FINAL REPORT A

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IMPACT OF CLIMATE CHANGE ON RIVER WATER TEMPERATURES AND FISH GROWTH

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INTRODUCTION

Atlantic Salmon

Atlantic salmon, *Salmo salar*, inhabit cool temperate streams on Canada's eastern shore. In the Miramichi River, Atlantic salmon are located towards the southern limit but within the most productive area of its distribution. Adult Atlantic salmon in the Miramichi River spawn in October and November. Juvenile fish emerge from the gravel in spring and spend 3-5 years in freshwater before beginning their seaward migration. Salmon return to freshwater habitat to spawn after 1 or more years at sea [1].

Water temperature and streamflow are among the most important environmental conditions determining the distribution and productivity of Atlantic salmon in freshwater habitats. Water temperature and streamflow can affect fish growth [2], behaviour [3-5], and survival [3,6].

Atlantic salmon tolerate waters with temperatures ranging from 0-28 °C [7-11]. Juvenile Atlantic salmon begin feeding in the spring at water temperatures of 6-7 °C, and grow optimally at 16-19 °C [2,11-17]. At water temperatures ranging from 22-24 °C, juvenile salmon seek refuge from thermal stress at [18]. Smolts begin their seaward migration at water temperatures of 8-10 °C, while upstream migration of adult salmon is also water temperature dependent [5,19-20]. Spawning of adult salmon occurs at temperatures ranging from 0-10 °C [21].

Climate Change

Global climate change is currently taking place due to elevated concentrations of “greenhouse” gases (CO_2, CH_4, N_2O, and others) in the atmosphere [22]. In the 1900’s, mean global surface temperature increased 0.6±0.2 °C. Snow cover decreased by 10% since the late 1960’s, and the duration of ice cover in lakes and rivers decreased by two weeks in the mid and high latitudes of the Northern Hemisphere. Average sea level rose 0.1-0.2 metres globally, and precipitation increased by 0.5-1%, with an increase in the frequency of heavy precipitation events [23].

From 1990-2100 mean surface air temperature is projected to increase by 1.4-5.8 °C, with more rapid warming in the Northern regions of North America [23]. In Atlantic Canada, a 2 to 6 °C increase is expected in the next century [24]. Increases in air temperature are expected to be greatest in western New Brunswick and Quebec, and lowest in Labrador [25]. Minns et al. [25] projected a net decline in runoff, except in western New Brunswick and southeast Labrador. Conversely, IPCC [26] projects a net increase in run-off for Atlantic Canada, with the exception of New Brunswick, where a slight increase or slight to moderate decrease is predicted, depending on the model employed.

Climate change has been identified as an important source of aquatic disturbance on a global scale [27]. Climate change may alter species composition and dominance in aquatic ecosystems [26]. Cold-water ecosystems are particularly at risk [26], with climate change driving populations further north or altering life-history traits [25,28].

Climate Change in the Miramichi River, New Brunswick

Atlantic salmon rivers in the Miramichi are already experiencing water temperatures approaching upper lethal limits for fish [29-30]. Record high summer air temperatures were observed in 1999, which resulted in a long duration of high water temperatures (≅30 °C). The most severe low flow conditions in the past 60 years have been observed recently [30]. Coincident with these conditions, juvenile salmon at age were smaller than expected (G. Chaput, DFO unpublish. data). While high juvenile Atlantic salmon abundance has been observed in the Miramichi River, this has not translated into high adult returns. In fact, returning adults have declined [31]. Further increases in air temperature, altering water temperature regimes and streamflow conditions, could adversely affect growth and survival of juvenile Atlantic salmon and contribute to reduced sea survival.

Objectives

The objective of the project was to examine hydrological conditions and river temperatures in the Miramichi River during the past 50 years and to assess the potential consequences of climate change on the growth of juvenile Atlantic salmon. Specifically, this project will:

1) simulate water temperature in the Northwest and Southwest Miramichi Rivers (1970-1999; to matches long-term biological data base) using a stochastic model based on air temperature (1970-1999) and water temperature (1990-1999);

2) examine change in air (1955-1999) and water (1970-1999) temperature, discharge (1960-1999), and size-at-age of juvenile Atlantic salmon (1970-1999) with time;

3) examine the association between meteorological and hydrological conditions (temperature and discharge) and size-at-age of juvenile Atlantic salmon (1970-99);

4) estimate the potential for growth, based on water temperature, of juvenile Atlantic salmon (1970-1999) using the growth model of Elliott and Hurley [2] and compare to

size-at-age. The utility of this model will be examined using biweekly collected growth data from juvenile Atlantic salmon in the Miramichi River from 2000.

This study will address the biological response of Atlantic salmon juveniles (e.g. growth) to warmwater temperatures and low flows and provide a better understanding of these dynamics relative to climate change. Air and water temperature are expected to increase, while discharge and size-at-age of juveniles are expected to decrease over the period of study. From 1970-1999, air and water temperatures are projected to be negatively correlated, and discharge positively correlated, with size-at-age of juveniles. Growth potential is expected to decline in the Miramichi River from 1970-1999 and be negatively correlated with size-at-age of juveniles.

MATERIALS AND METHODS

Juvenile Atlantic Salmon

Data Collection

Fork length and density of juvenile Atlantic salmon, from 1970-1999, were obtained from annual electrofishing surveys conducted by Fisheries and Oceans Canada in the Miramichi River system [32]. During this time, populations from ten different rivers were surveyed at 146 site locations. Three rivers were surveyed in the Northwest Miramichi River System; Little Southwest Miramichi (1971-1999), Main Northwest Miramichi (1970-1999), and Sevogle (1974-1984, 1993-1999). Seven rivers were surveyed in the Southwest Miramichi River System; Barnaby (1971-1978, 1982-1984, 1993-1999), Bartholomew (1994-1999), Cains (1971-1990, 1992-1999), Dungarvon (1974-1984, 1993-1999), Renous (1970-1986, 1988, 1993-1999), Main Southwest Miramichi (1970-1999), and Taxis (1972-1986, 1993-1999). Juvenile salmon were divided into fry (0+), small parr (1+) and large parr (2+) categories on the basis of modes in length-frequency distribution [33].

Data Analysis

Data from individual river surveys were combined according to river system (Northwest or Southwest Miramichi River). Trends in date of sampling (calendar day) and density (no./100 m^3) of 0+, 1+ and 2+ juvenile Atlantic salmon were analysed by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Data were transformed ($\log_{10}$) prior to statistical analysis.

Fork lengths of juvenile Atlantic salmon (0+, 1+, and 2+) were adjusted for sampling day and density using a General Linear Model (GLM) in SAS (SAS Institute Inc., Cary, NC). The model specified fork length as the dependent variable and sampling day, density of age-class, year (categorical variable, 1970-1999) and system (categorical variable, i.e. Northwest or Southwest) as independent variables. The interaction between year and system was also incorporated into the model. Adjusted least square means of fork length (with standard errors) were generated. Separate analyses were run for each age-class (0+, 1+, and 2+). Date of sampling and density of age-class data were transformed (ln) prior to incorporation into the GLM model.

Mean annual adjusted fork length of 0+, 1+ and 2+ juvenile Atlantic salmon from 1970-1999 was analysed by linear regression (STATISTICA™, StatSoft, Tulsa, OK).

Air Temperature

Data Collection

Meteorological stations in the Miramichi region, operated by Environment Canada and Fisheries and Oceans Canada, recorded daily minimum, maximum, and mean temperature from January to December. Air temperature at the McGraw Brook and Doaktown meteorological stations were considered representative of air temperature in the Northwest and Southwest Miramichi River basins, respectively (Fig. 1). Air temperature time series extended from 1969-1995 (27 years) in the Northwest Miramichi River basin and from 1952-1999 (48 years) in the Southwest Miramichi River basin. Air temperature data at Catamaran Brook meteorological station, located 7-km from McGraw Brook, was used to extend the Northwest Miramichi river basin air temperature series from 1995-1999.

Data Analysis

Daily minimum, maximum, and mean temperature were examined on an annual, a seasonal, and a monthly basis. The seasons were defined as follows: winter (January 1-March 31), spring (April 1-June 30), summer (July 1-September 30) and fall (October 1-December 31). Air temperature in the Northwest and Southwest Miramichi Rivers was further examined according to the fry and parr growing and non-growing seasons. The fry and parr growing seasons both began on the day that the 3-d moving average of water temperature reached 6 °C. The fry growing season ended on August 31, while the parr growing season ended on July 15. The fry and parr non-growing seasons occupied the remainder of the year, preceding and following the growth season. The timing of the end of the season was based on results of a biweekly growth study of juvenile Atlantic salmon in the Miramichi River in 1999 and 2000 [34].

Mean annual, seasonal, and monthly air temperature was examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), or ≥3 (monthly) days of temperature data were missing. Prior to linear regression analysis, normality of the air temperature data was examined according to both graphical (frequency distributions, normal probability plots) and statistical (Kolmogorov-Smirnov, Lilliefors, and Shapiro-Wilk) methods. Data displaying non-normal distribution were $\log_{10}$ transformed prior to linear regression analysis.

The frequency of days exhibiting high temperatures and degrees, by which a high temperature threshold was exceeded, were assessed annually and seasonally. A high temperature threshold was established for each month by dividing mean daily air temperature data into quartiles. Days experiencing temperatures above the 75th quartile, for a given month, were considered "high temperatures". The number of degrees by which the high temperature threshold was exceeded on a given day was summed annually, seasonally, and monthly. Frequency of high temperatures and degree-days were analysed by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), and ≥3 (monthly) days of temperature data was missing. Data were $\log_{10}$ transformed prior to linear regression analysis provided distributions were non-normal.

Water Temperature

Data Collection

Water temperature was collected from the Little Southwest Miramichi River (tributary of the Northwest Miramichi River) from 1992-1999 and in the Southwest Miramichi River (at Doaktown) from 1999-2000 (Fig. 1). Using a stochastic model [35], mean daily air temperature was used to simulate daily water temperature from 1970 to 1999 in both the Little Southwest Miramichi (using McGraw Brook air temperature) and Southwest Miramichi (using Doaktown air temperature) Rivers. Water temperature in the Little Southwest Miramichi River and the Southwest Miramichi River at Doaktown was considered representative of the Northwest and Southwest Miramichi River systems, respectively.

Data Analysis

Mean annual, seasonal, and monthly water temperature in the Northwest and Southwest Miramichi Rivers from 1970-1999 was examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Changes in water temperature during the fry and parr growing and non-growing seasons were also examined. Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), or ≥3 (monthly) days of temperature data was missing. Data were $\log_{10}$ transformed prior to linear regression analysis provided distributions were non-normal.

The frequency of days exhibiting high temperatures and degrees, by which a high temperature threshold was exceeded, were assessed annually and seasonally. The frequency of high temperatures and degree-days were analysed by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), and ≥3 (monthly) days of temperature data was missing. Data were $\log_{10}$ transformed prior to linear regression analysis provided distributions were non-normal.

River Discharge

Data Collection

Daily discharge was monitored at hydrological stations in the Northwest (01BQ001) and Southwest (01BO001) Miramichi Rivers (Fig. 1). The Southwest Miramichi station had the longest time series of discharge data (57 years, 1918-32, 1937-38, 1960-99) while the Northwest Miramichi had 39 years of data available (1961-99).

Data Analysis

Mean, maximum, and minimum annual, seasonal, and monthly discharge from the Northwest (1961-1999) and Southwest (1960-1999) Miramichi Rivers were examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). River discharge was also examined according to the fry and parr growing and non-growing seasons.

Timing (calendar day) of maximum and minimum discharge and the timing of maximum discharge associated specifically with snowmelt/spring runoff (i.e. March-June) were examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK).

Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), and ≥3 (monthly) days of discharge data was missing. Data were $\log_{10}$ transformed prior to linear regression analysis provided distributions were non-normal.

Functional Model for Maximum Growth

Elliott and Hurley [2] proposed a model that estimated the functional growth of Atlantic salmon fry (0+) and parr (1+). The model was developed from laboratory growth studies on two populations of Atlantic salmon in northwest England, and verified with field data from these same populations.

Growth Rate

Growth was calculated initially, in terms of the specific growth rate, G_w, expressed as a percentage, at a water temperature of T °C and at an instant in time when the fish mass was W g:

$$G_w = cW^{-b} \frac{(T - T_{LIM})}{(T_M - T_{LIM})}, \qquad \text{equation 1}$$

where $T_{LIM}=T_L$ if $T \leq T_M$ or T_U if $T>T_M$. The temperature for optimum growth was T_M (=15.9 °C), and T_L (=6.0 °C) and T_U (=22.5 °C) represented the lower and upper temperature limits, respectively, at which growth rate was zero. Growth rate of a 1 g fish at optimum temperature was c (=3.53), while the mass exponent b (=0.31) was the power transformation of mass that produces linear growth with time [2].

Specific growth rate (G_w) was estimated by the observed growth rate (G_O) according to:

$$G_O = 100 [\ln (W_t/W_o)] / t, \qquad \text{equation 2}$$

where initial fish mass (g) was W_o, final fish mass (g) was W_t and t represented the number of days between observations [2].

Specific and observed growth rate models were applied to water temperatures and fish mass in the Northwest (Bridge Pool) and Southwest (Burntland Brook and Ponds Chalet) Miramichi Rivers in 2000. Specific growth rate (G_w) was calculated daily based on mean daily water temperature (T) and mean fish mass (W) (eqn. 1). Initially, fish mass (W) represented the mean fish mass from the first sampling effort. Subsequent fish mass (W) represented the product of the previous day's fish mass and the current value for specific growth rate. Predicted mass and observed mass of juveniles were compared.

Observed growth rate was calculated (eqn. 2) from fish mass of juvenile Atlantic salmon collected at all three stations, and compared to specific growth rate.

Growth Potential Index

According to the growth model (eqn. 1), juvenile Atlantic salmon grow at water temperatures ranging from 6 (T_L)-22.5 (T_U) °C, with optimal growth at 15.9 (T_M) °C. Outside of these limits, growth of juvenile Atlantic salmon is limited. We could not apply the growth rate model (eqn. 1) to the electrofishing data (1970-1999) because fork length rather than fish mass was recorded and each site was sampled only on an annual basis. Therefore, the growth model (when W=1g) was modified to reflect the potential for growth (G_P) in these systems on an annual basis, which we would subsequently compare to mean annual fork length of juveniles. Growth potential was estimated according to:

$$G_P = m_{LIM}T + b_{LIM}, \qquad \text{equation 3}$$

where m_{LIM} and $b_{LIM}=m_L$ and b_L if $T \leq T_M$ or m_U and b_U if $T > T_M$. The rate of change in growth potential was represented by m_L (=0.10) or m_U (=-0.15), while b_L (=-0.61) and b_U (=3.42) represented the growth potential when water temperature was zero. Maximum growth potential (G_P=1) was observed at 15.9 °C, while minimum growth potentials (G_P=0) were observed at 6 or 22.5 °C. No growth potential was recorded when water temperature was <6 or >22.5 °C.

