant coastal cell and its sediment budget, as well as environmental forcing (sea level, storms, surges, waves, wind, ice) and interactions among various components of the coast, including the whole system above and below water. Such an integrated approach is needed to ensure a full understanding of the system, so that adaptation measures adopted in one location are not counterproductive in another. The section on adaptation later in this report (Section 4.8) suggests further considerations in the development of appropriate and effective adaptation strategies.

4.5.5 Glossary

Beach
Accumulation of unconsolidated marine deposits. The size of the materials varies from fine sand (0.2–2 mm) to gravel (0.2–2 cm) to pebbles (2–20 cm). The critical point for the formation of beaches is when the quantity of material available surpasses the volume of sediment that the waves and the longshore drift can extract; under such conditions, accumulation wins out over erosion.

Brackish transition marsh
Surface that is slightly raised in relation to the salt marsh (with which it connects), the brackish transition marsh is located between the salt marsh and the mainland. It is only occasionally submerged by seawater from high astronomical tides or during storm surges.

Breach
Hole in the dune front resulting from marine action, most often erosion caused by storm waves. The base of the breach is at the same level as the rest of the beach; wrack-line and marine debris can be seen scattered randomly in the breach, attesting to the action of the waves.

Cliff
Abrupt to strong slope (from steep to vertical) marking the contact between the earth and the sea, caused by marine action. Cliffs are often preceded at their base by a rocky or sandy foreshore, with a relatively soft slope (shore platform).

Coastal dune
Any accumulation of sand deposited and modelled by the wind's action. Coastal dunes are formed when there is a source of sediment, wind from the sea that is strong enough to move the sand, an area sheltered from the major tides where sand can be deposited, and vegetation that can trap and hold the sand in transit (beach grass).

Coastal zone
Contact zone between the continental environment and the ocean environment. The coastal zone is divided into three parts: the coast, the shore and the nearshore. The coast forms the higher part of the coastal zone. It extends between the continental limit of the effect of sea spray and the higher high-water line, but excludes sectors affected by high storm levels (waves, flooding). The coast is therefore only indirectly affected by the ocean. The shore refers to the medial part of the coastal zone. It lies between the higher high-water line and the lower low-water line. The shore therefore forms the fluctuation zone for tides (over the year). Broadly speaking, it is the foreshore. The nearshore forms the lower part of the coastal zone. It extends from the lower low-water line to the depth that corresponds to the limit of the waves' effect on the seafloor. The nearshore is therefore only indirectly affected by the continental influence.

Control point
Artifact used for the correction or digital georeferencing of aerial photographs. Control points represent elements in the landscape that are identifiable from one photograph (year) to another and that have not changed in position. They can include house corners or sheds, road intersections or even boundaries of cultivated fields. In areas with little or no human presence, as in the middle of salt marshes or in the distal section of sand spits, control points are less identifiable. In these cases, natural elements are used, such as isolated trees, bayberry groves, dune ponds or other small bodies of water that have not changed visibly.

Erosion
All geomorphological processes responsible for loosening and removing materials on the earth's surface. In the coastal zone, marine erosion corresponds to the attack on the coasts by the sea's action (hydrodynamic processes, waves and sea currents). The effects of marine erosion are numerous, but the main result (when there is wear and loss of materials) is the movement of the shoreline and coastline landward: retreating cliffs, shrinking salt marshes and coastal dunes.

Longshore bars
Marine-generated sand crests located basically on the nearshore (always submerged), but may sometimes reach the lower beach and be partially above water at low tide. Their position and their shape vary seasonally and from one year to the next. In the Northumberland Strait sector, the parallel and distinct crests of the longshore bars diminish. They are instead replaced by vast areas of sandy shoals, which assume a slightly wavy appearance.

Longshore drift
Lateral transport of sandy materials by waves along the coast. The longshore drift is a current of water and sediment running parallel to the shore. The continual zigzagging of sandy materials caused by the ebb and flow of waves creates a sea current, which helps mobilize, transport and nourish beaches along its path. The direction of the drift can be reversed seasonally depending on the direction of the prevailing winds, which generate the waves.

Multiyear georeferenced mapping
Digital maps in which all the elements that appear are positioned in space (known latitudes and longitudes). They are developed using a geographic information system (GIS), based on documents such as topographical maps, bathymetric charts or images such as aerial photographs or satellite images. This exercise of assigning geospatial coordinates to documents, maps or images is called geocoding (or georeferencing).

Overwash deposit
Marine deposit of sand, gravel and organic matter left beyond the dune cliff by storm waves. For overwash deposits to be created, several factors must usually coincide: a high tide level, a substantial storm surge (a significant atmospheric depression), strong waves and strong winds. On the New Brunswick coast of the Gulf of St. Lawrence, the process by which sand spits, barrier islands and coastal dunes migrate landward primarily occurs through successive overwash deposits.

Protection structure
Rock embankments, rubble mounds, walls made out of concrete, wood or steel installed parallel to the coastline. Rock embankments look like a long mound of large rock or concrete blocks, placed at the base of a cliff or an infrastructure to protect the coast against waves. The inclined and uneven surface of the rock embankment dissipates the wave energy and slows down the inevitable thinning of the beach located in front. In contrast, a wall’s vertical, smooth surface tends to reflect wave energy and promote underwashing at the base, which is why the beach thins rapidly.

Relative sea-level rise
Result of the increase in the volume of water in the oceans and the lowering of the earth’s crust on the edge of continents affected by Quarternary glaciation. On the New Brunswick coast of the Gulf of St. Lawrence, fossil dating indicates that the sea level has risen at a speed of 17 cm/century over the last 6000 years. Data from various tide gauges installed since the beginning of the 20th century indicate that the sea level is currently rising at a relative pace of approximately 33 cm/century. These data allow us to conclude that the relative contribution of the increase in sea level due to the increased volume of the oceans would be 17 cm/century, while the relative contribution of the increase in sea level

due to the sinking of the earth's crust (downward movement) would represent 16 cm/century (for a total of 33 cm/century). Under the influence of this relative sea-level rise, the coastline and the shoreline have migrated landward at a pace of 25–100 cm/year, depending on the sectors.

Salt marsh
Low, relatively flat surface made up of deposits such as mud, fine sand and organic matter, generally covered by vegetation. Salt marshes develop on softly sloping shorelines that are sheltered from wave energy — i.e., zones that are favourable to the accumulation of fine sediment, often behind coastal dunes. Salt marshes are submerged by seawater during monthly high tides or during storms.

Sand spit
Type of sandy beach that forms a hook, that is anchored to the mainland at one extremity and that extends freely into the sea at the other end. The attached part of the sand spit is called the proximal section, while the unattached part is called the tip or distal section; the area between the two is known as the medial section. Spits are often covered with dunes.

Sediment budget
Expression of the availability of sediment in the nearshore, beach and the coastal dunes. When the beach's sediment budget is positive — that is, when there is excess sand transiting the beach — the coastline migrates seaward (advance or progradation). When the beach's sediment budget is negative — that is, when there is a deficit of sand transiting the beach — there is erosion (coastline retreating landward).

Tidal inlet
Narrow body of water maintained by tidal currents; pass or channel through which seawater enters and leaves a lagoon or other similar body of water. A tidal inlet can also be a breach in a coastal dune whose base is always occupied by seawater (submerged bottom).

Till
Deposit of glacial origin, generally heterogeneous, unconsolidated, sometimes stratified. It is composed, in variable proportions, of clay, silt, sand, pebbles, cobbles and blocks.

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4.6 Ecosystem impacts

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4.6.1 Introduction to impacts of sea-level rise, storm surge and climate change on the coastal ecosystem[11]

There are many species, habitats and animal communities that comprise the coastal ecosystem. Our analysis of the ecosystem impacts of sea-level rise focused on those terrestrial species and habitats that would be impacted by a change in sea level and also by storm-surge events. The short duration of the study necessitated the use of existing data.

This section provides an overview of the work that was conducted for the sea-level rise study. Full technical details of the various research projects can be found in Canadian Wildlife Service Technical Report Series No. 463 (Hanson, 2006).

4.6.1.1 Reference

Hanson, A.R. (Editor). 2006. Ecosystem impacts of sea-level rise and climate change on the coastal zone of south-eastern New Brunswick. Technical Report Series No. 463, Canadian Wildlife Service, Atlantic Region, Environment Canada, Sackville, New Brunswick, 223 pp.

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[11] Authors: Alan Hanson, Lee Swanson and Eric Tremblay.

4.6.2 Overview of coastal habitat in southeastern New Brunswick[12,13]

4.6.2.1 Introduction

Data from the Maritime Wetland Inventory were summarized for the study area in order to better understand the relative importance of sea-level rise and climate-change-induced impacts on habitat. The amount of this coastal habitat that would be flooded under different water-level scenarios is also presented.

4.6.2.2 Methods

Data on coastal habitat features for coastal units between Point Escuminac and Cape Tormentine were obtained from the digital database of the Maritime Wetland Inventory (Figure 1; Hanson and Calkins, 1996). These data provide excellent habitat information, but the spatial extent of coastal habitat features is not available digitally, and therefore these data could not be used in the flood-prediction modelling.

Service New Brunswick (2004) geographic information system (GIS) layers of natural and cultural features were downloaded from their web site. The hydrographic layers from 60 mapsheets (1:10 000) were acquired and merged in ArcGIS software (Figure 2). The area of study was restricted to those areas for which light detection and ranging (LiDAR) digital elevation data were collected (Figure 2; see Section 4.4 for more details on creation of digital elevation models).

Four different flood scenarios were analyzed: 0.60 m above digital elevation model (DEM) datum (approximate present mean water level), which assessed impacts from anticipated sea-level rise in the region by the year 2100; 2.55 m above DEM datum, representing the storm-surge water level reached during the storm of January 21, 2000; 3.05 m above DEM datum, representing the January 21, 2000, water level + 50-cm sea-level-rise scenario; and 3.25 m above DEM datum, representing the January 21, 2000, water level + 70-cm sea-level-rise scenario. The flood scenarios were based on elevations and the presence of a flooding pathway (Section 4.4.2.7). For Kouchibouguac National Park only, the 60-cm flood-extent scenario was not available. For complete GIS methodology, please see Hanson (2006).

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[12] Authors: Alan Hanson, Matthew Mahoney and Lee Swanson.

[13] The authors thank Tim Webster and colleagues for providing the extent of flood mapping.

Figure 1. Boundaries of coastal units in the Maritime Wetland Inventory.

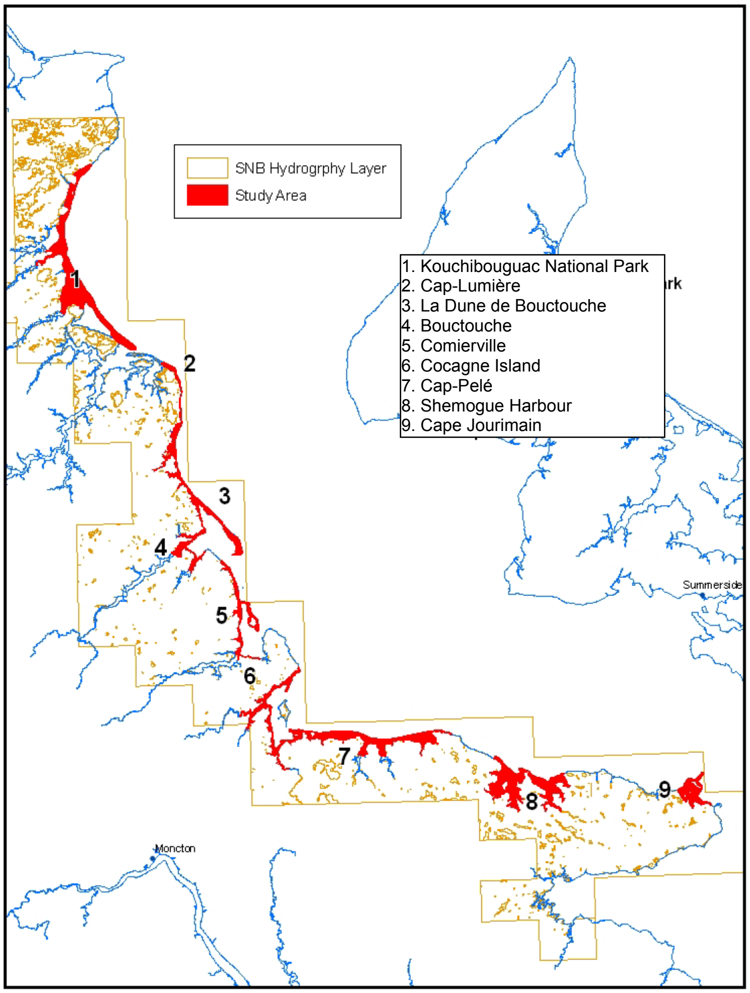

Figure 2. Location of LiDAR acquisition and coastal habitat flooding study area.

4.6.2.3 Results

Based on the Maritime Wetland Inventory (Hanson and Calkins, 1995), the number and area of coastal habitat features are greatest in the northwestern and southeastern parts of the study area (Table 1). Coastal Unit 7 (Figure 1) contains large amounts of salt marshes and saline ponds, as well as mudflat, beach and dune habitat. Unit 7 contains Kouchibouguac National Park and the relatively undisturbed coastline between Pointe-Sapin and Escuminac to the north of the park. Coastal Units 8 and 9, which include the communities of Cocagne, Shediac and Cap-Pelé, have less coastal habitat. La Dune de Bouctouche in Coastal Unit 8 contributes a lot to the unit total of dune habitat. Coastal Unit 10 contains 700 ha of salt marshes, much of it associated with Shemogue and Cape Jourimain National Wildlife Area (Figure 1).

With increasing water levels, the area and depth of flooding of coastal habitat increase (Table 2). The Service New Brunswick Enhanced Topographic Database was not used to report on the total amount of coastal habitat present because there was no standard way to identify if a feature was truly coastal in nature. For example, some salt marshes may be located a considerable distance inland if associated with a tidal river. Therefore, the data presented in Tables 1 and 2 should be seen as complementary to each other, but direct comparisons between the two are not possible.

The area and depth of flooding of coastal features are in direct relation to the relative elevation of these features (Table 2). Coastal rivers, marshes and beaches are first to be flooded, followed by backshore rock platform and dune. The water level of 0.60 m above DEM datum floods a much smaller area and number of coastal features compared with the 2.55-m and greater events associated with storm surge and the 3.05- and 3.25-m events associated with storm surge and sea-level rise.

The 2.55 m above DEM datum scenario flooded 1397 ha of upland, 1634 ha of coastal marsh, 388 ha of dune, 159 ha of swamp and 226 ha of beach. The average depth of flooding for the 2.55 m water level was 0.74 m for upland, 0.84 m for swamp, 1.13 m for dune, 1.58 m for beach and 1.64 m for coastal marsh.

Table 1. Number and total area of coastal features in Coastal Unit 7 (Point Escuminac to Cap-Lumière), 8 (Cap-Lumière to Cap-des-Caissie), 9 (Cap-des-Caissie to Trois-Ruisseaux) and 10 (Trois-Ruisseaux to Cape Tormentine). Data from the Maritime Wetland Inventory. See Figure 1 for geographic extent of coastal units.

	Salt marsh		Pond		Beach		Dune		Mudflat		Island	
Unit	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)
7	207	457.2	20	133.2	40	352.2	27	518.2	61	8 412.7	2	140.3
8	61	169.4	21	69.1	26	121.6	19	310.7	28	3 965.7	1	275.9
9	51	234.6	5	23.8	16	51	22	50.7	20	2 593	1	275
10	76	701.2	3	63.4	17	51.9	17	51.1	16	1 088	0	0
Total	395	1 562.4	49	289.5	99	576.7	85	930.7	125	16 059.4	4	691.2

Table 2. The number of coastal-habitat polygons flooded, total area flooded and mean depth of flooding under four different sea-level-rise (SLR) scenarios. Data from New Brunswick Enhanced Topographic Database.

	SLR of 0.60 m		SLR of 2.55 m			SLR of 3.05 m			SLR of 3.25 m		
Habitat	Number	Area flooded (ha)	Number	Area flooded (ha)	Mean depth (m)	Number	Area flooded (ha)	Mean depth (m)	Number	Area flooded (ha)	Mean depth (m)
Upland	12	11.62	21	1396.88	0.74	21	2127.17	0.96	21	2431.45	1.12
Backshore beach	255	13.66	341	226.41	1.58	342	231.06	2.02	342	231.92	2.26
Coastal marsh	382	81.83	473	1634.34	1.64	480	1670.16	2.08	481	1672.30	2.34
Dune	76	4.97	113	388.19	1.13	114	487.15	1.48	114	509.06	1.72
Backshore rock platform	3	0.02	3	0.26	1.33	3	0.28	1.60	3	0.28	1.96
Lake	3	1.32	9	7.31	1.16	14	8.63	1.29	16	9.60	1.29
River	1	0.00	1	0.18	1.83	1	0.18	2.32	1	0.18	2.52
Swamp	4	0.01	21	159.36	0.84	26	211.92	0.99	27	229.10	1.18

4.6.2.4 Summary and conclusions

Within the overall study region, there are varying amounts of coastal habitat present. Between Cocagne and Cap-Pelé, there is less coastal habitat than in the contiguous regions to the northwest and southeast. The coastal habitats of salt marsh, beach, dune and rock platform are all situated in relatively low-lying areas. They are therefore potentially subject to flooding-induced change.

The impact of tidal flooding on various coastal features cannot be easily generalized from the data presented in Table 2. Some coastal features and plant species are resilient to saltwater inundation. Within the coastal marsh designation, there may be wetlands of various levels of adaptation to salinity. The duration and depth would also have a large influence on the impacts of flooding. Duration and depth of flooding are highly correlated in tidal systems. As is discussed in Section 4.6.5, the vegetative community of salt marshes is very much influenced by frequency and duration of saltwater flooding. The purpose of the data presented in this section was to present information on the amount of coastal habitat that will be impacted by these forces of change.

It is noteworthy that 27 swamps will be impacted by flood levels of 3.25 m. Tree species in New Brunswick are not resilient to saltwater inundation. In many locales throughout Atlantic Canada (e.g., Escuminac), the death of seaward-edge trees is one of the first visible indicators that sea levels are rising.

Sea-level rise and storm surge can have various impacts on coastal habitat features. The nature of these potential changes will be discussed in the next sections.

4.6.2.5 References

Hanson, A.R. (Editor). 2006. *Ecosystem impacts of sea-level rise and climate change on the coastal zone of south-eastern New Brunswick*. Technical Report Series No. 463, Canadian Wildlife Service, Atlantic Region, Environment Canada, Sackville, New Brunswick, 223 pp.

Hanson, A. and Calkins, L. 1996. *Wetlands of the Maritime provinces: Revised documentation for the Wetlands Inventory*. Technical Report Series No. 267, Canadian Wildlife Service, Environment Canada, Sackville, New Brunswick.

Service New Brunswick. 2004. *Digital Topographic Data Base — 1998 (DTDB)* (https://www.web11.snb.ca/snb7001/e/2000/2900e_1c_i.asp)..

4.6.3 Impacts of sea-level rise and residential development on salt-marsh area in southeastern New Brunswick, 1944–2001[14,15]

4.6.3.1 Introduction

Salt marshes are unique ecosystems resulting from complex interactions between hydrology, sedimentation, salinity, tidal amplitude and periodicity, and primary productivity

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(Bertness, 1999). The same physical and biological features that make salt marshes one of the most productive ecosystems in the Temperate Zone also supported European settlements during colonization of northeastern North America (hereafter referred to as the Northeast). Since initial European settlement, increasing human populations and expanding cities and towns have resulted in the continued draining, infilling and alteration of salt marshes.

In addition to direct human impacts on coastal wetlands, there are also the potential impacts related to climate change and predicted sea-level rise and increased frequency and strength of storms. Salt marshes are dynamic systems and can respond to rising water levels by growing vertically, by accumulating sediments and organic matter; they can also grow horizontally, through inland migration. Whether salt marshes can grow vertically to keep pace with rising sea levels will depend on many local factors, such as sediment supply, primary productivity and decomposition rates. Modelling the response of salt marshes to rising sea levels can therefore be very complex and limited by the availability of input data (Galbraith et al., 2002).

The capacity for inland migration of salt marshes in response to rising sea levels will depend on the relative elevation of adjacent land, existing infrastructure and human intervention. The inability of coastal wetlands to migrate inland in response to rising sea levels due to human infrastructure such as dikes has been termed “coastal squeeze” (Nicholls and Branson, 1998).

Salt marshes provide many ecosystem functions and services (Bertness, 1999), including providing habitat for a variety of bird species during all stages of their annual cycle. Salt marshes are important breeding habitat for many birds (Hanson and Shriver, 2006). In the Northeast, species such as Nelson’s Sharp-tailed Sparrow, Saltmarsh Sharp-tailed Sparrow and Willet have been identified as species of concern by state, provincial and federal agencies.

Whereas there are limited data on vertical accretion rates for salt marshes along the Northumberland Strait, this retrospective analysis provides insight on how marshes may respond to future sea-level rise. The second important aspect of this study was to document change in salt marshes due to human activities such as drainage and infilling.

4.6.3.2 Methods

All of the study sites were located in southeastern New Brunswick along the Gulf of St. Lawrence (Figure 3). For a description of the study site and salt marshes, please consult Hanson (2006).

4.6.3.2.1 Study sites

The 563-ha Cape Jourimain study site was located within the boundaries of the Cape Jourimain National Wildlife Area (NWA) and centred on the (NWA) Interpretation Centre and the Confederation Bridge to Prince Edward Island (Figure 4). The Shemogue study site was approximately 13 230 ha and covered 105 km of coastline (Figure 5). The Aboiteau study site, which was contiguous with the western boundary of the Shemogue study site, was approximately 6501 ha and covered 59 km of coastline (Figure 5).

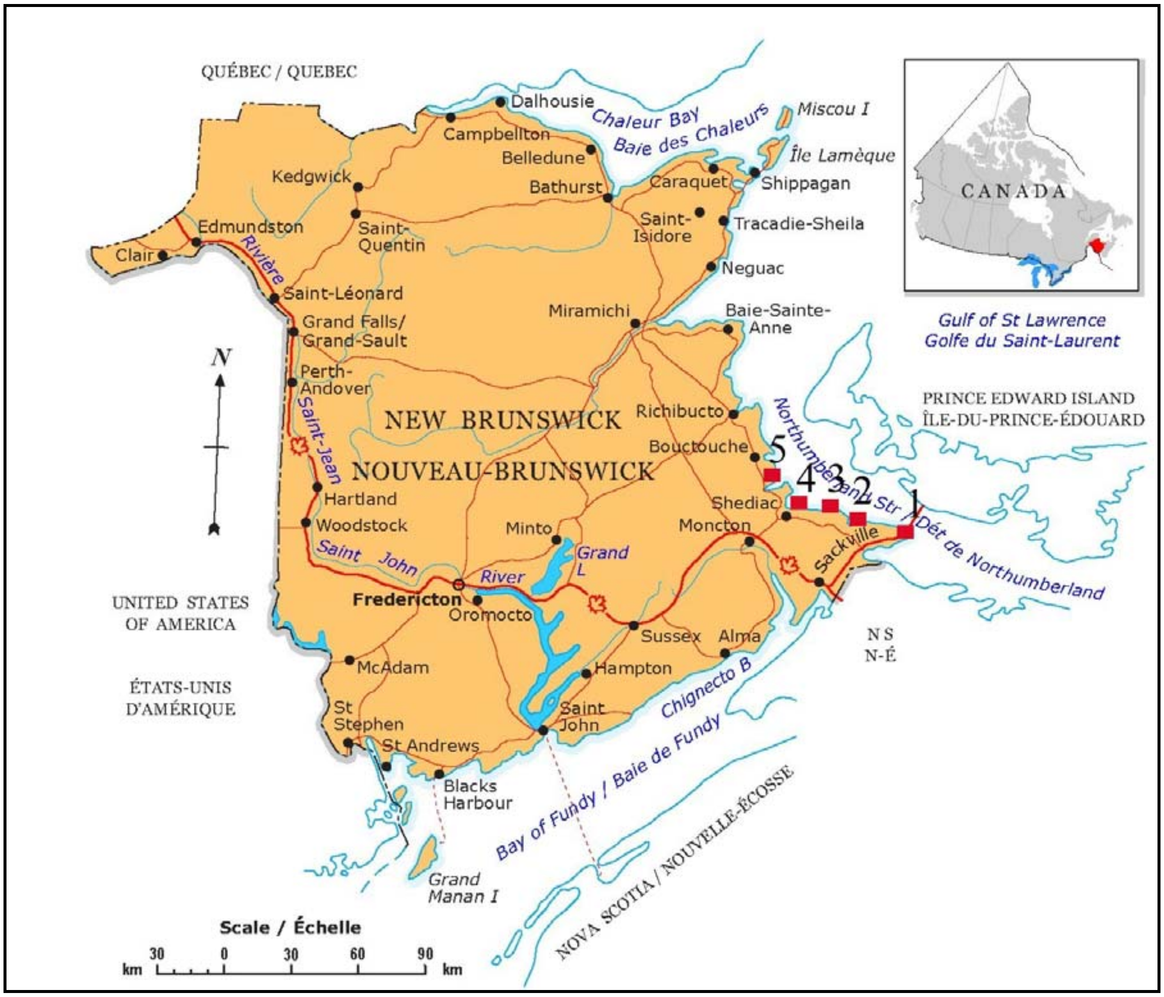

Figure 3. Approximate locations of study sites in southeastern New Brunswick (1 – Cape Jourimain; 2 – Shemogue; 3 – Aboiteau; 4 – Shediac; 5 – Cocagne).

The Shediac study site was contiguous to the western boundary of the Aboiteau study site and was approximately 1240 ha (Figure 6). This study site has the greatest density of residential, recreational and cottage development of all the study sites.

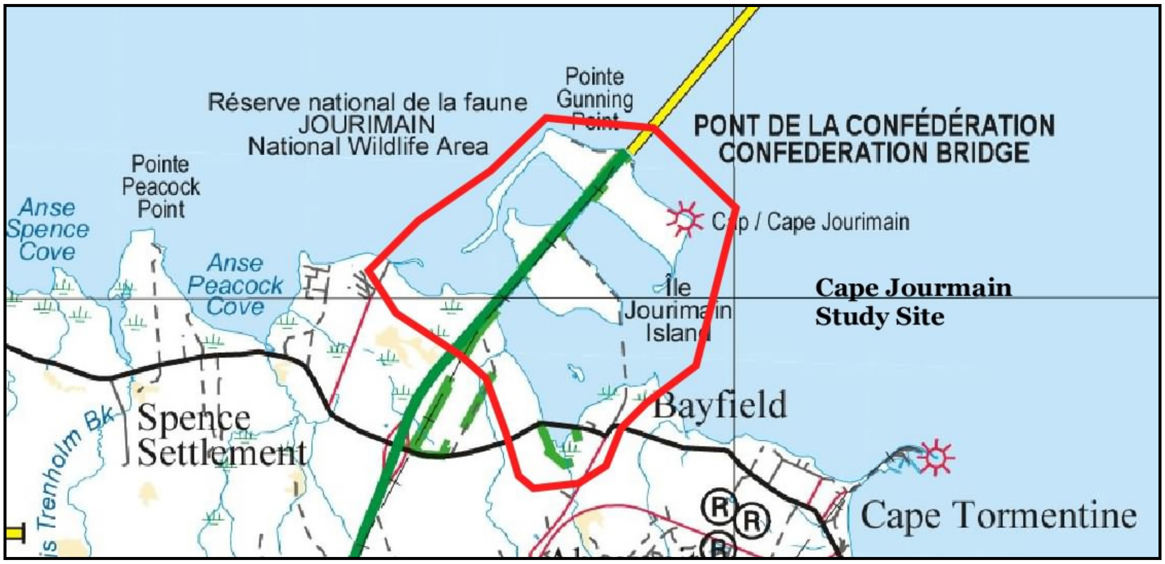

Figure 4. Approximate boundaries (in red) of the Cape Jourimain study site in southeastern New Brunswick.

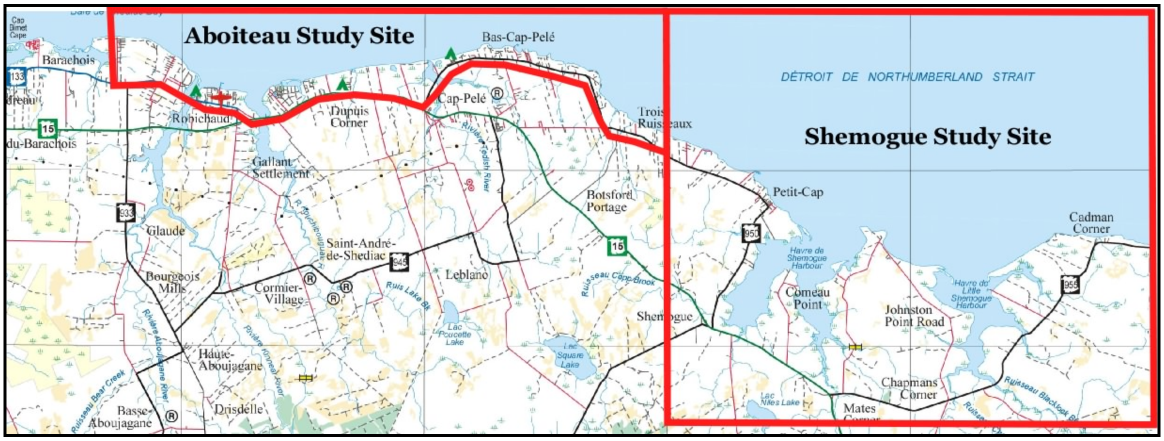

Figure 5. Approximate boundaries (in red) of the Shemogue and Aboiteau study sites in southeastern New Brunswick.

The Cocagne study site was just to the west of the Shediac study site and was approximately 14 395 ha and 66 km of coastline (Figure 7). This study site had a moderate density of residential development.

Figure 6. Approximate boundaries (in red) of the Shediac study site in southeastern New Brunswick.

Figure 7. Approximate boundaries (in red) of the Cocagne study site in southeastern New Brunswick.

4.6.3.2.2 Mapping procedures

A total of 940 aerial photographs were scanned at an appropriate resolution so that one pixel represented approximately 0.25 m^2 ground units. A minimum of 10 ground control points was used for the rectification of an aerial photograph. New Brunswick's 1996 digital orthophotos (digitized and georeferenced orthophotographs) were used in the rectification of all scanned aerial photographs. Once the maps were produced for all years of aerial photography coverage (e.g., 1944, 1953, 1963, 1971, 1973, 1982, 1996 and 2001, depending on the study site), these individual georeferenced maps were superimposed to generate the final multiyear map.

Coastal feature topology was developed that could be identified on all air photographs, including early black and white photographs. The vegetated salt marsh included the *Spartina alterniflora*, *Spartina patens* and *Juncus gerardii* plant communities. Low marsh (*Spartina alterniflora*) was not separated from middle marsh (*Spartina patens*) due to the difficulties in visually separating the plant communities on historical black and white air photos with no ground validation. The upland transition marsh included other halophytic and brackish plant communities at the higher elevations of the marsh. These plant species included *Juncus balticus*, *Carex paleacea* and *Spartina pectinata*. Salt-marsh area included the total area of vegetated salt marsh and water. Barachois marshes and ponds form between shoreline features such as dunes and the upland. The dunes reduce the frequency of saltwater flooding of this area. Total coastal wetland area includes salt marsh, brackish transition marsh and barachois marsh.

4.6.3.3 Results

In both undeveloped areas, there was less salt marsh present in 2001 than in earlier time periods. For Cape Jourimain (Table 3), there was 28% less vegetated salt marsh in 2001 than in 1944 (175 ha versus 156 ha). This change is partially due to the construction of a roadbed through the marsh, which physically destroyed 10 ha of marsh area as well as changed the hydrology. There was also an increase in the amount of open water during this time period.

For Shemogue, there was 5% less (15 ha) vegetated salt marsh in 2001 than in 1944 (Table 4). During the same period, the amount of open water on the salt marsh increased by 18% (9 ha). The number of open-water pannes increased in number between 1944 and 1971, and the pannes had coalesced to form larger ponds by 2001. Ditches were maintained in the marsh in 1944, but not by 1971. The total area of ditching decreased from 1.1 ha to 0.8 ha. In 2001, there was only 0.42 ha of visible drainage ditches left in the salt marshes of this study site. There was less than 0.5 ha of coastal wetland area lost due to infilling. There were 141.7 ha of brackish transition marsh identified in 1944, 134.1 ha in 1971 and 134.1 ha in 2001 (Table 4), indicating a loss of 7 ha. The amount of breakwater increased from 0 m in 1944 to 1084 m in 2001.

For Aboiteau, the amount of vegetated salt-marsh area was 85 ha in 1944 and 62 ha in 2001 (Table 5), a reduction of 27% (23 ha). For brackish transition marsh, there was a reduction of 24% (30 ha), with 119 ha, 104 ha and 91 ha present in 1944, 1971 and 2001, respectively. In total, there was a decrease of 43 ha of coastal wetland during the period 1944–2001. Infilling of coastal wetland was documented on 19 ha (primarily brackish transition marsh), and wharf infrastructure on 3.2 ha. The amount of breakwater increased from 454 m in 1944 to 8324 in 2001.

For Shediac, the amount of vegetated salt-marsh area was 93 ha in 1944 and 74 ha in 2001 (Table 6), a reduction of 21% (19 ha). For brackish transition marsh, there was a reduction of 32% (30 ha), with 66 ha, 58 ha and 45 ha present in 1944, 1971 and 2001, respectively. In total, there was a decrease of 35 ha of coastal wetland during the period 1944–2001. Infilling was documented on 46 ha (primarily brackish transition marsh), and wharf infrastructure on 0.8 ha.

In Cocagne, the amount of vegetated salt marsh decreased from 53 ha in 1944 to 34 ha in 2001, representing a decrease of 36% (Table 7). Brackish transition marsh declined from 51 ha to 42 ha, representing a decrease of 17%. During this same period, infilling of coastal wetland occurred on 8.9 ha, and wharf facilities on 5.7 ha. The amount of breakwater increased from 100 m in 1944 to 13 287 in 2001.

Table 3. Amount of coastal habitat types in Cape Jourimain study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Salt marsh**	**311.6**	**236.4**	**223.5**
1.a	Vegetated salt marsh	174.5	151.7	156.4
1.b	Water	137.1	84.7	67.1
1.b.1	Enclosed open water	3.7	7.2	6.1
1.b.2	Semi-enclosed open water	132.9	77.0	60.9
1.b.3	Tidal creek	0.5	0.0	0.0
1.b.4	Ditch	0.1	0.4	0.1
1.c	Sandy deposits	0.0	0.0	0.0
2	**Brackish transition marsh**	**0.0**	**0.0**	**0.0**
3	**Barachois marsh**	**20.7**	**89.6**	**86.2**
3.a	Barachois vegetated marsh	20.7	31.0	30.3
3.b	Barachois lagoon or panne	0.0	58.6	55.9
3.c	Barachois creek	0.0	0.0	0.0
3.d	Barachois drainage ditch	0.0	0.0	0.0
Note	**Total area of coastal wetland** (salt + brackish + barachois)	**332.3**	**326.0**	**309.7**
4	**Human infrastructure**	**1.1**	**10.9**	**10.8**
4.a	Wharf	0.0	0.0	0.0
4.b	Causeway & bridge	0.0	10.3	10.3
4.c	Infilling of marsh	0.0	0.0	0.0
4.d	Building	0.0	0.0	0.0
4.e	Breakwater or seawall	0.0	0.0	0.0
4.f	Road in marsh	1.1	0.6	0.6
4.g	**Length of seawall (m)**	**0**	**0**	**0**

Table 4. Amount of coastal wetland habitat and land use in Shemogue study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Salt marsh**	**336.4**	**339.2**	**339.2**
1.a	Vegetated salt marsh	285.2	282.7	282.7
1.b	Water	48.4	55.1	55.1
1.b.1	Enclosed open water	34.2	42.4	42.4
1.b.2	Semi-enclosed open water	7.3	6.9	6.9
1.b.3	Tidal creek	5.7	4.9	4.9
1.b.4	Ditch	1.1	0.8	0.8
1.c	Sandy deposits	2.8	1.4	1.4
2	**Brackish transition marsh**	**141.7**	**134.1**	**134.1**
3	**Barachois marsh**	**0.0**	**0.0**	**0.0**
3.a	Barachois vegetated marsh	0.0	0.0	0.0
3.b	Barachois lagoon or panne	0.0	0.0	0.0
3.c	Barachois creek	0.0	0.0	0.0
3.d	Barachois drainage ditch	0.0	0.0	0.0
Note	**Total area of coastal wetland** (salt + brackish + barachois)	**478.1**	**473.3**	**473.3**
4	**Human infrastructure**	**0.8**	**2.4**	**2.4**
4.a	Wharf	0.0	0.3	0.3
4.b	Causeway & bridge	0.8	2.2	2.2
4.c	Infilling of marsh	0.0	0.0	0.0
4.d	Building	0.0	0.0	0.0
4.e	Breakwater or seawall	0.0	0.0	0.0
4.f	Abandoned road in marsh	0.0	0.0	0.0
4.g	**Length of seawall (m)**	**0**	**32**	**1084**

Table 5. Amount of coastal wetland habitat and land use in Aboiteau study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Salt marsh**	**99.6**	**85.0**	**72.9**
1.a	Vegetated salt marsh	84.9	73.2	61.8
1.b	Water	14.3	10.6	10.3
1.b.1	Enclosed open water	6.9	4.6	3.9
1.b.2	Semi-enclosed open water	5.3	4.2	5.3
1.b.3	Tidal creek	0.9	0.5	0.5
1.b.4	Ditch	1.1	1.3	0.6
1.c	Sandy deposits	0.5	1.3	0.8
2	**Brackish transition marsh**	**119.2**	**104.0**	**90.6**
3	**Barachois marsh**	**47.1**	**49.5**	**44.7**
3.a	Barachois vegetated marsh	40.7	37.7	37.7
3.b	Barachois lagoon or panne	5.5	11.4	6.9
3.c	Barachois creek	0.6	0.1	0.2
3.d	Barachois drainage ditch	0.3	0.4	0.0
Note	**Total area of coastal wetland** (salt + brackish + barachois)	**266.0**	**238.5**	**212.9**
4	**Human infrastructure**	**4.4**	**8.8**	**27.6**
4.a	Wharf	0.3	1.4	3.2
4.b	Causeway & bridge	1.1	2.0	2.5
4.c	Infilling of marsh	2.8	5.2	19.2
4.d	Building	0.1	0.1	0.0
4.e	Breakwater or seawall	0.1	0.0	2.6
4.f	Abandoned road in marsh	0.0	0.0	0.0
4.g	**Length of seawall (m)**	**454**	**868**	**8324**

Table 6. Amount of coastal wetland habitat type and land use in Shediac Bay study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Salt marsh**	**108.9**	**109.5**	**83.0**
1.a	Vegetated salt marsh	93.3	95.8	74.0
1.b	Water	15.6	13.7	9.0
1.b.1	Enclosed open water	10.0	8.1	7.2
1.b.2	Semi-enclosed open water	5.2	3.4	1.0
1.b.3	Tidal creek	0.0	0.0	0.0
1.b.4	Ditch	0.4	2.2	0.8
1.c	Sandy deposits	0.0	0.0	0.0
2	**Brackish transition marsh**	**65.8**	**58.3**	**45.0**
3	**Barachois marsh**	**1.9**	**11.2**	**13.4**
3.a	Barachois vegetated marsh	0.9	8.9	11.6
3.b	Barachois lagoon or panne	1.0	2.3	1.8
3.c	Barachois creek	0.0	0.0	0.0
3.d	Barachois drainage ditch	0.0	0.0	0.0
Note	**Total area of coastal wetland** (salt + brackish + barachois)	**176.5**	**179.0**	**141.4**
4	**Human infrastructure**	**6.0**	**19.9**	**46.9**
4.a	Wharf	0.0	0.1	0.8
4.b	Causeway & bridge	0.6	0.7	0.3
4.c	Infilling of marsh	3.2	18.6	45.5
4.d	Building	0.0	0.0	0.0
4.e	Breakwater or seawall	0.3	0.5	0.1
4.f	Abandoned road/dike in marsh	0.8	0.0	0.0
4.g	**Length of seawall (m)**	**365**	**1079**	**9408**

Table 7. Amount of coastal wetland habitat and land use in Greater Cocagne study area in 1944, 1973 and 2001.

		Area (ha)		
	Habitat type	1944	1973	2001
1	**Salt marsh**	**60.1**	**48.5**	**38.6**
1.a	Vegetated salt marsh	52.9	41.1	34.2
1.b	Water	5.4	7.3	4.0
1.b.1	Enclosed open water	3.3	4.8	3.0
1.b.2	Semi-enclosed open water	1.2	1.7	0.5
1.b.3	Tidal creek	0.4	0.4	0.5
1.b.4	Ditch	0.5	0.3	0.1
1.c	Sandy deposits	1.8	0.1	0.4
2	**Brackish transition marsh**	**50.6**	**49.6**	**42.2**
3	**Barachois marsh**	**5.8**	**5.6**	**3.9**
3.a	Barachois vegetated marsh	5.0	5.1	3.8
3.b	Barachois panne	0.7	0.3	0.1
3.c	Barachois creek	0.0	0.0	0.0
3.d	Barachois drainage ditch	0.1	0.1	0.0
Note	**Total area of coastal wetland** (salt + brackish + barachois)	**116.4**	**103.6**	**84.5**
4	**Human infrastructure**	**2.6**	**4.4**	**21.2**
4.a	Wharf	0.6	1.6	5.7
4.b	Causeway & bridge	1.1	2.0	1.8
4.c	Infilling of marsh	0.0	0.1	8.9
4.d	Building	0.3	0.1	0.0
4.e	Breakwater or seawall	0.0	0.2	4.8
4.f	Abandoned road in marsh	0.6	0.3	0.0
4.g	**Length of seawall (m)**	**100**	**593**	**13 287**

4.6.3.4 Summary and conclusions

This section presents data from a study designed to quantify change in the areal coverage of salt marshes along the Northumberland Strait in southeastern New Brunswick during the period 1944–2001. Two study sites (Cape Jourimain and Shemogue) currently have large areas of salt marsh present, whereas the other three study sites (Shediac, Aboiteau and Cocagne) currently have a large amount of residential development. All sites have been affected to varying degrees by human activity and sea-level rise. Human activities in these marshes and the coastal zone preclude us from being able to assess the impacts of climate change independently from direct anthropogenic disturbance.

At Cape Jourimain, there was less salt marsh present in 2001 than in 1963. This change is at least partially due to the construction of the road approach to the Confederation Bridge to Prince Edward Island in 1966. This roadbed resulted in the physical loss of salt marsh due to the footprint of the road in addition to the subsequent loss of salt marsh due to the change in hydrology. The roadbed created a large brackish-water pond to the northwest of the road and reduced the tidal prism of this estuary.

The results for the Shemogue study site provide the clearest indication of the potential changes that sea-level rise could bring to the region. This region has experienced an apparent (relative) sea-level rise of 25–32 cm over the past century, and climate models project a more rapid rise in future. During the period of 1944–2001, there was no large-scale direct anthropogenic disturbance to the salt marshes in this study site. It was observed that the amount of open water on the salt marsh increased during this period and that the pannes increased in size and then coalesced to form larger ponds. This sequence of events has been observed in other marshes where vertical accretion rates are less than relative sea-level rise (Hartig et al., 2002; Erwin et al., 2006). Based on visual interpretation of the multiyear map, there also appeared to be some loss of the seaward edge of the salt marshes in this study site. The upland boundaries of the marsh did not appear to change significantly for this study area, and the overall area of transition marsh decreased during this period, indicating that there was little inland migration of coastal wetland. The brackish transition marsh is of critical importance to ground-nesting passerine birds like Nelson's Sharp-tailed Sparrow (Hanson, 2004).

There were loss and conversion of coastal wetland in all of the developed study sites (Aboiteau, Shediac and Cocagne). This included vegetated salt marsh, brackish transition marsh and, to a lesser extent, barachois marsh. The maps and documented increase in the land area that was infilled or used for roads, causeways and wharves indicate that this loss in habitat was due to human activities. The amount of habitat lost during the period 1944–1971 was minor compared with the losses observed during the period 1971–2001. It is suspected, based on the number of building permits issued by local planning commissions and personal observation, that additional coastal habitat has been lost due to infilling and human infrastructure development during the period 2001–2005. Our preliminary results suggest that a significant amount of coastal habitat along the Northumberland Strait has already been lost due to human activities and that future sea-level rise will result in additional losses.

4.6.3.5 References

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4.6.4 Temporal changes in beach and dune habitat in southeastern New Brunswick, 1944–2001[16,17]

4.6.4.1 Introduction

In addition to direct human impacts on coastal beach and dune habitat, there are also the potential impacts related to climate change and predicted sea-level rise and increased frequency and strength of storms. Latest estimates for relative sea-level rise for the period 2000–2100 range from 53 to 60 cm (±30 cm) across the study area, increasing to the southeast (see Section 4.1 of this report). Beaches and dunes are dynamic systems, and some long-term trends can be reversed by storm events. Modelling future change in beach and dune habitat can therefore be very complex and limited by the availability of input data. Beaches and dunes are important habitat for many species of wildlife and are important socio-economically because of the recreational opportunities they afford.

Whereas there are limited data on erosion and deposition rates and how they may change in the future, this retrospective analysis provides insight on how beach and dune habitat may respond to future sea-level rise. The second important aspect of this study was to document change in beach habitat due to human activities such as sand mining and infrastructure development.

4.6.4.2 Methods

Methods were similar to those described in Sections 4.5 and 4.6.3. For further details, see Hanson (2006). Coastal-feature topology was developed that could be identified on all air photographs, including early black and white photographs. Poor-quality aerial photography in 1944 for Cape Jourimain and Shediac did not allow beach and dune habitat to be further differentiated into various subtypes.

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4.6.4.3 Results

In both relatively undeveloped areas, there was less beach and dune habitat in 2001 than in 1944. For Cape Jourimain (Table 8), there was 22% less beach and dune habitat in 2001 than in 1944 (18.0 ha versus 23.1). For Shemogue (Table 9), there was 8% less beach and dune habitat in 2001 than in 1944 (51.6 versus 56.1 ha). This overall result was driven by a loss of 26% of beach habitat and a 2% increase in dune habitat.

At Aboiteau, there was an overall decline of 12% in the amount of beach and dune habitat in 2001 compared with 1944 (Table 10). The amount of beach and dune habitat was 63.7, 59.0 and 56.6 ha during 1944, 1971 and 2001, respectively. Beach habitat declined more than dune habitat during the period (17% versus 5%).

For the Shediac study area, there was a decline of 32% in the area of beach and dune habitat between 1944 and 1971 (Table 11), with little additional loss occurring during 1971–2001. There were 52.5 ha of beach and dune habitat in 1944, but only 35.7 ha in 1971.

In Cocagne, the amount of beach and dune habitat decreased from 48.7 ha in 1944 to 35.4 ha in 2001, representing a decrease of 27% (Table 12). Beach declined from 27.0 to 16.4 ha, representing a decrease of 40%. During this same period, the amount of dune decreased from 21.7 to 19.0 ha, representing a 12% decline.

For the Aboiteau, Shediac and Cocagne study sites, there was a substantial increase in the amount of hardened shoreline present in 2001 compared with the earlier periods (Tables 8–12). The amount of hardened shoreline in 2001 was 8324 m in Aboiteau, 9408 m in Shediac and 13 287 m in Cocagne.

Changes in the amount and distribution of coastal habitat at Cape Jourimain can be seen in the multiyear maps in Figures 8–10 and for Shediac in Figures 11–13. The topology for these maps is described in Table 13. Changes in the amount and distribution of coastal habitat at Cape Jourimain can be seen in the multiyear maps in Figures 8–10 and for Shediac in Figures 11–15. The topology for these maps is described in Table 13. Multiyear maps for Shemogue, Aboiteau and Cocagne are presented in Section 5, Annex D.

Table 8. Amount of coastal beach and dune habitat in the Cape Jourimain study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
3.a	Beaches and dunes	22.5	18.5	17.9
3.b	Sandy surfaces	0.0	0.0	0.0
3.c	Breach	0.0	0.0	0.0
3.d	Gullies	0.6	0.2	0.1
3	**Total for beach and dune**	**23.1**	**18.7**	**18.0**
	Length of seawall (m)	**0**	**0**	**0**

Table 9. Amount of coastal beach and dune habitat in the Shemogue study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Beach habitat**	**19.5**	**21.5**	**14.4**
1.a	Sand beach	13.7	18.6	13.2
1.b	Breach of foredune	0.9	0.0	0.2
1.c	Washover fan	2.0	0.0	0.0
1.d	Sandy surface in marsh	2.8	1.4	0.3
1.e	Boulder beach	0.1	1.6	0.7
2	**Dune habitat**	**36.6**	**38.2**	**37.2**
2.a	Active and fixed dune	36.5	38.1	37.2
2.b	Blowout	0.1	0.1	0.0
2.c	Incipient dune	0.0	0.0	0.0
2.d	Cliff-top dune	0.0	0.0	0.0
3	**Total for beach and dune**	**56.1**	**59.7**	**51.6**
	Length of seawall (m)	**0**	**32**	**1084**

Table 10. Amount of coastal beach and dune habitat in the Aboiteau study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
1	**Beach habitat**	**32.9**	**35.7**	**27.2**
1.a	Sand beach	28.3	31.6	26.2
1.b	Breach of foredune	1.4	1.8	0.1
1.c	Washover fan	2.7	0.0	0.1
1.d	Sandy surface in marsh	0.5	1.3	0.8
1.e	Boulder beach	0.0	1.0	0.0
2	**Dune habitat**	**30.8**	**23.3**	**29.4**
2.a	Active and fixed dune	30.8	22.6	29.4
2.b	Blowout	0.0	0.7	0.0
2.c	Incipient dune	0.0	0.0	0.0
2.d	Cliff-top dune	0.0	0.0	0.0
3	**Total for beach and dune**	**63.7**	**59.0**	**56.6**
	Length of seawall (m)	**454**	**868**	**8324**

Table 11. Amount of coastal beach and dune habitat in the Shediac Bay study area in 1944, 1971 and 2001.

		Area (ha)		
	Habitat type	1944	1971	2001
3.a	Beaches and dunes	40.6	35.7	34.9
3.b	Sandy surfaces	11.9	0.0	0.3
3.c	Breach	0.0	0.0	0.0
3.d	Gullies	0.0	0.0	0.0
3	**Total for beach and dune**	**52.5**	**35.7**	**35.1**
	Length of seawall (m)	**365**	**1079**	**9408**

Table 12. Amount of coastal beach and dune habitat in the Greater Cocagne study area in 1944, 1973 and 2001.

		Area (ha)		
	Habitat type	1944	1973	2001
1	**Beach habitat**	**27.0**	**25.4**	**16.4**
1.a	Sand beach	22.8	23.3	13.7
1.b	Breach of foredune	1.2	0.4	0.0
1.c	Washover fan	0.0	0.0	0.3
1.d	Sandy surface in marsh	1.8	0.1	0.4
1.e	Boulder beach	1.3	1.5	2.0
2	**Dune habitat**	**21.7**	**21.7**	**19.0**
2.a	Active and fixed dune	21.1	20.3	17.8
2.b	Blowout	0.0	0.0	0.0
2.c	Incipient dune	0.0	0.0	0.8
2.d	Cliff-top dune	0.6	1.5	0.3
	Total for beach and dune	**48.7**	**47.1**	**35.4**
	Length of seawall (m)	**100**	**593**	**13 287**

Table 13. Description of mapping topology used in Figures 8–13.

Feature code	Brief description of mapped landform
Area features mapped as polygons	
BAMARSH	Salt marsh turned into brackish/freshwater barachois marsh located behind a sand spit; cut off from tidal influence. Found in Grande-Digue and west of Cap-Brûlé area
BREAKWATER	A linear structure made up of piled boulders or concrete; typically part of wharf infrastructure
BRECHE	Coastline, breach (erosion and destruction of foredune by marine processes)
BRIDGE	Bridge
CAUSEWAY	Highway infrastructure crossing a body of water and preventing the flow of water on either side
DRAIN	Artificial linear drainage system typically located in the marsh
DUNE or DUNEX	Dune habitat, including active and fixed dune environments
ENTAILLE	Anthropogenic notch in dune or foredune crest (pedestrian beach access point, off-road vehicle trail, etc.)
ETIER	Tidal creek, direct connection to the sea and subject to tidal fluctuations
GALETS	Shoreline, cobble and rock beach
GOULET	Inlet (channel permitting the exchange of water between the sea and the inland areas)
INFILLINGW	Site part of wharf infrastructure and where the shore or a coastal feature other than a marsh was infilled
JETTY	Anthropogenic structure projecting into the water perpendicular to the shore
LAGUNE	Lagoon; shallow, brackish body of water located behind a barrier beach and linked to the sea by a tidal inlet
MARAIS*	Salt marsh*; *S. alterniflora/S. patens* zone; defined by the presence of numerous parallel drainage channels, pans
MAREART	Artificial pond located on the shore and contained within a human-made structure
MARE_DOM	An area of salt marsh composed of 60% low/mid-marsh and 40% semi-open pannes. This code was used where pannes were too numerous to be digitized individually and/or where the poor resolution of the photos and the abundance of the pannes made it impossible to delineate them with any accuracy.
MARE	Salt-marsh pan (pond); water body located within the salt marsh, typically in the middle marsh zone
MAREDRY	Dried-up pan; appearing on the 2001 map only (can be mapped on colour photos only)
MARESO	Semi-open pond, connected to a tidal inlet. Located within the salt marsh. Covers vast expanses in the Cape Jourimain marshes
NAPPE	Storm overwash (recent), not revegetated yet
SPECTINATA**	*Spartina pectinata* zone; brackish transition marsh**; defined by the presence of numerous parallel drainage channels, typically devoid of pannes; located between the salt marsh and the forest edge

Feature code	Brief description of mapped landform
SANDYSURF	Flat, sandy area on the coast other than a dune, beach or overwash
WETLAND	A marsh whose vegetation composition is unclear
Linear features mapped as polylines on separate shapefiles	
ProtecS01	Protection walls; line feature included with the Shediac 2001 map
ProtecS71	Protection walls; Line feature included with the Shediac 1971 map
ProtecS44	Protection walls; line feature included with the Shediac 1944 map

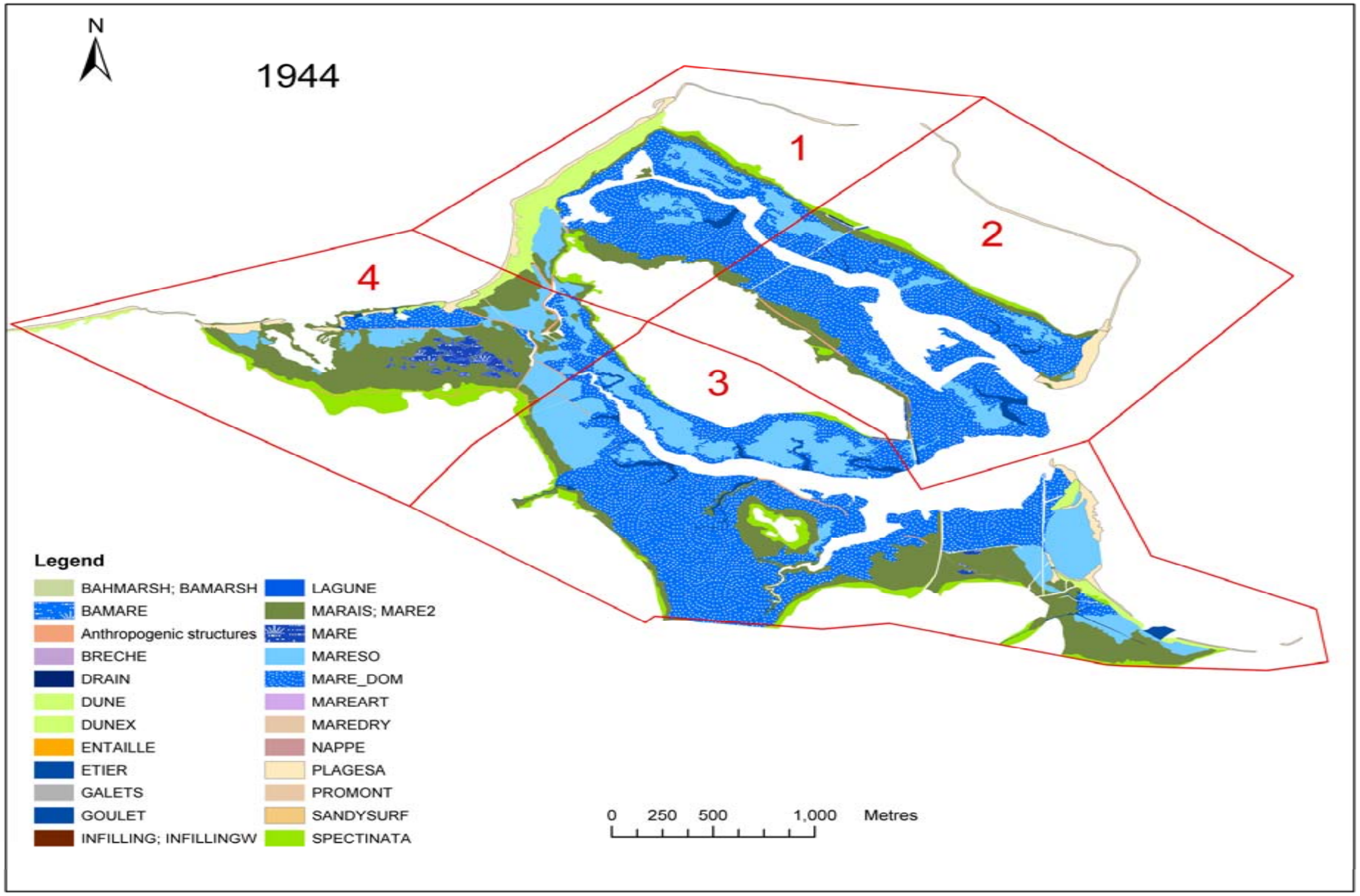

Figure 8. Map of coastal features at Cap Jourimain, 1944. See Table 13 for description of map topology.

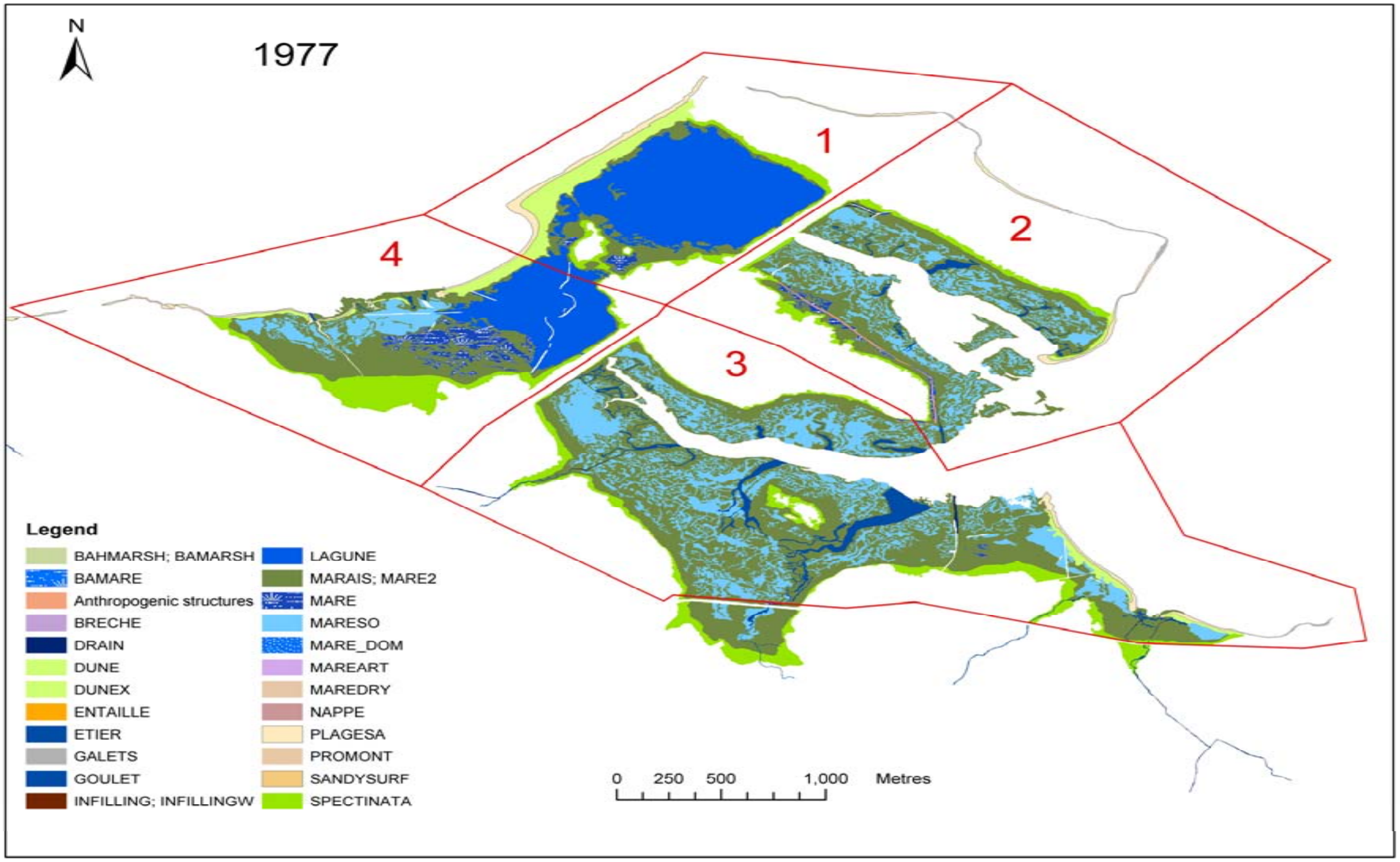

Figure 9. Map of coastal features at Cap Jourimain, 1977. See Table 13 for description of map topology.

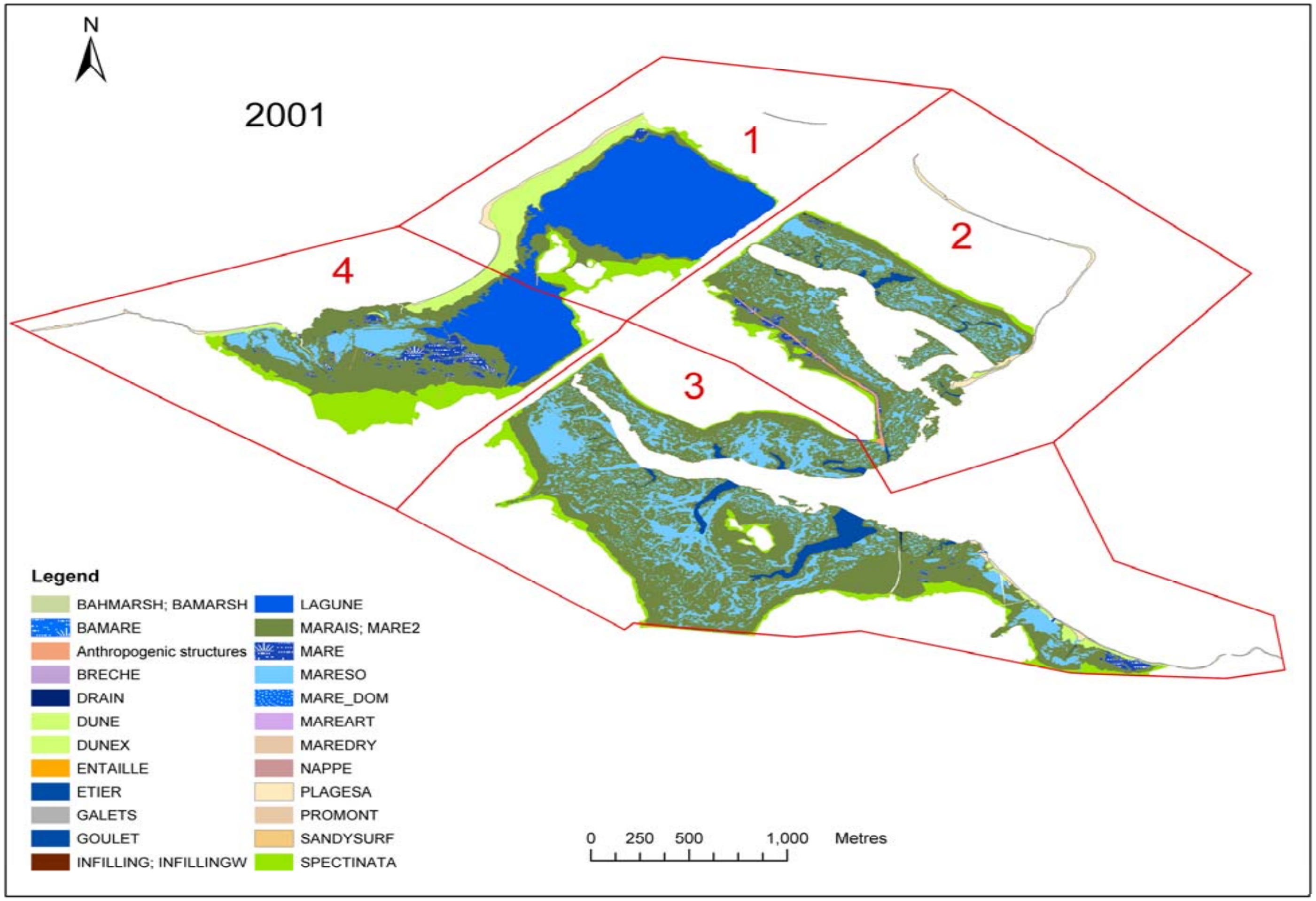

Figure 10. Map of coastal features at Cape Jourimain, 2001. See Table 13 for description of map topology.

