Prepared in cooperation with the International Joint Commission St. Croix River Watershed Board and the Maine Bureau of Sea Run Fisheries and Habitat

Estimates of Growth and Mortality of Under-Yearling Smallmouth Bass in Spednic Lake From 1970 Through 2008

Scientific Investigations Report 2014–5164

U.S. Department of the Interior
U.S. Geological Survey

Cover. Sunrise, looking west, Spednic Lake, October 23, 2009.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Area	
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), and Geodetic Survey of Canada Datum.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

C_{max}	maximum length criteria, in millimeters
C_{min}	minimum length criteria, in millimeters
COOP	National Weather Service Cooperative Observer Program (National Oceanic and Atmospheric Administration)
DD	degree days, in degrees Celsius
DGI	daily growth increment, in millimeters
DGI_i	daily growth increment, in millimeters, for the ith day of the year
IJC	International Joint Commission
J	Julian date
L	total growth length for the year
MBSRFH	Maine Bureau of Sea Run Fisheries and Habitat
NOAA	National Oceanic and Atmospheric Administration
SD	spawning delay
T	daily mean water temperature, in degrees Celsius
$T_{air\ max}$	maximum daily air temperature, in degrees Celsius
$T_{air\ min}$	minimum daily air temperature, in degrees Celsius
T_i	estimated mean daily lake surface-water temperature for the *i*th day of the year
T_{lake}	estimated lake surface-water temperature, in degrees Celsius
T_{min}	minimum daily mean water temperature, in degrees Celsius
USGS	U.S. Geological Survey
WD	winter days, or the duration of the starvation period
YOY	young-of-the-year

Estimates of Growth and Mortality of Under-Yearling Smallmouth Bass in Spednic Lake From 1970 Through 2008

By Robert W. Dudley[1] and Joan G. Trial[2]

Abstract

This report is the product of a 2013 cooperative agreement between the U.S. Geological Survey, the International Joint Commission, and the Maine Bureau of Sea Run Fisheries and Habitat to quantify the effects of meteorological conditions (from 1970 through 2008) on the survival of smallmouth bass (*Micropterus dolomieu*) in the first year of life in Spednic Lake. This report documents the data and methods used to estimate historical daily mean lake surface-water temperatures from early spring through late autumn, which were used to estimate the dates of smallmouth bass spawning, young-of-the-year growth, and probable strength of each year class. Mortality of eggs and fry in nests was modeled and estimated to exceed 10 percent in 17 of 39 years; during those years, cold temperatures in the early part of the spawning period resulted in mortality to fish that were estimated to have had the longest growing season and attain the greatest length. Modeled length-dependent overwinter survival combined with early mortality identified 1986, 1994, 1996, and 2004 as the years in which temperature was likely to have presented the greatest challenge to year-class strength in the Spednic Lake fishery. Age distribution of bass in fisheries on lakes in the St. Croix and surrounding watersheds confirmed that conditions in 1986 and 1996 resulted in weak smallmouth bass year classes (age-four or age-five bass representing less than 15 percent of a 100-fish sample).

Introduction

Spednic Lake is a large, undeveloped lake on the United States-Canadian border in the headwaters of the St. Croix River Basin (fig. 1); the lake straddles the international border comprising the eastern border of the State of Maine and the western border of the Province of New Brunswick. The International Joint Commission (IJC), formed in 1912 as a result of the Boundary Waters Treaty Act, which went into effect in 1910, was invested with the authority to regulate flows and water levels for United States-Canadian boundary waters, which include the St. Croix River (Flagg, 2007). The IJC created the International St. Croix River Watershed Board to supervise compliance with IJC orders of approval that guide the regulation of flows and water levels at hydraulic structures in the St. Croix River Basin and to keep the IJC informed about transboundary issues relating to the ecological health of the St. Croix River (International Joint Commission, 2005).

Spednic Lake is known for its smallmouth bass (*Micropterus dolomieu*) and landlocked salmon (*Salmo salar*) fishery (Maine Department of Inland Fisheries and Wildlife, 2013). The quality of the smallmouth bass fishery in Spednic Lake declined precipitously in the early 1980s (International Joint Commission, 2005). The smallmouth bass fisheries in St. Croix watershed lakes exploit age-four and older fish (Dill and others, 2010); quality is assessed on the basis of angler catch rates and mean size of bass caught (Jordan, 2001). An increase in the population of alewife (*Alosa pseudoharengus*) that resulted from improved fish passage at dams in the St. Croix River (International Joint Commission, 2005) was hypothesized as a potential cause of the decline in the number of smallmouth bass recruited to the fishery. Lake-level management, growing-season temperature, and recreational harvest also were implicated in the decline. To improve the smallmouth bass fishery, alewives were denied access to Spednic Lake in 1988, and lake-level and fisheries management practices were altered. In May 1995, the Maine State Legislature passed a bill to prevent alewife migration in the St. Croix River. The smallmouth bass fishery has improved; however, controversy remains about the factors responsible for the decline and recovery (International Joint Commission, 2005).

To provide information that might help resolve the controversy, the IJC entered into cooperative agreements in 2009 and 2013 with the U.S. Geological Survey (USGS) and the Maine Bureau of Sea Run Fisheries and Habitat (MBSRFH) to quantify the effects of historical lake-level management and meteorological conditions (from 1970 through 2008) on the survival of smallmouth bass in the first summer of life (termed the 2009 and 2013 USGS–IJC–MBSRFH studies in this report). Given adequate numbers of

