Coastal Impacts of Climate Change and Sea-Level Rise on Prince Edward Island

Climate Change Action Fund project CCAF A041

Synthesis Report

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SYNTHESIS REPORT

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EXECUTIVE SUMMARY

1. Purpose of the study

The coast of Prince Edward Island (PEI) was initially targeted for this climate-change study in part because it had been identified in at least two recent studies as one of the regions most sensitive to sea-level rise in Canada. For example, although Charlottetown Harbour is largely protected from the Northumberland Strait and the Gulf of St. Lawrence, relative sea level is rising and storm-surge events are increasingly common, as exemplified by the storm of 21 January 2000. Unusually high tides, accompanied by a storm surge in the late evening, caused ice ride-up and pile-up on the shore and flooded downtown Charlottetown, communities such as Mount Stewart up the Hillsborough River, and other communities along the PEI, Nova Scotia, and New Brunswick coasts in the southern Gulf. It is estimated that the 21 January 2000 storm-surge event caused nearly a million dollars worth of (insurable) damage to PEI, undoubtedly an underestimate of the true cost.

Parts of the North Shore of PEI were rated highly sensitive because this coast is exposed to the open Gulf of St. Lawrence, with potential wave-generating fetches of several hundred kilometres. High energy wave action, rising mean sea levels, and an increase in heavy storm activity on the North Shore of PEI can have detrimental effects on shoreline stability and coastal ecosystems as well as on human activities and well-being. Property will be lost, wetlands encroached upon and forced inland, and coastal infrastructure and community-related resources put at risk by accelerating coastal erosion. In many communities, wharves, roads and bridges, businesses and residences were greatly affected by the 21 January and 29 October 2000 storms.

The goal of this project was to assess the physical and socio-economic impacts of climate change and accelerated sea-level rise on the coast of PEI, particularly in relation to:

- anticipated increased frequency and extent of storm-surge flooding in Charlottetown, and
- anticipated decreased sea ice, increased wave energy, and potentially increased shore erosion on the North Shore of PEI.

Another important objective was to consider feasible and effective adaptation measures that might be adopted in PEI to minimize the impacts of these changes. Finally, because this study is one of the first of its kind, it is intended to serve as a template for future studies and it was deemed important to assess how well the study met its aims and how future studies could be improved.

2. Components of the study

The project, carried out by a team from Natural Resources Canada, Environment Canada, Dalhousie University, the Centre of Geographic Sciences of the Nova Scotia Community College and the City of Charlottetown, with other partners was organized into several components. Many of these components were carried out concurrently, although some obviously had to wait for the conclusion of others.

1. Digital elevation models (DEMs) were developed by the Centre of Geographic Sciences and Natural Resources Canada using airborne LIDAR surveys. This resulted in high resolution topographic maps of the Charlottetown and Rustico areas for flood impact analysis.
2. A climatological analysis was carried out by Environment Canada, Natural Resources Canada and the Canadian Hydrographic Service of sea level, storm surges, winds, waves, and ice cover in the Gulf of St. Lawrence.

3. A meteorological storm surge model was developed by Dalhousie University. This model was then tested using data from the storm of 21 January 2000 which resulted in flooding in Charlottetown.

4. Sensitivity studies with the surge model and statistical studies of long-term sea-level rise, astronomical tides and annual maxima based on observations at Charlottetown were combined to provide flooding forecasts at the following three critical levels: a) 4.23 metres above Chart Datum (the 21 January 2000 storm), b) 4.70 metres above Chart Datum (a lesser storm surge superimposed on higher sea level) and, c) 4.93 metres (the 21 January 2000 storm plus 100 years of predicted relative sea-level rise at Charlottetown). These water levels were then superimposed upon the high resolution topographic map produced in Step 1 to predict what areas in Charlottetown would be flooded in the three scenarios.

5. A socioeconomic analysis was then carried out by Environment Canada to estimate the number and value of properties in Charlottetown at risk from the above three flooding scenarios, the effects upon coastal infrastructure, and the effects upon health, education and employment. For the North Shore, an assessment was carried out of the effects of increased erosion on real property loss for cottage properties and non-cottage properties, and on non-market values for wetlands, forested land, beaches and dunes.

6. A review of adaptation measures (protection, accommodation, and retreat) demonstrated that proactive retreat or avoidance is feasible and highly cost-effective in many rural areas in PEI but may not be easy to implement where subdivision and dense development have occurred in coastal communities or in the urban centres of Charlottetown or Summerside. Criteria for set-back and other adaptive measures were developed from the results of this study.

3. Summary of findings

3.1 Socio-economic impacts of future flooding in Charlottetown

- Private and public property in both the residential and commercial sectors in Charlottetown are at risk of damage from flooding events. There is a high concentration of commercial businesses in the zones that are most vulnerable to the effects of storm-surge events. With flooding to 4.23 metres above Chart Datum (the 21 January 200 storm), approximately 460 properties are either flooded, or at risk of flooding from the event with assessed property values of **$172 Million**, of which $110 Million is residential. The 'at-risk' property value for flooding to 4.70 metres above Chart Datum is **$190 Million**, of which one-third is commercial properties and buildings. Flooding to the 4.93 metres Chart Datum level will have an impact in terms of assessed property values amounting to approximately **$202 Million**, of which non-commercial properties represent $134 Million, while commercial properties total over $68 Million.

- Over 1.1 Million tourists visited the Island in 2000 and spent approximately $257 Million. According to the provincial government's *Economic Impact: Tourism 2000* report, 29.9% of all pleasure private motor vehicle and air visitors to Prince Edward Island (for the summer tourism season) reported Charlottetown as their "main overnight destination". There are approximately 335 municipally designated heritage properties, most of which lie south of Euston Street in and around the downtown core. Federally, there are about a dozen recognised sites. Many of these sites and areas lie within the probable flood plain outlined by the Digital Elevation Model, implying that there are many heritage values at risk. A flooding level of 4.23 metres above Chart Datum would render a total of 30 municipally designated heritage properties at risk of flooding, for a total assessed value of $8.6 Million. Flooding levels of 4.70 and 4.93 metres CD would render an additional 11 and 19

properties at risk, respectively, totaling approximately **$10.5 Million** and **$11.3 Million** in assessed property values.

- The City of Charlottetown has invested millions of dollars in developing its stormwater, sewage, and waste treatment systems, including a number of upgrades (such as the primary treatment plant in 1974) in the recent past. The three immediate concerns for storms with respect to the effects of sea-level rise on the storm/sewage system are: 1) A sufficient rise in water level could cause a surcharge in the sewage lines from outfalls and lift stations, leading to back-ups in residential and commercial areas; 2) A water level high enough to reach the level of the lift station could result in sea water being pumped along with sewage materials (or solely sea water) to the sewage treatment plant, and; 3) Prolonged inundation and submersion of a lift station and/or the treatment plant could render it inoperable.

- The value of the infrastructure at risk in Charlottetown is as follows: water system pipe **$1, 950,000**; sanitary system pipe **$2,223,000**; storm sewer pipe **$3 million**; force main **$1,155,000**; small lift station **$320,000**; large lift station **$2 million**; sewage treatment plant **$25 million**; proposed secondary expansion to the treatment plant **$13.5 million**. Total value as assessed by the City of Charlottetown is just over **$46 Million**.

- Estimates from the City of Charlottetown show that flooding to the level of 4.23 metres above datum would affect approximately 150,000 m^2 of right-of-way, to an approximate value of **$12 Million**. Further, the value of sidewalks at risk in this scenario is approximately **$1 Million**. These estimates are preliminary and do not purport to estimate the value of the land on which the roads and sidewalks are located.

- Located on the shore of the Hillsborough River near the hospital causeway is the Trigen Energy-from-Waste Facility that provides district heating services to 75 customers (mainly downtown businesses) in 80 buildings. Many of these customers do not have other sources of heating and rely on the services of the facility. It is estimated that the facility's replacement cost is **between 25 and 30 Million dollars.**

- During the surge event of 21 January 2000, the Maritime Electric facility sustained damage to both their pumphouse, located on the Hillsborough River, and to their main facility, which is located further inland. The scenarios modelled in this study show some risk of damage to the Maritime Electric facility, which carries an approximate asset value of **$48 Million**.

- It is realistic to attribute some "community costs and/or damages" to lost wages and health care costs (paid by the province's health care system). For example, if it were necessary for homeowners to spend time the following day on activities such as pumping out flooded basements, removing ice floes from yards, and removing damaged items from flooded areas, the time it took away from their normal productive days would be considered to be a cost, directly related to the surge incident. Furthermore, restaurants and businesses that closed for repairs following the storm will suffer the effects of lost revenue as a direct result of the event. The employment created in the clean-up efforts to repair, service, and rebuild commercial establishments should not be seen as employment revenue which offsets the costs of the storm felt by the community as a whole. The revenue generated by clean-up and remediation efforts is often paid out of insurance funds, and is generally considered a drain on society.

- In the health-related infrastructure component, we see that the Queen Elizabeth Hospital and the Hillsborough Hospital and Special Care Unit are both partially affected, though

through property only. The study concludes that there does not appear to be any danger of flooding in the main buildings themselves; however, with flooding levels of 4.70 and 4.93 metres, there is some risk to one of the auxiliary buildings. Erosion could lead to seepage causing risk to structural integrity, and/or surcharge in sewer lines for instance. In these scenarios, it is shown that the causeway and the road that provide access to these facilities would be affected and could cause delays and degrade the quality of the service available to the public.

3.2 Socio-economic impacts of future coastal erosion on the North Shore

- Rising mean sea levels, less sea ice, and higher wave energy along the North Shore of PEI can be expected to cause more severe erosion damage and possibly rapid coastal change in some places. Photogrammetric analysis of air photographs dating back to the mid-1930s shows significant change along much of the coast, including severe erosion in places and shoreline recovery or dune growth in others. The longer-term view from marine geological surveys shows that the coast on average has been retreating by at least 0.5 m/year for several thousand years. Property is lost, wetlands are encroached upon and migrate inland (but can be permanently lost if migration is limited by infrastructure), and coastal infrastructure and community-related resources are put at risk in a situation of accelerated shoreline erosion. The value of the lands lost due to coastal erosion represents a real cost of climate change (i.e. a lost 'value' of land and the services produced by or from it).

- The value of *cottage*-land lost to erosion between the years of 1935 and 1990, based on average percentage loss of property and average property value of cottage-designated properties, is **$816,000** (or $15,000 per year). Between the years of 1980/81 and 1990, the value of cottage-land lost was **$242,000** (or $22,0000 per year).

- The value of *non-cottage* land lost to erosion between the years of 1935 and 1990, based on assessment values, is **$63,400** (or $1,100/year). From 1980/81 to 1990, the number is $10,600 (or $1,000/year), meaning approximately one-sixth of the erosion since 1935 happened in the last decade. Comparing this to the total assessed value, we see that 4.24% of the value of the non-cottage land has eroded since 1935, and given that the total area of the properties is 646 hectares, a total amount of land eroded is approximately 15 hectares (between 1935 and 1990).

- Preliminary estimates of future erosion rates under climate change and relative sea-level rise suggest a potential increase to 1.5 to 2 times the 1935-1990 mean rates of erosion for the study area. The rate of increase may change over the forecast time frame and will in this case be affected by significant year-to-year and interdecadal variance seen in the historical data.

- **At double the present erosion rate, almost 10% of the present area of coastal properties in the study area will be lost within the next 20 years, and almost one-half in the next 100 years.**

- The study area includes a number of saltwater marshes, most of which are not located on the North Shore facing the ocean but further inland along channels and inside Tracadie Bay and Savage Harbour.   Using a value of $21,206/ha per year, wetlands **add the value of $188,448** (in the form of benefits from ecological services) to the assessed value of the land.

- Using a value of $2.74 per square metre for water filtration, removal of air pollutants and control of runoff, the assessed value of the 18 hectares of forested land in the study area on the North Shore can be augmented by **$49,800** to account for the inclusion of ecosystem values, as contributed by the presence of the forest in the study area. One service whose inclusion could raise the augmented total value of the land is the role of forest in erosion control.

- The coastal dunes of PEI are among the key natural tourist attractions of the province. From Cavendish Beach to the Nature Reserve east of Tracadie Bay, there exists a long, interconnected system of dunes, which are at risk of being breached by wave action in severe storms. The total area of the land designated as "sand dune" by the Province of PEI within the detailed study area was estimated at 100 hectares. One study used willingness to pay surveys to approximate the value of beaches, and identified an *annual* value of between US$200 and US$250 (1987 dollars) per respondent. Another study placed a 'per-household' value on prevention of 30% of erosion of $33.35. In addition to its tourism value, it would appear that the very presence of the sand dune system on the North Shore is the most important land-conservation tool currently available in nature. The absence of the dune system could lead to accelerated rates of erosion in vulnerable areas.

3.3 Sea-level rise

- An examination of tide gauge data indicates that the mean sea level at Charlottetown has been rising at a rate of **32 centimetres per century** since records began in the first decade of the 1900s. The calculated rate of sea level rise at Rustico is **29 centimetres per century**, consistent with that calculated for Charlottetown. However, confidence in the Rustico data is lower because of the shorter record and large periods of missing data. Part of the long-term sea-level rise (perhaps 20 centimetres/century) is due to crustal subsidence following postglacial adjustments to changing ice and water loads: the remaining 12 centimeters per century is a signal of global and regional sea-level rise. It should be noted that storm surges and ocean waves are also factors at the coastline and are carried to higher levels on rising mean sea level. Even in the absence of climate change, the present rate of sea-level rise in PEI will bring challenges in the future to human interests and ecological systems in the coastal zone.

- Based on various considerations, this study has adopted the Intergovernmental Panel on Climate Change (IPCC) central value of about 0.5 metres for sea-level rise, combined with a risk-conservative estimate of 0.2 metres for crustal subsidence, to obtain a **total projection of 0.7 metres relative sea-level rise to 2100** in the Charlottetown region. This value has been used in estimating future storm-surge and other flood levels, recognizing that some projections imply a lower increase, but that the total rise from 1990 to 2100 using our estimate of crustal subsidence combined with the maximum IPCC projection could amount to a rise in mean sea level at Charlottetown of **as much as 1.10 metres**.

3.4 Storm surges

- Storm surges are the 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) high tide are events which lead to coastal inundation.

- Generally speaking, storm surges above **60 centimetres** are frequent events in Charlottetown, occurring about **8 times a year** on average (compared, for instance, to twice a year along the Atlantic coast in Halifax). They are mainly associated with winter storms and show great variability over the years. Storm surge events above 120 centimetres are uncommon and occur on average about twice a decade.

- The Digital Elevation Model for Charlottetown determined that sea water begins to flood the waterfront at a level of about 3.6 metres above chart datum. A storm surge of less than 60 cm combined with highest predicted tide (2.91 metres) cannot reach this level. Of all the storm surge events noted in the period 1911 to 1998 only **6** events reached this level and had an impact on the Charlottetown waterfront. If sea level rise to the year 2000 is taken into account then **8** of these storms would have caused some flooding of the waterfront if they had occurred in the year 2000. The change from the present situation is even more pronounced if one accounts for sea level rise to the year 2100. Whereas presently for instance, we can expect one exceedance of 3.6 metres above chart datum every 7 years or so, in the year 2100 we could expect **one such exceedance on average each year with one event every 10 year or so in excess of 4.0 metres!** With sea level rise and global warming, not only will flooding move to higher levels but that the floods at the lower levels will become much more frequent in Charlottetown.

- A numerical model to forecast storm surges was developed at Dalhousie University and is now run operationally by Environment Canada. This model is driven by wind and sea-level atmospheric pressure. The model can forecast storm surges to within about 10 centimetres with a lead time of the order of one day. The model was tested on the 21 January 2000 storm and performed well.

- The Probable Maximum Storm (PMS) methodology consists of modifying the initial conditions for the atmospheric model in such a way as to maximize the development of the storm. An additional modification for some runs is to change the location of the initiation of the storm and the atmospheric conditions that influence its evolution. The surface pressure and wind fields forecast by the atmospheric model are then fed to the storm surge model. Preliminary results of this testing indicate that storm surges in the Gulf of St. Lawrence are highly sensitive to changes in storm trajectory, and in particular the storm surges associated with the 21 January 2000 storm could have been significantly higher had the storm been slightly further to the west.

- A new statistical method (the Conditional Probability Method) was developed to estimate the probability that a specified level will be exceeded at least once by a given date. The CPM suggests that under the present rate of sea level rise and no increase in storminess, the probability that sea level in Charlottetown will exceed 4.22 metres above Chart Datum at least once by 2050 is about 0.8. With an accelerated sea level rise of 70 cm/century (about double the present rate), the probability increases to 0.95 by 2050, a highly likely event. The probability that 4.93 m will be exceeded at least once by 2100 under the present rate of sea level rise is about 0.04, a highly unlikely event. If however the sea level rise doubles, this probability increases to 0.36. In the worst scenario we envisaged (sea level rise about double the present rate and a 10% increase in wind speed) the probability of exceeding 4.93 m at least once by 2100 is almost 0.7. This highlights the importance of relatively small increases in wind speed on flooding risk. This is of particular concern given

the evidence in the observed Charlottetown record of significant increases over the last 60 years of the biggest surges.

3.5 Winds

- High wind speeds are an important result and indicator of storms and contribute to both wave and surge development. The wind climatology was examined in this study as a complement to the storm-surge and wave analysis, in order to gain a better understanding of interannual, interdecadal, and longer-term variation in storminess and to investigate the possibility of an increase in wind intensity over the period of record. Variation in wind direction was also considered in relation to storm-surge occurrence.

- A list of 464 storms between 1953 and 2000 with winds greater than or equal to 50 km/hour for at least 6 hours was constructed from the transformed, composite Magdalen Islands record and was filtered to include only the 334 storms with mean northerly wind directions (i.e. blowing from between 270° and 90° through north), corresponding to the most common storm wind direction, the directions of longest ice-free fetch, and the exposure of the PEI North Shore. Stormy periods appear to have occurred between the late 1950s and early 1960s and during the 1980s whereas less stormy periods appear to have occurred prior to 1955, in the 1970s and after 1991.

- Analysis of storm-surge events indicated a significant correlation between large surges in the southern Gulf of St. Lawrence and strong northeast winds. Other surges are related to winds out of the north and northwest. The storms that most often cause surges follow a preferred track in which they move northeast from an area of cyclogenesis off the coast of the southeastern USA. The wind records show some periods of greater or lesser northeasterly wind activity consistent with the seasonal and interdecadal variation in storm-surge occurrence at Charlottetown.

3.6 Waves

- Waves are one of the most widely recognized indicators of storm activity and constitute a significant natural hazard for shoreline erosion and infrastructure damage in coastal settings. Coastal erosion, increased sediment mobility and damage to infrastructure can be caused by waves impinging on the shoreline, especially when they are superimposed on higher than normal water levels during storm surges.

- Wave data were collected off the North Shore of PEI in the autumn of 1999 and 2000, contributing to knowledge of waves impacting this shoreline. New data include one benchmark storm on 29-31 October 2000 during which waves up to 14 metres maximum height were recorded and the significant wave height peaked at greater than 7 metres.

- Time series of the hindcast data show that waves tend to be largest and most numerous in the fall as waves are fetch-limited by ice in winter and wind storms are uncommon in summer. The direction of high waves is hindcast to occur most frequently from the northwest mode whereas low waves tend to be also from the southwest. Northeast waves may also be important but, because northeast winds may occur most often in winter, these waves are not measured and maybe also not well hindcast. The northeast fetch may be artificially reduced by the Magdalen Islands.

3.7 Ice cover on the Gulf of St. Lawrence

- The presence of sea ice in the Gulf of St. Lawrence inhibits wave development, thereby reducing winter storm erosion. Waves are expected to increase if sea ice in the Gulf decreases as predicted in future global change scenarios. There may be some effect on storm surges as well but this is less clear.

- The study showed that, during the 30-year period of study 1971-2000, ice cover on the Gulf was highly variable from one year to another. The Total Accumulated Ice Coverage can be used as an ice severity index for the whole season. Extreme values ranged from 1.1 million square kilometres in the year 2000 to almost 3.0 million square kilometres in 1993.

- The latest results of the Canadian Global Circulation Model (GCM) indicate that, by the year 2050, the ice extent in the northern hemisphere may be limited to higher latitudes and that the Gulf of St. Lawrence may be free of ice. Trends in ice cover for the Gulf are not statistically significant. The dominant characteristic of the time series shown in Figures 12 and 13 is the oscillation between years of maximum ice cover such as 1993 and years in which the total accumulated ice cover is 50% less, as in the early 1980s and again in 1998-2000. Year-to-year fluctuations can be expected to continue, but the possibility of significantly reduced ice coverage, with its implications for more severe wave conditions in winter, should not be overlooked.

- Other impacts of ice include direct damage caused by ice ride-up or pile-up on the coast; and nearshore ice or icefoot protection of the coast against wave erosion. Both effects were documented in this study in relation to large storms. During the storm of 21 January 2000, ice ride-up pushed a lighthouse in Charlottetown off its foundation, caused severe damage to a golf course in the Charlottetown area. Combinations of ice ride-up and pile-up damaged wharves and other infrastructure around the Island. The most severe ice damage during that storm, including partial demolition of homes and harbour structures, occurred along the New Brunswick coast.

- Wave damage along the North Shore of PEI was limited because of the presence of ice against the coast. On the other hand, when open water develops seaward of a grounded nearshore ice complex or when waves impinge directly on the vertical face of the icefoot, unusual scour and profile downcutting may occur in the nearshore, promoting more rapid shore erosion.

3.8 Flooding maps

- In order to predict areas at risk of coastal storm-surge flooding, it is necessary to have an accurate and high-resolution representation of the topography. An emerging technology known as LIDAR (Light Detection and Ranging) involves an aircraft emitting laser pulses towards the ground and measuring the return time of the pulse. The LIDAR system produces a series of point measurements with associated heights above the ellipsoid, a smooth mathematical surface representing the earth.

- Water levels associated with storm surge events were defined in terms of height above Chart Datum. Three flood levels were selected for modeling the extent of flooding in Charlottetown: 4.23 metres, 4.70 metres, and 4.93 metres above Chart Datum. The areas flooded from the three scenarios were projected to the PEI double stereographic map

projection and delivered to the City of Charlottetown Planning Division for incorporation into their GIS. The information is being used for planning and adaptation purposes and was used for determining the economic impact of future storm surges as part of this CCAF project.

3.9 Coastal geology and shoreline change

- Estuarine deposits mapped and sampled offshore include several sites presently at depths of 18 to 25 metres, with ages of approximately 6000 years. Recognizing that the outer coast at the time may have been anywhere from less than one to more than five kilometres further seaward, these observations indicate a long-term mean coastal recession rate of at least 50 metres per century (0.5 metres per year).

- Historical map evidence suggests that large-scale shoreline adjustment and landward sand movement occurred in response to large storms prior to 1880 and that extensive washover was maintained on some beaches by storms prior to 1935, after which the dunes began to recover.

