U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Trends in Streamflow, River Ice, and Snowpack for Coastal River Basins in Maine During the 20th Century

Water-Resources Investigations Report 02-4245

In cooperation with the
MAINE ATLANTIC SALMON COMMISSION

Cover Photograph: Sheepscot River at North Whitefield, Maine, late January, 2001. Photograph courtesy of Jason Cyr.

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By Robert W. Dudley and Glenn A. Hodgkins

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Augusta, Maine
2002

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CONVERSION FACTORS, VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second ($ft^{3/}s$)	0.02832	cubic meter per second

To convert temperature in degrees Fahrenheit (°F) to degrees Celsius (°C) use the following equation:

$$°C = 5/9 * (°F - 32)$$

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

Trends in Streamflow, River Ice, and Snowpack for Coastal River Basins in Maine During the 20th Century

by Robert W. Dudley and Glenn A. Hodgkins

ABSTRACT

Trends over the 20th Century were examined in streamflow, river ice, and snowpack for coastal river basins in Maine. Trends over time were tested in the timing and magnitude of seasonal river flows, the occurrence and duration of river ice, and changes in snowpack depth, equivalent water content, and density. Significant trends toward earlier spring peak flow and earlier center-of-volume runoff dates were found in the extended streamflow record spanning 1906-21 and 1929-2000. Only one of the six coastal rivers in the study analyzed for trends in cumulative runoff had a significant change in total annual runoff volume. Last spring river-ice-off dates at most coastal streamflow-gaging stations examined are trending to earlier dates. Trends in later fall initial onset of ice also are evident, although these trends are significant at fewer stations than that observed for ice-off dates. Later ice-on dates in the fall and (or) earlier ice-off dates in the spring contribute to a statistically significant decrease over time in the total number of days of ice occurrence at most gaging stations on coastal rivers in Maine. The longest, most complete snow records in coastal Maine indicate an increase in snow density for the March 1 snow-survey date during the last 60 years. The historical trends in streamflow, ice, and snow are all consistent with an earlier onset of hydrologic spring conditions in coastal Maine.

INTRODUCTION

Global land and ocean surface temperatures have increased between 0.7 and 1.4 $^{\circ}$F (95-percent confidence interval) during the 20th Century with most of the warming taking place during 1910-45 and from 1976 to the present (Intergovernmental Panel on Climate Change, 2001). Global annual surface temperature trends, calculated from combined land-surface air and sea-surface temperature data and presented in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2001), show an overall surface temperature trend for New England for the period 1901-2000 of 0.4 $^{\circ}$F per decade. The trend is variable over the century—for the period from 1910 to 1945, the temperature warmed at about 0.7 $^{\circ}$F per decade, then cooled from 1946 to 1975 at a rate of about -0.9 $^{\circ}$F per decade, and warmed again from 1976 to 2000 at about 1.1 $^{\circ}$F per decade. Greatest seasonal warming rates for New England during 1976-2000 occurred during the winter months of December, January, and February (Intergovernmental Panel on Climate Change, 2001).

In addition to warming trends in air temperature, precipitation also has increased in the mid- to high latitudes of the northern hemisphere during the last century. Land-surface precipitation records show an increase of 0.5 to 1 percent per decade, and total cloud cover has increased by about 2 percent over many mid- to high latitude land areas since the beginning of the 20th century (Intergovernmental Panel on Climate Change, 2001).

Because snowpack and the timing of snowmelt is a major component of the hydrology of river basins in New England, the hydrologic response of the region to warmer winters may be important. In a study of 13 river basins throughout Vermont, New Hampshire, and Massachusetts, Hartley and Dingman (1993) demonstrated sensitivity of snowmelt-dominated runoff to air temperature. They found that, on average, maximum streamflows (in spring) occur earlier in basins with higher average air temperatures.

The flow of a river represents the integrated basin response to precipitation, temperature, and other climatic inputs. Because the methods of collecting hydrologic data differ from those associated with collecting meteorological data, analyzing the effects of climate change on hydrology of stable, unregulated basins provides a method of quantifying climate change that is independent of analyses of meteorological measures such as air temperature (Zhang and others, 2001). To analyze these effects of climate change in unregulated basins, the U.S. Geological Survey (USGS) and the Maine Atlantic Salmon Commission began a cooperative study in 2001. Of particular concern are seasonal changes in water temperatures and streamflows that may affect the behavior and subsequent survivability of Atlantic salmon in Maine. Because Maine's coastal rivers are at the southern extent of the Atlantic salmon's habitat range, Atlantic salmon in Maine may be particularly sensitive to climatic changes that affect hydrologic or thermal regimes.