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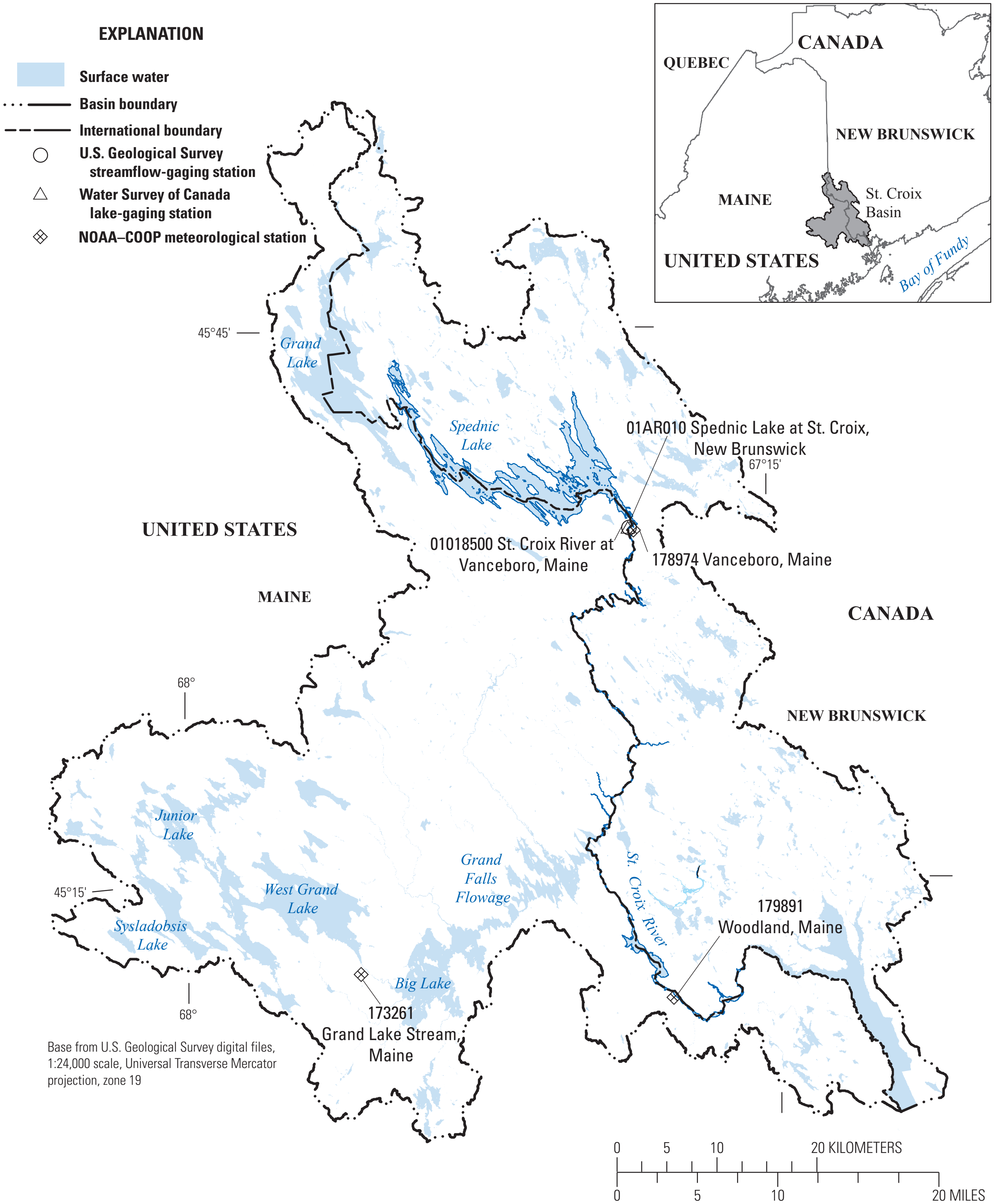

Figure 1. Spednic Lake and the St. Croix River Basin, Maine and New Brunswick. For visual clarity, distances among clustered stations have been exaggerated. NOAA–COOP, National Oceanic and Atmospheric Administration National Weather Service Cooperative Observer Program. Modified from Dudley and others (2011).

spawners, year-class strength (reproductive success measured by population) of smallmouth bass in northern climates (such as eastern Maine) depends on the growth and survival of juveniles during the first year (MacLean and others, 1981). Poor summer survival has been linked to changes in water level (Neves, 1975; Ploskey and others, 1996; Clark and others, 1998), nest success (Shuter and others, 1980, 1985; MacLean and others, 1981; Goff, 1985; Finlay and others, 2001) and water temperature, with cooler summers corresponding to poor growth and survival (Serns, 1982). Growth during the summer, a function of food availability and temperature (Rowan, 1962; DeAngelis and Coutant, 1979; Shuter and others, 1980), can be used to estimate the likelihood that young bass will survive their first winter (Shuter and others, 1980, 1985; Shuter and Post, 1990). Variations in lake surface-water temperatures within and among basins (Finlay and others, 2001) and between lake windward and lee shores (Kaevats and others, 2005) affect smallmouth bass spawning and juvenile growth and survival; however, mean thermal conditions in a lake can be used to estimate the probable year-class survival in year one (Shuter and others, 1985). Although first-year survival is important to year-class strength in the fishery 4 years later, survival in subsequent years and of other year classes also can affect year-class strength (Dong and DeAngelis, 1998).

The 2009 USGS–IJC–MBSRFH study estimated the available smallmouth bass spawning habitat as a function of lake level by using bathymetry and bottom character data (Dudley and others, 2011). The amounts of spawning habitat were estimated as a function of bottom substrate classification and depth (on the basis of lake levels during the most likely spawning period each year from 1970 through 2009) for two categories of littoral bottom slopes. For shallow areas of the lake, which typically had low bottom slopes, minimum lake level had the most influence on available spawning habitat, whereas changes in lake level during the spawning period explained most of the variability in the amount of available habitat on steeper bottom slopes (between 10 and 40 degrees; Dudley and others, 2011). Spawning habitat availability was low for both slope categories in 1978, 1981, and 2006; therefore, these smallmouth bass cohorts were the most likely to have been affected by lake levels during spawning (Saunders and others, 2002; Clark and others, 2008). If habitat availability did affect year-class strength, the recreational fisheries should have detected weak year classes 4 years later in 1982, 1985, and 2010. If age-four or age-five bass represent less than 15 percent of a 100-fish sample, the year class is considered weak (Dill and others, 2010). Year-class strength data for Spednic Lake fisheries are limited (1995, 1998, 2001, 2004, and 2007) and not useful in evaluating the model estimates.

The objectives of the 2013 USGS–IJC–MBSRFH study were to develop a method to estimate daily mean lake surface-water temperatures in Spednic Lake from early spring, before spawning, through late autumn and to use those estimated temperatures to estimate the dates of spawning, young-of-the-year (YOY) growth, and probable growth and survival of each year class (Shuter and others, 1980).

Purpose and Scope

The purpose of this report is to document the data and methods for estimating daily mean lake surface-water temperatures and the effects of water temperature conditions on growth and survival of smallmouth bass in the first year of life for the historical period of from 1970 through 2008. Estimates of growth and survival of smallmouth bass are for Spednic Lake.

Description of Spednic Lake

Spednic Lake has a surface area of about 6,970 hectares (ha) and about 170 kilometers (km) of shoreline and is part of the St. Croix River Basin (fig. 1; Maine Volunteer Lake Monitoring Program, 2014). Outflow from the lake into the St. Croix River is controlled by a dam at Vanceboro. The dam was originally a timber crib structure built in 1836 that raised the natural lake level 4.6 meters (m); the dam was replaced in 1965 with a concrete structure outfitted with two tainter gates capable of controlling lake level over a range of 4.38 m (Flagg, 2007). Lake level at the dam has been gaged by the Water Survey of Canada at station 01AR010 from January 19, 1967, to the present (2014); the minimum recorded lake elevation was 113.89 m (Geodetic Survey of Canada Datum) on February 10, 2002, and the highest recorded lake elevation was 117.77 m on May 1, 1973 (Environment Canada, 2013).