- Records of erosion and accretion for a 12 kilometre section of the North Shore for various periods between 1935 and 1990 show that there is considerable temporal and spatial variation in the rates of erosion. Overall, however, at least in some sections, erosion prevailed during the 55-year period, with coastal retreat rates generally ranging from 0.2 to 2.5 metres/year and even higher in places. This is consistent with rates seen elsewhere along the coast . A number of damaging storms have hit in recent years, including early December 1998 and late October 2000. The latter storm caused $250,000 damage to park facilities and much more to small craft harbours along the coast.

- Using a simple sediment conservation model and a conservative estimate of 5.0 millimetres/year for future relative sea-level rise, we obtain estimates of future coastal retreat ranging from 0.62 to 0.85 metres/year, an increase of ~55% over observed rates in the past. This provides the rationale for rates of 1.5 times present recession used in the socio-economic analysis of property losses due to accelerated coastal erosion. A higher rate of sea-level rise averaging 0.7 m over the coming 100 years would produce estimates of shore recession about 2.2 times the present rate, hence the alternative analysis for twice the present rate in our socio-economic analysis.

- Areas showing significant erosion over the airphoto record can be expected in many cases to experience long-term future erosion at rates at least equal to those of the past 65 years. Some areas could experience massive breaching and rapid landward migration if a sufficiently energetic storm leads to replication of impacts experienced sometime before 1935 and possibly predating 1880.

3.10 Adaptation to sea-level rise and climate change in Prince Edward Island

As recognized for some years, there are three broad categories of adaptation to sea-level rise and climate change in the coastal zone. These are:

1. protection
2. accommodation
3. retreat or avoidance.

- *Protection* is an understandable response to coastal erosion threatening backshore property or infrastructure. In general, protection is costly and may have limited long-term effectiveness in exposed locations, though it may be successful as flood protection where wave energy is limited.

- *Accommodation* represents a middle way between protection and retreat. It may involve redesign of structures to minimize impacts, zoning to encourage appropriate land use with low capital investment on vulnerable properties, or other measures. In cases where flood risk rather than erosion is the predominant issue, raising foundations or freeboard on structures may be an appropriate measure. Accommodation may also involve efforts to increase natural resilience, through such measures as coastal dune rehabilitation, dyke opening and wetland renewal, substitution of bridges in place of causeways, or 'soft' protection measures such as beach nourishment..

- *Retreat*, which may also be defined as *avoidance* of risk, represents a form of proactive adaptation to eliminate a direct impact. The simplest form of retreat involves avoidance of vulnerable properties by individual buyers, or decisions against building within flood or erosion hazard zones. This may be encouraged by public education efforts or other management strategies, including tax, insurance, or zoning policies. Legislated setback regulations are perhaps the most common approach and are often based on projected future erosion losses, as is the case in Prince Edward Island.

- Selection of setback distances in terms of a fixed time interval (e.g. 60 years in the PEI Coastal Area Regulations) implies an ability to predict erosion rates into the future over that time interval. Simple extrapolation of historical rates may not be appropriate and the validity of the historical rates adopted for such calculations may be questionable. Other ideas being promoted in some jurisdictions include rolling easements or changes in flood insurance. Land swapping may be another public policy option, particularly where wholesale resettlement of a vulnerable community may be needed.

- A number of specific options were recommended, involving hazard identification and monitoring, managed retreat, accommodation and enhanced resilience, protection, coastal management, awareness raising and public education. There may be no one option that is best or effective in isolation. Appropriate adaptation may require a mix of options and the best mix will vary from place to place and possibly from time to time. Adaptation can be at various scales and local adaptation needs are best solved locally or at least with participation and buy-in of local stakeholders.

- Adaptation strategy needs to adaptable. Vulnerability may change with time and should be reassessed on a regular basis. This may require adjustment of the mix of adaptation measures.

1. The problem addressed by this project

1.1 Background

Since the Industrial Revolution there has been a marked increase in the human sources of the so-called "greenhouse gases", i.e., carbon dioxide, methane, chlorofluorocarbons (CFCs), nitrous oxides and ozone, and there is concern that the observed and significant increases in the atmospheric concentrations of these gases are altering the radiative balance of the atmosphere. It is anticipated that this may bring about widespread and pronounced changes in the Earth's climate, including increases in temperature, altered precipitation patterns, increased storminess, and a rise in sea level.

Even if fully implemented, the 1997 Kyoto Protocol will slow but not prevent the effects of climate change; therefore, work on adapting to the unavoidable effects must start now. The recent decision of the United States, one of the largest emitters of greenhouse gases, to abandon implementation of the Kyoto Protocol means that planning for adaptation to climate change will be even more important that it has been in the past. With a growing migration of human settlements to coastal areas for economic and aesthetic reasons, human society is becoming increasingly vulnerable to the possible coastal effects of climate change, such as rises in mean sea level, and an increase in the frequency of storm surges due to an increase in storminess.

Global mean sea level has been rising by 0.1 to 0.2 m (metres)[1] per century over the past 100 to 200 years. However, it should be noted that changes in local sea level will be different from the global average due to movement of the earth's crust. For the past 6000 years, relative sea level (RSL or apparent sea level in relation to the ground surface) around east-central Prince Edward Island has risen by about 0.3 m/century and more slowly in the past 2000 years. This study shows, from 90 years of tide-gauge records at Charlottetown, that relative sea level has risen by 0.32 m/century since 1911. With increasing concentrations of greenhouse gases, sea-level rise is expected to accelerate and the Intergovernmental Panel on Climate Change predicts that global average sea level may increase by 0.09 to 0.88 m with a central estimate of 0.5 m between 1990 and 2100.

Storm surge is generally defined as the algebraic difference between the observed water level and that predicted from tide tables. Increased storminess is anticipated over the next 100 years (the general scale of this study) for a number of reasons. Although the frequency of severe storms may not change, there is evidence to suggest a potential increase in storm intensity, with implications for storm surge amplitude. Furthermore, decreased sea-ice cover in winter in the southern Gulf of St. Lawrence may increase the amount of open water fetch (the distance the wind blows across open water), creating larger waves superimposed on storm surges. The combined effects of accelerated sea-

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[1] Throughout this report, various quantities and rates are given, using standard SI abbreviations in most cases (km ≡ kilometre; m ≡ metre; cm ≡ centimetre; ha ≡ hectare; kPa ≡ kiloPascal) and some non-SI abbreviations where conventional (h ≡ hour; millibar ≡ mb; x million Canadian dollars ≡ $x Million) or simpler and self-explanatory (m/yr; m/century, km/h).

level rise, larger storm surges, and higher wave energy at the coast could lead in the next 100 years to more flooding of coastal areas and increased erosion and property loss.

The coast of Prince Edward Island (PEI) was initially targeted for this climate-change study in part because it had been identified in the Canada Country Study on Climate Impacts and Adaptation and in a Canada-wide study by the Geological Survey of Canada (Bulletin 505) as one of the regions most sensitive to sea-level rise in the entire country. Factors contributing to this sensitivity include soft sandstone bedrock, a sandy and dynamic shore zone (sediment starved in places), an indented shoreline with extensive estuaries and salt marsh, low terrain behind the shore with significant flooding potential, documented high rates of shore retreat, and submergence of the coast that is ongoing today.

Charlottetown Harbour is well protected from Northumberland Strait and the open Gulf of St. Lawrence. Relative sea-level is rising nonetheless, as shown by the tide-gauge records, and storm-surge events are increasingly common. The storm of 21 January 2000 saw unusually high tides accompanied by a storm surge in the late evening, causing record high water levels. Ice was piled up on the shore and downtown core of Charlottetown was extensively flooded, while communities such as Mount Stewart up the Hillsborough River and others along the PEI, Nova Scotia, and New Brunswick coasts in the southern Gulf experienced damaging floods. It is estimated that the 21 January 2000 storm surge caused nearly a million dollars worth of (insurable) damage in PEI. These figures are grossly underestimated, however, considering the eligibility requirements of the Disaster Financial Assistance Arrangements (DFAA) and the types of damages known to have been incurred on the Island.

Parts of the North Shore of PEI have also been rated as highly sensitive because this coast is exposed to the open Gulf of St. Lawrence, with potential wave-generating fetches of several hundred kilometres. High wave energy, rising mean sea levels, and an increase in heavy storm activity on the North Shore of PEI can have detrimental effects on shoreline stability and coastal ecosystems as well as on human activities and well-being. Property will be lost, wetlands encroached upon and forced inland, and coastal infrastructure and community-related resources put at risk by accelerating coastal erosion. In many communities, wharves, roads and bridges, businesses and residences were greatly affected by the 21 January and 29 October 2000 storms.

1.2 Goals of this project

The goal of this project was to assess the physical and socio-economic impacts of climate change and accelerated sea-level rise on the coast of PEI, particularly in relation to:

- anticipated increased frequency and extent of storm-surge flooding in Charlottetown, and
- anticipated decreased sea ice, increased wave energy, and potentially increased shore erosion on the North Shore of PEI.

Another important objective was to consider feasible and effective adaptation measures that might be adopted in PEI to minimize the impacts of these changes. Finally, because

this study is one of the first of its kind, it is intended to serve as a template for future studies and it was deemed important to assess how well the study met its aims and how future studies could be improved.

Figure 1. Prince Edward Island showing main CCAF study areas in Charlottetown and along the central North Shore.

The study areas are shown in Figure 1. These include the urban area of Charlottetown and a larger rural area along the central North Shore, including North Rustico, Covehead (Stanhope), Grand Tracadie, Savage Harbour, St. Peters Harbour, and Morell/Red Head (St. Peters Bay). It also includes most of Prince Edward Island National Park, originally extending from Cavendish Beach (New London Bay) in the west to Blooming Point (Tracadie Bay) in the east, but now also including the Greenwich Dune adjunct adjacent to St. Peter's Bay.

1.3 Components of the project

The project, carried out by a team from Natural Resources Canada, Environment Canada, Dalhousie University, the Centre of Geographic Sciences of the Nova Scotia Community College and the City of Charlottetown, was organized into several components. Many of these components were carried out concurrently, although some obviously had to wait for the conclusion of others.

1. Digital elevation models (DEMs) were developed by the Centre of Geographic Sciences and Natural Resources Canada using airborne LIDAR surveys. This

        resulted in high resolution topographic maps of the Charlottetown and Rustico areas for flood impact analysis.

2. A climatological analysis was carried out by Environment Canada, Natural Resources Canada and the Canadian Hydrographic Service of sea level, storm surges, winds, waves, and ice cover in the Gulf of St. Lawrence. A decrease in ice cover on the Gulf could increase the open-water fetch and thereby enable large waves to form and impinge on the coast. Less ice would also decrease the extent and duration of coastal protection by landfast ice along the shore.

3. A numerical storm surge model was developed by Dalhousie University. The purpose of this model was to predict, using meteorological input such as atmospheric pressure and wind, the height of an upcoming storm surge. The model was tested using data from the storm of 21 January 2000 which caused record flooding in Charlottetown.

4. The analyses of long-term sea-level rise, storm-surge records, and extreme water levels were then combined to estimate the probabilities of flooding various levels through time as a function of the rate of sea-level rise and possible changes in storm intensity.

5. Using the high-resolution digital topographic model developed earlier, the extent of flooding was determined for three selected high water levels: (a) 4.23 m above Chart Datum (the 21 January 2000 storm), (b) 4.70 m above Chart Datum (lesser event superimposed on higher sea level) and, (c) 4.93 m above Chart Datum (the 21 January 2000 storm plus 100 years of predicted relative sea-level rise at Charlottetown).

6. A socio-economic analysis was carried out by Environment Canada to estimate the number and value of properties in Charlottetown at risk from the above three flooding scenarios, the effects upon coastal infrastructure and on health, education and employment. For the North Shore, an assessment was carried out of the effects of increased erosion on real property loss for cottage properties and non-cottage properties, and on non-market values for wetlands, forested land, beaches and dunes.

7. A review of adaptation measures (protection, accommodation, and retreat) demonstrated that proactive retreat or avoidance is feasible and highly cost-effective in many rural areas in PEI but may not be easy to implement where subdivision and dense development have occurred in coastal communities or in the urban centres of Charlottetown or Summerside. Criteria for set-back and other adaptive measures were developed from the results of this study.

8. Because this study is one of the first and most comprehensive of its type in Canada, a "template" or guide for future studies was developed. This included an analysis of what went right in this study and what could have been improved upon.

This synthesis report summarizes the component and overall results of the project. Section 2 presents the socio-economic impacts. Although this aspect of the work was necessarily one of the last carried out, depending as it did on other results, it is covered first because of its prime interest to municipal and provincial authorities concerned with developing adaptation measures. Section 3 covers the important underlying physical impacts of climate change in the study areas, without which the socio-economic impacts could not have been evaluated. Section 4 covers adaptation strategies and Section 5 is an

assessment of the accomplishments of this study. The supporting appendices contain the detailed technical results of various components of the project, authored by the individual project team members. They also provide the underpinning of this Synthesis Report and relevant lists of references.

2. Socio-economic impacts of climate change in the study areas

2.1 Goal and scope of the socio-economic analysis

The goal of this socio-economic analysis is to paint a comprehensive, holistic picture of the types of effects that may felt from accelerated sea-level rise, increased frequency and severity of storm-surge flooding in the City of Charlottetown, and increased erosion along the North Shore. Damage from severe events goes beyond physical impacts to buildings and structures, and traditional assessments rarely include additional impacts and spin-off effects. Disaster situations create negative effects for the population, causing stress, personal injury, and sickness and disease, all of which are often omitted from damage assessments following disaster events. Furthermore, lost working days due to clean-up efforts and repairs have negative effects on the economy, even though the efforts to repair affected areas create employment and are profitable in some sectors of the economy (i.e. in construction and building materials, waste removal, public works). As well, the types of impacts that can be assessed may be monetary or non-monetary.

The study did not attempt to include:
 ➢ direct or indirect impacts on the fishery or the recreational boating industries;
 ➢ the possibility of saltwater intrusion into coastal groundwater aquifers which would have direct impacts on the community (either through abandoning of certain sources of water or through mitigation costs);
 ➢ impacts on the agricultural sector resulting from inundation.

The areas of focus for the Charlottetown portion of the study were as follows:

- Property
  ❑ residential properties and structures
  ❑ commercial properties
  ❑ publicly owned properties and facilities

- Historical and Heritage Resources
  ❑ tourism values
  ❑ heritage amenities
  ❑ recreational values

- Coastal Infrastructure
  ❑ municipal infrastructure - storm and sanitary sewer, water systems
  ❑ coastal infrastructure - wharves, etc.
  ❑ other infrastructure amenities

- Health, Education and Employment
  - ❑ educational facilities
  - ❑ health-related facilities
  - ❑ employment costs to society

For the North Shore, this report will include the past erosion rates for the study area, the possible effects of future erosion on cottage and non-cottage properties, and the effects of the erosion on wetlands, forests, beaches and dunes.

2.2 Climate-change futures

To examine the socio-economic impacts on Charlottetown, three scenarios of sea-level rise were chosen:

1. First, it was decided to re-create the storm of 21 January 2000, in order to test the accuracy of the model. This storm generated a maximum water level of 4.23 m above Chart Datum (CD) in Charlottetown. A socio-economic analysis of this flood level was undertaken to estimate the degree of risk, damage actually done, and the socio-economic effects experienced by the community (above and beyond the insurable damages and those damages which are valued by market processes and conventional evaluation techniques).
2. A lower storm surge than 21 January 2000 superimposed on future sea-level rise to give a flood level of 4.70 m CD.
3. A level equivalent to the 21 January 2000 flood level superimposed on an estimated 0.7 m relative sea-level rise by 2100, giving a flood level of 4.93 m CD.

2.3 Results of the socio-economic analysis for Charlottetown

a) Study area and methodology

Charlottetown, considered to be the 'Birthplace of Confederation', has a population of over 33,000 (1996 census figures) following amalgamation in 1996. There are a number of historic sites in the city, contributing to its importance as a tourism destination for Canadians and non-Canadians alike. Its key sectors are government services and health and social services, making up over 27% of the labour force in the city. Charlottetown has 83 parks, including two major waterfront parks, and an extensive system of walking and recreation trails throughout the city. Charlottetown Harbour is a popular destination for recreational fishing and boating. Charlottetown has also become a popular destination for commercial cruise liners, with 24 ships and over 1100 passengers expected to visit the city in 2001.

In Charlottetown, the general methodology for the socio-economic evaluation was constructed around the assessed values of properties, the model predictions for the three above scenarios, and the resources available to the project.

b) Residential and commercial properties

Private and public property in both the residential and commercial sectors are at risk of damage from flooding events. Charlottetown has a well-developed waterfront area with a high concentration of commercial businesses in the zones that are most vulnerable to the effects of storm-surge events. Housing, business establishments, and publicly owned resources (wharves, heritage areas, etc.) are particularly at risk in the waterfront area. As well, the contents of these structures could be at risk of being damaged or lost in surge events. It would be difficult to estimate the amount and value of personal belongings and, in the case of commercial establishments, the value of stock at risk from flooding, since these are often moveable items and can be taken out of the "at risk" areas given adequate warning.

Estimation of the total value of the land and the structures at risk can be done through various means. This study used the Province's land registry information reflecting the assessed value of specific parcels of land and associated structures. These values are updated often.

In Scenario 1 (Fig. 2), approximately 460 properties are either flooded, or at risk of flooding from the event. Assessed property values from 'at-risk' properties total $172 Million, of which $110 Million represents residential property values (and assessed residential building values).

Scenario 2 reflects an increase in the number of properties affected, while further affecting many of the properties at risk in the first flooding scenario. The 'at-risk' property value in Scenario 2 is $190 Million, of which one-third is commercial properties and buildings. In this scenario, there is also a 'farm' value of $7900. The value of farmland is likely underestimated in assessment values, as farmland is taxed at a lower rate than residential properties within the city. Furthermore, the value of non-residential, natural land, is generally underestimated vis-à-vis the value of the ecological processes (water filtration, erosion control, carbon sequestration, toxics retention, etc.) and other functions the land performs.

Scenario 3 again shows an increase in the number of properties, and therefore the value of the 'at-risk' properties, affected. Flooding to this level will have an impact in terms of assessed property value of approximately $202 Million. Non-commercial property values represent $134 Million, while commercial properties total over $68 Million.

There are three main parks that could be affected by sea-level rise in Charlottetown. They are Queen Elizabeth Park, Victoria Park, and Confederation Landing Park. In all scenarios, amenities at risk of flooding include a portion of Victoria Park, Confederation Landing Park, and a number of heritage properties that are recognized by the City of Charlottetown. These park and heritage resources will be considered separately from the discussion of residential and commercial property impacts, and this will include a discussion of the need for alternative valuation.
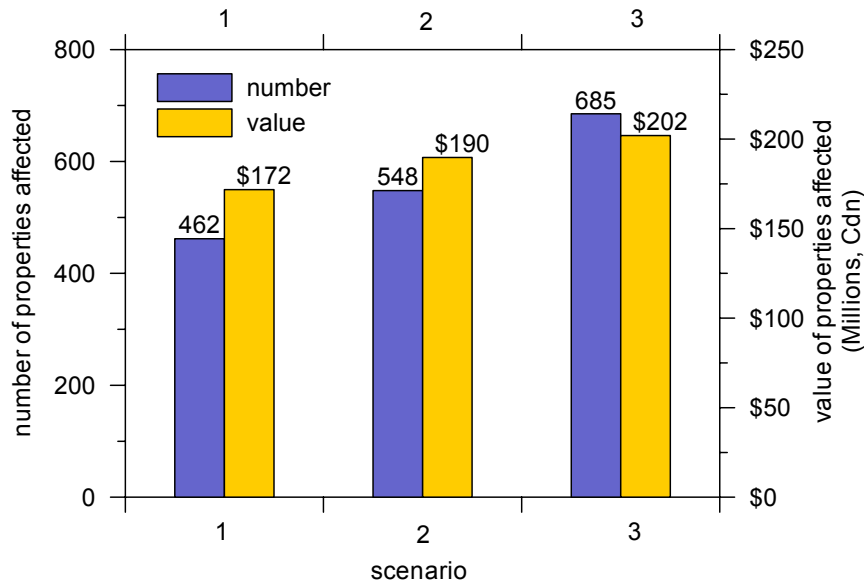
Figure 2. The number of properties, and their assessed values, affected by the three flooding scenarios: (1) 4.23 m above Chart Datum [CD]; (2) 4.70 m CD; and (3) 4.90 m CD.

It is important to note that 'at-risk' areas could sustain varying degrees of damage. In many flooding events around the world, only portions of structures are damaged, so assessed values may overestimate the amount of damage actually incurred due to these types of events. For example, a flood level of 4.23 m CD will not automatically result in damages of $172 Million. Repair costs can be much lower in the event that only portions of structures are damaged. If reliable per-unit replacement costs are available, these can be used in assessing damages following a flood event.

The assessment values approach leaves one obvious omission – the Riverview Estates mobile home park located up the Hillsborough River beyond the hospital. Some properties in this development are shown to be vulnerable to flooding, but because it is located on private land, there are no assessment data for the subdivided properties in question. About 200 mobile homes are located on this property, and though the flood scenarios do not show extensive inundation by seawater, it is clear that structures, as well as property, are at risk. Furthermore, the community has its own sewer and water system, which could be affected.

A more detailed list of properties at risk may be found in Appendix 6.

c) Heritage properties and tourism value

Over 1.1 Million tourists visited the Island in 2000 and spent approximately $257 Million. According to the provincial government's *Economic Impact: Tourism 2000* report, 29.9% of all pleasure private motor vehicle and air visitors to Prince Edward Island (for the summer tourism season) reported Charlottetown as their "main overnight destination". Of those who stated Charlottetown as their main overnight destination, 5% said their main motivator was touring and sightseeing, and 45% stated that 'pleasure vacation' was the main motivator. Furthermore, 51% of visitors stayed in hotel and motel accommodations while visiting Charlottetown. Thirty-two percent of expenditure was spent on accommodation, and 16% was spent on a combination of admissions and crafts/souvenirs.

Heritage properties and areas of historical importance have socio-economic value beyond any value assessed by traditional markets. The information, culture and recreation and the accommodation and food services sectors of the province employ 6,300 people. A decline in the tourist draw to the island would have detrimental effects on these sectors.

The City of Charlottetown is home to many municipally and federally designated Heritage areas and structures, including historically significant buildings recognised for historical importance or unique architecture, open greenspaces, and other cultural importance in the city's historic developmental roots.

There are approximately 335 municipally designated heritage properties, most of which lie south of Euston Street in and around the downtown core. Federally, there are about a dozen recognised sites. Many of these sites and areas lie within the probable flood plain outlined by the Digital Elevation Model, implying that there are many heritage values at risk. In other words, the 'heritage cost' of flooding is nontrivial.

In Figure 3, Scenario 1 shows a total of 30 municipally designated heritage properties at risk of flooding, for a total assessed value of $8.6 Million. Scenarios 2 and 3 show an additional 11 and 19 properties at risk, respectively, totaling approximately $10.5 Million and $11.3 Million in assessed property values. Many of the heritage sites designated by the City of Charlottetown are residential housing and likely do not have 'cultural significance value' reflected in their market prices. The houses and commercial spaces may actually be *devalued* or *undervalued* due to building and renovation restrictions (of housing exteriors, storefronts, etc.), and for that reason the market values in Figure 2.2 can be misleading in that they underestimate the societal losses associated with damage to these amenities.