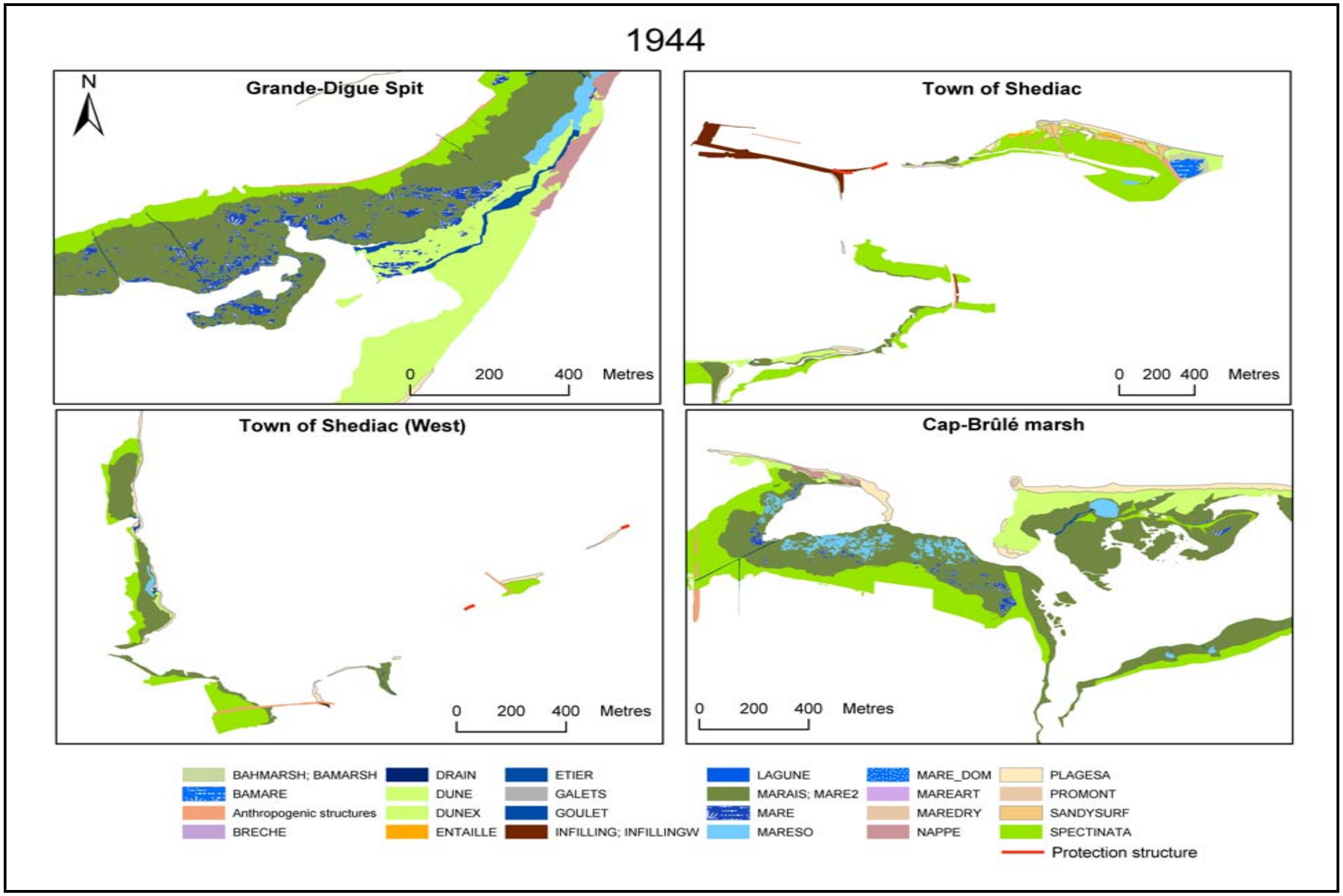

Figure 11. Map of coastal features at Shediac, 1944. See Table 13 for description of map topology.

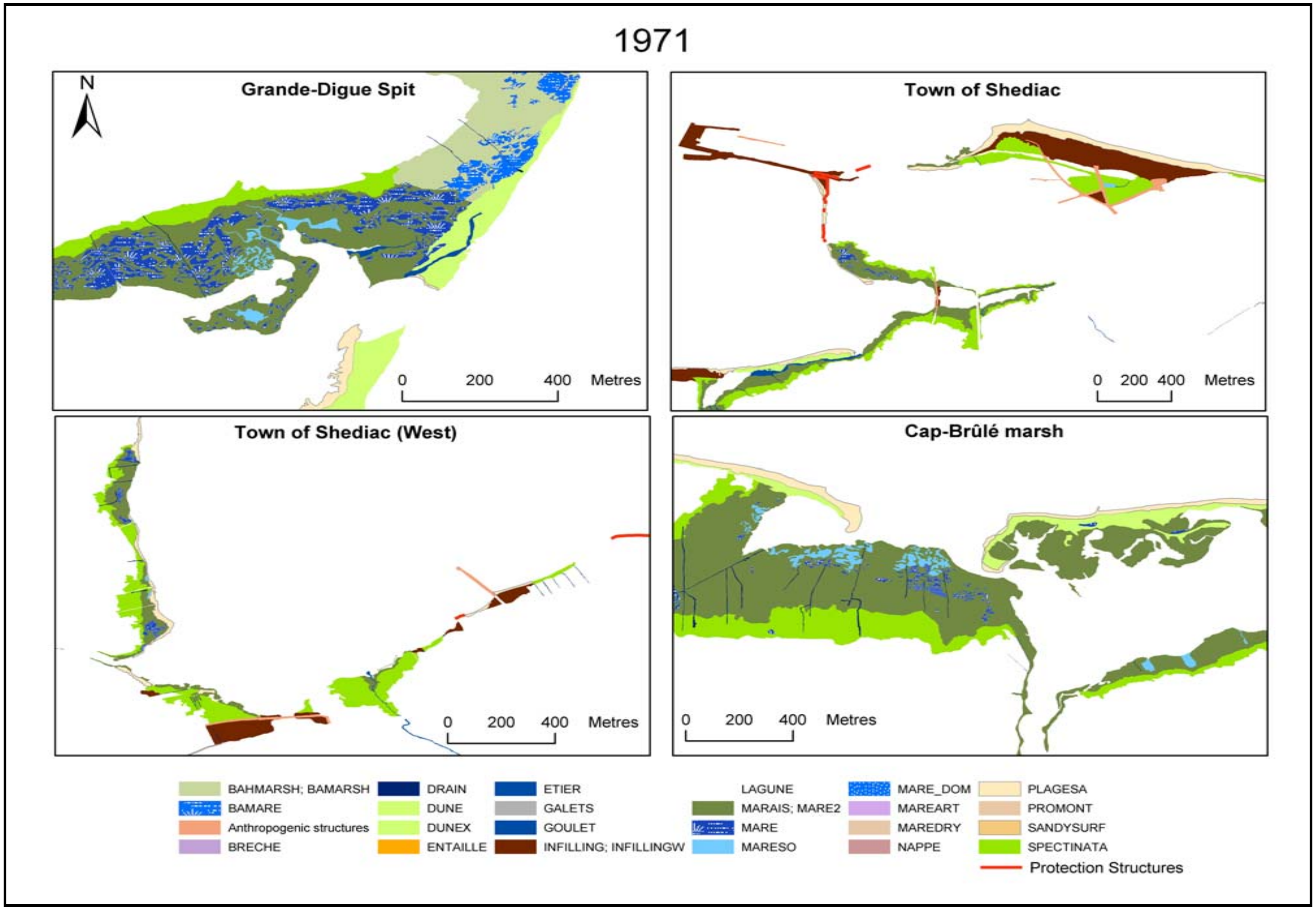

Figure 12. Map of coastal features at Shediac, 1971. See Table 13 for description of map topology.

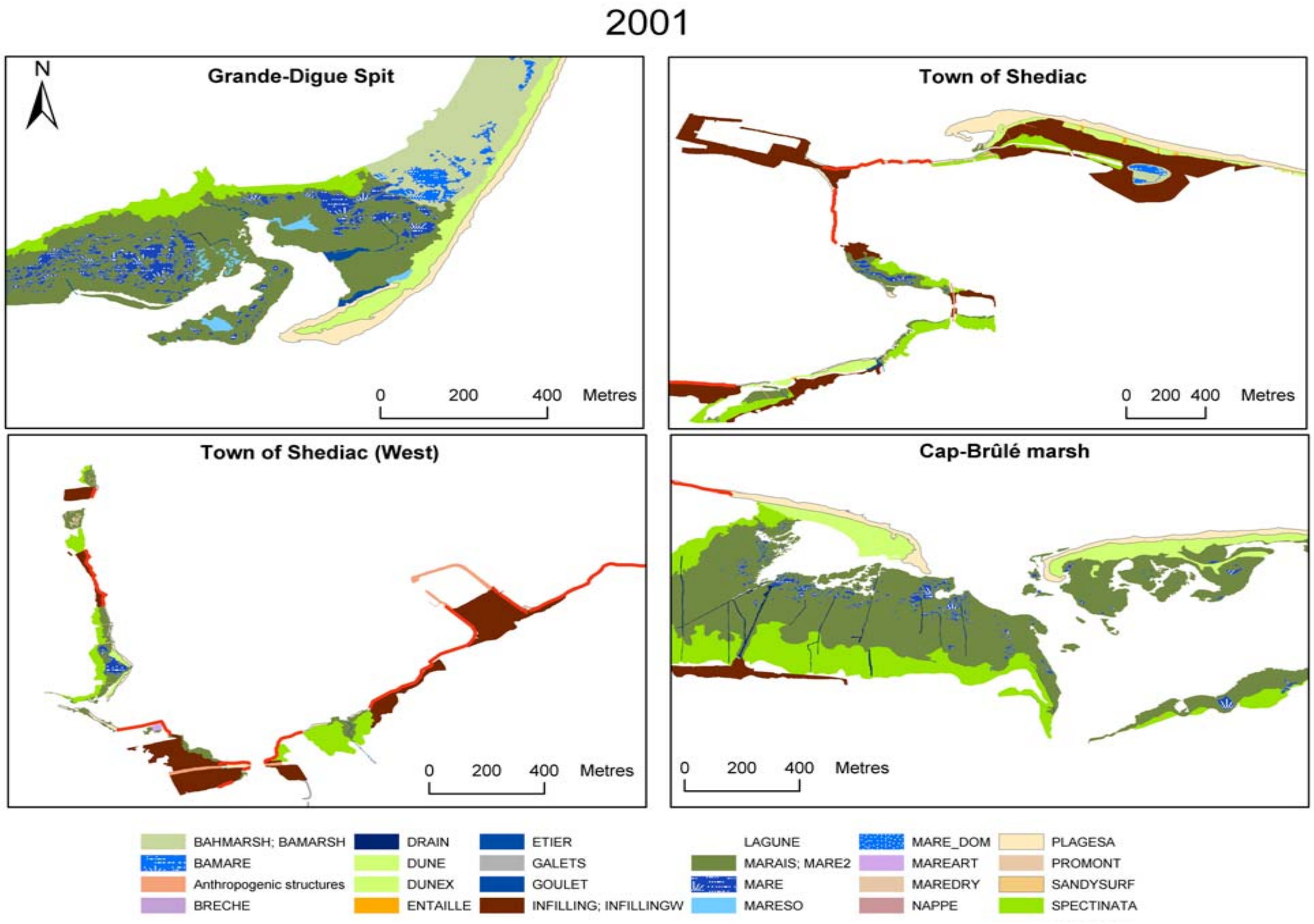

Figure 13. Map of coastal features at Shediac, 2001. See Table 13 for description of map topology.

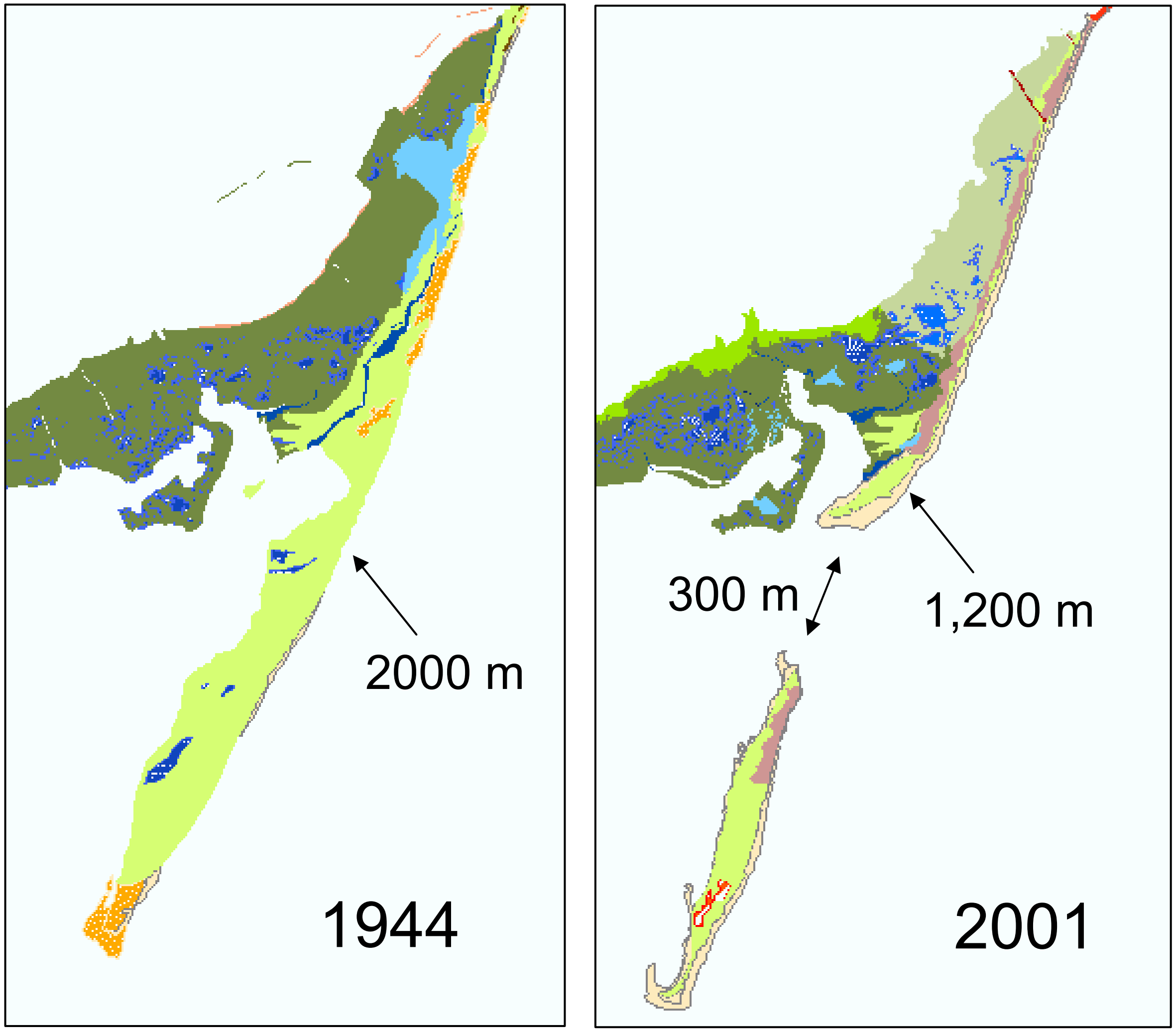

Figure 14. Grande-Digue Spit, 1944 and 2001. See Table 13 for description of map topology.

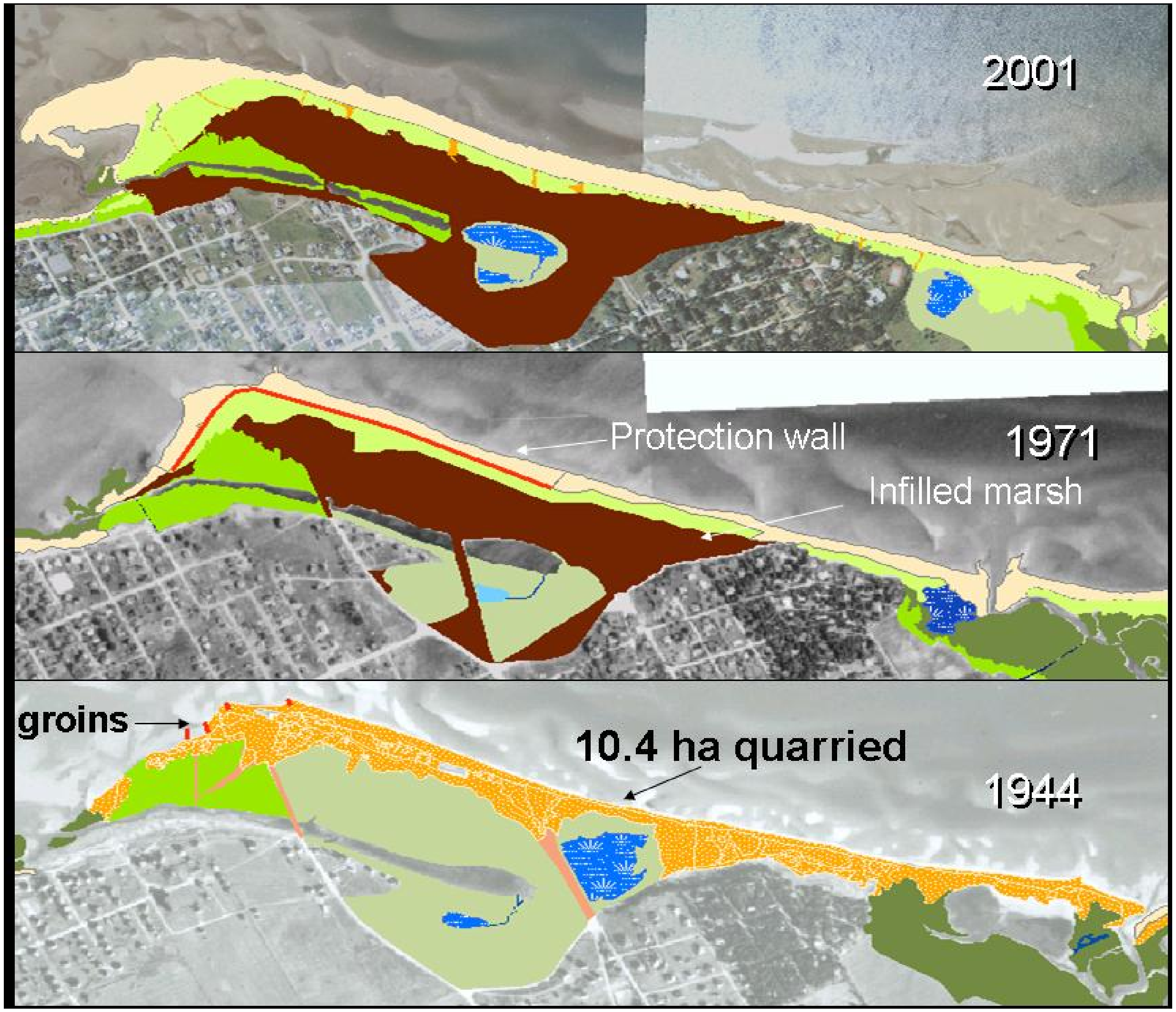

Figure 15. Parlee Beach area, 1944, 1971 and 2001. See Table 13 for description of map topology.

4.6.4.4 Summary and conclusions

At Cape Jourimain, there was less beach habitat present in 2001 than in 1944. This change may be partially due to the construction of the road approach to the Confederation Bridge to Prince Edward Island in 1966. The roadbed created a large brackish-water pond to the northwest of the road and reduced the tidal prism of this estuary. The impact of this construction on sediment dynamics is unknown. There was considerable loss of beach habitat in the eastern parts of map sections 2 and 3.

At the Shemogue study site, there was loss of 5 ha of beach habitat during the period 1944–2001, although dune habitat remained relatively constant. It was reported in Section 4.5 of this report that considerable decadal variation occurred in the location and shape of beaches in this study area, with the amount of beach habitat increasing in some locations and decreasing in others.

Overall, there was a loss of 17.4 ha of beach in the Shediac study region. However, the maps for Shediac show considerable variation in temporal trends in beach and dune habitat among locations (Figures 11–13). There was considerable decline at the Grande-Digue spit in beach and dune habitat between 1944 and 1971 (Table 11, Figure 14). This area had a considerable amount of sand removed from here. This removal of material coupled with storm events is probably responsible for the Grande-Digue spit being breached. Regulations to control the amount of material were introduced in 1954 (*Sand Removal Act*) and 1968 (*Quarriable Substance Act*). However, between 1968 and 1971, there were still 17 000 m^3 of sand removed from Grande-Digue Bar. Sand removal would have impacted many beaches. By 1971, regional economic activity and demand for construction aggregates had accelerated to the point that all beaches along the Northumberland Strait had been quarried, with the exception of Cape Jourimain, Grant's Beach and Bouctouche Bar (Airphoto Analysis Associates, 1975).

Trends for the Town of Shediac site are influenced by the beach nourishment program on Parlee Beach (see Section 4.5), whereby sand material from the intertidal zone is deposited on the beach (Figure 15). This has resulted in a substantial increase in the amount of beach habitat in this area and reduces the net significance of the loss of beach and dune habitat in other parts of the study area (Table 4).

The trend in the Town of Shediac west zone has been for the shoreline to be hardened (Figures 11–13). There has been an increase in the amount of erosion-control structures and infrastructure along the shoreline throughout much of the study area. The technique of placing large rocks, concrete blocks or walls along the shoreline has reduced the availability of habitat for cavity-nesting birds such as Bank Swallows and Belted Kingfishers. Improper installation of rock erosion walls has often led to large areas of beach being covered by rocks. For the Cap-Brûlé marsh, there has been an enlargement of the spit at the distal end over time.

For the Cocagne study area, there was a 10.6-ha decrease in beach area. Much of this change was due to loss of beach habitat on Cocagne Island and Cocagne Bar. The changes to these coastal features are consistent with sea-level rise and storm impacts.

The physical gain of beach and dune area, especially through beach nourishment programs, should not be equated with a gain in good-quality wildlife habitat, and therefore any large-scale general analysis of beach and dune wildlife habitat based on air photos must be treated with caution, due to the difficulties of quantifying human impacts on these habitats.

All sites have been affected to varying degrees by human activity and sea-level rise. Human activities in the coastal zone preclude us from being able to assess the impacts of climate change independently from direct anthropogenic disturbance.

For a variety of reasons, some perhaps associated with rising sea levels, there has been a net decrease in the amount of beach and dune habitat during the period 1944–2001 in the study area. The variety of change observed within the study area during the period 1944–2001 highlights the importance of local accretion and erosion processes, storm events and human activity. To accurately predict how future sea-level rise and climate change will impact the amount of beach and dune habitat in the future, we will need better information on the physical processes that affect beach establishment and persistence, how these could change because of sea-level rise and climate change, and how human activities will be impacting the beaches and dunes. This information can be gained iteratively, and management responses developed accordingly. The impacts of sea-level rise and climate change will be realized over a longer period compared with severe storm events and human activities, which can have an immediate impact on beaches and dunes. Like many other resources at potential risk from sea-level rise and climate change, these risks cannot be managed in isolation from others. From a wildlife-habitat perspective, a prudent course of management action will be to prevent further physical alteration and disturbance of existing beach and dune habitat.

4.6.4.5 References

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4.6.5 Impacts of sea-level rise on salt-marsh plant communities[18,19]

4.6.5.1 Introduction

One of the striking aspects of salt-marsh environments is the vertical zonation of vegetation, visible both on-site and from aerial photos. This distinctive trait is well known and has been the focus of numerous studies (Bertness, 1991; Sanchez et al., 1996;

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Zedler et al., 1999; Sanderson et al., 2001; Bockelmann et al., 2002; Ursino et al., 2004; Pennings et al., 2005; Silvestri et al., 2005). Little has been done, however, to study this phenomenon on the coastline of the Maritimes.

This study's aim was to investigate the relationship between halophyte zonation in salt marshes of the Northumberland Strait and the Bay of Fundy and the influence of ground elevation on these spatial patterns. By understanding this phenomenon under current sea levels and tidal regime, insight on how rising sea levels will impact salt-marsh plant communities could be gained. Comparing results from these two different coastlines and tidal regimes allowed for greater insight into the role of mean sea level and tidal extremes on salt-marsh plant-community zonation. In addition to ground elevation, the distribution of halophytic species' distributions was examined as a function of tide levels.

4.6.5.2 Methods

4.6.5.2.1 Study areas

This study focuses on two very different coastlines, which, although separated at their narrowest point by only a 24-km isthmus, exhibit significant differences in tidal regime and coastal processes. The Bay of Fundy is a highly dynamic body of water, with tides greater than 15 m in its upper reaches. The Northumberland Strait is characterized by small tides, less than 2 m in height. Both study areas have semi-diurnal tidal cycles. See Hanson (2006) for more description of the tidal marshes in these regions and methods.

4.6.5.2.2 Plant community surveys

In total, 12 salt marshes were investigated between July and September 2004. Vegetation and global positioning system (GPS) surveys were carried out in nine sites on the Northumberland Strait and three on the Bay of Fundy. Vascular plant species were identified, and areal percentage cover was estimated within a 1-m^2 quadrat at 385 locations. Quadrats were located in the marsh in a random stratified manner so that all plant communities and elevations were sampled, and the absolute ground elevation of each plot was measured and recorded using a Trimble Pro XR GPS unit with a vertical resolution of ±5 cm in the vertical and ±3 cm in the horizontal.

4.6.5.2.3 Determining tide levels

The higher high water mean tide level (HHWMT) and the higher high water large tide level (HHWLT) are referenced to chart datum (CD) (or mean water level) and therefore had to be converted to a geodetic datum (CGVD28), also equivalent to mean sea level (MSL), to allow their comparison with GPS elevations. This was done by subtracting the mean water level value from the HHWMT and HHWLT values (Webster et al., 2004).

4.6.5.3 Results

Plant-species zonation was very much influenced by elevation in Northumberland Strait salt marshes (Figure 16). The quantitative differences between absolute marsh surface elevation (and hence vegetation ranges) among Bay of Fundy marshes are notable, and the differences between Bay of Fundy marshes and Northumberland Strait marshes are striking (see Hanson, 2006).

With regard to differences in tidal amplitudes, plants were found to occur at significantly lower elevations in the Northumberland Strait compared with the Bay of Fundy. *Spartina* *alterniflora*, a species that typically occupies the lowest elevations of a marsh, was found to occur at mean elevations ranging between 3.0 and 5.2 m in the Bay of Fundy compared with 0.44 and 0.70 m in the Northumberland Strait. Similar patterns were observed for *Spartina pectinata*, which occurred on the landward edge of marshes between 3.8 and 6.8 m in the Bay of Fundy and 0.90 and 1.1 m along the Strait. The small tidal amplitude prevalent along the Northumberland Strait likely explains these narrow ranges. The important point to note is that differences in plant-species elevational ranges exist due to differences in tide levels.

Referencing plant species' elevations according to a specific tide level allows for better among-site comparisons, because these values then become relative to one another. Elevations referenced to mean sea level compared (Figure 17) compared to Higher High Water Large Tide –HHWLT (Figure 18) for *Spartina pectinata* shows the importance of what is used as the refence point. S.pectinata occurs above HHWLT levels.

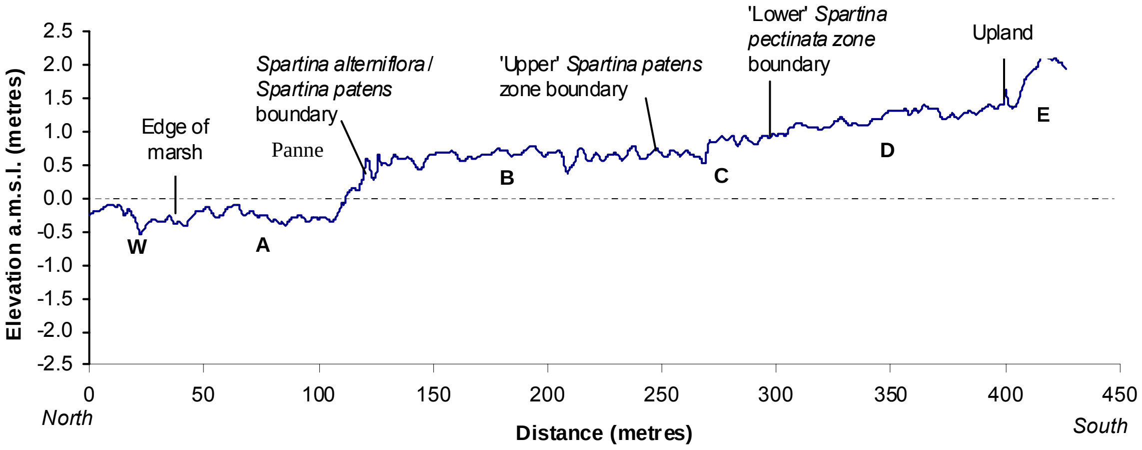

Figure 16. Cross-section of a transect in saltmarsh at Shediac (Cap-Brûlé), New Brunswick.

Legend: (W) Water, (A) "*Spartina alterniflora* zone" or "Low marsh" [*Spartina alterniflora*, *Salicornia europaea*, *Spergularia canadensis*, *Sueda maritima*], (B) "*Spartina patens* zone" or "Mid-marsh" [*Spartina patens*, *Atriplex* sp., *Plantago maritima*, *Glaux maritima*, *Triglochin maritima*], (C) Transition zone [*Juncus gerardii*, *Juncus arcticus*, *Carex paleacea*, *Hierochloë odorata*, *Potentilla anserina*], (D) "*Spartina pectinata* zone" or "High marsh" [*Spartina pectinata*, *Festuca rubra*, *Solidago sempervirens*, *Calystegia sepium*, *Aster novi-belgii*, *Schoenoplectus tabernaemontani*], (E) "Upland" [*Phragmites australis*, *Typha latifolia*, *Impatiens capensis*, *Rosa virginiana*]. Selected species were surveyed along the transect and are diagnostic of their respective marsh zone.

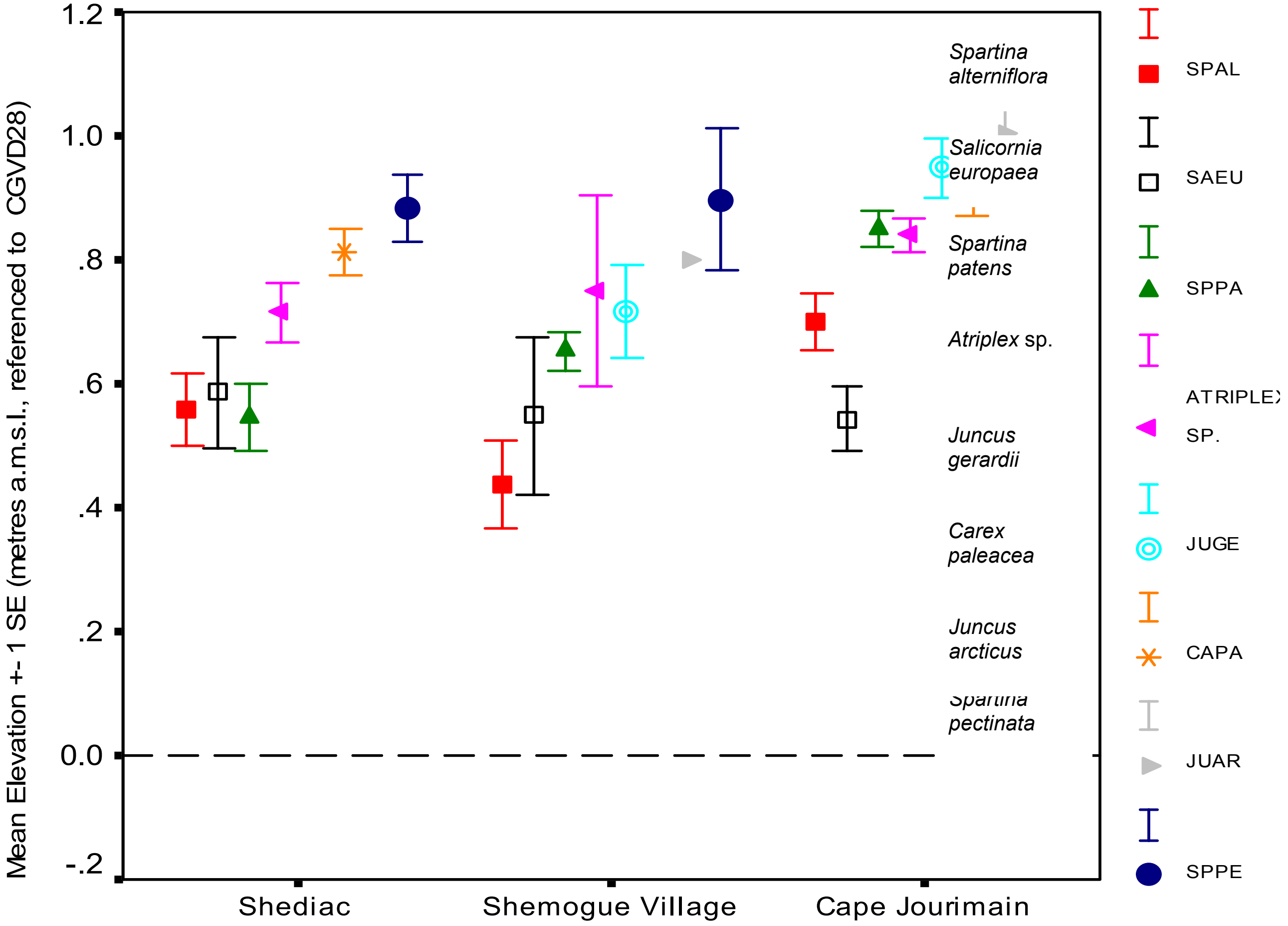

Figure 17 Elevations (± 1 standard error) of halophytic vegetation species in selected salt marshes, Northumberland Strait, New Brunswick (y-axis values are in metres). Species abbreviations are: SPAL – *Spartina alterniflora*, SAEU – *Salicornia europaea*, SPPA – *Spartina patens*, ATRIPLEX SP – *Atriplex* sp. JUGE – *Juncus gerardii*, CAPA – *Carex paleacea*, JUAR – *Juncus arcticus*, SPPE – *Spartina pectinata*.

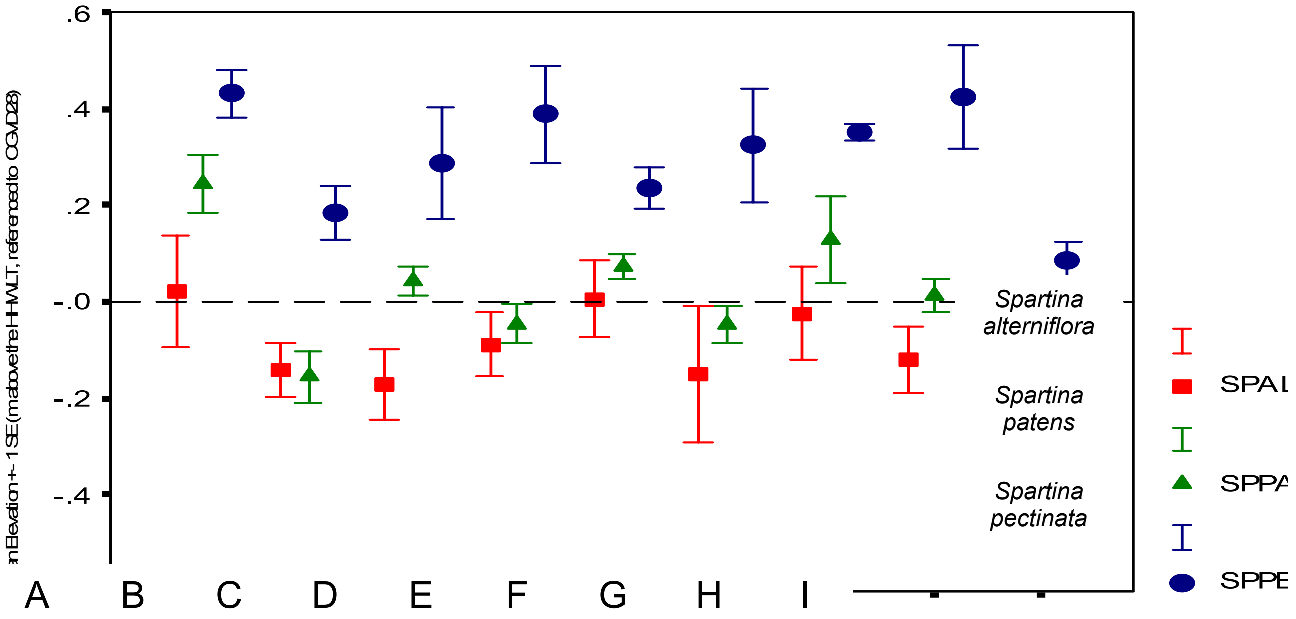

Figure 18. Vertical distribution of *Spartina* species in relation to the higher high water large tide (HHWLT) level in nine salt marshes of the Northumberland Strait, New Brunswick: (A) Cap-de-Cocagne, (B) Shediac, (C) Shemogue Village, (D) Petit-Cap, (E) Comeau Point, (F) Fox Creek, (G) Johnston Point, (H) Grant Creek, (I) Cape Jourimain (y-axis values are in metres). Species abbreviations are: SPAL – *Spartina alterniflora*, SPPA – *Spartina patens*, SPPE – *Spartina pectinata.*

4.6.5.4 Summary and conclusions

Certain plant species tend to occupy relative elevation niches as demonstrated by their mean elevation ranges and their vertical relationship to other vascular plant species, which tend to repeat across study sites on both coasts. *Spartina alterniflora*, *Spartina patens*, *Juncus gerardii* (black grass), *Carex paleacea*, *Juncus arcticus* and *Spartina pectinata*, for instance, consistently occur in bands along the same elevational gradient (from low to high) in surveyed salt marshes. These latitudinal patterns are clearly visible from the ground and aerial photos and are characteristic of salt marshes. These patterns are likely linked to tide levels and flooding duration and frequency. Thus, this study indicates that measurements of marsh surface elevation *per se* can provide great insight into the probability of occurrence for these plant species' assemblages.

Other plant species, such as *Atriplex* spp., *Salicornia europaea* and *Solidago sempervirens*, tend to display more variability. They tend to be distributed in a slightly more random fashion, occurring alternately as bands running along an elevational gradient, adjacent to tidal channels or salt pannes, or aggregated on mud deposits left by floating ice. These species' distributions are influenced by a variety of mechanisms that, in conjunction with elevation, control their zonation patterns such as interspecies competition and edaphic conditions (deposition of mud through ice, waterlogging of soils, salinity, etc.).

The conditions responsible for *Spartina patens* and *Spartina pectinata* occurring above the HHWLT mark on the Northumberland Strait could be linked to flooding frequency and/or duration. Marshes with a small tidal amplitude are likely to be flooded more often than marshes with a larger one (Desplanque and Mossman, 2004). It is therefore hypothesized that flooding (and/or prolonged periods of submersion) is more frequent in the Northumberland Strait and that *Spartina patens* and *Spartina pectinata,* with regards to physiological limitations, may have to grow at relatively higher levels in the marsh than their Bay of Fundy counterparts for edaphic conditions to be suitable to their development and sustenance.

Results from this study reaffirm the importance of relative elevation in determining the distribution and abundance of plant species within salt marshes. The differences in plant zonation in relation to elevation among marshes and between Bay of Fundy salt marshes and Gulf of St. Lawrence marshes highlight the fact that elevation is only an index to the proximal factors of frequency and duration of saltwater inundation, which influence plant communities. The strong relationships between plant communities and elevation in our research indicate that it would be possible to predict how plant communities in salt marshes respond to changes in relative elevation. At present, accurate predictive quantitative modelling of plant-community response to sea-level rise is not possible, because only limited quantitative information on changes in marsh surface elevation, especially in response to rising sea levels, exists. The establishment of sites in the Gulf of St. Lawrence to measure accretion rates as part of the global surface elevation table network will facilitate this predictive work (D. Cahoon, U.S. Geological Survey, pers. comm.). Our research does allow us to predict that a change in relative mean sea level of 25 cm could result in a shift in the major plant-community zones of *Spartina alterniflora*, *Spartina patens* and *Spartina pectinata*.

An important component of the potential impacts of sea-level rise on salt marshes and plant communities is the capacity for inland migration of coastal features. Based on ground and air photo observations as well as DEMs and flood-mapping models, it appears that there is limited capacity for inland migration of coastal marshes where they are situated directly along the coast. In these situations, there are often steeply rising elevations, which limit the areal gain in elevation with each vertical increase in sea level and/or adjacent human infrastructure that would prevent inland migration. In addition to changes in salt-marsh plant communities within the marsh, the inability of marshes to migrate inland could result in the elimination of higher-elevation plant species such as *Carex paleacea*. The higher-elevation zones of salt marshes are important for ground-nesting birds such as Nelson's Sharp-tailed Sparrow (Hanson, 2004; Hanson and Shriver, 2006). The spatial extent of our research did not extend to the limit of saline conditions along tidal rivers. The potential for salt marshes to extend farther inland along tidal rivers warrants future investigation.

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4.6.6 Impacts of sea-level rise on colonial-nesting gulls and terns[20]

4.6.6.1 Introduction

The coastline of New Brunswick is home to many species of birds, but none are more familiar to people and associated with the coast than the gulls, herons and terns. These birds require nesting locations that are free from human disturbance and other predators. These species of birds are known as colonial nesters because if suitable conditions exist, these birds will nest at high densities.

Surveys for Common Terns (*Sterna hirundo*), Great Black-backed Gulls (*Larus marinus*), Herring Gulls (*L. argentatus*), Ring-billed Gulls (*L. delawarensis)*, Double-crested Cormorants (*Phalacrocorax auritus*), Great Blue Herons (*Ardea herodias*) and Black-legged Kittiwakes (*Rissa tridactyla*) have been conducted along the New Brunswick coast with various levels of intensity since 1964 (Boyne and Hudson, 2002). Lock et al. (1984) estimated that in 1983, there were 15 500 pairs of Common Terns attempting to nest at 26 locations. By 2002, this number had decreased to 12 618 nests at 11 colonies (Boyne and Hudson, 2002).

To investigate the potential impacts of sea-level rise and storm surge on ground-nesting gulls and terns, we conducted an analysis of the elevation of colonies in relation to flooding scenarios.

4.6.6.2 Methods

4.6.6.2.1 Nesting colony surveys

The methodology for conducting surveys of colonial-nesting birds in New Brunswick has been described previously (Lock et al., 1984; Lock, 1987; Boyne and Hudson, 2002; Boyne et al., 2006). The most recent surveys conducted by Boyne and co-workers were conducted by fixed-wing aircraft with ground verification, with the timing and methodology of these surveys designed to census Ring-billed Gulls, Herring Gulls, Great Black-backed Gulls and Common Terns.

4.6.6.2.2 Mapping

ArcGIS software was used to determine the impacts of sea-level rise on nesting gulls and terns along the central and southeastern portions of the New Brunswick Gulf of St. Lawrence coastline (Figure 19). Details on mapping methodology can be found in Hanson (2006). Four different water-level scenarios were analyzed: 0.60 m, 2.55 m, 3.05 m and 3.25 m above DEM datum.

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[20] Authors: Alan Hanson, Matthew Mahoney, Andrew Boyne and Shawn Craik.

4.6.6.3 Results

There were 14 colonial nesting locations in the study area during the period between 1964 and 2000 (Table 14). Along the New Brunswick Gulf of St. Lawrence coastline, more nesting colonies are located north of Miramichi Bay compared with south. Only the colony at Cocagne Bar is impacted by increased water levels of 0.60 m. Water levels associated with a 2.55 m above DEM datum storm surge would inundate most (11/14) colonies. Those colonies that are not flooded by this 2.55-m flooding event also contain higher-elevation landforms in addition to the flat areas preferred by nesting terns and gulls. Most colonies are islands and not associated with upland habitat (Table 15). Data for Common Terns from 2000 and 2005 illustrate the importance of flat nesting habitat free of trees and other tall vegetation (Table 16).

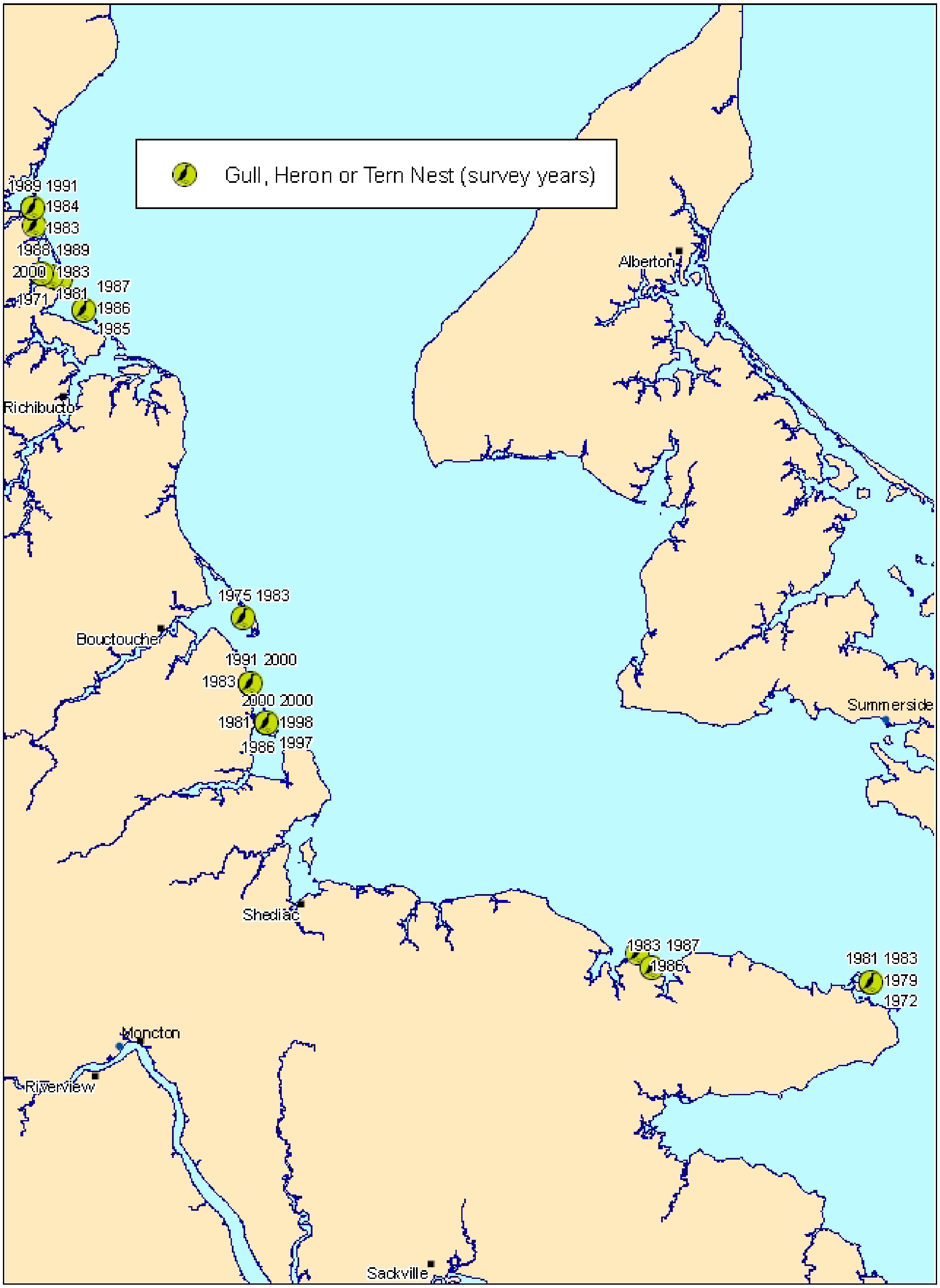

Figure 19. Location of gull, heron or tern nests, 1964–2000.

Table 14. Location of seabird (gull, heron, tern) colonies in study area (Cape Jourimain to Kouchibouguac National Park). The number of years in which a colony was recorded in the database is given as well as whether the colony is flooded with water levels of 0.60 m, 2.55 m, 3.05 m or 3.25 m above DEM datum.

Colony	**Years colony** present	Water level 0.60 m	Water level 2.55 m	Water level 3.05 m	Water level 3.25 m
Bouctouche Bar	1975, 1983	N	N	N	N
Cap-de-Saint-Louis Island Dune	1971	N	Y	Y	Y
Cape Jourimain	1972, 1979, 1981, 1983	N	N	N	N
Cocagne Bar	1964, 1969, 1979, 1983, 1991, 2000	Y	Y	Y	Y
Cocagne Island	1974, 1979, 1981, 1986, 1997, 1998, 2000	N	N	N	N
Hut Island	1989, 1993	N	Y	Y	Y
Johnston Point	1986	N	Y	Y	Y
Kouchibouguac, Loggiecroft Island	1973, 1976, 1981, 1983, 1984, 1989, 1991	N	Y	Y	Y
Kouchibouguac, North Richibucto	1985, 1986, 1987	N	Y	Y	Y
Kouchibouguac, South Beach	1986	N	Y	Y	Y
Kouchibouguac, South Dune	1981, 1983, 1988, 1989	N	Y	Y	Y
Kouchibouguac, Tern Islands (1, 2)	1971, 1974, 1975, 1976, 1984, 1987, 1989, 1990, 1991, 1992, 1994, 1995, 1996, 1997, 1998, 1999, 2000	N	Y	Y	Y
Little Shemogue Harbour	1983, 1987	N	Y	Y	Y
Richibucto Harbour	1983	N	Y	Y	Y

Table 15. Area of habitat within 500 m from nest site from Service New Brunswick Enhanced Topographic Database

	Area (m^2)						
Colony	Upland	Backshore beach	Coastline	Marsh	Dune	Swamp	Exclusion area
Bouctouche Bar	0	9 975	755 150	6 125	14 325	0	0
Cap-de-Saint-Louis Island Dune	0	0	614 625	54 400	0	116 425	0
Cape Jourimain	207 550	0	546 525	23 275	1 150	0	0
Cocagne Bar	133 800	12 350	558 500	77 225	475	3 225	0
Cocagne Island	0	11 025	260 625	152 400	8 850	0	352 200
Hut Island	0	55 700	711 975	4 275	13 600	0	0
Johnston Point	195 400	450	589 750	0	0	0	0
Kouchibouguac, Loggiecroft Island	0	55 700	711 975	4 275	13 600	0	0
Kouchibouguac, North Richibucto	0	17 525	577 375	28 350	161 975	0	0
Kouchibouguac, South Beach	285 375	9 075	286 700	110 700	93 725	0	0
Kouchibouguac, South Dune	37 250	4 175	719 850	6 650	0	15 850	1 575
Kouchibouguac, Tern Islands (1, 2)	0	51 125	703 300	0	30 100	0	0
Little Shemogue Harbour	72 750	2 175	469 800	227 275	13 525	0	0
Richibucto Harbour	0	55 700	711 975	4 275	13 600	0	0

Table 16. Number of Common Tern nests in colonies surveyed along the Gulf of St. Lawrence coast of New Brunswick, 2000 and 2005 (from Boyne and McKnight, 2005).

Location	Latitude	Longitude	Nests 2000	Nests 2005
Shediac Marina	46.2275	−64.5453	2	121
Richibucto Harbour	46.6737	−64.8607	0	8
Tern Island, Tabusintac	47.3298	−64.9326	2607	3463
Inkerman I	47.6619	−64.7935	0	165
Inkerman II	47.6597	−64.7947	0	465
Fox Dens Beach	47.8867	−64.5049	678	880
Tracadie Sand Spit	47.5260	−64.8670	0	2161
Tern Islands, Kouchibouguac National Park	46.7770	−64.8750	6911	6020
Neguac North Spit	47.2570	−65.0000	601	0
Neguac 3	47.2920	−64.9500	546	0
Grande Anse Unnamed	47.6700	−64.7770	656	0
Caraquet Island	47.8250	−64.8960	128	0
Maisonette Dune	47.8150	−64.3965	180	0
Bathurst Harbour Island 3	47.6330	−65.6480	240	0
Dalhousie (Bowater Jetty)	48.0720	−66.3700	69	0
Totals			12618	13283

4.6.6.4 Summary and conclusions

Great Blue Herons nest colonially in trees. In the study area, their nests and trees are at higher elevations and will be relatively unaffected by a sea-level rise of 0.60 m at normal high tide and storm-surge events of 2.55 m above DEM datum. Saltwater inundation could impact the roots of nesting trees in some locations, depending on local groundwater flow, local relative elevation and the increased water levels. Common Terns and gulls are susceptible to the impacts of storm surge because they nest on the ground and in locations that are low-lying relative to sea level. The impact of rising sea levels on offshore nesting islands will be greatly influenced by erosion and deposition processes. A water level of 2.55 m above DEM datum was predicted to flood most tern nests and colonies.

Common Terns breeding on the three Tern Islands and Kelly’s Island at Kouchibouguac during 2002–2006 often nested in island regions where vegetation density, concealment and elevation were lower than those at merganser nest sites (Craik et al., 2006). Tern nests were distributed at varying distances from the high-tide line (e.g., 0.5–30 m), but nesting densities were usually highest along the islands’ peripheries, where vegetation densities were often lowest. Many tern nests would have been subjected to flooding in all three storm-surge scenarios. The spring storm of 1993 resulted in flooding and failure of many tern nests and a considerable reduction in annual breeding attempts in years following the storm (Richard, 1996; E. Tremblay, pers. comm.). A total of 6400 nests were discovered on the three Tern Islands in 1992, whereas only 3698 and 4104 nests were observed in 1994 and 1995, respectively (Richard, 1995, 1996). Field observations on nesting success indicate that the rain and waves associated with summer storm events do cause flooding of nests on the offshore nesting islands (Boyne et al., 2006). Common Terns are known to change breeding sites after reproductive failures and accumulate at sites where flooding is infrequent (Nisbet, 2002).

Currently, and in the future, the biggest potential impact on nesting habitat for colonial-nesting bird species is that from human disturbance and terrestrial predators. The recent colonization of a sunken barge, used as part of the Shediac Marina breakwater, by nesting Common Terns (Table 16) indicates that nesting habitat could be created for terns if human disturbance and/or sea-level rise cause nesting habitat to become limiting in certain locales.

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4.6.7 Impacts of sea-level rise on colonial-breeding Red-breasted Mergansers at Kouchibouguac National Park[21,22]

4.6.7.1 Introduction

The Red-breasted Merganser (*Mergus serrator*) is a piscivorous, medium-sized sea duck that breeds in a variety of fresh, brackish and saltwater wetlands at both mainland and island sites throughout the northern hemisphere (Titman, 1999). Mergansers have historically nested colonially at Kouchibouguac National Park, New Brunswick, on several small coastal barrier islands that separate the marine waters of Kouchibouguac Bay in Northumberland Strait from shallow saltwater lagoons (Young and Titman, 1986). Population dynamics of the colony were initially monitored in 1984 and have been followed annually since 1992 (Young and Titman, 1988; Titman, 1997). Merganser nests, which have ranged from 25 to 91 attempts annually since 1992, have been found in tall and dense stands of marram (*Ammophila breviligulata*) and sea lyme (*Leymus mollis*) grasses (Bouchard, 2001). Nest sites consist of a shallow depression in the sand lined with dead grasses and down plucked from the breeding hens' belly (Titman, 1999). Annual estimates of merganser nest success have often exceeded 60% and have reached 70% (Mayfield, 1961; R. Titman, unpubl. Data.

The objectives of this study were 1) to determine the height above sea level of Red-breasted Merganser nests occurring on several barrier islands at Kouchibouguac National Park; 2) considering merganser nest heights, to predict the propensity of merganser nests to be flooded under various sea-level-rise scenarios; 3) to delineate coastal habitat types occurring at the Kouchibouguac study site; and 4) to calculate the amount of each coastal habitat occurring within a 500-m radius surrounding the nest site. Red-breasted Merganser breeding data at Kouchibouguac were collected as part of a five-year (2002–2006) study on nest-site and brood-habitat selection (R. Titman, unpubl. data).

4.6.7.2 Methods

From 2002 to 2005, Red-breasted Merganser nests at Kouchibouguac National Park were recorded on the three Tern Islands, a 4-ha barrier-island complex located in the Saint-Louis Lagoon at the mouth of the Kouchibouguacis River (Figure 20). Nest coordinates were recorded using a Garmin® eTrex (1–5 m position accuracy). Distance between the centre of each nest bowl and nearest high-water line was recorded with a tape measure. Full details of GPS mapping procedures can be found in Hanson (2006).

4.6.7.3 Results

From 2002 to 2005, Red-breasted Mergansers were observed to nest colonially on four offshore barrier islands at Kouchibouguac National Park (Figure 20). It should be noted that Kelly's Island was formed in 2000 when a large storm breached the Kouchibouguac Dune and is shown on the map in Figure 20 as being the distal portion of the dune. Mean

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[22] The authors are grateful to A. Rousseau, O. Fraser, P.-E. Hebert and B. Martin, who worked as field assistants at Kouchibouguac throughout the studies on merganser nest-site and brood-habitat selection from 2002 to 2005. Parks Canada, particularly E. Tremblay, provided logistical support throughout all merganser field studies. Funding for merganser research was provided by the New Brunswick Wildlife Trust Fund, the Province of Quebec Society for the Protection of Birds, the Canadian Wildlife Federation and Bishop's University.

annual number of merganser nests on Kelly's Island was five. Mean nest elevation was 2 m above MSL, and mean distance to water was 29 m (Table 17). Mean annual number of nests on Tern Island 1 was 27. Mean nest elevation was 2.29 m above MSL, and mean distance to water was 15 m (Table 17). Mean annual number of nests on Tern Island 2 was 13, whereas mean nest elevation was 2.01 m above MSL, and mean distance to water was 18 m (Table 17). Mean annual number of nests on Tern Island 3 was 10, whereas mean nest elevation was 1.95 m above MSL, and mean distance to water was 10 m (Table 17). The elevation of most nests occurring on the four barrier islands was greater than the 0.60 m associated with predicted sea-level rise. However, most nests would be flooded in a storm surge with water levels of 2.55 m above DEM datum (Table 17). All nests on Tern Island 3 would have been flooded under the 2.55-m storm-surge scenario, whereas almost 35% of nests on Tern 1 would have survived the 2.55-m surge. Several nests would survive the 3.05-m and 3.20-m surge levels. Merganser nests have been observed to occur at higher densities along a vegetated ridge on this island. It would appear that the mergansers are selecting this area for this combination of vegetation and elevation.

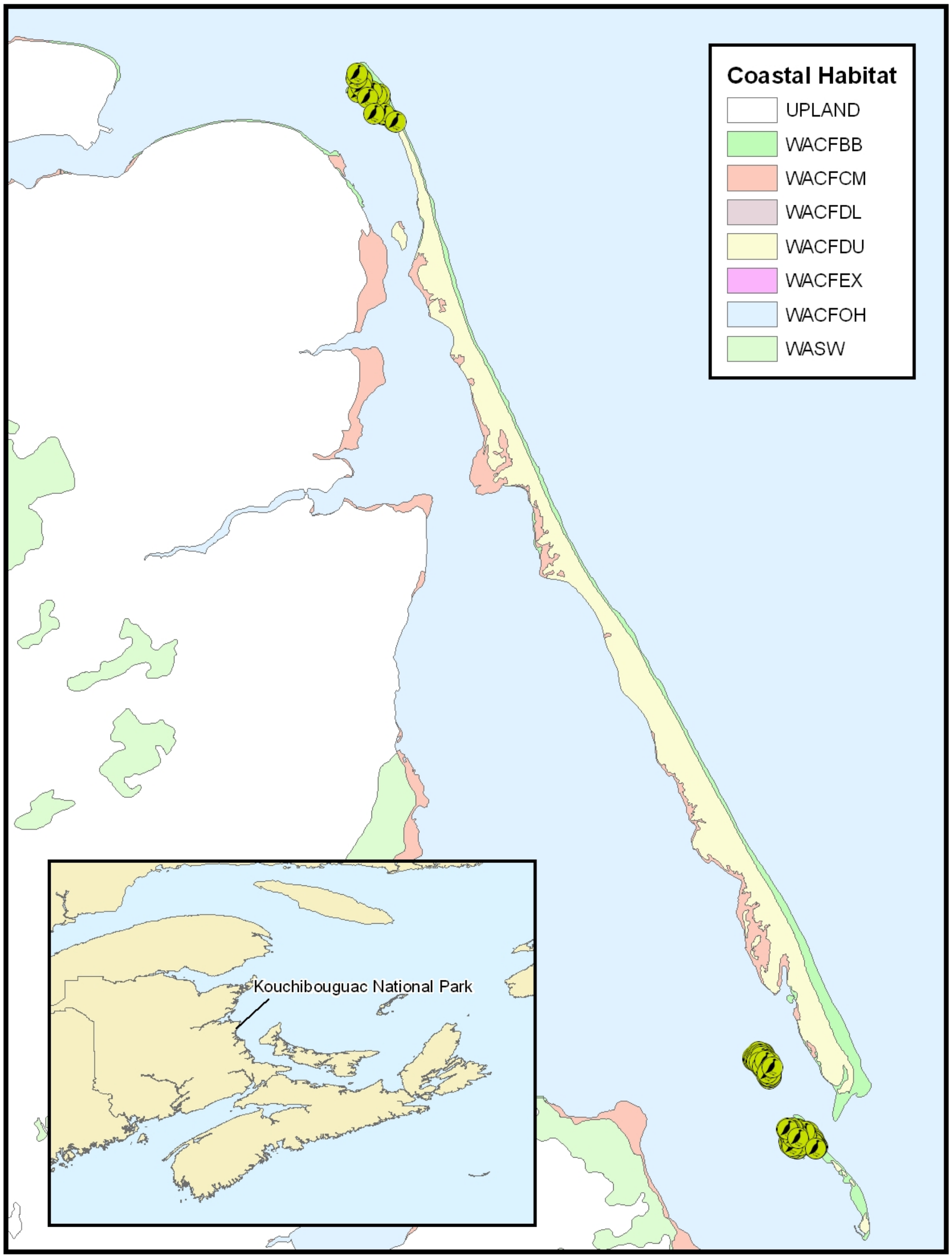

Figure 20. Red-breasted Merganser (*Mergus serrator*) nesting sites (represented as green circles) on Kelly's Island (north) and the three Tern Islands (south) at Kouchibouguac National Park, 2002–2005. Areas in yellow (WACFDU) are dunes, light green (WACFBB) is backshore beach and pink is coastal marsh (WACFCM).