This report presents the data and methods used to determine whether there are trends in hydrologic and cryospheric variables for coastal river basins in Maine that would indicate a hydrologic response to changes in climate. The timing and magnitude of streamflow, river ice, and snowpack data are used to quantify hydrologic changes, or lack thereof, in response to changes in climate for coastal river basins in Maine during the last century. The trend analyses presented in this report will be used to help determine if these hydrologic changes relate to historical data on Atlantic salmon smolt sizes, run timing or numbers and (or) adult return rates, or other biological and population data. Further analysis ultimately could lead to the development of predictive models of Atlantic salmon behavior and projected survivability.

DESCRIPTION OF THE STUDY AREA

The study area covers all coastal river basins in Maine that either currently are gaged or have been gaged by the USGS (table 1, fig. 1). The basins are heavily forested and are characterized by low-relief rolling topography with no urban development. The coastal river basins lie in a hydrophysiographic region of broad lowlands that were inundated by the ocean during deglaciation (Randall, 2000). Consequently, the surficial geologic materials in the basins are predominantly glacial till and fine and coarse-grained glaciomarine deposits with some ice-contact glaciofluvial deposits, eskers, and bedrock (Thompson and Borns, 1985).

The greatest changes in land use in Maine during the 20th Century have been the replacement of agriculture and pasture lands by forest. The State's overall forest cover, estimated at 70 percent in 1900, increased to 90 percent by 1995 (Irland, 1998). Six basins in close proximity in eastern coastal Maine (fig. 1) are in a sparsely populated part of the State. During the period 1880-1995, the estimated increase in forested area in eastern coastal Maine varies from about 18 to 22 percent (Irland, 1998). The remaining two river basins, Sheepscot and Royal, are in a historically more populated part of the State that was more heavily deforested. Reforestation estimates in these basins range from approximately 100 to 186 percent during the same time period (Irland, 1998).

Table 1. Coastal river gages in Maine

[na, not available]

U.S. Geological Survey streamflow gaging station		Latitude (north)	Longitude (west)	Drainage area (square miles)	Period of record for streamflow data	Period of record for ice data
Number	Name					
01021200	Dennys River at Dennysville, Maine	44° 54' 03"	67° 14' 56"	92.9	1955-98	na
01021500	Machias River at Whitneyville, Maine	44° 43' 23"	67° 31' 15"	458	1906-21, 1929-77	1929-77
01022000	East Machias River near East Machias, Maine	44° 46' 05"	67° 24' 30"	251	1927-58	na
01022260	Pleasant River near Epping, Maine	44° 41' 52"	67° 47' 16"	60.6	1980-91	1980-91
01022500	Narraguagus River at Cherryfield, Maine	44° 36' 29"	67° 56' 10"	227	1948-2000	1948-2000
01023000	West Branch Union River at Amherst, Maine	44° 50' 25"	68° 22' 22"	148	1909-19, 1929-79	1929-79
01038000	Sheepscot River at North Whitefield, Maine	44° 13' 23"	69° 35' 38"	145	1938-2000	1938-2000
01060000	Royal River at Yarmouth, Maine	43° 47' 57"	70° 10' 45"	141	1949-2000	1949-2000