Growth potential was calculated daily, based on the mean daily water temperature, during the growing seasons and summed to yield an annual growth potential index for fry and parr ($GPI=\Sigma G_P$).

Annual growth potential for fry and parr (1970-1999) were examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Data were excluded from analysis if ≥8 days of temperature data was missing. Data were $\log_{10}$ transformed prior to linear regression analysis provided distributions were non-normal.

Effects of Environmental Conditions on Juvenile Atlantic Salmon Size

Mean annual fork length of juvenile Atlantic salmon (1970-1999) was compared to meteorological and hydrological conditions annually and seasonally. Specifically, the relationship between fork length and 1) minimum, maximum and mean air temperature, 2) mean water temperature, 3) frequency of high air and water temperatures, 4) air and water temperature degree-days, 5) mean, maximum, and minimum discharge, and 6) fry and parr growth potential index were examined by linear regression (STATISTICA™, StatSoft, Tulsa, OK). Comparisons were done separately for the Northwest and Southwest Miramichi Rivers.

Data were excluded from analysis if ≥31 (annual), ≥8 (seasonal), and ≥3 (monthly) days of data was missing. Data displaying non-normal distribution were $\log_{10}$ transformed prior to subsequent analysis.

RESULTS

Juvenile Atlantic Salmon

The average timing of electrofishing surveys changed significantly from 1970-1999, occurring later and later each year ($p<0.001$, Fig. 2). Juvenile salmon were more abundant in the 1990s than previously observed in this time series and mean annual densities of fry and parr increased significantly from 1970-1999 ($p<0.001$, Fig. 3).

<u>Northwest Miramichi River</u>

Mean (±1SE) annual fork length of Atlantic salmon fry varied by as much as 1.4 cm, ranging from 4.0± 0.1 cm in 1978 to 5.4± 0.3 cm in 1987 (Fig. 4). However, mean annual fork length did not change significantly from 1970-1999 ($p<0.278$). Mean annual fork length of 1+ parr ranged from 7.6± 0.2 cm in 1979 to 9.1± 0.3 cm in 1972, while size of 2+ parr ranged from 10.6± 0.2 cm in 1993 to 12.3± 0.2 cm in 1974 (Fig. 4). Mean annual fork length of parr decreased significantly from 1970-1999, at a rate of 0.2 cm/decade ($p<0.029$).

<u>Southwest Miramichi River</u>

Mean (±1SE) annual fork length of Atlantic salmon fry were slightly smaller and parr slightly larger in the Southwest Miramichi River than in the Northwest Miramichi River. Mean annual fork length of fry were smallest in 1978 (4.0±0.1 cm) and largest in 1980 (5.4±0.1 cm; Fig. 4). However, mean annual fork length of fry did not change significantly from 1970-1999 ($p<0.573$). Mean annual fork length of 1+ parr ranged from 7.8±0.2 cm in 1979 to 9.3±0.1 cm in 1974, while size of 2+ parr ranged from 10.8±0.2 cm in 1978 to 12.5±0.2 cm in 1971 (Fig. 4). Mean annual fork length of parr decreased significantly from 1970-1999, at a rate of 0.2 cm/decade ($p<0.016$).

Air Temperature

Northwest Miramichi River

Mean annual air temperature from 1970-1999 ranged from 3.1-6.8 °C, with the warmest annual temperatures recorded in 1998 and 1999 (Fig. 5). Mean annual air temperature increased significantly, at a rate of 0.4 °C/decade from 1970-1999 ($p<0.024$). Mean air temperature in spring increased significantly, due to an increase of 0.6 °C/decade in April ($p<0.011$). Significant increases in mean air temperature were also observed during fall ($p<0.035$), and outside of the fry ($p<0.021$) and parr growing seasons ($p<0.020$). Seasonal minimum and maximum air temperatures did not change significantly.

High temperatures were most frequently observed in 1999 (152 days), tripling the frequency of high temperatures in 1986 (53 days) (Fig. 6). Annually, the frequency of high temperatures increased significantly from 1970-1999, at a rate of 9 days/decade ($p<0.021$). Also, the frequency of high temperatures increased significantly in fall ($p<0.002$) and outside of the fry ($p<0.002$) and parr ($p<0.005$) growing seasons. Annually, the high temperature threshold was exceeded by 162.5 °C in 1986 and 471.2 °C in 1999, however, there was no significant change in degree-days from 1970-1999. Degree days have increased significantly outside of the fry ($p<0.006$) and parr ($p<0.010$) growth seasons, due to a significant increase in degree days during the month of December ($p<0.029$).

Southwest Miramichi River

From 1955-1999, mean annual air temperature ranged from 3.0-7.0 °C. 1999 was the warmest year in 45 years, while 1998 was the third warmest year (Fig. 7). Minimum and mean annual air temperature increased significantly, by 0.3 and 0.24 °C/decade, respectively, from 1955-1999 ($p<0.028$). Seasonally, minimum, maximum and mean daily air temperature increased significantly during spring ($p<0.001$) and summer ($p<0.002$). These trends were a result of significant increases in minimum and mean air temperature from May to September ($p<0.035$) and maximum air temperature from June to August ($p<0.017$). Minimum daily temperature also increased significantly outside of the fry ($p<0.050$) and parr ($p<0.043$) growing seasons.

High temperatures were slightly more frequent in the Southwest than the Northwest Miramichi River, ranging from 58 (1972)-156 (1999) days (Fig. 8). Annually, the frequency of high temperatures increased significantly from 1955-1999, at a rate of 6 days/decade ($p<0.021$). The frequency of high temperatures also increased significantly in spring ($p<0.006$) and summer ($p<0.008$). Annually, the high temperature threshold was exceeded by 171.2 °C in 1972 and

497.5 °C in 1999. Annual degree-days increased significantly from 1955-1999, at a rate of 21.8 °C days/decade ($p<0.024$). In spring ($p<0.024$) and summer ($p<0.002$), degree-days increased significantly, due to significant degree-day increases in March ($p<0.002$) and September ($p<0.042$).

Water Temperature

Northwest Miramichi River

From 1970-1999, mean annual water temperature ranged from 10.9-13.4 °C, reaching a maximum water temperature in 1999 (Fig. 9). However, no significant changes were observed in annual, monthly, or seasonal water temperature.

The frequency of high water temperatures ranged from 23 days in 1986 to 94 days in 1999 (Fig. 10). Annually or seasonally, the frequency of high water temperatures did not change significantly from 1970-1999 ($p<0.952$). The high temperature threshold was exceeded by 22.6 °C in 1986 and 181.7 °C in 1999. However, once again, degree-days did not change significantly on an annual or seasonal basis from 1970-1999 ($p<0.925$).

Southwest Miramichi River

Mean annual water temperature was warmer in the Southwest Miramichi R. than the Northwest Miramichi R., ranging from 12.3-15.3 °C (Fig. 11). As in the Northwest, 1999 had the warmest water temperatures in this 30-yr series. Mean annual water temperature increased by 0.23 °C/decade, however, this increase was not significant ($p<0.061$). Mean summer water temperature increased significantly from 1970-1999, at a rate of 0.3 °C/decade ($p<0.037$). No further significant changes were observed in annual, monthly, or seasonal water temperature.

The frequency of high water temperatures ranged from 22 days in 1986 to 114 days in 1999 (Fig. 12). Annually, the frequency of high water temperatures did not change significantly from 1970-1999 ($p<0.137$). However, the frequency of high water temperatures increased significantly during the parr growth season, by approximately 4 day/decade ($p<0.041$). The high temperature threshold was exceeded by 27.1 °C in 1986 and 261.1 °C in 1999. Degree-days did not change significantly on an annual or seasonal basis from 1970-1999 ($p<0.801$).

River Discharge

Northwest Miramichi River

Mean (±1SE) annual discharge in the Northwest Miramichi River ranged from 12.2 m^3/s in 1985 to 31.1 m^3/s in 1963, averaging 21.0± 0.8 m^3/s (Fig. 13). Maximum and mean annual discharge increased marginally, from 1962-1999, although these trends were not significant ($p<0.899$). Conversely, minimum annual discharge decreased significantly, by 0.3 $m^3 \cdot s^{-1} \cdot decade^{-1}$, from 1962-1999 ($p<0.003$; Fig. 14). Maximum and mean discharge decreased significantly during the fry ($p<0.041$) and parr ($p<0.032$) growing seasons, while minimum discharge increased significantly in spring ($p<0.035$). In April, maximum and mean discharge increased significantly ($p<0.026$), by 16.7 and 9.6 m^3/s/decade, respectively.

Annually, the timing of maximum and minimum discharge did not change from 1962-1999 ($p<0.720$). However, considering only the months of March through to June, the timing of maximum discharge decreased significantly ($p<0.026$), occurring 5 days earlier with each decade (Fig. 15).

Southwest Miramichi River

Mean annual discharge in the Southwest Miramichi R. was much higher than in the Northwest Miramichi R. Mean (±1SE) annual discharge ranged from 67.1 m^3/s in 1964 and 164.8 m^3/s in 1963, averaging 116.8±3.1 m^3/s (Fig. 13). Maximum and mean annual and seasonal discharge did not change significantly from 1960-1999, with the exception of discharge occurring outside the fry growth season, which declined significantly ($p<0.003$; Fig. 14). Minimum annual discharge decreased significantly, by 1.7 m^3/s/decade, from 1960-1999 ($p<0.040$). Maximum and mean discharge increased significantly in March ($p<0.030$), while minimum, maximum and mean discharge increased significantly in April ($p<0.011$).

Annually, the timing of maximum and minimum discharge did not change from 1960-1999 ($p<0.796$). However, considering only the months of March through to June, the timing of maximum discharge changed significantly ($p<0.020$), occurring 5 days earlier with each decade (Fig. 15).

Functional Model for Maximum Growth

Growth Rate

In 2000, mean daily water temperature ranged from 0.1-26.6 °C at three sites in the Northwest and Southwest Miramichi Rivers. From May 17-October 18, mean (±1SE) daily temperature was 16.5±0.4 °C at Ponds Chalet, 15.1±0.4 °C at Burntland Brook, and 13.5±0.4 °C at Bridge Pool. At Ponds Chalet, mean daily water temperature was, on average, 1.1 °C warmer than at Burntland Brook and 3.0 °C warmer than at Bridge Pool.

During May to October, mass of juvenile salmon ranged from 0.1-5.7 g for fry, 0.3-14.2 g for 1+ parr and 5.4-30.5 g for 2+ parr. Generally, fish mass increased during spring and early summer, levelling off or decreasing slightly in late summer. Juvenile salmon from Ponds Chalet and Burntland Brook were of similar size, and both were larger than juveniles at Bridge Pool (Fig. 16). In Ponds Chalet and Burntland Brook, observed growth rates were greatest from June to early July for fry, and in June for parr (1+ and 2+). At Bridge Pool, observed growth rates were greatest from late July to early August for fry, and mid June to mid July for 1+ and 2+ parr.

Based on water temperature from May to October, predicted mass of juvenile Atlantic salmon (maximum growth model) ranged from 0.3-3.5 g for fry, 1.7-12.5 g for 1+ parr, and 6.8-32.0 g for 2+ parr. Predicted mass increased throughout spring and summer, levelling off or decreasing slightly in fall. High specific growth rates for juvenile fry and parr were predicted throughout May to October.

Observed juvenile fish mass was consistently higher than that predicted from water temperature during May to August (Fig. 17-19). Predicted mass exceeded observed mass in August at Bridge Pool, September at Burntland Brook, and October at Ponds Chalet.

Growth Potential Index

In the Little Southwest Miramichi River, GPI ranged from 39.2-80.6 for fry and 25.5-52.0 for parr (1970-1999; Fig. 20), with most of the potential for growth occurring during June and August. Growth potential for juvenile salmon was lowest in 1973, and highest in 1992. From 1970-1999, growth potential index increased slightly for both fry and parr, however, this trend was not significant ($p<0.226$).

In the Southwest Miramichi River, GPI ranged from 34.9-67.4 for fry and 27.3-50.0 for parr (1970-1999; Fig. 20), with most of the potential for growth occurring during May and June. Growth potential for juvenile salmon was lowest in 1973 for fry and 1994 for parr, and highest for both fry and parr in 1986. Growth potential index decreased slightly from 1970-1999 for fry and parr, although this trend was not significant ($p< 0.992$).

Effects of Environmental Conditions on Juvenile Atlantic Salmon Size

Fork Length vs. Air Temperature

Northwest Miramichi River

Fork length of Atlantic salmon parr was correlated to annual and seasonal air temperature trends. Increased mean annual air temperature was significantly correlated with decreased fork length of 2+ parr ($r^2=0.16$, $p<0.028$; Fig. 21). Seasonally, increased maximum ($r^2=0.15$) and mean ($r^2=0.18$) air temperature in spring were significantly correlated with decreased fork length of 2+ parr ($p<0.048$). Mean air temperature in fall was negatively correlated with fork length of 1+ parr ($r^2=0.16$, $p<0.030$). Finally, mean air temperature outside of the parr-growing season was negatively correlated with fork length of 2+ parr ($r^2=0.15$, $p<0.032$). Fork length of 0+ fry did not change significantly according to trends in annual or seasonal air temperature and minimum daily air temperatures were not significantly correlated to fork length of either fry or parr.

Increased annual frequency of high temperatures was significantly correlated to decreased fork length of 2+ parr from 1970-1999 ($r^2=0.14$, $p<0.041$; Fig. 22). Mean annual fork length of parr (1+ and 2+) decreased significantly with increased frequency of high temperatures in fall (1+: $r^2=0.23$, $p<0.008$; 2+: $r^2=0.16$, $p<0.028$) and outside of the parr-growing season (1+: $r^2=0.13$, $p<0.047$; 2+: $r^2=0.19$, $p<0.017$). Mean annual fork length of 1+ parr decreased significantly with degree-days in fall ($r^2=0.15$, $p<0.033$) and outside of the parr-growing season ($r^2=0.16$, $p<0.027$), while fork length of 2+ parr decreased significantly with degree days outside of the parr growing season ($r^2=0.15$, $p<0.032$).