In Charlottetown, as well as in other major centres, the true value of parks and recreational spaces is typically underestimated in government assessments and economic analyses. Zoning by-laws that prohibit development on park lands often result in the assessed value of the parks being limited to the value of the land. Victoria Park, Queen Elizabeth Park, and Confederation Landing Park are three areas of concern with regard to this study. To some extent, all three of these parks are potentially affected by the three scenarios, and the provincial assessment values for these parks understate the value of the park due to zoning and ownership restrictions. It has been proposed in other studies of heritage

assets and areas such as parks, that a proxy value can be obtained on the basis of the value of adjacent properties.
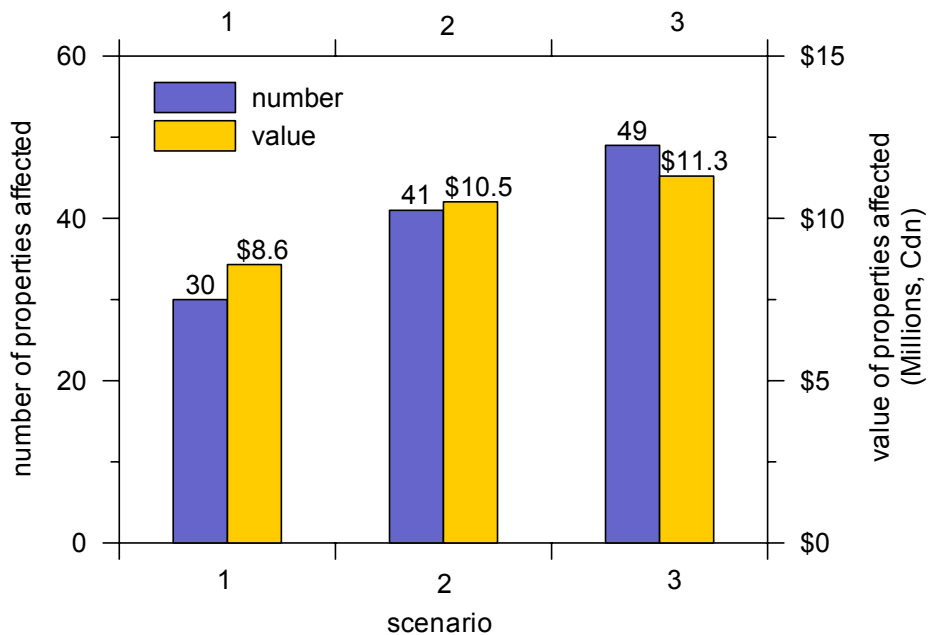
Figure 3. The number of heritage properties, and their assessed values, affected by the three flooding scenarios: (1) 4.23 m CD; (2) 4.70 m CD; and (3) 4.90 m CD.

d) Municipal infrastructure at risk – sewer, water and storm systems

The City of Charlottetown has invested millions of dollars in developing its stormwater, sewage, and waste treatment systems, including a number of upgrades (such as the primary treatment plant in 1974). The initial storm and sewer system dates back to the late 19th Century. Some areas of Charlottetown have dedicated storm water lines, while others use storm water to assist the sanitary sewer system to bring materials via gravity to the waterfront areas (usually the lowest areas of the city). Lift stations on the waterfront transfer material to the primary sewage treatment plant located on the Hillsborough River, not far from the Hillsborough Bridge. In dedicated storm water systems, there are outfalls along the shore of the North and Hillsborough Rivers, and along the harbourfront.

If the lift stations' capacity is surpassed, the two rivers and the harbour receive sewer overflow. The nine sewer lift stations (including the Treatment Plant) are situated mainly between west end of Victoria Park and the causeway to the hospital, with the exception of the West Royalty Lift Station near the intersection of North River Road and Beach Grove Road. There are overflow outfalls at each lift station and at dedicated storm sewer outfalls, for a total of 12 storm water outfalls throughout the city.

The three immediate concerns for storms with respect to the effects of sea-level rise on the storm/sewage system are:

1. A sufficient rise in water level could cause a surcharge in the sewage lines from outfalls and lift stations, leading to back-ups in residential and commercial areas;

2. A water level high enough to reach the level of the lift station could result in sea water being pumped along with sewage materials (or solely sea water) to the sewage treatment plant, creating an unnecessary amount of activity in the plant and causing problems such as corrosion, and

3. Prolonged inundation and submersion of a lift station and/or the treatment plant could render it inoperable, either temporarily or causing permanent damage, resulting in further costs to repair or relocate, exacerbating problems with disposal of untreated sewage into the marine and aquatic environment.

Table 1. Infrastructure items and associated costs

Infrastructure Item	Cost of Replacement/ At Risk	Total Amount At Risk	Total Cost At Risk
Water System Pipe	$300/m	6,500 m	$1,950,000
Sanitary System Pipe	$285/m	7,800 m	$2,223,000
Storm Sewer Pipe	$300/m	10,000 m	$ 3 Million
Force Main[1]	$350/m	3,300 m	$1,155,000
Lift Station (small)	$80,000	4 units	$320,000
Lift Station (large)	$400,000	5 units	$2,000,000
Sewage Treatment Plant	$5 million (1974 dollars)	1 unit	>$25,000,000
Proposed Secondary Expansion	$13.5 million	1 unit	$13,500,000

Estimates provided by City of Charlottetown Water and Sewer Utility
[1]Force Main is the pipe by which material is transferred from lift stations to the treatment plant.

Table 1 shows the estimated replacement costs for the types of infrastructure mentioned above. The figure for storm sewer line reflects the cost of installing storm sewer in an area that is currently 'open ditch' sewer, so is more an emplacement cost than a replacement or extension cost. However, it begins to estimate in the most basic terms the value of this type of amenity at risk. Total value as assessed by the City of Charlottetown is just over $46 Million.

Estimates from the City of Charlottetown show that the Scenario 1 water level would affect approximately 150,000 m^2 of right-of-way, to an approximate value of $12 Million. Further,

the value of sidewalks at risk in Scenario 1 is approximately $1 Million. These estimates are preliminary and do not purport to estimate the value of the land on which the roads and sidewalks are located.

Located on the shore of the Hillsborough River near the hospital causeway is the Trigen Energy-from-Waste Facility that provides district heating services to 75 customers (mainly downtown businesses) in 80 buildings. Many of these customers do not have other sources of heating and rely on the services of the Trigen facility. Its replacement cost is between 25 and 30 Million dollars. None of the scenarios shows flooding of the building itself, but floodwaters could affect the heating lines that run at a depth of about 1.1 m beneath Riverside Drive between the facility and the downtown core. It is estimated that there is nearly 1000 m of line running along Riverside Drive, and that the cost of replacing the lines is about $1000 per metre, bringing the total value of the heating line system at risk to $1 Million.

During the surge event of 21 January 2000, the Maritime Electric plant sustained damage both to the pumphouse, located on the Hillsborough River, and to the main generating facility, located further inland. The flood models show some risk of damage to the Maritime Electric facility, which carries an approximate asset value of $48 Million. Though its role is to provide back-up power when supply from New Brunswick is interrupted, loss of this service in critical situations could impact the social and physical well-being of the communities it serves, and therefore be a cost to society.

e) Other effects: health, employment, and education

Community health effects of events such as flooding are generally short-term in nature, but should be taken into account when summing up the 'damages'. There is an inherent risk of the spread of water-borne illness in some communities, as well as stress disorders in the short term immediately following events. The Intergovernmental Panel on Climate Change notes that it is difficult to quantify the full extent to which human communities can be affected by flooding events, due to the fact that the total number of health disorders due to climate change and flooding is also a function of migration, population density, quality of drinking water and sanitation systems, and vulnerability to vector and non-vector-borne diseases. A survey following the flood of 1997 in southern Manitoba revealed that there were many social impacts in the aftermath of the flood, some lasting well into the remediation process. Child-care concerns, stress disorders, loss of sleep, depression, irritability, difficulty coping with problems, confusion concerning lack of and quality of information, confusing and inadequately explained post-remediation compensation claims processes, and other effects were reported by victims of that particular flood.

Though no reliable aggregate data are available on the health and employment effects of the 21 January 2000 storm-surge event, it is realistic to attribute some "community costs and/or damages" to lost wages and health care costs (paid by the province's health care system). In many cases, the statistics are not available to attribute hospital visits directly to storm events, and comparing seasonal statistics is not feasible due to the high variability involved in health-related incidents (e.g. the timing of flu season, etc.). If it were necessary for homeowners to spend time the following day on activities such as pumping out flooded

basements, removing ice floes from yards, and removing damaged items from flooded areas, the time it took away from their normal productive days would be considered to be a cost, directly related to the surge incident. Furthermore, restaurants and businesses that closed for repairs following the storm will suffer the effects of lost revenue as a direct result of the event. As stated earlier, the employment created in the clean-up efforts to repair, service, and rebuild commercial establishments should not be seen as employment revenue which offsets the costs of the storm felt by the community as a whole. The revenue generated by clean-up and remediation efforts is often paid out of insurance funds, and is generally considered a drain on society.

In the health-related infrastructure component, we see that the Queen Elizabeth Hospital and the Hillsborough Hospital and Special Care Unit are both partially affected, although there does not appear to be any danger of flooding in the main buildings themselves. In Scenarios 2 and 3 there is some risk to one of the auxiliary buildings. Erosion could lead to seepage causing risk to structural integrity, and/or surcharge in sewer lines for instance. In Scenarios 2 and 3, it is shown that the causeway and the road that provide access to these facilities would be affected and could cause delays and degrade the quality of the service available to the public, which could become critical when coupled with possible increased demand due to storm effects.

Impacts on education appear to be minimal. Although some school properties adjacent to the Hillsborough River are susceptible to flooding, the school buildings themselves are not likely to be affected. While there is a potential for some disruption if flooding were to occur while school is in session, this is not judged to be a major issue. Some lost school time might occur and major damage in the community might require more extended closure, but time lost could probably be made up through the year, in the same way that days of closure due to major snowstorms are accommodated.

2.4 Results of the socio-economic analysis for the North Shore of PEI

a) General considerations

Rising mean sea levels, less sea ice, and higher wave energy along the North Shore of PEI can be expected to cause more severe erosion damage and possibly rapid coastal change in some places. Photogrammetric analysis of air photographs dating back to the mid-1930s shows significant change along much of the coast, including severe erosion in places and shoreline recovery or dune growth in others. The longer-term view from marine geological surveys shows that the coast on average has been retreating by at least 0.5 m/year for several thousand years. Property is lost, wetlands are encroached upon and migrate inland (but can be permanently lost if migration is limited by infrastructure), and coastal infrastructure and community-related resources are put at risk in a situation of accelerated shoreline erosion. Restricted capacity for adaptation to change of natural systems can result in significant and irreversible damage. The value of the lands lost due to coastal erosion represents a real cost of climate change (i.e. a lost 'value' of land and the services produced by or from it).

b) Study area and methodology

A detailed case study area was selected for this analysis, covering just under 12 km of coast between Tracadie Bay and Savage Harbour on the central North Shore. The area is known for its green fields, red sandstone cliffs, spectacular sand dunes and beaches, freshwater wetlands and salt marshes providing habitat to shorebirds, ducks and other birds including the endangered piping plover, nearshore habitat for lobster, and overall value to the tourism industry, although the case study area is less developed for visitors. Land use in the area is divided mainly between idle land, some farming, and some permanent residential dwellings and cottage development (in concentrated sections). The area has a mixture of sand dunes and beaches, sandstone or till cliffs, mixed forest cover, and some wetlands. The western third of the area is a nature reserve.

Since initial European settlement in the early 1700s, the Island's landscape has undergone shifts from forested land to agricultural land, and a gradual reversion of some areas back to woodland due to abandonment of some agricultural lands. There is evidence to suggest that aboriginal peoples have harvested biological resources of the area for thousands of years.

Erosion rates were calculated from repetitive beach surveys and from comparing the shoreline in digitally rectified aerial photographs from 1935, 1958, 1968, 1980, and 1990. Over 100 transects were measured between Tracadie Bay and Savage Harbour. Provincial assessment data were used to compare historical erosion rates with property values for various type of shoreline property in the affected areas. The study estimated the total amount of shorefront property (in square metres) lost to erosion and highlighted those areas that are susceptible to high rates of erosion in the near future.

Market-based real estate valuation reflects only a portion of the possible total value of the ecosystems found on the shoreline. For instance, wetlands may be undervalued or devalued because they are not 'productive' to human communities, and cannot be developed or farmed. They do, however, perform many functions that can be valued by humans, such as flood control, groundwater recharge, filtration, toxics retention, and maintenance of biodiversity. Hence, other non-market approaches must be used to assess the value of these areas. In this case, benefit transfer is used to assess the per square kilometre economic and environmental value of any wetlands contained within the study area. Many studies have been undertaken in order to approximate the value of wetland function, and estimates have ranged between $6,200 and $72,000 per hectare per year.

Agricultural land values can differ according to value of crop production, general productivity of the land, as well as its current and future use. For example, using marginal land for residential purposes can increase its market value by as much as 200 times. Thus usage dictates the extent of conventional economic value placed on the natural environment. Hence, land on the North Shore may have highly variable values depending on current usage, and therefore may be valued more under 'risk-of-erosion' scenarios. Valuation of agricultural-use land would therefore only be accurate as long as that land remained designated and used as agricultural, and not subdivided for commercial or residential use. Conversely, 'cottage country' parcels on the coastline will have a greater impact on the total 'at-risk' value of the land (per hectare, for example).

Table 2. Cottage properties in the North Shore case study area.

Description	
Number of Cottage Lots in Study Area	37[2]
Average Cottage Lot Size	0.79 hectares, or 1.96 acres
Average Cottage Lot Assessed Value	$ 39,156.00[3]
Total Cottage Lot Value (by calculation)	$ 1,449,000.00 - $1,723,000.00
Data Set 1935-1990	
Maximum Rate of Retreat, 1935-1990	1.01 m/year
Minimum Rate of Retreat, 1935-1990	0.24 m/year
Average Rate of Retreat, 1935-1990	0.53 m/year
Maximum Retreat Distance, 1935-1990	56.52 m
Minimum % of Property Eroded, 1935-1990	0.1 %/year
Maximum % of Property Eroded, 1935-1990	3.93 %/year[4]
Average % of Property Eroded, 1935 – 1990	1 %/year
Data Set 1980/81-1990	
Maximum Rate of Retreat, 1980/81-1990	2.25 m/year
Minimum Rate of Retreat, 1980/81-1990	0.29 m/year
Average Rate of Retreat, 1980/81-1990	0.76 m/year
Maximum Retreat Distance, 1980/81-1990	24.37 m
Minimum % of Property Eroded, 1980/81-1990	0.08 %/year
Maximum % of Property Eroded, 1980/81-1990	8.62 %/year
Average % of Property Eroded, 1980/81-1990	1.52 %/year
Summary	
Value of Land Lost, 1935-1990	**$ 816,000.00**
Value of Land Lost, 1980/81-1990	**$ 242,000.00**

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[2] Discrepancies between assessment values and subdivided properties could raise the number of cottage subdivided properties to 44 lots, since 4 Property Identification numbers (PIDs) currently describe 11 parcels, according to the PEI Department of Provincial Treasury Geomatics Information Centre. It is not known to the author whether there is currently cottage development on these parcels.

[3] This calculation excludes two properties whose assessed value has dropped to $100.00 due to erosion. These lots are now considered "essentially valueless."

[4] This implies that an area equivalent to twice the property size (at time of mapping) has eroded between 1935 and 1990.

The evaluation of non-property related assessment values within the study area focuses on the land cover type and degree of coverage within the study area (and within projected erosion scenarios), and an approximate value for augmenting conventional assessment values. Where this type of proxy is not available, multi-criteria analysis, that is, the provision of qualitative data *in lieu* of monetary assessment is provided.

c) Past erosion of cottage properties

Table 2 shows the number, size, and average value of cottage properties susceptible to erosion in the North Shore case study area. Some parcels of land have large permanent dwellings (a growing trend), while others are seasonal cottage residences.

The results illustrate that, although certain years might see accretion as opposed to erosion, there is a net erosion effect on the cottage lots in the case study area. Furthermore, some areas are more susceptible to erosive processes than others, putting structures at greater risk. One cottage lot in the study area was affected to such an extent that the service well-head could be seen emerging from the beach, where the rest of the lot once was situated.

The value of cottage-land lost to erosion between the years of 1935 and 1990, based on average percentage loss of property and average value of cottage-designated properties, is **$816,000** (or $15,000 per year). Between the years of 1980/81 and 1990, the value of cottage-land lost was **$242,000** (or $22,000 per year).

It is worth noting that the rates of shoreline retreat and property loss are higher during the more recent period (1980/81-1990) than during the overall study interval (1935-1990).

d) Past erosion of non-cottage properties

Table 3 shows a breakdown of assessed property values and erosion rates for the years 1935-1990 and 1980/1981-1990. There are 30 parcels of land not dedicated to cottage developments, and much of this land is dedicated to farming activities. Some is left idle due to soil conditions and erosion risk. A further limitation to delineating amount of cropland is that the land-cover mapping is somewhat inaccurate in reporting the inland extent of the dune system, due to the appearance of dunes where there might have been only a light covering of sand on the surface.

The results show that for a few properties, there is a net accretion effect, but in most others, there is a definite erosion effect. Four properties show a net accretion in the 1935-1990 series, but only one of them shows a net accretion in the 1980/1981-1990 series. The study area portion of non-cottage lots spans an average alongshore length of 0.02 hectares, or approximately 0.052 acres. Thus, most of the land parcels are long and narrow, and only one property has extensive ocean frontage (1.05 km in the parcel that lies furthest east).

The value of land lost to erosion between the years of 1935 and 1990, based on assessment values, is **$63,400** (or $1,100/year). From 1980/1981 to 1990, the number is $10,600 (or $1,000/year), meaning approximately one-sixth of the erosion since 1935 happened in the last decade. Comparing this to the total assessed value, we see that 4.24% of the value of the non-cottage land has eroded since 1935, and given that the total area of the properties is 646 hectares (1600 acres), a total amount of land eroded is approximately 15 hectares (37 acres) (between 1935 and 1990).

Again, as in the case of cottage properties, we see an acceleration of erosion and property loss for non-cottage properties during the past decade.

Table 3. Non-cottage properties in the North Shore case study area.

Description	
Number of Lots	30[5]
Average Lot Size	21.53 hectares, or 53.19 acres
Average Lot Assessed Value	$ 49,783.00
Total Assessed Value	**$ 1,493,500.00**
Data Set: 1935-1990	
Maximum Rate of Retreat, 1935-1990	1.18 m/year
Minimum Rate of Retreat, 1935-1990	- 0.07 m/year (accretion)
Average Rate of Retreat, 1935-1990	0.32 m/year
Maximum Retreat Distance, 1935-1990	65.83 m
Minimum % of Property Eroded, 1935-1990	0.55 %/year
Maximum % of Property Eroded, 1935-1990	- 0.01 %/year (accretion)
Average % of Property Eroded, 1935 - 1990	0.07 %/year
Data Set: 1980/81-1990	
Maximum Rate of Retreat, 1980/81-1990	1.82 m/year
Minimum Rate of Retreat, 1980/81-1990	-0.30 m/year
Average Rate of Retreat, 1980/81-1990	0.35 m / year
Maximum Retreat Distance, 1980/81-1990	19.99 m
Maximum % of Property Eroded, 1980/81-1990	0.85 %/year
Minimum % of Property Eroded, 1980/81-1990	-0.03 %/year (accretion)
Average % of Property Eroded, 1980/81-1990	0.07 %/year
Summary	
Value of Land Lost, 1935-1990	**$ 63,400.00**
Value of Land Lost, 1980/81-1990	**$ 10,600.00**

---

[5] Two lots showing subdivision lines were included in the non-cottage calculations. In addition, one farm lot includes a sub-assessment value of $100/acre as "buffer zone."

e) Estimated future property losses from erosion

Preliminary estimates of future erosion rates under climate change and relative sea-level rise suggest a potential increase to 1.5 to 2 times the 1935-1990 mean rates of erosion for the case study area (see Appendix 5). The rate of increase may change over the forecast time frame and will also be affected by significant year-to-year and interdecadal variance seen in the historical data. Accurate erosion-forecasting models are difficult to apply to climate change scenarios.

For this study, calculations of future erosion and associated effective loss are restricted to lost land area. Any assumptions regarding the changing market price of land parcels due to erosion would be speculative at this point. It is assumed that calculations regarding the value of land lost on the North Shore refer specifically to 'one point in time', that being the assessment data provided from January 2001. All figures are reported in 2001 Canadian dollars and reflect current land-use types in cases where entire properties erode.

Calculations of forecasted erosion rates are based on the 1935-1990 series data, though it has been seen that the 1980/81-1990 series shows higher annual retreat rates. Tables 4 and 5 show the total land loss and value loss, assuming a stable rate of erosion for the next 20 and 100 years, as well as increased rates of erosion (150 and 200 percent of current erosion rates) for the 20 and 100-year time frames. For example, Table 5 shows that, at double the present erosion rate, almost one-half of the present area of coastal properties in the study area will be lost within the next 100 years.

Table 4. 20-year erosion forecast, all properties – 1935-1990 erosion data.

	Total area	**Erosion at 100%**	**Erosion at 150%**	**Erosion at 200%**
Area	703 ha (1740 acres)	6.95 ha (17 acres)	10.4 ha (26 acres)	13.9 ha (34 acres)
Value lost		$128,000	$191,000	$255,000
Percentage of Current value		4.9%	7.4%	9.8%

Table 5. 100-year erosion forecast, all properties – 1935-1990 erosion data.

	Total area	**Erosion at 100%**	**Erosion at 150%**	**Erosion at 200%**
Area	703 ha (1740 acres)	34.7 ha (85.8 acres)	52.1 ha (129 acres)	69.5 ha (172 acres)
Value lost		$638,000	$957,000	$1.28 Million
Percentage of Current value		24.6%	36.9%	49.1%

f) Wetlands

The study area includes a number of saltwater marshes, most of which are not located on the North Shore facing the ocean but further inland along channels and inside Tracadie Bay and Savage Harbour. The GPI *Atlantic* water quality accounts estimate the value of coastal wetlands at approximately $10,000 per hectare per year (for their ecosystem services as described above), which is considered a relatively conservative estimate. At this level, coastal wetlands have a value of approximately $1/m^2 per year. Freshwater wetlands, however, have been valued at $21,206/ha per year. This translates to approximately $2.12/m^2 per year. These values should be used to augment the existing assessment values, as it is assumed that "ecological services" is not included in the methodology by which land is assessed. Using the value of $21,206/ha per year, this **adds the value of $188,448** (in the form of benefits from ecological services) to the assessed value of the land.

g) Forested land

Forested watershed values derived by GPI *Atlantic* use water-based values to approximate the value of the ecosystem services provided by forests. For instance, they approximate the value of water filtration at $2,587/ha/yr; the value of removal of air pollutants at $75/ha/yr; and the value of interception water and control of runoff at $86/ha/yr. This method, when summed, brings the value of forested lands to $2,748 per hectare per year of forested land. This is equal to $2.74/m^2. Using the GPI *Atlantic* values, the assessed value of the 18.11 hectares of forested land in the study area can be augmented by **$49,800** to account for the inclusion of ecosystem values, as contributed by the presence of the forest in the study area. One service whose inclusion could raise the augmented total value of the land is the role of forest in erosion control. The additional values contributed by forested lands should be considered when evaluating the cost of erosion, or the value 'at-risk' from erosion processes over the next 100 years.

h) Beaches and dunes

The coastal dunes of PEI are among the key natural tourist attractions of the province. From Cavendish Beach to the Nature Reserve east of Tracadie Bay, there exists a long, interconnected system of dunes, which are at risk of being breached by wave action in severe storms. There was little information available to approximate the value of the dune system, though some information was available regarding the value of beaches, through benefit transfer. One study used willingness to pay surveys to approximate the value of beaches, and identified an *annual* value of between $200 and $250 1987 US dollars per respondent. Another study placed a 'per-household' value on prevention of 30% of erosion of $33.35.