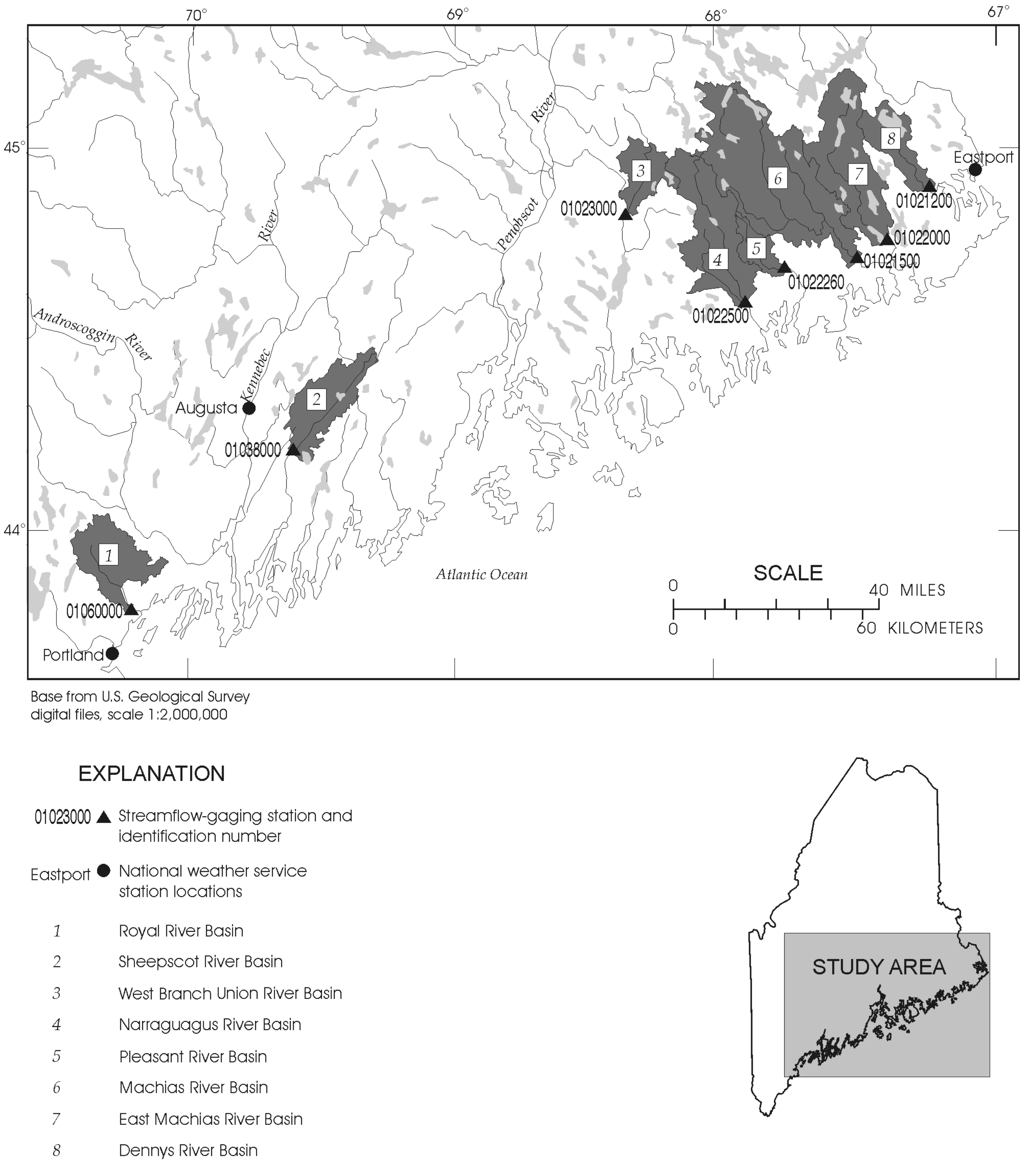


Figure 1. Location of USGS-gaged coastal river basins in Maine.

The climate of Maine's coast is typified by mild summers and cold winters. Records from National Weather Service (NWS) stations indicate normal annual temperatures, based on the 30-year period 1961-90, of 45.4 °F in Portland and 45.6 °F in Eastport (fig. 1). Mean monthly temperatures range from 20.8 °F in January to 68.6 °F in July in Portland and 21.8 °F in January to 63.0 °F in July in Eastport. The average annual precipitation is 44.3 in. at Portland and 43.4 in. at Eastport and is fairly evenly distributed throughout the year (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 2000).

DATA COLLECTION

Data sets were assembled for streamflow, river ice, and snowpack data and were used to analyze historical trends. The methods of how these data sets were assembled are described below.

Streamflow

Daily mean streamflow data for the eight streamflow-gaging stations (table 1, fig. 1) were obtained from the USGS National Water Information System (NWIS) accessed on the World Wide Web at URL http://water-data.usgs.gov/nwis. The stations have periods of record ranging from 11 to 65 years in length with an average of 48 years (table 1). Because the Pleasant River near Epping (USGS station number 01022260) has only 11 years of record, the Pleasant River station was not used in any historical trend analyses for this report. The flow of the Dennys River at Dennysville (01021200) is regulated by a dam at the outlet of Meddybemps Lake 14 mi upstream with a usable capacity of about 1.5 billion ft^3 (Nielsen and others, 1998). Because of the effect of regulation on this river, streamflow data for this gaging station was omitted from any historical trend analyses.

Two additional stations, Machias River at Whitneyville (01021500) and East Machias River near East Machias (01022000), have or historically have had some minor low-flow regulation. The regulation at these sites is thought to be small enough to have no effect on the computation of a monthly mean streamflow value computed on the basis of the daily mean streamflow (Slack and Landwehr, 1992). Although monthly means and longer term (for example, seasonal or annual) means and high-flow statistics are thought to be unaffected by regulation at these sites, it is important to note that low-flow statistics and averages computed on timeframes shorter than 1 month (especially during summer months) could be affected and should not be interpreted as representative of natural flow conditions; such statistics are censored in this report. The remaining four stations, Narraguagus River at Cherryfield (01022500), West Branch Union River at Amherst (01023000), Sheepscot River at North Whitefield (01038000), and the Royal River at Yarmouth (01060000) have little or no regulation, and daily and longer averages of streamflow are representative of natural conditions (Slack and Landwehr, 1992).