Table 17. Distribution of Red-breasted Merganser nests in Kouchibouguac National Park, 2002–2005: the mean estimated elevation of the nest (m above mean sea level, CGVD28), standard deviation and number of nests flooded at sea levels of 0.60 m, 2.55 m, 3.05 m and 3.20 m above DEM datum. The distance of the nest to the normal high-tide line is also provided.

Island	Year	No. of nests	Elevation (m)	SD	Flood 0.60 m	Flood 2.55 m	Flood 3.05 m	Flood 3.20 m	Distance to water (m)	SD
Kelly’s	2002	5	1.69	0.96	0	3	5	5	43.82	25.71
Kelly’s	2003	6	2.26	0.17	0	6	6	6	31.85	17.15
Kelly’s	2004	3	1.96	0.51	0	3	3	3	24.03	16.78
Kelly’s	2005	4	2.01	0.26	0	4	4	4	10.25	6.25
Kelly’s	**All**	**18**	**2.00**	**0.57**	**0**	**16**	**18**	**18**	**29.07**	**20.90**
Tern 1	2002	19	2.02	0.55	0	17	18	19	19.89	9.77
Tern 1	2003	23	2.30	0.49	0	18	21	22	14.87	7.34
Tern 1	2004	23	2.05	0.38	0	19	23	23	15.16	8.99
Tern 1	2005	43	2.54	0.49	0	19	38	41	13.08	6.36
Tern 1	**All**	**108**	**2.29**	**0.52**	**0**	**73**	**100**	**105**	**15.10**	**8.08**
Tern 2	2002	10	1.88	0.32	0	9	10	10	27.62	18.81
Tern 2	2003	13	1.98	0.27	0	13	13	13	13.83	9.08
Tern 2	2004	11	2.14	0.34	0	10	11	11	19.35	10.79
Tern 2	2005	16	2.04	0.23	0	16	16	16	14.88	11.36
Tern 2	**All**	**50**	**2.01**	**0.29**	**0**	**48**	**50**	**50**	**18.14**	**13.25**
Tern 3	2002	6	1.45	0.38	0	6	6	6	14.00	9.22
Tern 3	2003	12	2.13	0.16	0	12	12	12	12.34	4.74
Tern 3	2004	7	1.84	0.43	0	7	7	7	6.47	2.23
Tern 3	2005	14	2.07	0.18	0	14	14	14	8.44	3.86
Tern 3	**All**	**39**	**1.95**	**0.35**	**0**	**39**	**39**	**39**	**10.14**	**5.57**
All	**All**	**215**	**2.14**	**0.48**	**0**	**176**	**207**	**212**	**16.08**	**11.62**

4.6.7.4 Summary and conclusions

Spring and early-summer coastal storm surges in eastern New Brunswick may have severe impacts on the population dynamics of breeding Red-breasted Mergansers on the barrier islands of Kouchibouguac National Park. Most merganser nests monitored from 2002 to 2005 at Kouchibouguac were found to be close to the water both horizontally and vertically, and results from the four water-level scenarios suggested that most would have been subjected to flooding with most storm-surge scenarios. A storm surge with a water level of 2.55 m above DEM datum (like the level of the storm of January 21, 2000) during the breeding season would have led to flooding of most nests and possibly inflicted high nest and egg mortality within the local population throughout the four-year period. Storm surges in excess of 3.05 m would have flooded all but eight nests, whereas surges over 3.2 m would have flooded all but three nests. The predicted sea-level rise of 0.60 cm over the next century would exacerbate catastrophic flooding during periods of storm surges. Also, flooding may occur during other periods of the year such as fall storms and would subject the nesting islands to additional forces of physical change.

A coastal storm in the Gulf of St. Lawrence on June 23, 1993, resulted in a tidal surge that had a direct impact on merganser breeding success on the three Tern Islands (Titman, 1997). This event was recorded as a water level of 2.07 m above CD at the Escuminac tide gauge, with an associated storm surge of 0.725 m (see Section 4.6.9). Flooding of the barrier islands led to many breeding hens abandoning their nests, and nest success was lowest in 1993 (22.3%) since annual monitoring of reproductive success began at Kouchibouguac in 1992 (Mayfield, 1961; R. Titman, unpubl. data). The spring storm surge in 1993 also appeared to influence the number of females returning to breed on the islands in several years following the storm.

As discussed in Section 4.6.6, sea-level rise and storm surges would also flood Common Tern nests, and this reduced tern vigilance would possibly result in increased predation on merganser nests and hens by a variety of avian species, including gulls, crows, owls and Northern Harriers (Young and Titman, 1986).

Merganser hens at Kouchibouguac may actively seek elevated nest sites to reduce flooding probabilities. From 2002 to 2005, nests were more often found clumped at higher densities along island ridges than in lower-lying regions (S. Craik, pers. obs.). These elevated beach ridges, which may extend more than 3 m above sea level, are created by wind accretion when southwest winds deflate back dune areas and build up dunes along the ocean dune cliffs (Desloges, 1980). An extensive ridge at Tern Island 1 supported 10–15 nests annually, and many of these nests were located less than 1 m from another nest site. These observations supported our findings that nearly 35% of nests on Tern Island 1 would not have been flooded during a storm surge of 2.55 m, whereas all but four nests on the remaining three islands would have been flooded at the 2.55-m surge level. Since microhabitat conditions at ridge locations often appear similar to those observed at lower-lying regions (e.g., vegetation height, density and concealment), it is possible that merganser hens prefer nest sites that are elevated in order to reduce flooding probabilities.

Many of the observed and predicted changes in coastline and offshore islands discussed in Section 4.5 will change the suitability of the nesting islands from year to year. Over time, if there is change versus annual variation in the distribution and quality of habitat for nesting Red-breasted Mergansers, there is the potential for impacts. Conserving habitat for the Red-breasted Merganser and other ground-nesting birds of sandy habitats will require a landscape approach, due to the potential for annual and longer-term variation in habitat suitability.

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4.6.8 Impacts of sea-level rise and storm surge on Piping Plover habitat[23,24]

4.6.8.1 Introduction

Atlantic Canada's coastal zones are important as both foraging and breeding habitat for numerous migratory bird species. Several of these birds have been designated as Endangered, Threatened or Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The Piping Plover relies on the sandy coastal beaches in Atlantic Canada for breeding. This species was listed as Endangered by COSEWIC in 1985 (Goossen et al., 2002). In May 2001, the species was re-examined and split into groups according to subspecies. Both Piping Plover subspecies, *Charadrius melodus melodus* and *Charadrius melodus circumcinctus*, were listed separately as Endangered.

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The Piping Plover arrives on the beaches in New Brunswick between late April and early May and immediately begins to establish breeding territories. If nesting attempts are successful (i.e., if eggs hatch), the birds will remain on the beaches until the chicks fledge. If first nesting attempts are unsuccessful, Piping Plovers may renest. In some years, renesting Piping Plovers will remain on the beaches until late August. Threats to this species involve depredation, human disturbance (by beach visitors and all-terrain vehicle users) and habitat loss and degradation (Haig, 1992; Melvin et al., 1994; Goossen et al., 2002).

In New Brunswick, there exist both provincial and federal legislation for the protection of species at risk, including the Piping Plover (Goossen et al., 2002). There are also Piping Plover monitoring programs put in place by the Piper Project (the Acadian Peninsula), the Irving Eco-Centre in Bouctouche and Kouchibouguac National Park. These programs monitor the breeding activity of Piping Plovers, gather productivity data, fence off nest sites or close breeding beaches and aim to educate beach visitors and the general public about Piping Plover biology and conservation (CWS, 2004).

Although there is much work being done to help manage and conserve Piping Plovers in New Brunswick, global climate change and local crustal subsidence have the potential to negatively impact these individuals. It is thought that rising sea level will directly impact the availability of habitat, including breeding habitat for Piping Plovers (Austin and Rehfisch, 2003). While a loss of breeding and foraging habitat may lead to a reduction in population size, it is unknown exactly how sea-level rise will affect this population, as the impacts are largely dependent on the ability of the species to alter its habitat use (Dolman and Sutherland, 1995; Galbraith et al., 2002).

This study examined current habitat availability for breeding Piping Plovers in southeastern New Brunswick to determine whether habitat is currently limiting population growth and how the amount of available habitat will change with sea-level rise.

4.6.8.2 Methods

The Canadian Wildlife Service Piping Plover database (CWS, 2004) was queried to identify all beaches between Kouchibouguac National Park and Cape Jourimain National Wildlife Area with occupied, unoccupied or potential breeding beach (Table 18; Figure 21).

An occupied breeding site was considered to be any beach that had at least one breeding pair of Piping Plovers during the period 2000–2005. Former breeding sites had breeding Piping Plovers in the past, but remained unoccupied for the period 2000–2005. These sites continue to be surveyed. Potential breeding sites are those sites that have been determined to contain habitat suitable for breeding Piping Plovers. These sites are censused on a yearly basis or at least during the International Piping Plover Census years and have not yet had a recorded breeding pair (Goosen and Amirault, 2004).

Table 18. List of current, former and potential Piping Plover breeding sites along the New Brunswick Northumberland Strait coast from Kouchibouguac National Park (KNP) to Cape Jourimain National Wildlife Area.

Current breeding sites	Former breeding sites	Potential breeding sites
Bouctouche Bar	Bar-de-Cocagne	Cap Bimet West
Cape Jourimain	Cadman (Corner) Point	Cap-Brûlé East
Chockpish	Johnston Point	Cocagne Island
Côte-Sainte-Anne	Little Cape	Pointe Grande-Digue
North Kouchibouguac Dune, KNP	North Island, KNP	Quai de Saint-Édouard
North Richibucto Dune, KNP	Petit Barachois	Shediac Island
Pointe-Sapin Dune, KNP	Tern Islands, KNP	
Portage River Dune, KNP		
South Kouchibouguac Dune, KNP		
South Richibucto (Cap-Lumière)		
South Richibucto (North Barrier Island)		

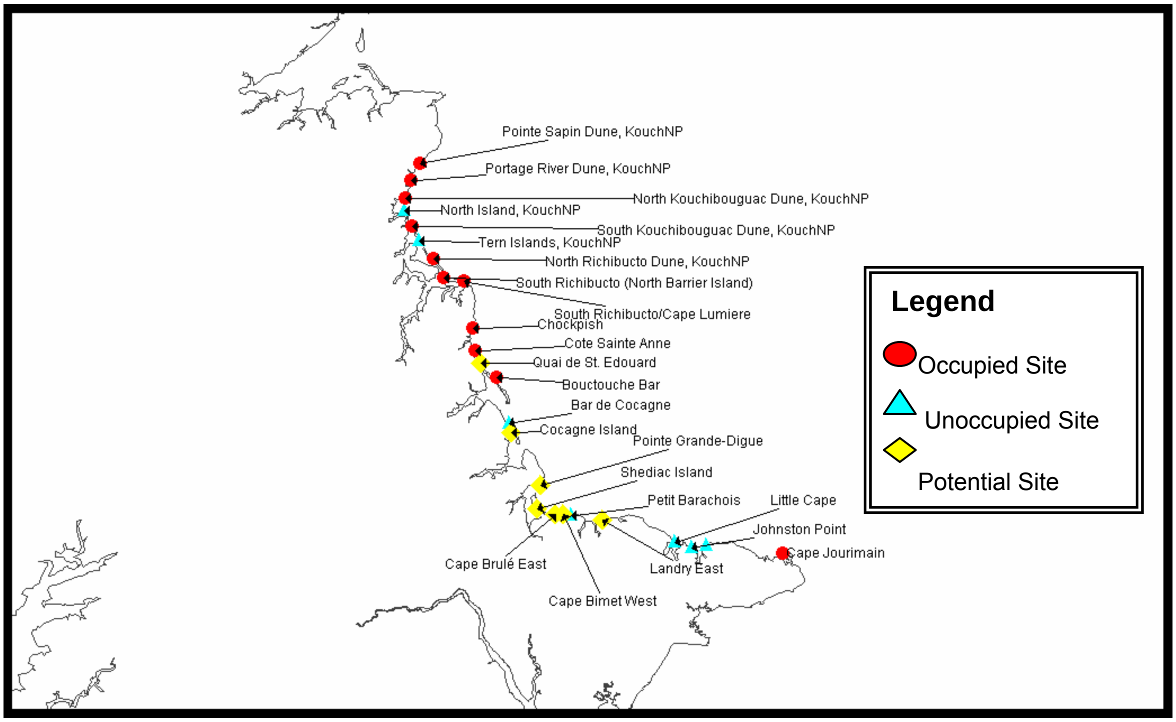

Figure 21. The distribution of occupied, unoccupied and potential Piping Plover habitat along the southeastern New Brunswick coastline.

Details of GIS mapping techniques can be found in Hanson (2006).

4.6.8.3 Results

4.6.8.3.1 Beach length

The length of coastline was measured on 11 occupied, 11 unoccupied and 11 potential Piping Plover breeding sites. Mean length of occupied Piping Plover beaches was significantly greater than mean length of the unoccupied or potential breeding beaches (Tables 19 and 20). There was no significant difference detected between the lengths of unoccupied or potential beaches.

4.6.8.3.2 Beach width

Beach widths were measured at 50-m intervals along the entire coastline on each study beach. The beach width was greatest at the occupied sites, which had a mean width of 43 ± 12 m (Figure 22). There was a marginal difference in the beach widths of unoccupied (22 ± 34 m) and potential (16 ± 4 m) breeding sites. A t-test (95% significance level) was used to compare the means of the beach widths among occupied, unoccupied and potential sites (Table 19). When the beach widths were compared, there was a significant difference in beach width detected between occupied and potential beaches.

Table 19. Comparison of beach length, mean beach width and the area of sand between occupied, unoccupied and potential breeding beaches.

Grouping variable	Test variable	t	Degrees of freedom	p-value
Occupied vs. unoccupied	Beach length	4.35	9.73	≤0.001
Occupied vs. potential	Beach length	4.455	19	≤0.001
Unoccupied vs. potential	Beach length	0.059	20	>0.05
Occupied vs. unoccupied.	Mean beach width	1.955	12.542	>0.05
Occupied vs. potential	Mean beach width	7.133	12.35	≤0.001
Unoccupied vs. potential	Mean beach width	0.586	10.298	>0.05
Unoccupied vs. potential	Area of sand	−1.271	14.480	>0.05

Table 20. Mean beach lengths of occupied, unoccupied and potential Piping Plover breeding sites in southeastern New Brunswick.

Status of beach	Mean beach length (m)
Occupied (n = 11)	5033 ± 2910
Unoccupied (n = 11)	913 ± 662
Potential (n = 11)	900 ± 276

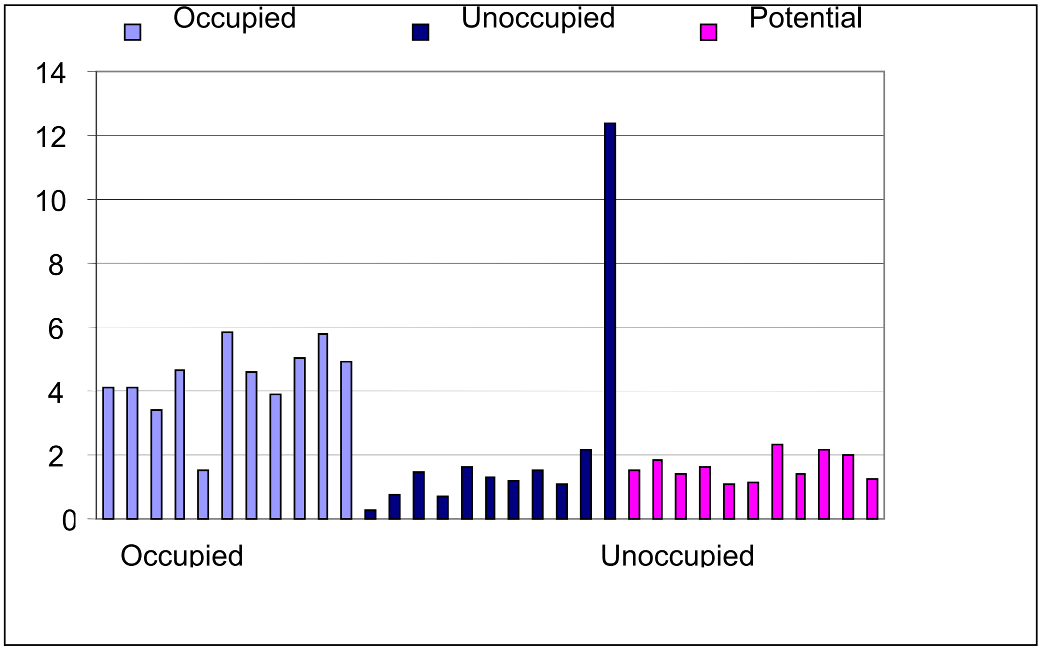

Figure 22. Mean width (in metres) of occupied (n = 11), unoccupied (n = 11) and potential (n = 11) Piping Plover breeding beaches.

4.6.8.3.3 Area of sand

The area of open sand was calculated at 9 unoccupied and 11 potential breeding sites. There was a significant difference in the area of sandy habitat on unoccupied (10 987 ± 8321 m^2) and potential (15 233 ± 6174 m^2) breeding beaches (Table 19).

4.6.8.3.4 Beach slope

Minimum, maximum and mean slopes were obtained from the slope images created with the DEM (Table 21). Potential breeding beaches had the highest minimum and maximum slopes, and occupied beaches had the lowest minimum and maximum slopes.

Table 21. The minimum, maximum and mean beach slopes on occupied, potential and unoccupied Piping Plover breeding beaches.

Status	Minimum slope	Mean slope	Maximum slope
Occupied (n = 2)	0	2.5	5
Potential (n = 7)	0.57	3	7.72
Unoccupied (n = 3)	0	5.8	6.33

Unoccupied Potential

4.6.8.3.5 Beach characteristics

Air photos or vector layers for every study site were studied, and beach characteristics were analyzed. Occupied beaches had the highest proportion of blowouts (0.45), ephemeral pools (0.45) and forest patches (0.64) (Figure 23). No potential sites contained blowouts or ephemeral pools, and all unoccupied sites were adjacent to back bays and sand spits.

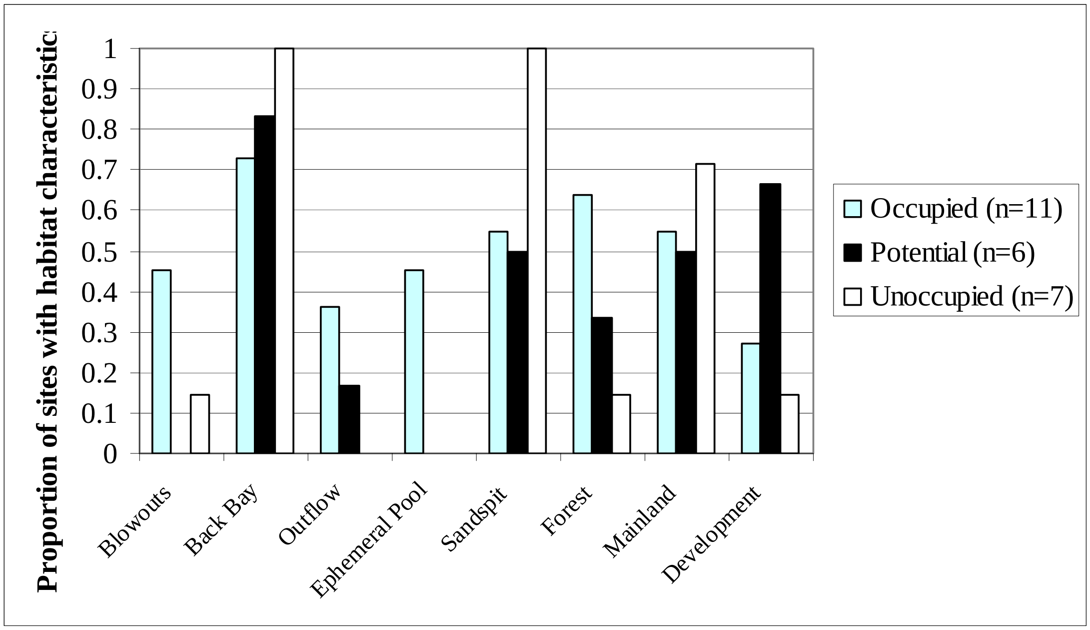

Figure 23. The proportion occupied (n = 11), potential (n = 6) and unoccupied (n = 7) Piping Plover breeding beaches characterized by blowouts, back bays, outflows, ephemeral pools, sand spits, forest patches, mainland and human artifacts or development.

4.6.8.3.6 Shemogue trends

Habitat attributes were measured at two sites (Petit-Cap and Johnston Point) on vector images representing the shorelines of these locations during 1944, 1953, 1963, 1971, 1982, 1996 and 2001. The length of the Petit-Cap beach decreased by 55% between 1944 and 1953 and then increased by 30% between 1953 and 2001 (Figure 24). The length of Johnston Point beach decreased by 21% between 1944 and 2001.

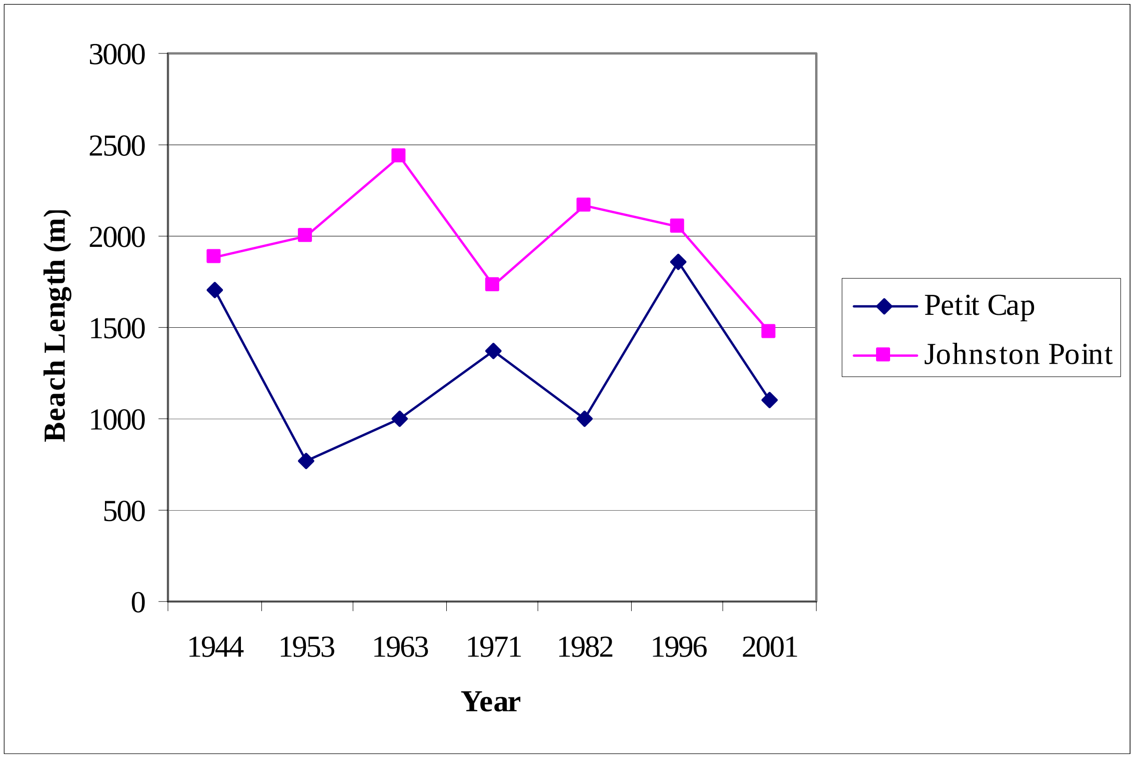

Figure 24. The length of coastline at Petit-Cap and Johnston Point beaches from 1944 to 2001.

Beach width was quantified at Petit-Cap and Johnston Point by measuring transects at 50-m intervals along the coastline. Mean beach width in 1971 increased from 1944 (Petit-Cap, 25%; Johnston Point, 31%). However, beach width declined for both Petit-Cap and Johnston Point (by 48% and 34%, respectively) in 2001 (Figure 25).

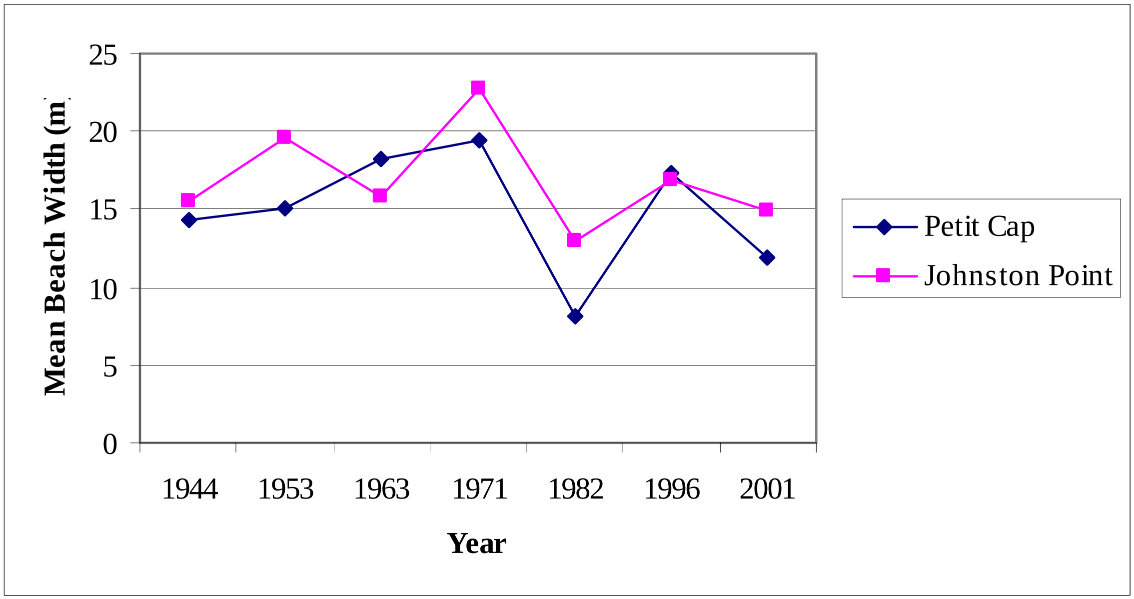

Figure 25. The mean beach width of Petit-Cap and Johnston Point sites from 1944 to 2001.

The area of sand at Petit-Cap and Johnston Point was calculated from 1944 to 2001. The area of sand for both Petit-Cap and Johnston Point increased from 1944 levels in 1971 (by 33% and 52%). By 2001, however, the area of sand for both sites had decreased by 37% (Petit-Cap) and 63% (Johnston Point) (Figure 26).

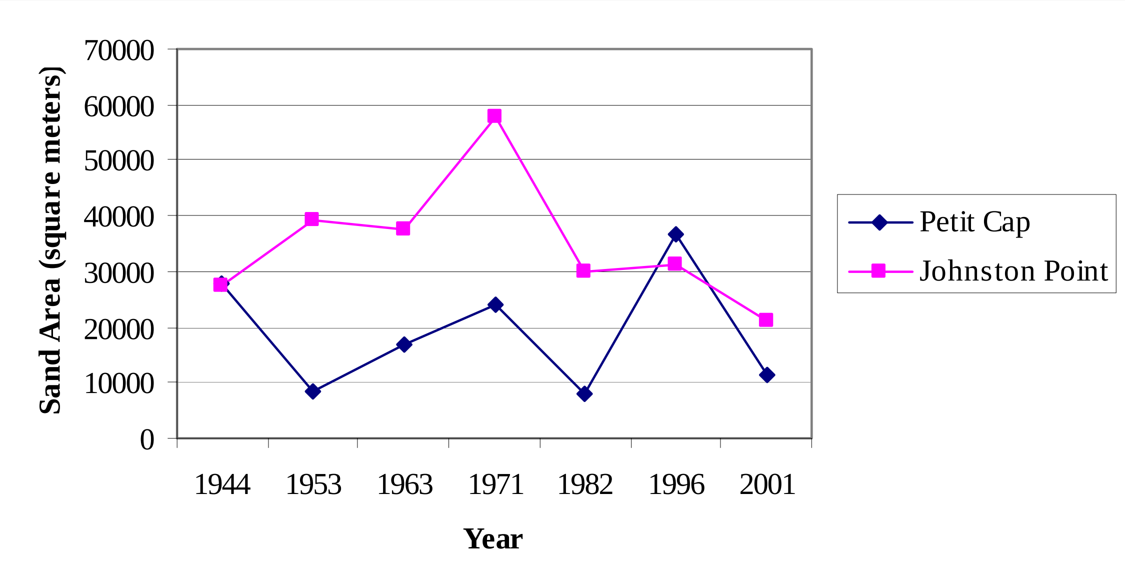

Figure 26. The total area of sand at Petit-Cap and Johnston Point from 1944 to 2001.

4.6.8.4 Summary and conclusions

4.6.8.4.1 Current habitat conditions

Habitat features on occupied, unoccupied and potential breeding beaches were analyzed and measured by studying aerial photos, representative vector layers and Quickbird imagery. Significant differences existed between the physical attributes of occupied, unoccupied and potential habitat.

Occupied beaches were greater in length than unoccupied and potential beaches. Piping Plovers forage along the shoreline and in the intertidal zone following the receding tide (Cairns, 1977; Burger, 1984; Loegering and Fraser, 1995); hence, beach length would be a very important feature.

The importance of beach width has been documented by Prindiville Gaines and Ryan (1988), Dundas (1995), Boyne and Amirault (1999) and Stewart (2004). It is thought that nests on wider beaches can be situated farther from the mean high-water mark and the vegetation line, making them less prone to flooding and more difficult for predators to detect (Burger, 1987; Prindiville Gaines and Ryan, 1988; Espie et al., 1996).

The area of sand was measured on both unoccupied and potential sites. Whereas occupied beaches were significantly wider and longer, the highly correlated variable of area was not calculated. There was no significant difference detected between the amount of sandy habitat on unoccupied and potential sites.

Occupied beaches have the lowest surface slopes, and potential sites have the highest surface slopes. This is consistent with previous findings of Boyne and Amirault (1999), who observed that Piping Plovers nesting on the Gulf of St. Lawrence occupied sections of beach that had shallower slopes. Beaches with a shallow, vegetated foredune are superior for raising broods because they provide additional cover for broods from the sun, wind, rain and avian predators (Burger, 1987).

Several occupied beaches had blowouts present. Blowouts are wide, sparsely vegetated areas where a dune breach has occurred. These areas have been documented to be important as habitat for nesting Piping Plovers (Cairns, 1977; Burger, 1987; Boyne and Amirault, 1999; Stewart, 2004).

The majority of study sites had access to a back bay or were considered to be sand spits. Outflows and ephemeral pools occurred only on occupied beaches, with the exception of Quai de Saint-Édouard-de-Kent. This is a potential breeding beach with an outflow. Beaches that are sand spits or that have access to a back bay are considered to be higher-quality habitat for breeding Piping Plovers. Stewart (2004) found that occupied beaches were characterized by having a greater proportion of bay and mudflat habitat.

Piping Plovers forage along the shoreline or in the intertidal zone during low tide and will retreat to other areas such as the wrack line to forage during high tide (Cairns, 1977; Burger, 1984; Loegering and Fraser, 1995). If the breeding beach has access to two shorelines as opposed to just one, the amount of foraging habitat is essentially doubled.

The majority (63%) of breeding beaches in southeastern New Brunswick are protected or occur in parks. Very few (15%) of the unoccupied/potential sites are protected beaches. These protected breeding beaches are undeveloped and do not have infrastructure in close proximity to the beach. Areas with high human recreational activity experience reduced fledge rates, as disturbance results in a decrease in foraging time and adult maintenance (Cairns and McLaren, 1980; Flemming, 1984; Flemming et al., 1988; Burger, 1991; Goldin and Regosin, 1998).

4.6.8.4.2 Shemogue trends

The beach length, mean width and area of sand were measured at two sites in the Shemogue Area, from images taken in 1944, 1953, 1963, 1971, 1982, 1996 and 2001. Although beach area changed dramatically over time, there was no overall trend associated with these changes. However, when the results from the entire Shemogue area were analyzed (O'Carroll et al., Section 4.5 of this report), the amount of sand habitat in the region decreased by 25% between 1944 and 2001. Also, the amount of blowout area decreased by 53%, and the amount of infrastructure increased from 0% to 3% of coastal habitat in the region (O'Carroll, 2004).

These findings indicate that while the amount of sandy beach or Piping Plover habitat in the region is decreasing, the amount of infrastructure (and consequently human disturbance) is increasing. It has been suggested that increasing human disturbance rather than physical habitat change has been the reason for abandonment of previously occupied breeding habitat.

While a given beach currently may have the habitat characteristics to be a suitable breeding site for Piping Plovers, it is important to keep in mind that coastal environments are very dynamic and that a site that is currently suitable may become unsuitable, and vice versa. The extent to which coastal morphodynamics will impact wildlife populations depends on the species' ability to use other habitats or disperse (Dolman and Sutherland, 1995).

4.6.8.4.3 Implications for habitat management

Based on the findings of this study and the literature, occupied beaches have these characteristics: longer stretches of coastline; wider sections of beach; a greater area of sand; shallower beach and dune slopes; blowouts or dune breaches; sand spits; access to a back bay, outflows or ephemeral pools; and less infrastructure adjacent to the beach.

With sea-level rise, coastal habitat could be lost, and Piping Plovers could be forced to nest in suboptimal habitat. This is a concern, as nesting in suboptimal habitat could impact productivity, although research has indicated that habitat analysis has not been successful in predicting reproductive success (Knetter et al., 2002; Stewart, 2004). Factors that could influence productivity include nesting in close proximity to predator habitat, especially if nest exclosures are not used (Burger, 1991; Patterson et al., 1991; Knetter et al., 2002), and nesting on beaches that experience high levels of human disturbance (Cairns and McLaren, 1980; Flemming, 1984; Flemming et al., 1988; Goldin and Regosin, 1998).

Therefore, to successfully manage Piping Plover habitat in the future, it is important to determine which areas would be least impacted by sea-level rise. It is thought that the areas that are least impacted will not be abandoned by Piping Plovers, as they are known to abandon territory with the poorest habitat first, in favour of high-quality habitat (Boyne and Amirault, 1999). Piping Plovers are a management-dependent species; they require protection and conservation actions in order to survive, given the current level of coastal development and disturbance. Therefore, efforts should be made to acquire, protect and manage predator populations in areas that are projected to be of higher quality for breeding Piping Plovers in the future.

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4.6.9 Impacts of storm surge on Piping Plover nesting success at Kouchibouguac National Park[25]

4.6.9.1 Introduction

The Piping Plover (*Charadrius melodus*) is a shorebird species listed as Endangered by COSEWIC and breeds in only three Canadian national parks. Kouchibouguac National Park, proclaimed in 1979, boasts over 23 km of sandy beaches and provides some of the best potential nesting habitat for Piping Plovers in the Maritimes (see Section 4.6.8.1).

Between 1985 and 2005, an average of 14.7 breeding pairs per year were recorded in Kouchibouguac National Park. Predator exclosures have been employed where they can be monitored on a regular basis. Communications with the public, including interpretation programming, have been increased. Most management actions have

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focused on reducing the impacts of predation and human disturbance on Piping Plover nesting success. However, flooding can also have a negative impact on reproductive success of Piping Plovers. Corbett (1997) reported that in Prince Edward Island National Park, the percentage of nests lost to flooding ranged from 4% to 40% (Table 22).

The purpose of this study was to quantify the impacts that storm events have had on Piping Plover nesting success in Kouchibouguac National Park and how this may change with sea-level rise and climate change.

Table 22. Piping Plover nest losses due to storm flooding in Prince Edward Island National Park, 1983–1992 (from Corbett, 1997).

Year	No. of nests	No. of nests flooded	% loss
1983	31	2	6.4
1984	34	8	23.5
1985	34	13	38.2
1986	28	6	21.4
1987	42	1	2.4
1988	59	15	25.4
1989	45	2	4.4
1990	23	1	4.3
1991	54	19	32.2
1992	32	5	15.6
Total	382	72	18.8

4.6.9.2 Methods

For a full description of methods, see Hanson (2006).

4.6.9.2.1 Study site

Kouchibouguac National Park consists of forest lands, salt marshes, bogs, swamps and 23 km of sand dunes and secluded beaches along the Northumberland Strait of New Brunswick. The strait is very shallow near shore, and the shoreline is protected from the Gulf of St. Lawrence swells by the bulk of Prince Edward Island extending across the strait and offshore sandbars.

4.6.9.2.2 Piping Plover nesting surveys

Piping Plover surveys in national parks have employed a standard technique since 1980 to determine the number of breeding pairs, locate nests and report clutch sizes, number of eggs successfully hatched and, in most cases, the number of young successfully fledged.

4.6.9.2.3 Storm-surge events at Pointe-Sapin and Escuminac from 1964 to 2005

Storm-surge events in excess of 60 cm during the Piper Plover nesting season (May 15 to July 22) were identified in the water-level data from Pointe-Sapin (1964–1972) and Escuminac (1973–2005). This period of the year has the fewest storm events; on average, only 2.0% of all recorded storm-surge events at Escuminac occur in May, only 1.5% occur in June and only 0.5% occur in July (Parkes et al., 2006 this report. Figure

27 shows water-level data for 1995, which was a successful year for the Piping Plover at Kouchibouguac. It is a typical water-level profile for the time of year and shows modest atmospheric influences and an absence of storms. When water-level data were missing at Pointe-Sapin or Escuminac, then the water-level data at Pointe-du-Chêne or Charlottetown were scanned for events. Only one such missed event was identified (July 15, 1981), and this was reconstructed (approximately) by adding the storm surge at Pointe-du-Chêne to the predicted tide at Escuminac.

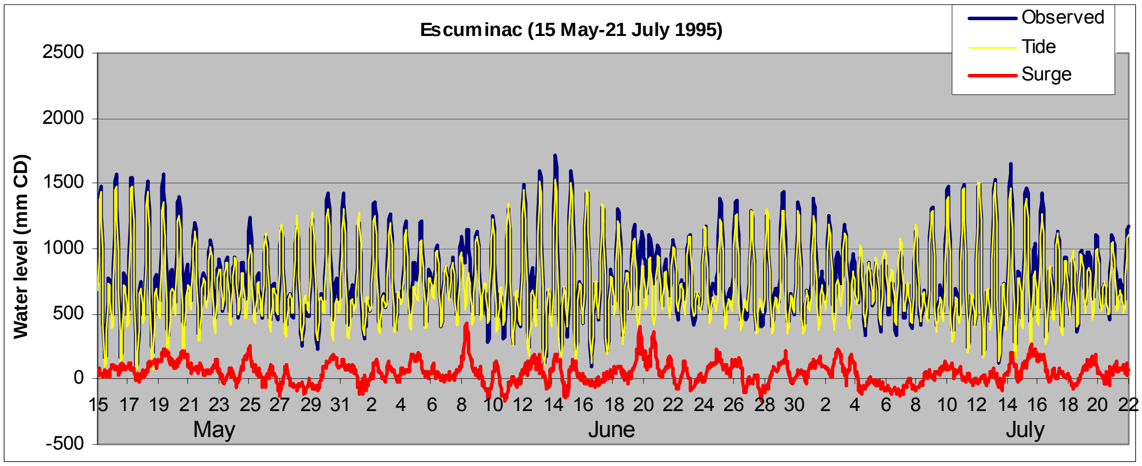

Figure 27. Typical water-level data from Escuminac during the Piping Plover nesting season.

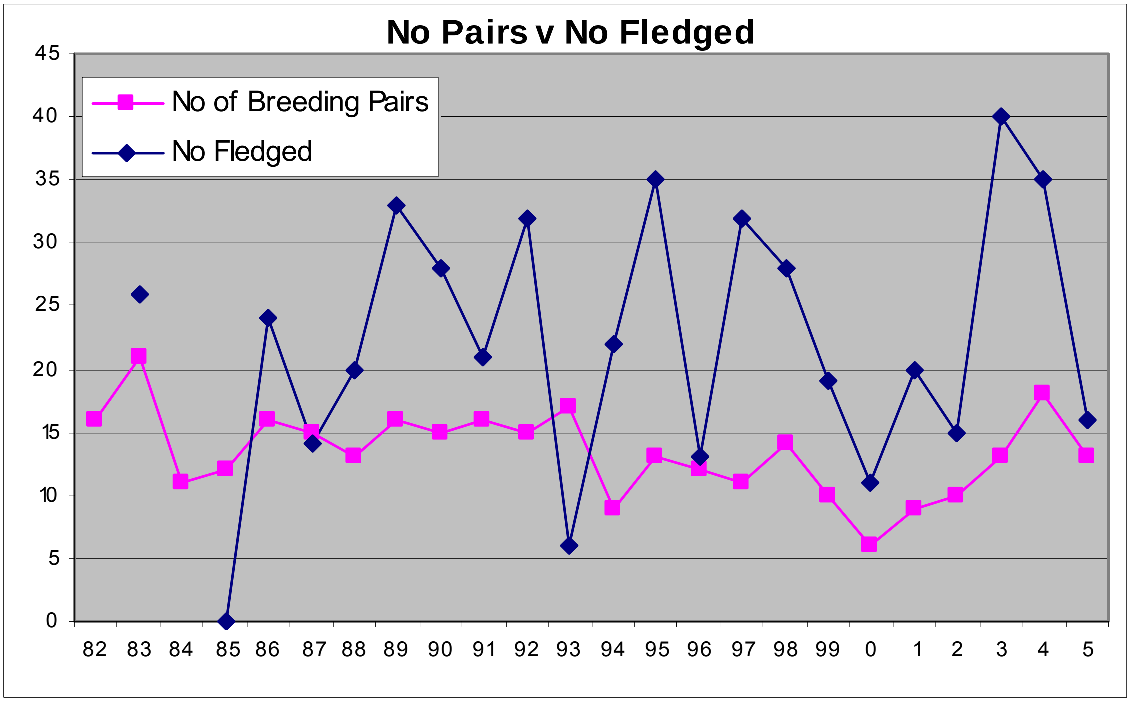

Figure 28. Total number of breeding pairs and number of young fledged at beaches at Kouchibouguac National Park, 1982–2005.

Table 23. Number of Piping Plover breeding pairs and fledged young observed at Kouchibouguac National Park, 1973–2005. NI indicates not included in surveys, NA indicates the habitat was not available.

	Number of breeding pairs in each breeding season																									
Location	73	79	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05
Plage de Pointe-Sapin	0	NI	1	1	0	1	0	0	0	0	0	1	0	1	0	1	1	1	2	2	1	1	1	1	1	1
Plage de Rivière-au-Portage	1	NI	0	1	0	0	2	0	3	3	3	3	3	3	2	1	2	2	2	1	1	4	3	1	6	0
Dune de Kouchibouguac Nord	2	NI	11	12	7	6	7	8	3	5	5	5	5	7	4	5	3	4	3	3	1	2	3	7	4	7
Île Kelly	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NA	NA	NA	NA	NA	3
Dune de Kouchibouguac Sud	3	3	2	4	2	3	7	5	6	5	5	6	6	5	3	6	6	4	7	4	3	2	3	4	6	2
Île au Sterne	1	NI	1	1	2	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dune Richibucto Nord	3	NI	0	1	NI	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0
Île du Nord	1	NI	1	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NI
Total number of pairs	11	3	16	21	11	12	16	15	13	16	15	16	15	17	9	13	12	11	14	10	6	9	10	13	18	13
Total young fledged	—	—	—	26	—	0	24	14	20	33	28	21	32	6	22	35	13	32	28	19	11	20	15	40	35	16
Ratio of young to breeding pairs	—	—	—	1.2	—	0.0	1.5	0.9	1.5	2.1	1.9	1.3	2.1	0.4	2.4	2.7	1.1	2.9	2.0	1.9	1.8	2.2	1.5	3.1	1.9	1.2

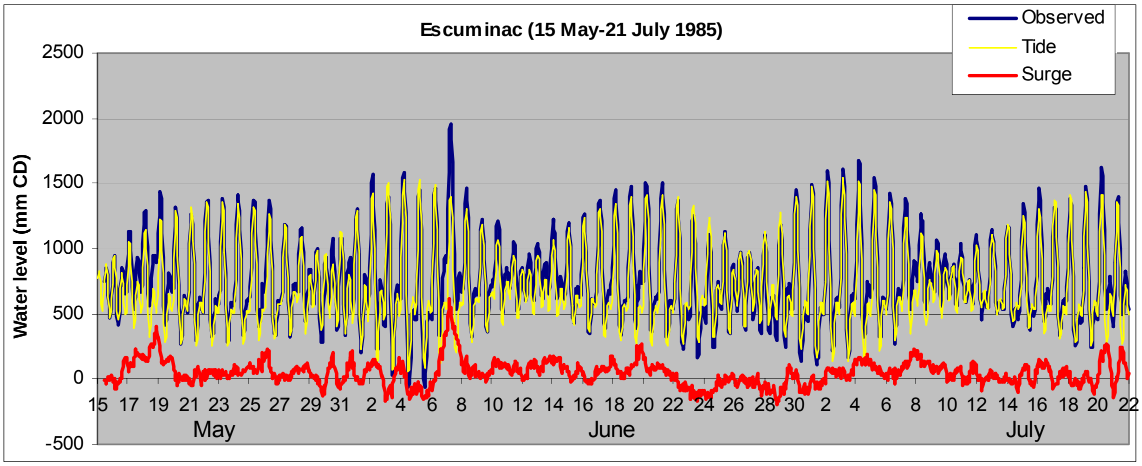

Figure 29. Water level (mm Chart Datum) from tide gauge at Point Escuminac, May 15 – July 21, 1985.

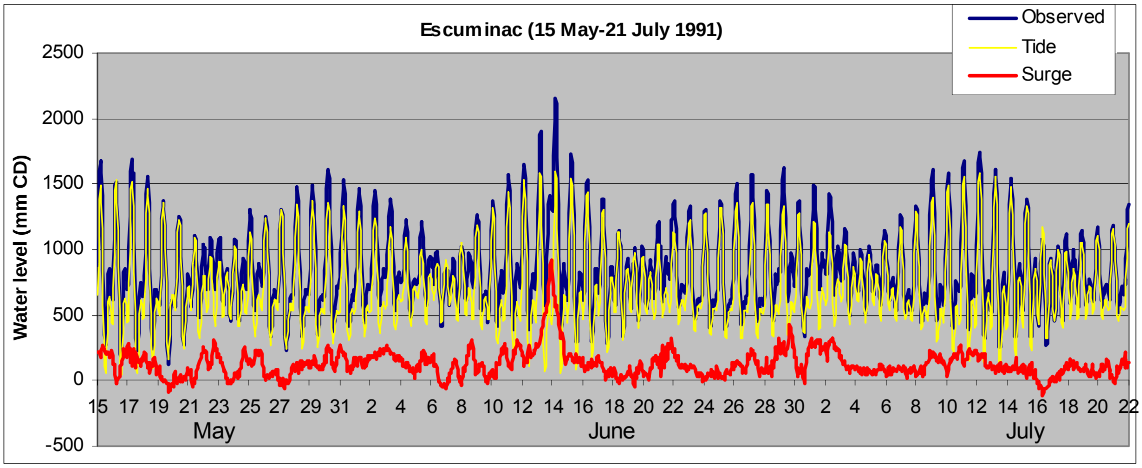

Figure 30. Water level (mm Chart Datum) from tide gauge at Point Escuminac, May 15 – July 21, 1991.

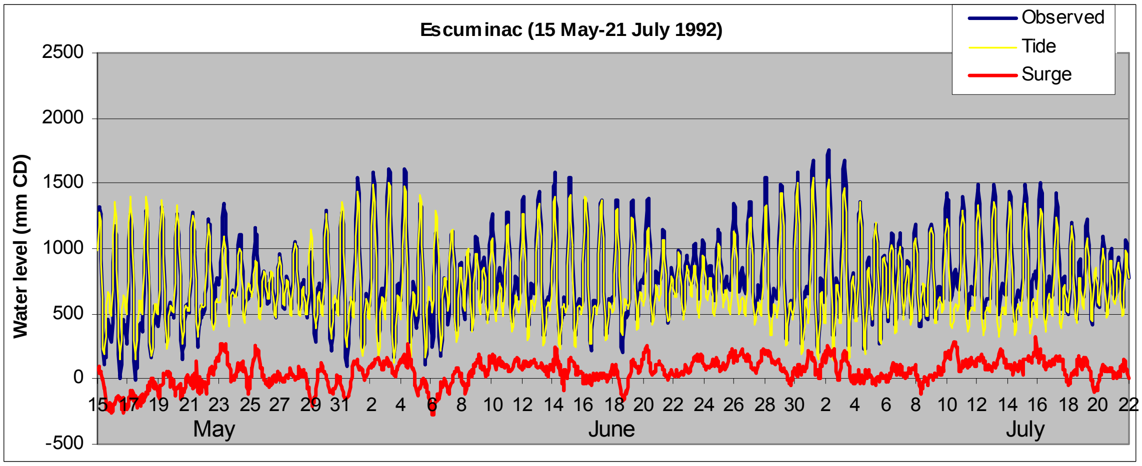

Figure 31. Water level (mm Chart Datum) from tide gauge at Point Escuminac, May 15 – July 21, 1992.

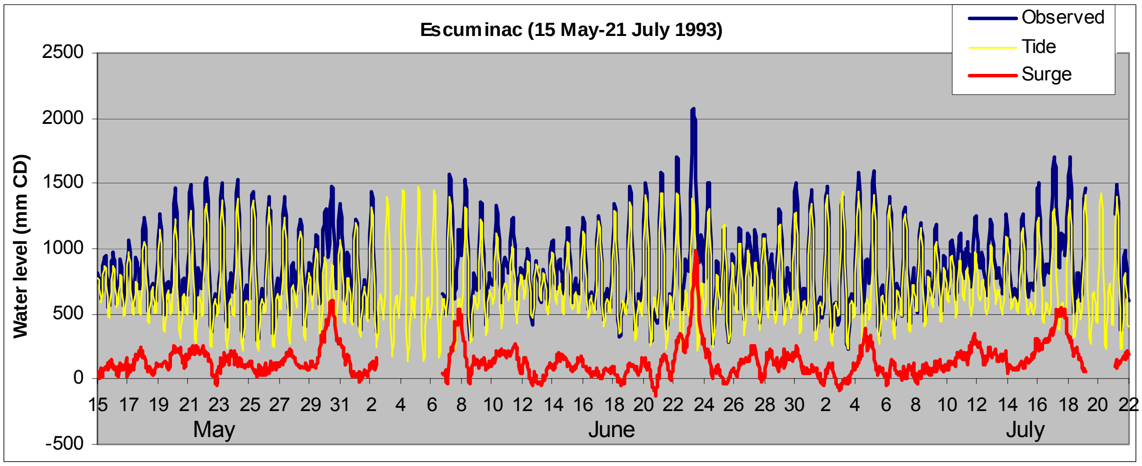

Figure 32. Water level (mm Chart Datum) from tide gauge at Point Escuminac, May 15 – July 21, 1993.

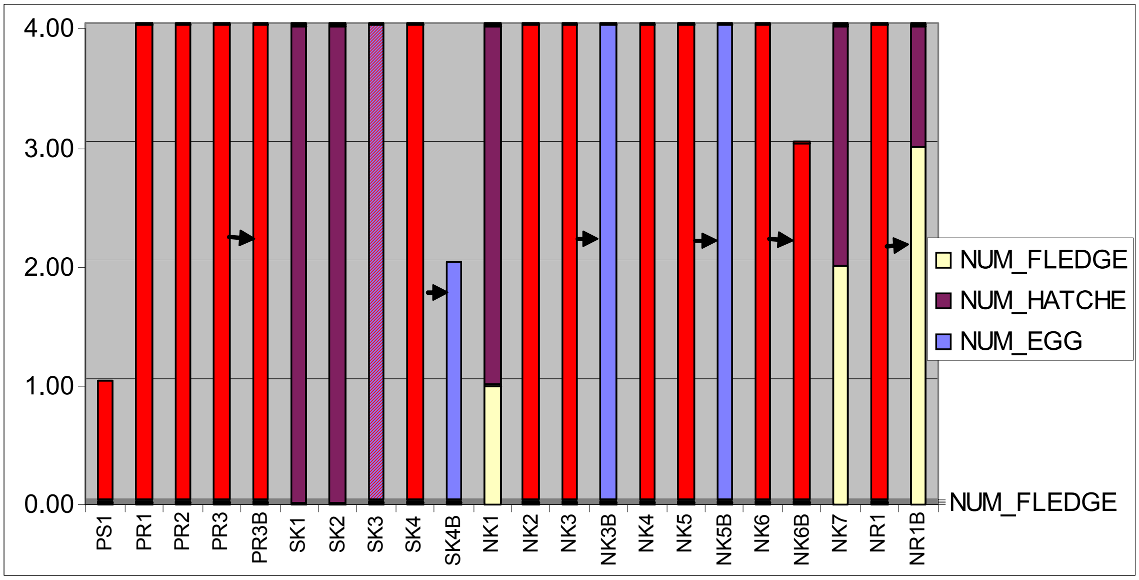

Figure 33. Piping Plover nesting success in 1993. Red indicates nest flooded. Arrows indicate renesting attempt.

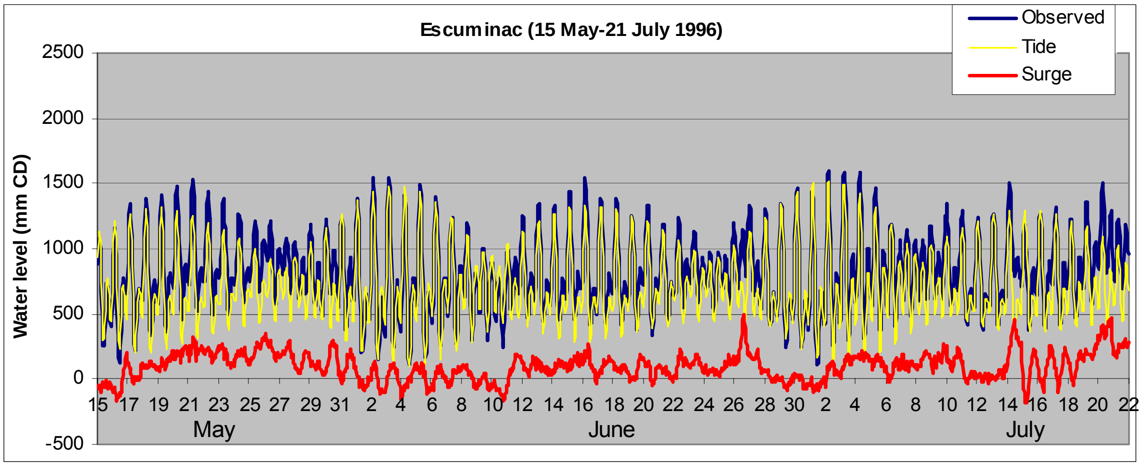

Figure 34. Water level (mm Chart Datum) from tide gauge at Point Escuminac, May 15 – July 21, 1996.

4.6.9.3 Results

4.6.9.3.1 Piping Plover breeding pairs and reproductive success

The number of Piping Plover territorial pairs and young fledged at the various nesting locations in Kouchibouguac National Park is presented in Table 23. There is considerable annual variation in the number of adults attempting to breed and reproductive success (Figure 28). In 1985, there was no young raised to fledging (Figure 28). Field observations in 1985 suggested that the reason for failed breeding was a summer storm event that flooded nests. Water-level data from Escuminac show a storm event and water levels above 2.0 m CD on June 8 associated with a new moon/high tide and a large surge event (Figure 29).

There was also lower than average reproductive success in 1991 that was associated with a major storm event on June 14, when a new moon/high tide coincided with a storm surge of 0.575 m, which resulted in a water level of 2.12 m at Escuminac (Figure 30). Field observations provided direct evidence that the cause of failure for eight nests was flooding. In contrast to 1991, there were no storm-surge events in 1992, and reproductive success was higher (Figures 28 and 31).

Breeding success was once again low in 1993 (Figure 28). Field observations indicated nest-flooding events around June 1 (three nests), June 24 (13 nests), July 10 (one nest) and July 19 (one nest, Figure 33). A storm event on June 23 with a recorded water level of 2.07 m CD and a storm surge of 0.73 m happened during the peak of nesting season (Figure 32). Water levels of 1.5 m CD on June 1, 1.60 m on July 5 and 1.70 m CD on July 18 were probably responsible for flooding those nests that were at lower elevations (Figure 32). The large storm event of June 23 during the peak of nesting was largely responsible for lack of recruitment of Piping Plovers at Kouchibouguac National Park into the population.

There was also low reproductive success in 1996. The official cause of nest loss was not well documented, with nine nests failing to hatch any eggs. Water-level data from Escuminac indicate water levels of 1.5–1.6 m CD during July 2–3 (Figure 34), indicating that flooding was probably not responsible for the low reproductive success.

4.6.9.3.2 Storm-surge events at Pointe-Sapin and Escuminac from 1964 to 2005

Whereas water levels have an impact on nesting success of Piping Plovers, we examined the historical water levels at Point Escuminac to determine the frequency of events during the Piping Plover nesting season. Nine 0.6-m or greater storm-surge events were identified, and these are listed in Table 24. There was one event during the period 1964–1969, one event during the 1970s, three events during the 1980s and four events during the 1990s. There have been no events yet during the 2000s. This relatively short period does not allow for determination of whether this decadal variation represents a trend, but it does indicate that a series of storm events may have been a contributing factor to population declines of Piping Plovers during the last 20 years.

Table 24. Storm-surge events recorded at Pointe Escuminac. The "duration" is the duration in hours of the event in excess of 60 cm.

Event	Date	Year	Duration (hours)	Surge height (m CD)	Maximum water level (m CD)
1	July 7	1969	2	0.64	1.13
2	June 12	1976	7	0.83	2.30
3	June 10	1981	13	0.71	1.66
4	July 15	1981	8	0.83	1.88
5	June 7	1985	0	0.59	1.95
6	July 11	1989	2	0.61	1.48
7	June 13–14	1991	10	0.89	2.16
8	June 23	1993	9	0.96	2.07
9	May 26	1997	5	0.65	1.57
10	June 5	1998	2	0.61	1.44

Wave data collected during this study confirm a close correlation between storm-surge height and wave height off the coast of southeastern New Brunswick, so that the storm-surge values may be used to some degree as a proxy for wave heights. Storm-surge events, however, may not be coincident with high tide and may not therefore generate unusually high mean water levels, although their attendant waves will still run to some higher level over the beach. Storm surges at high tide are, as always, the main events of concern. Highest astronomical tide (HAT) at Escuminac is approximately 1.7 m CD. Of the 10 storm-surge events listed in Table 24, 5 of them were at or near low tide and failed to reach HAT (events 1, 3, 6, 9 and 10). The other five events (which were generally larger and of longer duration) exceeded or far exceeded HAT.

It should be noted that lesser storm surges at the very highest tides could create high water levels (i.e., a 30-cm surge at HAT would reach 2.0 m CD, and a 40-cm surge would reach 2.1 m CD). These lesser storm-surge heights, however, would have less impact, because the attendant ocean waves would be considerably smaller. The database was examined for water levels in excess of 1.8 m during the Piping Plover nesting season. Only four such events were found:

- May 27 and June 23, 2005, when very minor residuals (of 16 and 10 cm) combined with runs of the highest tides to reach 1.81 m CD;

- June 15, 1984, when a 45-cm storm surge combined with high tide to reach a water level of 1.80 m CD; and
- May 27, 1994, when a 56-cm storm surge combined with high tide to reach a water level of 1.94 m CD.

The event of May 27, 1994, is the only other threatening candidate in the database and could potentially have had significant impacts on the Piping Plover. The event, however, was early in the nesting season, and the Kouchibouguac Park staff field notes for that year only recorded one nesting pair at the time, which apparently was in an elevated, well-protected site.

Event number 2 in Table 24 on June 12, 1976, was a very significant storm. It ranks number 10 in the list of high-water-level events in the entire annual 43-year Pointe-Sapin and Escuminac water-level database (Parkes et al., 2006a this volume It reached a water level of 2.30 m CD (Figure 35), just 17 cm less than the record set by Hurricane Gladys on October 21, 1968. The storm predates monitoring of Piping Plovers at Kouchibouguac National Park, but its arrival in the middle of the nesting season indicates that it would have had a highly disruptive impact on the birds and their habitat.

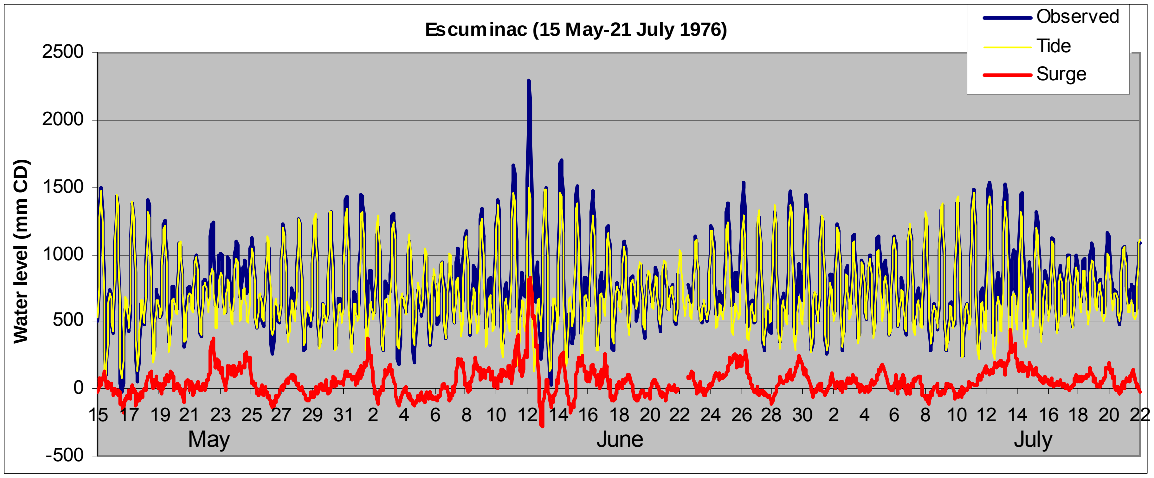

Figure 35. Escuminac water-level data during the 1976 Piping Plover nesting season.

4.6.9.3.3 Storm-surge events at Charlottetown from 1938 to 2005

The Charlottetown storm-surge database from 1938 to 2005, created for the storm-surge climatology section of this report (see Section 4.2.4), was examined for 60-cm storm-surge events during the period of the Piping Plover nesting season. This database is of a longer period than that for Escuminac, so it was examined for decadal trends. Only four such events came to light, even fewer than at Pointe-Sapin/Escuminac (Table 25). Fewer storm-surge events at Charlottetown than at Escuminac may reflect the somewhat protected nature of Charlottetown compared with Escuminac. It also should be noted that the majority of Piping Plovers nesting in Prince Edward Island do so along the north shore.

Table 25. Storm-surge events greater than 0.60 m CD at Charlottetown, Prince Edward Island, during 1938–2005.

Event	Date	Year	Duration (hours)	Surge height (m CD)	Maximum water level (m CD)
1	May 25	1953	4	0.79	2.54
2	June 20	1959	2	0.63	2.28
3	May 23	1972	1	0.65	2.74
4	July 5	1979	1	0.66	–

Four of the 10 events found at Pointe-Sapin/Escuminac show up as 50- to 60-cm events at Charlottetown. The other six show up as residuals in the range of 30–50 cm.

The storm of June 19–20, 1959, is the only tropical cyclone identified in these 14 storm-surge events found during the Piping Plover nesting season. This storm is also known as the Escuminac Disaster, since it caught the Escuminac salmon fishing fleet at sea, with tragic consequences and loss of life. The storm surge at Charlottetown was out of phase with the tide and occurred during a run of spring tides. Along the New Brunswick coast, storm-force northeasterly winds prevailed (since the storm was centred over Northumberland Strait) and the storm surge was almost certainly larger. Very high tides are reported to have accompanied the storm (Saunders, 1960), with overtopping of wharves in the Newcastle area (Kindervater, 1984) and massive pounding surf in the nearshore.