The total area of the land designated as "sand dune" by the Province of PEI within the detailed study area was estimated at 100.22 hectares[6]. This estimate includes one area currently designated as cottage development land, which could decrease the estimated area by 8.67 ha.

One point to consider is that, without the presence of the dune system, the sandstone cliffs are particularly vulnerable to erosive processes. In this way, it would appear that the very presence of the sand dune system on the North Shore is the most important land-conservation tool currently available in nature. The absence of the dune system could lead to accelerated rates of erosion in vulnerable areas.

Table 6 illustrates the added value attributable to ecosystem services provided by the natural environment within 200m of the shoreline in this particular study area.

Table 6. Added value from natural environment – wetlands, forests, and dunes.

| Ecosystem Type	Amount	Value (per hectare per year)	Total Added Value
Wetlands	8.9 ha	$21,206.00	$188,448.00
Forested Land	18.11 ha	$2,748.00	$49,800.00
Beaches / Dunes	100.22 ha	not available	not available

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[6] Representative only of sand dunes located on properties designated as cottage and non-cottage; does not include the Nature Reserve area between Tracadie Bay and the study area.

3. Physical impacts of climate change in the study area

3.1 Long-term sea-level rise

a) Establishing the vertical reference level for the elevation of land and water surfaces

All water level elevations and bathymetric soundings are referred to a low water hydrographic datum called Chart Datum. Chart Datum is presently set at Lower Low Water Large Tide (LLWLT) which is the lowest predicted water level, averaged over several years. The relationship between land and sea datums can vary dramatically, as the range of tidal behaviour changes from place to place. This relationship is essentially a disjoint and complicated one. Indeed, there is often a great deal of confusion within the coastal engineering community as to where tidal levels fall on land, relative to geodetic zero (the reference level for land elevations). It is important to develop an intimate understanding of the changing nature of this relationship between reference levels when attempting to merge terrestrial and marine data.
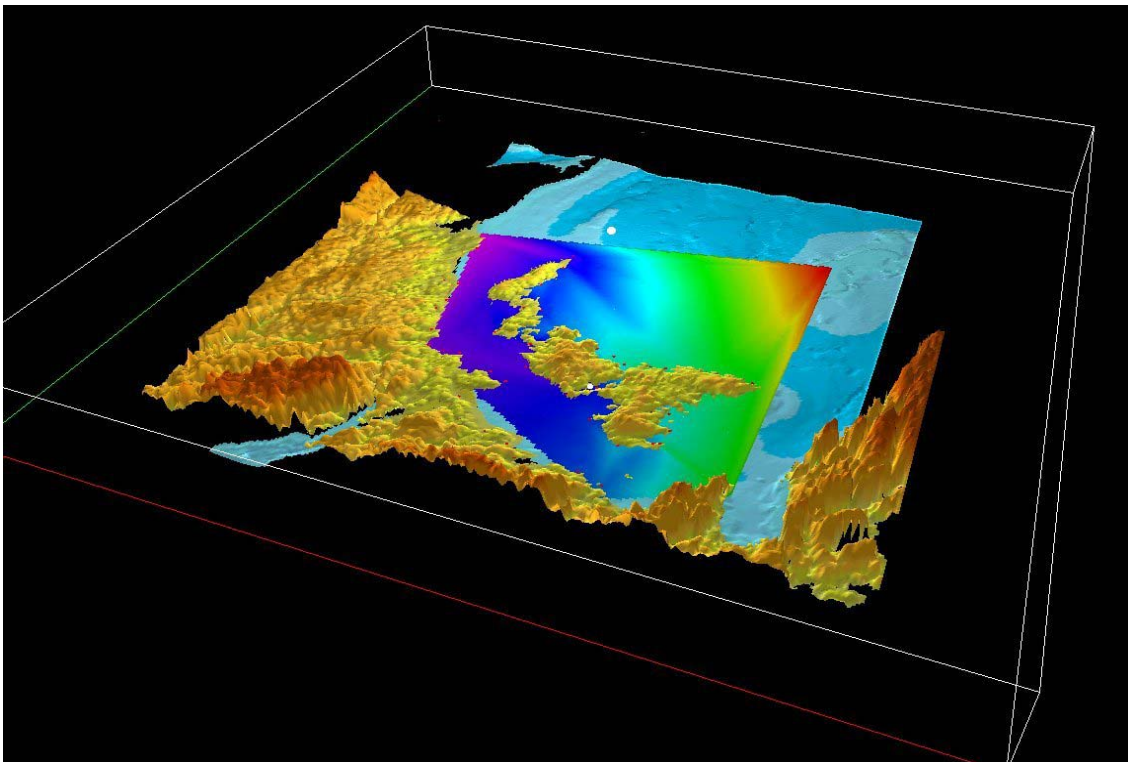
Figure 4. Three-dimensional fusion of terrestrial and marine data in the southwest Gulf of St. Lawrence. A 'shoreline' is defined by the intersection of a specific tidal datum surface with the digital elevation model (DEM) landform. Using a high resolution DEM, the shoreline and/or a 'flood map' is made possible for a given water level.

Land elevations can be measured using airborne LIDAR (scanning-laser) technology. This system produces digital elevation models (DEMs), which are effectively very high precision topographic maps of land surfaces (see Section 3.4 and Appendix 4). The geographic positions of the LIDAR measurements must be known accurately and this is achieved using Global Positioning System (GPS) receivers operating in differential mode (DGPS) to obtain positions at sub-metre resolution. As DGPS technology has no inherent spatial knowledge of either geodetic datum or Chart Datum, this information must be provided in order to move all information onto a common datum reference. To supply this information to the project, an extensive high-precision DGPS survey campaign was carried out over the southwest quadrant of the Gulf of St. Lawrence surrounding PEI. The details of this campaign are provided in Appendix 3. This survey work involved over 50 tidal stations in PEI, New Brunswick and Nova Scotia. Its prime purpose was to tie the coastal hydrographic measurements to the geodetic or land-based control network, as shown in Figure 4.

The high density of survey sites allowed three-dimensional interpolation of several tidal datums with decimeter accuracy. Of particular interest are the datums which define the high and low shorelines. These are the thresholds between which almost all tidal activity occurs. In particular, the Higher High Water Large Tide (HHWLT) threshold approximates the maximum water level to which the tides can reach, and determines the 'official' shoreline on hydrographic charts. By adjusting HHWLT and a given digital elevation model showing land elevations to the same datum reference, and then superimposing various storm surge scenarios, high precision maps of hypothetical floods can be produced.

b) Sea-level rise over the past 10 000 years

As shown in Figure 5, following initial flooding after the last Ice Age, relative sea level has risen by almost 45 m or more over the past 10 000 years, drowning the former land surface that joined PEI to the Nova Scotia and New Brunswick mainland. River valleys on the floor of Northumberland Strait (former extensions of the Hillsborough and other rivers on PEI) have been progressively backflooded to form the present bays and estuaries such as Hillsborough Bay and Charlottetown Harbour. Similar processes have operated on the North Shore, where imagery from multibeam bathymetry shows the seaward extensions of rivers across the inner shelf (Appendix 5). Rising relative sea levels on this coast have formed the flooded-valley estuaries such as Rustico Bay, Savage Harbour, and St. Peters Bay. The rate of relative sea-level rise (combination of land subsidence and sea-level rise) over the past 6000 years along the central North Shore of PEI has averaged about 30 cm/century, but decelerated through time from an earlier more rapid rate of rise to a somewhat lower rate over the past 2000 years. As shown below and in Figure 5, the rate of relative sea-level rise during the 20th Century appears to have been higher again.
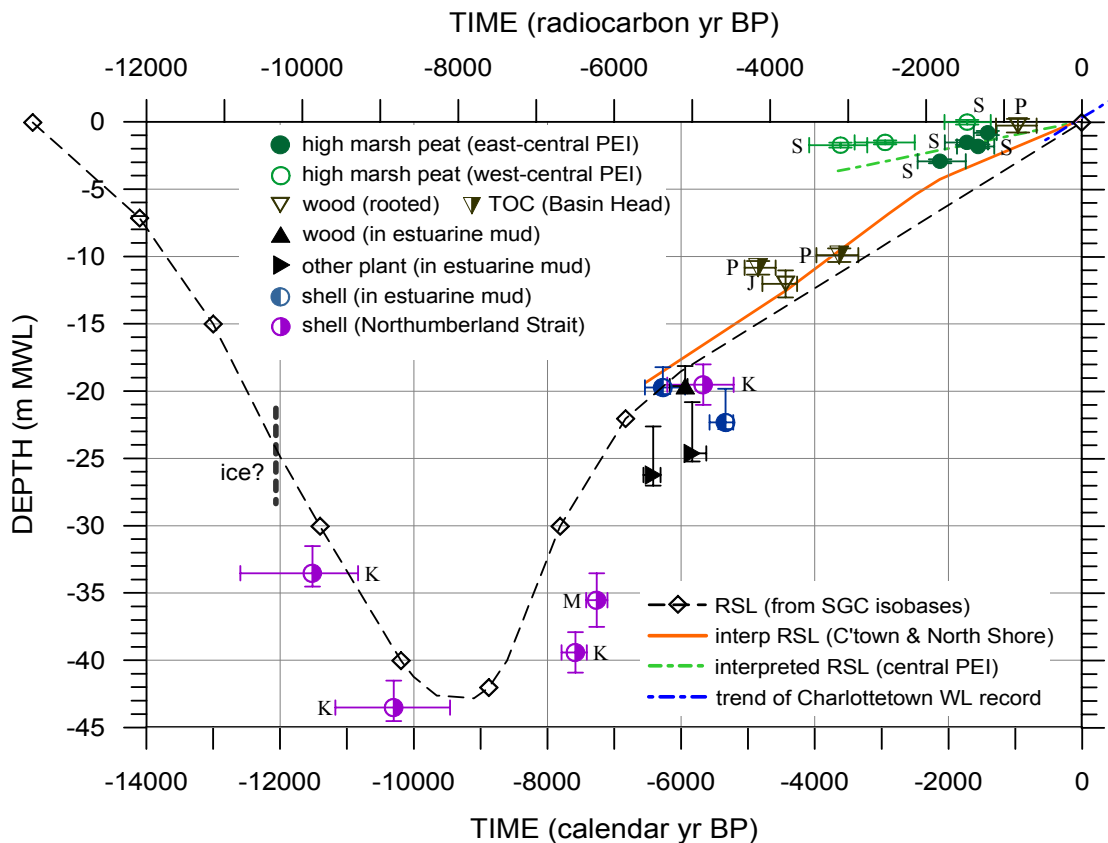
Figure 5. Relative sea-level changes since the last glacial maximum in central and eastern Prince Edward Island. Note this represents the combination of sea-level change and vertical land movement. The black broken line indicates the general trend and the solid (orange) line is the best estimate of trend for Charlottetown and the central North Shore over the past 6000 years (see Appendix 1, Part 1 for details).

c) Sea-level rise in recent times (since 1911)

To examine changes in sea level around PEI in more recent times, an exhaustive analysis was carried on tide-gauge data from Charlottetown and Rustico, PEI; Pictou, NS; and Pointe-du-Chêne (Shediac) and Lower Escuminac, NB. Errors such as spikes, outliers, missing data, interpolated data, calibration drift and wrong date stamps were removed. Since atmospheric pressure affects sea level, adjustment were made to bring all data to a standard atmospheric pressure of 1013.4 mb (101.34 kPa). The final results for Charlottetown, shown in Figure 6, indicate that the mean sea level has been rising at a rate of 32 cm/century since records began in the first decade of the 1900s.

The water level data for Rustico are available from 1972 to 1996. The calculated rate of sea-level rise at this location is 29 cm/century, consistent with that calculated for Charlottetown. However, confidence in the Rustico data is lower because of the shorter

record and large periods of missing data. With a longer record, it is likely that the Rustico water-level data would show a slightly higher trend, closer to that obtained from the records in Charlottetown.

Part of the long-term sea-level rise (perhaps 20 cm/century) is due to crustal subsidence following postglacial adjustments to changing ice and water loads: the remaining 12 cm/century at Charlottetown is a signal of global and regional sea-level rise. It should be noted that storm surges and ocean waves are also factors at the coastline and are carried to higher levels on rising mean sea level. Even in the absence of climate change, the present rate of sea-level rise in PEI will bring challenges in the future to human interests and ecological systems in the coastal zone.

Charlottetown - annual mean water levels adjusted for missing data and pressure variation

$$y = 0.3229x + 146.45$$
$$R^2 = 0.9282$$
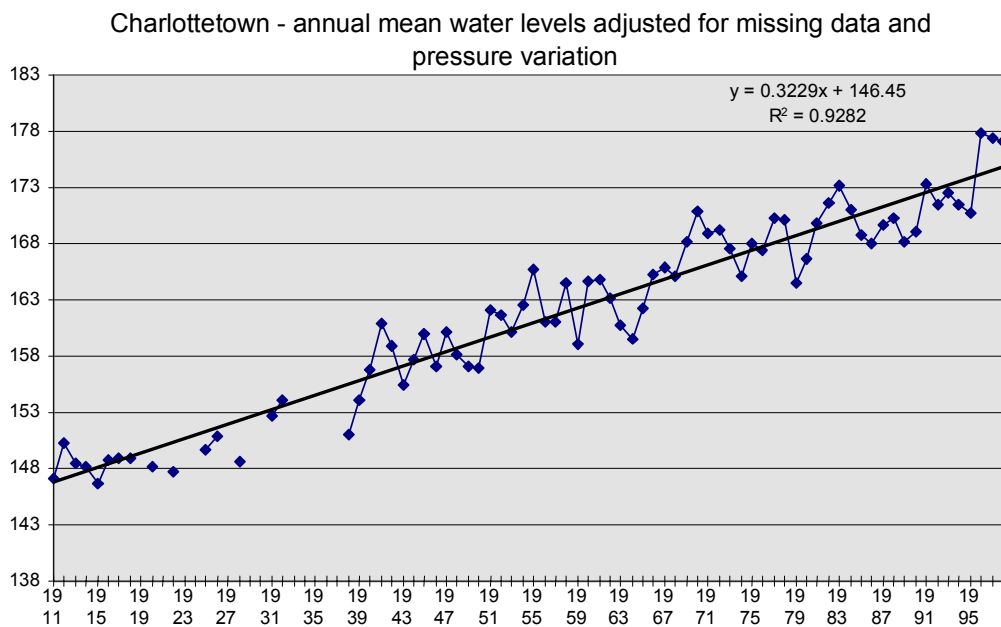
Figure 6. Annual means (centimetres above Chart Datum) for Charlottetown water level data 1911-1998, adjusted for missing data and variations in atmospheric pressure (see Appendix 1, Part 1 for details.)

d) Sea-level rise in a future warmed climate

Rising global sea level is one of the most confidently predicted impacts of climate warming, with major implications for coastal communities around the world. The latest analysis issued by the Intergovernmental Panel on Climate Change (IPCC) predicts an increase in global sea level from 1990 and 2100 between 0.09 and 0.88 m with a central value of 0.48 m, based on the IPCC greenhouse gas emission scenarios. This central value corresponds to 2.2 to 4.4 times the average rate of global sea-level rise during the 20th Century, as deduced from tide-gauge data.

There is broad consensus that 20th Century sea-level rise was in the range from 1.0 to 2.0 mm/yr and that, based on the few tide-gauge records of exceptionally long duration in Europe (e.g. Amsterdam ~1700-1920, Brest ~1810-1990, Stockholm ~1780-1990), there is evidence for accelerated sea-level rise in the 20th Century relative to the rates observed earlier. This is consistent with our results, showing that the Charlottetown tide-gauge record of relative sea-level rise, averaging 3.2 mm/yr since 1911, is greater than the rate of approximately 2 mm/yr over the past 2000 years, deduced from geological evidence.

The regional implications of the IPCC global predictions for relative sea-level rise on the coast of Prince Edward Island are less clear. The latest IPCC projections of global sea-level rise, incorporate the following components:

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

Based on various considerations, this study has adopted the central IPCC value of about 0.5 m for sea-level rise, combined with a risk-conservative estimate of 0.2 m for crustal subsidence, to obtain a total projection of 0.7 m relative sea-level rise to 2100 in the Charlottetown region. This value has been used in estimating future storm-surge and other flood levels, recognizing that some projections imply a lower increase, but that the total rise from 1990 to 2100 using our estimate of crustal subsidence combined with the maximum IPCC projection could amount to a rise in mean sea level at Charlottetown of as much as 1.10 m.

3.2 Increased storminess and storm surges

### a) The frequency of occurrence of storm surges in the past

Storm surges are the 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) high tide are events which lead to coastal inundation. 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 of the region. To this end, statistics of storm-surge events in excess of 60 cm at Charlottetown and Rustico were developed and extreme water level events were examined.

Storm surges at Charlottetown 1960-1998

Predicted astronomical tides for Charlottetown were subtracted from the adjusted observed water level data for the period 1960-1998. To qualify as separate storm surge events, differences in excess of 60 cm must have peaks separated by at least 12 hours and must pass through a trough of less than 40 cm. In addition to the height of the storm

surge, the maximum water reached during the event was also noted. This was evaluated as the highest observed water level associated with the storm-surge event while the surge was in excess of 40 cm. This was usually different from the water level at the time of the peak surge. 302 events were identified during the period 1960-1998.

It should be remembered that water levels must be adjusted for sea level rise during the period of the record. Using 1977 as a base year, the observed water level data at Charlottetown before and after 1977 were corrected for relative sea level rise (i.e. 32 cm/century). Therefore, the maximum water level reached during a given event is not the actual observed water level but may be considered as the level the event would have reached if it had occurred in 1977.

Charlottetown - average yearly events 1940 to 1998 by height
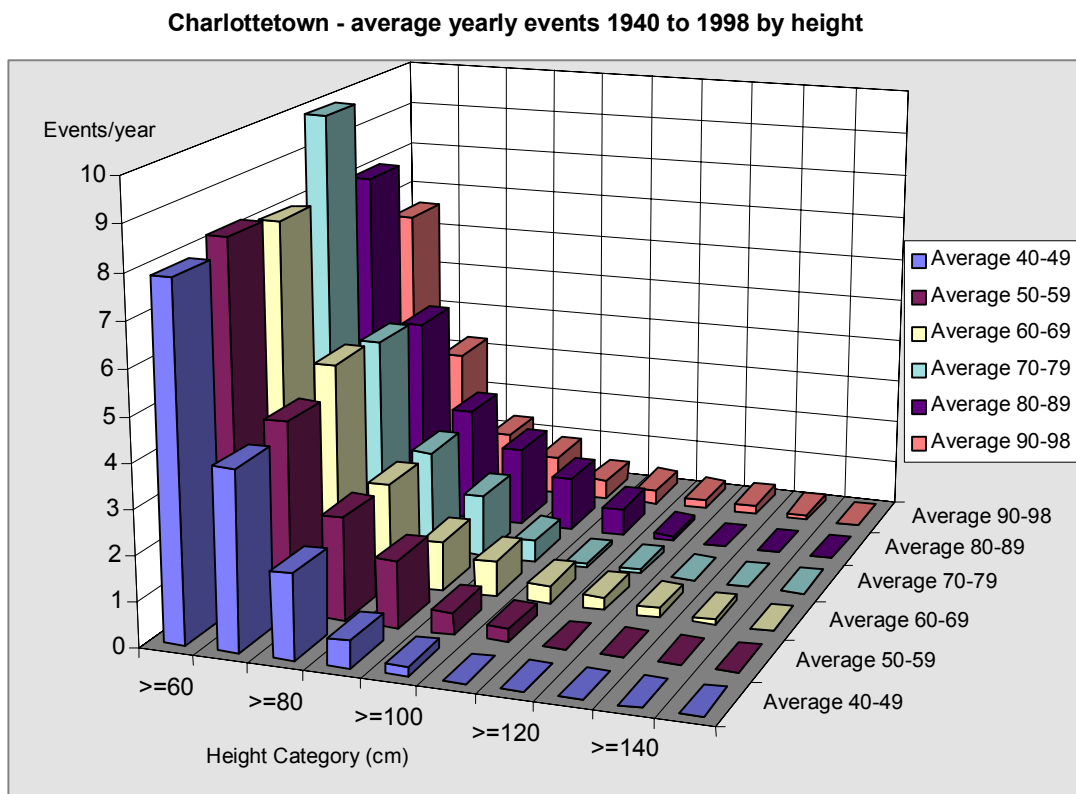
Figure 7. The average number of storm surge events per year at Charlottetown in each decade (1940-1949, …, 1990-1998), classified by height $\Delta\zeta$ ($60 \leq \Delta\zeta < 70$ cm, $70 \leq \Delta\zeta < 80$ cm , …, $\Delta\zeta > 140$ cm).

Figure 7 shows some results of the analysis. Generally speaking, storm surges exceeding 60 cm are frequent events in Charlottetown, occurring about 8 times a year on average (compared, for instance, to twice a year along the Atlantic coast at Halifax). They are mainly associated with winter storms and show great variability over the years. Storm-surge events above 120 cm are uncommon and occur on average about twice a decade.

During the years 1960-1998, there were times when the storm surges were clustered, however it is difficult to see any obvious trends in the data. Storm surges appear to have become a little more frequent from the 1940s to the 1950s to the 1960s and larger surges (>120 cm) not present at all in the 1940s and 1950s show up thereafter, although they remain uncommon events. The 1970s and 1980s were characterized by more frequent large surges, 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 7 the water-level data were adjusted to the base year 1977 assuming a linear sea-level rise of 32 cm/century. These data were subsequently adjusted to a base year of 2000 by adding a further sea-level rise of 7.36 cm to the water-level values. This time series then represents the approximate level that any storm-surge event from the past might have reached if it had occurred in the year 2000. The water levels were also adjusted to a third base year of 2100 assuming that the sea level continues to rise at 30 cm/century. Table 7 shows the frequency of occurrence of water levels for the new base years of 2000 and 2100.