Ice

Ice data were obtained from annual USGS Water-Resources Data reports for Maine, USGS Water-Supply Papers for the North Atlantic Slope Drainage Basins, and USGS files used to compute streamflow. The ice data set consists of days during which river ice was present in sufficient quantities to cause backwater at the gaging station and affect the computation of streamflow (Rantz, 1982). River ice can include both surface ice and anchor ice near the hydraulic control at the gaging station. The days of ice-effect are referred to as "ice-days." The first day of ice effect following a period of no ice-effect is called an "ice-on" day. The last day of ice-effect for a consecutive period of ice-days is called an "ice-off" day. The occurrence of ice-days can be discontinuous throughout the winter season; thus, for any given winter season, there can be many ice-on and ice-off dates.

At most streamflow-gaging stations in the early streamflow record (before the 1930's), ice-days were determined by a local observer. Observers were later replaced by continuous recorders. In an effort to avoid any potential bias from an observer, only ice-effect data determined from a continuous recorder is used for this study. For this reason, data from a brief period of observer ice-days at the West Branch Union River from 1910 to 1919 was not used. No ice data were available for the Dennys and East Machias River stations because of the proximity of these stations to upstream regulation that kept the gaged river reach free of ice. There are no ice data for the Machias River station prior to 1929 for the same reason; however, in 1929, the station on the Machias River was relocated to a site farther downstream where conditions were favorable for ice formation.

Snow

Snow data were obtained from the Maine Cooperative Snow Survey Program database that stores snow depth and equivalent water content by site and survey date. The snow-survey program is run jointly by the Maine Geological Survey (MGS) and the USGS. The data are collected by many agencies and private companies on a regular basis in late winter and spring (Loiselle and Hodgkins, 2002).

Several criteria were used to select the 11 coastal snow-survey sites used for this study. First, all snow-survey sites either in or near the eight coastal drainage basins were selected. These were then further narrowed to include only sites with records up to the year 2001 and those with records spanning at least 40 years. The average period of record for the 11 snow-survey sites is 55 years, with a minimum of 43 years at Dedham and a maximum of 79 years at Amherst (fig. 2). The snow-survey site at Amherst has the longest and most complete snow-survey record in this study.

DATA ANALYSIS

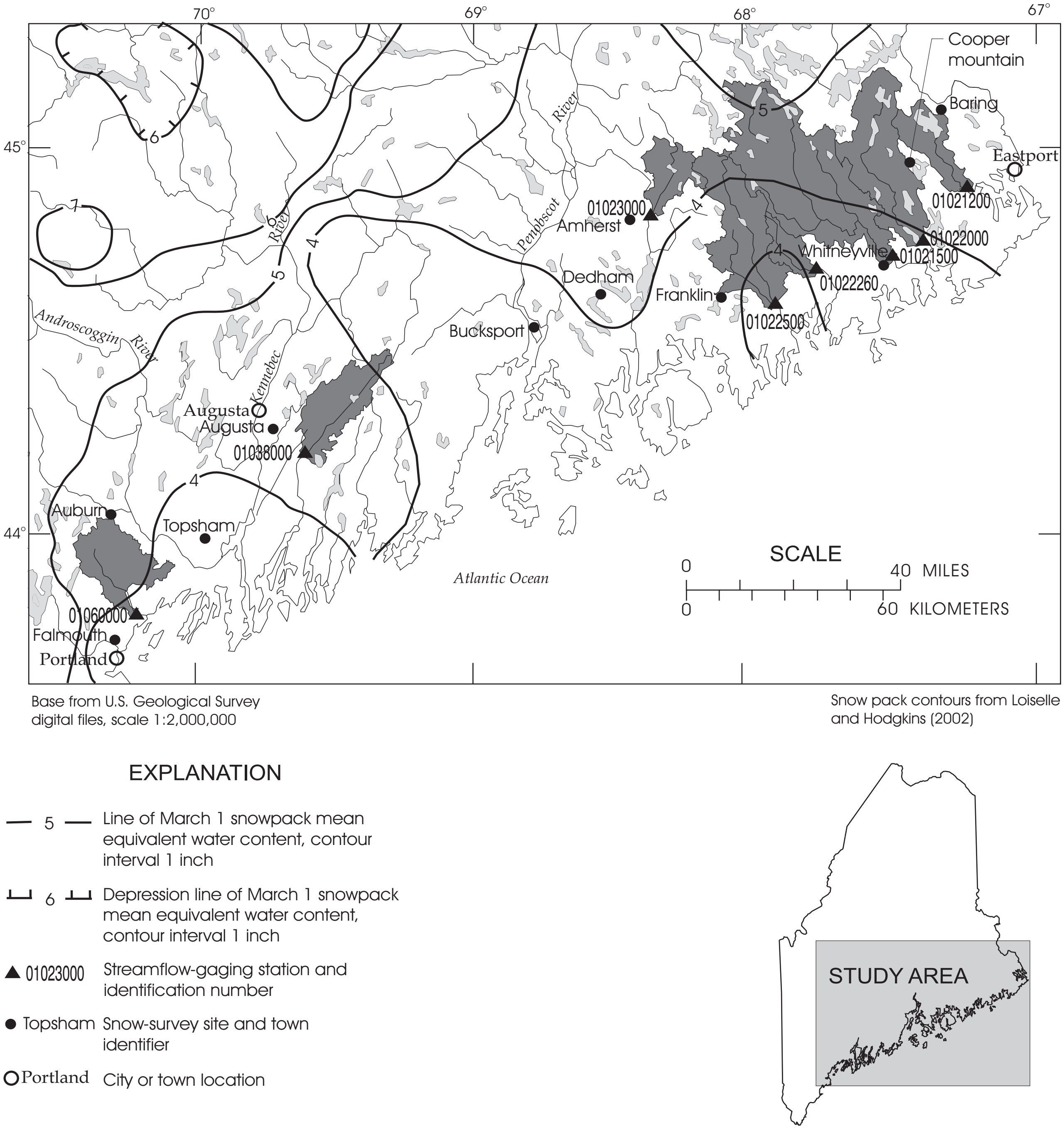
Temporal trends were analyzed for all data sets using the non-parametric Mann-Kendall test (Helsel and Hirsch, 1992), because changes over time do not seem to be linear. The data were smoothed for graphical presentation and serial correlation testing by use of locally weighted regression (Loess) (Cleveland and Devlin, 1988) with locally linear fitting and a robustness feature. There must be no serial correlation for the p-values from the Mann-Kendall test to be correct. Serial correlations in the trend tests were analyzed by computing the Durbin-Watson statistic on the residuals of the Loess regressions for each river with a significant temporal trend (p-value less than 0.1) in any category. In this report, a p-value less than or equal to 0.10 is referred to as significant and a p-value less than or equal to 0.01 is referred to as highly significant. All net changes cited in this report are computed using the end-point values of Loess regression lines.