4.6.9.4 Summary and conclusions

Several previous studies have determined the negative impact of human disturbance on Piping Plover reproductive success. Strauss (1990) studied a breeding population of Piping Plovers on Cape Cod, Massachusetts, between 1982 and 1989. The population was subject to variable degrees of human disturbance that ranged from occasional pedestrian activity to intensive off-road motor vehicle traffic. He found that reproductive success (fledglings per pair per year) was higher for plovers nesting in low-disturbance regions (1.12) than in areas of high human disturbance (0.47). Hatching success did not vary significantly between areas, but the probability of a chick fledging was higher in areas of low human disturbance (54% versus 23%). MacIvor (1990) studied Piping Plovers on outer Cape Cod, Massachusetts, between 1985 and 1988. Hatching success on nine study areas was 14.5–66.3%; fledging success was 41.5–78.3%; and the number of young fledged per breeding pair was 0.30–1.33 during this period.

An analysis of Piping Plovers in the three Canadian national parks conducted by Parks Canada during the period 1985–1997 indicated that there was an overall higher rate of reproductive success (1.61 fledglings per pair per year) than for the populations studied by Strauss (1990) or MacIvor (1990), as well as a somewhat higher probability of a chick fledging (68%) compared with Strauss' least disturbed study population (Corbett, 1997). These findings suggested that the Parks' management regimes have been successful at reducing the impacts of human disturbance and predation on Piping Plovers' reproductive success. However, the ratio of young fledged to breeding pairs for Kouchibouguac National Park for the period between 1985 and 2005 indicates that the reproductive output is less than 1 in some years (Table 22).

Our analyses of water levels and storm events during the breeding seasons of 1985, 1991 and 1993, when the ratios of young fledged per adult were 0, 1.3 and 0.4, respectively, indicate that storm events can have a catastrophic impact on breeding success. The impact of storm events on overall annual Piping Plover nesting success at Kouchibouguac National Park is dependent on the relative elevation of the nest sites in addition to the number of nests that are active at the time of the storm. Storm events associated with levels of 1.5 m at the Escuminac gauge will flood only a small proportion of the nests, whereas the water levels of 2.0 m associated with the storm events of 1985, 1991 and 1993 appeared to have flooded most nests. The other factor that will influence the severity of storm impacts is its timing in relation to breeding phenology. After the storm event on June 14, 1991, there were additional nesting and renesting attempts observed. The storm event on June 24, 1993, had a devastating impact on reproductive success because it happened so late in incubation that there was little opportunity for renesting. In contrast, the storm event of June 8, 1985, caused a total breeding failure. This lack of renesting in 1985 may have been due to a large amount of human disturbance on the breeding beaches starting in mid-June. Beach disturbance was reduced by management activities in 1991.

The impacts of storms on Piping Plover nesting success should be considered additive to the impacts of predation and human disturbance. Reducing human disturbance would increase the probability of renesting by Piping Plovers should nests be destroyed by a storm event in early June. Storm events have been viewed by wildlife managers as stochastic processes that cannot be controlled. However, the impacts of storm events on nesting Piping Plovers could potentially be mitigated by managing the relative elevation of their beach nesting habitat. The ability of storm-surge models to predict (see Thompson et al., 2006, Section 4.3 of this report) storm-surge events also presents an opportunity for drastic management intervention, such as sandbagging to prevent flooding or removing eggs from nests and placing in incubators, if storm-surge models predict storm surges of 1.8 m or greater.

Currently, there is no statistical evidence based on historical water levels that the frequency of June storm events is increasing for the southern Gulf of St. Lawrence. Nor is there consensus that climate change will increase the frequency of storm events. Conservation efforts for Piping Plovers should continue to focus on efforts to reduce predation and human disturbance factors that will reduce nesting and renesting success of Piping Plovers.

4.6.9.5 References

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4.6.10 Impacts of sea-level rise, storm surge and climate change on Piping Plover populations[26,27]

4.6.10.1 Introduction

The Piping Plover (*Charadrius melodus*) breeds in several locations in North America, with the Atlantic population (*C. m. melodus*) currently designated as Endangered by COSEWIC (see Section 4.6.8.1).

There are many potential threats to their migration and wintering habitats, with unknown consequences for Piping Plover persistence. Climate and climate change can impact the breeding habitat of Piping Plovers (Stewart et al., this volume) and reproductive success (Tremblay et al this volume). However, the relative importance of these factors can be determined only in the context of the entire annual cycle. This section presents information on current population dynamics and an evaluation of the possible consequences of future habitat changes and impacts associated with climate change and possible conservation actions.

4.6.10.2 Methods

4.6.10.2.1 Study population

In Atlantic Canada, Piping Plovers nest at relatively low densities on beaches scattered throughout the provinces of Nova Scotia, New Brunswick, Prince Edward Island, Newfoundland and Labrador and the Magdalen Islands of Quebec (Figure 36). The Gulf of St. Lawrence (hereafter the Gulf) is considered a separate population from those nesting in southern Nova Scotia.

Breeding data collected included an annual beach census, detailed monitoring of reproductive success and marking of adult and juvenile birds with individually coded metal leg bands (Amirault et al., 2006). Census data suggest that both subpopulations have been growing fairly steadily in recent years, at rates of 2.8% and 5.7% per year from 1998 to 2003 (assuming exponential growth) in the Gulf and southern Nova Scotia, respectively (Figure 36). However, abundance estimates indicate that both subpopulations still remain well below stated recovery targets (Amirault, 2004).

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4.6.10.2.2 Population model structure

Based on banded individuals (Amirault et al., 2006), a population model was constructed for the Piping Plovers of eastern Canada (Calvert et al., accepted). Annual survival probabilities were estimated using live-recapture models in program MARK (White and Burnham, 1999), based on birds marked at breeding grounds and reobserved or recaptured in subsequent breeding seasons (see Amirault et al., 2005, 2006 for details).

4.6.10.2.3 Perturbations and population recovery

The impacts of a number of different population-perturbation scenarios on Piping Plovers were investigated:

- Scenario 1: Storm frequency increases or sea-level rises
- Scenario 2: Human development, disturbance and destruction
- Scenario 3: Conservation efforts

4.6.10.3 Results

Population models developed by Calvert et al. (submitted) suggested that Piping Plovers in the Gulf of St. Lawrence were decreasing at about 3.6% per year ($\lambda = 0.9651$) and that the southern Nova Scotia population was stable ($\lambda = 1.0043$; Table 26). In addition, both southern Nova Scotia and Gulf of St. Lawrence results suggest that of all the population vital rates, adult survival had proportionally a much stronger impact on population growth than juvenile survival or any reproductive parameters, and that age-specific breeding success had the least impact.

The higher estimate of juvenile survival in southern Nova Scotia compared with the Gulf would result in the higher estimate of population growth rate in southern Nova Scotia. Thus, if the Gulf population is indeed experiencing a decline and the southern Nova Scotia population is stable, differences in juvenile survival could explain the majority of this difference. However, this also suggests that any bias in the estimate of juvenile survival for either subpopulation could misrepresent the difference in dynamics between the subpopulations.

Table 26. Demographic parameters for Piping Plover population model.

Parameter	Notation	Definition	Southern Nova Scotia	Gulf
Adult survival	Φ_A	Probability second year or older bird survives 12 months post-census	0.7324	0.7331
Juvenile survival (from hatch)	Φ_J	Probability hatch year bird survives 12 months post-census	0.3279	0.2395
Fledging success	f	Probability that a hatchling survives to fledge	0.6171	0.7014
Juvenile survival (after fledging)	$\Phi_J^w = \Phi_J/f$	Probability that hatch year bird survives after fledging	0.5314	0.3415
Second-year recruitment	y_S	Probability that second year bird nests	0.8095	0.8504
Third-year	y_T	Probability that third year bird	0.9910	0.9823

Parameter	Notation	Definition	Southern Nova Scotia	Gulf
recruitment		nests		
Number of eggs laid	*E*	Mean number eggs laid per nest	3.8065	3.9389
Hatching success	*h*	Probability that an egg hatches	0.4603	0.5120

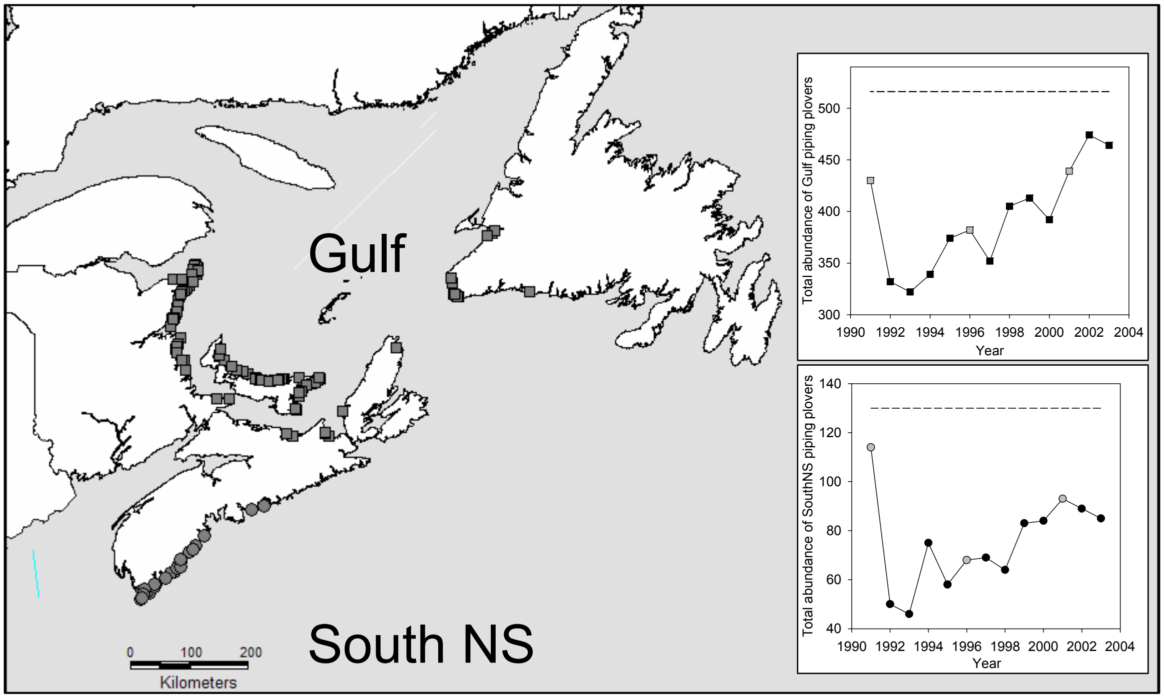

Figure 36. Location of beaches used by Atlantic Canada Piping Plovers breeding in the Gulf of St. Lawrence and southern Nova Scotia.

4.6.10.3.1 Recovery goals and parameter perturbations

For southern Nova Scotia, attaining the stated recovery goal would necessitate a ~35.4% increase in abundance from 2003 levels, requiring population growth rates of λ = 1.0625 for recovery in 5 years, λ = 1.0308 in 10 years or λ = 1.0204 in 15 years (assuming an immediate change in growth rate). For the Gulf, the recovery goal requires a ~24.6% increase and population growth rates of λ = 1.0450 for recovery in 5 years, λ = 1.0223 in 10 years or λ=1.0148 in 15 years (assuming an immediate change in growth rate). Because of the high elasticity of Φ_A, the change in reproductive parameters required to attain these growth rates would be approximately three times the change required in adult survival. Given that the current estimate of the Gulf population growth is below 1, we used the same type of calculation to determine what individual perturbations would be required to reach stability, i.e., a growth rate of λ = 1, demonstrating again that a much smaller change would be required in adult survival than in reproductive parameters in order to reach stability.

In order to maintain the Gulf subpopulation at its current abundance (i.e., $\lambda = 1$), productivity would have to increase by 15.5% to reach 1.63 fledglings per nest; to reach the recovery goal within 10 years, productivity would need to be 1.77 fledglings per nest.

4.6.10.4 Summary and conclusions

Estimates of annual adult survival probability for both the Gulf and southern Nova Scotia by Calvert et al. (accepted) were similar to those estimated for the Atlantic U.S. Piping Plover population (0.738; Plissner and Haig, 2000). In contrast, juvenile survival in the Gulf was much lower than in the Atlantic United States and closely matched that of Great Plains and Great Lakes Piping Plovers. Given that the vast majority of Atlantic Canada Piping Plovers nest in the Gulf area, their low juvenile survival might explain the difference in population dynamics observed in recent years, where U.S. birds have experienced a great increase and Canadian numbers have changed very little (Haig et al., 2005).

The point estimates of population growth in the two Atlantic Canada subpopulations suggest that Piping Plovers are remaining stable in southern Nova Scotia while declining in the Gulf, but these values must be interpreted with caution. The large variance associated with each parameter estimate reflects the short time span over which vital rates were calculated.

For both subpopulations, adult survival had a much higher importance than juvenile survival or reproductive parameters, as is common for many migratory birds (Saether and Bakke, 2000) and consistent with other Piping Plover populations (Ryan et al., 1993; Plissner and Haig, 2000; Wemmer et al., 2001). This implies that improvement of adult survival rates could greatly impact the population trajectory. Potentially high winter site fidelity in Piping Plovers (Drake et al., 2001; Amirault et al., 2005; Haig et al., 2005) suggests that monitoring of Piping Plovers outside the breeding season should be a priority for managers.

The perturbation analysis reinforced the findings that adult survival had the largest impact on population growth rate, which changed three times more with a change in adult survival than with an equivalent change in juvenile survival or reproductive parameters (Calvert, 2004). While this may suggest that adult survival should be the target for conservation efforts, we should be cautious in the interpretation of these results. The adult survival rates we have estimated here appear to be at the maximum end of the range of rates estimated in other studies. Juvenile Gulf survival rates, on the other hand, are generally lower than those of other studies

The perturbation scenarios showed that habitat destruction or other changes affecting adult survival could have much more serious consequences for population persistence than equivalent changes to other parameters. For example, if adult survival is particularly affected by wintering habitat, then any destruction or disturbance of wintering areas could be really damaging to the population, even if conservation efforts on breeding grounds could maintain strong reproductive values and high summer survival rates.

Given the many potential threats to Atlantic Piping Plover habitat from human disturbance (Patterson et al., 1991; Haig, 1992; Melvin and Hecht, 1994), identification of the links between habitat and population vital rates is crucial to its protection.

Population modelling emphasizes the need for (1) a better understanding of threats to both adult and juvenile survival during non-breeding seasons; (2) more precise estimation of natal dispersal rates of Piping Plovers in Atlantic Canada; and (3) quantification of the effectiveness of specific conservation actions in increasing population vital rates.

Our analysis, based on the Piping Plover population of the Gulf of St. Lawrence during 1998–2003, indicated that reproductive success and issues related to storm events and habitat conditions were not controlling the population dynamics during this time period. In order to better quantify the impacts of future sea-level rise and climate change on Piping Plover populations, it will be necessary to continue to quantify reproductive success, habitat change and storm events.

4.6.10.5 References

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4.6.11 Summary of impacts of sea-level rise, storm surge and climate change on the coastal ecosystem

The research on the impacts of sea-level rise and climate change focused on coastal habitat and associated wildlife. The short duration of this work necessitated the use of existing data sources on wildlife resources and habitat requirements. It is hoped that this study will encourage future research on coastal wildlife populations and habitat to incorporate analyses of the impacts of sea-level rise and climate change.

An analysis of the DEM showed that a flood level of 2.55 m above DEM datum (approximate present mean water level), as occurred in the storm of January 21, 2000, results in the flooding of 1397 ha of upland, 1634 ha of coastal marsh, 388 ha of dune, 159 ha of swamp and 226 ha of beach. The average depth of flooding for the 2.55-m storm flood was determined to be 0.84 m for swamp, 1.13 m for dune, 1.58 m for beach and 1.64 m for coastal marsh. These analyses indicate that large areas of coastal habitat will be influenced by future increased water levels associated with storm surges superimposed on rising sea level.

Whereas there were limited data on vertical accretion rates for salt marshes and sediment dynamics of beaches and dunes along the Northumberland Strait, a retrospective airphoto-based analysis was conducted at five study sites. These analyses provided insight on how marshes, dune habitat and beaches have responded to past storms and changes in sea level, as a basis for considering how they may respond in future.

For Cape Jourimain, the area of vegetated salt marsh was 28% (88 ha) less in 2001 than in 1944. This change was primarily due to the construction of a road through the marsh in 1966, which changed the hydrology and also physically destroyed some marsh area. For Shemogue, there was 5% (15 ha) less vegetated salt marsh in 2001 compared with 1944, and open water increased by 18% (9 ha). These changes at Shemogue were consistent with the hypothesis that marsh vertical accretion and horizontal migration were not sufficient to compensate for rising sea levels. The amount of vegetated salt-marsh area decreased by 27% (23 ha) for the Aboiteau study site, with visible evidence that 24 ha of coastal wetland had been infilled between 1944 and 2001. For Shediac, 40 ha of human infrastructure were built in coastal wetland, and 9100 m of seawall were constructed during the period between 1944 and 2001, with a 21% (19 ha) decrease in vegetated salt marsh. There were a 35% (19 ha) decrease in vegetated salt marsh and infilling of 19 ha of coastal wetland in the Cocagne area between 1944 and 2001.

At all study sites, the amount of beach and dune habitat was lower in 2001 than in 1944, with a greater decline in beach habitat compared with dune habitat. For Cape Jourimain, there was 22% less beach and dune habitat in 2001 compared with 1944; for Shemogue, there was 8% less; at Aboiteau, there was an overall decline of 12%; for the Shediac study area, there was a decline of 32% in the area of beach and dune habitat between 1944 and 1971, with little additional loss occurring between 1971 and 2001; and in Cocagne, beach area decreased by 40%. Removing sand from beaches for the production of aggregate during the period between 1944 and 1971 probably had an impact on beach area in the region, as did the expansion of hard shore protection. The loss of beach habitat during the last 60 years makes any additional loss of beach habitat in the future due to sea-level rise more critical from both a wildlife habitat and a recreational perspective. An increasing demand for beach recreational areas coupled with decreasing availability due to sea-level rise and climate change would increase human development and disturbance pressures on those beaches that currently provide wildlife habitat.

For the Aboiteau, Shediac and Cocagne study sites, there was a substantial increase in the amount of hardened shoreline present in 2001 compared with the earlier periods. The amount of hardened shoreline in 2001 was 8324 m in Aboiteau, 9408 m in Shediac and 13 287 m in Cocagne. Hardening of the shoreline has an impact on the amount of beach available for recreational and wildlife habitat purposes and also reduces sediment supply, which could lead to more beach loss in the future.

Overall, the results of these retrospective airphoto analyses indicate that our ability to understand and manage the impacts of climate change on coastal ecosystems will be confounded by human activities in the coastal zone and that rising sea levels have the potential to further reduce salt-marsh, beach and dune habitat in areas that have already lost a substantial amount due to human activities.

The relationship between vascular plant species' zonation and surface elevation in salt marshes along the coastline of the Northumberland Strait was determined and compared with results from the Bay of Fundy. Results indicate that elevation can be used to predict the impacts of sea-level rise on coastal wetland plant communities.

The potential impacts of sea-level rise and storm surge on colonial-nesting gulls and terns were evaluated by determining which colonies would flood under the different scenarios of sea-level rise and storm-surge flooding. Of the known nesting sites in the study area, only Cocagne Bar would be flooded at mean water level by a sea-level rise of 60 cm, but many, if not all, are vulnerable to destruction by flooding or wave runup in a large storm, even without further sea-level rise. Most (11/14) nesting locations would be impacted by a storm surge combined with tide to reach a water level of 2.55 m above DEM datum. The largest Common Tern colony in the study area (Tern Island in Kouchibouguac National Park) contained over 6020 nests in 2005 and would be flooded at a water level of 2.55 m above DEM datum. A summer storm event comparable to the January 21, 2000, storm would therefore have a devastating impact on the breeding success of the Common Tern population in New Brunswick along the Gulf of St. Lawrence. However, accelerated sea-level rise leads to an increased probability of maximum storm-water levels reaching this level.

We also examined the potential impacts of sea-level rise and storm surges on nesting Red-breasted Mergansers on four barrier islands in Kouchibouguac National Park. The elevation of most nests was higher than 0.60 m but well below the maximum observed storm flood level of 2.55 m above DEM datum. Impacts on nesting Red-breasted Mergansers are not hypothetical, as a storm in 1993 resulted in many nests being flooded and an annual reproductive success of only 22%. Sea-level rise and increased frequency and intensity of summer storm surges would have a negative impact on Red-breasted Merganser nesting success.

The endangered Atlantic Canadian breeding population of Piping Plover was estimated at only 255 breeding pairs in 2003. Breeding habitat availability and suitability for Piping Plovers were studied in an effort to predict the impacts of projected sea-level rise on habitat. Analyses indicated that beaches currently occupied by Piping Plovers are longer, have a greater mean width and have a greater area of sand than beaches that do not have nesting Piping Plovers. In addition, occupied beaches have a greater number of dune breaches, have access to back bays, outflows or ephemeral pools, and have less human development than non-occupied beaches. Coastline changes over time were mapped and measurements were taken for two beaches in the Shemogue area. There were no obvious trends detected in habitat change; rather, these analyses indicated temporal variability presumably related to storm events. It is known that Piping Plovers prefer to use the early-succession habitat created by dune breaches and that the conversion of spits to barrier islands through storms also improves habitat suitability. The hypothesis that sea-level rise and climate change will result in a decrease in preferred breeding habitat for Piping Plovers needs to be further tested and quantified. The observation that Piping Plovers predominantly use protected beaches indicates the importance of managing human impacts now and in the future as society responds to rising sea levels. To successfully manage Piping Plover habitat, it is important to increase our understanding of which beaches will be negatively impacted by sea-level rise.

The number of adult Piping Plovers attempting to breed and reproductive success at Kouchibouguac National Park during the period 1985 and 2005 were highly influenced by summer storm-surge events. In 1985, there were no young raised to fledging, and many nests were flooded. Water-level data from the Escuminac tide gauge showed a storm event and water levels above 2.0 m CD on June 8, 1985. There was also lower than average reproductive success in 1991 associated with a major storm event on June 14, 1991, when a water level of 2.12 m CD was recorded at Escuminac. Breeding success was once again low in 1993, and field observations indicated nest-flooding events, with a recorded water level of 2.07 m CD at Escuminac. An examination of historical water levels at Point Escuminac indicated that nine 60-cm or greater storm-surge events during the Piping Plover nesting season occurred during the period 1964–2004. There was one event during the period 1964–1969, one during the 1970s, three during the 1980s and four events during the 1990s. There have been no events yet during the 2000s. Assuming co-occurrence with high tides, some or many of these storm events would have had an impact on reproductive success and perhaps on population dynamics during the past 20 years. Currently, there is no statistical evidence that the frequency of June storms is increasing in the southern Gulf of St. Lawrence, but increased frequency of summer surges would have a negative impact on Piping Plover populations. This may require actions to protect nests and eggs from flooding.

An analysis of Piping Plover population dynamics was conducted in order to understand how changes in climate and habitat may affect Piping Plover populations. These analyses suggested that during the period 1998–2003, there was population stability in southern Nova Scotia (+0.4% per year) and a decline in the Gulf of St. Lawrence (−3.5% per year).

The negative growth projected for the Gulf was largely driven by low estimated juvenile post-fledging survival. Threats to juveniles following departure from nesting beaches need to be quantified. Similarly, population growth in both subpopulations was particularly sensitive to changes in adult survival. Very little is understood about the threats to Piping Plover survival during migration and overwintering periods. It would therefore appear that efforts to protect Piping Plovers from predators and human disturbance on breeding beaches have been successful and that annual climate-induced variability in reproductive success or habitat conditions is not controlling population growth at present. We suggest that future recovery efforts for Piping Plovers should quantify and manage the largely unknown sources of both adult and juvenile mortality during non-breeding seasons while maintaining current levels of nesting habitat protection.

Overall, our analyses indicate that coastal ecosystems have a natural capacity to respond to climate and water-level variability. Human alteration and disturbance have historically had a larger impact on coastal wildlife habitat and wildlife populations than sea-level rise and climate change. Any future impacts of sea-level rise and climate change could be exacerbated by development pressures or infrastructure protection projects. Continued monitoring of climatology, water levels, wildlife populations and habitat is required in order to develop adaptation strategies that will protect both human infrastructure and wildlife habitat from increased water levels and storm-surge events.

4.7 Socio-economic impacts

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4.7.1 Introduction

The *Canada Country Study* (Environment Canada, 1997 identified a series of potential impacts of concern within the coastal zone of Atlantic Canada. These include accelerated rates of coastal erosion and shoreline changes, flood hazards, storm damage and associated property loss. Communities that are vulnerable to coastal erosion and storm-related flood or surge would be at greatest risk.

This project employs socio-economic analysis in concert with biophysical sciences to understand the process and impact of climate change in the area and focuses on the potential impact of sea-level rise, increased frequency and intensity of storm surges, and accelerated shoreline change from an economic perspective.

Given the variety of biophysical changes anticipated from a changing climate and the scarcity of socio-economic analyses of these same changes, this research endeavours to employ a case-study approach to evaluate impacts in greater detail and to apply a variety of analytical techniques for assessing and understanding the social and economic dimensions of climate change.

The socio-economic analysis relies heavily on the scientific results provided by the other components within this study, which examined the complex physical and biophysical impacts expected under a changing climate. This integration of science and social science provides a comprehensive and informed platform for examining potential adaptation strategies.

4.7.1.1 Research objective

The objectives of the socio-economic component were to:

- identify local knowledge of climate impacts (past and present);
- enhance "case-study" communities' understanding of the economic implications of climate change and adaptation in the coastal zone of southeastern New Brunswick;
- provide a template for applying various economic techniques to climate-change impact analysis; and
- assess the communities' ability to act in response to climate change, and identify ways to enhance adaptation capacity in the coastal zone of southeastern New Brunswick.

4.7.1.2 Research components

4.7.1.2.1 Stakeholder or community engagement

An important element of this project is the engagement of the community and building upon local knowledge and understanding of coastal-change process and adaptation. Community engagement and participation enable researchers to identify and understand the level of local knowledge about climate-change impacts and adaptation. They also facilitate dialogue between scientists and citizens to enable local knowledge, experience and observations to be incorporated into the analysis of past and potential future changes in the coastal zone.

This dialogue is also important for informing the process of identifying potentially viable adaptation strategies and the costs of implementing those strategies. In the end, it is the community, various levels of government and other stakeholders that will need to assimilate all of the results from this project, interpret them in terms of their community context and begin the process of acting on the information to enhance community resilience to climate-change impacts. It is more effective to transfer knowledge if the recipient has a sense of engagement and ownership over that knowledge at an early stage.

To facilitate integration of science and local knowledge, a series of community meetings and discussions throughout the study area were held. Specifically, the community-engagement process provided an opportunity to:

- enhance the community's understanding of climate-change impacts;
- assess the community's perception of risk associated with extreme weather, flooding, erosion and future climate change, resilience to climate-change impacts and adaptive capacities;
- incorporate community knowledge into the economic analysis; and
- transfer research results to the community.

4.7.1.2.2 Impacts on economic sectors

The effects of climate change are an increasing concern for tourism operators in southeastern New Brunswick because 1) ecotourism and cultural tourism sectors have developed rapidly in the last decade and 2) tourism operations are feeling the effects of a rise in sea level, erosion and storm surge. Many tourism operations have incurred significant damages from the extreme storms in the coastal area of southeastern New Brunswick. It is estimated that the October 2000 storm caused almost $500,000 in damage to the boardwalk at the Irving Eco-Centre of Bouctouche (G. Arsenault, Irving Eco-Centre, pers. comm.) and almost $785,000 in damage to Kouchibouguac National Park (É. Tremblay, Kouchibouguac National Park, pers. comm.).

This research evaluated the potential economic impacts of climate change on the cultural tourism and ecotourism sectors. Through working with tourism operators, the analysis incorporated their local knowledge and expertise in the assessment of economic impacts.

4.7.1.2.3 Impacts on community attributes

The southeastern coast of New Brunswick has been impacted in the past by extreme events that led to significant health and safety threats and damage to coastal infrastructure. As a result of the January 21, 2000, storm-surge event, declared a disaster by the federal government, there were 198 damage claims submitted to the New

Brunswick Emergency Measures Organization (EMO), 43 of which were eligible for funding totalling close to \$1.5M (K. Wilmot, New Brunswick EMO, pers. comm.). On October 29, 2000, another extreme storm-surge event impacted the southeastern coast of New Brunswick, resulting in close to 459 damage claims being submitted to the New Brunswick EMO, of which 159 were eligible for funding totalling close to \$1.3M (K. Wilmot, New Brunswick EMO, pers. comm.).

The coastal area of southeastern New Brunswick continues to be developed and is vulnerable to coastal impacts, as has been demonstrated over the last few years. Understanding climate-change impacts and the future development patterns of these communities is an important element in identifying and assessing adaptation strategies. This component of the socio-economic analysis will estimate some of the damage costs to community attributes from sea-level rise and storm surge in support of sustainable management, community resilience and the development of adaptation strategies.

4.7.1.2.4 Costs and benefits of adaptation

Assessing climate-change impacts and adaptation strategies from a socio-economic perspective is a field of study still in its infancy. There are numerous empirical challenges and methodological issues still to be overcome. Indeed, there is no one agreed-to approach for assessing impacts or adaptation strategies. In order to be able to determine the most appropriate strategy, an evaluation of multiple options must be conducted.

To facilitate adaptation discussions, this component of the study assessed some of the costs and benefits associated with possible adaptation options for reducing the economic impacts to the tourism sector and the damage costs to coastal property.

4.7.1.3 Rationale for each component and case study

A case-study approach was used to evaluate the economic impacts from two different perspectives: impacts on a specific economic sector and impacts on property. The communities of Bouctouche and Shediac Bay were selected for case studies because they provided opportunities to examine the significance of different types of economic impacts using different approaches to economic analysis.

4.7.1.3.1 Bouctouche: Evaluating integrated effects upon the tourism industry

There were several reasons for conducting a case study in the Bouctouche area. Bouctouche has invested considerable resources into developing its ecotourism and cultural tourism resources over the last several years, particularly from a coastal-destination perspective. In addition, this community has already experienced impacts from previous severe storm events (flooding and coastal erosion):

- the Irving Eco-Centre at La Dune de Bouctouche was damaged during the October 29, 2000, storm; and
- the tourist and historic site Le Pays de la Sagouine was flooded on January 21 and October 29, 2000.

Further, this community has been at the forefront of planning initiatives for regional sustainable development and has seen rapid growth in provision of ecotourism and cultural tourism services over the past few years. More recently, this community adopted a Municipal Green Plan, a first in New Brunswick.

4.7.1.3.2 Shediac Bay: Potential damage costs from storm surge and coastal flooding

The shores in Cocagne Bay and Shediac Bay are becoming increasingly built up and are vulnerable to coastal impacts because of low coastal slope and erodible substrate. Shediac, as a “bedroom community” for Moncton, is the centre for residential and commercial development along this portion of the coastline and maintains a considerable municipal and residential infrastructure in the coastal zone, making it particularly vulnerable to damage from storm surge. Shediac Bay is a complex coastal watershed area, highly vulnerable to coastal flooding. Nearby Parlee Beach is also a highly valued provincial asset and tourist attraction. Longer-term economic effects of climate change need to be considered in land-use planning and in regulating development and settlement.

4.7.2 Community-engagement process

4.7.2.1 Purpose and rationale

The complexity of the many problems related to the coastal zone is increased by the existence of the different users of the coastal space and a variety of activities and factors, including coastal, residential, industrial and tourism development, together with the associated environmental constraints, exploitation of marine resources, the presence of those who benefit from those resources, living within or outside the environment, the need to protect the coast, public access to the zone, and so forth. For this reason, integrated, collaborative management of the coast requires cooperation by all users, to more effectively define the conditions for compatibility among the various users of the coastal space. Reducing the impacts of climate change, whether environmental or socio-economic, is a new issue in the coastal zone, and there is a widespread view that it requires an integrated approach (van den Hove, 2000).

The community-engagement component of the project sought to increase local capacities to adapt to the impacts of sea-level rise and climate change on the coastal zones of southeastern New Brunswick. This integrated management approach is part of an inclusive, participatory local governance movement — in other words, one in which all community stakeholders (citizens, government and intermediaries) are involved and share in the decision-making process (Macdonald, 2005). The term governance means any coordination process by a number of democratically elected (governmental and non-governmental) players for the purpose of managing local problems (Marsden and Murdock, 1998; van den Hove, 1999). With this contribution, the project — in addition to gathering information to facilitate decision-making — seeks to promote the involvement of all coastal environment stakeholders for the purpose of more effective planning for current and future climatic conditions.

4.7.2.2 General approach

To promote development of communities’ capacities to adapt, it was becoming important to assemble the traditional knowledge and local awareness of the area’s various socio-economic and cultural groups and compare these with scientific knowledge concerning the impacts of sea-level rise and climate change in the regions in question. The initial phase, therefore, consisted of gathering the local knowledge and perceptions of individuals in the communities through interviews and discussion groups, reaching the largest possible range of the area’s population.

Second, to promote local-area responsibility and stewardship, it was necessary to work on raising public awareness of the risks stemming from climate change and sea-level rise; this requires strategies related to information and education. For this purpose, various public presentations were made in a number of communities from 2003 to 2005, and a Canada-wide community workshop was held in Bouctouche in the fall of 2004. During these presentations and workshop, the data collected concerning the impacts of climate change and sea-level rise were shared. Throughout the project as well, radio and television interviews and newspaper articles were used as a dissemination method.

For the interviews and public meetings, the researchers ensured participation by the largest possible number of stakeholders from non-governmental organizations and representatives of various government levels. For example, citizens, members of drainage basin organizations, urban planners, municipal councillors and mayors, Local Service District committee members, provincial public servants and others participated in the activities. Each presentation or discussion group held in the various communities allowed time for discussion, to enable the participants to share their concerns and perceptions of problems in the local context.

4.7.2.3 Outcomes of engagement process

The data gathered in the various southeastern New Brunswick communities provided the researchers with a detailed tabulation of local perceptions and concerns.

The preliminary results obtained during the initial interviews in the communities show that attitudes to the impacts of extreme events were reactive in nature; in other words, attempts to adapt more effectively to climatic reality are triggered mainly when episodes or storms cause major damage. However, it is very much in the interests of the communities to adopt a more proactive approach, in which development is planned in light of the risks associated with vulnerability to the climate. This type of adaptation is in fact more effective and less expensive than unavoidable or emergency adaptation (Burton, 1996, in Smit and Pilifosova, 2003). Engagement by the communities should promote this kind of approach; indeed, the actions of certain communities, as presented in Section 4.8.3, are in this sense.

The dialogue undertaken with the communities provided an opportunity to ensure that the concerns and problems encountered locally concerning the impacts of climate change and adaptation are taken into account by the researchers. In fact, many barriers to adaptation seen by the communities were noted and were the subject of recommendations. It was essential to include these in order to enable the present research to respond more effectively to the needs of the local populations and propose relevant recommendations for adaptation.

Since the interviews, discussion meetings and public presentations were held over a certain period of time, it was possible to see how perceptions and knowledge relating to climate change and adaptation evolved in the various communities. In general, the researchers noted an increase in awareness of the climate-change phenomenon during the study period.

4.7.3 Methodological issues

The overall approach to this project considers the important interplay between the information needs of the stakeholders, the state of the science of impact prediction and the limits of the economic-analysis tools available to date. The results from the other components within this study provided essential information on sea-level rise, storm surge and coastal-erosion impacts and were used as inputs into the socio-economic analysis. This was done either quantitatively or qualitatively. Similarly, the results of the economic analysis were also incorporated into the “Adaptation” (see Section 4.8) and “Building Adaptive Capacity” (see Section 4.9) components.

4.7.3.1 Use of storylines and socio-economic scenarios

The New Brunswick sea-level-rise study projects climate-change impacts 50–100 years in the future, and future socio-economic conditions are incorporated into the analysis in order to estimate the resulting economic impacts. By integrating climate-change scenarios with possible future socio-economic conditions, analysts can better understand the possible impacts on future societies.

Using storylines and scenarios to create a potential future picture of socio-economic and biophysical conditions under climate change is one way to address sources of uncertainty. Storylines and scenarios allow the analyst to conceptualize quantitative changes that can be incorporated into the economic analysis and present decision-makers with a range of possible future outcomes.

Scenarios have been defined as “a plausible description of how the future *may* develop based on … a set of assumptions about key relationships and driving force’’; however, they “are neither predictions nor forecasts” (Nakicenovic and Swart, 2000).

Developing and employing future socio-economic scenarios in the evaluation of climate-change impacts are important improvements in the methodology. Rarely in the literature does socio-economic research build in a “future” dimension of the community under study. Often, the evaluation of future impacts is based upon present-day development held constant in the future. However, communities change over time in terms of socio-political structure, settlement, economics, culture, function and more. Thus, to improve upon the methodology to evaluate damage costs from storm surge (e.g., the method employed in the Prince Edward Island sea-level-rise study), the research required the development of future socio-economic scenarios. These scenarios were then coupled with the predicted biophysical changes to present a more complete and realistic assessment of future damages, impacts and costs.

Storylines and scenarios were used in the economic analysis of both case studies and were developed based on the results from the scientific analysis undertaken by project partners, information pertaining to physical changes in the environment, storm events, coastal erosion and sea-level rise and general knowledge of future climate change in Atlantic Canada. Scenarios were also developed and informed through the dialogue with the case-study communities.

In the Bouctouche case study, a storyline was used to guide the development of the adaptation scenarios and to provide a framework in which linkages could be made between biophysical changes and socio-economic responses. The Bouctouche storyline described expected biophysical changes associated with climate change, specifically sea-level rise, storm surge and coastal erosion in the Bouctouche area. Storylines were presented to a number of stakeholders, and, through the engagement process, two adaptation scenarios were defined.

The adaptation scenarios integrate climate-change and socio-economic responses. The expected biophysical changes to Bouctouche are constant between the two scenarios, but the socio-economic responses to these changes differ. The pessimistic scenario describes the Bouctouche community as not attempting to adapt to climate-change impacts. The optimistic scenario describes the Bouctouche community as implementing adaptation measures. These scenarios include changes to key tourism drivers, such as impacts on beaches, the Irving Eco-Centre, local shellfish availability, Le Pays de la Sagouine, local hiking trails, accommodations, restaurants and shops, all of which are important to the Bouctouche tourism industry. Details of the two scenarios are provided in Table 1.

Table 1. Bouctouche case-study scenarios.

Impacts and mitigation	Optimistic	Pessimistic
Adaptation measures	Governments and stakeholders respond to climate change and coastal erosion by implementing adaptation measures. The tourism industry will experience growth through protecting the community's natural resources and through broadening into research and information centres.	Governments and stakeholders will continue to respond to climate change and coastal erosion as they do today. The tourism industry has experienced marginal growth, and the community as a whole has not taken any adaptation measures to mitigate the impacts of climate change and coastal erosion. This future state could be taken as a worst-case scenario, while at the same time as a reasonable expectation if current practices continue.
Impact on beaches	Through adaptation measures, the quality and quantity of beaches available to tourists have been preserved.	In the future, we can expect to see a decrease in the availability and quality of beaches in Bouctouche as a result of sediment transportation. Sand will continue to be removed from the beaches, and gravel and rock will continue to be deposited. With time, the beaches will disappear.
Impact on La Dune de Bouctouche	The dune will continue to erode. In this scenario, however, the southern tip of the dune breaks off and becomes an island. The detached section of dune could become a nesting habitat and would then be designated as a protected area, restricting human activity. Boat tours are offered to tourists who are interested in learning more about endangered species and the changing coast.	The dune will continue to erode on the ocean side, sand will be projected over the crest of the dune and habitat will migrate towards the land, approaching human development. As the beach disappears, the local population of endangered Piping Plovers will be lost. In addition, as a result of the increasing frequency and intensity of extreme events, the Irving Eco-Centre continues to incur damage costs. Efforts to repair damage to the boardwalk become too costly, and this portion of the facility is eventually closed.

Impacts and mitigation	Optimistic	Pessimistic
Impact on Le Pays de la Sagouine	Through technology, Le Pays de la Sagouine has upgraded the facility to minimize the damage from flooding and extreme events. In addition, a new facility has been acquired as a contingency location in the event that flooding occurs during the season.	During extreme events and for a short period after the event, Le Pays de la Sagouine may be temporarily closed until repairs to the bridge, sewage piping and other sections of the facility can be completed. This may result in the cancellation of shows should the area experience an early tropical storm.
Availability of local shellfish	Through technology and sustainable management practices, the local shellfish industry is able to provide tourists with a high-quality product to meet their demands. A community sewage treatment facility has been built with the capacity to service the growing number of businesses and residential areas.	Because the sewage and water treatment facilities are located at low elevations and in close proximity to the coastline, extreme events overwhelm the systems and result in contamination of drinking water and shellfish grounds. Tourism operators and businesses may not be able to serve local shellfish at their facilities for a period of time after the event.
Impact on hiking trails	Increasing frequency and intensity of extreme events result in occasional closure of some riverside trails. The bridge over Black River, however, has been upgraded and raised and no longer floods.	Increasing frequency and intensity of extreme events and flooding lead to temporary closure of some riverside hiking trails. In particular, the bridge over Black River is frequently closed.
Impact on small operating facilities	As a result of policy implementation, facilities are at minimal risk of being damaged during extreme events. Tourism operators have invested in practices that are sustainable, and the majority of the facilities are nestled inland.	As a result of extreme events and flooding, some tourism operators such as shops, restaurants, lodging and camping facilities may not be able to absorb non-insured costs associated with repairs. This may not be financially sustainable for some operators and may result in temporary closure of those facilities.

The Shediac storylines were structured similarly to the format used by the UK Climate Impacts Programme (2001). The storylines provided overarching context about the story itself and greater details according to relevant themes: economic development, population, housing, public services and environmental quality. Specifically, the storylines described, through narratives, possible future changes in the area's population, economic development, the environmental quality of the Bay and how the population lives and is served by public infrastructure.

The optimistic storyline assumed a moderate yet relatively strong pace of economic development, population growth, diversity, improved environmental quality and expansion of public services. The pessimistic story focused on the same areas, but assumed a lower rate of economic development, a decline in total population and age diversity and a decline in environmental quality.

Community stakeholders played an important role in forming future-oriented socio-economic scenarios. Through workshops, the community identified new buildings, infrastructure and green zones in the Shediac Bay area. Under the optimistic scenario, the following new developments and green spaces were identified (illustrated in Figure 1):

- 10 low-density and high-density residential zones, including mobile homes, condominiums and seniors' residences;
- three expanded commercial zones, including tourist facilities and attractions;
- expansion of the Pointe-du-Chêne marina, construction of shops at the Shediac marina and a proposed community centre and swimming pool; and
- nine green zones along the coast.

Under the pessimistic scenario, the following new developments and green spaces were identified (illustrated in Figure 2):

- five low-density and high-density residential zones, including housing and condominium developments;
- a new museum surrounded by parkland, expansion of the Shediac marina and closure of the Pointe-du-Chêne marina and some waterfront facilities;
- a proposed community centre; and
- closure of the Parlee Beach Provincial Park and development of a new park near Barachois.

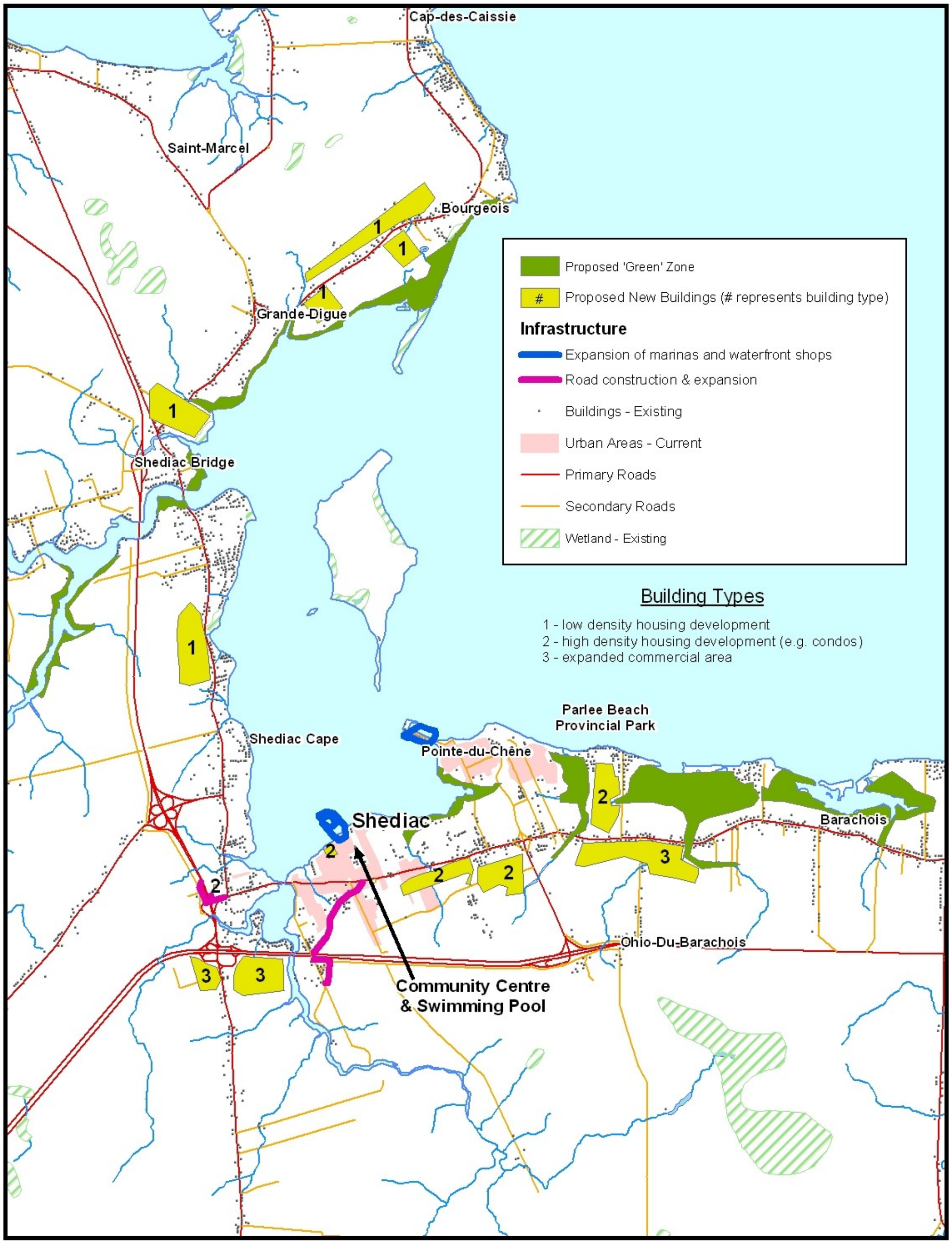

Figure 1. Future developments under the optimistic scenario.

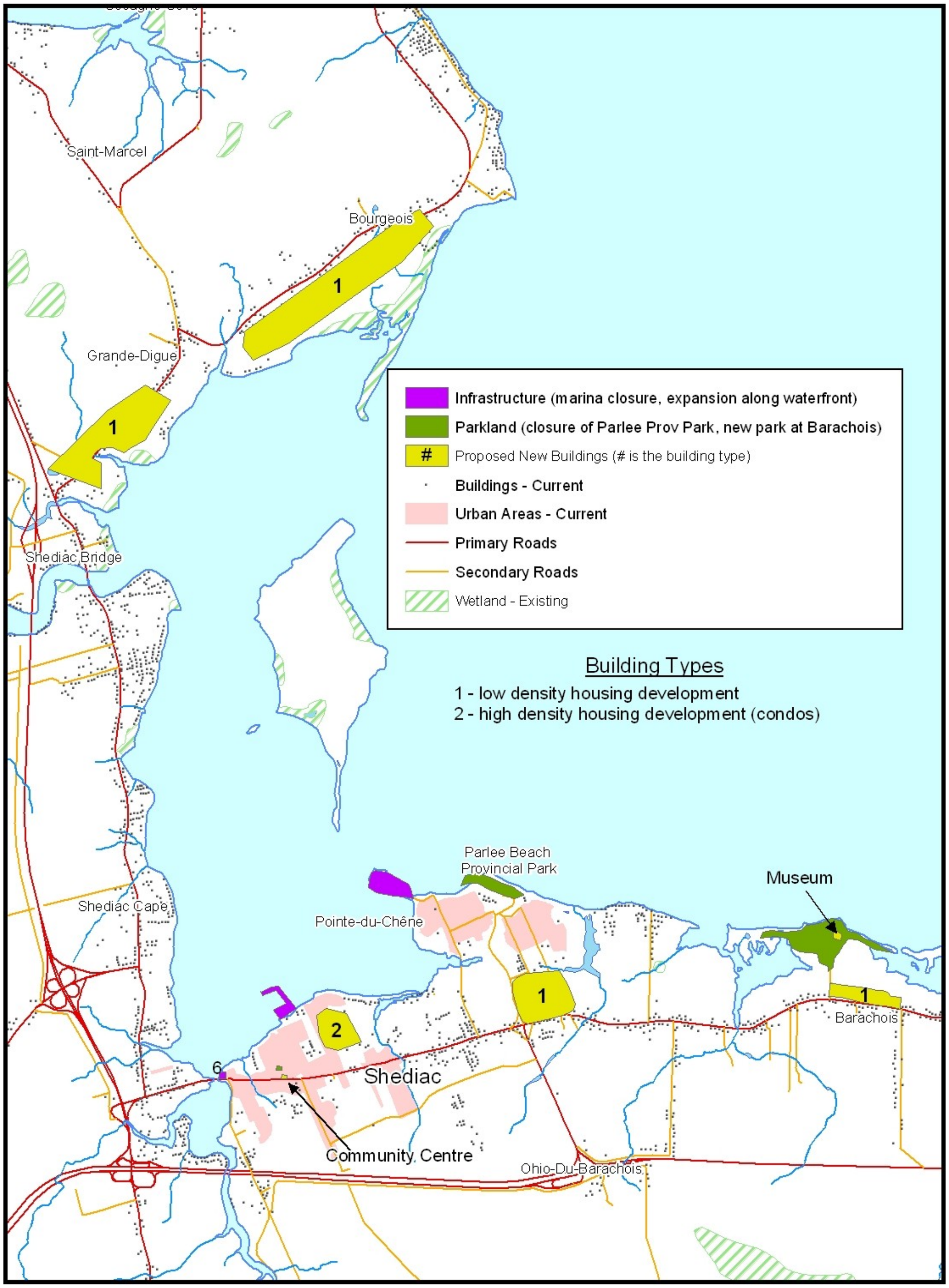

Figure 2. Future developments under the pessimistic scenario.

4.7.3.2 Study areas and methodology

The economic evaluation in each case study is based on constant climate-change impacts over a plausible economic time frame. The overall approach links atmospheric changes to ecological changes (physical and biophysical responses). Ecological changes are then linked to resulting social and economic impacts. Scenarios have been derived through a community-engagement process and are used in each case study to address uncertainty associated with future social and economic conditions.

Socio-economic impacts have been evaluated from two different perspectives: impacts upon the tourism sector and damage costs to infrastructure. To evaluate these impacts, two economic analysis approaches were used: an economic impact analysis was completed to examine the impact upon the tourism sector in Bouctouche, and flood depth–damage cost functions and assessed values for properties were used to estimate damage costs to properties in Shediac.

4.7.3.2.1 Bouctouche: Evaluating integrated effects on the tourism sector

The geographical boundaries for the Bouctouche case study were limited and included the Bouctouche and Chockpish river watersheds. This region extends north to Sainte-Anne-de-Kent, west to Sainte-Marie-de-Kent and south to Saint-Thomas. Saint-Antoine, Cocagne, Rexton, Kouchibouguac National Park and Cap-Lumière, among other locations, were excluded from this case study.

The methodology for this project was developed by Vanderlinden and Jacques (2004). The effects of climate change and resulting economic impacts are linked to ecological responses to climate change and human responses as a result of the ecological changes. Ecological responses represent the changes to the biophysical environment as a result of climate change (such as erosion of dunes), whereas the human responses represent the behaviour change by both the tourism operators and tourists (e.g., retreat, protection and accommodation).

Storylines, scenarios and a survey were used to link ecological responses to human responses. The storylines and scenarios were developed based on the results of the scientific analysis undertaken by the other components of the study and were informed through dialogue with community stakeholders. A survey was used to determine tourists' reactions to each scenario and to capture changes in their planned activities and their lengths of stay in Bouctouche. These changes determined the magnitude of the impact on the local economy.

An input–output model was used to estimate economic impacts of the changing behaviour of tourists through what is known as an economic shock. The shock can be derived through any change to spending, including that caused by natural events. The effect of the shock is then carried through to the whole economy, which is disaggregated into sectors. In this study, the two socio-economic scenarios represent the economic shocks.

4.7.3.2.2 Shediac Bay: Potential damage costs from storm-surge and coastal flooding

The geographical boundaries of this case study were limited to and included three census subdivisions: Shediac Parish, Shediac Town and Beaubassin East. The general methodology used for the socio-economic analysis was to identify, assess and value current and future properties and infrastructure at risk as a result of storm-surge events. The analysis and assignment of flood depth were completed for the study area at two water levels: the high water level experienced on January 21, 2000, and a hypothetical high water level corresponding to a worst-case extreme event and sea-level rise, under optimistic and pessimistic future socio-economic scenarios.

The future socio-economic scenarios were developed by community members to illustrate future development patterns. Community attributes within each scenario were assigned flood depths under the two water levels. The resulting risk assessment provided a basis for estimating the costs of storm-surge flooding under three scenarios:

- *Scenario 1*: 2.5 m above digital elevation model (DEM) datum, with existing structures (baseline event). This level represents the January 21, 2000, storm surge, which generated a maximum water level of 2.5 m above DEM datum. This event was projected as a 1-in-40-year occurrence.
- *Scenario 2*: 3.0 m above DEM datum, with existing structures and structures proposed under the optimistic scenario (worst-case storm-surge event). The January 21, 2000, water level is not considered to be a worst-case event. Had a worst-case event occurred, the maximum water level would have been close to 2.8 m above DEM datum. Currently, this event is projected as a 1-in-100-year occurrence. The worst-case water level was superimposed on an estimated 0.2 m relative sea-level rise by 2025, giving a flood level of 3.0 m above DEM datum.
- *Scenario 3*: 3.0 m above DEM datum, with existing structures and structures proposed under the pessimistic scenario (worst-case storm-surge event).

Flood depth–damage cost functions were used to relate the damages from a storm-surge-related flood in terms of the flood depth and the cost to repair damage. An attempt was made to determine a relationship between flood depth and damage costs based on damage incurred in the January 21, 2000, storm-surge event; however, there were not enough data points to define a statistically valid relationship. Therefore, standardized depth–damage functions[28] from the U.S. Army Corps of Engineers (USACE, 2003) were used (research was unable to identify standardized depth–damage functions from Canada).

To estimate total flood damage costs in the case-study area, the depth–damage functions were applied to those properties that are at risk of flooding to over 0.5 m under the two water-level scenarios. This analysis assumed that a minimum flood depth of 0.5 m is required before damage to structures occurs. This assumption attempts to mitigate some of the uncertainty associated with the vertical accuracy of the light detection and ranging (LiDAR) data (±30 cm) and the fact that the DEM does not clearly indicate the location of structures on each parcel of land. Because some damage costs may be incurred at flood levels under 0.5 m, this assumption may therefore lead to an underestimation of damage costs.

This analysis also estimated some of the possible costs associated with generic adaptation options: retreat, protection and accommodation. Under the retreat option,

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[28] These functions are based on actual damage from flood events that occurred throughout the United States between 1996 and 2001.

property assessment values were used as a proxy for minimum compensation and as a basis for estimating forgone provincial and municipal tax revenues. For the protection option, information collected from the community-engagement process was used to estimate the capital costs associated with protection and accommodation measures used by the community in the past. This analysis has not assessed the full realm of costs associated with either option, nor has it assessed the specific benefits (avoided damages) of either option; therefore, the results are for discussion purposes only, and recommendations have not been made within this study.

4.7.3.3 Role of uncertainty, limitations of analysis, sources of error

Economic analysis of climate-change impacts and adaptation can proceed best when rooted on a foundation of science that describes the potential biophysical changes in the coastal zone within the acceptable ranges of uncertainty.

Coupling economic valuation techniques (which have their own inherent sources of uncertainty) with scientific results creates a challenge in terms of quantifying the cumulative uncertainty and representing that uncertainty within reasonable confidence intervals. Generally, economic analysis that proceeds using assumptions that can be verified or tested for sensitivity can more easily quantify and represent uncertainty or errors associated with the final estimates.

Predicting socio-economic changes 50 or 100 years in the future does not allow for the verification of socio-economic assumptions (e.g., the pace of future development, the nature of continuous infrastructure investment or the changing public perception of habitat values), all of which will likely affect the accuracy of analytical results. It is also very difficult to test those assumptions in order to understand how sensitive the final outcome is to that assumption.

Where possible, this study tried to quantify and qualify the uncertainty associated with the analysis. Scenarios were used to try to capture uncertainty related to future socio-economic conditions, as well as impacts resulting from climate change. The results from each case study are estimates based on expert judgement and the best available data, tools and techniques. In order to complete this study, key assumptions[29] were made throughout the analysis. The following sections include a broad discussion of some of the limitations and sources of error within the study.

4.7.3.3.1 Climate-change impacts

The precise impacts of climate change on the natural and socio-economic environments cannot be predicted with precision. Some scenarios developed for this study were therefore necessarily vague in their description of impacts. As such, it is possible that the scenarios were interpreted differently by different participants.

4.7.3.3.2 Digital elevation modelling

Multiple storm-surge scenarios were used to capture two possible events: one event has already occurred, whereas the other one is a worst-case scenario superimposed on an estimate of sea-level rise. The estimated water depth from storm-surge flooding includes a margin of error. The DEM used to assign water depth to each parcel of land is accurate to within ±30 cm vertically (see Section 4.4). In addition, the exact location of each

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[29] For more information on uncertainty and assumptions, see the Bouctouche and Shediac Bay case-study reports (Murphy et al., 2006a,b).

structure on a parcel of land is not clear, and, consequently, an average flood depth was calculated for each parcel. Because of these uncertainties, the damage cost estimates excluded those properties having an average flood depth of 0.5 m or lower.

4.7.3.3.3 Future socio-economic scenarios

The scenarios and storylines described in this analysis are neither predictions nor forecasts, but rather plausible future states based on a number of assumptions. In the development of these scenarios, many variables have been held constant, such as technology, security, macro-economy (e.g., exchange rate) and commodity prices. In both case studies, optimistic and pessimistic scenarios were developed to present a range of possible future outcomes in which the economic impacts are likely to fall.

4.7.3.3.4 Time horizon

There are multiple dimensions to uncertainty associated with time, such as timing of impacts, time and valuation, and time frames in which data sets were collected.

The exact time horizon of climate-change impacts cannot be predicted with precision; therefore, constant climate-change impacts have been assessed over a plausible economic time frame. However, this analysis has assessed impacts only for one year or one occurrence. In reality, impacts will be cumulative over time. This study assumed that climate-change impacts occur by 2025.

Scenarios developed in the case studies are based on biophysical changes, human responses and future development patterns over a 20-year time horizon; however, economic impacts and damage costs are based on today's economy and assessed property values. The economic impacts were not based on the number of employees and firms, revenues and expenditures in the local economy in 2025. Nor did the damage cost analysis project what future assessed values may be by 2025. Inflation and economic growth would have been offset to some degree through discounting; however, it is unknown to what degree these estimates would vary.

The information on parcels and features in the Shediac area obtained from Service New Brunswick and the planning commissions was based on data sets collected between 2001 and 2004, whereas the LiDAR data were collected in 2003. Keeping in mind that development along this coast occurs rapidly, many features in place in 2005 are not captured in the collected LiDAR data, nor are they accurately represented in the property layers from Service New Brunswick and the planning commissions.

4.7.3.3.5 Full cost and benefit analysis

The analysis undertaken for each case study does not capture the full spectrum of costs or benefits associated with climate-change impacts or adaptation. For example, while the Bouctouche case study attempts to capture some of the benefits to the tourism sector from adapting to climate change, it does not assess the capital costs or opportunity costs associated with implementing adaptation strategies.

In the Shediac Bay case study, the costs of damage to structures were estimated; however, other costs, such as replacement cost of lost contents, alternative accommodations, cleanup of debris or landscape improvements, were not assessed. The damage costs to roads, municipal water and sewage infrastructure and other features were also not assessed.

Because a full cost analysis was not completed, the results are likely an underestimation of actual damage and adaptation costs. In addition, the benefits (avoided damages) or the effectiveness of these options have also been excluded from the analysis. Therefore, one cannot make a decision on whether there is a net adaptation benefit or if an option is an effective means of mitigating the impacts of sea-level rise, coastal erosion and storm surge.

4.7.3.3.6 Valuation

Tourism expenditures and damage costs used in the two case studies do not reflect actual costs or expenditures; they were derived through an analysis of trends and questionnaires and are based on a number of assumptions.

In the Bouctouche case study, expenditures by tourism in several sectors were estimated based on information obtained through a survey and data from external sources. They do not represent actual expenditures by tourists in the Bouctouche case-study area. Because the analysis includes only key economic sectors associated with tourism, it is likely that this case study underestimates the total expenditures made by tourists.

Damage costs in the Shediac Bay case study were estimated based on the assessed value of a property. Assessed value was also used as a proxy for estimating compensation under the retreat adaptation option. Assessed value does not necessarily reflect the “true” value of a property; market values generally better reflect the true value. Therefore, it is likely that the use of assessed values in this analysis underestimates damage costs and compensation. In addition to sea-level rise, storm-surge flooding and coastal erosion, many communities along the southeastern coast are also affected by the impacts of wind and ice during extreme events. Much of the damage from past storms has resulted from a combination of wind, ice and flooding. The Shediac results are damage costs from storm-surge flooding, and the estimates likely underestimate total damage that would occur during a storm-surge event, such as that generated by the January 21, 2000, storm.

4.7.3.3.7 Geographic limitations

The economic impacts estimated in this study focus only on those impacts limited to specific geographical regions. The Bouctouche case-study area was limited to and included the Bouctouche and Chockpish river watersheds. This excludes key tourism attractions along the southeastern coast of New Brunswick, such as Kouchibouguac National Park and Parlee Beach. The Shediac Bay case-study area included three census subdivisions (Shediac Town, Shediac Parish and Beaubassin East). Damage costs have occurred in other census subdivisions outside of these boundaries; however, those census subdivisions were not included in the study area.

4.7.3.3.8 Economic analysis

Methodologies and frameworks for evaluating the economic impacts of climate change are continually evolving. Throughout the stages of this analysis, experts from various organizations and academic institutions have reviewed and provided constructive feedback to foster the development of the methodologies used in this study. There are, however, some sources of error associated with the methodologies used.

The survey analysis for the Bouctouche case study generated relatively large standard deviations. Some of the reasons for the large standard deviations include a small sample size, variation in survey response and cumulative error. In addition, there were a number of limitations and biases associated with the survey tool, including a possible non-representative sample, non-response bias, stated behaviour versus actual behaviour and closed-ended questions. It is recommended that the results from the survey not be interpreted literally; rather, they should be used as indicators of direction and magnitude.

Because flood depth–damage cost functions were not available for Canada or the Shediac Bay case-study area, functions based on historical flood damage in the United States were used. These functions were directly transferred to the case-study area, and no adjustments were made. In addition, these functions are based on different types of flooding (riverine and storm surge) and reflect damage to a variety of residential structures. There are likely multiple sources of error associated with these assumptions; however, a quantitative assessment of the sensitivity of these assumptions could not be made. Therefore, these results should not be interpreted literally, but they can be used as indicators of direction and magnitude.

4.7.4 Review of case-study results

Sea-level rise, storm surge and coastal erosion continue to impact communities, the economy and the environment in southeastern New Brunswick. This analysis evaluates the economic impacts resulting from climate change in the coastal area; however, the results are limited to specific geographic areas, economic sectors and types of impacts.

The results from the case-study analyses should not be interpreted literally, as they are estimates based on the best available information. However, the results can be used as indicators of the direction of economic impact and damage costs (i.e., positive or negative) and general estimates of magnitude. This information can be used to educate and raise awareness as well as be incorporated into planning tools and decision-making processes to enhance future development.