Table 7. Frequency of water levels in Charlottetown exceeding a specified level above chart datum

Threshold level above chart datum (metres)	No of storm surges per year above threshold (year 2000)	No of storm surges per year above threshold (year 2100)
>=3.2	2.28	?
>=3.3	1.00	?
>=3.4	0.51	?
>=3.5	0.15	2.28
>=3.6	0.15	1.00
>=3.7	0.10	0.51
>=3.8	0.08	0.15
>=3.9	0.03	0.15
>=4.0	0	0.10
>=4.1	0	0.08
>=4.2	0	0.03
>=4.3	0	0
>=4.4	0	0
>=4.5	0	0

The digital elevation model for Charlottetown (Section 3.4 and Appendix 4) demonstrated that sea water begins to flood the waterfront at a level of about 3.6 m above Chart Datum. 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 between 1911 and 1998, only six events have reached this level and had an impact on the Charlottetown waterfront. If sea-level rise to the year 2000 is taken into account, then eight of these storms would have

caused some flooding of the waterfront if they had occurred in the year 2000. The change from the present situation is even more pronounced if one accounts for sea-level rise to the year 2100 (right-hand column of Table 7). Whereas, at present, we can expect one exceedance of 3.6 m above Chart Datum every 7 years or so, in the year 2100 we could expect one such exceedance on average *every year* with one event above 4.0 m CD every 10 year or so; and this is based on a simple linear extrapolation of present relative sea-level rise without the anticipated acceleration due to climate change. Table 7 demonstrates that with sea-level rise and global warming, not only will flooding move to higher levels but that the floods at the lower levels will become much more frequent in Charlottetown.

Storm surges at Rustico (1975-1995)

The climatology of storm surges of Rustico is not as reliable as that for Charlottetown due to the large amount of missing data and interpolated events. The data set proved to be particularly disappointing in that the biggest storms that showed up during this period in Pointe-du-Chêne and Lower Escuminac were missing in the Rustico water-level data. The highest observed water level at Rustico is therefore considerably lower than the level that we might reasonably expect could occur today.

As at Charlottetown storm surges at Rustico are mainly associated with the passage of winter storms but there does seem to be a slightly larger percentage of events present in the warmer weather months.

b) Storm surges in the future

At least two indicators of climate change are giving warnings that the frequency of occurrence and severity of storm surges may increase in the future. First, as discussed in Section 3.1, the sea level in the vicinity of PEI has been rising at a rate of about 30 cm/century and may be accelerating; the total relative sea-level rise by 2100 may be as much as 0.7 m or more. Second, as discussed in Section 3.3 below, ice cover in the Gulf of St. Lawrence in the winter, when many severe storms occur, may be a thing of the past by 2050. This means that the dampening effect of sea ice on waves (and any negative effect on storm-surge amplitudes) could be absent.

Two approaches were used in this project to address the question of storm surges in the future. First, a numerical model to forecast storm surges was developed at Dalhousie University and is now run operationally by Environment Canada. A detailed description of this model is provided in Appendix 2. This model uses, among other things, wind and sea-level atmospheric pressure as input data. Testing the model showed that it forecast storm surges generally to within about 10 cm with a lead time of the order of one day.

Could the 21 January 2000 storm have been much worse? The Probable Maximum Storm (PMS) methodology consists of modifying the initial conditions for the atmospheric model in such a way as to maximize the development of the storm, hence generating the largest possible storm, and/or modifying the storm track. These modified initial conditions are then used to rerun the atmospheric model which produces more intense surface wind and pressure fields. An additional modification for some runs is to change the location of the

initiation of the storm and the atmospheric conditions that influence its evolution. The surface pressure and wind fields forecast by the atmospheric model are then fed to the storm-surge model. The resulting surges are compared with the original and observed ones, to examine their sensitivity to modified storm track and intensity.

Preliminary results of this testing indicate that storm surges in the Gulf of St. Lawrence are highly sensitive to changes in storm trajectory, and in particular the storm surges associated with the 21 January 2000 storm could have been significantly higher had the storm been slightly further to the west.

The second approach to looking at storm surges in the future was to carry out a statistical analysis of the hourly sea levels recorded at Charlottetown and to try to incorporate the effects of future climate change. Annual maximum sea levels were available from 1938 to
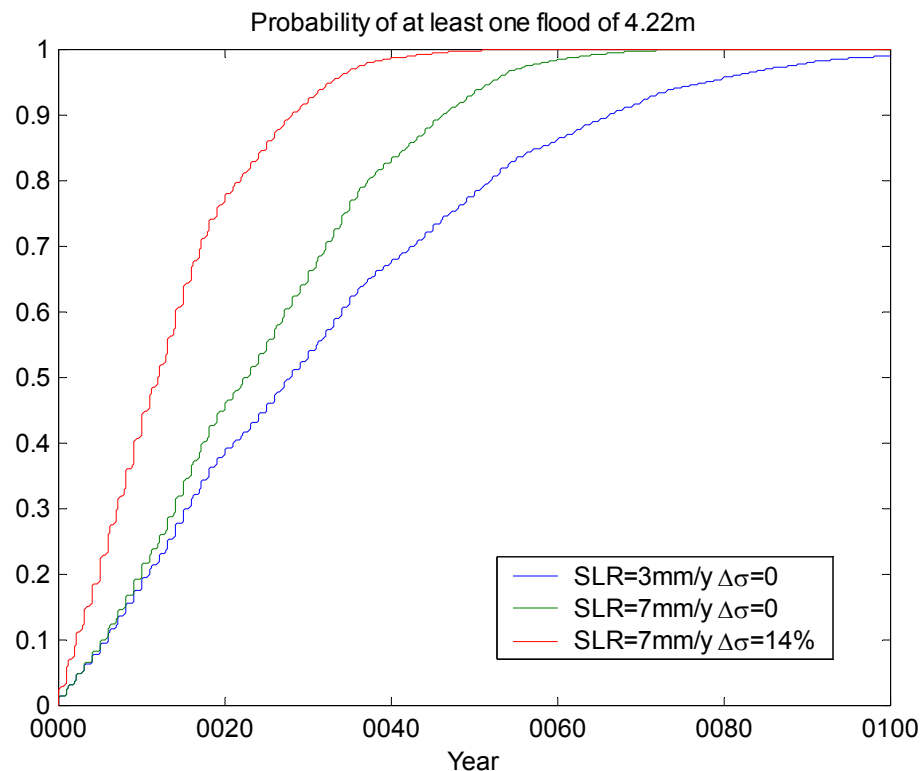
Figure 8. Probability of water levels equal to or greater than 4.22 m CD with the passage of time. Probability is shown on the y-axis and time on the x-axis (ranging from 1 January 2001 to 31 December 2099). Recall that a water level of 4.22 m CD is what occurred in Charlottetown on 21 Jan 2000. The lowest line corresponds to a rate of increase of sea level of 3 mm/yr; the middle line corresponds to a sea level rise of 7 mm/yr. The upper line corresponds to a sea level rise of 7 mm/yr plus an increase in wind speed of 10% resulting from greater storm intensity.

2000; hourly maxima were available from 1962 to 2000. Because the data after 1960 were based upon 15 minute means rather than hourly means, it was determined that the annual maxima after 1960 would be biased about 2 cm higher than those before 1960. To make the entire record consistent, a 2 cm adjustment was added to the annual maxima before 1960.
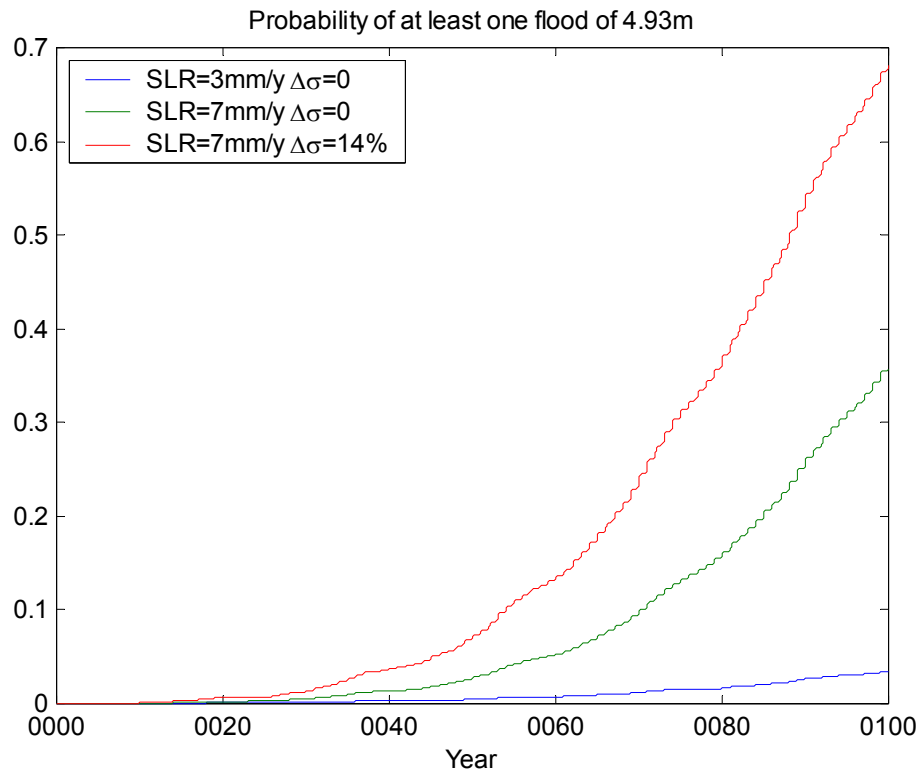
Figure 9. Same format as Figure 8 but for a critical level of 4.93 m CD.

Because statistical analyses of the frequency of occurrence of past storm surges do not take account of factors such as increasing sea levels and storminess in the future, it was necessary to develop and employ a new method (the Conditional Probability Method, CPM) to examine storm surges in the future. The analysis is described in detail in Appendix 2.

Figure 8 shows the probability of exceeding 4.22 m at Charlottetown (approximately the level of the 21 January 2000 flood) at least once before the date shown. The figure shows that, with the present rate of sea-level rise and no increase in storminess, the probability of sea level in Charlottetown reaching 4.22 m CD by 2050 is about 0.8; this increases to about 0.99 by 2100. With an acceleration of sea-level rise to 70 cm/century (about double the present rate), the probability increases 0.95 by 2050 and to a virtual certainty by 2100. In the worst-case scenario, with sea-level rise about double the present rate and with a 10% increase in wind speed, it is virtually a certainty that there will be another 4.22 m flood in Charlottetown between now and 2050. If one looks at the period between now and

2050, an increase in storm intensity (wind speed) has a greater effect upon the chances of having a 4.22 m flood than a doubling of the rate of sea-level rise.

The effect of an increase in storm intensity shows up even more for a flood level of 4.93 m CD, as shown in Figure 9. The possibility of at least one 4.93 m flood by 2100 is almost 0.7 with a doubling of sea-level rise and a 10% increase in wind speed.

3.3 Wind climatology of the Gulf of St. Lawrence

High wind speeds are an important indicator and effect of storms and contribute to both wave and surge development. The wind climatology was examined in this study as a complement to the storm-surge and wave analysis, in order to gain a better understanding of interannual, interdecadal, and longer-term variation in storminess and to investigate the possibility of an increase in wind intensity over the period of record. Variation in wind direction was also considered in relation to storm-surge occurrence and a list of storm events was compiled.
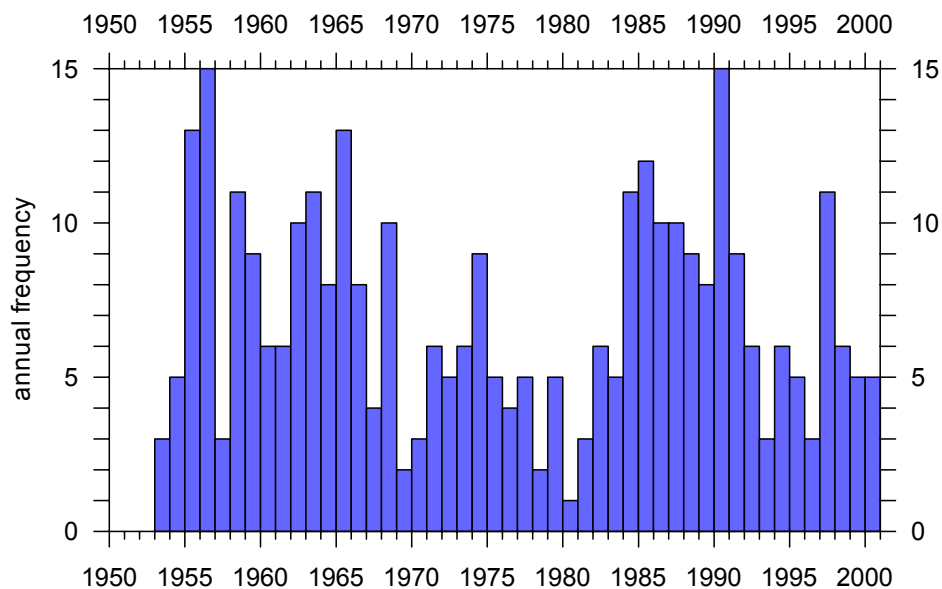
Figure 10. The annual frequency of northerly wind storms consisting of at least 6 hours of northerly winds >50 km/hour.

Wind data consisting of hourly to 6 hourly wind speeds and directions at various locations in the Gulf of St. Lawrence and along Northumberland Strait were obtained from the Meteorological Service of Canada and compiled in a database (see Appendix 1, Part 3). Three stations in the Magdalen Islands together give a nearly continuous record of marine storm winds from 1953 to the present but comparison of the overlapping portions of the three records shows that considerable variability in wind speeds exists and that the records must be adjusted to create a single time series.

A list of 464 storms between 1953 and 2000 with winds greater than or equal to 50 km/hour for at least 6 hours was constructed from the transformed, composite Magdalen Islands record and was filtered to include only the 334 storms with mean northerly wind directions (i.e. blowing from between 270° and 90° through north), corresponding to the most common storm wind direction, the directions of longest ice-free fetch, and the exposure of the PEI North Shore. Most storms occur in winter and fall. Fall storms can be tropical or extratropical in origin whereas winter storms are extratropical. High winds tend to be northwesterly in the fall and northeasterly in winter.

The analysis indicated that there has been annual and seasonal variability in the frequency, direction and intensity of wind storms in the Gulf of St. Lawrence since 1953 and that no significant trend is present. Different measures of 'storminess', the tendency for some years or decades to have either more or stronger storms, do not perfectly agree but can be generalized to indicate stormy and calm periods. Stormy periods appear to have occurred between the late 1950s and early 1960s and during the 1980s whereas less stormy periods appear to have occurred prior to 1955, in the 1970s and after 1991.

Analysis of storm-surge events indicated a significant correlation between large surges in the southern Gulf of St. Lawrence and strong northeast winds. Other surges are related to winds out of the north and northwest. The storms that most often cause surges follow a preferred track in which they move northeast from an area of cyclogenesis off the coast of the southeastern USA. The wind records show some periods of greater or lesser northeasterly wind activity consistent with the seasonal and interdecadal variation in storm-surge occurrence at Charlottetown.

No trend in wind speed is observed in the historical record and similarly the latest version of the Canadian General Circulation Model (CGCM) indicates only a slight increase in mean wind speeds to 2060 and a slight decrease to 2100. Seasonally, however, fall and winter storminess are expected to increase beginning after 2010 indicating an increase in winds that cause surges and high waves.

3.4 Wave climatology of the Gulf of St. Lawrence

Waves are one of the most widely recognized indicators of storm activity and constitute a significant natural hazard for shoreline erosion and infrastructure damage in coastal settings. Coastal erosion, increased sediment mobility and damage to infrastructure can be caused by waves impinging on the shoreline, especially when they are superimposed on higher than normal water levels during storm surges.

In this study, available wave data were compiled in a database (see Appendix 1, Part 4) and analyzed to investigate the wave climatology of the southern Gulf of St. Lawrence. Also as a contribution to this project, wave data were collected off the North Shore of PEI in the autumn of 1999 and 2000, contributing to knowledge of waves impacting this shoreline. New data include one benchmark storm on 29-31 October 2000 during which waves up to 14 m maximum height were recorded and the significant wave height peaked at greater than 7 m (Appendix 1, Part 4).

Measured data are sparse and unavailable in winter so previous research has focused on the development of hindcast time series using models of varying complexity and often with limited validation data. Analysis of a recent long-term wave hindcast shows that waves tend to be largest and most common in the fall. Waves are more often fetch-limited by ice in winter and storms are less frequent or severe in summer. Some fall seasons have more frequent wave events than others (Figure 11): the early 1960s was a period of generally frequent high waves; individual years of both high and low frequency of fall waves occurred in the 1970s and 1980s; and, in the 1990s, unlike previous decades, large autumn waves occurred in most years of hindcasting. The direction of high waves is hindcast to have a northwest mode whereas low waves tend to be also from the southwest. Northeast waves may also be important but, because northeast winds may occur most often in winter, these waves are not measured and may also be poorly hindcast.
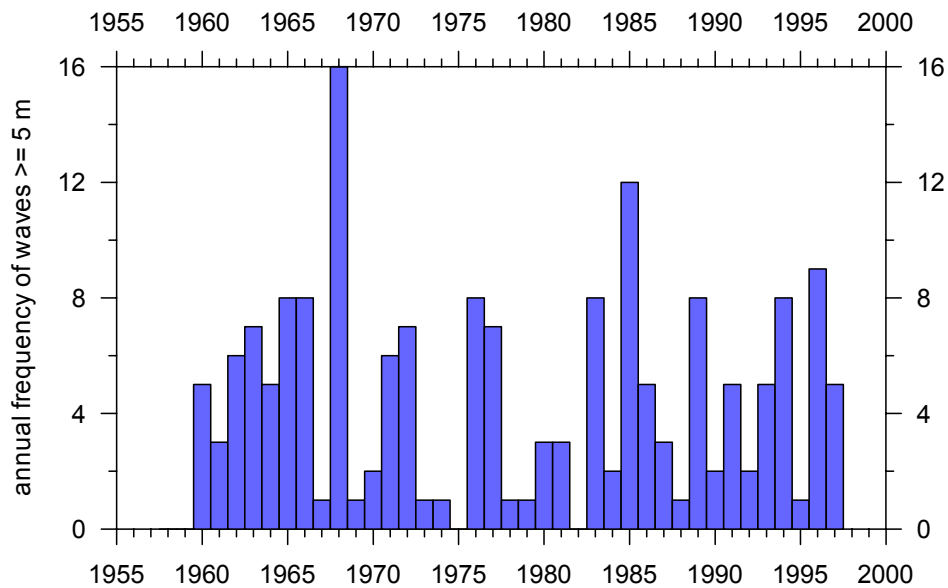
Figure 11. The annual frequency of hindcast waves with $H_s \geq 5$ m. Data include fetch limitation by sea ice after 1971.

It is useful to include ice in long-term hindcasting because sea ice limits wave formation by reducing available fetch; also the energy of breaking waves is absorbed by nearshore ice rather than the shoreline and coastal infrastructure. All available ice data, however, are required to be implemented in the hindcast and, for comparison, waves should also be remotely measured. This would allow stronger conclusions to be drawn about the role of ice in the dampening of waves. It would also give one insight into the possible effects of a decreased or absent ice cover in the Gulf in the future due to climate change.

Some models of future climate indicate that after 2030 winters are expected to have stronger winds and, after 2045, no sea ice, thus strongly indicating a worsening of the wave climate in the Gulf of St. Lawrence. The frequency of extreme waves during severe

winter storms may increase causing increased shoreline erosion, coastal sediment mobility and damage to infrastructure.

3.5 Decreased ice cover in the Gulf of St. Lawrence

Storm surges and waves are expected to increase if sea ice in the Gulf decreases as predicted in future global-change scenarios. In this study, the Canadian Ice Service sea-ice chart database was used to derive an up-to-date climatology of sea ice in the Gulf. Interannual and interdecadal variability of the ice cover was examined and an ice severity index was derived. This information is required for quantitative studies of the dampening effect of sea ice on storm surges and waves. Past trends and future scenarios of sea ice in the Gulf of St. Lawrence were also examined.

The study showed that, during the 30-year period of study 1971-2000, ice cover in the Gulf was highly variable from one year to another. The total accumulated ice coverage (TAIC) can be used as an ice severity index for the whole season. A quick glance at Figure 12 shows that TAIC ranged from 1.1 million km^2 in the year 2000 to almost 3 million km^2 in 1993. We also see that the last three years (1998-2000) have been low ice years but we also had a similar situation in the early 1980s. Although the number of years is small, Figure 12 also seems to indicate the presence of cycles in the variability of TAIC, with approximate periods of 15 years and maximums in the mid 1970s and again in early 1990s. Researchers have observed that there may also be possible links between various ice parameters and environmental indices such as the North Atlantic Oscillation, El Niño/ Southern Oscillation, solar flux or volcanic eruptions.
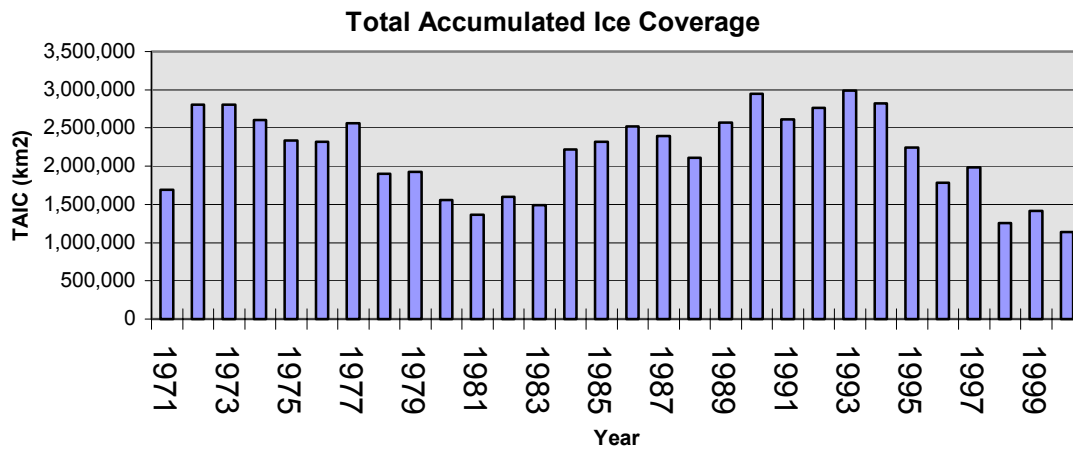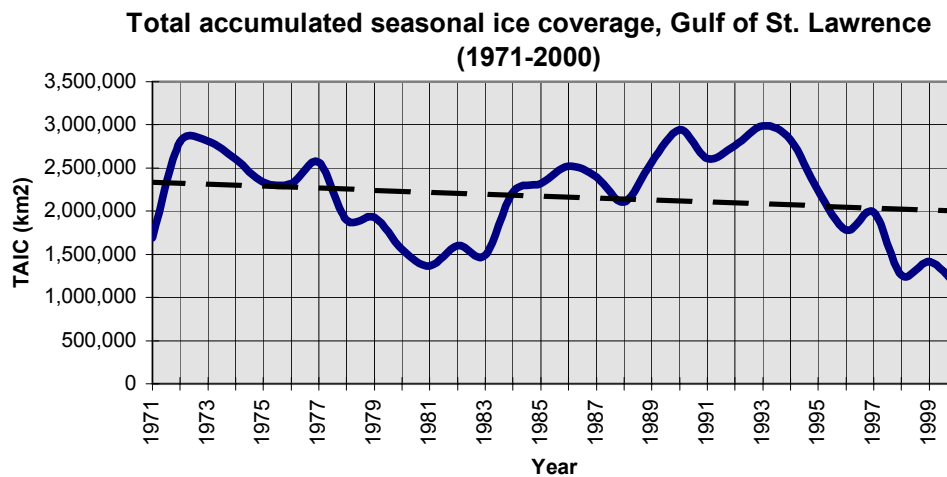

Figure 12. Total accumulated ice coverage (TAIC), Gulf of St. Lawrence, 1971-2000.