Southwest Miramichi River

Fork length of juvenile Atlantic salmon parr in the Southwest Miramichi River was also correlated to changes in annual and seasonal air temperature. Mean annual fork length of 2+ parr decreased significantly with increased annual (maximum: $r^2=0.23$, $p<0.009$; mean: $r^2=0.15$, $p<0.041$) and spring (maximum: $r^2=0.21$, $p<0.011$; mean: $r^2=0.16$, $p<0.032$) air temperature (Fig. 21). Increased air temperature (minimum, maximum, and mean) in spring was also significantly correlated with decreased fork length of 1+ parr (minimum: $r^2=0.13$, $p<0.048$; maximum: $r^2=0.14$, $p<0.040$; mean: $r^2=0.17$, $p<0.026$). In fall, minimum air temperature was negatively correlated with fork length of 2+ parr ($r^2=0.14$, $p<0.043$). Outside of the parr-growing season, increased maximum air temperature was significantly correlated to decreased fork length of 2+ parr ($r^2=0.15$, $p<0.045$). Once again, fork length of 0+ fry did not change significantly according to trends in annual or seasonal air temperature.

Annual frequency of high temperatures and degree-days were not significantly correlated to fork length of fry or parr from 1970-1999. However, mean annual fork length of parr decreased significantly with the increased frequency of high temperatures during the parr-growing season (1+: $r^2=0.17$, $p<0.028$; 2+: $r^2=0.20$, $p<0.018$) and fall (2+: $r^2=0.14$, $p<0.046$). Increased degree-days during the parr-growing season was also significantly associated with decreased fork length of 1+ parr ($r^2=0.20$, $p<0.016$).

Fork Length vs. Water Temperature

Northwest Miramichi River

Generally, fork length of 0+ fry increased and fork length of 1+ and 2+ parr decreased with increased annual and seasonal water temperature. However, mean annual fork length of juvenile Atlantic salmon was not significantly correlated to annual or seasonal trends in water temperature in the Little Southwest Miramichi River ($p<0.973$; Fig. 23). Also, mean annual fork length of fry and parr did not change significantly with increased frequency of high water temperatures or degree-days on an annual or seasonal basis ($p<0.974$).

Southwest Miramichi River

Increased mean annual water temperature was significantly correlated to decreased fork length of 1+ parr ($r^2=0.15$, $p<0.037$; Fig. 23). Seasonally, increased mean water temperature in spring was significantly correlated with decreased fork length of both 1+ ($r^2=0.23$, $p<0.007$) and 2+ parr ($r^2=0.17$, $p<0.024$; Fig. 24). For 0+ fish, increased mean water temperature during the fry growing season was significantly correlated to decreased mean annual fork length ($r^2=0.15$, $p<0.036$).

Fork lengths of 0+ fry and 2+ parr were not significantly correlated to the frequency of high water temperatures and degree-days, annually or seasonally. However, increased frequency of high water temperatures and degree days in spring (freq: $r^2=0.14$, $p<0.044$; degree-days: $r^2=0.13$, $p<0.049$; Fig. 25) and during the parr growing season (freq: $r^2=0.17$, $p<0.024$; degree-days: $r^2=0.16$, $p<0.030$) was significantly correlated to decreased fork length of 1+ parr.

Fork Length vs. River Discharge

Mean annual fork length of juvenile Atlantic salmon in the Northwest Miramichi River was not significantly associated with changes in the minimum, maximum, and mean annual river discharge ($p<0.872$). However, some seasonal discharges were significantly associated with fork length of juvenile Atlantic salmon. Increased minimum spring discharge was significantly correlated to decreased fork length of fry ($r^2=0.19$, $p<0.017$). Increased maximum summer discharge was significantly correlated to decreased fork length of 1+ parr ($r^2=0.17$, $p<0.023$).

Mean annual fork length of juvenile Atlantic salmon in the Southwest Miramichi River was not significantly associated with annual or seasonal changes in minimum, maximum, and mean river discharge ($p<0.951$).

Fork Length vs. Growth Potential Index

In the Northwest and Southwest Miramichi Rivers, fork length of juvenile Atlantic salmon was unrelated to growth potential trends. Increased growth potential was associated with decreased fork length of fry and parr, but this trend was not significant (Fig. 26).

DISCUSSION

Atlantic salmon are cold-water species, with specific temperature requirements. Water temperature can affect survival, growth and behaviour of salmon in freshwater habitats. Climate change has the potential to alter thermal regimes in aquatic environments, adversely affecting Atlantic salmon populations.

Fork length of juvenile Atlantic salmon parr (1+ and 2+) declined significantly over the past 30 years, suggesting that conditions supporting growth have changed in the Northwest and Southwest Miramichi Rivers. Size (i.e. fork length) is an important characteristic in the life cycle of salmon, affecting such processes as competition, predation [36-37], smoltification [38], and marine survival [39-41]. Transformation of juveniles to smolts is largely size dependent [38,40, 42]. Parr that have reached or exceeded a certain size towards the end of the growing season are likely to become smolts in the following spring [38]. Slowed growth of juvenile Atlantic salmon could lengthen the time needed to reach this critical size, which would extend the freshwater portion of their life cycle, and thus increase juvenile mortality rates [43]. Age at the time of seaward migration would also increase.

In the past 30-50 years, environmental conditions, such as temperature and streamflow, changed significantly in the Miramichi River, potentially altering growing conditions for juvenile salmon. Air temperature increased in both the Northwest and Southwest Miramichi Rivers, as did the frequency of high air temperatures. The greatest increases in air temperature were observed in the fall in the Northwest Miramichi R. (1.9±0.9 °C; 1970-1999) and in spring in the Southwest Miramichi R. (2.0±0.4 °C; 1953-1999). Conversely, fewer changes in water temperature were observed from 1970-1999 compared to changes in air temperature. Water temperature in the Northwest Miramichi R. did not change significantly annually or seasonally, despite significant increases in annual, spring and fall air temperatures. In the Southwest Miramichi R., water temperature increased significantly in summer, but not in spring or annually.

The lack of similar trends in air and water temperature could be due to evaporative cooling, which contributes to the levelling off of stream water temperatures as air temperature exceeds 20 °C, and variations in streamflow [44]. However, it is likely that the lack of similarity in air and water temperature trends resulted due to limitations of the stochastic model. According to data from 1992-1999 (data not shown), the stochastic model was not equally proficient at modelling all water temperatures. Daily mean water temperatures of 20-25 °C were underestimated by, on average, 1 °C. This may have biased the water temperature data, obscuring more significant increases.

Consistent changes in streamflow were not observed in the Northwest and Southwest Miramichi Rivers, with the exception of discharge associated with snowmelt and runoff. Earlier snowmelt and runoff were observed in both the Northwest and Southwest Miramichi R., as evidenced by significant increases in discharge during March and April (1961-1999).

The effects of changing environmental conditions, particularly water temperature, on the growth of juvenile Atlantic salmon were estimated according to a functional model for maximum growth [2]. However, this model proved to be a poor predictor of fish growth in the Northwest and Southwest Miramichi Rivers. According to data from 2000, the model tended to underestimate fish mass in spring and summer and overestimate in fall. Elliott and Hurley [2] observed a similar pattern when they applied this model to data from Allen [45]. Higher than predicted growth in spring were attributed to seasonal rhythms in appetite [46], seasonal difference in the quality and quantity of food [47-48], compensatory growth after the winter cessation of growth, and/or size selective mortality of larger fish during the winter [2]. Considering the derivation of the growth potential index, it too was likely a poor predictor of conditions suitable for growth of juvenile Atlantic salmon. Therefore, for Atlantic salmon populations in the Miramichi, neither the functional model for maximum growth or growth potential index can be reliably used as predictors of fish growth in response to climate change.

Annual and seasonal changes in meteorological and hydrological conditions were correlated with decreased fork length of juvenile Atlantic salmon. Fork length of parr was most strongly associated with maximum annual and spring air temperatures and mean spring water temperatures in the Southwest Miramichi River. Fork length of parr was also strongly associated with the frequency of and extremity of high air temperatures in the fall in the Northwest Miramichi River and during the parr-growing season (May – July 15) in the Southwest Miramichi River.

In the Atlantic region, climate change scenarios predict further increases in air and water temperatures over the next 100 years [24,44]. The largest increases in air temperature are expected in winter [49], while the frequency and duration of summer hot spells are also expected to rise [23,26,50]. Water temperature is projected to increase 2-5 °C, with maximum changes occurring in spring and fall [44]. Timing of snowmelt and runoff is expected to advance by 2 weeks over the next 100 years [23], advancing the start of a drier spring-summer season and contributing to more extreme low flow conditions [51].

Climate change is projected to have significant implications for aquatic ecosystems, altering thermal regimes and streamflow conditions. These results would suggest that growth of juveniles in the Miramichi River will indeed be adversely affected by climate change, particularly during spring and summer months. Increases in air and water temperatures are expected to contribute to further declines in fork length and alterations in life history of juvenile Atlantic salmon in the Miramichi River.

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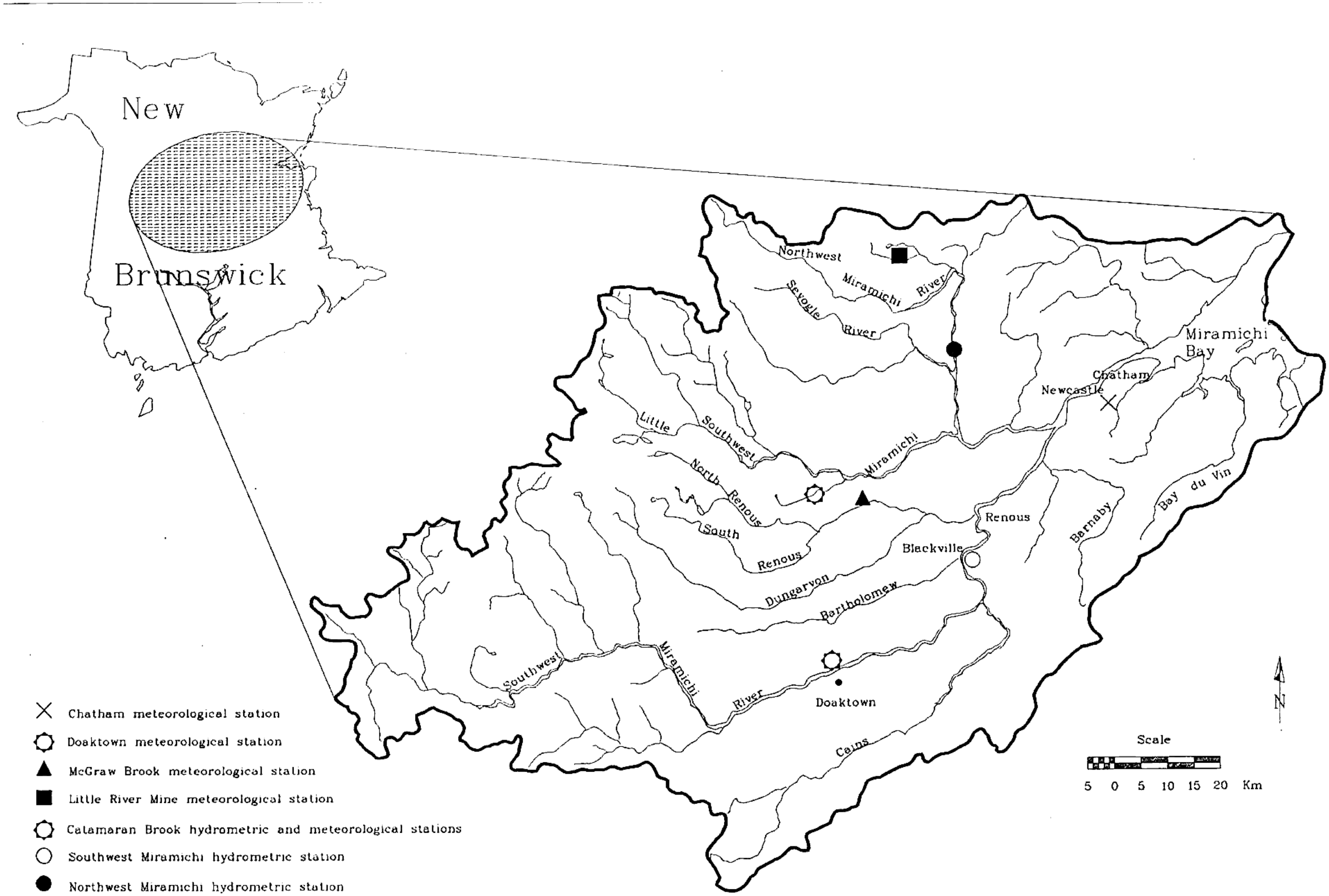

Figure 1. Hydrometric and meteorological stations of the Northwest and Southwest Miramichi Rivers, New Brunswick

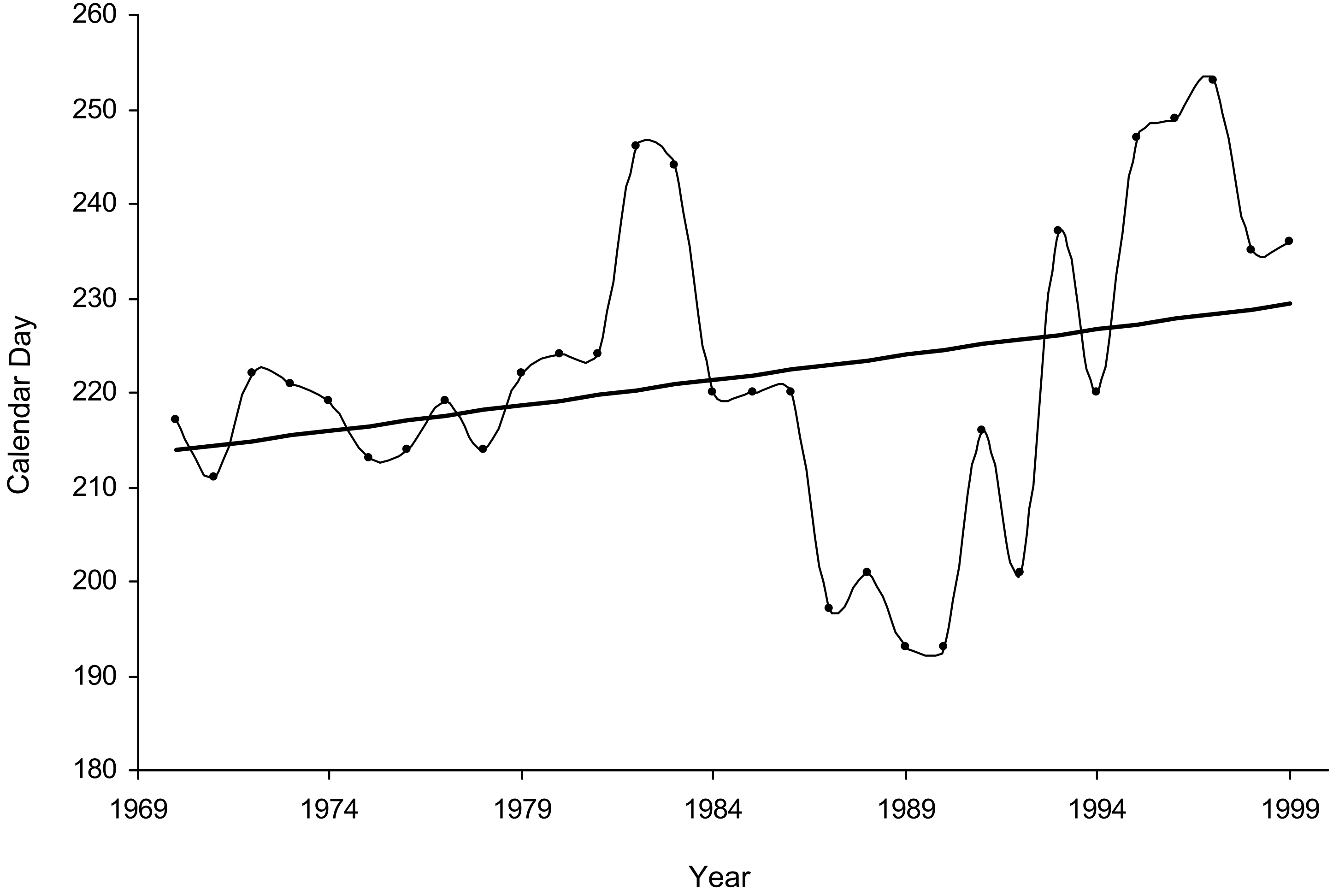

Figure 2. Mean annual date (calendar day) of electrofishing surveys in the Northwest and Southwest Miramichi Rivers (1970-1999).