4.7.4.1 Interpretation of Bouctouche case-study results

The tourism industry around Bouctouche makes a significant economic contribution to Kent County.[30] Table 2 and Table 3 show the potential economic gains and losses, compared with the baselines estimated in this analysis, for Kent County under the optimistic and pessimistic adaptation scenarios.

Table 2. Kent County: Comparing the economic impacts of climate change on the culture and ecotourism sectors of Bouctouche (mean).

Scenario	Employment (person-years)	GDP ($ million)
Baseline	408	11.3
Optimistic	482	13.5
Pessimistic	302	8.5
Change under optimistic	74	2.2
Change under pessimistic	−106	−2.8

Note: Employment estimates are rounded to the nearest one, and GDP estimates are rounded to the nearest hundred thousand.

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[30] Kent County is the New Brunswick census division where Bouctouche is located.

Table 3. Kent County: Comparing the economic impacts of climate change on the culture and ecotourism sectors of Bouctouche (mean plus one standard deviation).

Scenario	Employment (person-years)	GDP ($ million)
Baseline	1050	28.4
Optimistic	1137	31.4
Pessimistic	733	20.6
Change under optimistic	87	3.0
Change under pessimistic	−317	−7.8

Note: Employment estimates are rounded to the nearest one, and GDP estimates are rounded to the nearest hundred thousand.

There is potential for economic gains in Kent County, as respondents to the survey have indicated a clear interest in the tourist attractions of the Bouctouche area. If the impacts of climate change in the Bouctouche area are well managed through adaptation strategies (optimistic scenario), employment could increase by between 74 and 87 person-years, representing an 8–18% increase. Under the optimistic scenario, gross domestic product (GDP) in Kent County could also potentially increase by between $2.2M and $3.0M, representing an 11–19% increase.

Inversely, there is potential for economic losses in Kent County. Under the pessimistic scenario, employment could potentially decrease by between 106 and 317 person-years, representing a 26–30% decrease. In addition, GDP in Kent County could potentially decrease by between $2.8M and $7.8M, representing a 25–27% decrease.

Tourism in the Bouctouche case study also makes a significant contribution to the economy of New Brunswick. Table 4 and Table 5 show the potential impacts on New Brunswick's economy based on changes to the tourism industry in the Bouctouche area.

Table 4. New Brunswick: Comparing the economic impacts of climate change on the culture and ecotourism sectors of Bouctouche (mean).

Scenario	Employment (person-years)	GDP ($ million)	Tax revenue ($ million)	
			Provincial	Federal
Baseline	473	15.6	1.8	2.1
Optimistic	560	18.6	2.0	2.5
Pessimistic	353	11.9	1.3	1.6
Change under optimistic	87	3.0	0.2	0.4
Change under pessimistic	−120	−3.7	−0.5	−0.5

Note: Employment estimates are rounded to the nearest one, and GDP and tax revenue estimates are rounded to the nearest hundred thousand.

Table 5. New Brunswick: Comparing the economic impacts of climate change on the culture and ecotourism sectors of Bouctouche (mean plus one standard deviation).

Scenario	Employment (person-years)	GDP ($ million)	Tax revenue ($ million)	
			Provincial	Federal
Baseline	1214	39.2	4.4	5.4
Optimistic	1324	43.8	4.9	5.9
Pessimistic	857	28.9	3.2	3.9
Change under Optimistic	110	4.9	0.5	0.5
Change under Pessimistic	−357	−10.3	−1.2	−1.5

Note: Employment estimates are rounded to the nearest one, and GDP and tax revenue estimates are rounded to the nearest hundred thousand.

Under the optimistic scenario, employment in New Brunswick could potentially increase by between 87 and 110 person-years, representing a 9–18% increase. GDP could also potentially increase by between $3.0M and $4.9M, representing a 12–19% increase. As a result, tax revenues could also increase by between $0.2M and $0.5M provincially and by between $0.4M and $0.5M federally, representing an 11–18% increase.

Under the pessimistic scenario, employment in New Brunswick could decrease by between 120 and 357 person-years, representing a 25–29% decrease. GDP could decrease by between $3.7M and $10.3M, representing a 24–26% decrease. Federal and provincial tax revenues could also decrease as a result of the tourism industry in Boutouche not adapting to climate-change impacts. Provincial tax revenues could decrease by between $0.5M and $1.2M, whereas federal tax revenues could decrease by between $0.5M and $1.5M, representing a 24–27% decrease.

As a result of a small survey sample size, variation in the responses from tourists and cumulative error, the standard deviations of estimated visitation and spending patterns are large. It should be noted that dramatic climate changes could, theoretically, reduce employment in Kent County and in New Brunswick by much more than the estimates in Tables 2 through 5 for the pessimistic scenario. The estimated means in the pessimistic scenario minus one standard deviation represent a reduction in tourism expenditures in the Bouctouche area to zero. It is therefore conceivable that dramatic climate changes could have such a negative impact on tourism that the number of tourists and employment could decline to much lower levels.

More optimistically, with creative adaptation and mitigation, economic gains may be experienced. However, mitigation measures must be environmentally sound. A significant asymmetry noted in this analysis between the potential upside (optimistic scenario) and the potential downside (pessimistic scenario) is indicative of a tourism industry that is highly sensitive to a perceived decline in the quality of the environment in coastal areas around Bouctouche. Such a high rate of environmental quality elasticity could exacerbate the negative economic consequences of inadequate adaptation measures along the coast.

4.7.4.2 Interpretation of Shediac Bay case-study results

The Shediac Bay case study identified and assessed current and future properties at risk of storm-surge flooding under a 2.5-m and 3.0-m water level. The damage costs under each storm-surge event to residential and some recreational properties (cottages only) were also estimated. Finally, this analysis estimated some of the costs associated with generic adaptation options.

4.7.4.2.1 Existing properties at risk

Using the DEM and geographic information system (GIS) application tools, this analysis identified properties at risk of flooding during a storm-surge event and the average flood depth (in metres) that could be expected on each property in the study area under a 2.5-m and 3.0-m (worst-case) water level. Estimated flood depths were grouped together as Flood Classes, a scale of 0–6 representing increasing flood depth ranges:

Flood Class	Flood depth range
0	0 m
1	>0–0.5 m
2	>0.5–1.0 m
3	>1.0–1.5 m
4	>1.5–2.0 m
5	>2.0–2.5 m
6	>2.5 m

Figures 3 and 4 illustrate those parcels of land at risk of flooding during a storm-surge event under two water levels. Each parcel of land is colour-coded based on its Flood Class. For example, parcels shaded dark green are in Flood Class 1, meaning that average flood depth on that parcel during a storm-surge event is expected to be less than 0.5 m. Parcels shaded dark red are in Flood Class 6, meaning that the average flood depth on that parcel during a storm-surge event is expected to be greater than 2.5 m.

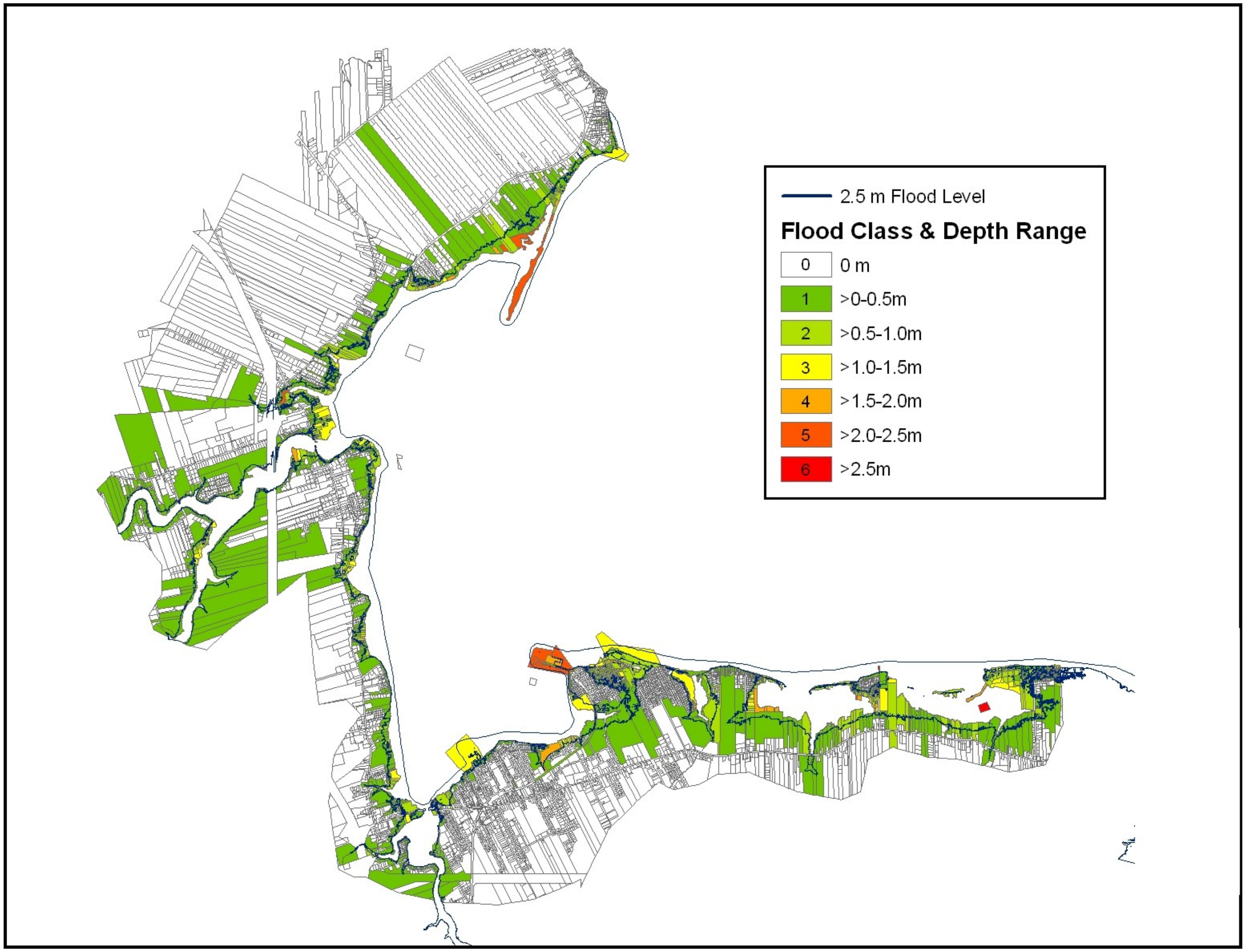

Figure 3. Flood risk to properties, 2.5 m above digital elevation model (DEM) datum water level, existing structures (baseline event). The blue line represents the maximum flood limit during the January 21, 2000, storm-surge event.

Figure 4. Flood risk to properties, 3.0 m above DEM datum water level, existing structures. The blue line represents the maximum flood limit during the January 21, 2000, storm-surge event.

Under the 2.5-m water level, it is estimated that 1639 existing properties in the Shediac Bay case-study area are at risk of flooding to some degree (Figure 3 and Figure 5). The total assessed value of the properties is estimated at $117.9M. Of the 1639 properties at risk, 1219 are developed properties assessed at $112.0M, and 420 are undeveloped properties assessed at $6.0M.[31] Table 6 highlights the properties by Flood Class and property type. The following is a list of property types:

- residential[32]
- recreational[33]
- commercial
    - industrial
    - institutional
    - farms
    - woodland.

Under the 3.0-m water level, an estimated 2003 existing properties in the case-study area are at risk of flooding, and their assessed values total approximately $139.3M (Figure 4, Figure 5 and Table 7). Of the properties at risk, 1498 are developed, assessed at $132.3M, and 505 are undeveloped, assessed at $7.0M. Table 7 identifies these properties by Flood Class and property type.

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[31] Properties were considered to be “developed” for the purposes of this study if some type of structure was indicated in the property description field of the Real Property Attributes Data (RPAD) files. Properties were considered to be “undeveloped” if no structure was indicated in the property description field of the RPAD files.

[32] A residential property type includes properties such as mobile homes, duplexes, single dwellings and condominiums. See Service New Brunswick (2000) for more information.

[33] A recreational property type includes properties such as parks, golf courses, clubs, community centres, marinas and cottages. See Service New Brunswick (2000) for more information.

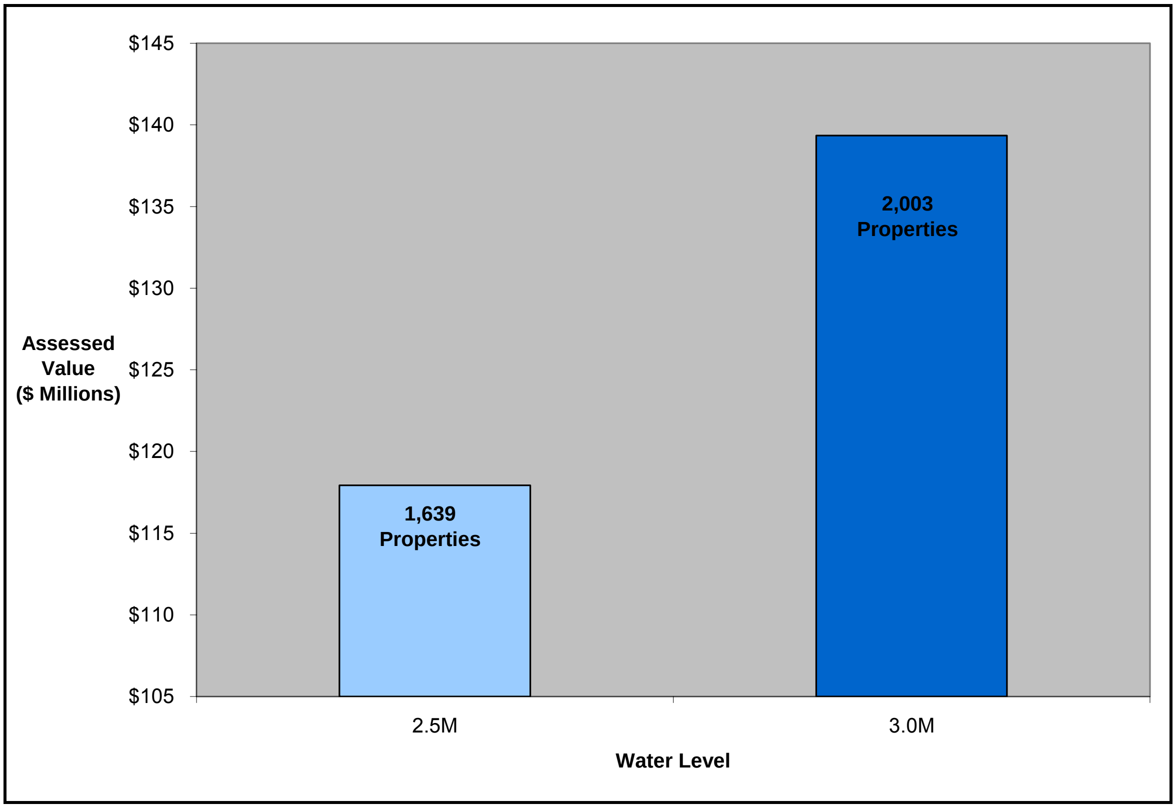

Figure 5. Total existing properties at risk of flooding, 2.5 m and 3.0 m above DEM datum water level.

Table 6. Existing properties at risk of flooding, 2.5 m above DEM datum water level.

Flood Class	Residential		Commercial & industrial		Institutional		Recreational		Farms & woodland	
	No.	Assessed value	No.	Assessed value	No.	Assessed value	No.	Assessed value	No.	Assessed value
1	535	$48,812,700	23	$4,165,900	9	$2,169,800	600	$32,105,700	21	$457,100
2	98	$8,501,700	8	$4,163,200	3	$39,700	234	$12,212,900	2	$57,400
3	20	$1,509,600	0	$0	1	$60,000	65	$3,309,200	1	$1,200
4	4	$14,400	1	$800	0	$0	7	$196,800	2	$2,700
5	1	$10,000	0	$0	1	$128,300	2	$3,300	0	$0
6	0	$0	1	$3,500	0	$0	0	$0	0	$0
Total	**658**	**$58,848,400**	**33**	**$8,333,400**	**14**	**$2,397,800**	**908**	**$47,827,900**	**26**	**$518,400**

Table 7. Existing properties at risk of flooding, 3.0 m above DEM datum water level.

Flood Class	Residential		Commercial & industrial		Institutional		Recreational		Farms & woodland	
	No.	Assessed value	No.	Assessed value	No.	Assessed value	No.	Assessed value	No.	Assessed value
1	530	$45,145,200	20	$4,736,200	10	$1,646,700	467	$25,235,000	23	$416,000
2	206	$17,951,700	13	$1,857,900	2	$740,500	336	$15,706,600	4	$123,000
3	69	$6,072,600	8	$4,163,200	4	$99,700	213	$10,820,800	0	$0
4	16	$1,072,000	0	$800	0	$0	62	$3,192,800	1	$1,200
5	4	$14,400	1	$3,500	0	$0	7	$196,800	2	$2,700
6	1	$10,000	1	$0	1	$128,300	2	$3,300	0	$0
Total	**826**	**$70,265,900**	**43**	**$10,761,600**	**17**	**$2,615,200**	**1,087**	**$55,155,300**	**30**	**$542,900**

4.7.4.2.2 Future developments at risk

Through the community-engagement process, two future socio-economic scenarios were developed that mapped future development patterns under optimistic and pessimistic economic growth conditions (Figure 4 and Figure 5). Future attributes identified in the optimistic and pessimistic scenarios were assigned Flood Classes based on a 3.0-m water level (future worst-case event). The estimated values of the future attributes under each scenario are presented in Table 8.

Under the optimistic scenario, there were a total of 10 residential developments indicated, of which 5 are expected not to be at risk of flooding and 5 are expected to be at risk of minimal flooding (less than 0.5 m). Two commercial zones and the community centre proposed under this scenario are expected to have no risk of flooding; however, one commercial zone identified is expected to have a risk of minimal flooding. Expansion of the Pointe-du-Chêne and Shediac marinas was identified, and both of these properties are at risk of flooding — the Pointe-du-Chêne marina is at risk of flooding between 1.5 and 2.0 m, and the Shediac marina is at risk of flooding between 1.0 and 1.5 m. The nine green zones identified for this scenario are located along the coast or slightly inland, but on the banks of the Shediac River. Proximity to the water puts these developments at risk of high flood levels — all the green zones are at risk of at least 0.5 m of flooding.

Under the pessimistic scenario, there were a total of five residential developments indicated, two of which are expected to have no risk of flooding and three of which are at risk of minimal flooding. The commercial property identified is located along the coast and has a Flood Class of 5. Closure of the Pointe-du-Chêne marina and expansion and improvement of the Shediac marina were also identified under this scenario, and both marinas are at risk of flooding. The closure of Parlee Beach Provincial Park and the development of a new park near Barachois were identified under this scenario; Parlee Beach has a Flood Class of 2 (average flood depth between 0.5 and 1.0 m), and the park near Barachois has a Flood Class of 3 (average flood depth between 1.0 and 1.5 m). The proposed community centre identified under this scenario is not at risk of flooding.

Table 8 groups the future attributes under each scenario by property type, and in some cases an assessed value has been estimated using average assessed values from nearby properties as a proxy.

Table 8. Value of features under the optimistic and pessimistic scenarios.

Property type	Assessed value (2004 Cdn $ millions)	
	Optimistic	Pessimistic
Residential – low density(e)	45.6	18.9
Residential – high density(e)	68.5	7.8
Commercial – expansion	unable to estimate	n/a
Commercial – closure	n/a	details not available
Community centre	unable to estimate	unable to estimate
Museum	n/a	unable to estimate
Marinas(av) Pointe-du-Chêne marina – expansion (optimistic) Pointe-du-Chêne marina – closure (pessimistic) Shediac marina – expansion (both scenarios)	0.54	0.54
Parlee Beach Provincial Park(p)	n/a	1.7

(e) Estimated based on 2004 assessed value of similar properties in 500-m radius or similar properties in the Shediac Bay case-study area.
(av) Assessed value in 2004.
(p) Partial – assessed value of Parlee Beach and buildings only.
n/a – Not applicable, i.e., the feature was not mentioned by the workshop participants.

4.7.4.2.3 Estimated damage costs for houses and cottages

Flood depth–damage cost functions were used to estimate the costs of structural damage to existing houses and cottages associated with flooding from 2.5-m and 3.0-m water levels in the Shediac Bay case-study area (Table 9 and Figure 6). It was assumed that a minimum flood depth of 0.5 m is required before damage to structures would occur, and those properties that are expected to have minimal flooding (Flood Class 1, flood depth less than 0.5 m) were excluded from the analysis. This includes all of the future residential properties indicated under the optimistic and pessimistic scenarios that are at risk of flooding; these properties are at risk of only minimal flooding in the event of storm surge with a 3.0-m water level.

There are 277 houses/cottages expected to incur damage in the event of storm surge with a 2.5-m water level (Table 9). The total assessed value of these properties is $21.7M, and the estimated damage costs are close to $7.1M, approximately 33% of the total assessed value.

Under a storm-surge event with a 3.0-m water level, 644 houses/cottages are expected to incur damages. The total assessed value of these properties is estimated to be close to $48.9M, and the estimated damage costs are close to $17.6M, approximately 36% of the total assessed value.

Figure 6 illustrates the estimated damage costs to houses and cottages associated with each water level by Flood Class. This study estimated damage costs to those residential properties at risk of flooding with a minimum flood depth of 0.5 m. All new residential zones identified under both the optimistic and pessimistic scenarios are estimated to be either at no risk of flooding or at minimal risk of flooding (less than 0.5 m flood depth); therefore, damage costs to these new residential properties are assumed to be zero.

Table 9. Estimated damage costs (2004 Cdn $) to existing houses and cottages, 2.5 m and 3.0 m above DEM datum water level.

Flood Class	2.5-m water level			3.0-m water level		
	No.	Assessed value	Damage costs	No.	Assessed value	Damage costs
2	230	$18,415,600	$5,793,694	408	$31,319,700	$9,908,503
3	47	$3,310,600	$1,336,620	194	$14,780,600	$6,319,199
4	0	$0	$0	42	$2,799,000	$1,411,735
5	0	$0	$0	0	$0	$0
6	0	$0	$0	0	$0	$0
Total	**277**	**$21,726,200**	**$7,130,314**	**644**	**$48,899,300**	**$17,639,437**

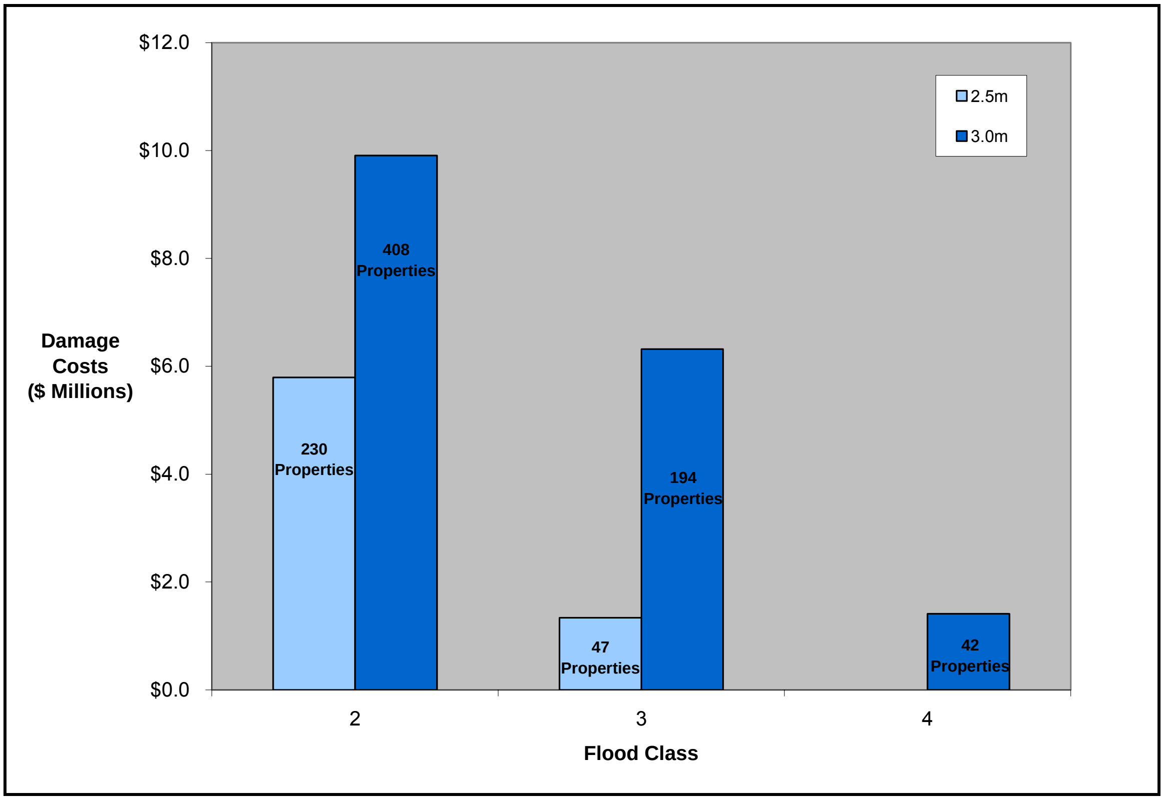

Figure 6. Estimated damage costs (2004 Cdn $) to existing houses and cottages, 2.5 m and 3.0 m above DEM datum water level.

4.7.4.2.4 Adaptation costs

Retreat

To minimize the impacts to humans of sea-level rise and storm surge in the coastal zone, retreat may be an option that is considered or combined with other adaptation options. In this analysis, the minimum compensation required by property owners and the forgone provincial and municipal tax revenues were estimated. In this hypothetical adaptation option, it was assumed that owners with properties that have an average flood depth of 1.5 m or more (Flood Classes 4, 5 and 6) as a result of a storm surge with a 3.0-m water level will need to be relocated.

Table 10 reports the number and total assessed value of developed and undeveloped properties (by property type) in Flood Classes 4, 5 and 6. In total, there are 42 developed properties and 52 undeveloped properties with a Flood Class of 4, 5 or 6, and the estimated minimum compensation costs are $2.8M for developed properties and close to $560K for undeveloped properties.

Table 11 reports the provincial and municipal tax revenues forgone under the retreat option. There are 92 residential properties and 2 non-residential properties in Flood Classes 4, 5 and 6. The total forgone provincial property tax revenue is estimated to be $50.4K annually, and the forgone municipal property tax revenue is estimated to be $49.7K annually. The total tax revenues forgone under the retreat option are estimated to be $100K annually.

Table 10. Estimated minimum compensation costs (2004 $ Cdn), retreat adaptation option

	Developed		Undeveloped	
Property type	No. of properties	Assessed value	No. of properties	Assessed value
Residential	12	$1,005,400	9	$91,000
Commercial	0	–	2	$4,300
Recreational	30	$1,793,600	38	$460,700
Farms	0	$0	3	$3,900
Total	**42**	**$2,799,000**	**52**	**$559,900**

Note: As per the assumption that the retreat option includes properties in Flood Classes 4, 5 and 6.

Table 11: Property taxes forgone (2004 $ Cdn), retreat adaptation option

Property type	No. of properties	Provincial tax rate	Municipal tax rate	Total tax
Residential	92	$50,319	$49,594	**$99,913**
Non-residential	2	$97	$95	**$192**
Total	**94**	**$50,416**	**$49,690**	**$100,106**

Note: As per the assumption that the retreat option includes properties in Flood Classes 4, 5 and 6. Taxes are calculated based on 2004 tax rates for Shediac Town.

Protection and accommodation option

Through dialogue with stakeholders, it was noted that a number of community members have already taken protective measures to reduce impacts from sea-level rise, storm surge and coastal erosion. Throughout the southeastern coast of New Brunswick, many property owners have tried to adapt to climate-change impacts through employing both protection and accommodation measures. Based on information from community members, organizations and other stakeholders, the following is a list of some of the previously used adaptation approaches in southeastern New Brunswick, along with some estimated costs:

- *Protection*: In order to protect properties from flooding, property owners have used hard protection structures such as seawalls to reduce the risk of flooding. Through various discussions with community members, the estimated cost to build a seawall is $1,000 per square metre of base surface.[34]

- *Accommodation*: Other measures taken to mitigate the impacts of sea-level rise and storm-surge flooding have been to continue to reside along the coast while making adjustments to buildings and infrastructure to accommodate sea-level changes. For example, many property owners have elevated buildings on piles to reduce their risk of flooding. The cost of elevating a building varies depending on a number of variables, including the size of the building, the height to be elevated to, the contractor and the materials required.

4.7.5 Summary and conclusions

Sea-level rise, coastal erosion and increased intensity and frequency of storm-surge events have significant socio-economic impacts on coastal communities, ecosystems and various economic sectors. This analysis has evaluated some of the costs and benefits associated with adapting to these impacts through both a community engagement and a case-study approach.

Important elements of this project are the engagement of the community and building upon local knowledge and understanding of coastal-change processes and adaptation. The following are among the key findings from the community-engagement process:

- Initial interviews in the communities showed that attitudes towards the impacts of extreme events were primarily reactive; however, it is very much in the interests of the communities to adopt a more proactive approach.

- The community-engagement process enabled this research to respond more effectively to the needs of the communities and propose relevant recommendations for adaptation. It also provided an opportunity to increase the communities' awareness of climate change.

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[34] Based on personal communication with New Brunswick sea-level-rise study team and members of the case-study community.

- For this study to help in building local capacity for adaptation to climate change, the communities in the study area will have to take ownership and interpret the results in their local context, involving all appropriate stakeholders and decision-makers.

Case studies were chosen to represent the types of impacts and issues expected under climate change and to enable a detailed analysis. The information and data used to estimate the economic impacts are limited to the geographical area of each case study. While the methodology and approaches used in this analysis are transferable, the results will not be directly applicable to other geographical locations.

The effects of climate change are an increasing concern for tourism operators in southeastern New Brunswick, because ecotourism and cultural tourism sectors have developed rapidly in the last decade, and tourism operations are feeling the effects of erosion and storm surges from extreme storms. The Bouctouche area was selected as a case study to evaluate the economic impacts associated with climate change on the tourism industry. This case study estimated the economic benefits to the tourism sector of implementing adaptation measures. Conversely, this analysis estimated the economic losses as a result of the tourism sector failing to mitigate or protect itself from the impacts of sea-level rise, coastal erosion and storm-surge events. Some key findings from the Bouctouche case study include the following:

- Many visitors to Bouctouche recognize that climate change is impacting coastal communities across eastern North America. Through thoughtful adaptation and mitigation strategies, the tourism sector of Bouctouche may see economic growth. In contrast, failure to adapt to climate change may result in losses to the tourism sector. Appropriate adaptation measures will be a key element in determining if the tourism industry in the Bouctouche area grows or declines over time as a result of the consequences of climate change.

- Under an optimistic scenario, whereby the tourism sector manages climate-change impacts through adaptation strategies, there is a potential for economic gains, compared with the estimated baselines, in Kent County and New Brunswick. Employment in Kent County could increase by 8–18%, and GDP in Kent County could increase by 11–19%. Provincial and federal tax revenues could potentially increase by 11–18%.

- Under the pessimistic scenario, whereby the tourism sector does not adapt to climate-change impacts, there is a potential for economic losses, compared with the estimated baselines, in Kent County and New Brunswick. Employment in Kent County could decrease by 25–30%, and GDP in Kent County could potentially decrease by 25–27%. Provincial and federal tax revenues could potentially increase by 24–28%.

Property and infrastructure within coastal communities of southeastern New Brunswick are also threatened by sea-level rise and storm-surge events. After the January 21, 2000, storm-surge event, declared a disaster by the federal government, there were 198 damage claims submitted to the New Brunswick EMO, 43 of which were eligible for funding totalling close to $1.5M (K. Wilmot, New Brunswick EMO, pers. comm.). In order to understand the magnitude of these impacts on coastal communities, the Shediac Bay case study has identified those properties that are at risk of flooding and has quantified the potential damage costs associated with storm-surge events. In addition, the analysis has estimated some of the types of costs associated with retreat, protection and accommodation adaptation options. Key findings from this case study include the following:

- Future scenarios were developed by community stakeholders based on storylines that described changes to key drivers. Under an optimistic economic development scenario, the community identified 10 new residential zones (estimated value \$114.1M), expansion of three commercial zones, expansion of two marinas and nine new green zones. Under a pessimistic economic development scenario, the community identified five new residential zones (estimated value \$26.7M), closure of some commercial enterprises, new public services and one new green zone. This study estimated damage costs to residential properties. All new residential zones identified under both the optimistic and pessimistic scenarios are estimated to be either at no risk of flooding or at minimal risk of flooding (less than 0.5 m flood depth); therefore, damage costs to new residential zones identified under both scenarios are assumed to be zero.

- Non-residential property and infrastructure in the Shediac Bay case-study area are at risk of flooding during storm-surge events. A storm-surge event with a water level 2.5 m above DEM datum (approaching the January 21, 2000, storm-water level) places approximately 1639 existing properties in the Shediac Bay case-study area at risk of flooding to some depth. The total assessed value of these properties is estimated at \$117.9M. In the event of a storm surge with a water level 3.0 m above DEM datum, approximately 2003 existing properties in the case-study area are at risk of flooding to some depth. The total assessed value of these properties is estimated to be \$139.3M.

- In the event of a storm surge with a 2.5-m water level above DEM datum in the Shediac Bay case-study area, it is estimated that 277 residential properties (including cottages) would incur damage. The total assessed value of these properties is \$21.7M, and the estimated structural damage costs are close to \$7.1M, approximately 33% of the total assessed values. If the storm flood level reached 3.0 m above DEM datum, it is estimated that 644 residential properties would incur damage. The total assessed value of these properties is estimated to be close to \$48.9M, and the estimated structural damage costs are close to \$17.6M, approximately 36% of the total assessed values.

- Minimizing the impacts of sea-level rise and flooding from storm-surge events can be achieved through implementing adaptation strategies. When evaluating various adaptation strategies, the full costs and benefits of each strategy should be incorporated into the decision-making process. Although this analysis has not assessed the total costs and benefits associated with specific adaptation options, it has estimated some of the possible costs associated with generic adaptation options. If retreat is an option under consideration, the estimated minimum compensation required for 94 property owners with properties in Flood Classes 4, 5 and 6 is close to \$3.4M, and the total forgone property tax revenue (provincial and municipal) is estimated to be $100K annually. A few protection and accommodation options have also been estimated based on dialogue with various communities and stakeholders. The estimated capital cost to build a seawall, based on various discussions with community members, is $1,000 per square metre of base surface.

The results from this analysis should not be interpreted literally, as they are estimates based on the best available information. They can be used as indicators and estimates of magnitude to educate and raise awareness. They can also be applied to local decision-making processes concerning governance, coastal zone management and adaptation.

4.7.5.1 Recommendations for future studies

Assessing climate-change impacts and climate-change adaptation strategies from a socio-economic perspective is a field of study still in its infancy. There are numerous empirical challenges and methodological issues still to be overcome. This analysis has employed a number of economic tools and techniques to evaluate climate-change impacts in the coastal zone, and throughout the study, opportunities and areas for improvement were noted. The following are recommendations for consideration in future studies to strengthen and evolve methodologies, approaches, tools and techniques:

- Data limitations place a constraint on the type of analysis that can be carried out and the scope of the study. Ensuring that monitoring structures are in place to collect physical and biophysical data will help reduce uncertainty and will enable an evaluation of the social and economic impacts.

- Continuing to collect information on how tourists' behaviour could change under various climate-change scenarios will enable the tourism sector to develop and implement adaptation strategies to ensure that the sector is viable and sustainable. Future surveys should ensure that information is collected from an appropriate sample size and that the survey tool used is effective.

- Expanding the scope of these types of studies to larger geographical areas and other sectors, communities and ecosystems is desirable. For example, one may want to evaluate the economic impact on the tourism sector for the entire Acadian Coastal Drive given that tourists visit many of the attractions throughout the southeastern coast of New Brunswick (Kouchibouguac National Park to Parlee Beach).

- Given time constraints, it was not possible to evaluate the non-market values associated with changing availability of habitat types (as a result of sea-level rise, coastal erosion and storm surge). The results and data from the ecosystem subcomponent could be used to advance an ecosystem valuation study.

- Further investigation with emergency measures offices, Public Safety and Emergency Preparedness Canada and the insurance industry to explore the possibility of developing depth–damage curves for flooding in Canada and/or Atlantic Canada would be desirable.

- The development and application of a costing framework for adaptation strategies would provide guidance to governments, economic development agencies, planning commissions and communities on how to evaluate the costs associated with various adaptation strategies and would enable them to incorporate this kind of approach into their decision-making framework.

- The results from this study will facilitate discussion and potentially lead to identifying multiple adaptation strategies for the province as well as for various sectors and communities. A full cost and benefit analysis of each adaptation strategy should be completed and integrated into a decision-making framework.

4.7.6 Acknowledgements

As a sub-project of the New Brunswick sea-level-rise study, the socio-economic piece received resources from the Climate Change Action Fund, Natural Resources Canada (Earth Science Sector) and Environment Canada (Strategic Analysis and Research Directorate [Ottawa] and Strategic Analysis and Research Division [Atlantic]) to evaluate the socio-economic dimensions of climate-change impacts — specifically, impacts resulting from sea-level rise, storm surge and coastal erosion.

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4.8 Adaptation strategies

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4.8.1 Introduction

Adaptation is the process of adjusting to a set of circumstances that have changed the natural or human-made environment. It includes the development of strategies to either counteract a threat to the existing environment or make use of a positive change. Since adaptation is a process, it is also intricately connected to impact analysis and mitigation strategies, such as reduction of carbon dioxide emissions or building protective structures along a shoreline. Therefore, the adaptation research presented here is directly connected to previous sections, especially Section 4.7 on evaluating the impacts, which in fact become part of the larger adaptation framework.

4.8.1.1 Objectives of the adaptation component and general methodology

The objectives of the adaptation component were as follows:

1. Develop a web site to establish contact with other researchers and to post results as developed for critique.
2. Develop a database, accessible through the web site, of adaptation strategies used nationally and internationally, together with an evaluation of their successes and limitations where available.
3. Develop a multidimensional framework for identifying, classifying and creating a range of adaptation strategies.
4. Hold a workshop in the pilot areas to obtain feedback from stakeholders and to communicate results.
5. Develop a set of guidelines/best practices for community involvement in adaptation strategies.
6. Test the framework in the pilot areas and recommend strategies.

The first two objectives were achieved in the first phase of the research. The web page was established at the University of New Brunswick:
http://gge.unb.ca/Research/Research.html

A report was prepared for the Office of Critical Infrastructure Protection and Emergency Preparedness in 2004, which summarizes the results of objective 2 above, i.e., the research on national and international strategies (Sutherland and Nichols, 2004).

Work then began on developing a multidimensional framework. This work was conducted in conjunction with the Environmental Studies Group at the Université de Moncton, which was funded under the Environmental Trust Fund of the New Brunswick Department of Environment and other sources to perform filed research in the area, including stakeholder and community meetings. In order to capitalize on the strengths of the Université de Moncton research, a decision was made in year 2 of the project to focus the adaptation-strategy research in two main directions:

1. This would be a *community-driven approach* (i.e., from the ground up) rather than an academic approach (i.e., solutions proposed, vetted by the community and tested). The communities would have complete ownership of the process and any results.

2. The research would result in a *process for community involvement* (based on a literature review and community input) that could be used in other jurisdictions.

Objectives 3 and 4 above were thus accomplished, but in a manner different from first envisaged. Rather than communicating results and strategies to communities, the research was focused on getting community input on:

- how people had adapted in the past to sea-level rise and storm surges;
- what their experiences have been during recent events;
- what threats did they perceive for the future;
- what measures they have taken (if any); and
- what best practices could be learned from the community efforts.

Four case studies were undertaken for the research, and these are described below. Each case study tested the adaptation process framework designed in the research to illustrate how the framework operated and to bring out lessons learned from the case studies. Achieving objectives 3, 4, 5 and 6 above thus became an overlapping process, as information was gathered from bilingual town hall meetings, community sessions and interviews with stakeholders at the local level. One major regional workshop was conducted in October 2005 to consolidate some of the findings and to give wider publicity to the project and its findings.

4.8.1.2 Layout of section

The results of the adaptation research are reported in this section, with an emphasis on how the research has developed capacity in the study area to understand the potential impacts of sea-level rise and storm surges. Additionally, using existing local knowledge, these results begin to develop a process for deriving appropriate adaptation responses. While these responses have not been implemented during the project itself (many are outside the scope and means of the project, and most would require additional assistance from the provincial government), the research has shown the need to include a wide range of responses from the policy level to engineering at the site-specific level.

The section is organized as follows:

- results of the literature review and international research on adaptation strategies;
- results of the research on traditional adaptation strategies in the study area;
- description of the conceptual framework for community-driven adaptation strategy development;
- exploration of the framework using four case studies from the study area; and
- guidelines and best practices for community-based adaptation strategies.

4.8.2 Adaptation strategies — Literature review

4.8.2.1 What is adaptation?

In response to the negative impacts of climate change, and to take advantage of the opportunities presented by positive impacts, communities may have to adjust their social, economic, political and environmental activities. Depending on the goal of the ameliorating activities, this adjustment is generally termed either adaptation to climate change or the mitigation of the negative effects of climate change. Mitigation aims to limit the overall scale of effects of climate change, while adaptation deals with the unavoidable effects of climate-change phenomena (DEFRA, 2004). Internationally, mitigation has been promoted more than adaptation. However, adaptation strategies may sometimes be combined with mitigation strategies to achieve targeted objectives (Michaelowa, 2001).

4.8.2.2 What are the frameworks available for thinking about adaptation?

There are a number of key documents that address the issue of adaptation to climate change and sea-level rise and set frameworks for designing adaptation strategies. These include the following (see, for example, Sutherland and Nichols, 2004):

- The 1994 Intergovernmental Panel on Climate Change (IPCC) *Technical Guidelines for Assessing Climate-Change Impacts and Adaptation* recommended certain adaptation strategies, such as:
    - Protection (e.g., continuing land-use activities, such as seawall construction);
    - Accommodation (i.e., making adjustments to human activities and/or infrastructure, e.g., enhancing natural resilience through coastal dunes and wetland rehabilitation); and
    - Retreat (i.e., avoiding risks, e.g., abandoning development in vulnerable areas).

- The United Nations Environment Programme's (UNEP) *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies* (Feenstra et al., 1998) is being developed to assist countries in the organization of national impact and adaptation studies and in making decisions about the scope and methods for these assessments.

To determine appropriate strategies to adapt to the potential positive and negative impacts of climate change, it is necessary to do assessments of communities' vulnerability to change, resilience and adaptive capacity. This is done in accordance with biophysical assessments of the spatial extent under threat (see Figure 1). Additionally, of course, an assessment of the nature of the potential threats has to be done (CPACC, 1999; Mendis et al., 2003).

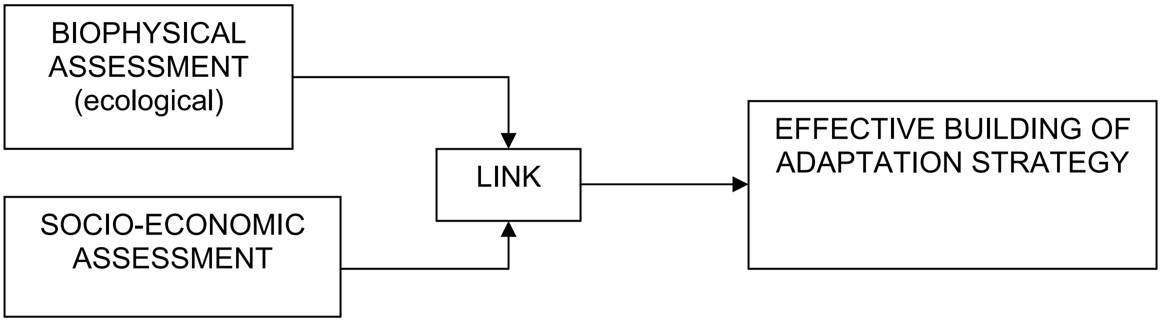

Figure 1. Effective building of adaptation strategies (from Mendis et al., 2003).

Generally, adaptation strategies may be grouped into information, technical and policy options. Information options may include such things as obtaining knowledge on the speed of sea-level rise, available human resources and planned countermeasures. Technical options for adaptation would include such things as the construction of seawalls and other structures and the reinforcement and improvement of infrastructure. Policy options would include, for example, land-use planning, legal reforms, environmental conservation, coastal management and sustainable-development policies (Sutherland and Nichols, 2004).

4.8.2.3 What can we learn from other provinces, programs and countries?

Mendis et al. (2003) stated that:

> Standard model used to predict climate change is Scenario-based Global Circulation Models (GCM). Keep in mind that although climate change phenomenon is happening globally, each community experiences weather patterns locally.

Therefore, adaptation strategies utilized in (or designed for) different geographical locations are unique due to the unique nature of the set of environmental and socio-economic problems experienced in, or threatening, each location. Processes of assessment, etc., may be applied by formula, but the appropriate set of strategies employed will often be unique to the geographic area under threat. Often the set of strategies will depend on, among other things (Mendis et al., 2003; Saleemul et al., 2003; UNFCCC Secretariat, 2003; Government of Australia, 2004):

- information that is available on the nature of the climatic threats;
- amount of resources and support available from different levels of government;
- amount of cooperation, collaboration, etc., among all stakeholders;
- community’s level of dependence on local resources;
- community’s population size and socio-economic significance;
- community’s vulnerability;
- community’s resilience; and
- community’s adaptive capacity.

The United Nations Development Programme (UNDP) also made certain suggestions to jurisdictions regarding preparations to be made in relation to the possible advent of adverse climate-change phenomena. These include (UNDP, 2003):

- ratification of the United Nations Framework Convention on Climate Change (United Nations, 1992) (aimed at assisting adaptation to the adverse consequences);
- monitoring, surveying and collecting data on climate change and sea-level rise;
- developing mitigation policies;
- mapping vulnerable areas;
- doing socio-economic assessment;
- promoting public education of the issues;
- doing information exchanges with similar jurisdictions;
- minimizing the effects of climate change through development planning;
- improving access to financial and technical resources for monitoring climate change; and
- increasing research on climate impacts.

Again, the unique nature of the set of environmental and socio-economic vulnerabilities associated with each location will determine the unique set of appropriate strategies to address the potential impacts of rising sea levels. To demonstrate this, Table 1 shows an international sample of strategies to address sea-level rise, one deleterious impact of climate change (Also see Appendix 1). However, strategic elements of overall jurisdictional plans appear to be common to at least some jurisdictions. These elements include:

- coastal engineering protection and stabilization strategies, such as breakwaters, seawalls and groynes (artificial structures built with concrete or boulders that are designed to prevent beaches from washing away); and
- coastal policies and land-use planning strategies (e.g., zoning, setbacks and reserves) designed to manage human activities in coastal zones and to protect coastal areas.

Table 1. International sample of adaptation strategies to sea-level rise and coastal flooding.

Region/country: risk/impacts	Strategy/response	Process
Canada: • *Sea-level rise and coastal flooding due to:* • *Decrease in sea ice* • *Increase in wave energy* • *Shore erosion*	*(Suggested strategies)* • *Protection* o *Costly protection options* o *Soft protection options (recommended)* • *Accommodation* o *Redesign structures to minimize impacts* o *Implement zoning to encourage land use with low capital investments on vulnerable lands* o *Increase natural resilience (e.g., coastal dune rehabilitation; wetland renewal, etc.)* o *Soft protection methods* • *Retreat* o *Avoiding risks, e.g., preventing vulnerable lands being inappropriately developed* *(Environment Canada, 2002)*	• *Top-down, based on sea-level-rise modelling case study in Prince Edward Island* • *Suggestion that adaptation problems be solved locally and preferably with the "buy-in of local stakeholders"*

Region/country: risk/impacts	Strategy/response	Process
Britain: - *Sea-level rise and coastal flooding*	*(Suggested strategies)* *Enacting and redesigning policies related to:* - *Transportation (coastal)* - *Health (coastal communities)* - *The financial sector* - *Land-use planning (coastal)* - *Coastal defence* - *Agriculture in coastal areas* *(Office of the Deputy Prime Minister, 2004)*	- *Top-down "advice"* - *Based on sea-level-rise forecasts* - *Suggests that local planners, developers and the wider community develop partnerships*
The Gambia: - *Sea-level rise and coastal flooding* - *Shoreline retreat* - *Coastal erosion*	*(Suggested strategies)* - *Innovative sand management* - *Building and rehabilitation of groynes (shoreline stabilization)* - *Construction of revetments to protect important areas* - *Construction of seawalls/bulkheads* - *Public outreach and awareness* - *Building regulations and urban growth planning* - *Wetland preservation and mitigation* - *Development of a coastal-zone management plan* *(Jallow et al., 1996)*	- *Top-down* - *Based on sea-level-rise modelling case study*

Region/country: risk/impacts	Strategy/response	Process
Western Australia: • *Sea-level rise and coastal flooding*	*(Suggested strategies)* • *Coastal policy (State Coastal Planning Policy)* • *General policy measures (e.g., the form and design of development, public rights and access, etc.)* • *Sustainable uses of the coast* • *Protection of significant features* • *Community participation* • *Location of land uses* • *Public access and reserves* • *Coastal processes and engineering works* • *Coastal strategies and foreshore management plans* • *Coastal plans* • *Setbacks* • *Coastal foreshore reserve* • *Setback for physical processes* *(Panizza, 2002)*	• *Top-down* • *State Coastal Planning Policy implemented by Western Australian Planning Commission and based on “increasing knowledge about the threats posed by sea-level rise”*

Region/country: risk/impacts	Strategy/response	Process
Israel: - *Sea-level rise and coastal flooding*	*(Suggested strategies)* - *Elevate port structures (berths, wharves) and offshore structures to protect them from overtopping and from increased maximum wave heights (measurements have already been taken in the ports of Haifa and Ashdod, where berths have been raised)* - *Protect low coastal areas and beachfront cliffs with breakwaters and other means (about 50 km of sensitive beaches)* - *Strengthen and repair existing breakwaters* - *Elevate power-station outlets* - *Transport sands northward ("artificial feeding") to refill sands of Israel's northern coast for reducing the risk of coastal erosion (about 100 km of sensitive beaches)* - *Design future offshore islands with higher elevations and greater volume of filling-in material* *(Pe'er and Safriel, 2000)*	- *Top-down* - *Based on a survey of literature and on interviews with Israeli scientists and policy-makers*

Region/country: risk/impacts	Strategy/response	Process
Philippines: • *Sea-level rise and coastal flooding*	*(Suggested strategies)* • *Closing policy gaps* • *Integrated coastal-zone management plan to prevent [destructive] initiatives in coastal areas* • *Requirement of setbacks (treat public easements and setbacks as separate lots during land surveys)* • *According lower-lying land to use of lower value (e.g., parks instead of housing, etc.)* • *Strict requirement of compliance with housing standards* • *Institutionalize mangrove development* • *Strict implementation of coastal laws* *(Perez, 2000)*	• *Top-down* • *Based on government study of sea-level-rise risks to coasts*

It is to be noted that the strategies in Table 1 are in fact only suggestions, based in part on sea-level-rise modelling scenarios and forecasts, because these jurisdictions (as with most jurisdictions in the world) have not actually experienced catastrophic sea-level-rise events.

However, some jurisdictions have experienced temporary catastrophic sea-level-rise events due to adverse weather conditions such as hurricanes and storms. A few jurisdictions have in these circumstances had opportunity to test their adaptation/mitigation strategies. For example, Sutherland and Nichols (2004) report that buildings erected in Florida on the seaward side and in contravention of a Coastal Construction Control Line fared worse than buildings that complied with the land-use planning regulation. Also, it was reported that in Bangladesh, the loss of life to coastal flooding caused by cyclones was greatly reduced after coastal dikes were erected, public awareness programs were implemented and non-governmental organizations and communities were involved in disaster adaptation/mitigation responses. The events in 2005 in the New Orleans area highlighted the need for more preparedness from the national to community level.

The processes for developing the adaptation strategies shown in Table 1 appear to be *ad hoc*, having not apparently been developed according to any identified process formula. Additionally, all the processes appear to have been developed in a “top-down” manner by government bodies. There is no evidence from the listed jurisdictions that local communities were consulted in the strategy development process, although some jurisdictions suggest that partnerships be created with communities as part of adaptation strategies.

4.8.3 A community-based approach

4.8.3.1 Scope and method of the community research

As described above, one of the major features of this research was the fact that the direction taken was not “top-down,” where researchers later communicated and tested results with the local community. A unique feature of the research was that it was “bottom-up” and focused on community values and perceptions in order to assess the need for adaptation and possible best practices. The research was based on the trust developed over a long period with the Université de Moncton researchers and local communities in the study areas.

As highlighted in Section 4.8.2 above, adaptation strategies need to be community driven (based on the specific situations in local areas) because:

- the impacts of climate change vary so greatly from locality to locality;
- the range of potential adaptation strategies and their implementation are constrained or enhanced by community resources and capacity and will be coloured by the values of specific individuals and groups[35]; and

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[35] Thus, for example, there are graveyards undergoing coastal erosion in the Bouctouche area that may require a more immediate response by the community, whereas larger problems, such as highway or bridge endangerment, may have to wait for provincial government intervention.

- top-down approaches, without community buy-in, can often fail (see, for example, the case study in Section 4.8.4.6.2.

Thus, throughout the research, community knowledge and awareness became the central point. In this respect, local residents and others potentially affected talked with researchers and officials in their own settings and at their own pace. In tandem, a more conceptual framework was developed that could be used to replicate this type of approach in other regions and for other climate-change issues. The approach was thus deemed more important than specific adaptation measures.

4.8.3.2 Community workshops: sharing experience and knowledge

As presented in Section 4.7.2, the community-engagement aspect of the project aimed at mobilizing communities towards increasing their adaptive capacity. To achieve this goal, researchers gathered information on local adaptation needs and initiatives as well as difficulties or barriers encountered. Scientific knowledge on climate-change impacts, sea-level-rise predictions for the next century and other pertinent data then needed to be presented to communities in order to base any adaptation on the best information available.

Information on the communities' adaptation status was mostly gathered through interviews and focus-group discussions conducted in different communities from 2003 to 2005. A total of 27 interviews were conducted in 2003–2004 with individuals representing different socio-economic groups who were living near the coast. The interviews were focused on perceptions towards climate-change impacts. The results from the interviews were validated using three focus-group discussions with 9–13 individuals from three different coastal communities.

In 2004, 12 interviews were conducted with different individuals who had undergone sea-level-related climate-change impacts on their properties or were susceptible to experiencing such impacts in the future. Questions focused on:

- the reasons for adaptation;
- past and present adaptation methods used and their effectiveness; and
- sources of information for decision-making.

Participants were also taken to sites with researchers to discuss impacts and adaptation methods. During this period, seven public information sessions were held in different communities to share some of the research results and build the link with communities. Also, a two-day workshop on the same topic was organized in the fall of 2004 in cooperation with the Southern Gulf of St. Lawrence Coalition on Sustainability and the Linking Science and Local Knowledge node of the Ocean Management Research Network (reference for final workshop report and Coastal Research Bulletin, November 2004, at http://www.sfu.ca/coastalstudies/publications.htm).

In the fall of 2005, a series of public information sessions on climate-change impacts and adaptation were held in five communities of southeastern New Brunswick. During these sessions, questionnaires on adaptation needs were distributed to some participants. Also, three focus-group discussions were held in Pointe-du-Chêne, Rexton and Elsipogtog First

Nation. These meetings were held to further validate results and gather more detailed information specific to the community.

For all presentations and focus groups, efforts were made to invite different community representatives, especially councillors, mayors, planners, Local Service District representatives, watershed protection groups and others. Information was presented at these meetings, and time was reserved for questions and discussions on local concerns and issues.

The relatively long period through which information was gathered in communities allowed some insight on changes in local perceptions. Researchers observed between 2003 and 2005 some changes in attitudes, mostly expressed as an increased sense of emergency and desire to act towards adaptation. Results from questionnaires and interviews also show that communities feel an urgent need for more support in terms of information, guidance and resources to help in their adaptation efforts. Many communities have expressed the importance of information sessions they have received and stress the need for more in the future. In at least one case, visits to communities in the context of the present project have generated community action (see case of Pointe-du-Chêne in Section 4.8.4.6.4).

4.8.3.3 Traditional strategies in southeastern New Brunswick

4.8.3.3.1 Impacts

All the individuals interviewed were well aware of climate change and the vulnerability of coastal areas. In most cases, the impacts witnessed have been flooding due to storm surges, increased coastal erosion and strong winds associated with storms. Others are concerned about losses of sand from beaches and dunes. For most participants, these impacts are not new, having been witnessed by them for at least 10–20 years, but others feel that they have become more obvious in the last 5 years. Many also believe that the impacts experienced in the last few years are inevitable and that we will see more in the future; this has some people very preoccupied. Some communities, such as Barachois, Pointe-du-Chêne and the Village of Rexton, have experienced events that have had important economic impacts and generated some health and safety concerns. Parts of these communities are in low areas and very susceptible to flooding when storm surges occur. Pointe-du-Chêne is particularly vulnerable, with the access road being flooded almost annually with extreme high-tide events. In storm-surge situations such as the one in January 2000, parts of the community's streets and houses are flooded, and the main road is blocked off. The community then literally becomes an island, and access to emergency services is difficult. There has been at least one incident in both Pointe-du-Chêne and Rexton where people have been evacuated from their homes using heavy equipment, the access roads being under water. In Richibouctou, flooding from the 2000 event had isolated at least one fish transformation plant, blocking a shipment worth $0.5 million. The problem was resolved after many efforts on the part of the owner.

4.8.3.3.2 Adaptation

Adaptation in coastal areas is not a new phenomenon, erosion and storms being a normal feature of the coast. Some of the individuals interviewed have been working with protection structures since the 1960s. However, most participants felt that the rhythm of change has accelerated; this poses additional needs in terms of adaptation.

Inquiries and community interviews show that many adaptation works have been undertaken by individual property owners or in some rare cases by local groups wanting concerted actions. Most of the efforts inventoried are shoreline protection work using armour stone, cement or wooden walls, gabion baskets or other structures built on the upper beach. Others, less numerous, have used an accommodation approach, raising the ground level by in-filling or raising houses or cottages. Some have taken action or talked of acting on causes that increase fragility of beach systems, such as limiting all-terrain vehicle traffic to avoid killing the grass that prevents shore erosion to a certain degree.

The different types of adaptation works have been undertaken mostly to protect properties, cottages or houses, roads or other infrastructure, but many also expressed worries concerning losses or changes to natural ecosystems and resulting losses to local economies by impacts on tourism. Participants have few comments on or knowledge of the effectiveness of the different protection methods used, but many admit that **whatever method is used, the effects are limited in time, and the work has to be redone eventually.**

Interestingly, almost half of the respondents are worried about **the negative impacts of the protection works undertaken,** mostly because of loss of sand on beaches, loss of habitat and resulting impacts on wildlife. Although significant resources are involved, most feel that the work has to be done to protect properties and infrastructures. The investments involved combined with the tremendous increase in the value of coastal properties in the last decades have many residents concerned that, more and more, local people, or at least the less fortunate, are being evicted from their waterfront properties. This is significant, since many have expressed the importance of the sites for historical, aesthetic, family or cultural values. In certain areas of southeastern New Brunswick, cottage owners are already mostly composed of people from outside nearby coastal communities. This raises other concerns, such as access to the beach.

There seems to be a minority of people in communities where interviews were conducted who view **retreat as an option**, although some admit that protection measures have a very limited effect in the long term and require tremendous resources. Most respondents in fact are very attached to coastal areas, both for economic and for non-economic reasons, and do not see retreat as an option they are ready to choose. Some individuals admit that living in the area entails some risks, but at the same time admit that they are ready to live with these risks because it is an area they value highly. There is, however, a feeling of urgency to act towards adaptation, respondents expressing fear concerning future impacts on the coast.

Inquiries also reveal that most of the protection projects undertaken have been done on an individual basis by property owners facing impacts. There have been few community or group projects, although almost half of the participants talk of the need for more collective and concerted action.

Some have used a shoreline restoration approach to adaptation. In New Brunswick, there have been over 15 sand-dune rehabilitation projects using beach nourishment and dune-grass planting on the whole east coast (Dominique Bérubé, pers. comm., 2005). These projects, using sand fences and dune-grass planting, have been led by individuals, local groups or coalitions, and most have been abandoned following severe losses due to major storms. A few are still active, but most admit that the projects have been important as educational and awareness tools, helping communities realize the severity of coastal retreat and erosion in certain areas.

Municipal and other levels of government have also been active in adaptation in or near coastal communities. The Town of Rexton in southeastern New Brunswick, for example, has been actively protecting some historically and culturally significant parts of its shoreline for at least a few decades. The first attempts at protection were made using gabion baskets; more recent attempts used sandstone in areas where it offered sufficient protection and armour stone in more heavily impacted areas. The provincial government, through the Department of Transportation, has also been involved in protection structures along the coast to protect roads and bridges. In some cases, such as in Cap-Lumière, old roads have had to be abandoned in favour of new ones located farther inland. The federal government has been involved with repairs and modification to wharves following major storms all along the coasts of Atlantic Canada through the Small Crafts and Harbour Section of the Department of Fisheries and Oceans. Federal parks, such as Kouchibouguac National Park, have also been involved in many repairs and modifications to boardwalks and roads because of storm surges (for Kouchigouguac National Park, since its creation in 1970). Officials there feel that changes in the last few years, however, have been more drastic.

4.8.3.4 Results of the community participation

Interviews, focus-group discussions and questionnaires have revealed many obstacles to adaptation perceived by many community members.

Many authors state that the knowledge available for adaptation is sufficient to begin action, but there is an important need for more research and assessment to support adaptation decisions (Adger et al., 2005; Baethgen et al., 2005). Our research supports this statement.

Results from interviews show that a majority of people have used a trial and error or an imitation approach in their protection techniques because of a **lack of information or knowledge on the most efficient or appropriate techniques**. Many have also underlined a lack of awareness in communities of the seriousness of climate-change impacts and the necessity to act towards proactive adaptation. Respondents from all areas have discussed the need for more public sessions and group discussions on the topic with stakeholders. An entrepreneur interviewed in the study area stated that he would not have built his factory close to the shore had he been aware of the vulnerability of the coastal area to such impacts. On the other hand, some individuals feel that although they are aware of the risks, they are still willing to build near the shore, wanting to retire in an area they value very much.

Avoidance is one approach to adaptation, and tools for this seem to be lacking. Although New Brunswick has promoted a Coastal Areas Protection Policy since 1996 (see, for example, Sustainable Planning Branch, 2002), the policy has limited legal power, and building is still going on in areas sensitive to sea-level rise and storm surges. Many stakeholders interviewed, including planners, admitted that the delay in implementation of the policy created a rush in development and home-building near the shore in coastal areas, owners wanting to build before any regulations would prevent them from doing so.

Individuals, municipality representatives and environmental groups have complained of the **lack of tools to manage development** in coastal areas in order to prevent building in areas of high risk and to save some natural features of the coast. Also, where some regulations apply, such as those protecting wetlands or watercourses, there is a perception by the participants of a lack of resources and of consistency in application by public servants.

In other provinces, there are no coastal policies yet in existence, and some areas are also facing significant pressures from development. Some studies in Prince Edward Island, New Brunswick and Newfoundland have underlined the need for better planning in rural and urban areas to include sea-level-rise and storm-surge considerations (Paone et al., 2003). Local knowledge gathered in some interviews shows that in some coastal communities, 50 years ago or more, people would not establish close to the shore and preferred sites up to near 1 km inland. Today, this precautionary approach has made way to an unprecedented demand for properties very close to the shore. In the eyes of most of the participants, this new demand stresses the need for a planning mechanism to limit building in some highly vulnerable areas, to protect both people and the ecosystem itself.

Many discussions with groups held in New Brunswick have focused on the **lack of governance, especially in rural areas**. Rural areas in this province are grouped in Local Service Districts, and a local committee of non-elected representatives makes recommendations to the provincial government regarding their needs. Many individuals interviewed find that this rural governance mechanism offers very little power to communities and that demands regarding adaptation in their area are diluted among requests made by other Local Service Districts in the province.