Julian dates were used for all annual timing analyses in this investigation except for those of ice-effect. For ice-effect dates, a modified Julian date system called a Water Year Julian date (WYJD) was used. The term "water year" denotes the 12-month period from October 1 to September 30 and is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1996 is called "water year 1996." The WYJD system begins numbering on October 1. This system was used to analyze ice-effect in order to capture the entire winter season in a single, sequentially numbered date-system. A small bias in Julian date is introduced by using a calendar date rather than using timing relative to the vernal equinox. The maximum bias is 0.8 day (Sagarin, 2001), for sites with data from 1900 to 2000.

Streamflow

Each daily mean streamflow data set was used to construct monthly, annual, and seasonal data sets described below. In addition to these data sets, an extended-record data set was constructed using streamflow records from the Narraguagus and Machias Rivers to examine trends in a single streamflow record spanning the 95-year period 1906-2000. The method of streamflow data extension, called MOVE.1 (Maintenance Of Variance Extension, type 1), uses the relation between the common data period of two streamflow records and produces streamflow estimates with a statistical distribution similar to that expected had the streamflow actually been measured (Helsel and Hirsch, 1992). In the case of the Narraguagus and Machias River data sets, the base-10 logarithms of streamflow from their common 30-year period of 1948-77 was used to develop the relation between the stations (fig. 3). Using this relation, the Narraguagus record was extended backwards to cover the additional years of 1906-21 and 1929-47, thus generating a streamflow data set that spans from 1906 to 1921 and from 1929 to 2000. The Narraguagus Extended Record is referred to as NER in the remainder of this report.

The linear relation (in log space) between the streamflow at the Machias and Narraguagus Rivers has an overall correlation coefficient of 0.93 (fig. 3). Because of the minor regulation of low streamflows on the Machias River and the absence of regulation at Narraguagus, the relation of low streamflows between the two rivers probably shows some non-linearity and greater variability than the relation at the higher range of streamflows (fig. 3). Low-flow data for the NER were censored because of the poor relation between the Machias and Narraguagus Rivers at the low end of the MOVE.1. Similarly, low-flow data for the Machias and East Machias Rivers were censored because of possible regulation effects. Monthly and annual data sets were not analyzed for trends if any streamflow value in the data set was lower than the minimum August mean flow for that station.



Base from U.S. Geological Survey
digital files, scale 1:2,000,000

Snow pack contours from Loiselle
and Hodgkins (2002)

Figure 2. Locations of coastal snow-survey sites used in this study and March 1 mean snowpack equivalent water content, in inches.