Streamflow in the St. Croix River at Vanceboro has been measured by USGS streamflow-gaging station 01018500, maintained by the United States under agreement with Canada and operated in cooperation with the IJC from October 22, 1928, to the present (2014). Monitoring an upstream drainage area of 1,070 square kilometers (km^2), the gage has measured mean monthly streamflows ranging from 13.4 cubic meters per second (m^3/s) (November) to 28.0 m^3/s (May) and mean annual streamflow of 22.8 m^3/s for the period of record ending September 30, 2012 (U.S. Geological Survey, 2013a). The minimum recorded daily mean (arithmetic average for a day) streamflow was 0.05 m^3/s on October 12 and 22 and November 4, 1936, when the streamflow was held back by a cofferdam to facilitate dam repairs; the highest recorded daily mean streamflow was 191.6 m^3/s on June 3, 1984 (U.S. Geological Survey, 2013b).

The climate of the St. Croix Basin is temperate, with mild summers and cold winters. The mean annual air temperature at Vanceboro (elevation 128 m, North American Vertical Datum of 1988) from 1971 through 2000 was about 5 degrees Celsius (°C), with mean monthly air temperatures ranging from about -10 °C in January to about 19 °C in July (National Oceanic and Atmospheric Administration, 2002). Mean annual precipitation during the same 30-year period was approximately 1,120 millimeters (mm), which was fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 2002). Mean annual evapotranspiration (loss of water to the atmosphere by evaporation from the soil and transpiration from plants) from 1951 through 1980 was about 430 mm (Randall, 1996). Measured mean annual runoff from 1929 through 2012 was about 612 mm (U.S. Geological Survey, 2013b).

Methods of Study

Serns (1982) observed that smallmouth bass YOY growth was positively related to lake and air temperatures. Though there are no lake surface-water temperature data for Spednic Lake, available historical air temperature data can be used to estimate lake surface-water temperatures. Sharma and others (2008) applied a variety of regression methods to estimate near-surface (0–2 m depth) maximum lake surface-water temperatures from air temperature for lakes across Canada, and McCombie (1959) used linear regression methods to relate monthly mean lake surface-water temperatures to air temperatures at nearby weather stations. This USGS–IJC–MBSRFH study used air temperature data measured at Vanceboro to estimate daily lake surface-water temperatures for Spednic Lake during spring, summer, and autumn from 1970 through 2008.

Lake Surface-Water and Air Temperature Data

Hourly lake surface-water temperature data were collected by the Maine Department of Inland Fisheries and Wildlife at Big Lake and Grand Falls Flowage, near Spednic Lake in the St. Croix River Basin. The period of record for Big Lake was 1994 and 1996–2004; the period of record for Grand Falls Flowage was 1994–99. Data collected during these years began in the spring (April or May) and ended in the fall (October or November). Daily time series of mean (arithmetic average of 24 hourly values) lake surface-water temperature records were derived from the hourly data. Other known sources of water temperature data in the St. Croix River Basin are summarized in appendix 1.

Daily precipitation and minimum and maximum daily air temperature data from meteorological stations (fig. 1) in the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service Cooperative Observer Program (COOP) were used. Meteorological data from the NOAA–COOP network stations at Vanceboro (NOAA station number 178974), Grand Lake Stream (NOAA station number 173261), and Woodland (NOAA station number 179891) were retrieved by using the USGS Downsizer computer application (Ward-Garrison and others, 2009), which was written in the Java programming language and designed for selecting, downloading, and verifying station-based time-series data for modeling environmental resources.

Models for Estimating Lake Surface-Water Temperature

A regression model for estimating lake surface-water temperature in Spednic Lake cannot be directly derived because there are no surface-water temperature data for the lake; however, Livingstone and Padisák (2007) demonstrated that daily lake surface-water temperatures in adjacent lakes respond similarly to regional meteorological and climatic conditions. This study therefore uses regression methods derived to estimate lake surface-water temperatures at nearby Big Lake to estimate lake surface-water temperatures in Spednic Lake.

A regression model was derived to estimate daily mean lake surface-water temperatures (degrees Celsius). Explanatory variables tested for this regression model were daily minimum and maximum air temperature (degrees Celsius) and daily precipitation (millimeters) at the nearby meteorological station at Grand Lake Stream, and a Fourier term—the sum of sine and cosine, which provides a periodic function to explain seasonal variability from spring to fall. The regression model was derived by using lake surface-water temperatures measured at Big Lake in 1994 and from 1996 through 2002. Lake surface-water temperature data from 2003 through 2004 were reserved for validation of the derived regression model.

Models for Estimating Smallmouth Bass Growth and Mortality

The dates of spawning were estimated on the basis of the preferred spawning temperature range of 15 to 27 °C and accumulated degree days above 10 °C (fig. 2; Shuter and others, 1980), as follows.

$$DD = \sum \left(T_i - 10\right),\ for\, T_i > 10, \tag{1}$$

where

DD is degree days, in degrees Celsius; and

T_i is daily mean water temperature for the *i*th day of the season, in degrees Celsius.

Spawning is triggered when T_i is greater than (>) 15 °C and less than or equal to (≤) 27 °C, and DD>10 °C and less than (<) 150 °C.

The spawning delay (SD), in days, is computed with the following equation:

$$SD = (8.0 - 0.055DD). \tag{2}$$

The delay, in days, is any value of SD>0. If SD≤0, then there is no delay. The delay is added to the trigger date to calculate each spawning date.

With the spawning period defined, mortality was estimated on the basis of the minimum daily mean lake surface-water temperature (T_{min}; Shuter and others, 1980) for the period from spawning date to spawning date plus 15 days (assumed period from fertilization to rise of fry from nests) each year (table 1).