In at least one case, the lack of local governance has generated local mobilization to take ownership of the problems related to climate-change impacts. Residents of the community of Pointe-du-Chêne, following storm-surge events of the last few years and some meetings with researchers from this project, have regrouped to take action. A special committee has organized an emergency shelter in the community in case of flooding events and is currently discussing, with different levels of government, required help in addressing the health and security problems related to flooding of the access road to the community during surges. Residents feel that they are particularly vulnerable because of the aging population. Discussions are also ongoing to find other solutions to flooding of parts of the community.

The **complexity of the regulatory process**, with many permit approvals and different departments involved, has also been stated as a problem regarding adaptation efforts in coastal areas. Many participants have stressed the need for a simplified and locally centralized process for permit approval on protection or other adaptation measures.

Finally, **lack of resources** is also a major obstacle that individuals and communities are facing in attempting to adapt. Protection structures, for example, are very costly, and not all have the means of putting them in place. In some cases, some conflicts between residents have been mentioned, resulting from the inability of some to contribute to structures deemed necessary by others, structures being more efficient if they are continuous on a given stretch of coastline. On the other hand, some private organizations, such as the Irving Eco-Centre — a privately owned nature park on the east coast of New Brunswick — have been able to invest considerable amounts to rebuild, elevate and move sections of boardwalks because of storm-surge damage from at least three major storms since 1997. Individuals and municipalities often do not possess such resources.

4.8.3.5 Summary of the results of the community-engagement process

Communities and individual property owners have traditionally adapted to coastal change, but the impacts of those changes are perceived as increasing in recent years. Various strategies have been developed, but most have been applied on an *ad hoc* basis, with little knowledge of effectiveness. In addition, some of the negative impacts of interventions on the environment and neighbouring properties are being acknowledged.

Some of the major concerns that communities have with respect to their ability to adapt are:

- lack of information on possible techniques and practices;
- lack of, and unequal, resources to address the coastal issues;
- lack of local governance and effective tools to manage coastal development; and
- complexity, inequity in application and ineffectiveness of the regulatory process.

4.8.4 Development of an adaptation-strategy framework for coastal-community empowerment

4.8.4.1 Description of the framework

The analytical part of the research involved creating a decision-making framework to help various stakeholders adapt to sea-level rise and climate change. In essence, it is a response to the communities' desire for more information about strategies; however, it did not focus on specific remedies.

The framework, which includes a process for choosing appropriate adaptation strategies for specific locations, was formed through discussions with communities, examination of key referenced works and analysis of accounts of personal experience. The framework was developed with three objectives:

1. to provide people developing adaptation strategies with a guide that emphasizes the importance of community involvement and empowerment;
2. to create an approach that would be transferable while making the process applicable to the local constraints and opportunities of unique communities; and
3. to provide communities with a decision-making tool that helps a diverse group of people to understand the range of adaptation options available to them with the aim of communally creating ones that "protect and enhance [the community's] wellbeing" (UNDP, 2003).

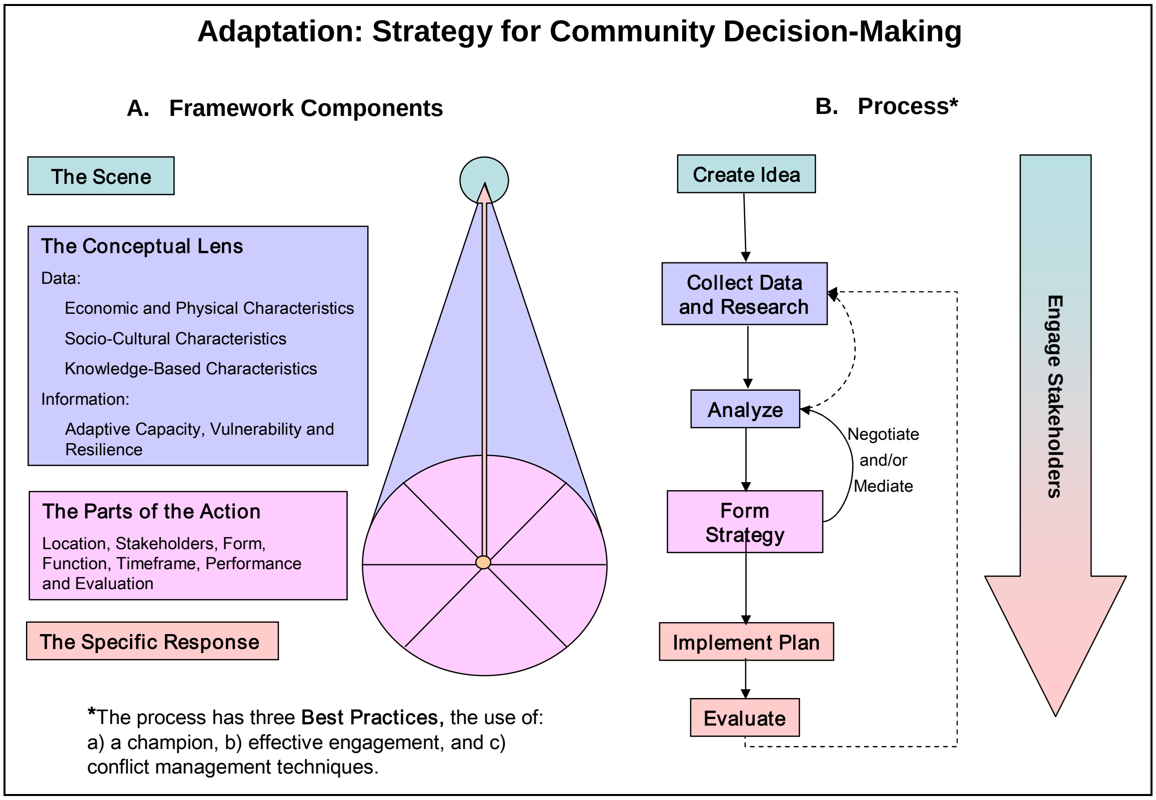

Figure 2. Adaptation: Strategy for community decision-making (after McCarthy et al., 2001, Table 18-1; Mendis et al., 2003, p. 45, Figure 7; Sutherland and Nichols, 2004, pp. 4–6; Sutherland et al., 2004, pp. 2–7; Scialabba, 1998, pp. 59, 79; Lim and Spanger-Siegfried, 2005, p. 11.

This adaptation framework is composed of two parts: 1) the framework components and 2) its processes (see Figure 2). This framework can be used to examine the rationale of previous adaptation strategies or to create new ones. Either applied as an analytical instrument or used as a community decision-making tool, it emphasizes the importance of an **empowered-community approach.**

4.8.4.2 The framework's components

The components of the framework can be examined in four consecutively dependent parts:

1. the scene;
2. the conceptual lens;
3. the parts of the action; and
4. the specific response.

1. *The scene*: This framework for community decision-making initiates from the scene, i.e., ***the location where key issues trigger a desire to adapt***. In fact, it is both a geographic location and a location in time that uniquely define the situation for the community. At this location, various lenses influence the available adaptive options.

2. *The conceptual lens*: The conceptual lens involves the way in which the situation is perceived by the participants. It is made up of the data on the scene's unique characteristics and from the information gained by analyzing the area's characteristics (Sutherland and Nichols, 2004, pp. 4–6; Sutherland et al., 2004, pp. 2–7; Mendis et al., 2003, p. 45, Figure 7).

The scene's *economic and physical characteristics* include its:

- infrastructure;
- financial resources;
- ecological attributes; and
- technology.

The *socio-cultural characteristics* of the scene are composed of its:

- legal framework;
- regulations and policies;
- stakeholder interaction;
- stakeholder values and priorities; and
- power dynamics.

Its *knowledge-based characteristics* consist of:

- education and perceptions;
- information and skill;
- expertise; and
- experience.

The conceptual lens can be enhanced by taking into account a variety of views or perspectives from community participants. This creates a shared understanding of the situations in the area and increases the resources that the community has available to it. This fortification of the community's conceptual lens amplifies the lens's probability of supporting an appropriate, sustained and purposeful adaptation action for the entire community.

3. The parts of the action: The conceptual lens creates the foundation for the various parts of the adaptation action (see Figure 3). Consequently, creating an appropriate adaptation strategy requires consideration of the a) function, b) stakeholders, c) location, d) form, e) time frame and f) performance and evaluation of the adaptive action. Within these categories, other adaptation options have to be examined (McCarthy et al., 2001). For example, when considering the action's performance and evaluation, the various costs of the adaptive action have to be considered, including ones that are hard to quantify and weight. These costs include fixed and variable costs (e.g., equipment and maintenance) as well as direct and indirect costs (e.g., costs to the property holder versus costs to the environment). These could also be the monetary costs of the materials, the emotional price of the action, the expenditures of time or the cost of other opportunities lost.

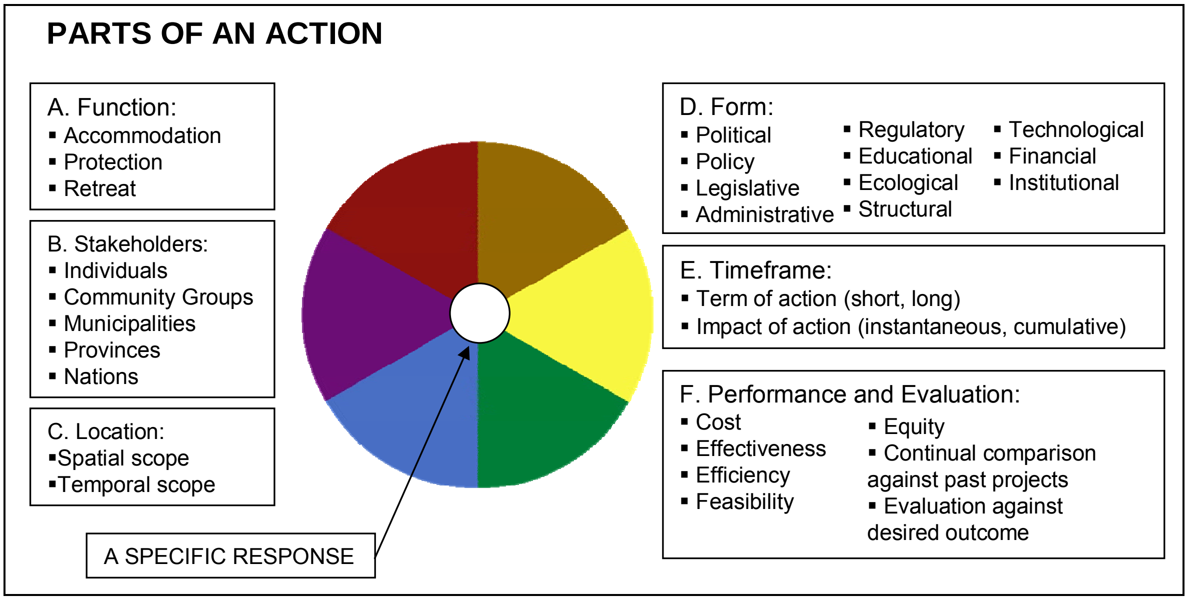

Figure 3. Parts of an action (after McCarthy et al., 2001, Table 18-1, and Mendis et al., 2003, p. 45).

4. *The specific response*: Most successful strategies will be multidimensional and have many components. From the analysis of the other three components, a community can generate a specific response. How this works in practice is through the framework's processes.

4.8.4.3 The framework's process

The creation and implementation of an adaptation strategy are composed of 1) a process methodology and 2) a supplemental list of best practices (see Figure 4).

1. *Create an idea*: Present issues and possible future situations trigger the inception of the process. From a community-empowered perspective, the decision to proceed with the adaptation process must be made by the action-taking individual or group of stakeholders. This assumes some initial organization and a common understanding of the threats (Scialabba, 1998, Part A; Mendis et al., 2003; Conde and Lonsdale, 2005).[36]

2. *Data collection and research*: This helps the community to communicate, examine the present situation and vocalize their values and goals. Overall, the community needs to be engaged to determine the performance of past strategies and to establish the base data (three primary characteristics) of their communal conceptual lens. It is important for actors not only to collect data, but also to share the data that they collect (in a participatory manner), in order to obtain a collective view. Knowledge and cooperation

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[36] In the study area, the Climate Change Impacts and Adaptation Program project described here became the catalyst for organization in some communities. In others, such as Pointe-du-Chêne, organization has existed because of the perception of threats and the existence of local champions.

facilitate the growth of the community's adaptive capacity (Scialabba, 1998, Part A; Mendis et al., 2003; Conde and Lonsdale, 2005).[37]

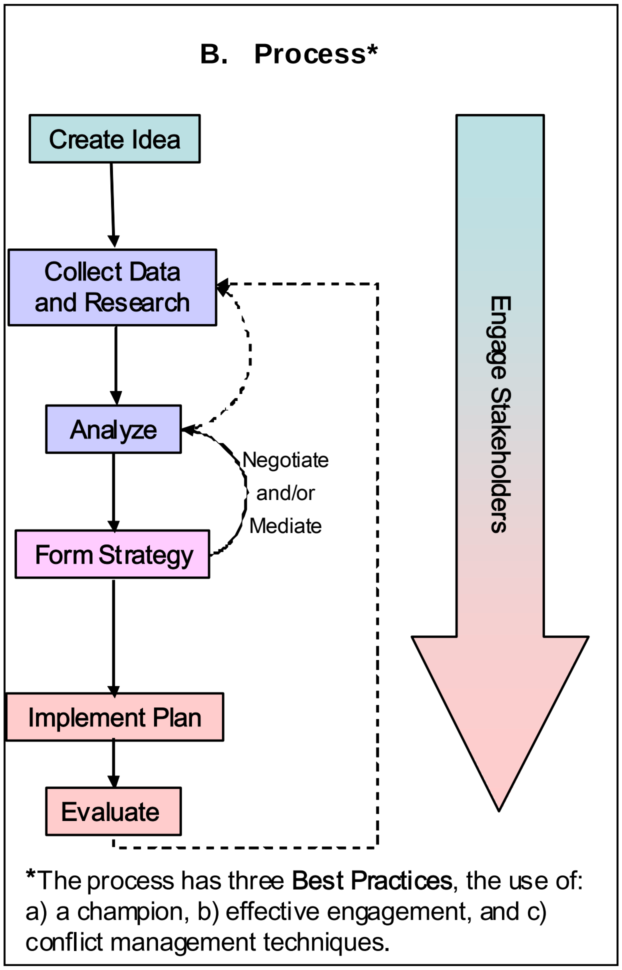

Figure 4. The adaptation process (after Scialabba, 1998, pp. 59, 79; Lim and Spanger-Siegfried, 2005, p. 11).

3. *Analyze the situation and options*: The analysis step requires the community to determine the unique character of its community lens from the primary characteristics that are collected (Mendis et al., 2003; Sutherland and Nichols, 2004). Ideally, through the process of integrating all of the collected information, a common understanding of the community's needs should be created; then the various desires of the stakeholders can be transformed into initial goals of the project, and what tools and barriers the community has can be identified (Scialabba, 1998, Part A; Conde and Lonsdale, 2005).

4. *Form a strategy*: This stage identifies the various components of the specific adaptive action based on the background knowledge gathered about the scene and the collective

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[37] The need for collective views can be illustrated by the situation of the coastal landholder who takes unilateral action to protect an eroding shoreline (e.g., with concrete or tires etc.) and thus creates erosion of neighbouring properties.

conceptual lens of the area. It is usually necessary to consult and negotiate with the greater community of stakeholders to reanalyze the situation (possibly collecting more data) to ensure the specific response (and actions necessary for it) to accomplish the desired goals. The strategy formation process includes identification of the resources required and the means for acquiring them. A major factor will therefore be who is paying for the implementation. Negotiation or mediation could be required to prevent and resolve conflicts; compromise may be necessary, or an entirely different approach may be required (Morris, n.d.; Scialabba, 1998, Part A and Part E; Rijsberman, 1999; Mendis et al., 2003; Conde and Lonsdale, 2005).

5. *Implement and evaluate*: Often, the actions of various stakeholders have to be coordinated in order to implement a specific response. This can be a complex process, and, accordingly, the existence of a champion, a well-defined adaptation strategy and an implementation plan are critical to its success.

The implementation of the plan could include a defined evaluation schedule, or the strategy's evaluation may be more informal. Nevertheless, evaluation is an important component of the process, which could affect another adaptation project or a continuation of the same one. Community participants identified feedback (whether in the form of formal reports or more informal sharing of positive and negative experiences) as a missing (but desirable) component in current attempts to adapt (Information Sessions, September 28, 2005; October 11, 2005; October 23, 2005; UNB and UdeM, 2005).

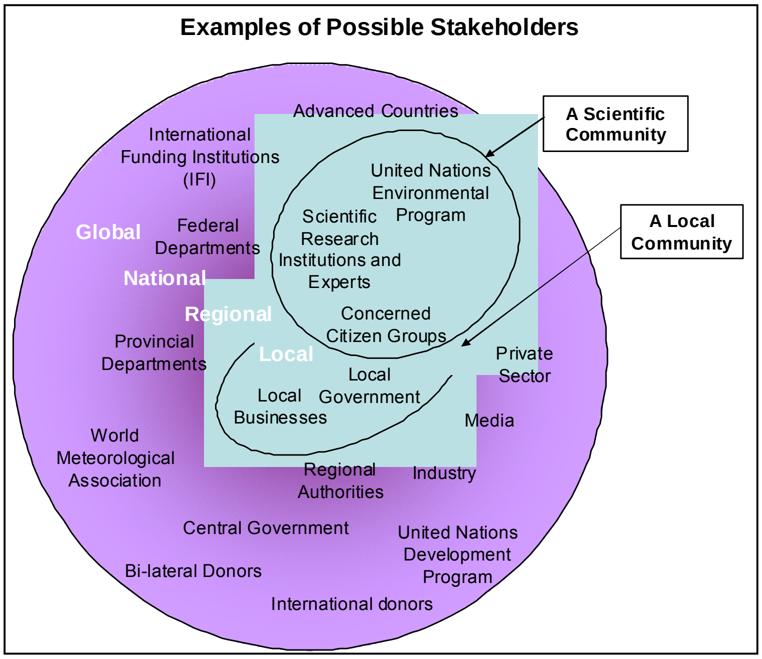

Figure 5. Examples of possible stakeholders (after Lim and Spanger-Siegfried, 2005, p. 39, and Scialabba, 1998, p. 41, Figure A.8).

4.8.4.4 Getting participation

Engaging the stakeholders is an essential component of the adaptation process. To build participation, it is also important to correctly identify (or, more importantly, not exclude) certain stakeholders, as well as to know what type of participation is expected. This research identifies two important types of stakeholders: 1) communities and 2) actors. Interest-based communities or communities of geographic origin are likely to be affected by or interested in the adaptation process. Their members may or may not actively participate in the adaptation process. In contrast, actors contribute to the creation or implementation of the specific adaptive action. Consequently, it is very important for the actors to acquire input from other stakeholders and be willing to cooperate and collaborate with their ideas, because stakeholders will not be the only ones affected by the outcome of the process (Scialabba, 1998, Part A and Part E; Conde and Lonsdale, 2005). Please refer to Figure 5 for examples of possible stakeholders.

Participation of a diverse group of stakeholders is essential in order to ensure the validity of the information collected and presented and the appropriateness of the adaptation strategies created. Consequently, it is important not only that the invitation to participate be inclusive, but that voices unused to being heard from are encouraged to speak. It is also important to realize that there are various types of participation that involve unique levels of activity: from being a champion and spokesperson to being a participant in meetings in order to learn more (Scialabba, 1998, Part A and Part E; Conde and Lonsdale, 2005, Figure 6).

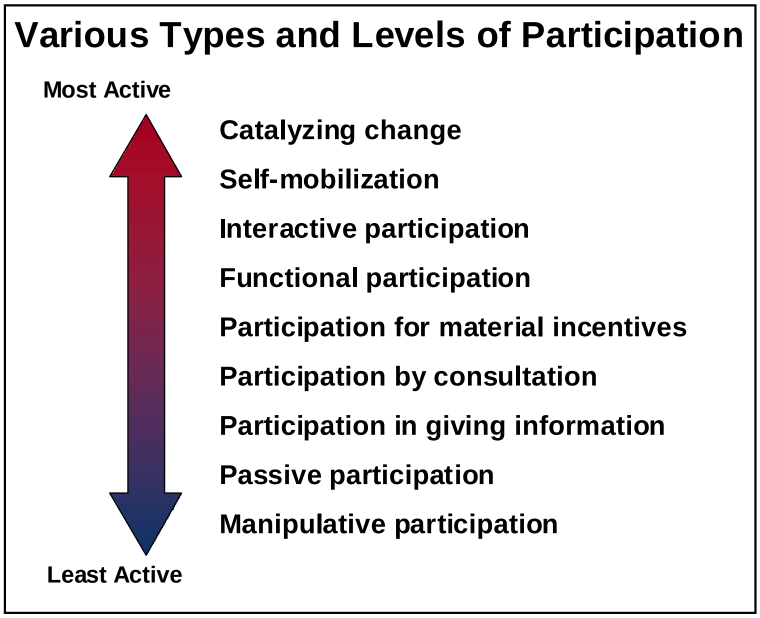

Figure 6. Various types and levels of participation (after Conde and Lonsdale, 2005, p. 52, and Scialabba, 1998, p. 41, Table A.4).

The benefits gained from stakeholder engagement are extremely valuable for the project's appropriateness, quality and longevity. Engaging a diverse group of stakeholders can teach community members how to work better with decision-makers, and vice versa. Often, government officials have little contact with community members; an organized community on a specific issue such as climate change can enhance the policy dialogue (Conde and Lonsdale, 2005). The process of communally creating adaptation strategies also gives stakeholders a feeling of ownership in the final outcome of the process and can build a shared awareness of the community's concerns and constraints. This communal understanding of issues can foster cooperation and empowerment, facilitating the enhancement of their adaptive capacity. The participatory process also facilitates sustainable, cost-effective results by disseminating and testing the adaptation ideas on those to be affected before they are actually implemented (Conde and Lonsdale, 2005).

Stakeholder participation in a project does not ensure a project's appropriateness, fairness, quality or sustainability, but it usually makes them more likely. To facilitate a project's success, it is also important to make efficient use of a champion, effective engagement and conflict-management strategies (Morris, n.d.; Scialabba, 1998, Part E; Rijsberman, 1999; Mendis et al., 2003; Lim and Spanger-Siegfried, 2005).

4.8.4.5 Best practices of the framework

Creating adaptive measures through a participatory process is time-consuming, is challenging and requires the consideration of certain integral issues embedded in the participatory process. The need for a champion, effective engagement and conflict-management techniques to be present in the process is intrinsically tied to the success of the adaptation strategy.

A. *Having a champion*: A champion is a concerned, conscious and active stakeholder or group of stakeholders who provides the adaptation process with **momentum.** These action-takers effectively lead the rest of the stakeholders through the adaptation process. They help to ensure the process's continuity and coordinate the various aspects of the complex procedure. Figure 7 illustrates the complexity of the coordination needed.

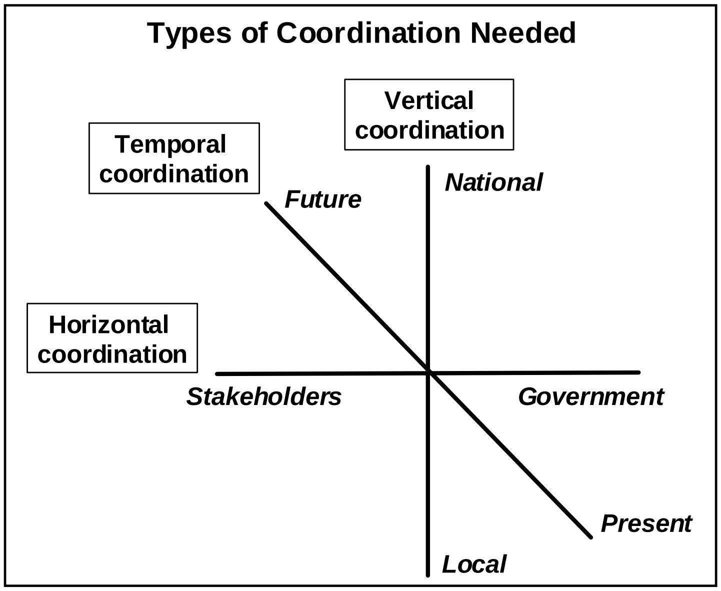

Figure 7. Types of coordination needed (from Scialabba, 1998, p. 39).

B. *Effective engagement*: In order to ensure a participatory process, with its already-mentioned benefits, a diverse group of stakeholders must be engaged effectively. Because people are best engaged in different manners, Conde and Lonsdale (2005, p. 53) note that it is helpful if the adaptation process is designed to foster certain traits:

- clarity;
- understanding of related processes;
- management of information;
- support and capacity development;
- transparency;
- trust-building;
- time for the process; and
- feedback and flexibility.

The goal of an exchange of information through a variety of media is to form a collective and realistic understanding of the constraints and benefits of the situation by all or most of the stakeholders. If this is achieved, the need for conflict management may be kept to a minimum (Morris, n.d.; Scialabba, 1998, Part E; Rijsberman, 1999).

C. *Conflict management*: The use of alternative dispute resolution is highly applicable to conflicts in coastal areas because of the many uses of the coast, the multitude of stakeholders and the multidimensional aspects of the conflicts. Conflict resolution can be described as “a process by which two or more conflicting parties improve their situation by cooperative action… [allowing] parties to expand the pie, or to prevent it from shrinking, giving each party a larger slice” (quoted from Melling, 1994, by Scialabba, 1998, p. 201).

Conflict management contains both a proactive and a reactive component. By stressing the need for stakeholder involvement in the adaptation process, this research has supported a proactive approach to conflict management, facilitating an open environment with communication between all stakeholders. Alternative dispute resolution requires the affected parties to work out the conflict; therefore, the solutions are most likely suited for the participants’ needs, and often in a quicker and cheaper manner than other resolution techniques. In addition, because techniques for alternative dispute resolution require stakeholders to communicate and create a mutual understanding, they are more likely to address the roots of their disagreements and form a better base for future interactions (Morris, n.d.; Scialabba, 1998, Part E; Rijsberman, 1999).Please refer to Figure 8 for details.

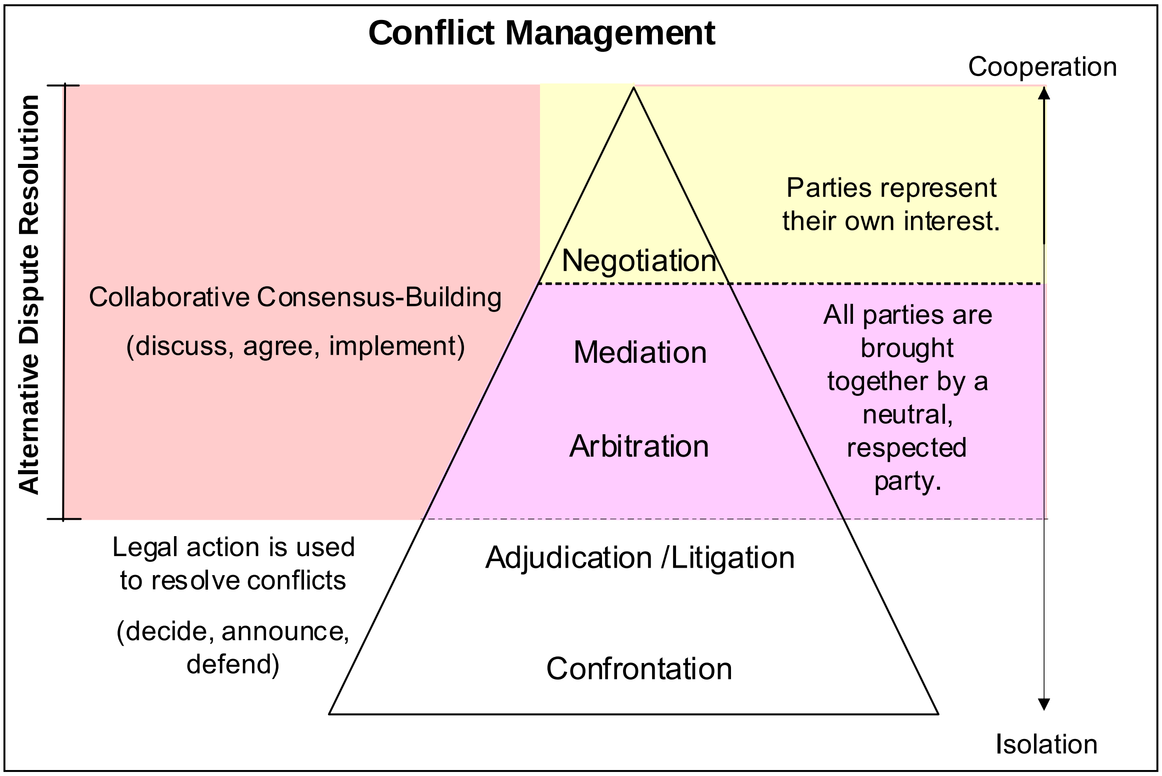

Figure 8. Conflict management (after Scialabba, 1998, p. 202, Figure E.1; and Morris, n.d.).

4.8.4.6 Application of the adaptation framework

Four case studies were undertaken to demonstrate that the conceptual framework can be used to analyze past adaptation strategies and to develop new ones. In two case studies, the framework was used to analyze past adaptive actions with influential traits, and the framework was applied to two present situations to explore its possible use as a community decision-making tool. These applications will illustrate this framework's ability to handle a variety of unique situations, the importance of its emphasis on community participation and essential considerations for the framework's ability to function.

4.8.4.6.1 Examples of framework application: Kouchibouguac National Park

A. Importance of the case study

Kouchibouguac National Park has managed to cut the costs of its adaptation measures by accommodating the changing nature of local ecosystems in its policies and by using these local systems to create temporary, but effective, adaptation strategies. This case study examines the low-cost (yet highly effective) adaptation methods used in Kouchibouguac National Park in order to discuss how these strategies are appropriate for the community of Kouchibouguac and how lessons learned from the application of these past adaptation strategies could be applied elsewhere. The information was gathered from Park records, site visits and interviews.

Figure 9. Kellys Beach in Kouchibouguac National Park (photos courtesy of Parks Canada, 1998 and 2002).

B. Framework application: The components

The scene: At Kouchibouguac National Park, human adaptation to sea-level rise was triggered by a number of issues. The Park was established in 1969 to preserve a home for a variety of plant and animal species, but many have been increasingly threatened by changes in the local environment. For example, the Piping Plover, a small bird that lives and makes its nest on the rare dunes, is threatened by the increased flooding and the erosion of the dune. Please refer to Figure 9 to see a visual record of a changing dune. Additionally, a particularly large storm in October 2000 highlighted another price of the increasing frequency of storms: the cost to repair boardwalks and trails used to provide access to the Park was estimated at $785,000 (Martin and Tremblay, 2005).

The conceptual lens: Kouchibouguac National Park is a unique site for the analysis of adaptation strategies because its conceptual lenses differ from those of other local communities affected by the changing nature of the southeastern New Brunswick coastline. Being a federal-government-funded entity, the Park has many economic and physical resources available to it in the forms of infrastructure, government funds for maintenance, knowledgeable staff and educational facilities. The Park's knowledge-based characteristics are also enhanced by staff who have extensive local knowledge of the area, formal education and access to a variety of resources; however, other local stakeholders really do not have any input into the adaptation strategies taken at the Park.

The values of the Park staff and the communities who depend upon the Park as an ecotourism attraction are governed by written guidelines. The influential socio-cultural characteristics of the Park include a legal framework that lays out its priorities:

- to provide greater heritage protection and maintain the ecological integrity of this representative coastal area;
- to increase public heritage understanding by enhancing heritage interpretation and diversifying appreciation opportunities; and
- to sustain the Park's role as a good neighbour, an ecological model and a major natural and cultural destination (Parks Canada, 2005).

Accomplishing and maintaining these mandates requires the use of adaptation strategies that have a relatively small impact on the local environment; however, this is not necessarily a non-intervention policy. Parks Canada staff are allowed to take certain measures when human actions have disrupted natural processes or to help species at risk survive and thrive (Éric Tremblay, Parks Canada, pers. comm., 2006).

The parts of the action and the specific response: The types of adaptation measures applied at the Park have consisted of two specific responses with a variety of parts. Park staff have continually repaired the boardwalks that provide access to the beach areas and have attempted to slow an assortment of erosion processes that threaten a variety of wildlife and access paths.

Looking at the components of the various actions taken, it seems that a growing understanding of the power of natural systems, including an inability to control them, has influenced the adaptation strategies used at Kouchibouguac. Knowledge of the complex local ecosystem has been used to effectively slow the changes or avoid the issues caused by natural processes, while minimizing possible large and negative interference with the natural ecosystem. Examples of such accommodation include (Martin and Tremblay, 2005):

- replacing fixed boardwalks with removable boardwalks (in 1981);
- replacement of two floating-bridge sections with a higher fixed link on metal posts (from 1995–1996);
- protection of beach areas by planting marram grass; and
- seasonal attempts to encourage accretion with snow fences.

A better understanding of the power of natural systems and a realization that all adaptive measures have a temporal limit have also helped Park staff to better weigh pros and cons to implement appropriate measures (Parks Canada, 2004; Éric Tremblay, Parks Canada, pers. comm.,. 2006). For example, a fixed boardwalk bridge and the relocation of the road to the Loggiecroft Wharf were more expensive in immediate monetary costs ($724,373.00 and $1,164,670.00, respectively) and ecological terms; however, they secured access to the Park facilities, part of the Park's mandate. For all adaptation measures, the measured costs from 1975 until 2005 totalled $2,853,892 in damages and reconstruction, and the majority of that cost has been associated with boardwalks. The effectiveness of the repairs varied; boardwalk repair is expensive, but removable boardwalks have significantly lengthened their performance. Marram grass, although less expensive, is easily destroyed in storm surges, and, while seasonal use of snow fences saves the expenses caused by their damage and cleanup, like any erosion control structure, they can only slow the process by so much. However, in both of these cases, the costs of these adaptation strategies on the environment were low, and they did not affect access to the Park.

C. Conclusion

After illustrating the potential costs and logic associated with the impromptu implementation of adaptation strategies at Kouchibouguac National Park, this case study demonstrates the ability of the Park to successfully sustain adaptation methods that provide a relatively low environmental impact. The case study also demonstrates a learning curve where evaluations of past adaptations determined what was most effective.

In the future, it is possible that the Park will need to change its impromptu adaptation strategy and create more detailed adaptation plans to further address its actions in changing circumstances. For example, to what extent should Parks Canada interfere with the Park's ecological integrity and natural evolution to preserve species at risk? However, because the actions of Park staff are guided by a similar conceptual lens (in contrast to many communities along the southeastern New Brunswick coast), their lack of a comprehensive plan has had little costs. The Park's actions could currently be labelled a success, because by continuing to preserve a low-impact way to access Kellys beach and other areas of the park, the adaptation strategies ensure the ecological integrity of the area and access to visitors (Parks Canada, 2005).

The specific actions taken by Kouchibouguac National Park have succeeded in finding a balance between social, political, environmental and economic concerns for their unique situation. Their specific strategies might not be applicable to other communities, but the local and researched knowledge of local ecosystems, the limited nature of any adaptation strategy, the more sustainable nature of natural strategies and the need to find an appropriate and thus sustainable balance between interests should be transferable. An evaluation of adaptation strategies used at Kouchibouguac demonstrates that the nature of the coast is changing, and a strength of humans as part of the natural environment is their ability to change with it.

4.8.4.6.2 Examples of framework application: the Coastal Areas Protection Policy (CAPP)

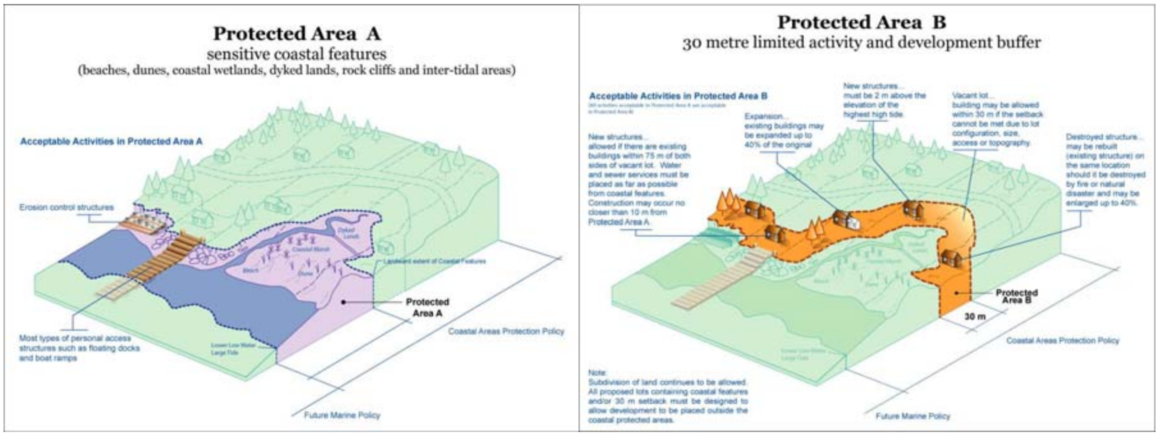

Figure 10. Zones of the Coastal Areas Protection Policy (from New Brunswick Environment, Information sessions, 2005 and 2006).

A. Importance of the case study

Perhaps the most common issue raised in community meetings and interviews during this research was the uncertainty surrounding provincial policy on protecting coastal areas. In the mid-1990s, the Province of New Brunswick led Canadian jurisdictions by proposing a coastal lands protection policy specifically aimed at two issues:

1. protection of special coastal features (especially dunes and wetlands); and
2. reduction of the damage and costs associated with coastal storms and flooding through planned development.

This policy provides landholders with development guidelines to prevent and mitigate the impact of climate change (see Figure 10 for graphical overview). It is thus a forward-thinking adaptation strategy.

At the time of its original proposal, the policy was a precedent; it provided a top-down adaptation guide to ensure that the protection of coastal wildlife and communities was unique in Canada. However, a decade later, the challenges in implementing this adaptation strategy continue, and the results have been mixed, in part because it involves a large number of stakeholders across a wide spatial and temporal scope.

This examination of the CAPP's creation and implementation process will explore the unique roles of government actors and demonstrate how effective adaptation methods need to be supported with a variety of actions, including effective consultation and dialogue and integrated planning among stakeholders.

B. Framework application: The process

Creation of an idea: The idea for the coastal policy came from a provincial government department, and it remained the primary actor in the CAPP development — i.e., there was no initial “ownership” of the idea by the communities that were to be affected. The process progressed because it had a champion with resources and valid concerns.

In the United States, for example, similar top-down approaches have been successful, whereby coastal-zone management policies and/or strict coastal land-use regulations have been implemented for a variety of reasons (e.g., wetland protection and public access to beaches). The American efforts come from both the federal level (Coastal Zone Policy of 1975, which also granted significant financial resources) and the state level to address specific state issues. Considerable effort was also made to define and respect private coastal property rights.[38] The Province of New Brunswick, therefore, was following current practice.

However, some of the results of this top-down approach include:

- *Limited community engagement* — There was a communications process, and numerous information sessions were held during the initial proposal to inform landholders in the mid-1990s and then after 2002, when a revised policy was disseminated. Most of the public meetings, according to community stakeholders, were basically information dissemination. Specific groups, such as the Association of New Brunswick Land Surveyors, had attempted to provide input to the policy from the outset, but most of the policy decisions had been taken before they were presented to the stakeholder communities. Basically, the policy is perceived by stakeholders as being “presented to them” rather than “discussed with them.” This approach was also witnessed during the course of this research.

- *Uncertainty over implementation* — Actual storms, such as that of October 2000, certainly reinforced within the public the need for some development control. However, because the drafting of regulations was a multiyear process and some regulations have yet to be enacted, stakeholders have become uncertain about the effects of the policy. “Stakeholders such as planners, lawyers and land surveyors are unable to provide complete and accurate advice to their clients in the absence of approved regulations” (S. Hartley, Association of New Brunswick Land Surveyors, 2006, pers. comm.). Planners who were interviewed in this research complained that the delays in having complete regulations for policy implementation over 6–10 years actually spurred rather than curbed development. There are numerous examples of inappropriate development since the mid-1990s, when the public first became aware that development controls were proposed.

- *Uniformity of approach* — The proposed policy did not treat specific geographical areas with specific issues differently. Thus, landowners on rocky cliffs on the Bay of

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[38] As states, including Florida, New Jersey and California, attempted to enforce provisions such as public access to beaches, protection of coastal wetlands and public ownership of in-filled coastal land, there was an explosion of litigation, which, for the most part, enforced the private ownership of coastal lands to the ordinary or mean high-water mark by presumption. Some of these cases lasted years, involved millions of dollars of real estate and required extensive resources for data collection and boundary location. In the end, a national system of defining water levels, which can now be used to predict sea-level rise, exists, and rigorous procedures for delimiting high- and low-water lines have been developed. Similar developments have lagged behind in Canada because there has been virtually no coastal lands litigation; in fact, in recent decades, long-term tidal observation stations have been cut, rather than enhanced.

Fundy wanted to know why a 30-m development setback was appropriate for them. However, the Department of Environment permits variances to the regulations to be made, and stricter regulations can be adopted at the local level to meet specific issues.

- *Narrowness of scope* — The proposed policy was not designed to provide a comprehensive coastal-zone management approach; it focused on only two issues — protection of coastal features and prevention of erosion and other property damage through planned development. These were not placed within a broader vision of integrated coastal-resource management. Also, the policy was limited to activities landward of the low water. At public meetings in Bouctouche during this study, for example, the impact of sea-level rise and storm surges on aquaculture was raised by the fishing community (October 26, 2005). Many traditional aquaculture activities on the Gulf of St. Lawrence involve facilities very near and sometimes on the shore, and the farmers were concerned about the risk to their investments. In the mid-1990s, government also began development of a marine policy, which has not yet been released to the public. The intersection of these two policies, presumably, is the shore, and activities straddling this “line” or “zone” will presumably be covered by one or both policies.

Data collection and research: In addition to a strong coastal erosion monitoring program, there was an extensive data-collection process in terms of coastal colour orthophoto mapping to support the process. This included geomorphological and environmental delimitation of coastal features and the approximate ordinary high-water limit from which the development setbacks were originally to be measured. The costs included from 1995 to 1999 were roughly (D. Finley, Service New Brunswick, pers. comm., 2006):

- a user requirements study (approximately $40,000);
- preparation, specifications, photography and production (approximately $770,000); and
- creation of the Coastal Lands Data Base and Quality Control (approximately $780,000).

This mapping put New Brunswick in the forefront of excellent quality coastal information, but there were several problems:

- *Lack of currency*: These maps were designed to be guidelines for planning officers in determining legal setbacks. In areas with significant coastal change over the last decade, there will be a need for fieldwork for verification. For example, the sea-level-rise and climate-change results from the research reported here would suggest that raising one’s home 2 m, as outlined in the current CAPP, is insufficient to protect one’s house from storm-surge events in many areas along the southeastern New Brunswick coastline. This has created the need for “coastal feature specialists” who can examine specific areas. However, their findings on elevations and boundaries (e.g., various water lines) are not necessarily prepared by a licensed professional land surveyor.

- *Limited legal research*: There was consultation with legal scholars from Nova Scotia, but it appears that little comprehensive research was conducted upfront on private property rights, jurisdiction and boundaries in coastal areas, especially for the original policy. While some of these issues are not entirely "clear" in the law, the lack of acknowledgement that the policy and subsequent regulations could affect traditional rights (including riparian and public rights in the foreshore) can potentially set up barriers to community and property holder buy-in. Similar approaches in the United States resulted in a flurry of legal challenges in the 1970s and 1980s.

- *Lack of public inquiry and research about local knowledge and concerns*: Information sessions were conducted by government officials; however, from stakeholder feedback during this research, none seemed to facilitate a sense of ownership or sustainable dialogue among local communities. This was in part due to the limited resources some communities had to manage specific storm-surge threats in their areas. Without the representation of a wide variety of stakeholders' concerns, effective engagement (including resources to cope with the impacts of the policy) and conflict-management strategies (see best practices), the creation of a successful and integrated implementation plan is limited. Thus, for example, stakeholders in this research noted their concerns about a) which parts of the policy are in force; b) whether public officials were applying the provisions equitably and uniformly; and c) where they could go to get assistance in developing specific protection strategies for their assets (e.g., Information Sessions, September 28, 2005; October 11, 2005; October 12, 2005, February 28, 2006).

Analysis and strategy formation: Unlike the process we have proposed in this report, the creation of the CAPP blurs the boundaries between the steps of data collection and research, analysis and strategy formation. The decision of what to protect and how appears to have been decided at an early stage in the policy-making process. For example, it seems apparent that the mapping was dictated by the strategy, as little attention was paid to intertidal areas, which may in the long run require different mapping and information criteria (Réjean Castonguay, Service New Brunswick, pers. comm., 2003).

The major drawback of the New Brunswick policy was the uncertainty it generated between its first announcement and public information sessions (1996) and its eventual implementation in parts nearly eight years later. Many stakeholders interviewed, including planners, admitted that the delay in implementation of the policy created a rush in development and home-building near the shore in coastal areas, owners wanting to build before any regulations would prevent them from doing so. Individuals, municipality representatives and environmental groups have complained of the lack of tools to manage development in coastal areas in order to prevent building in areas of high risk and to save some natural features of the coast (Information Sessions, September 28, 2005; October 11, 2005; October 12, 2005, February 28, 2006).

Implementation: The provincial government has implemented the CAPP in two ways: 1) through incorporation of provisions in other regulations and 2) through informal adoption of the provisions by the Local Service Districts. Some of the provisions of the policy have been included under the wetlands regulations to protect coastal features (in the *Clean Water Act*) and under the Environmental Impact Assessment Regulations (in the *Clean*

Environment Act). Up to 500 development plans were reviewed in 2005 (Paul Jordan, Dept. of Environment and Local Government, pers. comm.., December 12 2005). However, the delays in implementation and the perceived lack of transparency in the process by stakeholders have been major obstacles in fulfilling the policy goals. During this period, planning commissions who were to enforce the policy guidelines have not had the legal backing to prevent development in the zone.

Stakeholders are also concerned about the fact that those responsible for implementing the various adaptation strategies outlined in the policy (e.g., erosion control) do not have sufficient resources to do so. Protection structures, for example, are very costly, and not all have the means of building them. In some cases, some conflicts between residents have been mentioned, resulting from the inability of some to contribute to structures deemed necessary by others, structures being more efficient if they are continuous on a given stretch of coastline (Chouinard and Martin, 2006). Small communities are also concerned that they do not have adequate resources to follow the policy (e.g., Cap-Pelé, February 28, 2006) .Until it becomes law, it will be difficult to implement the spirit of the policy, even at the Local Service District level.

The main concern about the CAPP, for most property holders, continues to be the "no-development zone" extending 30 m inland from the "high-water line"[39] or coastal feature to be protected. There are some exceptions to the restrictions, based on existing development, but when coastal properties are small, this zone could be significant in terms of property value and use. Furthermore, the zone exists even on high rock cliff areas not susceptible to sea-level-rise damage or erosion (Sustainable Planning Branch, 2002). Landowners have expressed frustration at this seemingly blanket nature of the written policy (Information Sessions, September 28, 2005; October 11, 2005; October 12, 2005, February 28, 2006).

Another concern is the complexity of the regulatory process, with many permit approvals and different departments involved in coastal areas. Many participants stressed the need for a simplified and locally centralized process for permit approval on protection or other adaptation measures (Chouinard and Martin, 2006).

The policy outlines a number of activities that upland owners can perform to protect their property, including planting of native dune grasses or constructing approved control structures. When landholders build features (e.g., walls or barriers) to protect their property, they can also damage adjacent or downstream parcels by increasing the erosion there. Thus, a provincial policy such as the CAPP will eventually allow planning commissioners to advise landowners and ensure that protection mechanisms are a) effective and b) not harmful to other properties.

Until all of the policy provisions become law, government officials are limited in their regulatory actions, resources and ability to help communities. However, stakeholders are trying to encourage productive retreat and the implementation of stronger regulations through by-laws. Under the CAPP, plans are evaluated on a case-by-case basis, and the evaluators have acted as information distribution agents to counteract the limited nature of certain recommendations (Jordan, 2005).

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[39] The precise definition of this line has changed several times during drafting of regulations.

As noted in the community-engagement sessions of this research, the policy is currently perceived by many stakeholders as being ineffective and enforced inequitably, if at all; this may change as the development review process initiated by the Province of New Brunswick becomes part of routine development activities. Not having clear regulations hinders involuntary and voluntary community investment in the policy. The issues seem to be lack of money/resources, knowledge and consensus. Consequently, many community members have expressed frustration (Information Sessions, September 28, 2005; October 11, 2005; October 12, 2005, February 28, 2006).

Evaluation: In terms of adaptation, the CAPP has probably both caused problems and created opportunities. There is evidence that prudent landowners, aware of the issues through public education and consultation with Local Service Districts, have increased their property protection by building on higher ground, by raising structures or by providing appropriate shoreline protection. On the other hand, the pending policy appears to have driven inappropriate development in some areas.

What this case study illustrates for future adaptation strategies is the need for the effective engagement of a variety of stakeholders when creating adaptation strategies, despite the complexity of getting that engagement. Without this best practice, including the use of conflict-management strategies, creating a successful adaptation strategy that balances the interests of all stakeholders and creates community buy-in is unlikely. Communities need to “own” the strategy, and that takes active participation and effective dialogue as well as clear information dissemination throughout the process.

This brief review of the CAPP illustrates the unique advantages of government involvement in the creation of adaptation strategies (as traditional actors, champions and representatives of many stakeholders, especially those not residing permanently in the local area), while pointing out the need for more stakeholder participation and local support. The Province of New Brunswick took the lead in recognizing important coastal issues and created the first major coastal policy in Canada to address them. The evaluation above demonstrates how the proposed adaptation processes may have been more effective. The implementation process now needs to be monitored to help the province (and other jurisdictions) to learn from this experience.

Specific lessons learned for adaptation strategies at the policy level include the following:

- the need for a multidisciplinary and integrated approach to coastal policy development so that all of the issues are considered upfront, including strong research (science, law, etc.);
- the need for an effective stakeholder-involvement process early in strategy development to create community ownership of the strategy;
- the need for strong political commitment to back the efforts of planners and the need for resources to allow local communities to be engaged;
- the need for clear guidelines (e.g., appropriate protection mechanisms) and “one-stop information points” to be developed with the policy in order to answer questions from property owners appropriately, especially directing them to the specialists; and

- the need for support at the individual property-holder level, both in terms of adequate information on options and costs and in terms of resources for making an adaptation (e.g., property-tax incentives, community-based projects).

4.8.4.6.3 Examples of framework application: Bouctouche

Source: www.sagouine.com

Figure 11. Le Pays de la Sagouine.

A. Importance of the case study

Applying the decision-making framework to Bouchtouche demonstrates:

- the use of the framework in a participatory adaptation process;
- the logic of a multifaceted adaptation strategy; and
- the critical issues that are associated with the action-taking process.

Because this case study is based on the socio-economic study of Bouctouche (see Section 4.7.4.1 the adaptation measures mentioned will be focused on preserving and enhancing Bouctouche's tourist economy with the aid of a variety of stakeholders (Figure 11 shows one of the town's endangered attractions). The information for this case study was collected through comments at community information sessions, an informal survey and the optimistic scenarios provided by the socio-economic component of the project (see Section 4.7).

B. Framework application: The creation and implementation of a community adaptation strategy

1. The scene

Idea creation: In Bouctouche, because the more severe erosion, ice jams and storm surges caused by the increasing sea level are or will be threatening the population's way of life, a wide variety of local stakeholders are motivated to act (Martin, 2005a; UNB and UdeM, 2005). Since the town is unwilling to accept its increasing endangerment in the future and is often unable to retreat from all of its problems, it is important for the stakeholders to create a more proactive adaptation plan. For historical reasons, it may be assumed that the traditional elected officials along with concerned local leaders of the community will be the champions of this process.

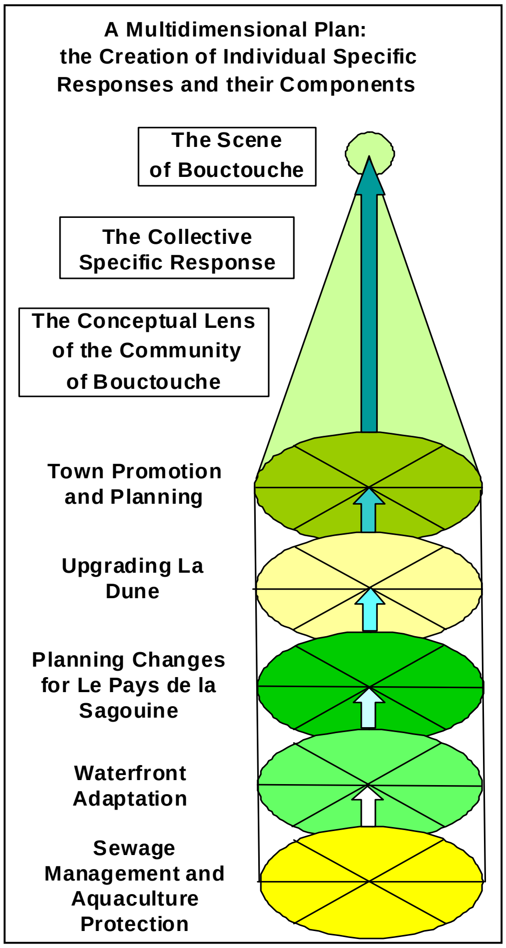


Figure 12. A multidimensional plan.

2. Identification of the conceptual lens

Data collection and research: In order to create an appropriate adaptation strategy, especially for an entire town, a variety of techniques can be used to gather data about the community's conceptual lens from the participants. Depending upon the types and levels of participation used, stakeholders could be engaged in a variety of ways to best facilitate the exchange of information. Additionally, because there is an energetic local government, it is especially important to make sure that traditionally less active voices are heard through a more active form of participation. It can be advantageous if most of the actors collecting data are from the local community, because they would be aware of local social issues or power relationships that could be problematic when trying to encourage an open, participatory environment. However, actors from outside the community with specialized knowledge are also valuable assets to the process, as they can provide valuable impetus for research.

Analysis: Data collected about the social, political, economic and environmental interests of the stakeholders must be weighted appropriately to accurately assess the conceptual lens of the community, not of individuals. The quality of this assessment will help to determine the true appropriateness of the adaptation strategy for the community, and thus its sustainability. An analysis of Bouctouche's conceptual lens also illuminates how recent and future changes in the dynamic coastal environment, coupled with existing infrastructure and policies, threaten town attractions, the health of the local ecosystem and local jobs.

3. Identification of the adaptation action's parts

Strategy creation: When a diverse group of stakeholders has many concerns and a similar motivation to adapt, it is often beneficial to coordinate their actions through realistic plans and time frames. It is also important to create a multifaceted adaptation strategy to combat the myriad of problems (Figure 12).

In Bouctouche, a variety of specific responses could help prepare for change by:

- coordinating a town campaign to publicize the effects of climate change and sea-level rise, and diversifying the local economy to lessen its economic vulnerability;
- outlining realistic short- and long-term adaptation plans for tourist attractions; and
- addressing possible health dangers before they occur.

The creation of a comprehensive plan will involve the prioritization of certain adaptation strategies. Conflict could erupt not only over the types of adaptation measures taken, but also around the prioritization and allocation of resources. Consequently, effective dialogue needs to be encouraged during the planning stage. This could be accomplished by the distribution of initial plans through public media or information sessions and addressing critiques and issues, either at public information sessions or in written correspondence.

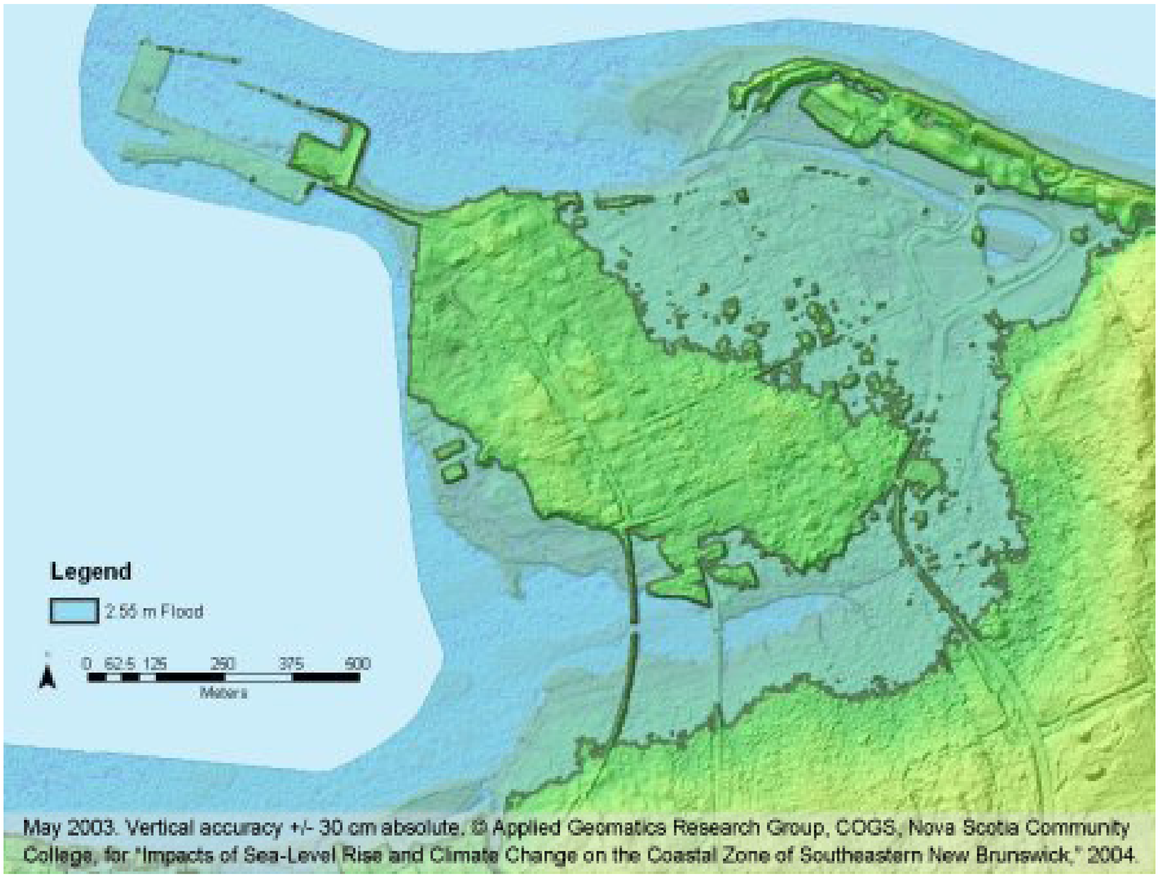
C. Conclusion

The application of Bouctouche's situation to the decision-making framework illustrates the advantages of the development of a multidimensional strategy that integrates defined plans and varied time frames. This case study also illustrates the importance of stakeholder participation in creating an appropriate, sustainable adaptation strategy.

4.8.4.6.4 Examples of framework application: Pointe-du-Chêne

A. Importance of the case study

In contrast to Bouctouche, Pointe-du-Chêne appears to have limited stakeholder engagement, different viewpoints (especially between seasonal and permanent residents) and limited resources. The case study demonstrates how the use of the adaptation framework could increase Pointe-du-Chêne's adaptive capacity. This would be accomplished through the use of preventative and responsive conflict-management techniques, the creation of various individual and communal adaptation strategies through effective, participatory practices and the consequential strengthening of their existing and newly formed synergies. The Pointe-du-Chêne case study will illustrate the ability of concerned residents with limited resources to use the framework to create a variety of adaptation strategies. Because of Pointe-du-Chêne's great vulnerability and outcry for help, this project conducted information sessions in the local district and visits to troubled areas.



May 2003. Vertical accuracy +/- 30 cm absolute. © Applied Geomatics Research Group, COGS, Nova Scotia Community College, for "Impacts of Sea-Level Rise and Climate Change on the Coastal Zone of Southeastern New Brunswick," 2004.

Figure 13. Flooding scenario at Pointe-du-Chêne on January 21, 2000, with a 2.55 m (DEM) water level (from Environment Canada, 2004).

B. Framework application: The creation and implementation of a community adaptation strategy

1. The scene

Idea creation: Pointe-du-Chêne, a low-lying peninsula in Shediac Bay, is home to 900 residents and a seasonal home to up to thousands of summer visitors, many of whom are strongly attached to the area. Residences and residents on the crowded peninsula are increasingly endangered by rising sea levels, storm surges, ice jams or erosion (see Figure 13). This vulnerability (coupled with a lack of resilience) had fostered major concerns associated with safety and a lack of information and expertise needed to best adapt to the dynamic, changing environment (Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005).

2. Identification of the conceptual lens

Data collection and research: In Pointe-du-Chêne, residents have traditionally acted as champions. Historically, residents have felt a lack of involvement from traditional government decision-makers (Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005). Consequently, when collecting data, researching or holding public meetings, there is a need to involve seasonal visitors, the press, the local public and government officials in order to build on that local tradition and create a community adaptation process open to all stakeholders, including government.

In other words, the socio-cultural characteristics of the scene at Pointe-du-Chêne are dominated by the complex relations (but missing communication) between a variety of stakeholders, including the government, Parks Canada, summer visitors and year-round residents of the area. Additionally, the major economic and physical characteristics in this case study are the attractive yet threatened coastal environment, shortage of monetary resources and lack of local infrastructure (Fisheries and Oceans Canada, 1997; Ru, 2001; Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005).

In contrast, the area's local knowledge-based characteristics have been enhanced through the experience of dealing with its challenging characteristics. The community of Pointe-du-Chêne has already successfully implemented some adaptation measures to address its deficiencies. For example, the community's creation of an emergency response team has addressed some of its safety concerns and heightened its knowledge of its political power. However, most of the community's adaptation experience is on an individual level and has not always had the same success rate. In fact, some individual adaptive actions have been detrimental to others. Consequently, while rich in local knowledge-based characteristics, Pointe-du-Chêne residents feel that they lack the expertise to make certain informed, collective adaptation decisions (or individual ones), and that the information flow between outside organizations and their local community is minimal (Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005).

Analysis: An analysis of the area might conclude that Pointe-du-Chêne is highly susceptible to the effects of rising sea levels and that its resilience and ability to effectively plan appropriate adaptation strategies on an individual or communal level is hindered by a lack of expertise, coordination and communication (Fisheries and Oceans Canada, 1997; Ru, 2001; Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005). The challenging lack of influence from those key stakeholders traditionally involved in "top-down" approaches to action also severely challenges the community's political power, access to outside expertise and overall ability to create an appropriate, sustainable adaptation strategy, thus increasing the area's vulnerability. However, by strengthening its relationships and increasing its local knowledge, the community can increase its overall adaptive capacity and its ability to make appropriate decisions.

3. Identification of the adaptation action's parts

Strategy creation: The creation of a strategy for Pointe-du-Chêne would have to focus on increasing the community's adaptive capacity by strengthening already-developed communication channels and by continuing to create new ones. In order to foster new communication and cooperation, a shared dialogue must be created, and conception of this mutual understanding requires an open, encouraging environment. To create this environment, not only would stakeholders have to ensure that they were willing to cooperate, but they would have to have a place and a way to do so.

One strategy that the community could identify would be the creation of an interactive forum (see Figure 14). This could also address the community's lack of information and expertise, as well as engage non-resident stakeholders and government authorities. For example, the interactive forum could be located on the Internet so that its spatial location is not an issue. Community portals could provide access to community members without personal Internet access. The accessibility of the forum would be critical to ensuring the strategy's feasibility and equity; if the Internet could not be used, a central resource centre (as simple as a bulletin board) could be set up. The stakeholders' use of the interface and access to the portal would determine the effectiveness and efficiency of the forum; its monetary cost would be minimal. The goal would be to provide a communications tool to:

- anticipate future issues by learning from others;
- raise awareness of the issues;
- foster an open, participatory means of communication;
- disseminate information on adaptation strategies and provide sources of expertise;
- share information on low-cost solutions;
- monitor past strategies and their impacts; and
- create and maintain meaningful relationships that lead to a community response versus individual actions.