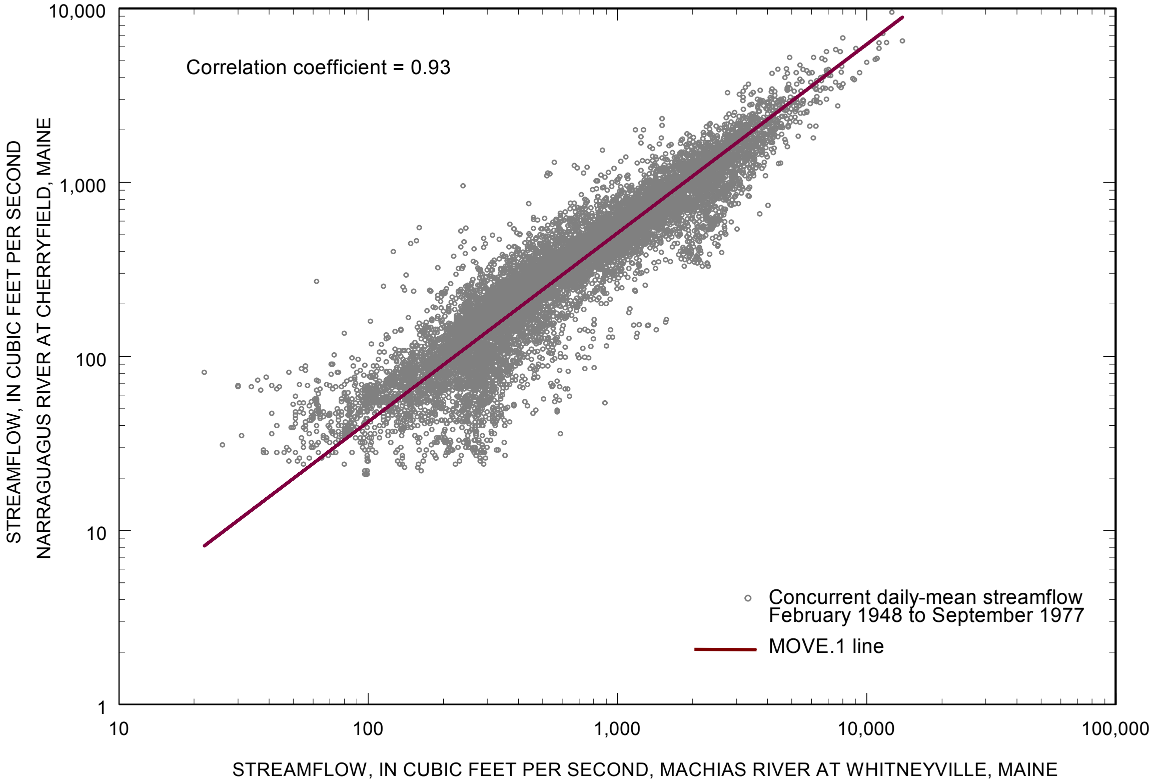


Figure 3. MOVE.1 relation between the streamflow at Machias and Narraguagus Rivers, Maine.

To examine trends over time in the quantity and timing of monthly and annual streamflow, selected streamflow statistics were computed on a monthly and calendar year basis: minimum, 75th percentile, median (50th percentile), 25th percentile, and maximum.

To examine trends over time in the timing and magnitude of seasonal streamflows, the daily mean flow data were partitioned into the following seasons: winter/spring (January 1 to May 31), spring/summer (June 1 to September 30) and fall/winter (October 1 to December 31). The winter/spring seasonal window was chosen in an effort to capture all the spring snowmelt runoff in a single seasonal window. The spring/summer window was terminated at the end of September because deciduous trees lose their leaves in October and November, and evapotranspiration accordingly decreases at this time. The fall/winter seasonal window was chosen to capture high streamflows that often occur at this time of year. Seasonal volumes were computed by summing the daily volumes from the start to the end of each seasonal window for each of the three seasonal windows.

The largest streamflows in Maine typically are in the spring when rain falls on a melting snowpack or on saturated soils. High streamflows also can occur in the fall after evapotranspiration decreases substantially and repeated rains saturate the soil. Hurricanes and tropical storms in the fall also sometimes will leave large amounts of rainwater in their path resulting in high streamflows. Because high streamflows tend to take place during the spring and fall, the center-of-volume dates and the peak-flow dates were computed for the winter/spring and fall/winter seasonal windows. The center-of-volume date is the date on which half the total volume of water for a given period of time flows by a streamflow-gaging station. For this study, the seasonal center-of-volume date (SCVD) was computed as the first date, from the start of the season, on which at least half of the seasonal volume had flowed by a gaging station (figs. 4 and 5). The peak-flow date is the date on which the highest daily mean flow occurs during a given time period (figs. 4 and 5). The annual winter/spring and fall/winter peak streamflows used in this report were the largest daily mean streamflows between January 1 and May 31, and October 1 to December 31, respectively. The SCVD is a useful variable for examining streamflow trends over time as it is more resistant to noise in the data than the peak-flow date. The SCVD also is more sensitive to changes in the timing of flow than is the percentage of flow occurring in one or more fixed months (Court, 1962).