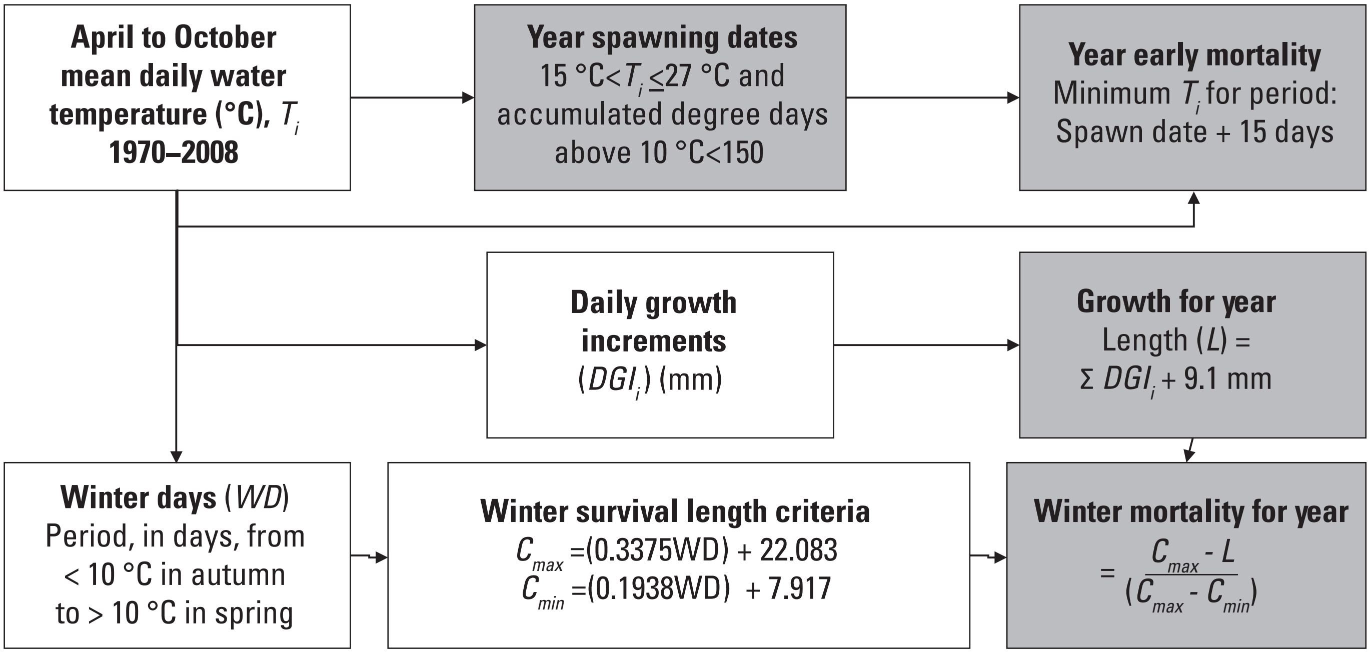

Figure 2. Modeling schema for estimating growth and mortality of under-yearling smallmouth bass in Spednic Lake, Maine and New Brunswick. [°C, degrees Celsius; T_i, estimated mean daily lake surface-water temperature for the *i*th day of the year; <, less than; ≤, less than or equal to; >, greater than; DGI_i, daily growth increment, in millimeters, for the *i*th day of the year; mm, millimeters; *L*, total growth length for the year; *WD*, number of winter days or starvation period; C_{max}, C_{min}, maximum and minimum winter survival length criteria, in millimeters.]

Growth models (Shuter and others, 1980) were then used to estimate daily growth increments throughout the summer for bass spawned on the first and last days of the spawning period (table 2). Daily growth increments (DGI_i, for the *i*th day of the growing period) were summed throughout the growing period and added to an assumed mean size at rise (9.1 mm) to estimate the total length (*L*, in millimeters) of juveniles at the start of the winter, as follows:

$$L = \sum DGI_i + 9.10. \quad (3)$$

Shuter and others (1980) emphasized that these values estimate the maximum length at the end of the growing season because growth is based solely on temperature; therefore, calculations do not account for lake productivity or food availability.

Estimated YOY bass sizes were compared with the length criteria (equations 4,5) for overwinter survival estimated from the duration of the starvation period (Shuter and others, 1980). For each year, the duration of the starvation period in days (winter days, *WD*) was estimated as the number of days between the dates on which the daily mean lake surface-water temperature was below 10 °C in the autumn and equal to or above 10 °C the following spring. Because of missing data in spring of 2009, the 2008 cohort used May 3, the median spring date when lake surface-water temperature was equal to or above 10 °C for the preceding years.

$$C_{max} = 0.3375WD + 22.083. \quad (4)$$

Table 1. Probability of mortality of smallmouth bass in Spednic Lake, Maine and New Brunswick, during the period from fertilization to rise of fry from nests.

[Data are from Shuter and others (1980). T_{min}, minimum daily mean water temperature in degrees Celsius; *p*, probability, where 1=100 percent; <, less than; >, greater than; ≥, greater than or equal to; ≤ ,less than or equal to]

T_{min}	*p*
<10 or >30	1
≥10 and ≤15	$3.0–0.2T_{min}$
>15 and <27	0
≥27 and ≤30	$0.33T_{min}–9$

Table 2. Summer daily growth increments for smallmouth bass spawned in Spednic Lake, Maine and New Brunswick, on the first and last days of the spawning period.

[Data are from Shuter and others (1980). *T*, daily mean water temperature in degrees Celsius; *DGI*, daily growth increment, in millimeters; <, less than; >, greater than; ≥, greater than or equal to]

T	*DGI*
<14.2 or >35	0
≥14.2 and <25.5	$0.12T–1.7$
≥25.5 and < 31.5	1.4
≥ 31.5 and <35	$14–0.4T$

$$C_{min} = 0.1938\,WD + 7.917\,, \tag{5}$$

where C_{max} and C_{min} are the maximum and minimum length criteria, respectively, in millimeters.

The length criteria were used to determine probability of winter mortality. If the calculated length (L) was greater than C_{max}, probability (p) of mortality was set equal to 0; if L was less than C_{min}, then p=1; otherwise, p was computed by using the following equation.

$$p = \frac{C_{max} - L}{C_{max} - C_{min}}\,. \tag{6}$$

Model outputs were compared to the known year-class failures (age-four or age-five bass representing less than 15 percent of a 100-fish sample) caused by cold, wet summers evident in all lakes in the Spednic Lake region in 1986 and 1996 (Dill and others, 2010) to validate the model used to estimate effects of water temperature on year-class strength of smallmouth bass in Spednic Lake. Of the limited fisheries data for Spednic Lake (1995, 1998, 2001, 2004, and 2007) the captures of the first 2 years have been aged. Growth estimates made by the model were validated by using length measures of 24 smallmouth bass YOY captured in Spednic Lake on September 1, 1988 (Jordan, 1988).