Ideally, the negotiation and mediation required in future adaptation processes would be facilitated by the previously created community-engagement strategy; however, the decision to implement the interface and the issues of its accessibility and cost would have to be weighed by the community.

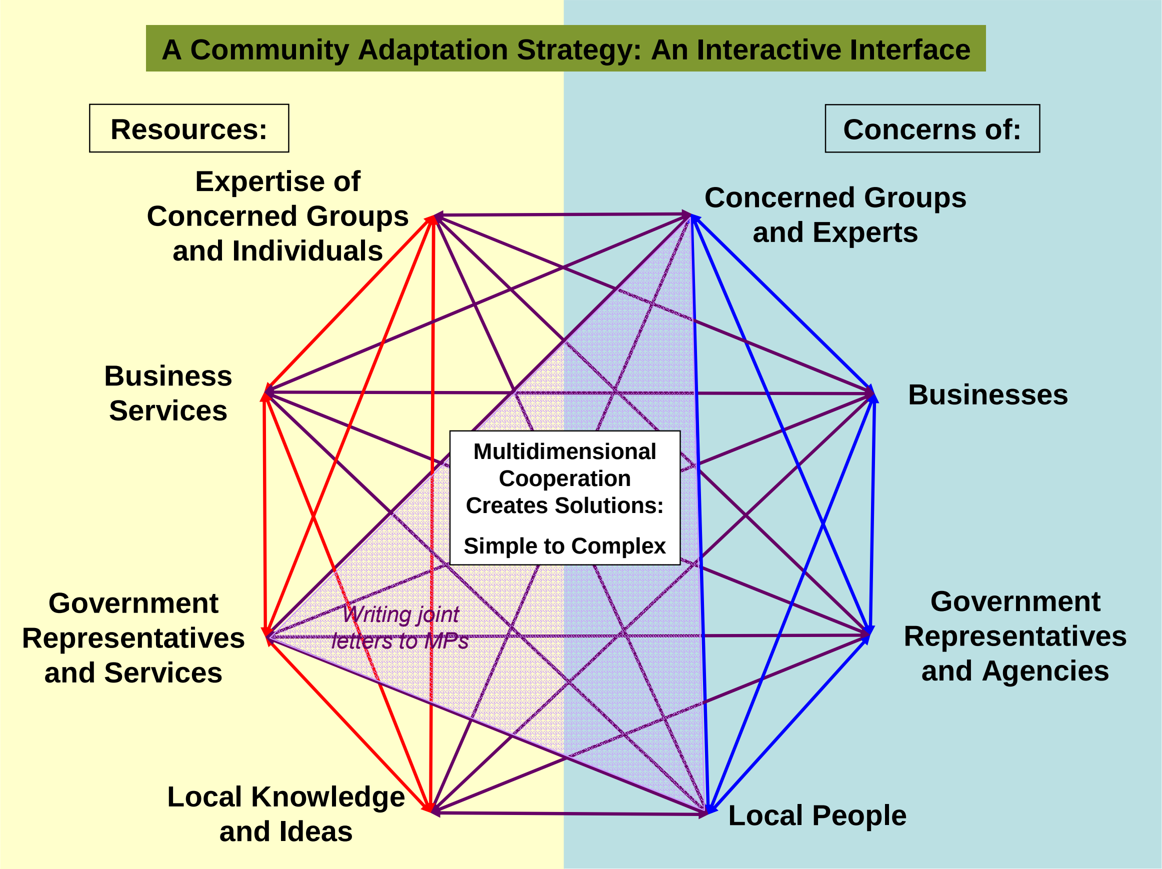


Figure 14. A community adaptation strategy: An interactive interface.

4. The specific response

Implementation and evaluation: If this adaptation strategy were implemented, the maintenance of an interactive interface would ideally foster continual negotiation, action and evaluation — for example, debate over the prioritization of strategies, the applicability of certain stakeholders' adaptive actions and the usefulness of the forum itself.

C. Conclusion

In the unique community of Pointe-du-Chêne, the most active stakeholders are primarily residents who are used to a lack of governance and a tradition of individual *ad hoc* adaptation (Information Session, October 11, 2005; Martin, 2005b; UNB and UdeM, 2005). Despite its limitations, the Pointe-du-Chêne case study illustrates the adaptation opportunities of a community and focuses its use of the framework on creating a variety of alternative adaptation strategies under specific constraints.

4.8.5 Summary and conclusions

Finding the crucial balance between stakeholders' unique environmental, social, political and economic interests is dependent upon participation of a wide range of stakeholders, including residents, community leaders and government representatives, among others.

Each brings unique expertise, insights, priorities and power to the community adaptation process. Effective adaptation strategies — ones that are implemented and have goals that respect local values — come from the ground up (i.e., from the community affected), rather than from the top down.

National and provincial strategies can be effective only if they address local issues and conditions; provide opportunities for local input and respect local values; and provide resources and expertise to the communities expected to implement the strategies. Even the best-intentioned provincial or national initiatives, if not effectively implemented at the local level, can lead to lack of trust and can even undermine the goals of the strategies.

Critical elements in developing community-level responses to sea-level rise and storm-surge threats are awareness of the issues, building of trust and communication, sharing of information and expertise, and having a champion (an individual or group) to lead the process. Successful community adaptation relies on continually fortifying the local conceptual lens by increasing the community's adaptive capacity and implementing best practices.

There needs to be a balance in adaptation-strategy design between addressing isolated issues and developing a comprehensive plan that addresses every dimension of the problem. The latter may require more research and organization than communities can absorb and still make meaningful changes. The former fails to address the needs of all stakeholders and can lead to strategies that further deteriorate other situations. Each community is unique and must determine its own balance.

Adaptation strategies need to include a wide spectrum of approaches, from policy and law to engineering and technology. Environmentally sensitive approaches can also be effective in minimizing change and cost. Raising public awareness and changing cultural values and perspectives can also be cost- and results-effective.

Past examples of adaptation in the study area include abandonment of erosion- and flood-prone lands and retreat from the coast. In many cases, older homes and infrastructure (except for port- and fishing-related infrastructure) were located well back from the coast and on higher ground. Low-value cottages were located along the shore but did not represent a large capital investment. More recently, the pattern of development in the region has been partly driven by market demand for homes with a view of the sea. Improved road infrastructure has favoured greater commuting distances, enabling those working in the growing Moncton economy to live along the coast. The result has been highly maladaptive, with expensive homes constructed along the coast in places where ice incursion, flooding and storm waves, and coastal erosion are all threats to the long-term stability and safety of the structures. Similarly, the demand for coastal land has encouraged in-filling and reclamation of coastal wetlands, reducing available habitat.

Appropriate adaptation strategies may take many forms and may include components at different scales. The provincial CAPP provides an umbrella for coastal-management and adaptation measures at a local level. Communication and coordination of efforts between various levels of government, community leadership, local organizations and citizens are essential ingredients for success. Hard and soft engineering, land-use regulation, innovative development policies and designs, land trading and institutional arrangements to promote exchange of ideas are among the many options that communities may consider to reduce future impacts and costs.

Communities need and want information and access to expertise. A simple web page giving "where to go if…" instructions can centralize desired data, foster communication and satisfy a large number of needs.

Local researchers at community colleges and universities can provide an effective link between communities beginning to organize and government agencies shaping regional and provincial policies and plans.

To be most effective, strategies for adapting to climate change need to be "owned" and driven by the local communities that are directly affected. Efforts to mobilize action at the local level require the support of planning agencies and governments at all levels.

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Appendix 1: List of some adaptation and disaster-mitigation strategies for storm-surge and coastal-flooding risks

Adapted from Sutherland and Nichols (2004)

Adaptation, mitigation and preparedness

- According lower-lying land to use of lower value (e.g., parks instead of housing, etc.)
- Building regulations and urban growth planning
- Closing policy gaps
- Coastal engineering works, such as revetments, seawalls, groynes, berms, breakwaters, etc.
- Coastal foreshore reserve
- Coastal policy
- Coastal sensitivity mapping
- Community participation
- Construction standards
- Create Good Practice Guide for coastal areas
- Create government organizations responsible for emergency management
- Develop emergency management plans and local mitigation policies
- Development of a coastal-zone management plan
- Elevate port structures (berths, wharves) and offshore structures
- Elevate power-station outlets
- Emergency-preparedness and mitigation legislation at both the federal and provincial/state levels
- Establish storage and sleeping areas high off the ground
- Flood-mapping programs
- Flood-warning systems
- Government financial support for research affecting the development of disaster-mitigation and preparedness strategies
- Include flood and storm surge in the Building Code of Australia (completed)
- Innovative sand management
- Institutionalize mangrove development
- Integrated coastal-zone management plan to prevent [destructive] initiatives in coastal areas
- Legislatively implement ocean monitoring systems
- Location of land uses
- Marine Geospatial Data Infrastructure
- Mitigation grant programs
- Modify appropriate legislation
- National flood-insurance program
- Obtaining and maintaining estimates of populations at risk from storm surges
- Output disaster-management publication series and other publications directed at the private sector and communities (including children)
- Protection of significant features
- Public access and reserves
- Public outreach and awareness

- Relocate structures out of areas at risk for flooding
- Requirement of setbacks (treat public easements and setbacks as separate lots during land surveys)
- Storm-surge vulnerability mapping
- Strict implementation of coastal laws
- Strict requirement of compliance with housing standards
- Supporting academic and other research into coastal risk factors
- Sustainable uses of the coast
- Training programs that support multi-service/agency preparedness and response to emergencies
- Use flood-resistant building materials (water-resistant materials, waterproof seals, strong foundations)
- Wetland preservation

4.9 Building adaptive capacity

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4.9.1 Introduction

The integration of the socio-economic considerations along with biophysical sciences into ecosystem management and decision-making processes is usually a complex task where few protocols have been developed to help decision-makers in this exercise. In many cases, questions of temporal and spatial scales as well as data compatibility are raised and lead to roadblocks difficult to surmount. This is even more of a challenge when the issue of climate change is integrated into the process. In many cases, either climate change or socio-economic considerations are avoided to simplify the process of decision-making regarding the adaptation of communities to climate change. The main challenge remains that few tools exist to enable the integration and linkages of ecosystem impacts with socio-economic perceptions in areas where a project is evaluated, and fewer in terms of adding the predictive dimension of climate change. Reasons for this lack of integration might include limited adequate information on the possible impacts of climate change on the ecosystems, limited level of education on these impacts in the population and, finally, the unavailability of protocols or tools to evaluate socio-economic perceptions when the other information is available. While in some cases climate change has been considered using historical data, very few attempts have been made to integrate current and predictive data and socio-economic surveys into the process. Since public consultations are elements of greater importance in more recent environmental management work, there is a way to incorporate, in the early stages, protocols that can integrate ecosystem response and socio-economic perceptions into a predictive model of climate-change impacts. However, very few attempts have been made in leading towards these integrative approaches, which remain the basis for the development of adaptation strategies for these communities. There is a need for better global understanding on how ecosystem management can be integrative by combining the various biophysical, climatic and socio-economic perspectives, leading to greater sustainability and decisions regarding climate change in which future adaptive strategies can be included.

Climate change is a topic frequently in the news in the past decades. With reports of extreme weather events such as flooding, severe droughts and storm surges, coastal communities have become more aware of the potential risks of climate change. There has been increasing pressure on governments in the countries of the world to initiate actions to reduce these risks. However, it seems that little progress has been made, despite scientific predictions, international protocols and the desires of some decision-makers and organizations to act. The major challenge is how to relate to people and mostly to communities. One of the ultimate goals of environmental education is to encourage the adoption of pro-environmental behaviour by citizens (Hungerford and Payton, 1976; Hewitt, 1997). Adoption of pro-environmental behaviours not only by the general community but mainly by decision-makers and developers is rather important in the context of climate change, considering the actions that will be needed to reduce greenhouse gas emissions globally. The main challenge, however, concerns to what extent education can be translated into behavioural change. Behaviours and habits such as the intensive use of cars, packaging, disposable items and electricity are well ensconced in contemporary lifestyles. These behaviours remain in the arena of mitigation. But can they be translated into adaptation strategies? Finally, how, through such approaches and others, can we have a better decision-making tool for policy-makers and planners to cope with not only mitigation but also adaptation strategies at the community level? Such questions remain to be answered if one were to achieve success in the relatively short term while at the same time balance the issue of sustainable development for such communities.

In this section, through integration of the information provided in the previous chapter, a theoretical framework for decision making process was developed in which the various aspects regarding climate change impacts and adaptations are combined. This includes planning and the use of the ecosystem approach to make the links workable and understandable, as well as the use of case studies to examine the possible outcomes for two communities. The use of such an approach can lead towards the development of an application system for decision-making and ecosystem management regarding climate-change mitigation and adaptation strategies. The section is therefore divided into three parts: 1) the issue of climate-change impacts and adaptation, 2) the importance of linking socio-economic and biophysical components to ecosystem management and 3) the discussion on these links in light of decision-making, planning and ecosystem management. This last point should consider where control and adaptation can be activated in order to sustain the system. The theoretical framework developed in this section was constructed in relation to two communities where greater information was available through this large project.

Given that the current economic environment tends to push decision-makers and developers to act upon environmental issues relatively rapidly, often reducing or avoiding public contact, it becomes essential to analyze the elements that are needed in considering climate-change impacts and adaptation. The importance of public input into decision-making has been recognized in most industrialized countries. In Europe, public considerations have become important, and several arguments are pressed upon to help enhance such an approach (Johnson and Dagg, 2003). For example, the 10th principle of the World Commission on Environment and Development encourages public input, and, as Johnson and Dagg (2003) report, European Council Directive 85/337/EEC (amended by 97/11/EC) encourages public involvement, but it can vary according to the nature of a project. When considering climate change, similar attitudes can be taken. However, without a better appreciation of the need for social considerations, this statement might be difficult to justify. Therefore, in-depth analysis of climate-change impacts on communities can help in understanding the linkages between knowledge, public input and integrated assessment of the environment. This is the main goal of this section, which aims to link knowledge and community understanding to potential use of adaptive strategies to sustain their livelihoods.

In Atlantic Canada, where most of the communities (60%) and their activities are included within the coastal zone (50-km zone), there is a need to better understand how climate change will impact on new economic development (NBDELG, 1998). Coastal ecosystems, especially on the Atlantic coast, have been shown to be highly sensitive to sea-level rise and other phenomena such as storm surges under the scenario of climate change (overview published by the Geological Survey of Canada in 1998: GSC Bulletin 505).

The overall objective is to develop and implement an integrated framework to discuss adaptation strategies in terms of the entire ecosystem and develop a guiding protocol (including ecological and social aspects) for assessing human-use impacts on coastal ecosystems in the scenario of climate-change influence during the development of a project. More specifically, the project aimed to first quantify the potential impacts of climate change — more specifically, sea-level rise, storm surge and coastal erosion — on two targeted communities along the Gulf of St. Lawrence coast of southeastern New Brunswick. Second, the project assessed the potential impacts of climate change on new human activities while taking into consideration social perceptions and ecosystem characteristics. Finally, data from these various sources were integrated to demonstrate the need for adaptation strategies and the development of a guiding protocol that could be used to help decision-makers consider the potential impacts of climate change during the development of a project.

The study targets two communities of the southern Gulf of St. Lawrence in New Brunswick: Bouctouche and Shediac. The reasons for choosing these communities are as follows: 1) they are of highest scientific interest and significant priority for governments and coastal stakeholders, 2) another project on climate-change assessment (the Canadian Environmental Assessment Agengy project on social considerations of assessing climate change) has been conducted in this region, and results from it complement this project, and 3) the increasing pressures from accelerated coastal development in this region is very well known and of concern for communities and for its ecosystem sustainability (fisheries, developing aquaculture and tourism). This section is based on data and information acquired in the other components of this report and took advantage of the data acquired from some of these components to be able to develop greater links between assessment, ecological and socio-economic issues and climate change.

This section integrates the information that was accumulated in terms of climate-change impacts and adaptation and considers these various aspects in the development of projects such as tourism activities (Bouctouche) and urban/housing development and economic activities coming from the coastal ecosystem (Shediac/Pointe-du-Chêne). The methodological section explains the various components that were considered in order to 1) acquire data on potential climate-change scenarios and the most important vulnerabilities for the communities, 2) integrate the information into a precise georeferenced digital elevation model (DEM), 3) overlap the previous data with the current community activities and 4) connect the data to the information that was provided through workshops, focus groups and public consultation sessions in the community.

From this integration, for each case, the results will be presented first, and then the information on vulnerabilities will be summarized and the strategies for adaptation defined. In the last section, lessons learned and limiting factors for such an approach will also be described.

4.9.2 Theoretical methodological framework used to visualize potential outcomes in terms of impacts, vulnerability, adaptation measures and adaptive capacity

In this section, the theoretical methodological framework used in these case studies is presented. It is important to acknowledge that in the present study, data acquisition was done with higher precision than in a usual climate-change impacts and adaptation study. In most cases, the light detection and ranging (LiDAR) and DEM components are not available but could be replaced by the acquisition of data from the literature and from climate-change scenarios already available for the studied regions. While this approach is somewhat more limited, it still gives a possible range of climate-change impacts and can lead to the development of adaptation strategies. Ideally, downscaling using global climate change scenarios could help complement the information.

The analysis of potential impacts of climate change on communties and their socio-economic activities can be completed either through interviews and surveys in the community. This information can be enhanced by acquiring property/cadastral and topographical maps of the region and integrating the information from the community into these maps. In addition, if flood scenario maps for example are also available, their overlap with cadastral maps can help define the zones that will be more at risk. Such an approach can be either done using geographic information system (GIS) technology or manually by overlaping the maps. Social considerations including interviews and acquisition of socio-economic activities in the region should be examined in parallel with the acquisition of the climate-change scenario data. This process is explained in the last part of the methodology section

4.9.2.1 Case studies

4.9.2.1.1 Bouctouche

Bouctouche is a small village where ecotourism has become one of the most important industries over the years. Among the attractions, Le Pays de la Sagouine, the Yacht Club and La Dune de Bouctouche are the main tourism infrastructures located on the coast or in the Bouctouche Bay that are the most at risk. La Dune de Bouctouche includes the Irving Eco-Centre, developed by J.D. Irving Limited to preserve and restore one of the few remaining undeveloped sand dunes on the northeastern coastline of North America. Located on the Northumberland Strait, opposite Prince Edward Island, the white sand dune stretches 12 km across Bouctouche Bay. This environmentally significant area is the habitat for a rich variety of marine and aquatic plants and animals and for shorebirds and migratory birds. For example, a few species considered rare or endemic at the provincial and/or federal levels are found there, such as the Gulf of St. Lawrence aster and the Piping Plover. In both cases, research is ongoing to understand their level of susceptibility to environmental changes and evaluate their potential for long-term survival. The village of Bouctouche also represents a very fragile but interesting setting where climate change, especially storm surges, can have disastrous consequences on community well-being and the economy.

In the past years, the research projects have targeted several areas of the La Dune de Bouctouche ecosystem, from population surveys to remote-sensing data analysis. The damage from the October 2000 storm was serious enough to change several components of the ecosystem and the infrastructure in place for tourists. During extreme storms, some streets of Bouctouche can flood easily, and some basements are inundated. These problems occurred on various occasions in the last few years (e.g., Gustav storm in 2002, Boxing Day 2004 storm) and are becoming a concern for the citizens who have tourism facilities, houses and cottages on this coast.

4.9.2.1.2 Shediac (Pointe-du-Chêne)

The community of Pointe-du-Chêne is located between 46°00'N and 46°30'N latitude and 64°30'W and 65°00'W longitude and is surrounded by the Northumberland Strait in the north/northeast, Scoudouc village in the south, Cap-Pelé in the east and the City of Moncton in the west. This community is rapidly growing and formerly was part of Shediac. Its watersheds comprise the Shediac and Scoudouc rivers. The topography of the region is characteristic of the Maritimes plains, with low-elevation lands that historically were used for agriculture. Historically, this community hosted cottages owned by citizens from larger cities such as Moncton, Fredericton and Halifax. However, over the past 50 years, with the rapid growth of the City of Greater Moncton, housing developments and subdivisions have become the norm, most being located close to the shore or in former salt marshes. The construction projects have put more pressure on the community to increase its municipal infrastructure, but not all houses are still appropriately connected to an efficient system. Population annual growth in Pointe-du-Chêne reached 2.8% between 1996 and 2001, with a current density of 21.5 persons/km^2, far greater than the provincial average of 10.2 persons/km^2 (Statistics Canada, 2001). Pointe-du-Chêne is also a tourist community, with one of the most popular beaches of the Atlantic region, Parlee Beach. This beach attracts a large number of visitors, especially from mid-July until the end of August, and plays an important economic role in the community. Its management and the current number of tourists may, however, jeopardize the sustainability of this beach, which needs to be nourished every year with several thousand tonnes of sand.

4.9.2.1.3 LiDAR acquisition and DEM

LiDAR data were provided by the Centre of Geographical Sciences, consisting of ASCII text files separated into ground-only points and non-ground points. Overall, there are 80 tiles of LiDAR data covering about 165 500 km^2 and over 45 million points.

The raw data were imported into ESRI ArcGIS Version 9.0, and points were generated from the raw data. The LiDAR point coverage was then used to interpolate three-dimensional grid surfaces. The ground-only hits were used to generate true ground-only DEMs of the surface to be used with the flooding simulation. The ground-hits point coverages were combined with the non-ground points to generate digital surfaces containing all features. The grid surfaces were then combined, forming larger grids representing each study area. Flood levels were calculated from the water-level data provided by Ritchie, Thompson, and Forbes (see Sections 4.3 and 4.4). The data were provided as levels above DEM datum and were converted to orthometric heights for each region. Three levels were provided: 2.55 m above DEM datum, which represents the best estimate of the high-water mark for the January 21, 2000, storm-surge event; and 3.05 and 3.55 m above DEM datum, which represent the extreme cases. These layers were then used to flood the DEMs to provide raster surfaces that were either flooded or not flooded. The layers were checked for connectivity to the ocean to ensure that low-lying areas that were not connected to the ocean got flooded. A flood-depth layer was generated to accompany the flood-extent layer for the January 2000 storm-surge event and the predicted 100-year level.

4.9.2.1.4 Ecosystem analysis

In the two communities, different ecosystems can be found. While in Bouctouche most of the ecosystem is composed of sand dunes and managed protected areas, the Shediac (Pointe-du-Chêne) case study area consisted mostly of human settlements, especially housing development along the coast. La Dune de Bouctouche has been a prominent feature of the Village of Bouctouche and a very important component of the ecotourism activities of the Bouctouche region. Each year, La Dune de Bouctouche and the Irving Eco-Centre attract several thousand visitors who come for the landscape and the ecosystem, the interpretative and educational walks, the beach and hiking or birding activities. The ecosystem has been previously under a certain level of stress, with the traditional use by 30–45 fishing families who also live there. With the increase of all-terrain vehicle traffic and other types of stresses, the ecosystem became gradually degraded and under greater stress. Gradually, through consultations and support of the Irving family, the dune became a protected area, where only research and mild activities such as birding and hiking have been allowed. These conservation initiatives certainly have helped protect this fragile natural ecosystem over the past decade. This ecosystem is 12 km in length with a 2-km boardwalk. It currently limits the number of daily visitors to about 2000 in order to reduce the “footprint” of humans on the ecosystem.

In 2000, the southeastern region of New Brunswick was affected by two major storms that triggered responses from communities, decision-makers and scientists in order to understand the potential impacts and possible adaptation measures to gradually implement in order to sustain the communities and the natural ecosystems. These storms had major impacts on this natural ecosystem and led to a loss of 24 000 m^3 of sand from the beaches (Giangioppi, 2004). In addition, breaches and overwash occurred in several areas along the spit. A few photographs have helped to explain the level of change that occurred at the dune in some areas over the past few years due to the storm surges, such as those of January and October 2000, as well as the one of September 2002. It is clear from the photographs taken in July 1999 and May 2004 that the level of erosion in some areas of the dune, such as the first 100 m from the Irving Eco-Centre, had been greater than expected; this means that in many sections of the dune system, there are possible breaking points that can be triggered if another major storm surge occurs. At the same time, the dune system in many sections has seen its sand accumulation reduced not only in width but also in height, leading to a flattening of the dune system.

These observations have been confirmed by people who have grown up there and have seen changes in the dune. In addition, the integration of the land-use map of 1975 from the province with the LiDAR DEM map indicates that coastal erosion has occurred and that this erosion is not constant and similar along the entire dune system, although the map of 1975 is far less precise than the LiDAR DEM. For example, in Figure 1, the difference between the lines in 1975 and 2003 suggests that the dune system not only has been moving, but in many sections has lost its width. This may, as a consequence, separate the dune into a few islands (Figure 1). The changes in the width of the sand beaches will have important impacts on the nesting habits of some of the bird species, such as the Piping Plover. In addition, over time, it has been observed that the dune has lost some of its height with frequent storms. This impact has influenced and will continue to influence the survival of other species, such as another species at risk, the Gulf of St. Lawrence aster. The potential breaking up of the dune system into islands would lead to a potential reduction in gene flow and migration of the species into other habitats; this might be serious for the survival of this species at risk.

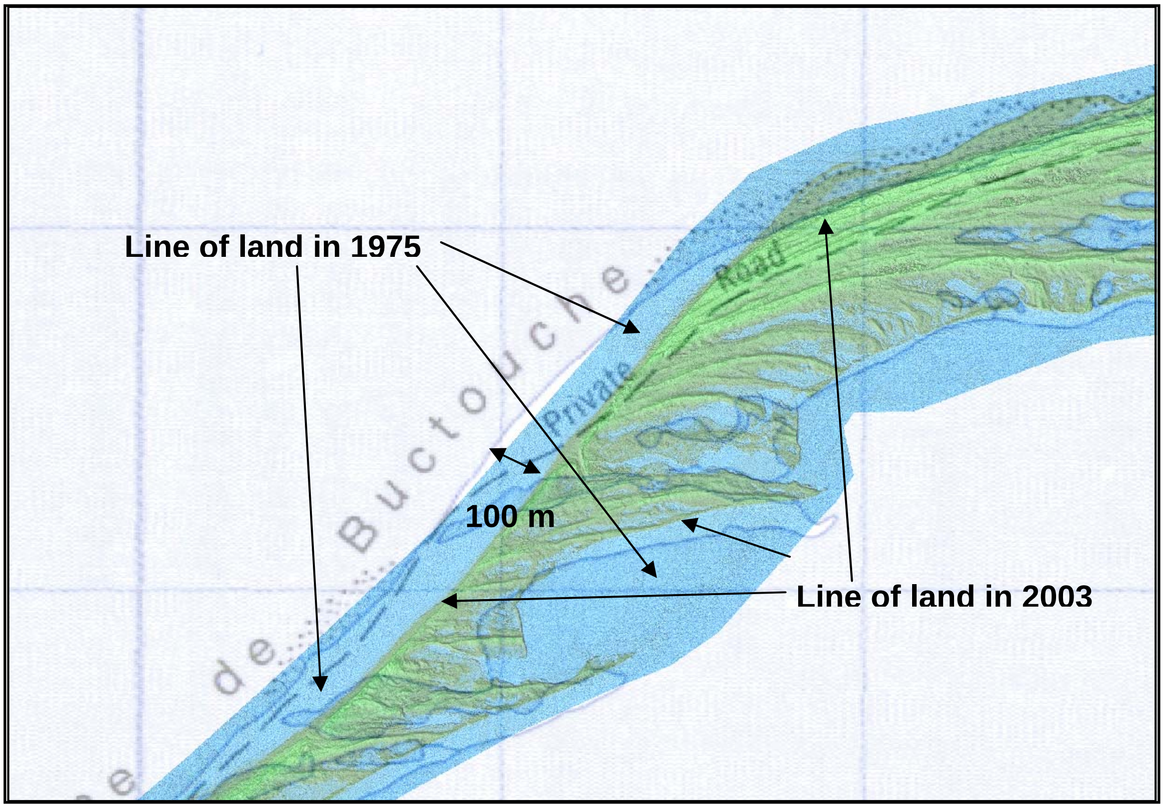

Figure 1. Part of the dune system of La Dune de Bouctouche and the changes that occurred between 1975 and 2003. In some cases, it can be shown that breaking points are located along the dune and may happen at any time with future storms because of the weakening of the system over the past decades.

The Pointe-du-Chêne/Shediac case study that has been initiated in this project is the impact of climate change on the infrastructure of the coastal area, including housing and other developments. As previously explained, the pressure for coastal land has dramatically increased in the past few years with the establishment of new residential areas. Infrastructure near the shore is dense and puts pressure on the natural ecosystems that usually buffer the habitats against storm surges and floods. Low land is more at risk, although it is the area with the most intensive use by the community. This is exemplified by the growing populations and economic activities of this area.

Figure 2 summarizes the details on which the framework for the analysis is based for the integration component in Shediac. This diagram describes how the information from the past, using the 1975 land-use data, is compared with the current LiDAR data to evaluate the changes of the past. Then, using the current data and the different projections (pessimistic and optimistic scenarios described from the socio-economic assessment), the possible changes can be evaluated for the future, depending on the ways in which the communities would deal with climate change. Looking at the differences between the different scenarios and the current scenarios using the LiDAR data, it is possible to estimate the level of community responses to future climate change. For example, Figures 3a and 3b show the changes in the level of occupancy of the coastal zone in Shediac between 1975 and 2003. The coloured zones demonstrate the increasing level of pressure that infrastructure has been adding to the coastal areas.

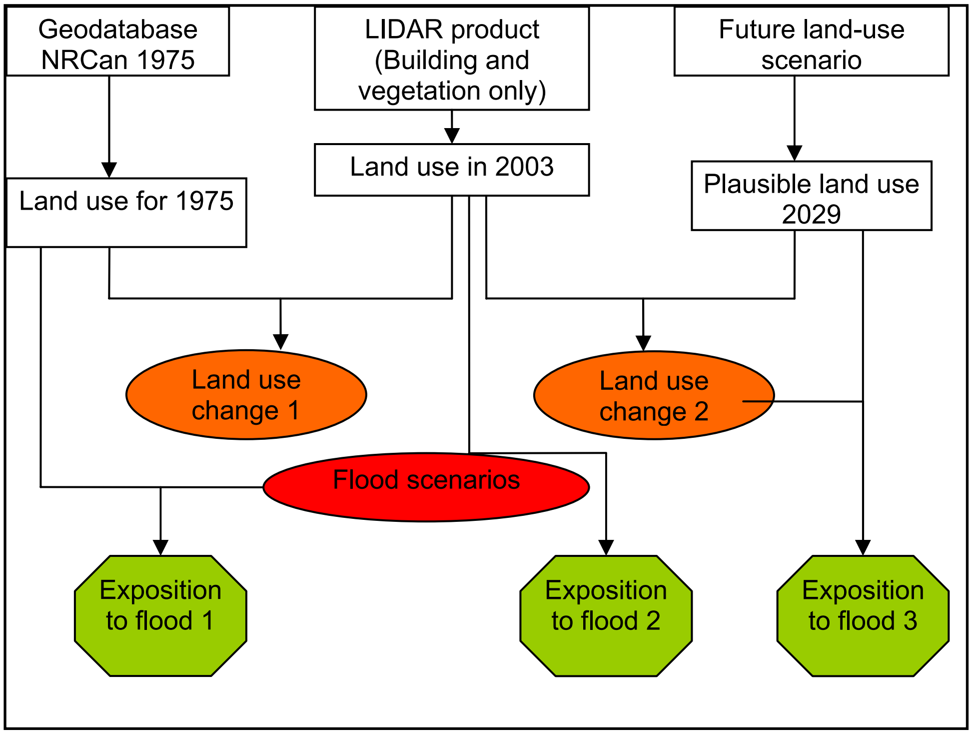

Figure 2. Diagram of the analytical framework used in this case study to examine the changes in land use and potential impacts of climate change in Shediac for 1975, 2003 and 2029.

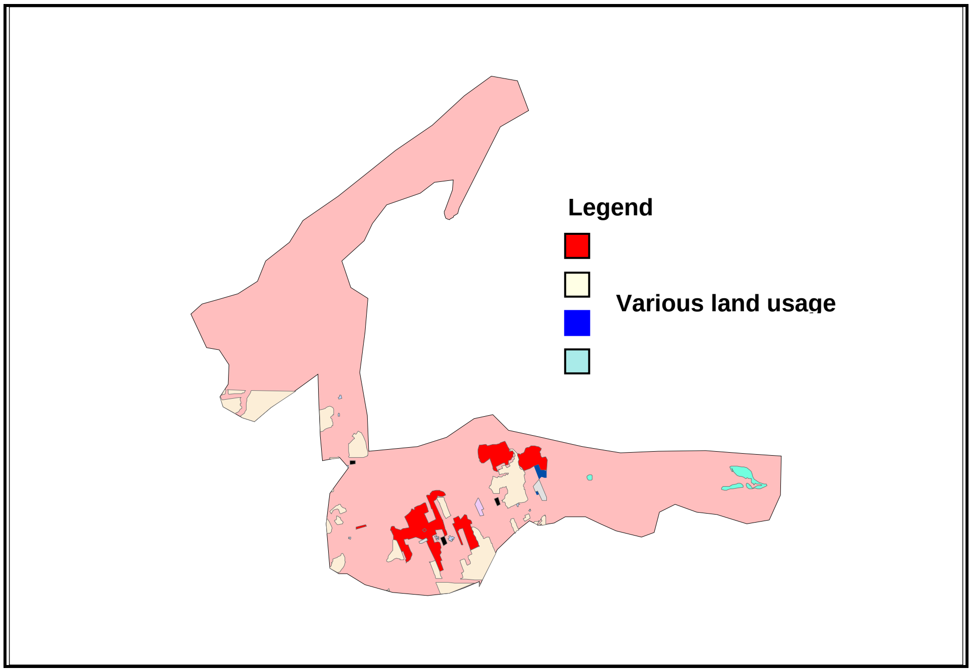

Figure 3a. Land use of the Shediac area in 1975.

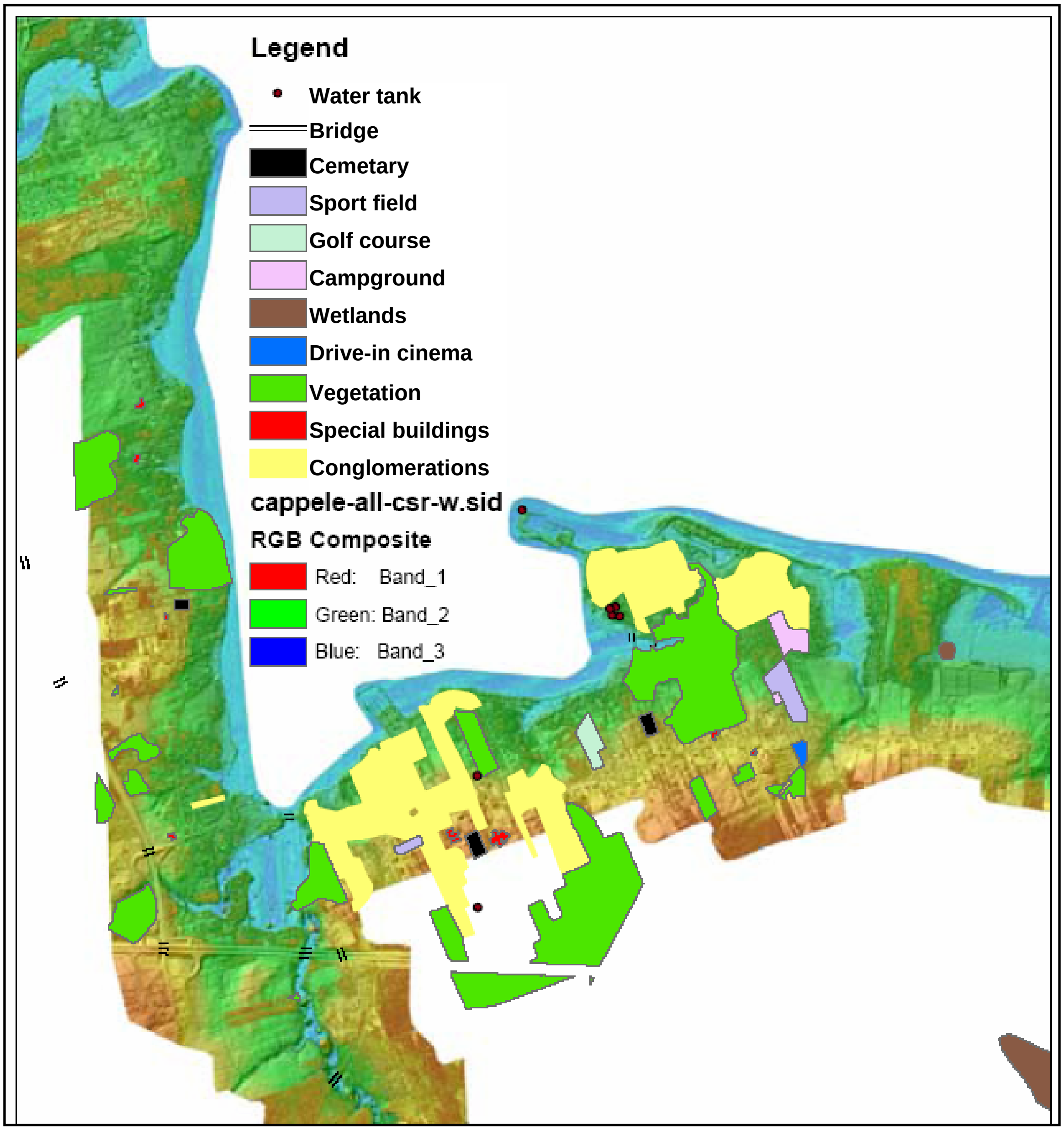

Figure 3b. Land use of the Shediac area in 2003: integration of the geodatabase of 1975 and the LiDAR DEM of 2003.

4.9.2.1.5 Community consultations

The methodology in these case studies tried to link traditional climate-change assessment to community stakeholders and community attributes such as stability and well-being (Mendis et al., 2003). For all human beings, stability generally reflects security, future sustainability and maintenance of socio-economic standing. For industries, stability is reflected in continuous productivity and allows all managers and staff to benefit in the long term, maintaining jobs and production (Bowles, 1992). On the other hand, well-being is a more complex concept that relates to how a person can thrive in a system mentally, physically, culturally, socially and psychologically (Prescott-Allen, 2001). Well-being is also linked to stability. For example, if there is a drought and the forest industry has to close its operations for two weeks (as occurred in 1999 in Nova Scotia), employees might be anxious and psychologically affected by this decision, which reduces not only the stability of the industry and the employment, but also the psychological and mental well-being of the employees. As Nadeau (2002) explained, understanding the well-being of a community can improve our understanding of this community's ability to adapt to change better than traditional measures of capacity alone. The capacity of a community to adapt refers to its ability to utilize resources and structures to respond to changing external or internal factors and to take advantage of opportunities that meet the needs of all community members for present and future generations (Kusel, 2001). In addition, through an understanding of well-being, it is possible to measure the collective resistance or willingness to proactively plan and adapt.

The study in both communities drew on linkages that already existed between all stakeholders in the community, including university, private sector and industry, non-governmental organizations (NGOs), municipal, provincial and federal governments, and citizens, including women, men and youth. The social consideration part of the project included two components: 1) assessment of community understanding of and vulnerability to climate change through focus groups; and 2) evaluation of potential measures for the various groups in the community (e.g., industries, NGOs, municipal decision-making and planning, emergency measures, etc.) regarding the ways to reduce climate-change impacts during the development of projects.

4.9.2.1.6 Assessment of community understanding of climate change and vulnerability

Without knowledge of the perception and understanding of the concept of climate change in a community, planning and decision-making as well as any actions towards adaptation are likely to be difficult to implement because of public resistance. Conservation in the use of resources is an adaptation strategy involving a change in behaviour that often leads members of the public to ask why they should change, since the issue is global and their individual part is only very small. The government, they say, should take responsibility. This reaction demonstrates the need to better understand the standpoint of all types of stakeholders in order to succeed in improving social acceptability of climate-change adaptation measures.

There are several approaches to assess community understanding and vulnerability in the face of climate change. In this project, a combination of several qualitative and quantitative approaches was used. In the first step, data collection included interviews with various stakeholder groups in the community mixed with focus groups in order to better verify and cross-reference some information. For the interviews, a "snowball approach" was used until saturation. The questions focused on the perceptions of what is climate change and the reactions of people to the impacts of climate change. For the general public and large stakeholder focus groups, individuals were randomly selected. Questions regarding risk perception, the level of understanding of climate-change impacts, the areas of vulnerability they perceive as important and their level of understanding of their own capacity were asked of all participants. The interviews were semi-structured and brought out any current actions that people are implementing to reduce the risks or adapt to climate change. All interviews were conducted under the supervision of O. Chouinard with the participation of M. Tremblay and K. Délusca and were conducted after Université de Moncton Research Ethics Board approval and consent of the participants.

The interviews were transcribed using Atlas.ti for thematic analysis (Paille, 1996). This type of qualitative analysis brings out the main factors or issues brought up by the interviewees. Thematic analysis included two steps, theme and interpretation, to underline what the issues are and what types of actions/reactions people have in response to these issues. The interviews would go on until saturation of the possible responses and no new ideas for climate-change impacts were brought up. The data were finally interpreted in order to provide a better understanding of what elements could be integrated for better social considerations of climate change during the process of an environmental impact assessment (EIA), especially during the decision-making and planning phase.

In summary, public presentations, interviews, focus groups and meetings were organized in 2003 and 2004 to discuss, in detail, perceptions and reactions of participants to climate-change impacts and how, under optimistic and pessimistic scenarios of project development, climate change could bring impacts and damage to the infrastructure and ecosystem in the region.

4.9.2.1.7 Integration

Vulnerability analysis can be defined as the second last step from climate-change impacts assessment to the definition of adaptation measures. Vulnerability assessment is often considered as the inverse of impacts assessment, since the ecosystem and its community are evaluated in terms of their potential to withstand climate-change impacts rather than from the standpoint of the impacts. It means that vulnerability is a property of the ecosystem that will integrate the notion of climate-change exposure and the adaptive capacity of the system (i.e., the potential of the system to respond in a sustainable manner to changes) (Smit and Pilifosova, 2001). Under this definition, it is clear that vulnerability and adaptive capacity are two concepts that are characterized at a community or ecosystem level. Since each system is different, including its natural setting and its community (socio-economic activities and social structure), it is expected that the levels of vulnerability and adaptive capacity of the case studies here will vary greatly. While, in a natural ecosystem, the adaptive capacity will depend upon the environmental and biological components and their capacity to resist and/or respond to change, in a human community, its ability to adapt will depend on the effectiveness of the social system and the flexibility to work on the infrastructure to help respond to changes (Adger, 2003). Figure 4 describes the components of the system that can be impacted by climate change, those that communities can control or not control and where decision-making for adaptation measures can be made. It is clear that humans will have no direct control of the changes in the natural physical environment, and only through decision-making on the human infrastructure will we be able to implement adaptation measures. Therefore, most adaptation measures will be linked to two main factors: social attitudes and infrastructure. While social attitudes relate to people and society, infrastructure will be influenced by decision-making at the community level. Higher levels of decision-making, such as by the provincial and federal governments, can also affect what can happen at the community level; however, without a very good understanding of the influence of the stakeholders in the community, adaptation measures cannot really be accepted and implemented. Developers looking at short-term gain without long-term environmental assessment that integrates climate-change impact and vulnerability will continue to affect adaptive capacity of a community and render the system more vulnerable to climate-change impacts. The balance can be achieved only once all aspects, from biophysical to socio-economic factors, are integrated and vulnerability and adaptive capacity are correctly assessed. These components are discussed in the last part of this section.

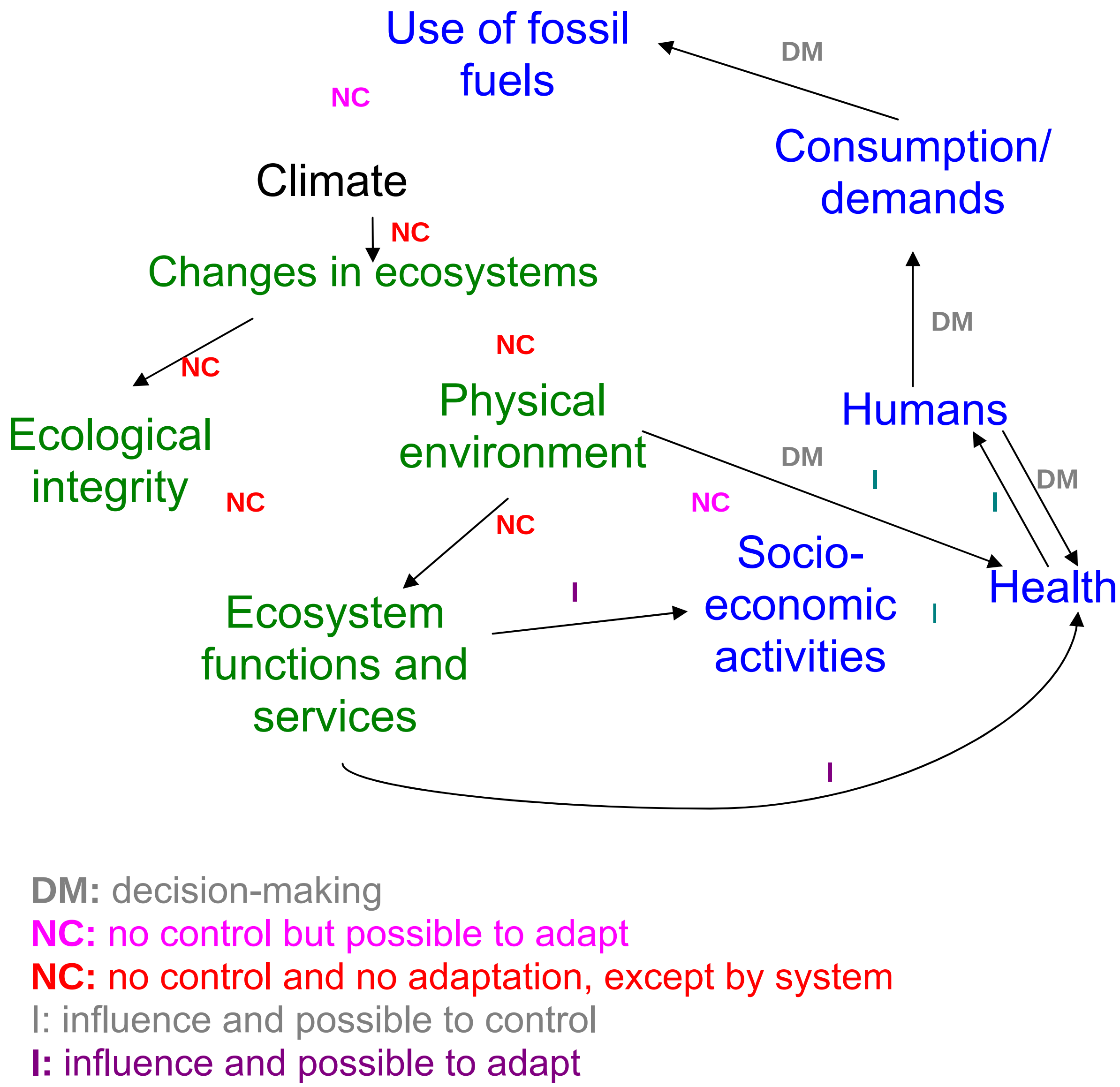

Figure 4. Theoretical framework for the linkages between various components of the ecosystem and the level of control or adaptation that can be accomplished by human communities in this ecosystem.

4.9.3 Results/discussion

4.9.3.1 Case study of La Dune de Bouctouche and the Village of Bouctouche

4.9.3.1.1 Types of impacts related to climate change

Sea-level rise was one of the main issues that raised public concerns regarding the negative impacts of climate change. As has been shown in many other regions, this will cause more frequent and regular flooding events, which will directly limit the potential to invest in long-term projects on the coast (Nicholls, 2002). Increases in storm surges and other extreme events will exemplify the changes already occurring under sea-level rise. Storm surges are already frequent in this region of the Atlantic (Danard et al., 2003; A. Robichaud, pers. comm., 2004). For example, coastal erosion has been one of the most important consequences that has been observed and dealt with as much as possible by the citizens living along the coast. All the changes occurring due to the change in climate as well as other anthropogenic activities such as wharf construction have led to greater erosion. This phenomenon is seen along the coast not only of southeastern New Brunswick, but also in other regions, such as the Gaspésie region in Quebec and the north coast of the St. Lawrence Seaway (Ouranos, 2004).

In Bouctouche, decision-makers and community stakeholders have been mostly concerned about the loss of their natural ecosystem, such as La Dune de Bouctouche, which has been a landmark for the province and the region. As a widely advertised tourism attraction, La Dune de Bouctouche and the Irving Eco-Centre represent a major focal point for the community. The main environmental impacts that can occur from climate change can be described as 1) coastal erosion on the dune and along the coast, 2) sea-level rise, 3) increased flooding, mainly during normal seasonal conditions, and 4) the continuous flattening of the dune ecosystem due to storm surges, mainly in the winter when ice scars the surface, either flattening the top of the dune or bringing sand wash. Figure 5 illustrates the changes in the profile of La Dune de Bouctouche and how rapidly the dune system can flatten with the influence of storm surges. It is important to understand how such change impacts the vegetation. For example, with erosion due to wind action, small seedlings are buried rapidly in the sand, thereby reducing their growth and survival rates. A study on the re-establishment of the vegetation after the impact of storm sand deposits suggests that clonal species such as *Ammophila breviligulata* can grow back rapidly from buried rhizomes, whereas other smaller annual species can take longer to reappear. In addition, disturbances lead to additional challenges (which might also be influenced by human activities at La Dune de Bouctouche) for the ecosystem, such as the introduction of invasive species, which significantly increased after the series of storm surges from 2000 to 2002 (Vasseur et al., in preparation). In the case of small annual plants, such as *Symphyotrichum laurentianum* (Gulf of St. Lawrence aster), and some bird species, such as the Piping Plover, flooding of their ecosystem and coastal erosion can lead to the disappearance of their habitat.

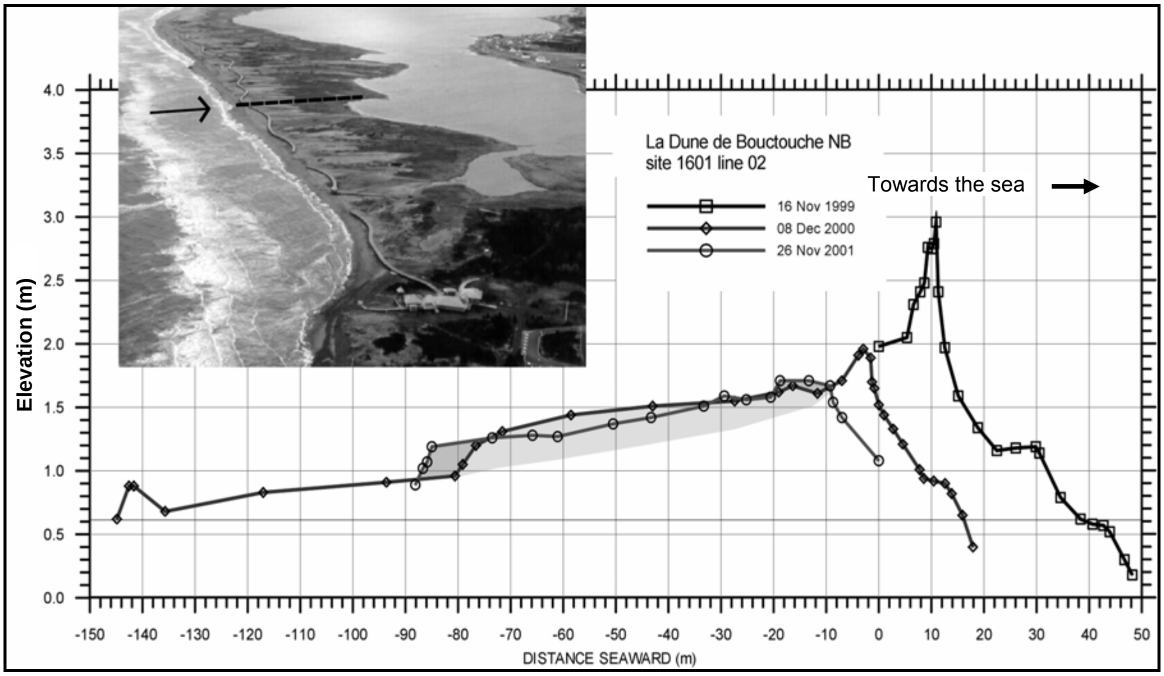

Figure 5. Successive profiles across La Dune de Bouctouche spit in November 1999, December 2000 following October 2000 storm and November 2001 following an earlier storm in that month (Forbes et al., 2004).

4.9.3.1.2 Vulnerability zones and assessment from biophysical to socio-economic factors

Many of the impacts that have been recorded at La Dune de Bouctouche can be directly or indirectly interconnected (Figure 6a), not only to the natural environment but also to the community of Bouctouche. From the natural ecosystem point of view, species at risk and species less common are the most vulnerable components of La Dune de Bouctouche. In addition, the reduction of the beaches due to past storm surges and mainly coastal erosion leads to reduction in space availability for species as well as to changes in its attractiveness to tourists, as we can see in the diagram. La Dune de Bouctouche with its Irving Eco-Centre has attracted approximately 120 000 visitors per year since its opening (G. Arsenault, 2005 pers. comm.). Considering that about 50% of the visitors are coming from Quebec and 20–25% from other regions, such as Ontario and the United States, a change in the infrastructure leading to beach reduction and greater limited access to the natural dune setting may greatly reduce the number of visitors. La Dune de Bouctouche has been, since its opening, one of the attractions advertised by the province, and, as described in Figure 6a, a change in its ecosystem may lead to changes in tourism. This would have an impact on the region, not only on the Irving Eco-Centre.

In Bouctouche, because the tourism sector is important, most of the infrastructure, such as Le Pays de la Sagouine, the cottages and the hiking trails, is of serious concern with respect to sea-level rise and coastal erosion. For example, all scenarios show that during extreme events and for a short period after the event, Le Pays de la Sagouine may have to temporarily close until repairs to the bridge, sewage piping and other sections of the facility can be completed. This may result in the cancellation of shows should the area experience an early tropical storm. Increased frequency and intensity of extreme events and flooding lead to temporary closure of some riverside hiking trails. In particular, the bridge over Black River is frequently closed. It is also clear that as a result of extreme events and flooding, some tourism operations, such as shops, restaurants, lodging and camping facilities, may not be able to absorb non-insured costs associated with the repairs. This may not be financially sustainable to some operators and may result in the temporary closure of those facilities. The first sectors that might be targeted include the cottages and lodging resorts located in the coastal area. One aspect in particular is the increasing demand for potable water at the height of the tourist season when the groundwater supply is diminished (e.g., the populations of Bouctouche and Shediac increase more than 100% during the summer months). Community members are concerned about the future of the groundwater supply and the impact of sea-level rise on the quality of the drinking water. The community of Bouctouche has invested significantly in its tourist facilities and attractions, the majority of which exist within the coastal zone and have already been impacted in some way by the effects of extreme weather events (storm surge and erosion).

4.9.3.1.3 Social component

Initially, six public presentations were given to the various communities along the coast in the study region to first introduce the project and receive their first general impressions of the problem. The general impression from the presentations was that members were most concerned about economic issues in relation to development and problems with tourism infrastructure. On the other hand, one Aboriginal community of the same region (Elsipogtog First Nation) expressed concerns about water, burial grounds and medicinal plants. Because a large part of their land is wetlands, they are concerned about any rise in sea level. Another critical issue is water quality and quantity. The drinking-water source is off-reserve, and there is some concern about security of supply with growing development in the Richibucto area. In general, the community was very appreciative that it was being consulted; it wanted to participate in the socio-economic survey. From our point of view, the interest of the communities in participating in this project was very positive and should help better integrate information, traditional knowledge and social perception into ecological and physical assessment of potential impacts of climate change on the coast.

In the case of Bouctouche, communities were mostly concerned about a number of different social and economic factors that relate to their lifestyles, such as fishing/aquaculture, ecotourism and cultural tourism. There were some reactions and information that suggested that social considerations should be considered at the initial stage of the development of adaptation measures. For example, the participants observed, as trends in the community’s development, significant “change” events in the past and things that they are doing now in response to sea-level rise, coastal erosion and storm surge. For example, the aquaculture industry, while still in major developmental stages in the region, especially in Bouctouche, suffered tremendous losses during these same extreme weather events, and some individual aquaculturists have not received any financial support or relief. The damage costs from the storm surge and coastal erosion have caused substantial economic setback in the coastal communities of southeastern New Brunswick.

One aspect that is important if social considerations of climate change are integrated into climate-change impact and vulnerability assessment is that local people in communities have a wealth of information about their environment and, through their local knowledge, can help evaluate the main stressors that can not only affect the project but also raise more concerns and stress in the community. For example, it was clear in Bouctouche that in some areas, the stress of being close to the coast and more exposed to the climate-change impacts of sea-level rise, coastal erosion and storm surges, and having no other possibility than to adapt to the conditions, since economically it is not possible for them to move, pushes them to be more careful about the possibility of new construction projects in the same area. In some cases, they had to install sump-pumps to remove water from around their homes' foundations. These were intended to operate only at times of heavy rain, but now they work most of the time during high tide. Others have built coastal barriers to harden the coastline against wave action and protect their coastal property against the rising sea and effects of erosion, although this practice should in most cases be avoided. These barriers may last for a few years, but eventually they have observed that seawater will penetrate behind the wall, which will collapse and bring more of the land with it. On the other hand, they have seen some new elevated homes built along the coast (i.e., in-fill and a taller foundation) using a height buffer associated with the highest high tide recorded. Therefore, their knowledge about what is happening on the coast and in their community can be invaluable for climate-change consideration. It has been reported in other studies that local knowledge and the need to examine the local conditions are crucial when climate-change vulnerability is considered in the planning of sustainable development of a community (Adger, 2003).

4.9.3.1.4 Potential adaptation measures

The long-term viability of the tourism industry is certainly an issue of concern, and several factors can influence the outcomes of the decisions made by the community. Figure 6b describes the links between changes and the places where economic and social considerations will have to be integrated and examined in order to make decisions that can help sustain the community, especially regarding the tourism industry. Since a large part of the community relies directly or indirectly on this industry, any changes can affect their way of life. The results of these activities show that six categories of considerations have to be included in the development of adaptation measures:

1. visible and inexorable erosion;
2. aesthetics of the landscape (non-polluted, etc.);
3. uncertainty and seasonal variations;
4. resistance or resignation to extreme events;
5. changing economy and role of the new economy; and
6. government responsibility and the role of the community.

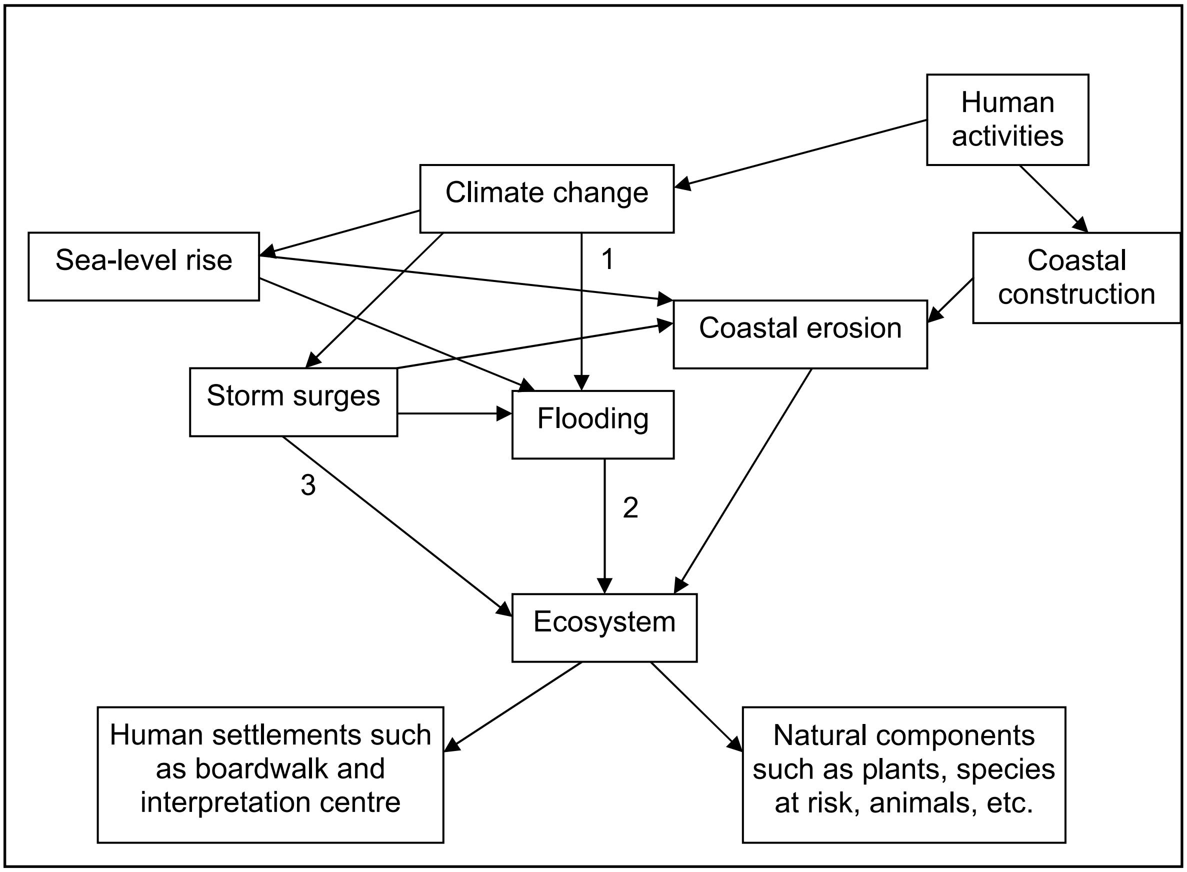

Figure 6a. Summarizing impacts of climate change on La Dune de Bouctouche: 1) Flooding as an impact of climate change through heavy rainfall or higher snow precipitation. 2) See Figure 6b for the detailed integrated impacts of flooding on La Dune de Bouctouche ecosystem. 3) See Figure 6c for the detailed integrated impacts of storm surges on La Dune de Bouctouche ecosystem.

Generally, communities such as Bouctouche and the stakeholders at La Dune de Bouctouche agree that there is a loss of habitat and that there is tremendous soil erosion, in addition to sea-level rise. In fact, the majority of the stakeholders consider that extreme events causing coastal erosion are not new, but it seems that these events are more frequent. In addition, communities such as Bouctouche (and, as seen below, Shediac) acknowledge that the shore and attraction to the coast (mainly beach and swimming), is a new economic phenomenon of the last 10–15 years. In many cases, the combined effect of tourism traffic and wave action increases the potential of coastal erosion.