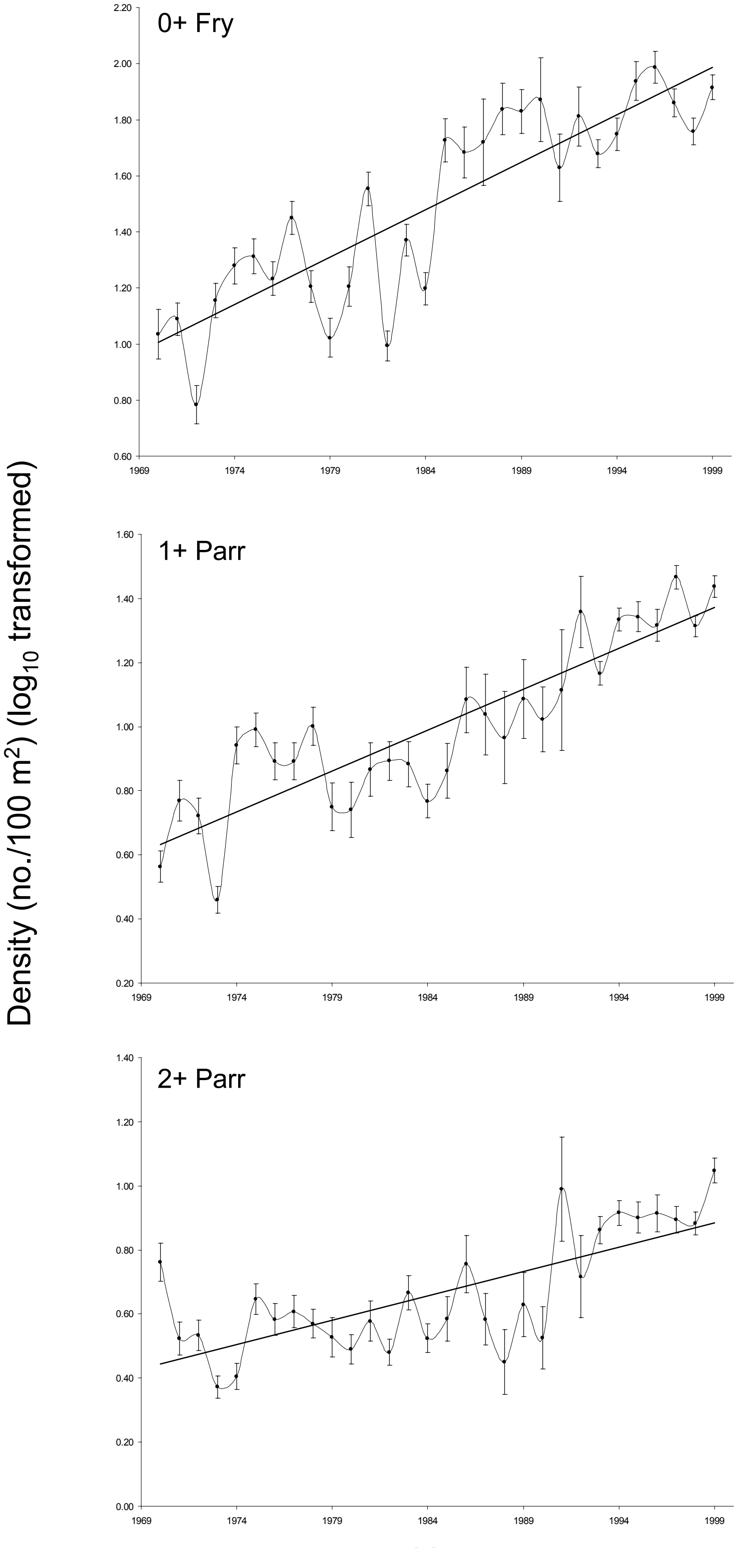

Figure 3. Density (no./100m^2) of juvenile Atlantic salmon in the Northwest and Southwest Miramichi Rivers (1970-1999).

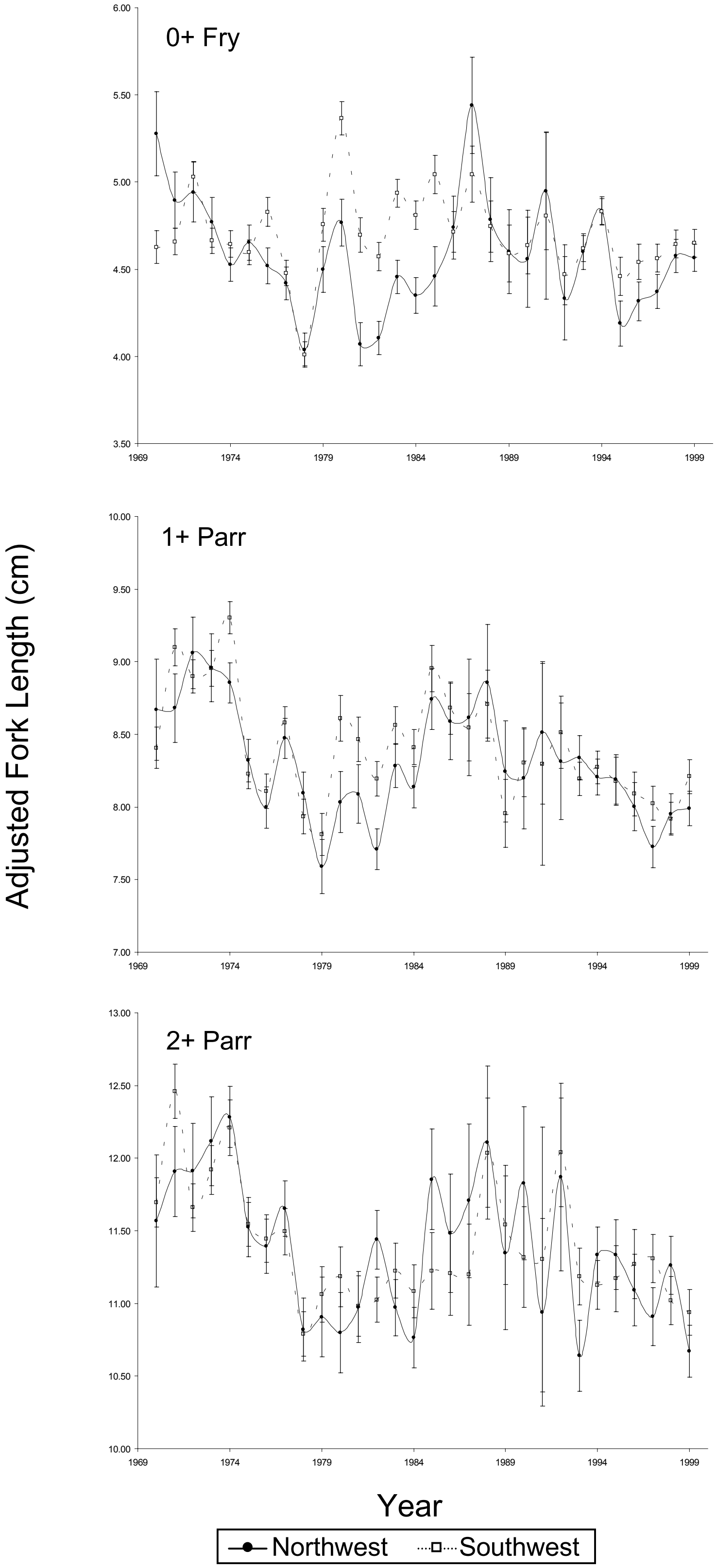

Figure 4. Adjusted fork length (cm) of juvenile Atlantic salmon in the Northwest and Southwest Miramichi Rivers (1970-1999).

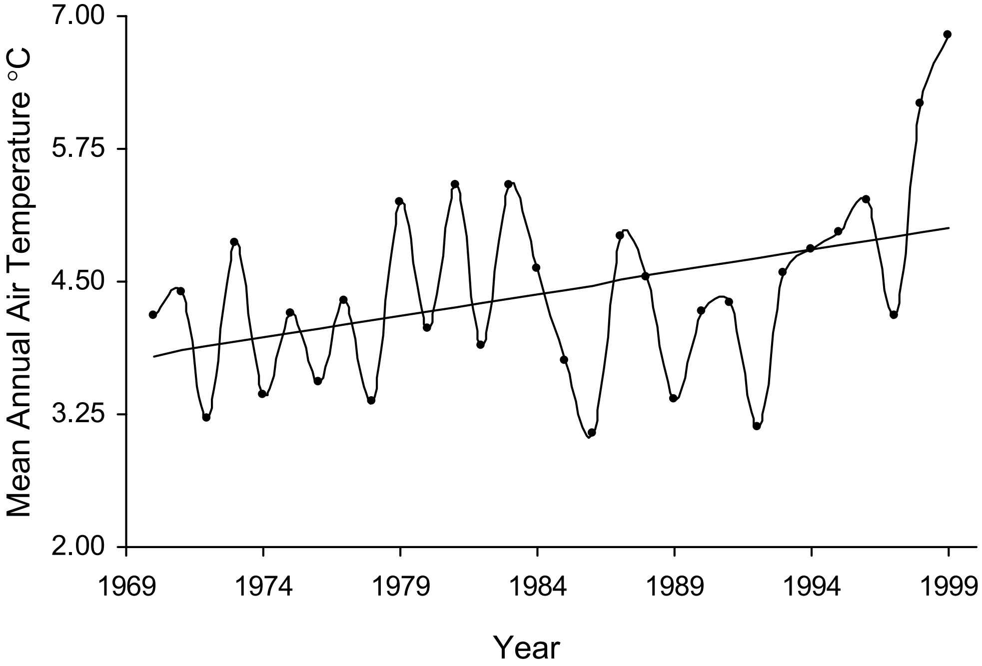

Figure 5. Mean annual air temperature in the Northwest Miramichi River basin (1970-1999).

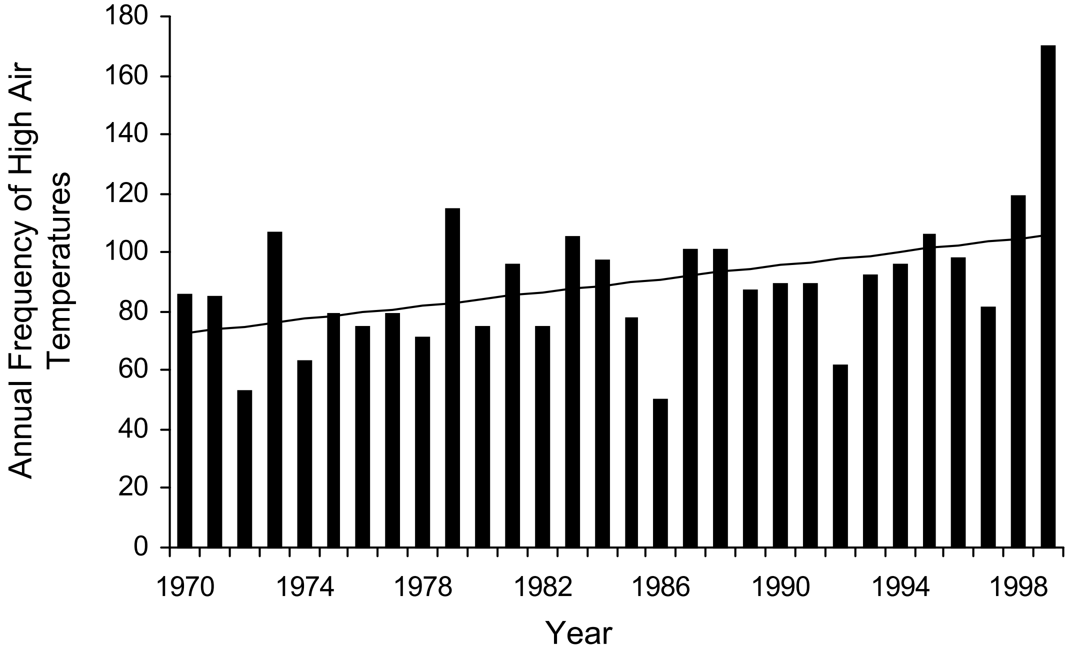

Figure 6. Annual frequency (no. of days) of high air temperatures in the Northwest Miramichi River basin (1970-1999).