The generalized hydrograph illustrated in figure 4 has a peak flow occurring (April 13) during the spring snowmelt in April. The runoff volume is the integrated area under the hydrograph. The spring SCVD is on April 12, located near the date of the peak flow. An early thaw event at the end of January is illustrated in Figure 5. The peak flow on January 29 is larger than the peak flow that occurs during the bulk of the spring snowmelt in late March and April. The spring SCVD (March 28), however, corresponds more closely to the bulk of the spring snowmelt.

Ice

Three variables were derived from the ice-effect data to test for significant changes over time: each water year's first ice-on day, last ice-off day, and total cumulative days of ice-effect. Because the occurrence of ice can be discontinuous throughout the winter, the total days of ice-effect is not simply the difference between the first day of ice-on and day of last-ice-off. The Mann-Kendall trend test was used to test for significant changes over time in these three variables.

Snow

Because snow surveys in Maine are not done on specific dates, the snow data for each survey site were

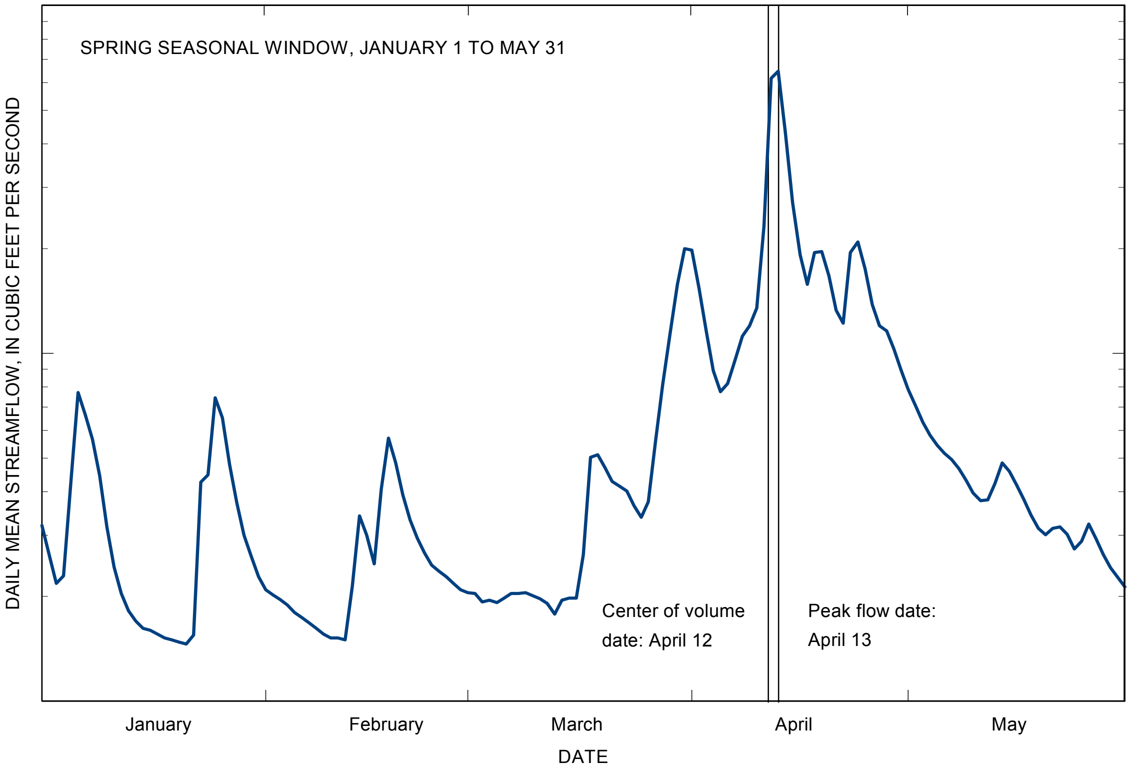


Figure 4. Generalized hydrograph showing date of peak flow and seasonal center-of-volume date for a typical spring, for coastal river basins in Maine.

grouped by arbitrary survey dates bracketed by 2-week windows-that is, +/- 1 week each side of each survey date. The chosen survey dates and their corresponding windows were: February 15, February 8-21; March 1, February 22-March 7; March 15, March 8-22; April 1, March 23-April 7; and April 15, April 8-21. For any given year, if more than one snow measurement fell within a window for a given survey date, the date most closely corresponding to the survey date was retained. If there was a tie, the average of the data values was used.

Historically, the snow-survey sites were not sampled every two weeks for the entire late-winter season and often not even every year. As a result, the snow data, grouped by survey dates, contain missing values. Only survey-date data sets with at least 60-percent completeness were retained for analysis. Historically, snow-survey efforts have been greatest near March 1; therefore the March 1 survey date yielded the most complete data sets for the most number of sites.