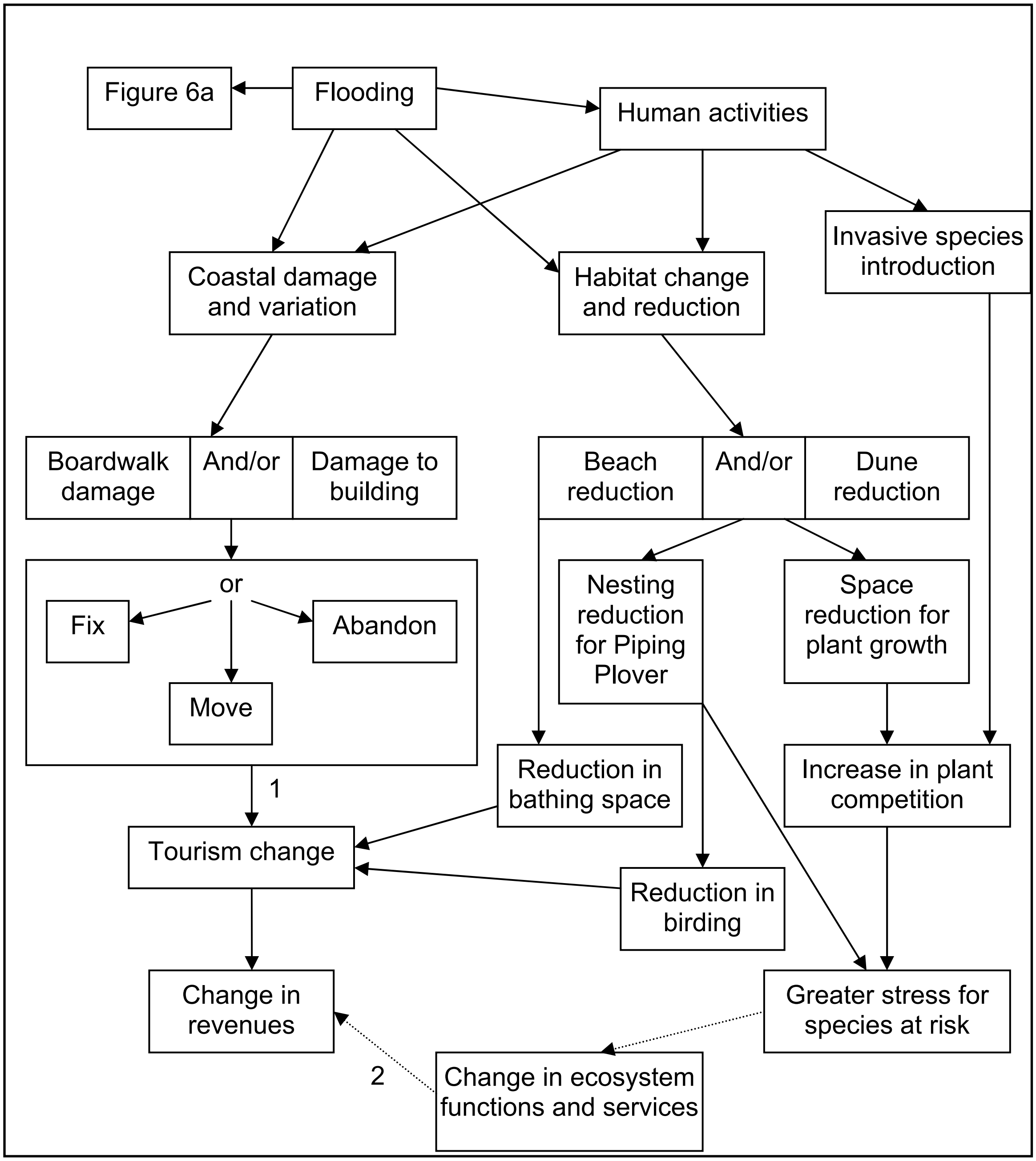

Figure 6b. Integration of the potential impacts from climate change and human activities on the ecosystem of La Dune de Bouctouche. The diagram explains the direct and indirect issues and considerations to take into account while evaluating impacts and possible responses to a development project from the point of view of sea-level rise. 1) Change in tourism can lead to fewer tourists and, as a result, fewer economic local activities, such as bed and breakfasts, restaurants, etc. Therefore, the main consequence would be a reduction in revenues for the community. Damage can lead to a less attractive site, less infrastructure and fewer attractions, etc. 2) Ultimately, as other studies (Costanza et al., 2000) have suggested that there could be changes in the ecosystem, with possible extirpation of species, changes in nutrient cycling, reduction in natural barriers, etc., there would be a change in the externalities and thus indirectly in the economic function of the ecosystem and its connected human community. In the case of the Irving

Eco-Centre, loss of Piping Plover leads to reduction of visitors for birding, leading to reduction of time spent in the community, such as in restaurants, bed and breakfasts, shops, etc.

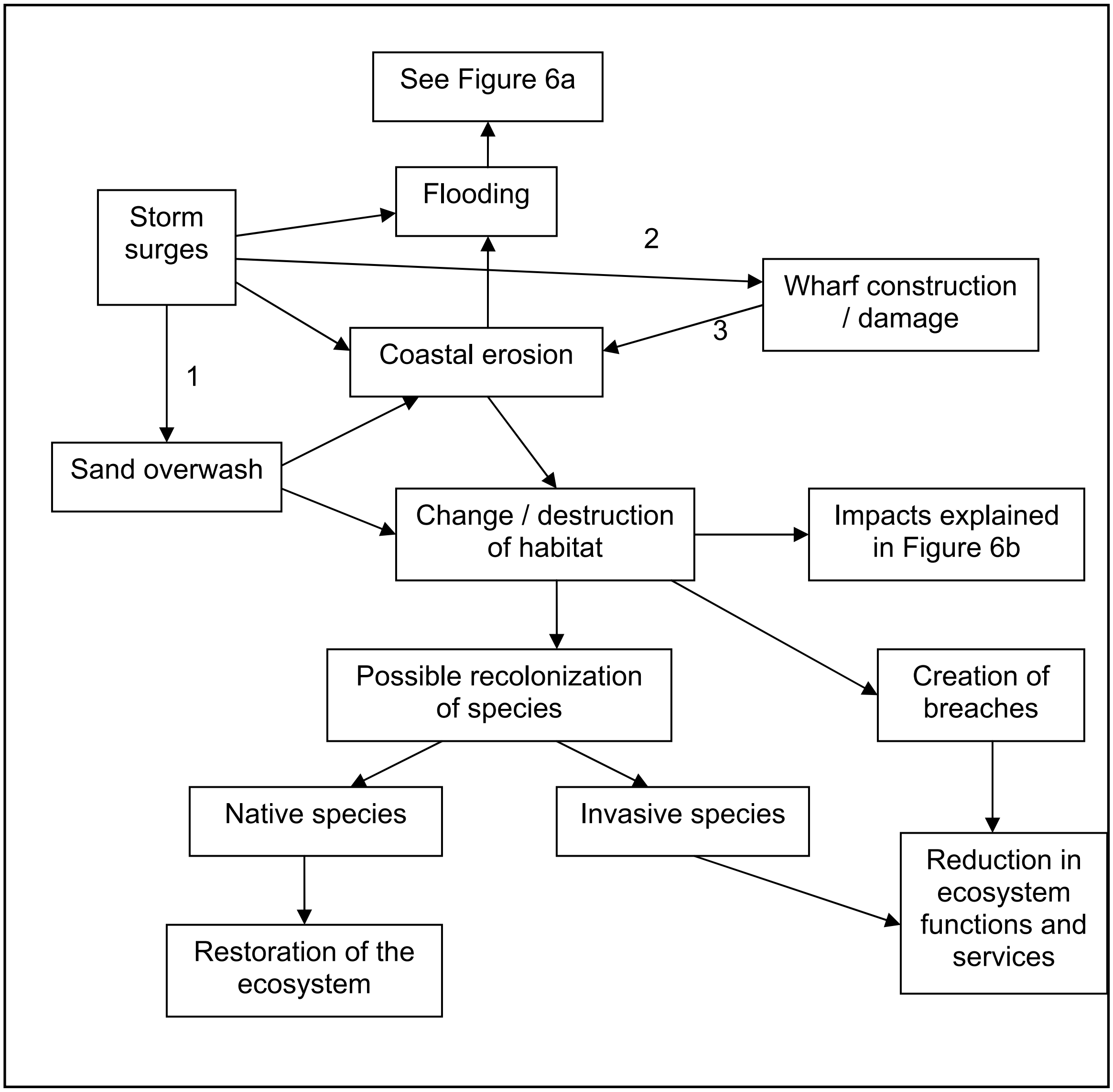

Figure 6c. Integration of the potential impacts from climate change and human activities on the ecosystem of La Dune de Bouctouche. The diagram explains the direct and indirect impacts and considerations to take into account from the storm-surge point of view. 1) The impacts of storm surges would lead to sand overwash, especially in the summertime. In the winter, the phenomenon might not be as important, but ice scars can also lead to similar consequences, such as greater coastal erosion and change in habitat. 2) Storm surges could cause damage to the Saint-Édouard-de-Kent wharf, leading to more sediments being carried towards La Dune de Bouctouche and thus reducing coastal erosion. 3) On the other hand, if the wharf sustains the storm and/or the wharf is immediately rebuilt, it is expected that coastal erosion would remain the same or increase due to instability in the system.

Adaptation measures should therefore include ways to maintain a sustainable level of economic activity that ultimately does not by itself impact heavily on the system. The analyses showed that the tourism industry will experience growth only if there is protection of the natural resources (as linkages clearly show in Figure 6c). The current results suggest that La Dune de Bouctouche will continue to erode. In this scenario, however, the southern tip of the dune could break off and become an island. It is possible that for Piping Plover, this detached section of dune could become a nesting habitat and would then be designated as a protected area, restricting human activity. In order to sustain its activities, the Irving Eco-Centre might have to invest in becoming a research and information facility and offer to tourists an environmental, educational and historical experience. Boat tours could be offered at the Eco-Centre to tourists who are interested in learning more about endangered species and the changing coast (G. Arsenault, 2003, pers. comm.). Other types of adaptation measures could include, for Bouctouche, sustainable-management practices for the local shellfish industry. This would enable them to provide tourists with a high-quality product to meet their demands. However, with growth in the tourism industry in the region, a community sewage-treatment facility might have to be built with the capacity to service the growing number of businesses and residential areas. Such a facility would also have to be built on higher ground, considering that the current lagoon of Bouctouche may become limited in terms of load and its location. Similarly, upgrades to hiking trails, Le Pays de la Sagouine and the small operators' settings would be needed to maintain the current level of economic activity coming from the tourism sector.

4.9.3.1.5 Evaluation of adaptive capacity and long-term conservation of the natural coastal ecosystem and of coastal tourism in Bouctouche

The main environmental impacts that can occur from climate change can be described as coastal erosion on the dune and along the coast, sea-level rise and, as a result, increased flooding. Most suggested adaptation measures relate to improved technology and change in location of some of the infrastructure. However, in a natural setting such as La Dune de Bouctouche, it is important to underline that most adaptive capacities will rely on the potential of the natural species not only to recover after an extreme event but also to compete, in the case of native plant species against incoming invasive species. These phenomena have already been observed at La Dune de Bouctouche in 2003–2004, with an increase in invasive species in the sand-deposit areas, and in 2005, in the populations of the Gulf of St. Lawrence aster. In this case, the Gulf of St. Lawrence aster is being displaced by a closely related introduced species from Western Canada, *Symphyotrichum ciliatum*. In fact, in this case, it is possible that the Gulf of St. Lawrence aster is already extirpated from its Bouctouche area, since the invasion occurred in only a year. Under such circumstances, it is difficult to expect that the current ecosystem will remain in its original form. The ecosystem will change to another type, which could include some of the original species, but also new species more adapted to current and future conditions. The present adaptive capacity is therefore not related to human activities and capabilities, but rather to the system itself (Figure 4 identifiers in the environmental factors).

In the present study, the adaptation measures for tourism infrastructure have been shown to be important in order to sustain the present economic activities of the community. They include the three components of avoidance, retreat and protection. Adaptive capacity for a community, as previously described, can be defined as a property of the system to deal with or respond to the changes due to climate change (Smit and Pilifosova, 2001). The Irving Eco-Centre and the Village of Bouctouche have injected into their economy some monies to be able to develop the entire current tourism infrastructure, and this has currently helped maintain economic activities of the region (Table 1). It has been shown, in the analysis of an optimistic scenario (with some adaptation measures), that the spending on tourism infrastructure by visitors will slightly increase, enabling the community to sustain its development. Under the pessimistic scenario, however, it is expected that tourism activities and spending will decline, leading to a reduction in sustainability of this industry in the community. The main factors that will influence the capacity of the community to adapt to climate-change impacts include their willingness to move Le Pays de la Sagouine and other infrastructures that are close to sea level from their current locations to higher ground. In the case of La Dune de Bouctouche and the Irving Eco-Centre, the continuous need to rebuild or fix the boardwalk when storm surges occur might be threatened by the increase in insurance rates to pay for damage and even the possibility, as has been seen in other coastal areas of New Brunswick, that some insurance companies will refuse to pay for damage due to flooding, storm surges and coastal erosion.

Table 1. Estimated spending in 2004 (baseline spending), optimistic-scenario spending and pessimistic-scenario spending at Bouctouche, New Brunswick, with standard deviations (SD). All values are rounded to the nearest hundred.

Sector	Baseline spending (± SD)	Optimistic-scenario spending (± SD)	Pessimistic-scenario spending (± SD)
Hotels, motels, inns, bed & breakfasts	$5,228,000 ± 13,012,200	$5,814,100 ± 5,851,000	$3,041,700 ± 3,182,700
Campgrounds	$864,000 ± 2,266,800	$1,420,700 ± 1,429,700	$589,900 ± 617,200
Arts, entertainment, & recreation	$1,865,000 ± 256,100	$3,578,421 ± 238,300	$2,493,529 ± 254,200
Food stores	$2,295,800 ± 2,897,100	$2,581,800 ± 3,783,900	$1,672,400 ± 3,026,200
Retail trade	$4,234,900 ± 5,548,200	$4,762,400 ± 8,669,000	$3,762,100 ± 6,930,200
Restaurants	$10,093,300 ± 11,779,700	$11,350,800 ± 19,525,800	$7,621,600 ± 13,295,000
Gas stations	$6,294,300 ± 8,568,900	$7,078,400 ± 13,148,400	$5,591,600 ± 10,506,100

It is possible to integrate the current analysis for the various sectors that are important in the economy of Bouctouche in such a way that the most important sectors for which adaptation measures should be developed are targeted. The approach used in the present study is similar to the analysis completed in Australia by Allen Consulting Group (2005), in which a risk-management approach was used to evaluate the different sectors of the economy of Australia. The difference here is that the analysis is completed at the local level and the input is limited to the sectors that are linked to the main economic activity (i.e., tourism). The criteria that are used to determine the priority in terms of need for adaptation measures are the exposure of the sector to climate-change impacts, the sensitivity of the sector to climate-change impacts (both factors leading to vulnerability of the sector), the adaptive capacity and the potential for the sector to benefit from climate change. For all but the last criterion, a low value means that the sector is, for example, not sensitive to climate-change impacts. This can be due to the fact that the infrastructure is not in close proximity to possible changes or the infrastructure is strong enough to withstand any impact. Potential benefits of climate change can occur when changes lead to improved conditions or alternative economic activities. For example, long summer seasons can lead to an increased length of the camping season. In Table 2, the integration of the current information is described in order to evaluate the priorities for the sectors of the community of Bouctouche. The two main priority sectors are 1) hotels, motels, inns and bed and breakfasts and 2) arts, entertainment and recreation, mainly due to their proximity to the shore. In both sectors, the main challenges would be the impossibility of relocation if sea-level rise becomes too important due to high costs, limited drinking water for places that are on wells and infrastructure damage during extreme events. On the other hand, since most gas stations and food retailers are located farther inland and constructed of different materials, it is not expected that climate change will have as much of an impact as would be expected for housing and recreation. Considering all these factors, we can conclude that for Bouctouche, infrastructure such as the Irving Eco-Centre, Le Pays de la Sagouine as well as some of the hotels and bed and breakfasts would have to become the main priorities for the community to ensure their adaptation to climate change. In most cases, it is expected that relocation would be needed as a means of adaptation. While a retaining wall and other construction may help in the short term for some of the settlements (mainly houses and bed and breakfasts), in the long term, other issues, such as flooding and drinking-water limitation, would add to the current stressed system.

Table 2. Estimation of priority and integration of vulnerability and adaptive capacity for the various tourism sectors of Bouctouche.

Criteria	Sector						
	Hotels, motels, inns, bed & breakfasts	Campgrounds	Arts, entertainment, & recreation	Food stores	Retail trade	Restaurants	Gas stations
Exposure	Low to High	Medium	High	Low	Low	Low	Low
Sensitivity	Low	Low	High	Low	Low	Low	Low
Adaptive capacity	Medium to high	High	Low to medium	High	Medium to high	Medium to high	Low
Potential to benefit	Low	Low to medium	Low	Low	Low	Low	Low to medium
Overall priority	Medium to high	Low	Medium to high	Low	Low	Low	Low

4.9.3.2 Case study of Shediac/Pointe-du-Chêne

4.9.3.2.1 Types of impacts related to climate change

The community of Pointe-du-Chêne covers an area of 609 413 m^2 and has slightly increased in size over the past 30 years (Figure 7) to reach 715 678 m^2, an increase of 14%. This component of the region of Shediac was analyzed in the present chapter as an illustration of a coastal suburban community where housing development is the main economic driving force. The present information was overlapped with the cadastral map and included 659 land properties (of different types such as individual houses, commercial installations, etc.) (Figure 8). The main types of impact from the climate-change scenarios for this community include damage from extreme events and mainly flooding. Figure 9 illustrates the land that was flooded during the January 2000 storm surge. The overlapping of the DEM data with the scenario of a storm surge like the one of January 2000 (level of 2.55 m above DEM reference) shows that several spatial polygons of Pointe-du-Chêne were flooded with water levels varying from 0.01 to 6.35 m. The categories of water depth from flooding are described in Table 3. From the results, it is possible to see that the first two categories include 75% of the land, which would be flooded under 0.5–1.0 m of water. Approximately 4% would be located in zones with more than 2.0 m of water. This was mainly observed in January 2000 in close proximity to the Pointe-du-Chêne wharf. Figure 7 illustrates the regions where flooding would occur. The variation in flood levels is mainly due to the topography of the region and the point of water infiltration such as streams. In terms of houses and other buildings being affected by the flood caused by a storm surge similar to that of January 2000, on 348 properties that were flooded (not including the wharf and the roads), most were in 1 and 2. Very few were exposed to category of 4 (Figure 9, Table 4).

Table 3. Categories of water depth during flooding periods in Pointe-du Chêne caused by a storm surge similar to the storm of January 2000.

Flood Class	Water level of flood(m)	Surface area (m^2)	%
1	0–0.5	122 313	37
2	>0.5–1.0	127 125	38
3	>1.0–1.5	45 082	13
4	>1.5–2.0	26 486	8
5	>2.0	13 247	4
Total		334 253	100

Table 4. Number of properties that would be flooded under the various categories of water depth in the region of Pointe-du Chêne caused by a storm surge similar to the storm of January 2000.

Flood Class	Level of flood (m)	Number of properties affected
1	0–0.5	218
2	>0.5–1.0	109
3	>1.0–1.5	20
4	>1.5–2.0	1
Total		348

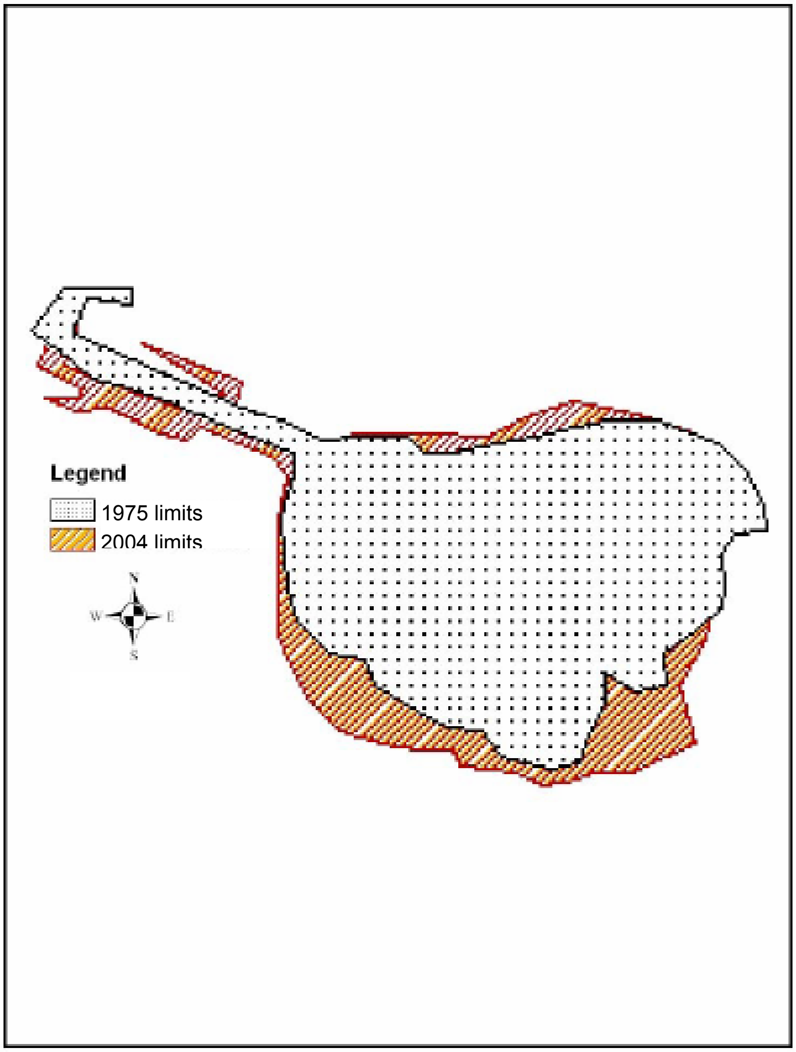

Figure 7. Comparison of the limits of Poine-du-Chêne between 1975 and 2004 (integrated into GIS map (ArcGIS).

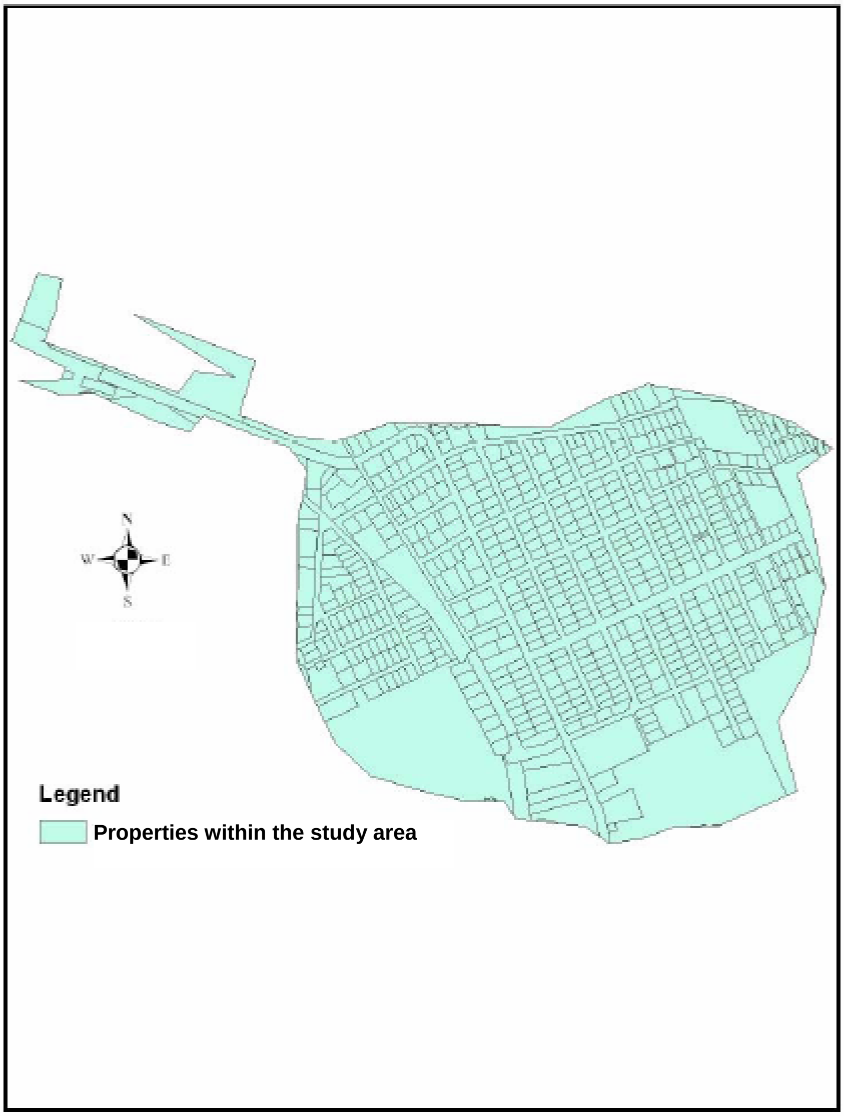

Figure 8. Cadastral land properties extracted from provincial and municipal maps for Pointe-du-Chêne and integrated into GIS map (ArcGIS).

Since the community of Pointe-du-Chêne is mostly residential and suburban, the damage can be quite significant for taxpayers and homeowners. In the economic analysis component of this report (Section 4.7), it was reported that for the January 2000 storm, there were 198 damage claims submitted to the New Brunswick Emergency Measures Organization, 43 of which were eligible for funding totalling close to $1.5M. On October 29, 2000, another extreme storm-surge event impacted the southeastern coast of New Brunswick, resulting in close to 459 damage claims, of which 159 were eligible for funding and totalled close to $1.3M. Considering the increase in housing-development projects along the coast in these communities and the construction of larger and more expensive houses, it is expected that the costs could increase in a significant manner.

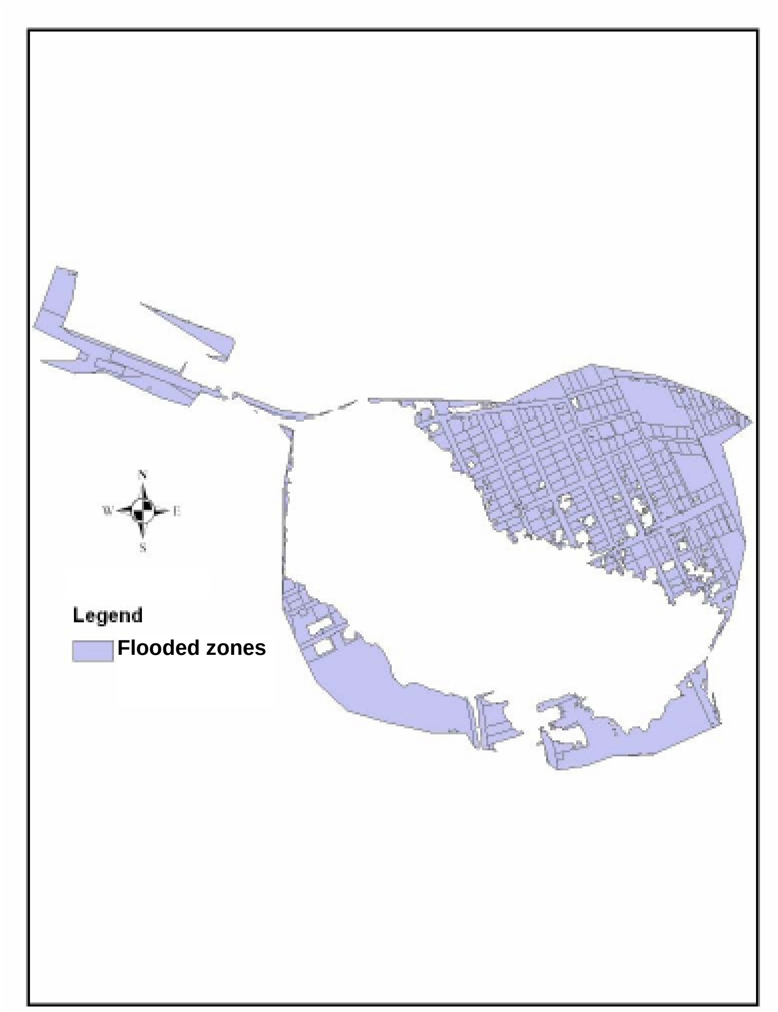

Figure 9. Surface areas in Pointe-du-Chêne that were flooded by the January 2000 storm surge of 2.55 m above DEM datum. This area represents 348 land properties.

4.9.3.2.2 Vulnerability zones and assessment from biophysical to socio-economic factors

Most of the community participants in this study were concerned about the sustainability of new coastal development projects. The main reason is that while historically they were used to and reported relocating homes, cottages, roads and other infrastructure because of the rising sea level or coastal erosion, it is unclear how this could be done with larger and more expensive houses. Yet other interviewees reported seeing little change in the coast over the years. Some of those who experienced the two record storms in 2000 felt that those were "once in a lifetime" events and that there is no need to worry about such events in the future. Participants explained that during the January and October 2000 storms, the wharves, fishing equipment, boardwalks and other coastal infrastructure were damaged and/or lost. Some of the damage was insurable, while much was not. Some wharves that suffered damage were unrepairable because small communities lack funding to pay for upgrades. There was a real sense that if the socio-economic situation of the community is not taken into consideration during the initial stages of any new projects, under the current trends with climate change, the pressure on the community could increase to a level that would be far from sustainable. Also, community members expressed concern for the future of their remaining wharf infrastructure and the impacts of coastal erosion and changes in ocean temperature on the ground fisheries.

If a risk-management analysis is considered, in which the number of affected land properties divided by the original number of land properties that could be affected is calculated, using the numbers from the previous situation of the January 2000 storm, the coefficient of risk would equal 0.53 (i.e., more than half of the properties being damaged or impacted by storm surge). While this risk value is a simplified coefficient of the flooded area, it allows evaluation of the importance of the situation in a relatively rapid manner. In terms of the number of family members affected, according to Statistics Canada (2001), this impact would translate into 1044 family members being affected by such a storm. Considering the data acquired during this project and the climate trends, including sea-level rise, etc., the level of vulnerability of the various coastal human infrastructures is relatively high, especially compared with the more natural ecosystem of Bouctouche (Table 5). The variation in the levels of adaptive capacity and vulnerability is mainly related to the type of scenario preferred by the community (pessimistic versus optimistic) and the type of decision-making and planning the municipalities will consider in the near future. Adaptive strategies such as the conversion of some of the potential development lands along the coast into protected areas would help in the next 30–80 years to buffer the impacts due to sea-level rise and thus help the community prepare for further adaptation strategies.

Table 5. Estimation of priority and integration of vulnerability and adaptive capacity for the various housing development and tourism sectors of Pointe-du-Chêne and Shediac. It is important to note that the analysis here includes the coastal component of the community, rather than the inland areas of the community. The main reason is that most current pressure for housing development and tourism is located within the coastal zone.

	Sector				
Criteria	Hotels, motels, inns, bed & breakfasts	Wharf	Restaurants, entertainment, & recreation (mainly beaches)	Food and retail stores	Housing development
Exposure	Medium to High	Medium to high	High	Low to medium	Low to high
Sensitivity	Medium	High	High	Low	Medium to high
Adaptive capacity	Low[1] to high[2]	Low[1] to high[2]	Low[1] to medium[2]	High[2]	Low to medium
Potential to benefit	Low	Low to medium	Low	Low	Low
Overall priority	Medium to high	Medium to high	Medium to high	Low	Medium to high

[1] If the pessimistic scenario is considered in which the strategies remain business-as-usual and protection using physical barriers.

[2] If the optimistic scenario is considered in which avoidance and retreat are the main strategies.

4.9.3.2.3 Data integration from impacts to adaptations

The linkage between socio-economic considerations and ecosystem changes suggests several significant impacts on the community of Pointe-du-Chêne and Shediac, especially if decision-makers and developers continue with a "business-as-usual" scenario (referred to as the pessimistic scenario in Section 4.7). The present results show clearly that zones in natural ecosystems and communities will be affected by floods and sea-level rise along the coast of southeastern New Brunswick. Diverse outcomes occurred at the integration of the results from the climate-change scenarios and analysis of impacts when presented and discussed with stakeholders. It was observed that, depending on the origin of the people involved in a project, the perceptions and reactions would greatly change. For example, in Shediac/Pointe-du-Chêne, most local people and decision-makers felt that it was important to adapt the planning process and integrate these potential impacts. In their case, this has led to change in zoning along the coast. Most of these stakeholders have grown up in the region and have had to deal with storms and changes over time, and they understand very well the dilemma regarding climate change and protection of their assets. Their socio-economic status probably influences their reactions, as damage can be costly and not always completely covered by insurance and governments. This might even be more important, as the province is on the verge of passing legislation for coastal-zone protection. However, from this study, it was also clear that people coming from other regions or who had never dealt with damage from storms or flooding are not necessarily reacting the same way. In many cases, since it is their land, they believe that they have the right to build close to the coast. The level of education does not influence the decision, but rather the level of income (or wealth) and the lack of traditional knowledge of the potential impacts of storm, coastal erosion and sea-level rise on their properties may have considerable influence on whether or not a project would go ahead or would be modified to prevent damage.

As described in Figures 10a and 10b, the complexity of the impacts and their interactions with other socio-economic activities should be considered while examining possible adaptation strategies. Integration of social considerations should not be taken as a separate component of this integrative view of the community. The possible climate-change impacts and adaptation responses that are available to the community have to be considered in terms of economic consequences in the short and long terms. For example, beach enrichment (Figure 10b) may be looked at as a current response to coastal erosion to maintain tourism in the community; in the long term, however, this would not be acceptable once sea-level rise is also integrated into the projections. Housing development along the coast would have to be planned in relation to the trends in sea-level rise and possible storm surges. In the short term, protection with physical barriers and reparations of the damage after a storm might be feasible. It might not be considered a current economic burden for the community, insurance companies and provincial government. However, it is expected that with greater risks of flooding and damage, other adaptation strategies, although more expensive and dramatic in terms of social changes, would be crucial. Changes will be triggered over the years by various incentives, including planning, insurance coverage, governmental policies and physical damage. How many times can a person rebuild? Figure 10b illustrates some of the possible outcomes from the decisions made by people in communities. While in some cases, as demonstrated above, short-term changes can lead to negative impacts, other decisions, such as protection of the wharf against sea-level rise and storm surge, can lead to a positive change in fisheries activities (Figure 10b).

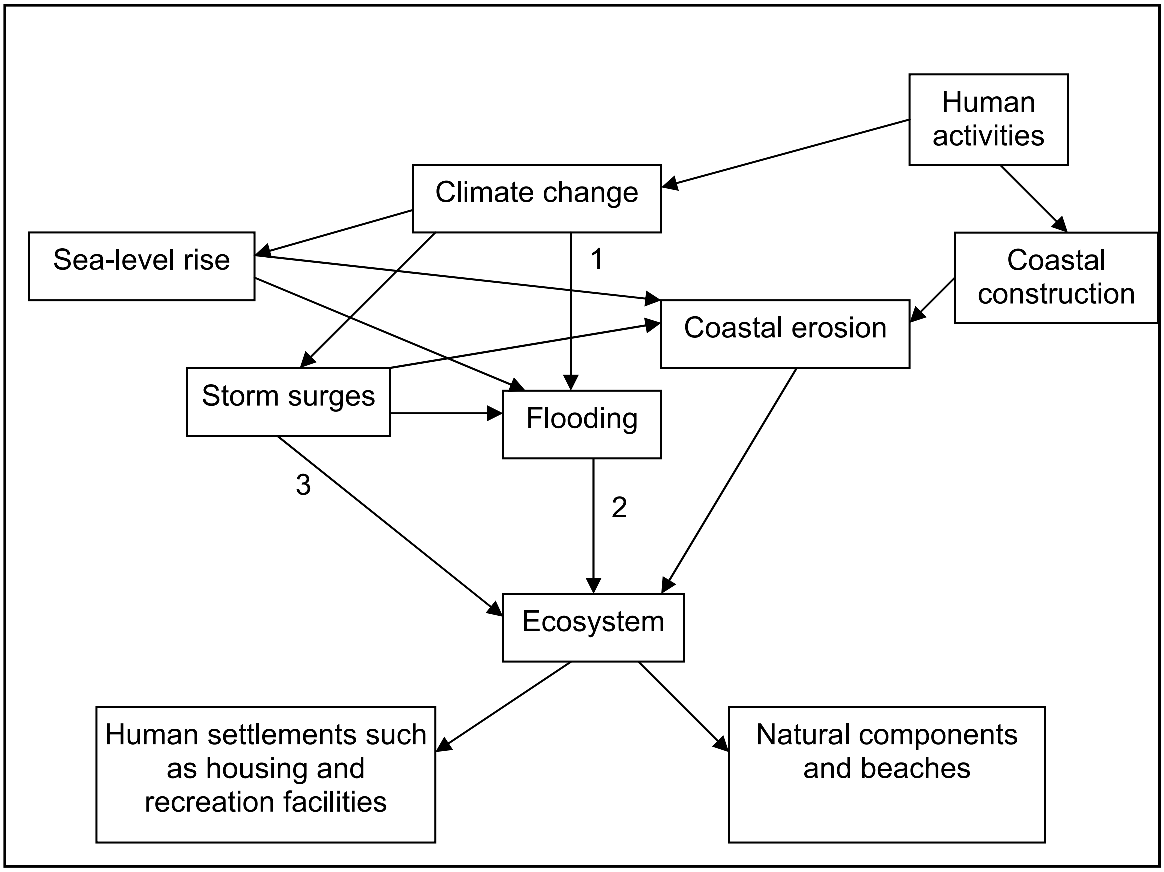

Figure 10a. Summarizing impacts of climate-change scenarios on the community of Pointe-du-Chêne/Shediac. 1) Flooding as an impact of climate change through heavy rainfall or higher snow precipitation. 2) and 3) See Figure 10b for the detailed integrated impacts of flooding and storm surges on this coastal community.

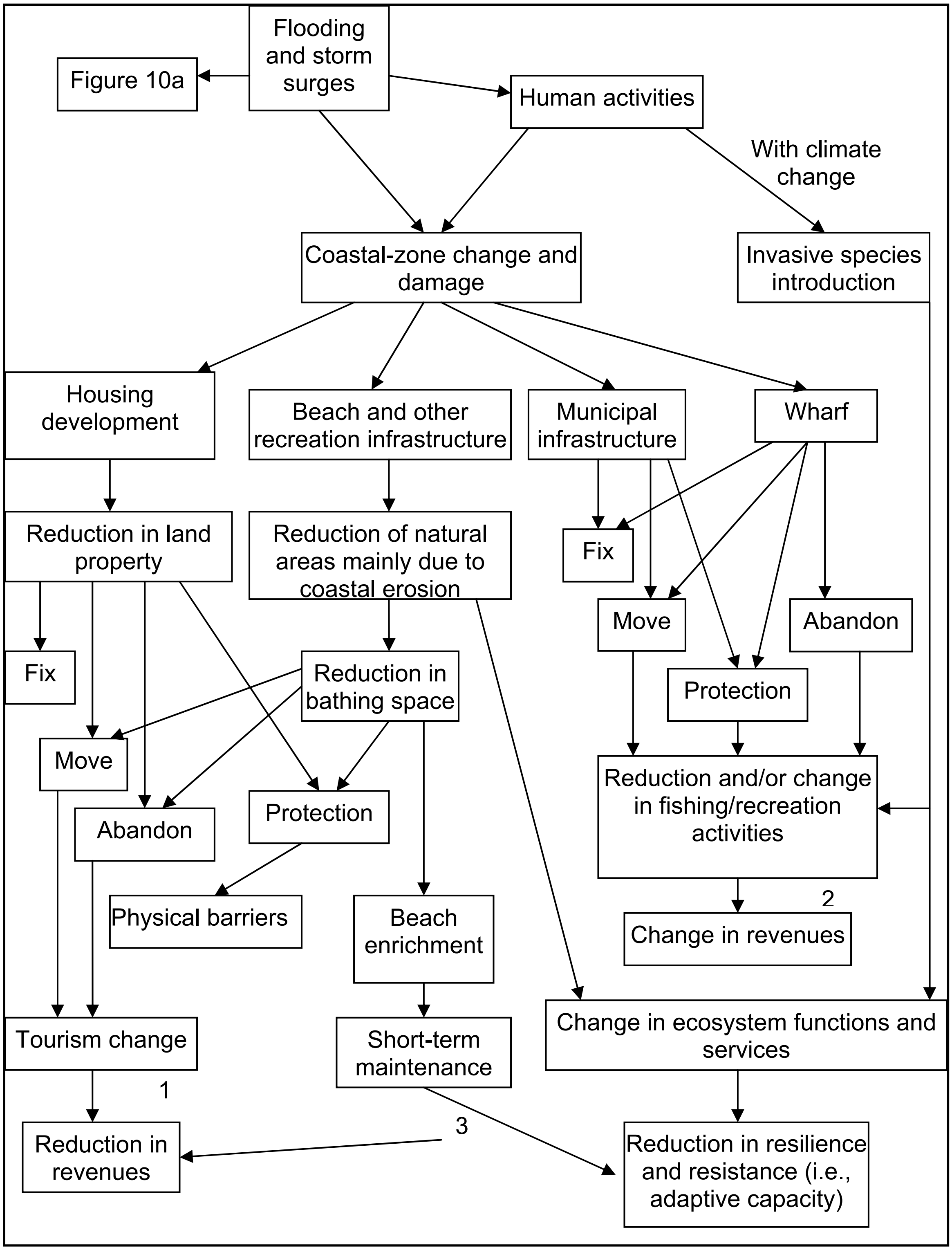

Figure 10b. Integration of the potential impacts and adaptation strategies for human activities in response to climate change in the Pointe-du-Chêne/Shediac area. The diagram explains the direct and indirect issues and considerations to take into account while evaluating impacts and possible

responses to a development project from the point of view of sea-level rise and storm surges. 1) Change in tourism areas such as beaches and recreation infrastructure can lead to fewer tourists and, as a result, to fewer economic local activities such as bed and breakfasts, restaurants, etc. and to a reduction in revenues for the community. Damage can lead to less attractive sites, fewer infrastructure and attractions, etc. 2) Damage to wharf and other municipal infrastructures would lead to a reduction of services. Depending on the type of adaptation strategies adopted, changes could bring reduction or change in fishing activities, for example. 3) The figure should be examined in function of the time scale being considered. For example, beach enrichment is a current short-term maintenance strategy that has been used to maintain tourism in the region. However, it is clear that this has potential important impacts on the resilience and resistance — i.e., the level of vulnerability and adaptive capacity of the ecosystem. In the long term, this may not be the best adaptive option for the community, leading to revenue loss, etc.

4.9.3.3 Potential adaptation measures and environmental impact assessment

In this study, communities have discussed at length the changes that have occurred over time in the coastal ecosystem and have mentioned the loss of natural protection features such as dunes, marshes and wharves (often damaged or destroyed during storms). These impacts were recorded in the past, as climate has been changing naturally. Over the past few decades, however, impacts have been recorded in larger numbers for two reasons: climate-change impacts are more evident, and coastal zones are under greater pressure due to human development. Such issues have led to additional considerations that were not examined in this study, such as the problem of freshwater availability and change in pollution patterns exemplified due to the proliferation of cottages and permanent houses on the coastline. There are uncertainties and scepticism regarding the real causes for these changes, and stakeholders often believe that they need more data for predicting and anticipating effects and finally making decisions.

Until recently, lack of understanding of the impacts and limited integration of communities and climate-change issues into discussions on development projects and planning has led to wrongdoing and pressures on the coastal regions and thus greater vulnerability to climate change. Under climate-change impacts and mainly due to lack of understanding and tools to assess impacts, the first reflex of respondents is to resist and then repair the damage. They are afraid to lose their projects, attractions or houses. While this might be a normal reaction, it does not preclude the fact that eventually, over a longer period of time, impacts of climate change will increase and lead to greater vulnerability of the community unless adaptive capacity is enhanced.

For most communities, moving from a current planning and decision-making framework to a more adaptive management system is demanding. Most communities feel that there is a need to better link community solidarity, cooperation, mutual aid and support services with the governmental assistance to address effects of climate change and extreme events. For developers and decision-makers, it is a question of having better integrated tools such as participative decision-making models or integrated EIA with climate-change considerations, in order to improve long-term sustainability and adaptive capacity of the community.

4.9.3.3.1 Environmental impact assessment (EIA) as a way to enhance adaptive capacity

Climate change remains a difficult concept for most citizens to grasp. This is true not only for the general public, but also for developers, decision-makers and the industry. There are many reasons that people surveyed in this study considered it difficult to think about long-term change and the amplitude of these changes (some being slowly happening, while others having a rapid catastrophic effect). In EIA, while most consultants may integrate climate change, there are some limitations in the effectiveness of this integration. As reported in Lee (2001), translating scenarios and potential impacts to people remains difficult, and it is often easier for EIA practitioners and project developers to examine historical data than to work on climate and ecosystem trends. Most projections used are based on short-term or historical data with a constant rate of return for storms that, however, have changed over the past decade. It is, therefore, not surprising that most projects requiring EIA do not include climate-change impacts and adaptation. The long-term vision of a project should already in part be considered using cumulative analysis; however, due to lack of time, funding and/or knowledge, climate change is often omitted or limited to vague possibilities. It is also not surprising at this point to conclude that social and long-term considerations of climate change and its adaptation are not being considered, as this step would require greater understanding and public consultation. As described in this study, the integration of social considerations with the biophysical components demands that the project developer and the assessor not only understand and integrate impacts of climate change into the assessment, but also ensure that the community where the project is planned understands these same issues and can contribute through discussions, interviews, surveys or roundtables to the balance between economic gains and ecosystem and community impacts.

The need for guiding principles and protocols for climate-change assessment and the inclusion of social considerations is great among EIA practitioners. Bell et al. (2002) recommended guiding principles for the integration of climate change into the EIA process. The guidelines go from evaluating the need to consider climate change to risk evaluation and assessment of potential impacts in terms of the available climate-change scenarios for the region. Integrating social considerations could be added to these guidelines in different ways. Figure 11 describes the typical phases of an EIA and includes the different components that could be integrated to better consider social perceptions and reactions of communities as well as climate-change impacts into project development. Considering the results obtained in the present study, it might be important to stress to all decision-makers and developers the importance of having public meetings before even submitting a project. This means that from the first step of planning and decision-making regarding a project (#1 in Figure 11), public consultation and understanding of their concerns may be the best approach. This should be done not uniquely for climate change but for other aspects that could influence the sustainability of the project and its impacts on the environment. However, such a first step can help improve the level of adaptive capacity of the community.

During the usual public consultation session in the scoping/identification/definition of potential environmental components, if climate change is to be considered, social considerations should also be included. The main issues here would be to first evaluate the level of understanding and the perceptions of what could be the impacts of climate change on the region where the project is planned (#2 in Figure 11). Since it is most likely that climate-change impacts can lead to problems with the planning of the project, the next steps, such as cumulative effects, mitigation and monitoring, would also have to consider climate change and the community's capacity to respond to impacts (#3 and #4 in Figure 11).

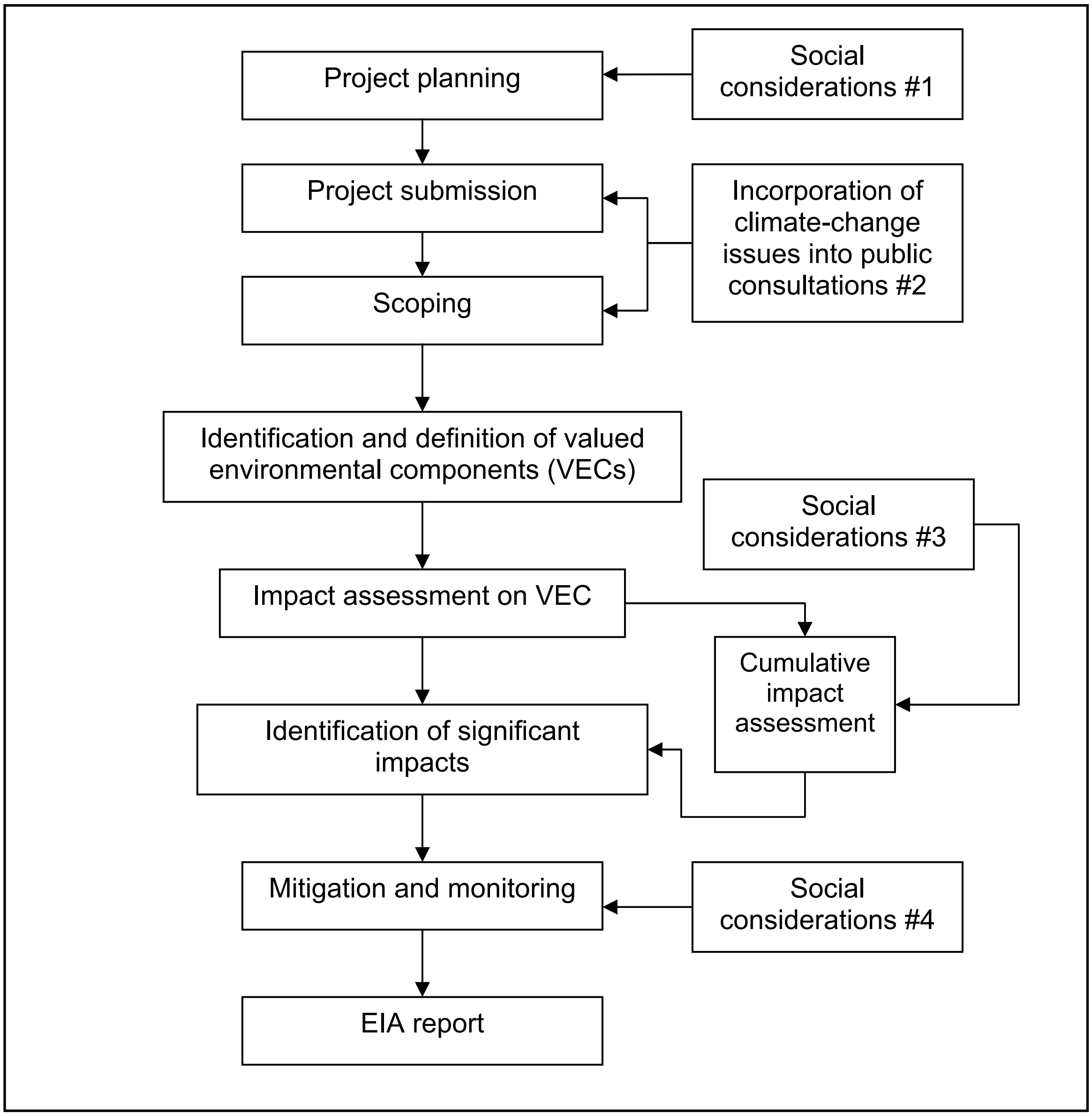

Figure 11. Integration of some social and climate-change considerations into a typical environmental impact assessment (EIA) process. The main issue is to enhance adaptive capacity and reduce vulnerability of new development projects in coastal communities.

These steps could be facilitated if the various stakeholders have been involved since the planning of the project. As previously mentioned, people who have lived for several years in a region have a better understanding of past changes. They are usually better prepared to adapt to changes. For example, in this study, older local citizens remarked that in previous centuries, if not decades, new families established their houses at the end of the field far from the coast to avoid storms, flooding and coastal erosion (a minimum of 200–300 m from the shore). Such knowledge can be useful in designing new strategies or ways to reduce problems related to climate change. At this step, local traditional knowledge could be of great value.

Social considerations are, however, demanding and have been reduced to a minimum level in most projects due to time and cost constraints. There are several levels of public participation in the decision-making process (Hance et al., 1990). Certain types of public consultation merely show the environmentally sound intentions of the project developers, but they do not usually consider public concerns in a meaningful way. At another extreme level, they may have to consult the population at each step of the process. In this case, the population has received the proper information and all the alternatives available to consider the project and the impacts that climate change could have on it. This type of public participation is more likely to be costly and may be a very slow process. It is especially not adequate for solving an immediate problem. The main challenge is in defining an approach in which decision-making and sustainable actions are well balanced. In addition, it is essential to define what the community's stake is. It is clear that different projects may require different levels of social consideration. In this line of thought, it might be efficient to integrate the current results into the guidelines and approach already used by Bell et al. (2002).

Although climate change is global, it is at the local level where environmental (mitigation and adaptation) measures will have to occur. Biophysical systems, including natural environmental services and resources, will have to change or adapt, causing indirect and direct impacts on society. Climatic conditions will directly affect the social, cultural and economic responses and potential capacity of human populations (Mendis et al., 2003) to deal with climatic influences on new development projects. Therefore, full integration of socio-economic considerations with biophysical impacts in assessing projects is a necessary ingredient if measures are to be developed at the local scale. Stepping from the current preoccupation with impact discussions into the social assessment sphere has been a serious challenge. This limitation rests partly on the fact that although social and cultural considerations should be integrated into scenarios, most data and actions remain superficial. Climate-change research case studies are numerous in Canada (e.g., Cohen, 1994, 1995; Etkin, 2001; Riedlinger, 2001; Berkes et al., 2002); however, at many conferences and workshops, participants have noted that we must move from impact research to developing a community's ability to deal with new projects and their integration into their lives for long periods of time in which climate change will have important impacts.

4.9.3.3.2 Adaptation: time and financial considerations

The current analysis has targeted different periods from 2020 to 2100. This approach is very common in most climate-change studies, and national assessment has its limitations. It would be a mistake for communities to believe that after 2100, issues regarding climate change are going to disappear. To the contrary, it is expected, even under a moderate scenario, that beyond 2100, impacts will be experienced at a greater scale. While the current adaptation strategies considered in this study are important and could demand a high level of human and financial commitment, one can imagine that in the longer term, for coastal communities, major economic issues will come up. Are our coastal communities at the present time sustainable in the future? This is a question that needs to be seriously considered by planners, developers and decision-makers. The short financial gain views of most developers and planners do not favour the possibility of continuously enhancing the capacity of communities to adapt to climate change. Costing adaptation options is much broader than estimating the capital costs associated with the short-term option; additional costs, such as social, environmental and other economic costs, must also be considered. In addition, the benefits of the proposed options should also be considered and factored into a decision-making framework. Section 4.8 of this study discusses in more detail some costs and benefits that should be considered when deciding on an adaptation strategy.

Figures 6 and 10 of this section suggest that many options are available to communities. Such figures, however, do not deal with issues such as time scale, people's interests and financial or regulatory limitations that communities have to face. While the diagrams show a linear model, it is important to note that the figures should be considered iterative; depending on the impacts that occurred, a new cycle of analytical iterations should be initiated in which some of the adaptation strategies might be favoured over others. For example, at La Dune de Bouctouche, it was decided in 2005 to rebuild the boardwalk but to change its location as the best strategy to adapt to more frequent storm surges (were climate-change impacts considered in the EIA, if any was done?). This approach is financially feasible under the current conditions in which insurance companies compensate, and the ecosystem seems stable enough to absorb this infrastructure. However, it is not obvious that in 20 years from now, rebuilding would be an option. It is therefore already important to consider the types of adaptation strategies that can be implemented in the long term for such systems.

4.9.3.3.3 Integration with the New Brunswick Coastal Areas Protection Policy

In the past decade, the Province of New Brunswick has been developing a Coastal Areas Protection Policy. The rationale for this policy was the protection of more than 5500 km of coastline for the benefit of 60% of the population of New Brunswick who live in coastal communities. The economic sectors that maintain these communities are resources based, including fisheries and aquaculture as well as tourism. The provincial government acknowledges that there has been a greater pressure in the past decade for development in coastal areas, threatening the survival of natural ecosystems where many native species, including species at risk, are distributed. In addition, with greater knowledge regarding salt marshes and other coastal ecosystem components, it is clear that their protection is essential for their resilience and the capacity of communities to maintain sustainability over time. The policy includes two zones for the protection of the coastal areas. Zone A represents the areas that are closest to the water (core area). Zone B consists of a 30-m buffer area that is located adjacent to Zone A.

The term climate change is mentioned in the rationale for the policy, but its integration is relatively weak. The present study can greatly contribute to the discussion on the integration of climate-change scenarios, impacts and future adaptation strategies that the provincial government will have to consider in order to enhance the policy.

From the results presented in this study, it is clear that the 30-m buffer area will be insufficient for the protection of natural ecosystems such as salt marshes and dune systems unless the zones can move in terms of the line of sea level, not as the basis defined in the policy in the early 2000s. According to the present study, it is suggested that for some areas, the policy would have to be modified to incorporate the phenomenon, which is more predominant on the southeastern than on the northeastern coast of New Brunswick. It is therefore recommended that the policy and the zoning be re-examined in relation to these new results. Further discussion should be initiated in order to define what type of adaptive strategies could be used with the change in the zoning. While, in some regions, retreat can be possible due to low levels of development (but the burden of the costs of the retreat will need to be established), in other cases, retreat or accommodation might not be possible, and other adaptations will have to be developed to ensure equitable long-term solutions. The importance of the integration of community consultation, the EIA process, which itself includes climate-change impacts, and adaptations with the use of the policy should help balance the approaches to be developed in the future.

It is now well established from this study that in responding to climate change, business as usual is insufficient and that social risk has to be integrated into development projects in order to avoid socio-economic problems over the medium and long terms. Similarly, business as usual for the policy would not help protect natural ecosystems in the long term. Uncertain and long-term projections of climate change should not restrict the possibility to address potential environmental impacts. Methodologies such as EIA, which allow integration of ecosystem data and climate-change scenarios at the community scale, can help reduce such challenges and improve the possible mitigation of impacts and commitment to monitoring strategies over years, if a given project is approved.

4.9.4 Summary and conclusions

4.9.4.1 Summary of the findings and common trends for these case studies

The coastal area selected for this study offered various examples, from ecotourism to suburban development, of community activities that will be affected by climate change. The integration of the human dimension from the social and economic risk perspectives into environmental assessment might help planners and decision-makers in those communities to deal with future projects. Few projects have integrated these aspects within a high-precision GIS in the past. However, as shown here, such an approach can lead to greater understanding of the linkages between various components of the ecosystem and the human communities. The main advantage of such an approach is to bring recommendations regarding ways to enhance the adaptive capacity of communities and to reduce vulnerabilities to climate change through suggested tools such as EIAs and strategies such as protection, accommodation and retreat.

One of the main reasons often cited for the limited inclusion of climate-change impacts and adaptations into a community planning and decision-making process is the lack of methodologies and clear directions on how to integrate such parameters into the planning process. Most communities do not completely understand the issues regarding climate change and the potential impacts they may face. Among the possible tools that can help communities, the EIA process should ensure that climate-change considerations are included prior to any new development projects being started. Similarly, discussion should occur regarding the need to enhance the flexibility and the adaptive management of the New Brunswick Coastal Areas Protection Policy in order to adaptively respond to climate-change impacts.

Adaptive capacity is linked to the potential actions that communities can initiate to help promote sustainable development. Some components of the ecosystem can be controlled and managed; for other components, control of the impacts is not possible, and communities must adapt to change. In addition, climate-change impacts are complex in the way in which they can influence, either directly or indirectly, some components of the ecosystem. In this project, the level of vulnerability varied greatly as a function of the location, exposure, adaptive capacity and resilience of the infrastructure. For La Dune de Bouctouche and the Village of Bouctouche, tourism along the coast is certainly more at risk than many other socio-economic activities of the region, such as agriculture. On the other hand, the results from Pointe-du-Chêne showed that human infrastructure (e.g., housing and wharves) is more vulnerable due to the greater pressure that human development projects have exerted over the past decade. The need for better planning in this case is greater, since more socio-economic activities may be threatened by climate-change impacts in the near future.

One conclusion that can be drawn from this research project is that without relevant information, adaptation policies and planning may not be fully effective. This applies to information on changes in climate forcing and physical forcing, as well as biophysical impacts in the coastal zone. Adequate information is equally critical to ensure that social considerations can be integrated into the adaptation planning process, and also into more general planning and policy-making that incorporate awareness of potential climate-change impacts. Climate change is rarely the primary issue in any community-planning context, but incorporation of climate-change impacts and proactive adaptation measures into all environmental assessment, planning and development activities is one way to avoid expensive mistakes and in many cases will result in the most cost-effective adaptation.

Although the information is still not complete, the visualization of scenarios using maps to portray different outcomes helps community participants to evaluate their own personal risks in terms of a possible future reality. The descriptive models can gradually be quantified using the level of risk, exposure, adaptive capacity and vulnerability of the components applicable to the communities. This will help define the real degree of adaptive capacity and vulnerability of the communities and their natural ecosystems.

4.9.4.2 Lessons learned from these examples

In summary, this project has greatly contributed in the development of methodologies and recommendations to integrate social and environmental considerations of climate-change impacts into future planning, development and sustainability of these communities. There are, however, some limitations of such studies. We have to admit that because this study originated from a large research project that had several collaborators and various grants, the level of sophistication in data acquisition and analysis is brought at a higher level than in a normal case study or analysis. The details and advantage of LiDAR DEM and their integration into climate-change scenarios cannot be done in each community. It can be suggested, however, that for coastal development projects, especially of significant socio-economic implications, such a more detailed approach be considered, including not only social considerations but fine-tuned data acquisition and analysis. Without such data, results in this study might have been limited. The challenges of integration can also limit some recommendations during this process, since it requires greater knowledge or more expertise in a team. For example, issues such as seawater infiltration into the freshwater table have not been examined due to lack of funding and limited time. However, like in the 1990s, when most assessment consulting firms had to begin using GIS models for mapping and analyzing, it is possible to predict that integrated socio-economic and biophysical aspects of assessment will gradually be integrated in a similar fashion. Integration is, however, a difficult step to accomplish, and one that many communities, assessors, decision-makers and planners barely want to deal with owing to complexity in data analysis and model building. In addition, integration of data for the purpose of developing comprehensive models of cause and effect is often left to the last minute as it is often considered non-important and / or by lack of time and resources. The results, however, can certainly be used for communities to better visualize the various issues and the relationships in decision-making and planning processes.

4.9.4.3 Challenges and issues regarding the implementation of adaptation strategies and measures

Most projects on climate change have relied on biophysical sciences and, most often, recently collected data from the field or from the published literature. With climate change, it is not as clear on where to get and how to use the relevant information in order to better assess impacts of climate change on a development or project. In most cases, historical and meteorological data are used, and extrapolations are made to predict potential impacts. Data from the federal government include maps with climate-change scenarios, but there is a need for minimal training in order to understand the trends and real threats to communities. However, this might not be the most appropriate solution, as new information becomes available and shows that climate-change impacts might be more complex than first expected. For example, while on the coast the amplitude of storms was thought to be the main changing factor, we can suggest that in fact the number of smaller storms might be more of an issue. Hence, communities (and their socio-economic dimensions) might be more influenced by the frequency of storm events, rather than by the impacts of larger, less frequent storms. Because of uncertainties, decision-makers are limited in their interpretation of the data. Moreover, most of the time, analyses are restricted to include only physical structures, the aquatic environment and flora and fauna or, conversely, only socio-economic components of the communities. Both aspects are rarely fully considered and integrated into the process, although they can play crucial roles in the decision-making process and the social acceptability of proposed developments.

Social considerations of climate-change impacts on a development project should take into account the level of awareness that the community has regarding climate change. In addition, education, lifestyle and social classes are all other factors that can influence the outcomes of the assessment. As mentioned in other studies (Barrow, 2000), these demographics should be carefully recorded, as they may affect the level of understanding and therefore plans for the projects. In this study, newcomers and wealthy citizens were often less influenced by the results, compared with local citizens who have lived there for many generations, and believed that they could still continue projects along the coast even if costs would be higher in the long term. The possibility of relying on insurance and other subsidies leaves the impression for certain categories of citizens that humans can beat the impacts of climate change. This false perception and assurance can be transferred to or from the developers, thus influencing the planning and assessment and gradually underestimating the need for social or biophysical considerations of climate change.

The results of these activities and the information gained from the interview analysis and the presentations in the three focus groups show that in terms of social perceptions and considerations, five challenges or issues were of concern:

- need for economic development and growth (driving force behind not reacting);
- misunderstanding of the potential impacts and their severity for coastal communities (i.e., the real risks of climate change);
- resistance of developers, newcomers and decision-makers to the new information (especially for climate-change impacts and adaptations);
- restrictions and additional burden due to new coastal zone policy; and
- fear of changing due to infrastructure damage.

4.9.5 References

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5. Annexes

Four series of maps, as described below, can be viewed on the attached CD.

Annex A: Storm-surge return-period maps for Shediac Bay

This section includes a series of sequential maps of the coastal zone of Shediac Bay from Cap-des-Caissie to Bas-Cap-Pelé. The maps depict return-period (for 2-, 5-, 10-, 40- and 100-year) flooding extents with present sea levels (blue line) and with a 60-cm sea-level-rise scenario (red line).

Annex B: January 2000 storm-surge flood maps

This section includes a series of sequential maps of the coastal zone of the study area, from Kouchibouguac National Park to Shemogue. The maps depict flooding extents that resulted from the January 21, 2000, storm with present sea levels (blue line) and with a 60-cm sea-level-rise scenario (red line).

Annex C: Coastal erosion maps

This section includes a series of maps showing calculated rates of coastline position change in the recent past in order to better predict future displacement, using sets of multiyear georeferenced aerial photographs (1944, 1971–1973 and 2001). Other series were used based on specific needs (1938, 1953, 1963, 1967, 1970, 1982 and 1995).

Annex D: Coastal habitat maps

This section contains a series of maps showing coastal habitat distribution using the same sets of aerial photographs as described under Annex C, above.