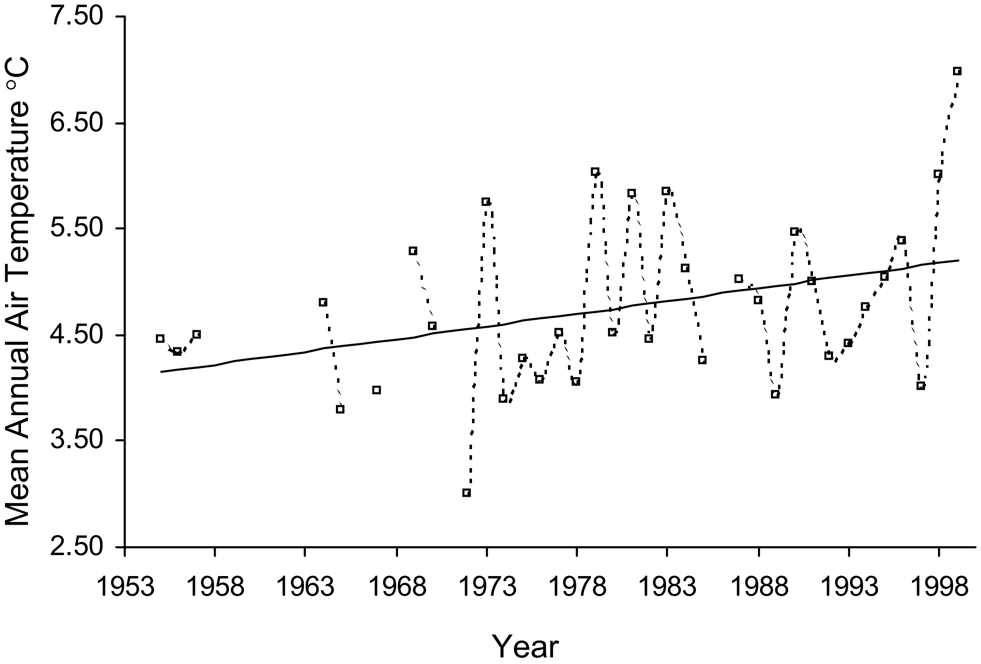

Figure 7. Mean annual air temperature in the Southwest Miramichi River basin (1955-1999).

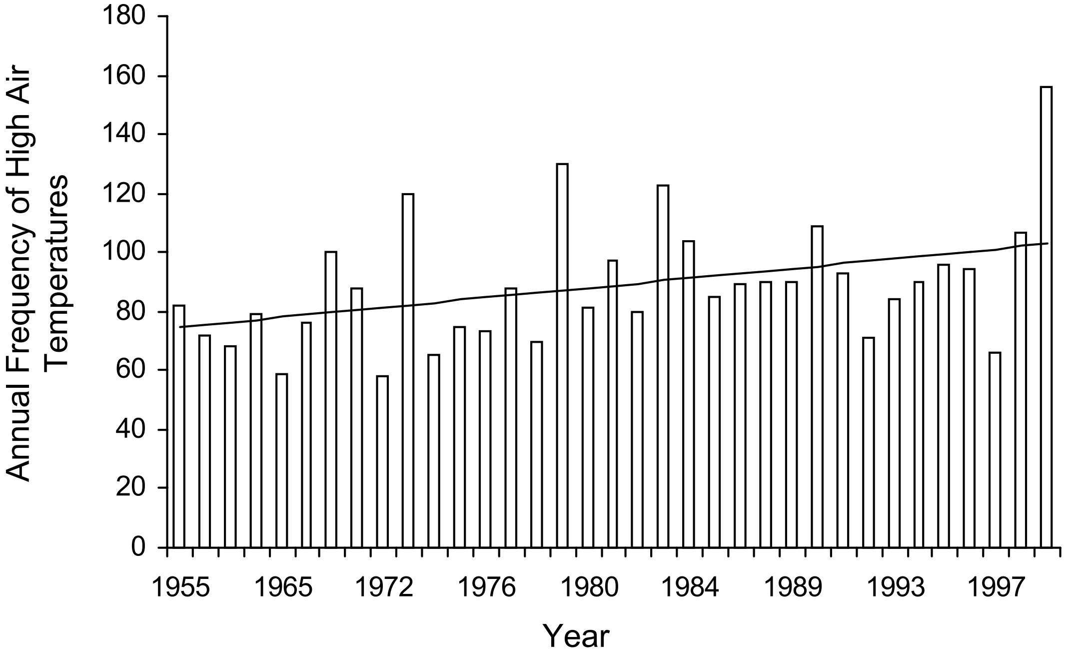

Figure 8. Annual frequency (no. of days) of high air temperatures in the Southwest Miramichi River basin (1955-1999).

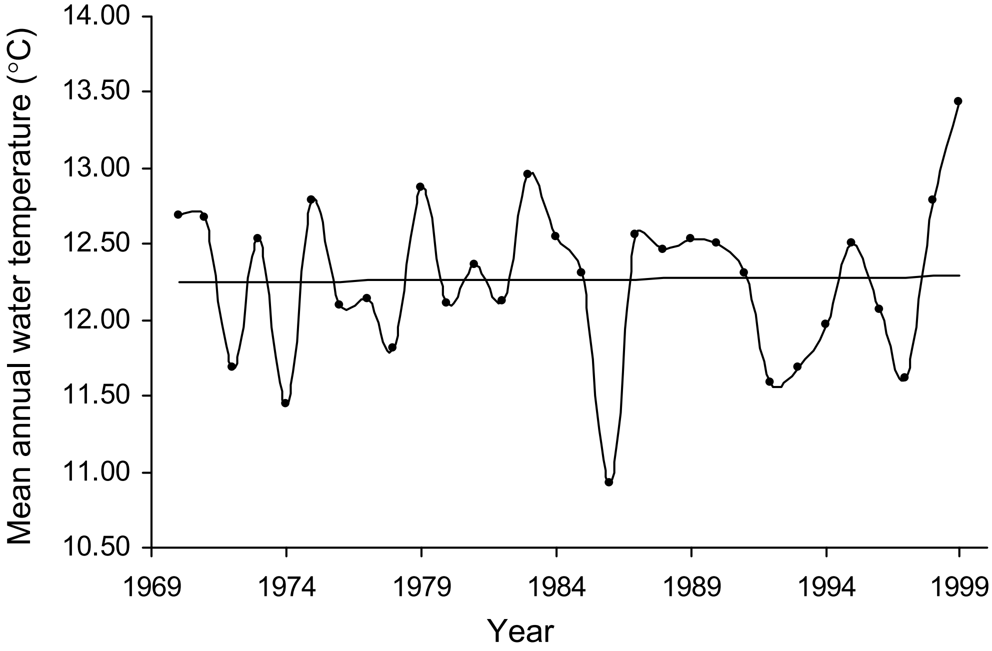

Figure 9. Mean annual water temperature (°C) in the Northwest Miramichi River (1970-1999)

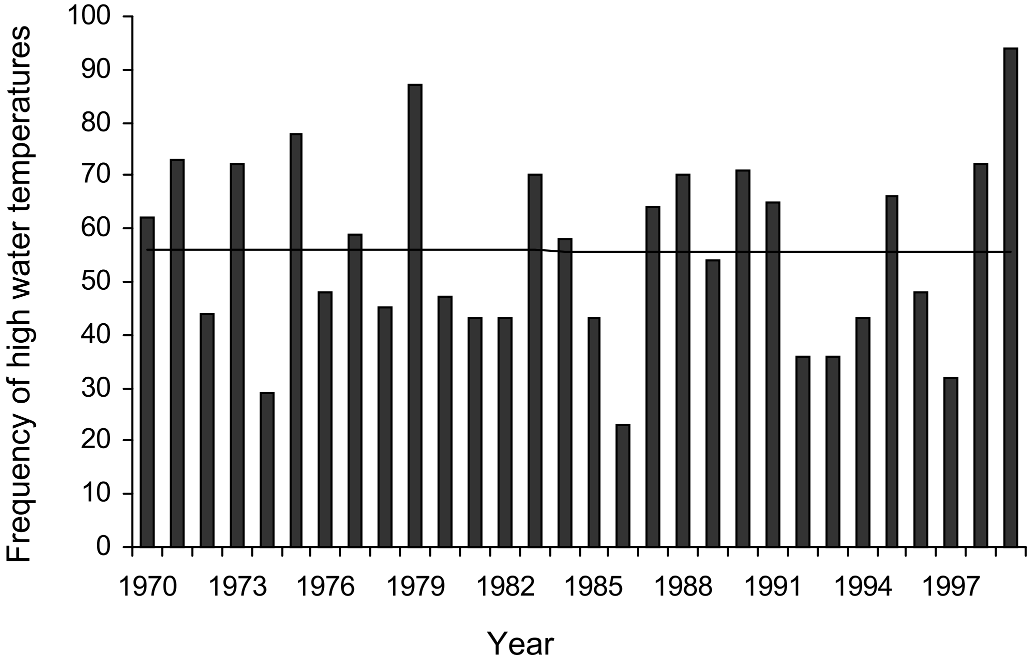

Figure 10. Frequency (no. of days) of high water temperatures in the Northwest Miramichi River (1970-1999)

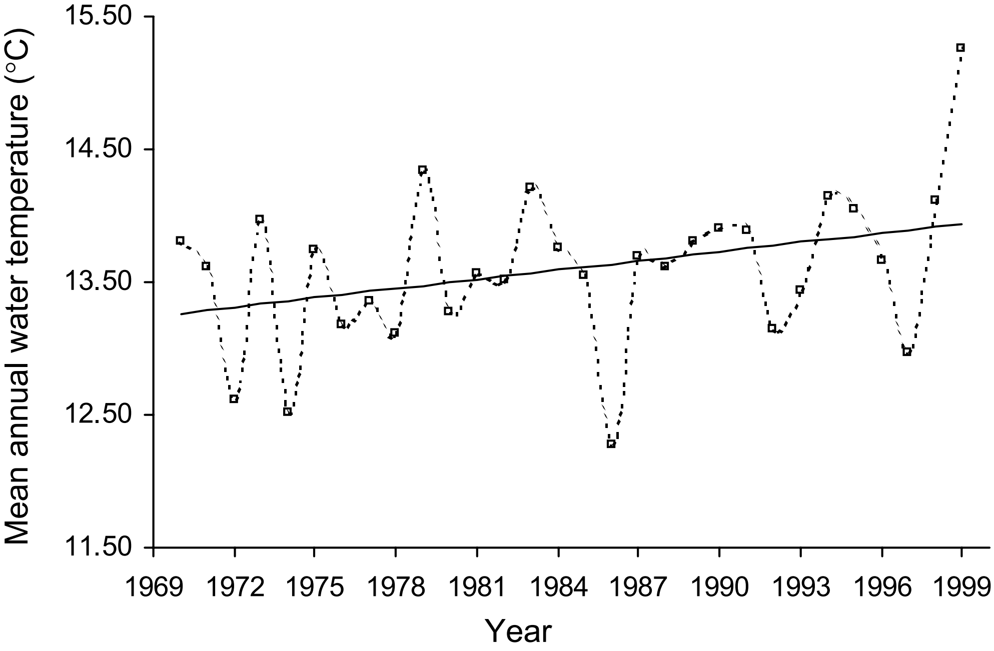

Figure 11. Mean annual water temperature (°C) in the Southwest Miramichi River (1970-1999)

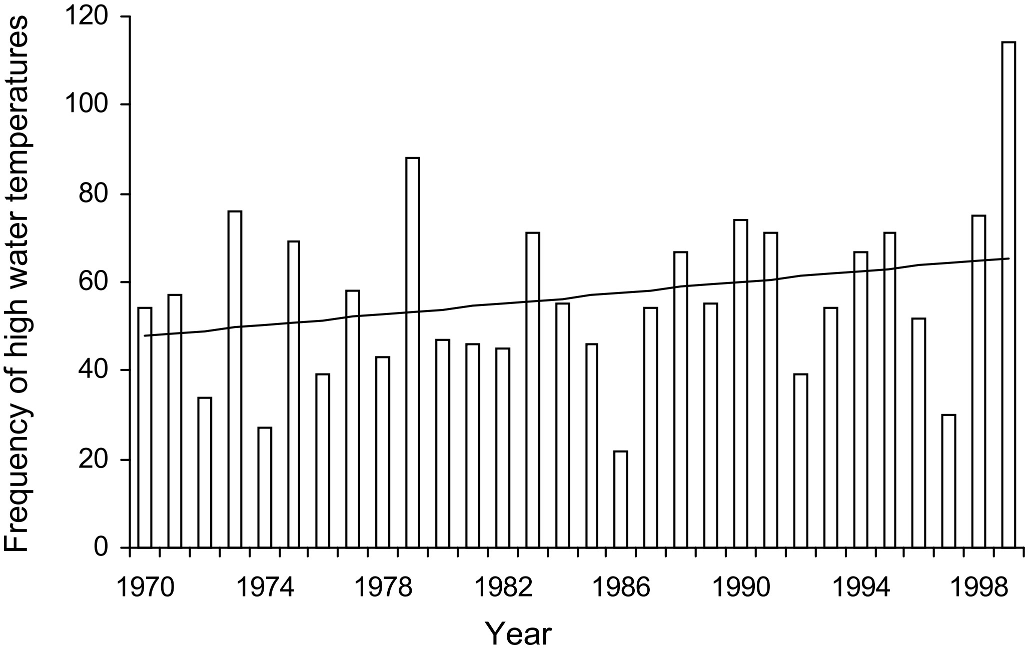

Figure 12. Frequency (no. of days) of high water temperatures in the Southwest Miramichi River (1970-1999)

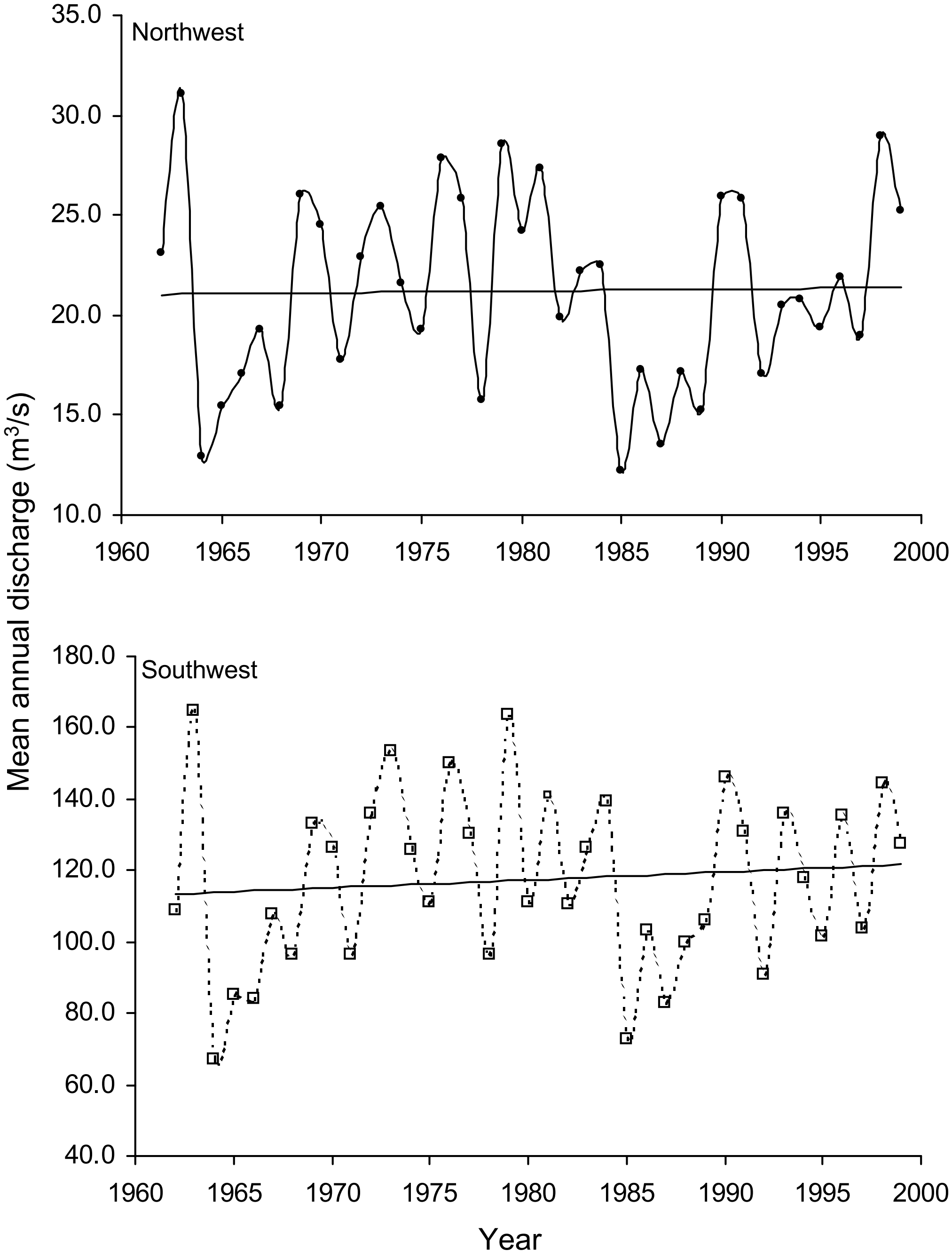

Figure 13. Mean annual discharge (m^3/s) in the Northwest and Southwest Miramichi Rivers (1962-1999).