Estimates of Growth and Mortality of Under-Yearling Smallmouth Bass in Spednic Lake, from 1970 through 2008

The best regression model for estimating daily mean lake surface-water temperatures was selected on the basis of linearity and distribution of residuals (Helsel and Hirsch, 1992). The model uses daily minimum and maximum air temperature and a Fourier term as explanatory variables, calculated as follows:

$$T_{lake} = 0.037T_{air\ min} + 0.209T_{air\ max} - 5.435\sin\left(\frac{2\pi J}{365.25}\right) - 9.671\cos\left(\frac{2\pi J}{365.25}\right) + 6.022\,, \tag{7}$$

where

T_{lake} is estimated lake surface-water temperature, in degrees Celsius;
$T_{air\ min}$ is minimum daily air temperature, in degrees Celsius;
$T_{air\ max}$ is maximum daily air temperature, in degrees Celsius; and
J is Julian date.

Daily precipitation was tested as an explanatory variable but was not statistically significant.

The derived regression model was satisfactorily validated by using lake surface-water temperature data from May 25, 2003, through November 16, 2003, and from May 21, 2004, through November 9, 2004, at Big Lake (fig. 3). The mean 95-percent confidence limits for validation of regression-estimated mean daily lake surface-water temperatures for Big Lake were plus or minus (±) 0.6 °C; this precision compares favorably with the precision of the types of thermographs used by fisheries agencies to measure lake temperatures (typically ±0.7 °C; Dunham and others, 2005). The regression model was further validated and demonstrated to be applicable to other lakes in the region by satisfactory comparison of model estimates of lake surface-water temperature to measured lake surface-water temperature data at Grand Falls Flowage from May 1, 1998, through October 31, 1998, and from May 1, 1999, through October 31, 1999 (fig. 4).

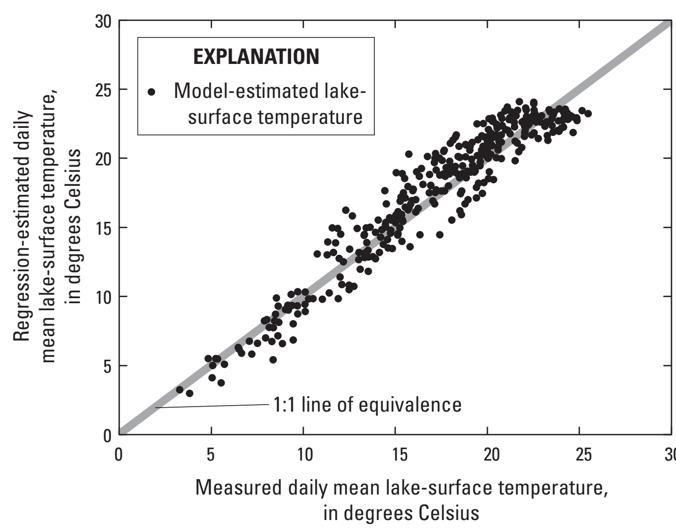

Figure 3. Validation of model-estimated daily lake-surface temperatures with measured daily water temperatures for Big Lake, Maine, from 2003 through 2004.

The validated regression model, derived from lake surface-water temperature data for Big Lake, was used to estimate historical daily mean lake surface-water

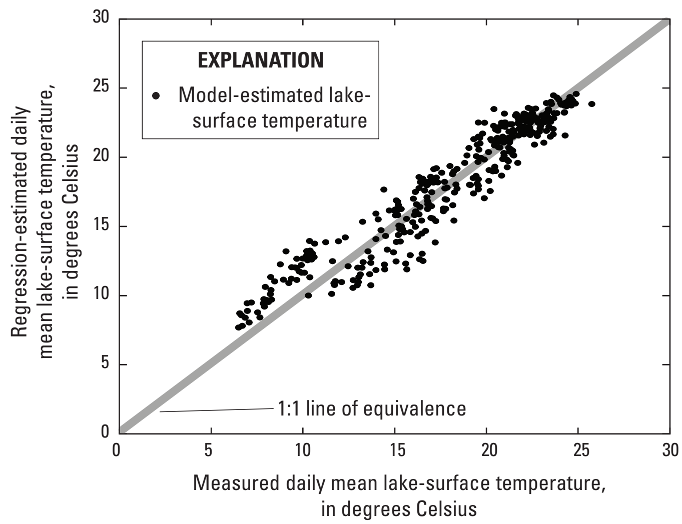

Figure 4. Validation of model-estimated daily lake-surface temperatures with measured daily water temperatures for Grand Falls Flowage, Maine, from 1998 through 1999, from regression model derived from data for Big Lake, Maine.

temperatures in Spednic Lake from May 1 through October 31 of each year from 1970 through 2008. Inputs to the model were daily minimum and maximum air temperature data, measured at the nearby NOAA–COOP station at Vanceboro, and day of the year. For days during 1970 through 2008 for which meteorological data were unavailable at the Vanceboro NOAA–COOP station, data from the NOAA–COOP station at Grand Lake Stream were used: October 1–31, 1978; April 1–June 30, 1993; September 1–30, 2007; and May 1–August 26 and October 1–2, 2008. For days for which meteorological data were unavailable at the Vanceboro and Grand Lake Stream stations, data from the station at Woodland were used: April 4, 6, 11, 20, 26, and May 6, 1993; and August 27–September 30 and October 3–31, 2008. For the 1 day (May 5, 1993) for which meteorological data were unavailable at all three stations (Vanceboro, Grand Lake Stream, and Woodland), minimum and maximum daily air temperatures were interpolated.

The regression-estimated daily mean lake surface-water temperatures in Spednic Lake from May 1 through October 31 each year from 1970 through 2008 followed the seasonal patterns expected for New England lakes (fig. 5). The estimated onset of spawning varied among years; the earliest annual first spawning date was May 22 (Julian date 142; 1991 and 1998) and the latest was June 4 (Julian date 155; 2005; fig. 6). The median (and mean) date for the start of spawning during 1970 through 2008 was May 28; the median (and mean) date for the end of spawning was June 10. The estimated mean annual spawning period was 12 days long (annual ranges of 8 to 18 days), and the longer periods of spawning activity occurred in years when water temperatures increased slowly in the spring. The earliest date on which spawning was estimated to have ended was June 6, and the latest end of spawning activity in all the years was June 13.

Mortality estimated on the basis of the minimum daily mean lake surface-water temperature during the spawning and incubation period was greater than zero for part of the cohort in 20 of the 39 years (fig. 7). The mortalities in these years affected reproduction in the first week of the spawning period. Mortality exceeded 10 percent for 17 of the years and exceeded 30 percent for 6 years (fig. 7; table 3); in the years in which mortality exceeded 10 percent, the numbers of YOY in the upper part of the estimated length range tended to be fewer than in years when less mortality was estimated. There was no mortality for eggs and fry for the last date of spawning in any year.