Total accumulated seasonal ice coverage, Gulf of St. Lawrence (1971-2000)

Figure 13. Trends in total accumulated ice coverage. Linear trend is not statistically significant but interdecadal variation is real.

The latest results of the Canadian Global Circulation Model (CGCM) suggest that, by the year 2050, the ice extent in the northern hemisphere may be limited to higher latitudes and that the Gulf of St. Lawrence may be free of ice. Using the TAIC as a measure of ice cover, we have asked the question whether the past 30 years of sea-ice data from the Gulf shows any indication of a downward trend. The linear regression in Figure 13 suggests a slight decrease in ice cover but is not statistically distinguishable from zero and explains only 3% of the total variance. Another 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. The dominant characteristic of the time series shown in Figures 12 and 13 is the oscillation between years of maximum ice cover such as 1993 and years in which the total accumulated ice cover is 50% less, as in the early 1980s and again in 1998-2000. Year-to-year fluctuations can be expected to continue, but the possibility of significantly reduced ice coverage, with its implications for more severe wave conditions in winter, should not be overlooked.

Other impacts of ice that were not addressed from a climate perspective in this study include:
- direct damage caused by ice ride-up or pile-up on the coast; and
- nearshore ice or icefoot protection of the coast against wave erosion.

Both effects were documented in this study in relation to large storms and their impacts (Appendix 7) and new information was also compiled on the extent and characteristics of the icefoot and nearshore ice complex along the North Shore (Appendix 5). In particular, during the storm of 21 January 2000, ice ride-up pushed a lighthouse in Charlottetown off its foundation, caused severe damage to a golf course in the Charlottetown area, and combinations of ice ride-up and pile-up damaged wharves and other infrastructure around

the Island. The most severe ice damage during that storm, including partial demolition of homes and harbour structures, occurred along the New Brunswick coast. Wave damage along the North Shore of PEI was limited because of the presence of ice against the coast. On the other hand, when open water develops seaward of a grounded nearshore ice complex or when waves impinge directly on the vertical face of the icefoot, unusual scour and profile downcutting may occur in the nearshore, promoting more rapid shore erosion.

3.6 Flooding of coastal areas

a) High-resolution digital elevation models for flood mapping

In order to map areas at risk of coastal storm-surge flooding, it is necessary to have an accurate and high-resolution representation of the topography. Traditional topographic mapping involves stereographic measurements from aerial photography, known as photogrammetry. The products from traditional photogrammetry include the generation of contour lines at a fixed interval or the production of mass points with associated heights. Extensive ground control in the form of precise survey coordinates associated with photo-identifiable locations is required for the process. The detail and accuracy of this mapping is insufficient however for modelling inundation from storm-surge sea-level increases in the order of 1 to 2 m.

An emerging technology known as LIDAR (Light Detection and Ranging) involves an aircraft emitting laser pulses towards the ground and measuring the return time of the pulse. By utilizing precise Global Position System (GPS) technology to determine the location of the aircraft and an Inertial Measurement Unit (IMU) to measure the attitude (pitch, yaw and roll) of the aircraft, the location of individual laser returns can be determined. The reported accuracy of the overall positioning system is quoted at ± 30 cm in the horizontal plane and ± 20 cm in the vertical.

As part of a larger research initiative in the region, in particular with the Applied Geomatics Research Group of the Centre of Geographic Sciences (COGS), Terra Remote Sensing Inc. of Sidney BC were contracted in the summer of 2000 to acquire LIDAR imagery over parts of Charlottetown and the North Shore from North Rustico and Greenwich. In addition to the LIDAR data acquisition, Hyperspectral Data International of Halifax NS were also contracted to acquire compact airborne spectrographic imaging (CASI) data for the same areas. Down-looking video imagery was collected simultaneously with the laser altimetry and was used to assist in interpreting the LIDAR returns.

The LIDAR system produces a series of point measurements with associated heights above the ellipsoid, a smooth mathematical surface representing the earth. To relate these height measurements to sea level, an adjustment must be made for the separation between the ellipsoid and the geoid; this uses a model produced by the Geodetic Survey Division of Natural Resources Canada. The accuracy of this model is reported at ± 5 cm. Application of the LIDAR data for flood modelling in Charlottetown required extensive validation work, using existing survey hydrographic and topographic survey data. Vertical offset errors were removed and the resulting LIDAR ground surface elevations were correlated to 3800 spot heights provided by the City of Charlottetown (R^2 = 0.99).

b) Flood simulation modeling

Water levels associated with storm-surge events were defined in terms of height in metres above Chart Datum (m CD). As described in Section 3.1, this is a locally defined vertical reference that represents the lowest water level at lowest tide.

As discussed in Section 2.2, three flood levels were selected for modelling the extent of flooding in Charlottetown:

- 4.23 m CD;
- 4.70 m CD;
- 4.93 m CD.
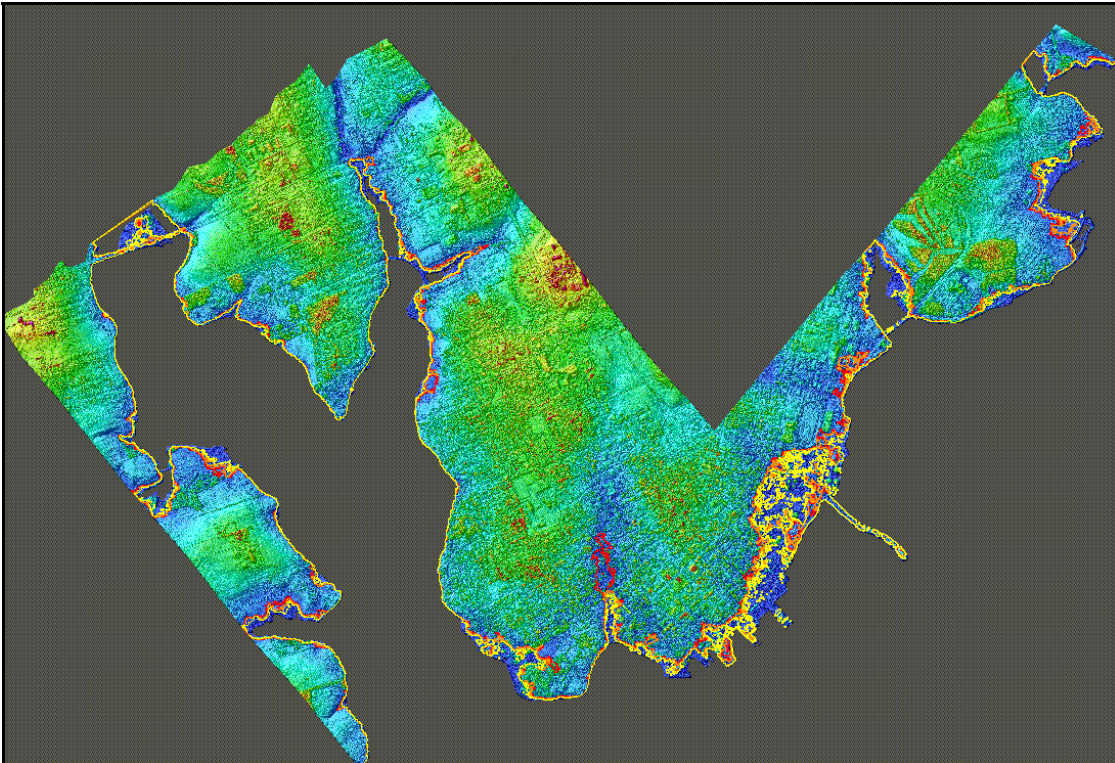
Figure 14. LIDAR digital elevation model and flooding extent in Charlottetown (yellow = 4.266 m CD; orange = 4.700 m CD, red = 4.930 m CD).

These flood levels in relation to Chart Datum were converted to heights above geodetic datum (CGVD28), which is 1.685 m above Chart Datum at Charlottetown (Canadian Hydrographic Service data acquired as part of this study, as described in Section 3.1).

In developing the maps of potential flood extent in Charlottetown, only those areas that contiguous with open water of the harbour were included; low-lying areas not connected to

open water were excluded from flooding, although obviously some flooding could occur in such areas due to seepage, raised water table, or accumulation of runoff. In some cases, where culverts allow water to flow past a barrier (such as a causeway), the areas could be included in the flood extent. An example of the flood limit modelling is shown in Figure 14, superimposed on a shaded-relief image representation of the LIDAR digital elevation model.

Areas flooded under the three water-level scenarios were projected from UTM to the PEI double stereographic map projection (ATS77) and delivered to the City of Charlottetown for use by the planning department through direct incorporation in their geographic information system (GIS). The information is being used for planning and adaptation purposes. The flood extents were also used for determining the economic impact of various storm-surge flood levels under sea-level rise as part of this CCAF project. A complete set of flood maps can be found in Appendix 6.

3.7 Coastal erosion and retreat

a) Long-term changes in the coast (during the past 10 000 years)

The changes in relative sea level described in Section 3.1 imply substantial alterations to the coastline. As indicated earlier, it is now known that the island formed part of the mainland for a time around 9000 years ago. Along the North Shore, the exposed land surface expanded seaward for some time after deglaciation, until about 9500 years before present, when the shoreline reversed its progress and began receding landward again. The lowstand shoreline was more than 10 km off the present coast in the central North Shore area and further seaward elsewhere around the Island. At this time, many of today's rivers flowed seaward across what is now the inner continental shelf to the former shoreline. We can trace their former courses in exposed or buried channels revealed by multibeam bathymetric imaging and seismic reflection profiling (see Appendix 5.)

Estuarine deposits mapped and sampled offshore include several sites presently at depths of 18 to 25 m, with ages of approximately 6000 years. Recognizing that the outer coast at the time may have been anywhere from <1 to >5 km further seaward, these observations indicate a long-term mean coastal recession rate of at least 0.5 m/yr or 50 m/century.

b) Coastal change over the past two centuries (1765-1935)

Detailed coastal hydrographic charting was first carried out around Prince Edward Island to meet the needs of the new British colonial administration in the mid-1700s. The resulting Holland map, completed in 1765, shows a number of striking differences from present conditions along the central North Shore (upper panel in Figure 15).

In the example illustrated here, a former channel linked Covehead and Rustico Bays behind Brackley Beach, which in 1765 was a barrier island with well developed dunes. By 1880 (lower panel in Figure 15), following a number of devastating storms in which large numbers of ships were wrecked along this coast, the dune system was largely reworked

as washover sand moved inshore to fill the former channel. The detailed morphology of Brackley Beach at this time is uncertain, but no indication of dunes is given on this map, whereas other areas such as the Blooming Point (Tracadie Bay) barrier and Robinsons Island fronting Rustico Bay are marked as having 'sand hills' (see Appendix 5).

The first aerial photographs in 1935 show Brackley Beach as wide washover flats, where today there are large dunes. Some of the highest dunes on this coast (up to 15 m) occur again in the vicinity of Brackley Point. It is reasonable to conclude that large-scale sand movement and shoreline adjustment occurred in response to large storms prior to 1880 and that extensive washover was maintained along Brackley Beach by storms prior to 1935, after which the dune system redeveloped.
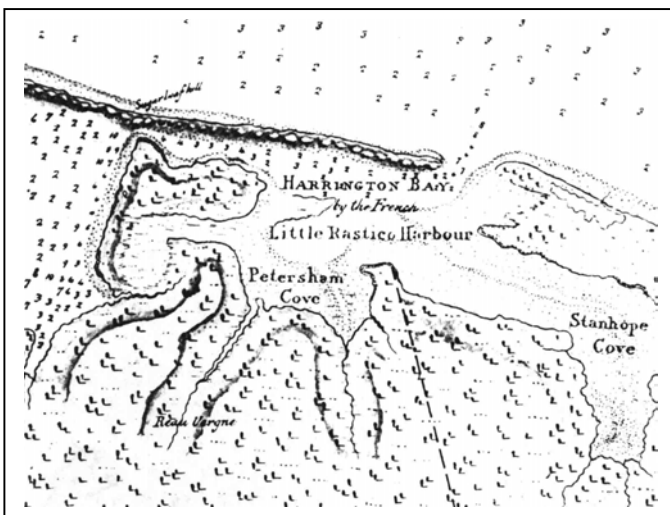
Figure 15. Changes in coastal configuration along the central North Shore of PEI from map evidence. Upper panel: Detail of 1765 Holland map (PEI Public Archives & Record Office), showing dunes on Brackley Beach barrier across the front of 'Harrington Bay' or 'Little Rustico Harbour' (present-day Brackley and Covehead Bays). Note high dune labelled 'Sugarloaf Hill' and channel linking 'Harrington Bay' to present-day Rustico Bay at left behind barrier. Lower panel: Detail of map from 1880 Meacham Atlas, showing same area with former channel infilled by washover sand. Whereas other dune areas are labelled 'sand hills', no such label appears here.
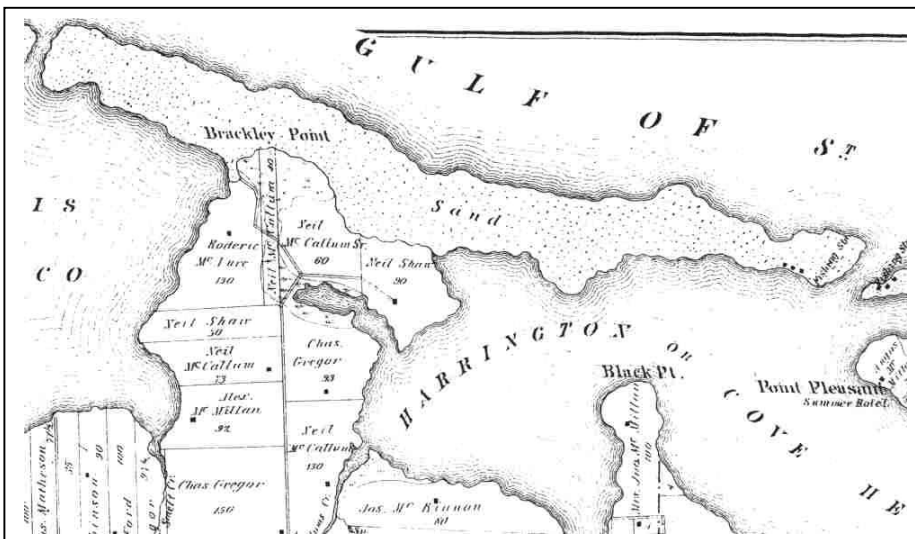
c) Recent coastal change (1935-2000)

Figure 15 shows the envelope of erosion and accretion for a 12 km section of the North Shore (the case study area used for the economic analysis in Section 2.4). The range of values is taken from detailed photogrammetric measurements on several sets of airphotos from 1935 to 1990 (see Appendix 5). There is considerable temporal and spatial variation in the rates of erosion and some parts of the western section (transects 1 to 50 in Figure 16) show significant positive growth, indicating dune consolidation and recovery from the conditions of widespread breaching and overwash prior to 1935. Overall, however, particularly between Pointe Deroche and Pigots Point (transects 60 to 112 in Figure 16), erosion prevailed during the 55-year interval 1935-1990, with coastal retreat rates generally ranging from <0.5 to 2.5 m/yr and even higher in the vicinity of Pigots Point.
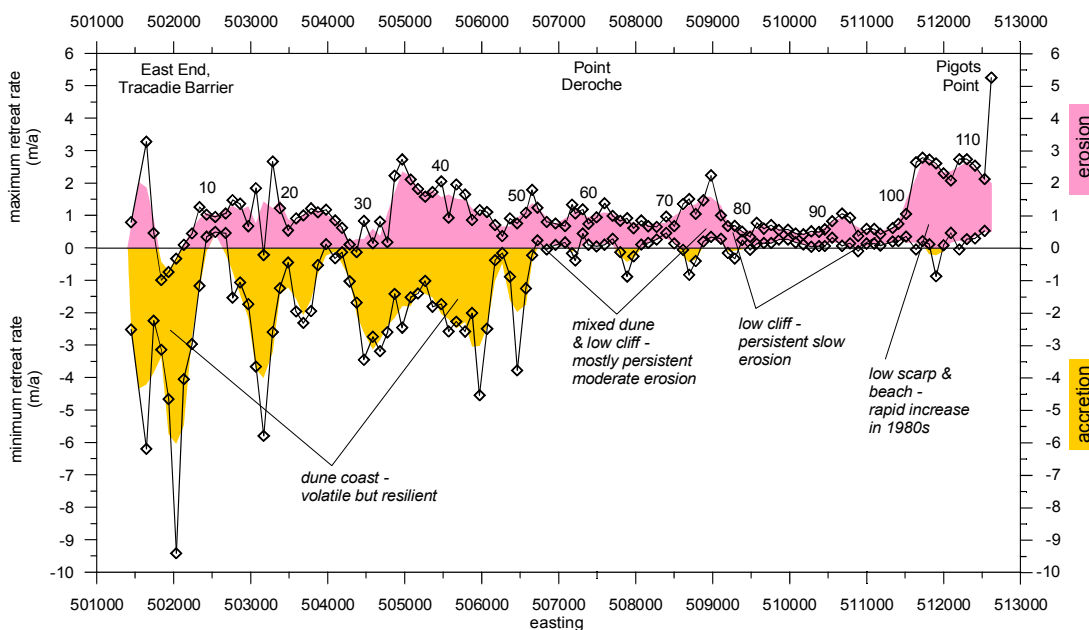
Figure 16. Envelope of erosion/accretion rates measured for the periods 1935-1958, 1958-1968, 1968-1980/1981, 1980/1981-1990, at approximately 100 m intervals along 12 km of coast between eastern Tracadie Bay and Savage Harbour, just east of Pigots Point. Small numbers above envelope identify every tenth transect.

This is consistent with rates observed elsewhere along the North Shore, as documented in a 1980s study commissioned by the provincial government, in management problems experienced along the shore in PEI National Park, and in widespread public recognition that a shoreline erosion problem exists along this coast. A number of severe storms have hit the coast during this time interval, including destructive events in early December 1998 and late October 2000. The latter storm caused $250 000 damage to walkways and similar structures in PEI National Park alone. Despite the impacts of these and other major storms over the past 65 years, none has resulted in major breaching and reworking of barrier dune systems, although a number of large washover channels have been maintained on

the Cavendish and Tracadie barriers. The scale of washover and landward sand movement recorded at Brackley Beach in the 1880 atlas (Figure 15) and attested to by the 1935 air photos suggest that storm impacts greater than any in the past 65 years may occur at random intervals in the future. This points to an added danger in assuming that simple linear extrapolation of recent erosion rates will define a safe limit of the hazard zone for erosion, storm-wave runup, or incursion of beach deposits.

Erosion along the North Shore of PEI over the past 65 years has resulted in the loss of cottage properties at Pigots Point, abandonment of a store and landward relocation of houses at Tignish, loss of wharves in outer Rustico Bay and elsewhere, shifting of tidal inlets in several places, truncation of the highway on Robinsons Island, destruction of park facilities in a number of locations, movement of sand dunes across a now-abandoned road at Cavendish Beach, and numerous other impacts along the coast. It is reasonable to assume that, without significant adaptive measures to reduce vulnerability, more severe effects will be experienced in the future with ongoing erosion at current or higher rates.

d) Future coastal change

Various methods are available for predicting future coastal change, but none is entirely satisfactory. Complex numerical models incorporating physical processes of sediment transport and profile adjustment can provide realistic results, as shown by the simulation of the morphology of nearshore bars at Stanhope Lane on the North Shore. The usefulness of such models for predicting medium-term coastal response to sea-level rise is limited, however, by the need for detailed specification of future wave climate and water-levels, as well as any changes in sediment supply. Less detailed parametric models may provide a useful alternative in future, but are not yet fully developed for application to real-world situations.

Previous work on shoreline response to climate change has suggested the use of well-known simple relations between sea-level rise and shoreline retreat, such as the widely recognized Bruun model (see Appendix 5.) While some recent scientific papers have reported good correlation between long-term shoreline adjustment and predictions using this approach, and others have applied the method with varying levels of qualification, there remain a number of conceptual difficulties. The assumptions of the basic Bruun model are rarely fully satisfied in the real world.

Nevertheless, because the empirical relations in this model were developed on the Danish North Sea coast in an environment similar to the PEI study area and because it is a conceptually simple approach that is widely used, this study undertook to test its applicability on the PEI North Shore. A comparison of measured coastal retreat with hindcast estimates of shoreline erosion output by the model, using the observed ~3 mm/yr rate of relative sea-level rise, showed surprisingly good correlation. Appendix 5 describes in detail the application of the model to the Point Deroche and Stanhope Lane sites. Using a conservative estimate of 5.0 mm/yr for future relative sea-level rise, the Bruun model gives estimates of coastal retreat ranging from 0.62 to 0.85 m/yr, an increase of ~55% over hindcast and observed rates in the past. This provides the rationale for rates of 1.5 times present recession used in our economic analysis of potential property losses due to

accelerated coastal erosion (Appendix 6). It should be noted, however, that a higher rate of sea-level rise averaging 0.7 m over the coming 100 years would produce estimates of shore recession about 2.2 times the present rate, hence the alternative analysis for twice the present rate in our economic analysis.

An alternative approach investigated in Appendix 5 is based on larger-scale equilibrium concepts related to development of the inner-shelf trailing ramp on a retreating coast and the ratio of long-term relative sea-level change to the slope of the ramp and shoreface. This method gave estimates of the rate of shoreline erosion in the Point Deroche area ranging from 0.6 to 0.8 m/yr, again comparable to observed rates. The estimated future rates at Point Deroche under assumptions of 5 and 7 mm/yr relative sea-level rise range from 0.9 and 1.3 m/yr at the low end to 1.3 and 1.8 m/yr at the high end. Obviously these estimates of long-term mean rates are only as good as the relatively simple models underlying them and each essentially projects erosion rates as a function of the rate of sea-level rise, modulated by the existing morphological adjustment of the coast to the incoming wave climate and sediment supply. It is also important to remember that short-term and alongshore variance as seen in Figure 16 will be superimposed on the long-term mean rates of retreat and that major changes in the shoreline resulting from very large storms may alter the long-term behaviour.

In summary, our conclusions on the rate of coastal erosion along the North Shore of PEI can be summarized as follows:
- areas showing significant erosion over the record of aerial photographs (1935-2000) can be expected in most cases to experience long-term future erosion at rates at least equal to that during the past 65 years;
- increases from 55 to 120% over past observed rates of shore retreat are entirely possible;
- areas of discontinuous dunes with washover channels (e.g. Cavendish Beach and Blooming Point) may, depending on storm sequences, wave energy and sediment supply, show further dune consolidation;
- these and other areas may experience massive breaching and destabilization leading to widespread washover and rapid landward migration, if a sufficiently energetic set of storm conditions leads to replication of the impacts experienced sometime before 1935 and possibly predating 1880.