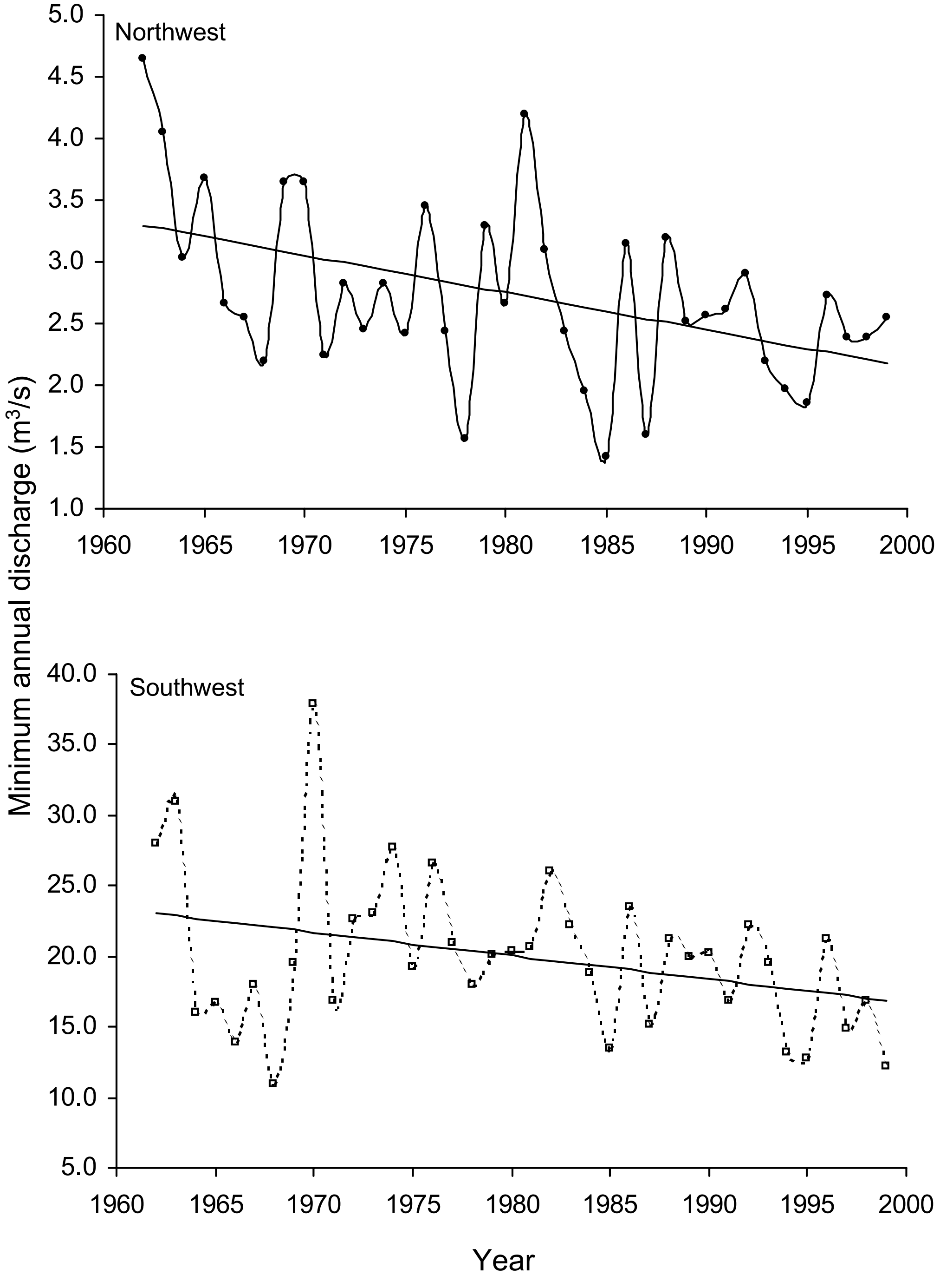

Figure 14. Minimum annual discharge (m^3/s) in the Northwest and Southwest Miramichi Rivers (1962-1999).

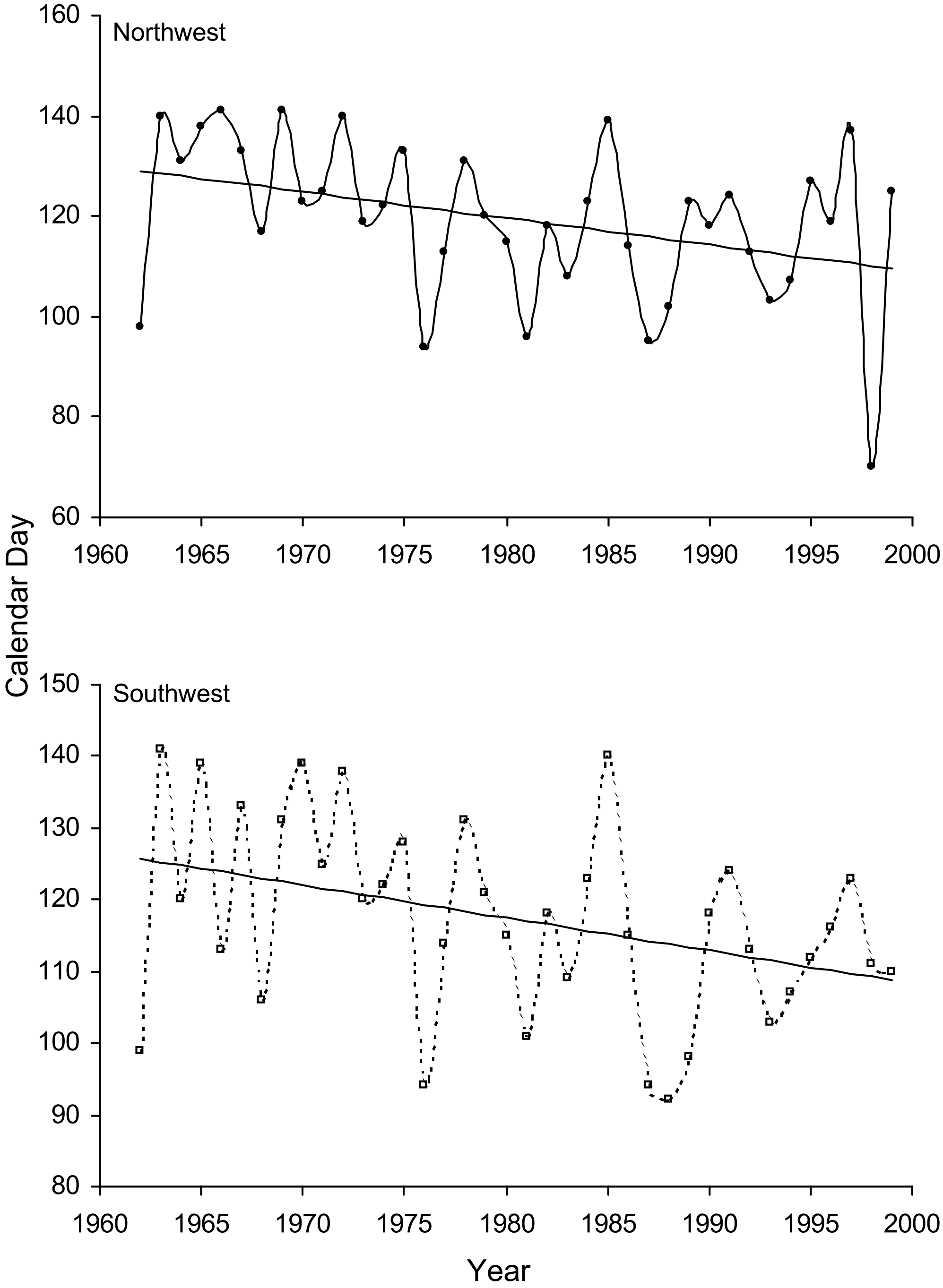

Figure 15. Date (calendar day) of peak runoff in spring (March - June) in the Northwest and Southwest Miramichi Rivers (1962-1999).

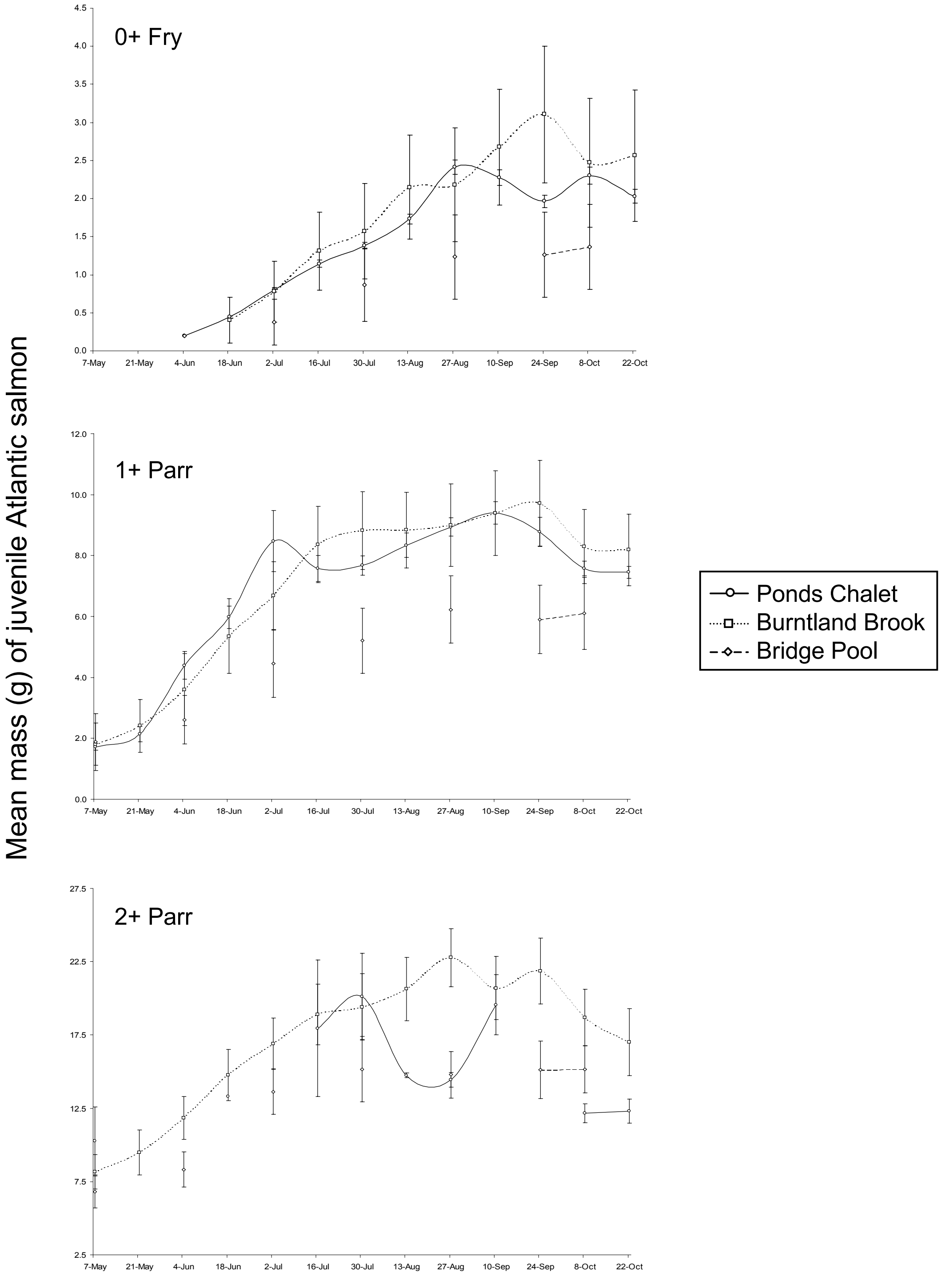

Figure 16. Mean mass of juvenile Atlantic salmon in the Northwest and Southwest Miramichi Rivers in 2000