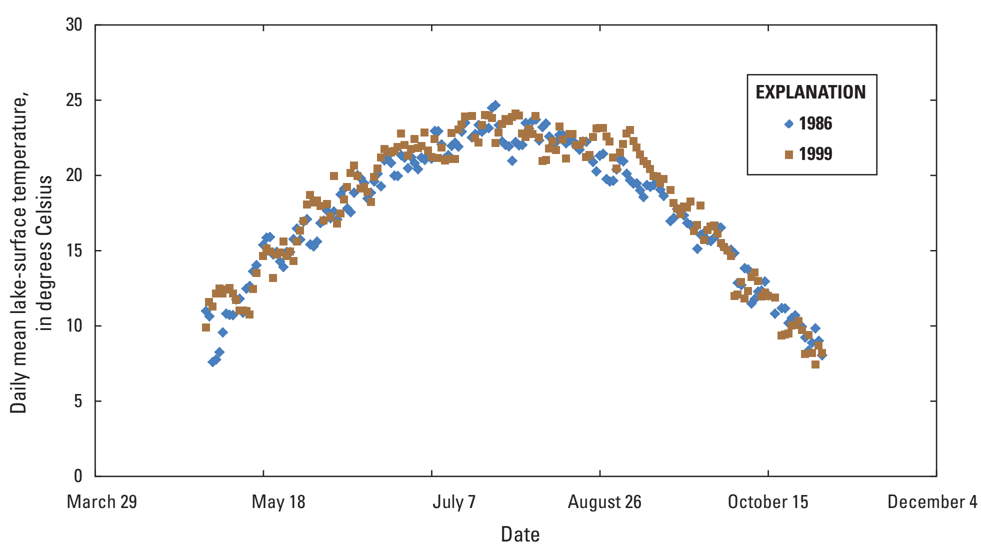

Figure 5. Graph showing two example seasons (1986 and 1999) of model-estimated daily lake-surface temperatures for Spednic Lake, Maine and New Brunswick

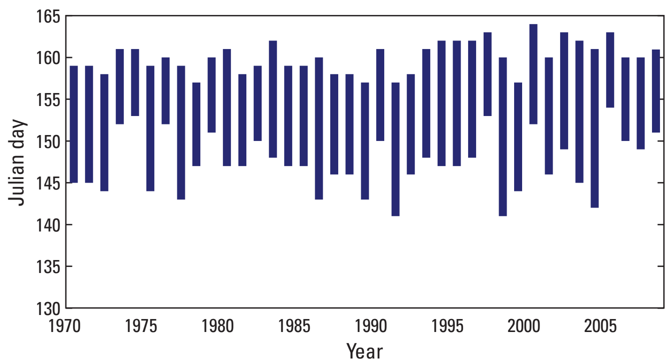

Figure 6. Estimated smallmouth bass spawning windows for Spednic Lake, Maine and New Brunswick, from 1970 through 2008.

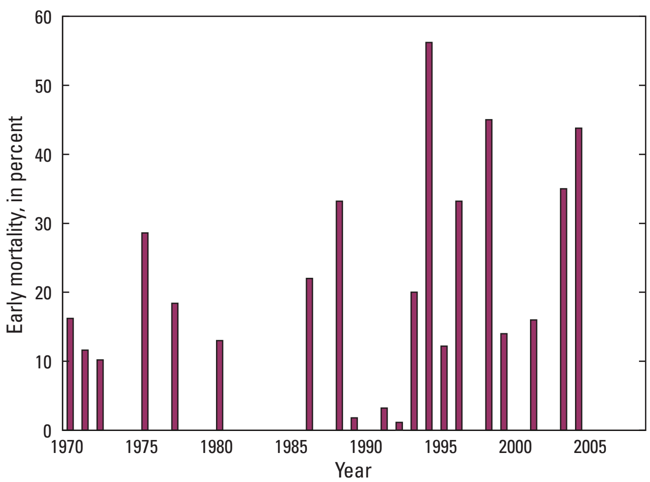

Figure 7. Estimated percent early mortality of smallmouth bass eggs and emerged fry (plus 15 days) for spawning on the first day of the spawning period in Spednic Lake, Maine and New Brunswick, from 1970 through 2008.

Table 3. Estimated percent early mortality of smallmouth bass eggs and emerged fry (plus 15 days) for spawning on the first day of the spawning period in Spednic Lake, Maine and New Brunswick.

[Estimated mortality was zero (no mortality) for years not shown in the table]

Year	Estimated early mortality
1970	16.2
1971	11.6
1972	10.2
1975	28.6
1977	18.4
1980	13.0
1986	22.0
1988	33.2
1989	1.8
1991	3.2
1992	1.0
1993	20.0
1994	56.2
1995	12.2
1996	33.2
1998	45.0
1999	14.0
2001	16.0
2003	35.0
2004	43.8

The estimated total lengths of YOY at the end of the growing season for fish produced at the start (92.4 mm±1.4 mm, standard deviation) and end (83.8 mm ±2.8 mm) dates of spawning differed by an average of 8.4 mm (±1.7 mm). Total length, computed by summing daily growth increments, was greatest for juveniles from the first spawn date because they had an extended growing season compared to those spawned on the last day. In 1988 and 1995, lengths of YOY collected at different locations in Spednic Lake were measured. At all locations, measured mean size was less than the model-estimated minimum length for the year, and in only two instances was the measured maximum length within the estimated length range (table 4).

The annual estimated starvation period (days from <10 °C in autumn to >10 °C in spring) averaged 208 days (±4 days, standard deviation) in Spednic Lake from 1970 through 2008. The shortest estimated juvenile bass length exceeded the criterion for 0-percent winter survival in all years (fig. 8); this criterion averaged 48.3 mm (±0.8 mm). The range of estimated YOY length did not include the criterion defining the minimum length for expected survival to be 100 percent for the overwinter period for most years (figs. 8 and 9); this criterion averaged 92.4 mm (±1.4 mm). The longest estimated YOY lengths were 1.0 mm or more below the upper criterion in 22 years, resulting in more than 3 percent winter mortality (table 5), and in 9 years the fish produced on the last spawning date had expected winter mortality (1-survival) greater than 25 percent (table 5) based on their size. Summer temperatures during 1974, 1986, 1996, 1997, and 2000 resulted in the highest estimated overwinter losses of YOY, on the basis of estimated YOY growth from 1970 through 2008 (table 5).

Discussion

Smallmouth bass survival modeling estimated greater than zero mortality of eggs and fry during incubation in most years, with mortality estimates exceeding 10 percent in 17 of 39 years and exceeding 30 percent in 6 years; during those

Table 4. Mean and range of total length for smallmouth bass young-of-the-year collected from Spednic Lake, Maine and New Brunswick.