4. Adaptation to climate change

4.1 General

The vulnerability of a community or ecosystem to climate change is a function of its exposure and susceptibility to environmental change and its inherent or managed adaptive capacity (resilience, ability to cope) in the face of such change. Adaptations are actions taken in response to a projected or actual change in the climate or other change in the environment. They aim to maximize any positive effects and to minimize adverse impacts, thereby reducing vulnerability. Adaptation may be spontaneous (autonomous) or planned, and may take place on local, national and international scales.

In general, adaptation falls into five broad categories:

➢ *prevent the loss* – adopt measures that reduce vulnerability to climate change;
➢ *tolerate the loss* – do nothing to reduce the vulnerability, and absorb the cost of the losses as they occur;
➢ *spread or share the loss* – do not reduce vulnerability, but spread the burden of the losses over different systems or populations (this is how insurance works);
➢ *change the affected activity* – stop doing things that cannot cope with changes in climate, and substitute other activities;
➢ *change the location of the activity* – move the activity or system to a more favourable location.

What adaptation measures would be most appropriate to Charlottetown and the North Shore, given the range of potential impacts identified in this study? As recognized now for some years, there are three broad categories of adaptation in the coastal zone:

• **protection**;
• **accommodation**;
• **retreat**.

4.2 Protection

Protection is an understandable response to coastal erosion which threatens backshore property or infrastructure.

There are many examples of this approach on Prince Edward Island, ranging from large-scale public projects to small-scale efforts by individual property owners. Protection generally takes the form of seawalls, revetments, coarse rip-rap, or groynes designed to trap sediment in the foreshore. In general, protection is costly and may have limited long-term effectiveness in exposed locations, though it may be successful as flood protection where wave energy is limited. On open coasts, such as the outer North Shore, strong wave reflection and scour at the base of vertical seawalls may promote removal of sediment seaward, loss of beach sand, and ultimately undercutting and toppling of the structure. Groynes are only effective where significant longshore transport occurs; they may also have limited effective life. Coarse rip-rap may provide temporary relief in places but is subject to wash-through or undercutting and toppling. Even in apparently sheltered locations, local waves acting on a high storm surge may destabilize rip-rap protection, as occurred on the approaches to Oyster Bed bridge at the head of Rustico Bay in the October 2000 storm. In the southern Gulf of St. Lawrence, seawalls and other structures are also vulnerable to damage by sea ice impinging on the shore.

Another issue with protective structures is the 'end-effect'. While groynes may be effective in protecting some properties within the zone of trapped sediment, locations downdrift of the groyne(s) may be starved of sediments, leading to enhanced erosion there, and to pressure for costly propagation of groyne construction along the coast. Seawalls and similar structures may also induce enhanced erosion at the ends of the protection

structure. Furthermore, where walls are constructed on sandy coasts such as in the study area, narrowing or loss of the beach in front of the steep reflective structure is a common outcome.

4.3 Accommodation

Accommodation represents a middle way between protection and retreat. It may involve redesign of structures to minimize impacts, zoning to encourage appropriate land use with low capital investment on vulnerable properties, or other measures. In cases where flood risk rather than erosion is the predominant issue, raising foundations or freeboard on structures may be an appropriate measure.

Accommodation may also involve efforts to increase natural resilience, through such measures as coastal dune rehabilitation, dyke opening and wetland renewal, substitution of bridges in place of causeways, or 'soft' protection measures such as beach nourishment. Enhancing or preserving natural resilience is becoming recognized as a potentially cost effective and multi-benefit strategy. Preserving resilience may take the form of controlling or prohibiting beach sediment removal, as the provincial government does in PEI. It may also take the form of measures to enhance the supply of sand in the beach system, particularly through storage in coastal dunes. These then act as buffers and as sand reservoirs from which sediment can be extracted under storm conditions. Healthy dunes provide valuable natural habitat as well as representing a form of 'soft' coastal protection, exemplifying the multi-benefit attributes mentioned above. In some cases, coastal engineering projects or other development in the coastal zone may have the potential to change sediment transport patterns in such a way as to increase erosion or diminish the sand supply on a given stretch of shore. Incorporating issues of coastal stability and adaptation into the environmental impact assessment process may help to maintain resilience in the system and serve a useful function of accommodation.

It is worth mentioning that some species such as the endangered piping plover require active beach habitat and favour environments such as washover channels through the dune system. Moreover, stability and maintenance of barrier beaches such as Cavendish, Brackley, or Blooming Point in the long run, under conditions of rapid sea-level rise, may actually benefit from landward transfer of sediment through washover processes, enabling the barrier to migrate landward with the rising ocean. Where beach and dune systems are backed by land under development, this natural tendency for coastal retreat may conflict with the desire of property owners to limit land loss or alienation. In this case, strategies of retreat may represent the best form of accommodation.

4.4 Retreat (avoidance)

Retreat, which may also be defined as avoidance of risk, represents a form of proactive adaptation to eliminate a direct impact. Although this may involve a real or opportunity cost, the net market cost is likely to be minimized using this option and non-market benefits in safety, habitat conservation, aesthetic values, or coastal resilience may also be realized. The simplest form of retreat involves avoidance of vulnerable properties by individual buyers, or decisions against building within flood or erosion hazard zones. This may be encouraged by public education efforts or other management strategies, including tax, insurance, or zoning policies.

Legislated setback regulations are perhaps the most common approach and are often based on projected future erosion losses, as is the case in Prince Edward Island. Other ideas being promoted in some jurisdictions include rolling easements or changes in flood insurance. Land swapping may be another public policy option, particularly where wholesale resettlement of a vulnerable community may be needed. There are cases in PEI where land swapping and resettlement may be more effective long-term alternatives to major coastal protection works with a high capital cost and limited long-term viability.

Selection of setback distances in terms of a fixed time interval (e.g. 60 years in the PEI Coastal Area Regulations) implies an ability to predict erosion rates into the future over that time interval. Simple extrapolation of historical rates may not be appropriate and the validity of the historical rates adopted for such calculations may be questionable, as demonstrated by our analysis of coastal change on the North Shore of PEI, presented in Section 3.5. If setback is defined in terms of a time interval and the potential for a significant increase in the rate of coastal retreat is not incorporated into the calculations, the intended factor of safety may not be achieved.

An important consideration in Atlantic Canada is the issue of adaptation to present environmental conditions, including ongoing relative sea-level rise at the reasonably rapid rate of approximately 0.3 m/century. In many cases, very little consideration has been given to this in the past, and some coastal development is poorly adapted or seriously at risk (a case of maladaptation), which may make appropriate adaptation to accelerated sea-level rise or other climate impacts more difficult or costly.

4.5 Past coastal adaptation and maladaptation on Prince Edward Island

Examination of Meacham's Atlas of PEI demonstrates many cases of forced abandonment and retreat around the coast of PEI since 1880. At Souris, a branch line of the Prince Edward Island Railway, including engine house and car house, a public wharf, store, and a number of residences and other structures have all disappeared from the west end of the beach. On Robinson's Island, across the mouth of Rustico Bay, more than half a dozen private fishing stages, a seaside hotel and bath house were removed from the barrier beach and dunes forming the west end of the island prior to the first aerial photographs in 1935. More recently, at Tignish Shore, near the far west end of the North Shore, a store was lost and several houses moved from the seaward side to the landward side of the road as a result of chronic shoreline erosion.

In PEI National Park in the 1970s and 1980s, efforts were still being made to maintain park infrastructure in the existing hazard zone against the forces of wave erosion and dune migration. Front-end loaders were used on a regular basis to keep open a road at Cavendish Beach, where landward movement of the dunes had crossed the road and sand was regularly infilling the artificial valley created to maintain it. Although the road was seen as an essential link and wetland on the landward side made simple realignment impossible, park managers eventually made the appropriate but difficult decision to retreat from the area and close the road. Similarly, where gabion seawalls were breaking down from corrosion and sandstone abrasion at the campground on Robinsons Island, leaving former infrastructure exposed at a low headland, this entire section of the campground was ultimately abandoned. Another seawall was holding back erosion in front of a parking lot at Stanhope Lane, while the beach in front of it grew narrower and the coast on either side continued to retreat. In the end the seawall was removed and the parking lot relocated further landward.

Private property losses have been sustained in a number of areas and various efforts made to reduce cliff erosion by construction of seawalls, revetments, and rubble protection. At one location, where some cottage lots have been lost, all that remained of one property in 1999 was the well pipe protruding from the beach (that too is now gone). The most rapid erosion here followed removal of the former narrow dune along the shore and the shoreline now consists of a thin gravel beach over a sandstone platform with a low scarp at the landward side. This site and other sites are subject not only to erosion but to storm wave runup and gravel deposition across the roadway. Slabs of concrete have been dumped over the cliff in places as a crude form of rubble protection, but these have limited endurance and effectiveness. At one headland, a residential property with a robust seawall on three sides now sits proud of the adjacent coast. Meanwhile, the pace of development on ocean-front properties continues to grow, with large homes being constructed where only cottages would have been considered before. The resulting increase in property values, can only exacerbate the economic vulnerability enumerated in this study, while loss of natural shoreline in areas of extensive shore protection represents a cost in habitat and other landscape amenities.

The introduction of setback requirements in the Coastal Area Regulations pursuant to section 8 of the *Planning Act* 1988 represents an enlightened approach. However the selection of setback in terms of various distances in relation to dunes or eroding banks or erosion distance in years may require refinement and the means of specifying the erosion rate is unclear. Development is also prohibited on any "primary or secondary sand dune, or a baymouth barrier sand dune" and buffers are specified between subdivisions and the landward boundary of migrating primary and secondary dunes.

4.6 Recommendations

A number of specific options can be suggested for proactive adaptation to (or strategic preparation for) accelerated sea-level rise and shoreline erosion in PEI.

a) Hazard identification and monitoring

New airborne imaging technology for high-resolution digital elevation modelling has been demonstrated in this study. Consideration might be given to more extensive application of this approach to flood hazard mapping in other urban and suburban areas, including Summerside, and more extensively on other parts of the Island coast, including tidal estuaries and rivers. Any such work will also require detailed validation efforts, both for the DEM itself and for any derived hazard zone specification. The definition of the flood hazard requires more than simple construction of the DEM, but also a statistical analysis of flood levels and probabilities.

This study has also developed a preliminary erosion hazard ranking scheme based on shore-zone morphology and materials, which is useful for obtaining an overall qualitative view of risk distribution. However, more detailed quantitative methods are required for purposes of specifying setback and further consideration needs to be given to realistic definition of erosion rates and potential future erosion. The high variability in historical measurements (related both to varying storminess and to varying response of the coastal system) needs to be recognized, as does the potential for rare but dramatic breaching, overtopping, and overwash under extreme storm conditions. This sort of change would not be captured in the estimates of mean historical retreat rates. Furthermore, improved estimates of possible acceleration in erosion rates under more rapid sea-level rise and possibly enhanced wave energy along the North Shore need to be considered.

The concept of changing vulnerability and the need for regular reassessment has been introduced in some places and points to the need for ongoing environmental and coastal monitoring. Existing coastal erosion monitoring reference sites provide control points for derivation of more extensive estimates from photogrammetry or alternative airborne or spaceborne imaging. It is highly desirable that some, at least, of these control sites be maintained in support of the planning, adaptation, and ongoing risk assessment needs, but funding and technical requirements such as frequency of surveys need further discussion.

A more fundamental issue remains in the specification of future flood risks for Charlottetown and other communities in Atlantic Canada. As this study has highlighted (Appendix 1, Part 1), there remain many uncertainties in the prediction of future local sea-level rise related not only to regional and broader global modelling uncertainty, but to lack of information on such fundamental factors as vertical motion of the crust. Strengthened research capacity for fundamental data acquisition of this kind, renewed densification of the tide-gauge network, and support of regional modelling for region-specific sea-level, ice, and coastal wave predictions would all strengthen the science underpinning adaptation decision making for coastal planning and management.

b) Managed retreat or avoidance

The simplest form of avoidance for the PEI North Shore is to restrict development in vulnerable locations. For a large part of the coast, this is promoted by the existence of PEI National Park. Within the park it is recognized that minimizing development of infrastructure in erosion-prone locations is more cost-effective and consistent with park conservation objectives than previous policies involving protection.

Land swapping may be another public policy option, particularly where wholesale resettlement of a vulnerable community may be needed. There are cases in PEI where land swapping and resettlement may be more effective long-term alternatives to major coastal protection works with a high capital cost and limited long-term viability. In a slightly different context, preservation of park land may be achieved where adjacent land is agricultural by a 'rolling carpet' approach in which land is purchased on the landward boundary to make up for erosion losses on the seaward side. Just such an approach has been suggested to make up for loss of shore frontage at Jacques Cartier Provincial Park in the damaging storm of 29 October 2000.

Selection of setback distances in terms of a fixed time interval (60 years in PEI Coastal Area Regulations) implies an ability to predict erosion rates into the future over that time interval. Simple extrapolation of historical rates may not be appropriate and the validity of the historical rates adopted for such calculations may be questionable, as demonstrated by our analysis of coastal change on the North Shore of PEI, presented above. If setback is defined in terms of a time interval and the potential for a significant increase in the rate of coastal retreat is not incorporated into the calculations, the intended factor of safety may not be achieved.

Retreat may not be a broadly viable option in urban settings such as Charlottetown, where alternative accommodation and protection strategies may need to be considered.

c) Accommodation and enhanced resilience

Accommodation options are already being considered in Charlottetown as a result of this study. These include flood-proofing of basements and other measures to reduce damage in the event of flooding, as well as more stringent assessment of building proposals in potentially flood-prone areas. These are progressive moves.

Enhanced resilience of natural coastlines is being promoted within PEI National Park and is supported by some of the provisions in the Coastal Area Regulations. Nevertheless, some recent development and ongoing pressures for ocean-front construction will strain the natural system in places. Any opportunities taken to strengthen natural resilience of dune buffers and other natural systems may pay dividends in reduced future impacts and economic losses.

d) Protection

There are situations in which hard or soft protection is required for specific high-value properties or amenities. In such cases, serious consideration should first be given to alternatives of accommodation or retreat and soft protection measures should be examined as alternatives to hard structural solutions.

If seawalls or revetments are deemed appropriate, they should be designed in light of new flood level probability assessments as developed in this study and in light of other potential climate-induced changes and sea-level rise from the latest global and regional predictions. In all cases where protection is the chosen adaptation option, the need for future

maintenance and potentially limited long-term feasibility of 'holding the line' should be considered at the outset.

e) Coastal management

There is, at present, no effective integrated coastal management process in Canada, although a number of coordinating bodies and more limited resource management and co-management processes exist. The lack of clear jurisdiction in this area between the federal and provincial governments is one obstacle to progress. Any such integrated management and planning in the coastal zone needs to take a holistic approach to the coastal system, incorporating both terrestrial and marine components. This introduces further jurisdictional complications. A potential alternative might be the creation of local or regional working groups, including residents and other local stakeholders, scientific advisory panels, and government representatives to develop management plans and recommendations for specific sections of the coast. A potential model is the Rustico Island Causeway Working Group in the late 1990s. Some landowners, such as PEI National Park, may have sufficiently large holdings that coastal management planning can be undertaken effectively on an internal basis, but involvement of a broader stakeholder community is desirable.

In the present study area, we distinguish between requirements in the major urban centres such as Charlottetown and those in rural areas of the North Shore. While both would benefit from ICZM approaches, the 1996 amalgamation of City of Charlottetown with surrounding municipalities created a sufficiently large administrative unit to enable some integration of planning policy in relation to the flood hazard. On a municipal basis, some planning strategies can be pursued to limit vulnerability, such as appropriate zoning, acquisition of flood-prone properties, flood-proofing, or taking advantage of replacement schedules to move key infrastructure to less vulnerable locations. Nevertheless, issues involving waterfront development would benefit from a broader harbour-wide approach.

On the North Shore, opportunities might be sought, possibly under provincial or joint federal-provincial government leadership, for development of coastal or shoreline management plans corresponding to the natural coastal cells (such as 'Brackley Bight', 'Tracadie Bight', or the coast from Point Deroche to Cable Head), in a manner similar to the Shore Management Plans approach in England and Wales described in Appendix 5.

f) Awareness raising and public education

An important factor in public acceptance of the need for adaptation and encouraging individual decision-making consistent with appropriate adaptive strategies in the coastal zone is a broader awareness and deeper understanding of the issues in the general public. Activities that promote wide dissemination of results from projects such as this should therefore be encouraged.

First steps in this process have been taken in the present project. Presentations have been made to federal, provincial, and municipal officials at various stages of the project. A presentation was made to the Council of the City of Charlottetown in February 2001 in partnership with the Federation of Canadian Municipalities. A public information meeting is scheduled for September 2001 to initiate a broader dialogue with residents and other

stakeholders. Successful public buy-in of the need for adaptation and creative contributions to integrated adaptation measures will be promoted by ongoing awareness raising and public education activities.

4.7 Selecting the adaptation strategy

There may be no one option that is best or effective in isolation. Appropriate adaptation may require a mix of options and the best mix will vary from place to place and possibly from time to time.

Adaptation can be at various scales and local adaptation needs are best solved locally or at least with participation and buy-in of local stakeholders.

Adaptation is a complex iterative process which typically involves four steps:
1 – identifying possible impacts and raising awareness;
2 – planning and design;
3 – selection and implementation of adaptation measures;
4 – monitoring and evaluation of the adaptation results.

Adaptation strategy needs to adaptable. Vulnerability may change with time and should be reassessed on a regular basis. This may require adjustment of the mix of adaptation measures.

5. A template for coastal impacts and adaptation studies

An impact and adaptation study for climate change can be divided into five main steps:

1 – Identification of climate factors (and changes in them) due to greenhouse gas emissions (e.g. changes in temperature, precipitation, storminess, sea level, ice cover, etc.)
2 – Determination of the susceptibility of the natural and human environments to climate change.
3 – Estimation of the biophysical impacts of the climate factors on the natural and human environments.
4 – Estimation of the socio-economic impacts.
5 – Recommendation of adaptation measures.

5.1 Identification of climatic factors

Analyses were carried out of the past climatology of the following climatic factors:

a) *Sea level rise (Appendix 1, Part 1):* An analysis was carried out, using tide gauges around the Gulf of St. Lawrence, of the rise in mean sea level since 1911. The local mean rise in sea level in PEI over the past century was determined from these data; it is much greater than the global average.

b) *Storm surges (Appendix 1, Part 2):* The issue of future storm surges was addressed in several ways in this project. First, a meteorological storm surge model which had been developed recently was tested on the 21 January 2000 storm and an analysis was carried out to see how much more intense that storm might have been. It turns out that the intensity of storms and the resulting storm surges are highly sensitive to storm trajectory, which might be changed under climate change to promote more rapid and pronounced intensification. Second, combining the analysis of the frequency of occurrence of storm surges in the past with the expected future rise in sea level and increase in wind speed (storminess) due to climate change enabled the project to estimate how the frequency of occurrence of storm surges of various heights will increase in the future.

c) *Wind (Appendix 1, Part 3):* Wind data consisting of hourly to 6 hourly wind speeds and directions at various locations in the Gulf of St. Lawrence and along Northumberland Strait were obtained from the Meteorological Service of Canada and compiled in a database.

d) *Waves (Appendix 1, Part 4).* Available wave data were compiled in a database and analyzed to investigate the wave climatology of the southern Gulf of St. Lawrence. Measured data is sparse and unavailable in winter so previous research has focused on the development of hindcasts. Comparison of the most advanced and longest hindcast method with time-correlated summer and fall measured data indicates good agreement between measured and hindcast wave heights but that agreement between wave periods is poor. The wave climatology in winter, which appears to be the season most affected by climate change, remains unverified by measurements. It is useful to include ice in long-term hindcasting because intermittent sea ice is considered to limit wave formation by reducing available fetch and also the energy of breaking waves as it is absorbed by nearshore ice rather than the shoreline and coastal infrastructure.

e) *Ice cover on the Gulf of St. Lawrence (Appendix 1, Part 3)*: The Canadian Ice Service sea-ice chart database was used to derive an up to date accurate climatology of sea ice in the Gulf of St-Lawrence. Inter-annual and inter-decadal variability of the ice cover was examined and an ice severity index was derived. This information is required for quantitative studies of the dampening effect of sea ice on storm surges and waves.

5.2 Estimation of the vulnerability of PEI to storm surges and coastal erosion

Physical factors which would make PEI vulnerable to storm surges and erosion are:

a) *Land that is at an elevation that is within the reach of expected storm surges (Appendix 4).* To determine this aspect of vulnerability, very accurate topographic maps were constructed for Charlottetown using airborne LIDAR measurements.

b) *Land that has a history of erosion in the past and which is subject to erosion in the future (Appendix 5).* A survey was carried out of past erosion rates along the North Shore of PEI and of the geology of the area using historical in atlases and maps, and photogrammetry.

5.3 Estimation of the biophysical impacts of future climate change

In this project, work concentrated on the forecasting of storm surges, and the flooding in Charlottetown that would result. A storm surge mode using wind and atmospheric pressure was developed and tested. This work is described in Appendix 2.

Observed water levels from the 21 January 2000 storm, and those to be expected from the predicted sea level rise during the next 50 and 100 years combined with a 21 January 2000 storm were applied to the very precise topographic map of Charlottetown to estimate what part of the city would be flooded during each of these three scenarios. The flood maps are described in Appendices 5 and 7.

In the future, storm surges predicted by the model described in Appendix 2 could be applied to the topographic map of Charlottetown to produce flood maps for any given scenario.

a) *Sea level rise (Appendix 1, Part 1):* A review of the literature indicated that climate change may cause the rate of sea level rise to double during the next century, making the need for adaptation in PEI even more urgent.

b) *Storm surges (Appendix 1, Part 2 & Appendix 2):* The issue of future storm surges was addressed in several ways in this project. A numerical storm-surge model was developed to predict, using meteorological input, the height of an upcoming surge. The model was tested using data from the record flood event of 21 January 2000. The analyses of long-term sea-level rise, storm-surge records, and extreme water levels were then combined to estimate the probabilities of flooding to various levels through time as a function of the rate of sea-level rise and possible changes in storm intensity.

c) *Wind, waves & Ice cover (Appendix 1, Parts 3,4,5):* A climatological analysis was undertaken of winds and waves in the southern Gulf. A review of the predictions of Global Circulation Models (GCMs) showed that ice cover may be absent from the Gulf of St. Lawrence by 2050. This has profound implications for enhanced generation of waves and accelerated coastal erosion.

d) *Flooding (Appendix 4):* The Digital Elevation Model was used to produce flood maps of Charlottetown for three plausible scenarios under climate change. The output from this part of the project was needed for the analysis of socio-economic effects in Appendix 6.

e) *Coastal erosion (Appendix 5):* Various methods in the literature of forecasting future erosion rates were reviewed and applied to the North Shore. Shoreline retreat is expected to increase under climate change. The output from this part of the project was also needed for the analysis of socio-economic effects in Appendix 6.