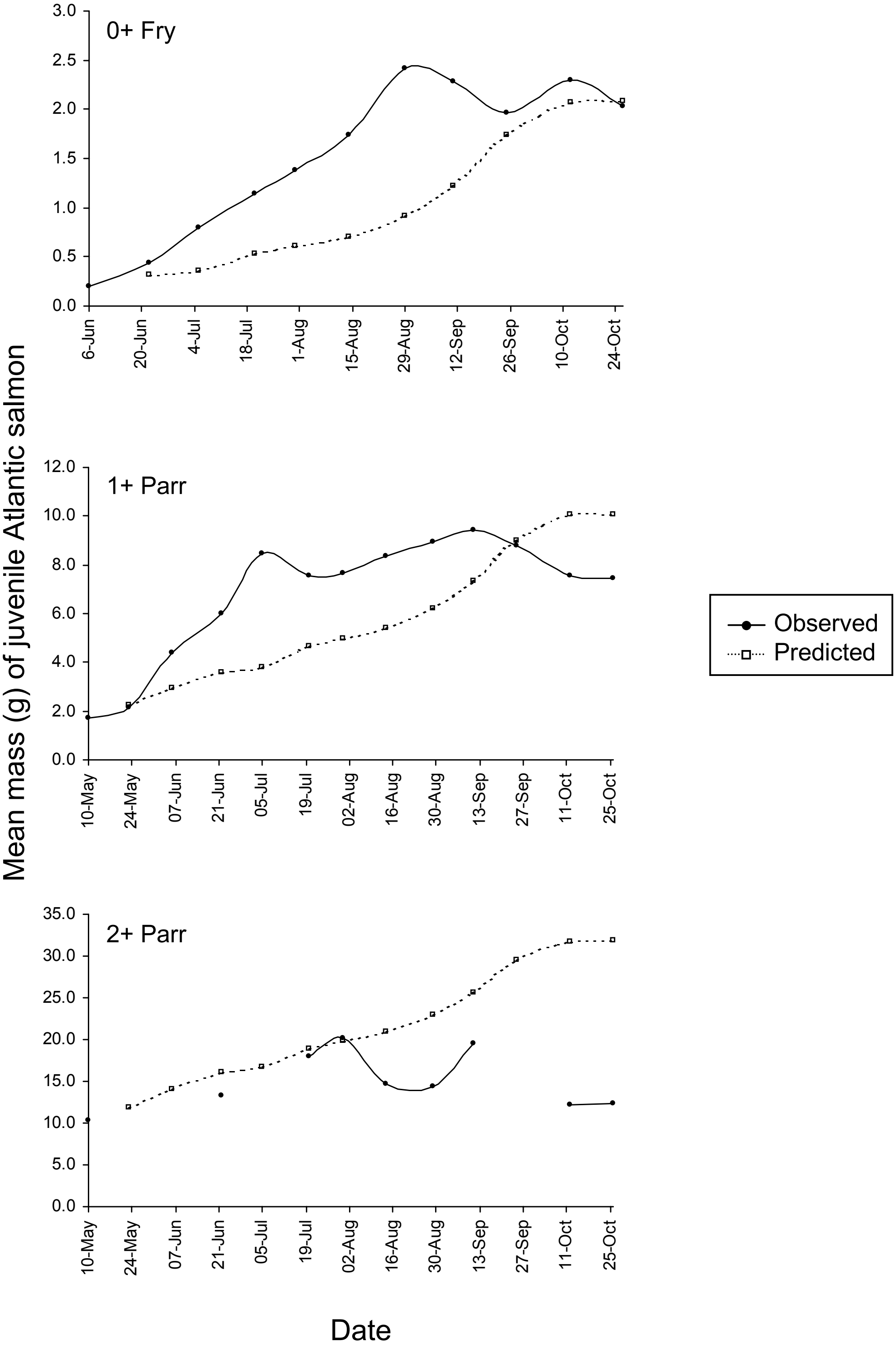

Figure 17. Observed and predicted mean mass of juvenile Atlantic salmon at Ponds Chalet in the Southwest Miramichi River. Mass was predicted from water temperature using the maximum growth model (Elliott and Hurley 1997)

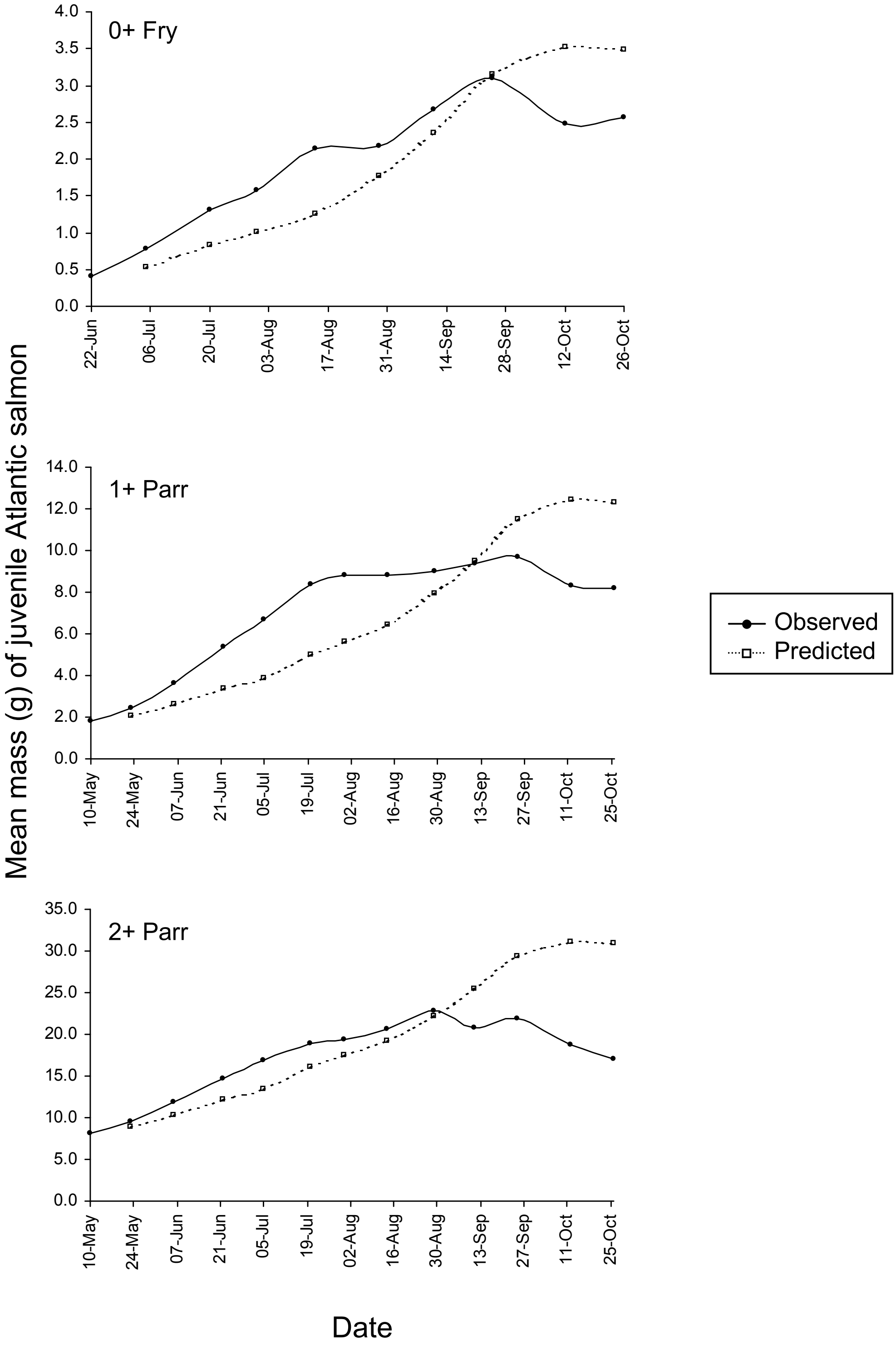

Figure 18. Observed and predicted mean mass of juvenile Atlantic salmon at Burntland Brook in the Southwest Miramichi River. Mass was predicted from water temperature using the maximum growth model (Elliott and Hurley 1997)

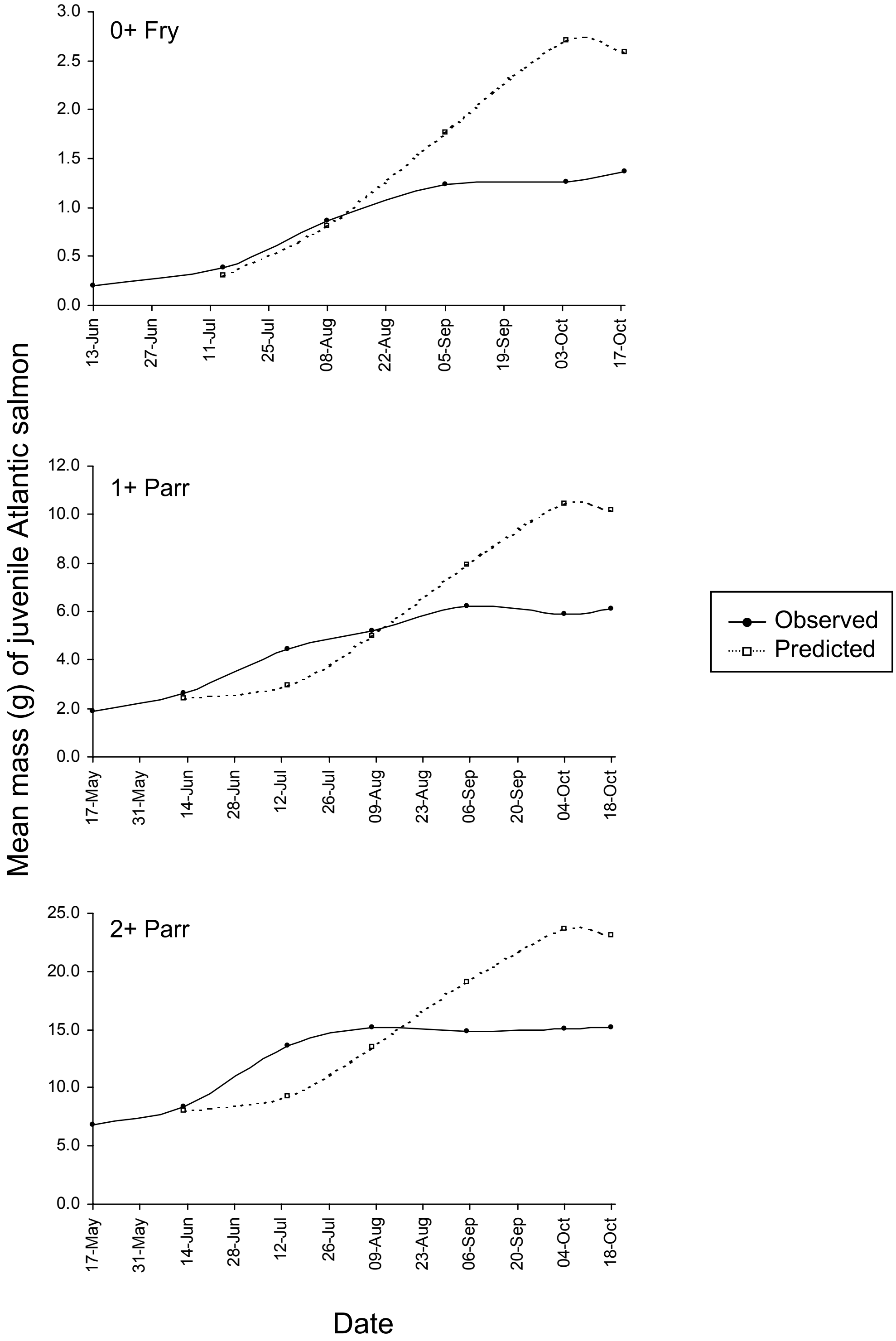

Figure 19. Observed and predicted mean mass of juvenile Atlantic salmon at Bridge Pool in the Northwest Miramichi River. Mass was predicted from water temperature using the maximum growth model (Elliott and Hurley 1997)

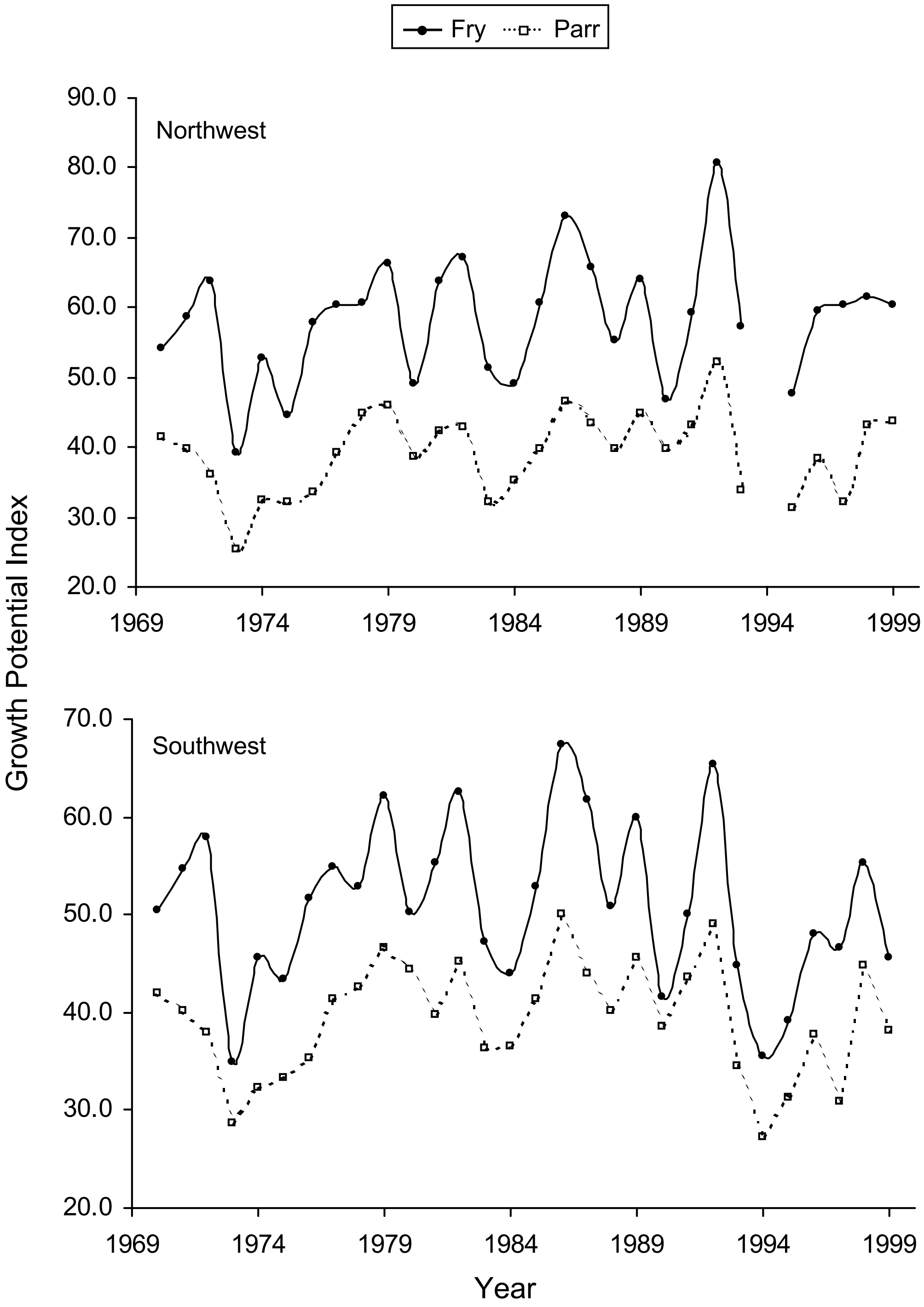

Figure 20: Growth potential (based on water temperature) in the Northwest and Southwest Miramichi River (1970-1999)