[The estimated length range for that year (the range of dates between the first and last estimated spawning dates) was determined by using modeled mean daily temperature during the growing season. YOY, young-of-the-year; N, sample number size; SE, standard error]

Year	Date	Number of samples	Length (millimeters)				Source
			Mean	Standard error	Measured range	Estimated range	
1988	9/1/1988	24	73.0	2.0	63–97	86–95	Jordan, 1988
1995	10/3/1995	7	76.3	0.7	74–80	80–91	Ardnt, 1996
1995	10/3/1995	13	71.2	1.1	66–78	80–91	Ardnt, 1996
1995	10/3/1995	21	70.7	0.9	65–80	80–91	Ardnt, 1996
1995	10/3/1995	8	75.5	1.7	68–82	80–91	Ardnt, 1996

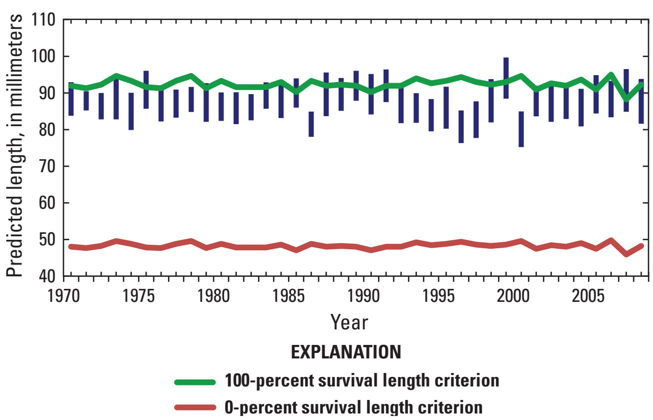

Figure 8. Estimated smallmouth bass young-of-the-year lengths in Spednic Lake, Maine and New Brunswick, from 1970 through 2008.

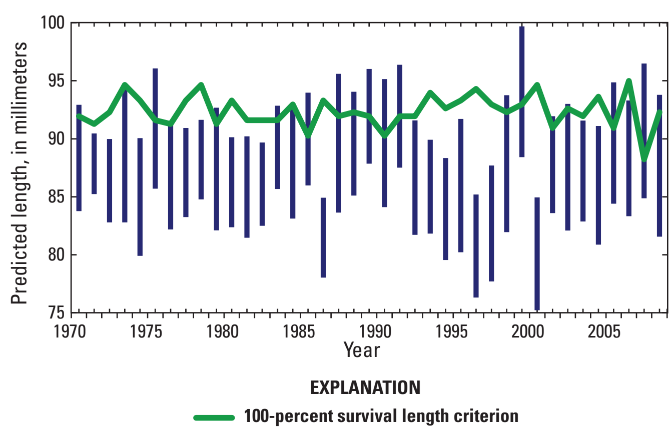

Figure 9. Estimated smallmouth bass young-of-the-year lengths in Spednic Lake, Maine and New Brunswick, from 1970 through 2008.

Table 5. Estimated nest mortality for the first day of the spawning period and overwinter mortality of young-of-the-year smallmouth bass produced on the first (early) and last (late) days of the spawning period in Spednic Lake, Maine and New Brunswick.

[Only years with greater than 1-percent overwinter mortality of early spawned young-of-the-year (YOY) are listed. Values for years when temperature likely presented the greatest challenge to year-class strength are in **bold** type. -, zero estimated mortality]

Year	Nest mortality (percent)	Winter mortality (percent)	
	Early spawned YOY	Early spawned YOY	Late spawned YOY
1972	10	1	19
1973	-	9	24
1974	-	15	28
1976	-	3	19
1977	18	3	20
1978	-	6	20
1979	-	5	19
1980	13	3	22
1981	-	5	21
1982	-	5	19
1984	-	2	20
1986	**22**	**9**	**32**
1992	1	3	21
1993	20	5	25
1994	**56**	**3**	**27**
1995	12	4	27
1996	**33**	**18**	**38**
1997	-	16	32
2000	-	20	41
2002	-	1	22
2004	**44**	**1**	**26**
2006	-	7	24
2008	-	8	22

years, cold temperatures in the early part of the spawning period resulted in mortality to those fish that were estimated to have had the longest growing season and attain the greatest length (Sabo and Orht, 1995; Phelps and others, 2008). This mortality explains, in part, why the mean length of YOY collected in Spednic Lake was less than the range estimated for the year of capture (table 4). The bias in the range of estimated length resulted in overestimates of winter survival and therefore provided a conservative method of identifying weak year classes. Combining estimated overwinter losses and nest mortalities, we identified 1986, 1994, 1996, and 2004 as the years in which temperature was likely to have presented the greatest challenge to year-class strength in Spednic Lake from 1970 through 2008. Only the 1994 year class was represented in the limited aged Spednic Lake fisheries data (1995 and 1998). Assuming that the unaged longer fish were older than age five, the age-four year class (1994) constituted 13 percent of the bass captured in 1998 and was thus considered weak. Age distribution of bass in the fisheries on lakes in the St. Croix and surrounding watersheds confirmed that conditions in 1986 and 1996 resulted in weak smallmouth bass year classes (Dill and others, 2010). The next step in validating the model is to age the remaining years (2001, 2004, 2007) of Spednic Lake fisheries captures.

This 2013 USGS–IJC–MBSRFH study, along with the spawning habitat study by Dudley and others (2011), completes the information necessary to reconstruct the history of spawning area availability and thermal conditions for spawning and the first year of bass growth, thereby providing insight into what contributed to the smallmouth bass fishery collapse and recovery in Spednic Lake. Our approach to this question is ongoing analyses that integrate the modeling estimates, with available smallmouth bass population and fishery data, and alewife passage and abundance data.

Summary

The quality of the smallmouth bass (*Micropterus dolomieu*) fishery in Spednic Lake declined precipitously in the early 1980s. Lake-level management, growing-season temperature, recreational harvest, and a contemporaneous increase in the alewife population because of improved fish passage were implicated in the decline. In attempts to improve the smallmouth bass fishery, alewives were denied access to Spednic Lake in 1988, and lake-level and fisheries management practices were altered. The smallmouth bass fishery has improved; however, controversy remains about the factors responsible for the decline and recovery.

The International Joint Commission (IJC) entered into cooperative agreements in 2009 and 2013 with the U.S. Geological Survey (USGS) and the Maine Bureau of Sea Run Fisheries and Habitat (MBSRFH) to quantify the effects of historical lake-level management and meteorological conditions (from 1970 through 2008) on the survival of smallmouth bass in the first summer of life in an effort to more clearly define the factors responsible for their decline and recovery. The 2009 USGS–IJC–MBSRFH study estimated the available smallmouth bass spawning habitat as a function of lake level by using bathymetry and bottom character data. The objectives of this USGS–IJC–MBSRFH study (2013) were to estimate historical daily mean lake surface-water temperatures in Spednic Lake, from 1970 through 2008, each year from early spring, before spawning, through late autumn and to use those estimated temperatures to estimate the dates of spawning, young-of-the-year (YOY) growth, and probable growth and survival of each year class for smallmouth bass.