5.4 Estimation of the socio-economic impacts

In Appendix 6, an analysis was carried out of the socio-economic impacts of storm surges in Charlottetown and erosion along the North Shore. In the former area, residential, commercial and heritage properties were included, as well as municipal infrastructure and possible effects upon health and education. It should be pointed out that the measure used for properties was the assessed values at risk; it is important to realize that a flooded property may not be a total loss. In the North Shore area, the measure of socioeconomic impact was the forecast value of cottage and non-cottage land, wetlands, forests, beaches and dunes lost to erosion in the future.

5.5 Recommendation of adaptation measures

Various adaptation measures (protection, accommodation and retreat or advance) were discussed. Protection includes seawalls, revetments, rip-rap, and groynes. Accommodation includes redesign of structures, zoning measures, coastal dune rehabilitation, dyke opening and wetland renewal. Retreat or avoidance includes tax, insurance or zoning policies such as setbacks. The pros and cons of these measures were reviewed in terms of their application to PEI. Some examples of past maladaptation in PEI were discussed.

6. Summary of findings

6.1 Socio-economic impacts of future flooding in Charlottetown

- Private and public property in both the residential and commercial sectors in Charlottetown are at risk of damage from flooding events. There is a high concentration of commercial businesses in the zones that are most vulnerable to the effects of storm-surge events. With flooding to 4.23 metres above Chart Datum (the 21 January 200 storm), approximately 460 properties are either flooded, or at risk of flooding from the event with assessed property values of **$172 Million**, of which $110 Million is residential. The 'at-risk' property value for flooding to 4.70 metres above Chart Datum is **$190 Million**, of which one-third is commercial properties and buildings. Flooding to the 4.93 metres Chart Datum level will have an impact in terms of assessed property values amounting to approximately **$202 Million**, of which non-commercial properties represent $134 Million, while commercial properties total over $68 Million.

- Over 1.1 Million tourists visited the Island in 2000 and spent approximately $257 Million. According to the provincial government's *Economic Impact: Tourism 2000* report, 29.9% of all pleasure private motor vehicle and air visitors to Prince Edward Island (for the summer tourism season) reported Charlottetown as their "main overnight destination". There are approximately 335 municipally designated heritage properties, most of which lie south of Euston Street in and around the downtown core. Federally, there are about a dozen recognised sites. Many of these sites and areas lie within the probable flood plain outlined by the Digital Elevation Model, implying that there are many heritage values at risk. A flooding level of 4.23 metres above Chart Datum would render a total of 30 municipally designated heritage properties at risk of flooding, for a total assessed value of $8.6 Million. Flooding levels of 4.70 and 4.93 metres CD would render an additional 11 and 19 properties at risk, respectively, totaling approximately **$10.5 Million** and **$11.3 Million** in assessed property values.

- The City of Charlottetown has invested millions of dollars in developing its stormwater, sewage, and waste treatment systems, including a number of upgrades (such as the primary treatment plant in 1974) in the recent past. The three immediate concerns for storms with respect to the effects of sea-level rise on the storm/sewage system are: 1) A sufficient rise in water level could cause a surcharge in the sewage lines from outfalls and lift stations, leading to back-ups in residential and commercial areas; 2) A water level high enough to reach the level of the lift station could result in sea water being pumped along with sewage materials (or solely sea water) to the sewage treatment plant, and; 3) Prolonged inundation and submersion of a lift station and/or the treatment plant could render it inoperable.

- The value of the infrastructure at risk in Charlottetown is as follows: water system pipe **$1, 950,000**; sanitary system pipe **$2,223,000**; storm sewer pipe **$3 million**; force main **$1,155,000**; small lift station **$320,000**; large lift station **$2 million**; sewage treatment plant **$25 million**; proposed secondary expansion to the treatment plant **$13.5 million**. Total value as assessed by the City of Charlottetown is just over **$46 Million**.

- Estimates from the City of Charlottetown show that flooding to the level of 4.23 metres above datum would affect approximately 150,000 m^2 of right-of-way, to an approximate value of **$12 Million**. Further, the value of sidewalks at risk in this scenario is approximately **$1 Million**. These estimates are preliminary and do not purport to estimate the value of the land on which the roads and sidewalks are located.

- Located on the shore of the Hillsborough River near the hospital causeway is the Trigen Energy-from-Waste Facility that provides district heating services to 75 customers (mainly downtown businesses) in 80 buildings. Many of these customers do not have other sources of heating and rely on the services of the facility. It is estimated that the facility's replacement cost is **between 25 and 30 Million dollars.**

- During the surge event of 21 January 2000, the Maritime Electric facility sustained damage to both their pumphouse, located on the Hillsborough River, and to their main facility, which is located further inland. The scenarios modelled in this study show some risk of damage to the Maritime Electric facility, which carries an approximate asset value of **$48 Million**.

- It is realistic to attribute some "community costs and/or damages" to lost wages and health care costs (paid by the province's health care system). For example, if it were necessary for homeowners to spend time the following day on activities such as pumping out flooded basements, removing ice floes from yards, and removing damaged items from flooded areas, the time it took away from their normal productive days would be considered to be a cost, directly related to the surge incident. Furthermore, restaurants and businesses that closed for repairs following the storm will suffer the effects of lost revenue as a direct result of the event. The employment created in the clean-up efforts to repair, service, and rebuild commercial establishments should not be seen as employment revenue which offsets the costs of the storm felt by the community as a whole. The revenue generated by clean-up and remediation efforts is often paid out of insurance funds, and is generally considered a drain on society.

- In the health-related infrastructure component, we see that the Queen Elizabeth Hospital and the Hillsborough Hospital and Special Care Unit are both partially affected, though through property only. The study concludes that there does not appear to be any danger of flooding in the main buildings themselves; however, with flooding levels of 4.70 and 4.93 metres, there is some risk to one of the auxiliary buildings. Erosion could lead to seepage causing risk to structural integrity, and/or surcharge in sewer lines for instance. In these scenarios, it is shown that the causeway and the road that provide access to these facilities would be affected and could cause delays and degrade the quality of the service available to the public.

6.2 Socio-economic impacts of future coastal erosion on the North Shore

- Rising mean sea levels, less sea ice, and higher wave energy along the North Shore of PEI can be expected to cause more severe erosion damage and possibly rapid coastal change in some places. Photogrammetric analysis of air photographs dating back to the mid-1930s shows significant change along much of the coast, including severe erosion in places and shoreline recovery or dune growth in others. The longer-term view from marine geological surveys shows that the coast on

average has been retreating by at least 0.5 m/year for several thousand years. Property is lost, wetlands are encroached upon and migrate inland (but can be permanently lost if migration is limited by infrastructure), and coastal infrastructure and community-related resources are put at risk in a situation of accelerated shoreline erosion. The value of the lands lost due to coastal erosion represents a real cost of climate change (i.e. a lost 'value' of land and the services produced by or from it).

- The value of *cottage*-land lost to erosion between the years of 1935 and 1990, based on average percentage loss of property and average property value of cottage-designated properties, is **$816,000** (or $15,000 per year). Between the years of 1980/81 and 1990, the value of cottage-land lost was **$242,000** (or $22,0000 per year).

- The value of *non-cottage* land lost to erosion between the years of 1935 and 1990, based on assessment values, is **$63,400** (or $1,100/year). From 1980/81 to 1990, the number is $10,600 (or $1,000/year), meaning approximately one-sixth of the erosion since 1935 happened in the last decade. Comparing this to the total assessed value, we see that 4.24% of the value of the non-cottage land has eroded since 1935, and given that the total area of the properties is 646 hectares, a total amount of land eroded is approximately 15 hectares (between 1935 and 1990).

- Preliminary estimates of future erosion rates under climate change and relative sea-level rise suggest a potential increase to 1.5 to 2 times the 1935-1990 mean rates of erosion for the study area. The rate of increase may change over the forecast time frame and will in this case be affected by significant year-to-year and interdecadal variance seen in the historical data.

- **At double the present erosion rate, almost 10% of the present area of coastal properties in the study area will be lost within the next 20 years, and almost one-half in the next 100 years.**

- The study area includes a number of saltwater marshes, most of which are not located on the North Shore facing the ocean but further inland along channels and inside Tracadie Bay and Savage Harbour. Using a value of $21,206/ha per year, wetlands **add the value of $188,448** (in the form of benefits from ecological services) to the assessed value of the land.

- Using a value of $2.74 per square metre for water filtration, removal of air pollutants and control of runoff, the assessed value of the 18 hectares of forested land in the study area on the North Shore can be augmented by **$49,800** to account for the inclusion of ecosystem values, as contributed by the presence of the forest in the study area.   One service whose inclusion could raise the augmented total value of the land is the role of forest in erosion control.

- The coastal dunes of PEI are among the key natural tourist attractions of the province. From Cavendish Beach to the Nature Reserve east of Tracadie Bay, there exists a long, interconnected system of dunes, which are at risk of being breached by wave action in severe storms. The total area of the land designated as "sand dune" by the Province of PEI within the detailed study area was estimated at 100 hectares. One study used willingness to pay surveys to approximate the value of beaches, and identified an *annual* value of between US$200 and US$250 (1987 dollars) per respondent. Another study placed a 'per-household' value on

prevention of 30% of erosion of $33.35. In addition to its tourism value, it would appear that the very presence of the sand dune system on the North Shore is the most important land-conservation tool currently available in nature. The absence of the dune system could lead to accelerated rates of erosion in vulnerable areas.

6.3 Sea-level rise

- An examination of tide gauge data indicates that the mean sea level at Charlottetown has been rising at a rate of **32 centimetres per century** since records began in the first decade of the 1900s. The calculated rate of sea level rise at Rustico is **29 centimetres per century**, consistent with that calculated for Charlottetown. However, confidence in the Rustico data is lower because of the shorter record and large periods of missing data. Part of the long-term sea-level rise (perhaps 20 centimetres/century) is due to crustal subsidence following postglacial adjustments to changing ice and water loads: the remaining 12 centimeters per century is a signal of global and regional sea-level rise. It should be noted that storm surges and ocean waves are also factors at the coastline and are carried to higher levels on rising mean sea level. Even in the absence of climate change, the present rate of sea-level rise in PEI will bring challenges in the future to human interests and ecological systems in the coastal zone.

- Based on various considerations, this study has adopted the Intergovernmental Panel on Climate Change (IPCC) central value of about 0.5 metres for sea-level rise, combined with a risk-conservative estimate of 0.2 metres for crustal subsidence, to obtain a **total projection of 0.7 metres relative sea-level rise to 2100** in the Charlottetown region. This value has been used in estimating future storm-surge and other flood levels, recognizing that some projections imply a lower increase, but that the total rise from 1990 to 2100 using our estimate of crustal subsidence combined with the maximum IPCC projection could amount to a rise in mean sea level at Charlottetown of **as much as 1.10 metres**.

6.4 Storm surges

- Storm surges are the 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) high tide are events which lead to coastal inundation.

- Generally speaking, storm surges above **60 centimetres** are frequent events in Charlottetown, occurring about **8 times a year** on average (compared, for instance, to twice a year along the Atlantic coast in Halifax). They are mainly associated with winter storms and show great variability over the years. Storm surge events above 120 centimetres are uncommon and occur on average about twice a decade.

- The Digital Elevation Model for Charlottetown determined that sea water begins to flood the waterfront at a level of about 3.6 metres above chart datum. A storm surge of less than 60 cm combined with highest predicted tide (2.91 metres) cannot reach this level. Of all the storm surge events noted in the period 1911 to 1998 only **6** events reached this level and had an impact on the Charlottetown waterfront. If sea level rise to the year 2000 is taken into account then **8** of these

storms would have caused some flooding of the waterfront if they had occurred in the year 2000. The change from the present situation is even more pronounced if one accounts for sea level rise to the year 2100. Whereas presently for instance, we can expect one exceedance of 3.6 metres above chart datum every 7 years or so, in the year 2100 we could expect **one such exceedance on average each year with one event every 10 year or so in excess of 4.0 metres.** With sea level rise and global warming, not only will flooding move to higher levels but that the floods at the lower levels will become much more frequent in Charlottetown.

* A numerical model to forecast storm surges was developed at Dalhousie University and is now run operationally by Environment Canada. This model is driven by wind and sea-level atmospheric pressure. The model can forecast storm surges to within about 10 centimetres with a lead time of the order of one day. The model was tested on the 21 January 2000 storm and performed well.

* The Probable Maximum Storm (PMS) methodology consists of modifying the initial conditions for the atmospheric model in such a way as to maximize the development of the storm. An additional modification for some runs is to change the location of the initiation of the storm and the atmospheric conditions that influence its evolution. The surface pressure and wind fields forecast by the atmospheric model are then fed to the storm surge model. Preliminary results of this testing indicate that storm surges in the Gulf of St. Lawrence are highly sensitive to changes in storm trajectory, and in particular the storm surges associated with the 21 January 2000 storm could have been significantly higher had the storm been slightly further to the west.

* A new statistical method (the Conditional Probability Method) was developed to estimate the probability that a specified level will be exceeded at least once by a given date. The CPM suggests that under the present rate of sea level rise and no increase in storminess, the probability that sea level in Charlottetown will exceed 4.22 metres above Chart Datum at least once by 2050 is about 0.8. With an accelerated sea level rise of 70 cm/century (about double the present rate), the probability increases to 0.95 by 2050, a highly likely event. The probability that 4.93 m will be exceeded at least once by 2100 under the present rate of sea level rise is about 0.04, a highly unlikely event. If however the sea level rise doubles, this probability increases to 0.36. In the worst scenario we envisaged (sea level rise about double the present rate and a 10% increase in wind speed) the probability of exceeding 4.93 m at least once by 2100 is almost 0.7. This highlights the importance of relatively small increases in wind speed on flooding risk. This is of particular concern given the evidence in the observed Charlottetown record of significant increases over the last 60 years of the biggest surges.

6.5 Winds

* High wind speeds are an important result and indicator of storms and contribute to both wave and surge development. The wind climatology was examined in this study as a complement to the storm-surge and wave analysis, in order to gain a better understanding of interannual, interdecadal, and longer-term variation in storminess and to investigate the possibility of an increase in wind intensity over the period of record. Variation in wind direction was also considered in relation to storm-surge occurrence.

- A list of 464 storms between 1953 and 2000 with winds greater than or equal to 50 km/hour for at least 6 hours was constructed from the transformed, composite Magdalen Islands record and was filtered to include only the 334 storms with mean northerly wind directions (i.e. blowing from between 270° and 90° through north), corresponding to the most common storm wind direction, the directions of longest ice-free fetch, and the exposure of the PEI North Shore. Stormy periods appear to have occurred between the late 1950s and early 1960s and during the 1980s whereas less stormy periods appear to have occurred prior to 1955, in the 1970s and after 1991.
- Analysis of storm-surge events indicated a significant correlation between large surges in the southern Gulf of St. Lawrence and strong northeast winds. Other surges are related to winds out of the north and northwest. The storms that most often cause surges follow a preferred track in which they move northeast from an area of cyclogenesis off the coast of the southeastern USA. The wind records show some periods of greater or lesser northeasterly wind activity consistent with the seasonal and interdecadal variation in storm-surge occurrence at Charlottetown.

6.6 Waves
- Waves are one of the most widely recognized indicators of storm activity and constitute a significant natural hazard for shoreline erosion and infrastructure damage in coastal settings. Coastal erosion, increased sediment mobility and damage to infrastructure can be caused by waves impinging on the shoreline, especially when they are superimposed on higher than normal water levels during storm surges.
- Wave data were collected off the North Shore of PEI in the autumn of 1999 and 2000, contributing to knowledge of waves impacting this shoreline. New data include one benchmark storm on 29-31 October 2000 during which waves up to 14 metres maximum height were recorded and the significant wave height peaked at greater than 7 metres.
- Time series of the hindcast data show that waves tend to be largest and most numerous in the fall as waves are fetch-limited by ice in winter and wind storms are uncommon in summer. The direction of high waves is hindcast to occur most frequently from the northwest mode whereas low waves tend to be also from the southwest. Northeast waves may also be important but, because northeast winds may occur most often in winter, these waves are not measured and maybe also not well hindcast. The northeast fetch may be artificially reduced by the Magdalen Islands.

6.7 Ice cover on the Gulf of St. Lawrence
- The presence of sea ice in the Gulf of St. Lawrence inhibits wave development, thereby reducing winter storm erosion. Waves are expected to increase if sea ice in the Gulf decreases as predicted in future global change scenarios. There may be some effect on storm surges as well but this is less clear.
- The study showed that, during the 30-year period of study 1971-2000, ice cover on the Gulf was highly variable from one year to another. The Total Accumulated Ice Coverage can be used as an ice severity index for the whole season. Extreme values ranged from 1.1 million square kilometres in the year 2000 to almost 3.0 million square kilometres in 1993.

- The latest results of the Canadian Global Circulation Model (GCM) indicate that, by the year 2050, the ice extent in the northern hemisphere may be limited to higher latitudes and that the Gulf of St. Lawrence may be free of ice. Trends in ice cover for the Gulf are not statistically significant. The dominant characteristic of the time series shown in Figures 12 and 13 is the oscillation between years of maximum ice cover such as 1993 and years in which the total accumulated ice cover is 50% less, as in the early 1980s and again in 1998-2000. Year-to-year fluctuations can be expected to continue, but the possibility of significantly reduced ice coverage, with its implications for more severe wave conditions in winter, should not be overlooked.
- Other impacts of ice include direct damage caused by ice ride-up or pile-up on the coast; and nearshore ice or icefoot protection of the coast against wave erosion. Both effects were documented in this study in relation to large storms. During the storm of 21 January 2000, ice ride-up pushed a lighthouse in Charlottetown off its foundation, caused severe damage to a golf course in the Charlottetown area. Combinations of ice ride-up and pile-up damaged wharves and other infrastructure around the Island. The most severe ice damage during that storm, including partial demolition of homes and harbour structures, occurred along the New Brunswick coast.
- Wave damage along the North Shore of PEI was limited because of the presence of ice against the coast. On the other hand, when open water develops seaward of a grounded nearshore ice complex or when waves impinge directly on the vertical face of the icefoot, unusual scour and profile downcutting may occur in the nearshore, promoting more rapid shore erosion.

6.8 Flooding maps

- In order to predict areas at risk of coastal storm-surge flooding, it is necessary to have an accurate and high-resolution representation of the topography. An emerging technology known as LIDAR (Light Detection and Ranging) involves an aircraft emitting laser pulses towards the ground and measuring the return time of the pulse. The LIDAR system produces a series of point measurements with associated heights above the ellipsoid, a smooth mathematical surface representing the earth.
- Water levels associated with storm surge events were defined in terms of height above Chart Datum. Three flood levels were selected for modeling the extent of flooding in Charlottetown: 4.23 metres, 4.70 metres, and 4.93 metres above Chart Datum. The areas flooded from the three scenarios were projected to the PEI double stereographic map projection and delivered to the City of Charlottetown Planning Division for incorporation into their GIS. The information is being used for planning and adaptation purposes and was used for determining the economic impact of future storm surges as part of this CCAF project.

6.9 Coastal geology and shoreline change

- Estuarine deposits mapped and sampled offshore include several sites presently at depths of 18 to 25 metres, with ages of approximately 6000 years. Recognizing that the outer coast at the time may have been anywhere from less than one to more than five kilometres further seaward, these observations indicate a long-term

mean coastal recession rate of at least 50 metres per century (0.5 metres per year).

- Historical map evidence suggests that large-scale shoreline adjustment and landward sand movement occurred in response to large storms prior to 1880 and that extensive washover was maintained on some beaches by storms prior to 1935, after which the dunes began to recover.

- Records of erosion and accretion for a 12 kilometre section of the North Shore for various periods between 1935 and 1990 show that there is considerable temporal and spatial variation in the rates of erosion. Overall, however, at least in some sections, erosion prevailed during the 55-year period, with coastal retreat rates generally ranging from 0.2 to 2.5 metres/year and even higher in places. This is consistent with rates seen elsewhere along the coast . A number of damaging storms have hit in recent years, including early December 1998 and late October 2000. The latter storm caused $250,000 damage to park facilities and much more to small craft harbours along the coast.

- Using a simple sediment conservation model and a conservative estimate of 5.0 millimetres/year for future relative sea-level rise, we obtain estimates of future coastal retreat ranging from 0.62 to 0.85 metres/year, an increase of ~55% over observed rates in the past. This provides the rationale for rates of 1.5 times present recession used in the socio-economic analysis of property losses due to accelerated coastal erosion. A higher rate of sea-level rise averaging 0.7 m over the coming 100 years would produce estimates of shore recession about 2.2 times the present rate, hence the alternative analysis for twice the present rate in our socio-economic analysis.

- Areas showing significant erosion over the airphoto record can be expected in many cases to experience long-term future erosion at rates at least equal to those of the past 65 years. Some areas could experience massive breaching and rapid landward migration if a sufficiently energetic storm leads to replication of impacts experienced sometime before 1935 and possibly predating 1880.

6.10 Adaptation to sea-level rise and climate change in Prince Edward Island

- As recognized for some years, there are three broad categories of adaptation to sea-level rise and climate change in the coastal zone. These are:
    - protection
    - accommodation
    - retreat or avoidance.

- *Protection* is an understandable response to coastal erosion threatening backshore property or infrastructure. In general, protection is costly and may have limited long-term effectiveness in exposed locations, though it may be successful as flood protection where wave energy is limited.

- *Accommodation* represents a middle way between protection and retreat. It may involve redesign of structures to minimize impacts, zoning to encourage appropriate land use with low capital investment on vulnerable properties, or other measures. In cases where flood risk rather than erosion is the predominant issue, raising foundations or freeboard on structures may be an appropriate measure. Accommodation may also involve efforts to increase natural resilience, through such measures as coastal dune rehabilitation, dyke opening and wetland renewal,

substitution of bridges in place of causeways, or 'soft' protection measures such as beach nourishment..

- *Retreat*, which may also be defined as *avoidance* of risk, represents a form of proactive adaptation to eliminate a direct impact. The simplest form of retreat involves avoidance of vulnerable properties by individual buyers, or decisions against building within flood or erosion hazard zones. This may be encouraged by public education efforts or other management strategies, including tax, insurance, or zoning policies. Legislated setback regulations are perhaps the most common approach and are often based on projected future erosion losses, as is the case in Prince Edward Island.

- Selection of setback distances in terms of a fixed time interval (e.g. 60 years in the PEI Coastal Area Regulations) implies an ability to predict erosion rates into the future over that time interval. Simple extrapolation of historical rates may not be appropriate and the validity of the historical rates adopted for such calculations may be questionable. Other ideas being promoted in some jurisdictions include rolling easements or changes in flood insurance. Land swapping may be another public policy option, particularly where wholesale resettlement of a vulnerable community may be needed.

- A number of specific options were recommended, involving hazard identification and monitoring, managed retreat, accommodation and enhanced resilience, protection, coastal management, awareness raising and public education. There may be no one option that is best or effective in isolation. Appropriate adaptation may require a mix of options and the best mix will vary from place to place and possibly from time to time. Adaptation can be at various scales and local adaptation needs are best solved locally or at least with participation and buy-in of local stakeholders.

- Adaptation strategy needs to adaptable. Vulnerability may change with time and should be reassessed on a regular basis. This may require adjustment of the mix of adaptation measures.