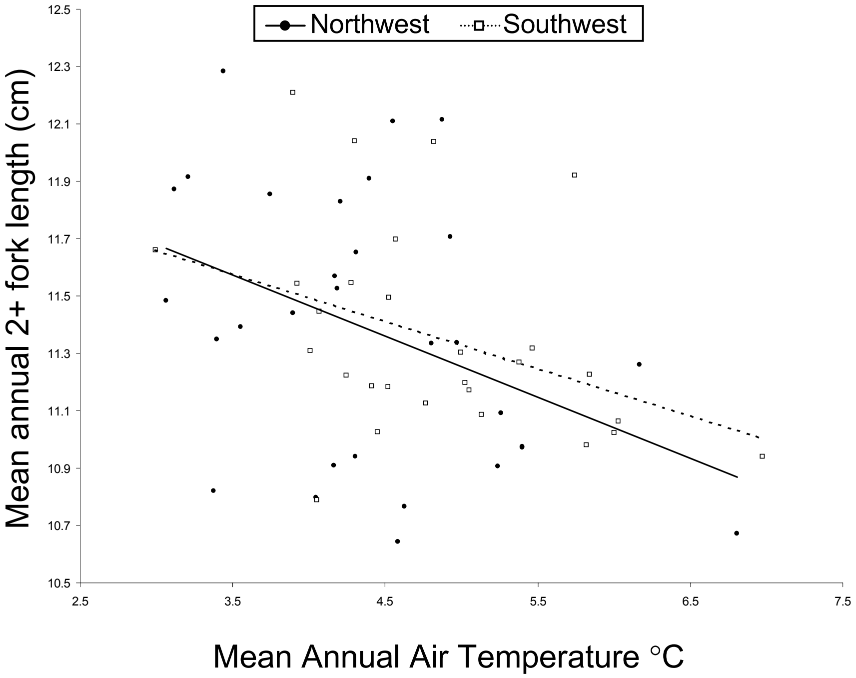

Figure 21: Relationship between mean annual air temperature and mean annual fork length of 2+ parr in the Northwest and Southwest Miramichi Rivers (1970-1999)

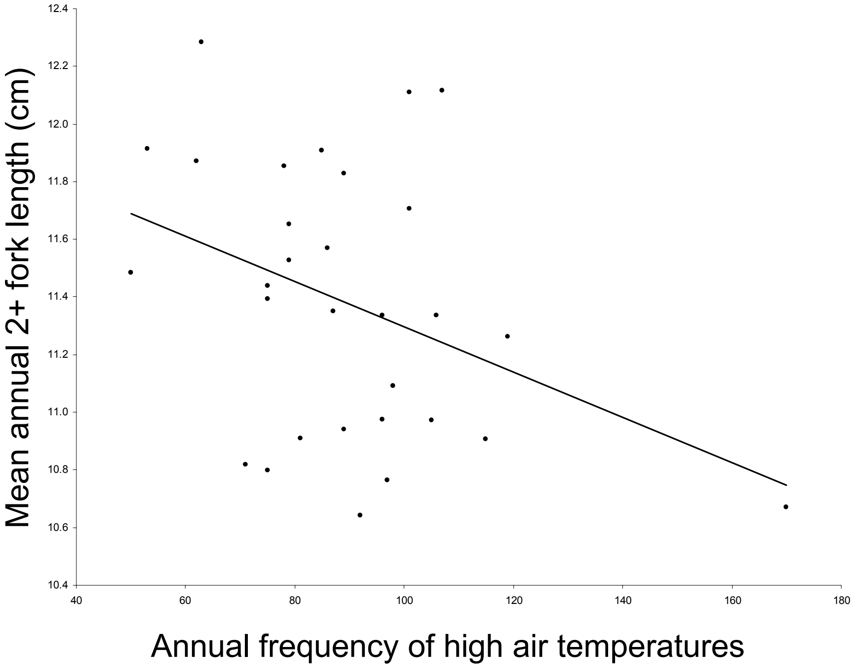

Figure 22: Relationship between annual frequency of high air temperatures and mean annual fork length of 2+ parr in the Northwest Miramichi River (1970-1999)

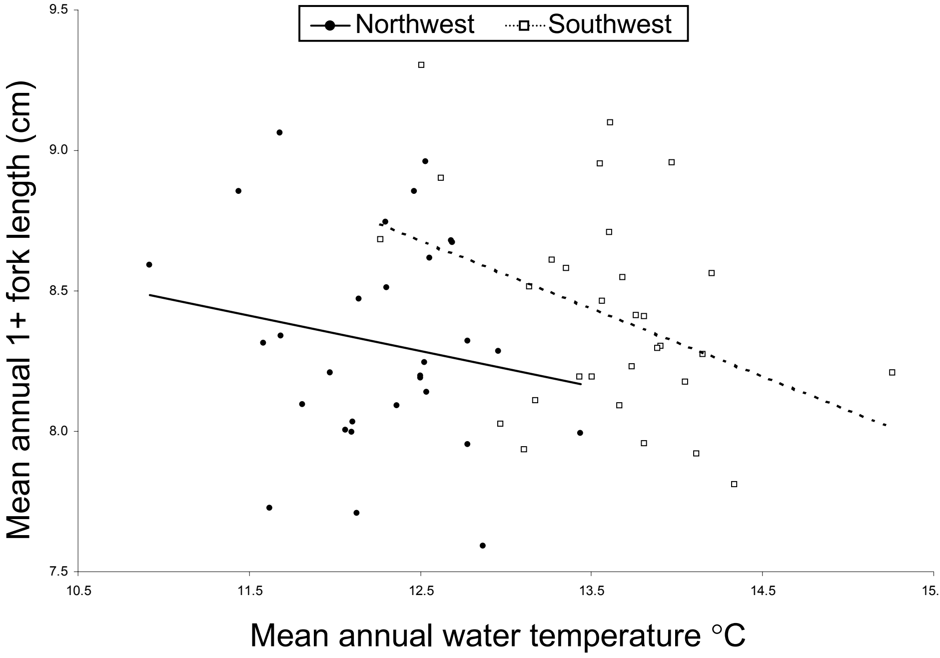

Figure 23: Relationship between mean annual water temperature and mean annual fork length of 1+ parr in the Northwest and Southwest Miramichi Rivers (1970-1999)

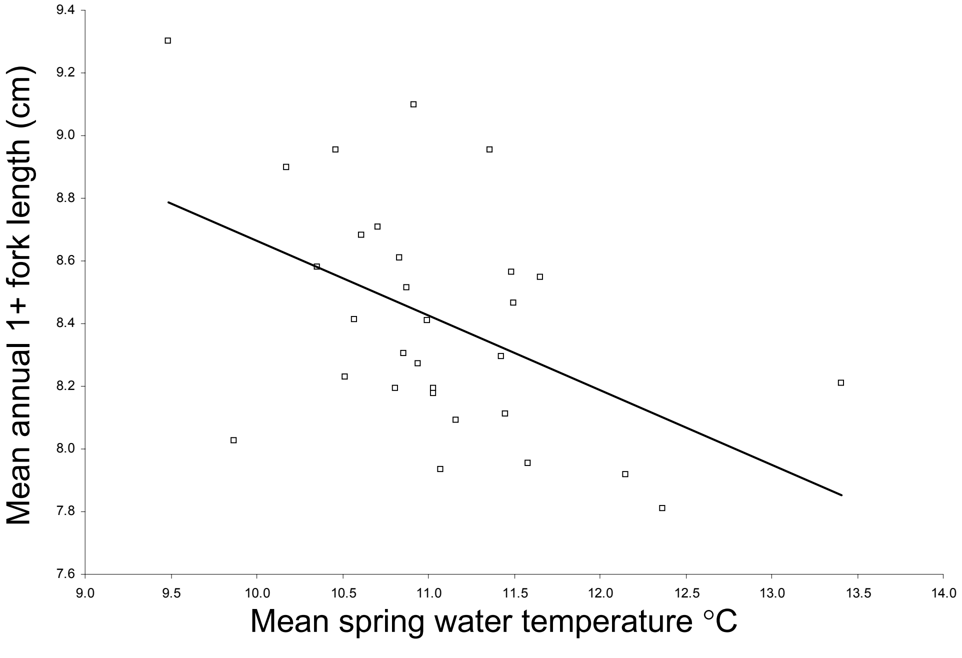

Figure 24: Relationship between mean water temperature in spring and mean annual fork length of 1+ parr in the Southwest Miramichi River (1970-1999)

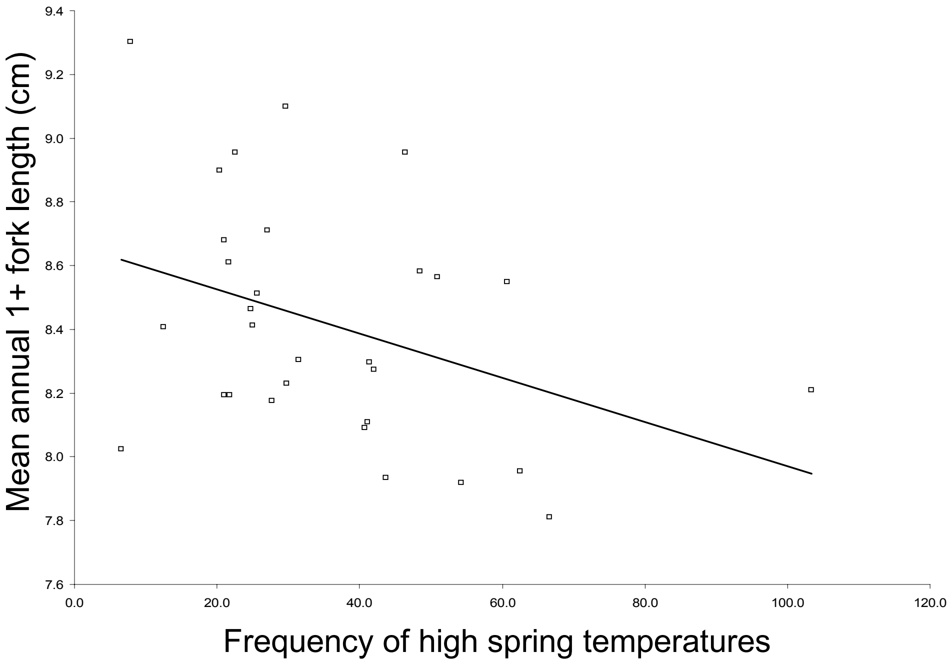

Figure 25: Relationship between the frequency of high temperatures in spring and mean annual fork length of 1+ parr in the Southwest Miramichi River (1970-1999)

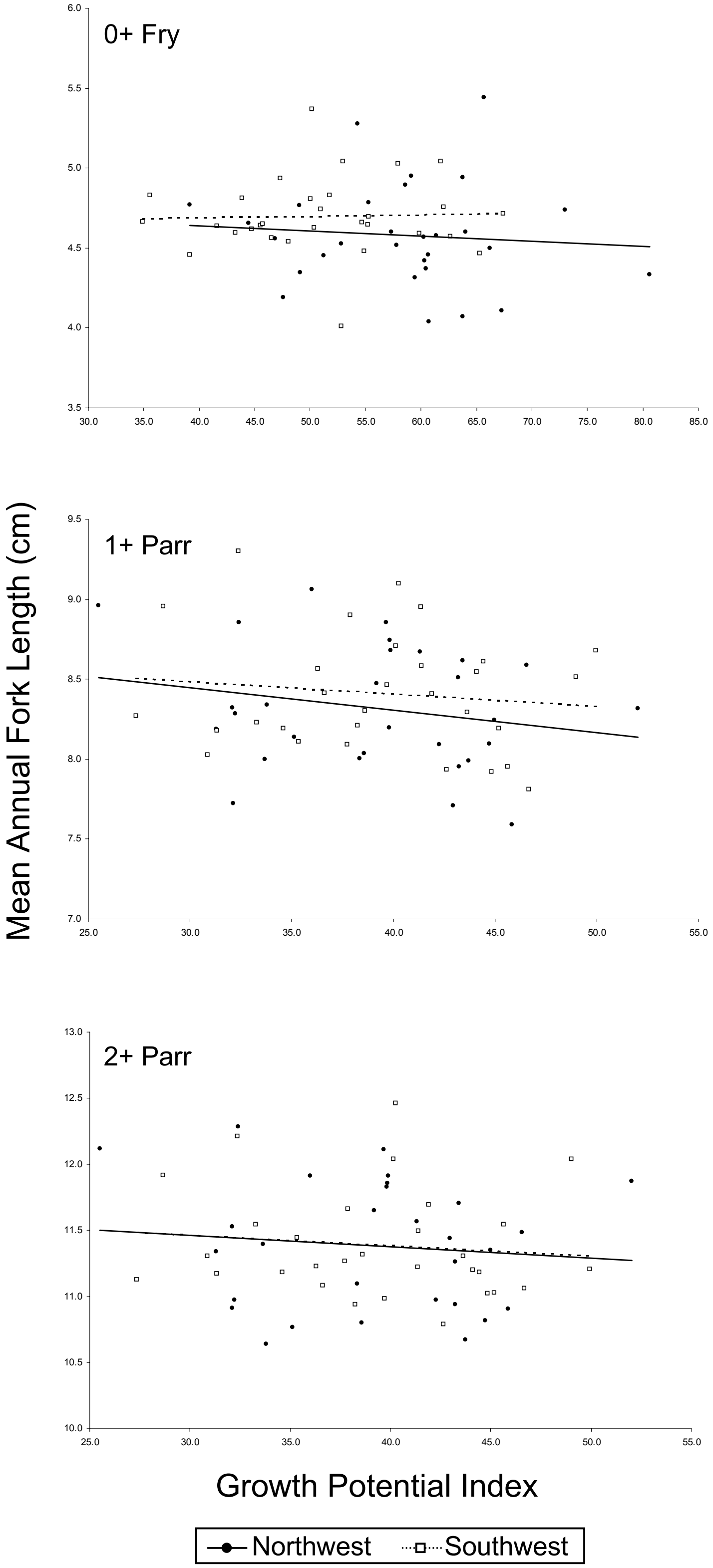

Figure 26. Association between growth potential index and mean annual fork length (cm) of juvenile Atlantic salmon in the Northwest and Southwest Miramichi Rivers.