There are no historical lake surface-water temperature data for Spednic Lake; therefore, this study uses a regression model to estimate daily mean lake surface-water temperatures (in degrees Celsius) by using explanatory variables of daily minimum and maximum air temperature (degrees Celsius) and a periodic function to explain seasonal variability from spring to fall. The regression model is derived from nearby Big Lake where lake surface-water data do exist. Model validation was done by using reserved Big Lake data and lake surface-water temperature data from another lake in the region, Grand Falls Flowage.

The derived regression model for estimating daily mean lake surface-water temperatures was satisfactorily validated with Big Lake and Grand Falls Flowage data; the mean 95-percent confidence limits for validation of regression-estimated mean daily lake surface-water temperatures for Big Lake were plus or minus (±) 0.6 degrees Celsius (°C). The validated regression model was used to estimate historical daily mean lake surface-water temperatures in Spednic Lake from May 1 through October 31 of each year from 1970 through 2008. Inputs to the regression model were daily minimum and maximum air temperature data, measured at the nearby Vanceboro station of the National Oceanic and Atmospheric Administration's National Weather Service Cooperative Observer Program, and day of the year.

By using the estimated historical record of lake surface-water temperatures, dates of spawning in Spednic Lake were estimated on the basis of the preferred spawning temperature range and accumulated degree days. The estimated onset of spawning varied among years; the earliest annual first spawning date was May 22 (1991 and 1998), and the latest was June 4, 2005. The median (and mean) date for the start of spawning was May 28; the median (and mean) date for the end of spawning was June 10. The estimated mean annual spawning period was 12 days long (ranging from 8 to 18 days annually), and the longer periods of spawning activity occurred in years when water temperatures increased slowly in the spring. The earliest estimated end date of spawning was June 6, and the latest end date was June 13.

Mortality was estimated each year on the basis of the minimum daily mean lake surface-water temperature during the period from spawning date to spawning date plus 15 days. Mortality greater than zero was estimated for a part of the cohort in 20 of the 39 years. Mortality exceeded 10 percent in 17 of 39 years and exceeded 30 percent for 6 years. Years with the greatest mortality were those when cold temperatures occurred in the early part of the spawning period, resulting in mortality to those fish that were estimated to have the longest growing season.

Daily growth increments were estimated throughout the summer for bass spawned on the first and last days of the spawning period. Total length was computed by summing daily growth increments and was greatest for juveniles from the first spawn date because they had an extended growing season compared to those spawned on the last day of the spawning period. The estimated total lengths of YOY at the end of the growing season for fish produced on the first date (92.4 millimeters [mm] ±1.4 mm, standard deviation) and end date (83.8 mm±2.8 mm) of spawning differed by an average of 8.4 mm (±1.7 mm).

Overwinter survival was estimated as a function of YOY size, length criteria, and the duration of the starvation period. For each year, the duration of the starvation period in days was estimated as the number of days between the dates on which daily mean lake surface-water temperature was below 10 °C in the autumn and equal to or above 10 °C the following spring. During the 39 years the estimated starvation period averaged 208 days (±4 days, standard deviation). Summer temperatures during 1974, 1986, 1996, 1997, and 2000 resulted in the highest estimated overwinter losses of YOY.

The combination of estimated overwinter losses and nest mortalities indicates that 1986, 1994, 1996, and 2004 were the years in which temperature was likely to have presented the greatest challenge to year-class strength in Spednic Lake from 1970 through 2008. Only the 1994 year class was represented in the limited aged Spednic Lake fisheries data (1995 and 1998); the age-four year class (1994) constituted 13 percent of the bass captured in 1998 and thus was considered weak. Age distribution of bass in the fisheries on lakes in the St. Croix and surrounding watersheds confirmed that conditions in 1986 and 1996 resulted in weak smallmouth bass year classes.

This 2013 USGS–IJC–MBSRFH study completes the information necessary to reconstruct the history of spawning area availability and thermal conditions for spawning and the first year of bass growth, thereby providing insight for determining what contributed to the smallmouth bass fishery collapse and recovery in Spednic Lake. An analysis integrating the two modeling estimates with available smallmouth bass population and fishery data and alewife passage and abundance data is ongoing to address this question.

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Appendix 1. Sources of Water Temperature Data in the St. Croix River Basin, Maine and New Brunswick

Table 1–1. Summary of sources of water temperature data in the St. Croix River Basin, Maine and New Brunswick, discovered during this study.

Source	Begin year	End year	Frequency	Water bodies	Data access
Maine Bureau of Sea Run Fisheries and Habitat	2002	2002	Hourly	Main stem St. Croix River	Richard Dill, Maine Bureau of Sea Run Fisheries and Habitat
Environment Canada, Water Survey of Canada	2006	Present	15-minute	St. Croix River at Milltown, Maine	Station number 02AR014; Paul Noseworthy, Water Survey of Canada, Fredericton.
Environment Canada, Water Survey of Canada	2006	Present	15-minute	St. Croix River at Forest City, Maine	Station number 02AR014; Paul Noseworthy, Water Survey of Canada, Fredericton.
Maine Department of Environmental Protection and Maine Volunteer Lake Monitoring Program	1974	Present	Weekly to monthly	Many across Maine; the St. Croix Basin includes Big Lake, Brackett Lake, East Grand Lake, Lewey Lake, Long Lake, West Grand Lake	Data can be downloaded from the Gulf of Maine Council Information Management Committee's database, KnowledgeBase, at http://www.gulfofmaine.org/kb/2.0/record.html?recordid=9214.
Passamaquoddy Tribe, Natural Resources Department	1992	Present	Monthly, biweekly	Unspecified lakes on the west branch St. Croix River	Joe Musante, Natural Resources Department, Passamaquoddy Tribe at Indian Township.
U.S. Geological Survey	1972	Present	Daily means computed from 15-minute	St. Croix River at Milltown, Maine	Station number 01021050; data can be downloaded from http://waterdata.usgs.gov/nwis/
U.S. Geological Survey	2010	Present	Daily means computed from 15-minute	West Grand Lake at Grand Lake Stream, Maine	Station number 01018900; data can be downloaded from http://waterdata.usgs.gov/nwis/
U.S. Geological Survey	2010	Present	Daily means computed from 15-minute	Lewy Lake at Princeton, Maine	Station number 01019300; data can be downloaded from http://waterdata.usgs.gov/nwis/

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