The remaining survey-date data sets were evaluated for potential bias associated with their missing values. If values were missing because snow conditions governed whether or not surveys were done, this situation could introduce bias. It was assumed that if snow conditions governed the decision to sample, only a no-snow condition would affect decision making. If values were missing because of a decision process unrelated to the snow conditions, such as sampling governed by a specific date, or no sampling at all for a particular year, then the missing values could be assumed to be unbiased-that is, had the snow been measured, it would have fallen within the normal distribution and variability of the measured values. As a result of this bias analysis, it was determined that all the data for the April 15 survey date could be biased because snow conditions (usually no snow) late in the winter season likely

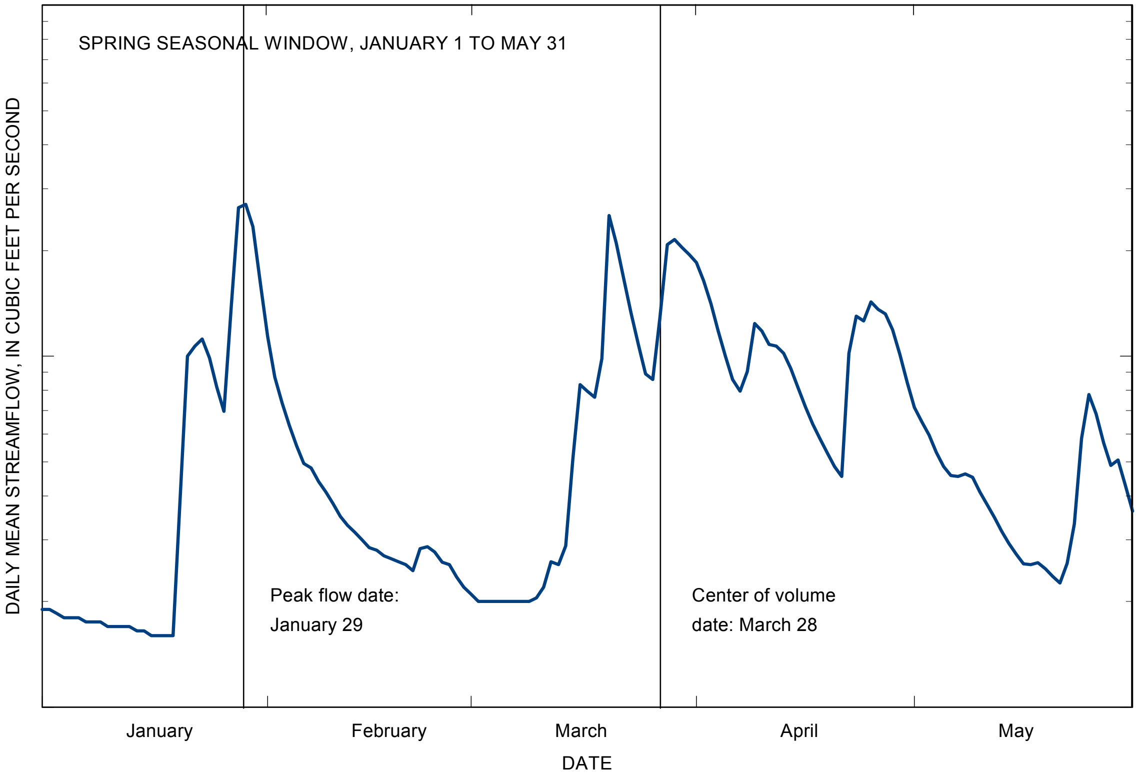


Figure 5. Generalized hydrograph showing date of peak flow and seasonal center-of-volume date for an atypical spring with a winter thaw event, for coastal river basins in Maine.

influenced whether sampling was or was not done, resulting in an under-representation of zero snowpack. The remaining survey dates were determined to be unbiased because it has been and still is common for snow to still be on the ground from mid-February to early April in coastal Maine.

The survey-date data sets also were evaluated for potential bias associated with sampling date to determine if the sampling date moved systematically over time within the 2-week window for a given survey date and location. The Julian date of each survey was tested for trends over time using a non-parametric Mann-Kendall trend test. As a result of this bias analysis, the following survey-site, survey-date pairs were eliminated because of potential sampling-date bias: Augusta, March 1; Baring, March 1; Topsham, March 15; Dedham, March 15; and Whitneyville, March 15. Trend tests were run for the remaining unbiased site-survey date combinations (table 2).

TRENDS IN STREAMFLOW, RIVER ICE, AND SNOWPACK FOR COASTAL RIVER BASINS IN MAINE DURING THE 20TH CENTURY

Streamflow

Based on the Narraguagus Extended Record (NER), streamflows have increased in winter and early spring and decreased in late spring and early summer (table 3); however, there are no significant trends in calendar-year streamflow statistics. The strongest trends for increasing (positive) streamflows were in February (fig. 6), and the strongest trends for decreasing (negative) streamflows were in May and June (table 3, fig. 7). These months have highly significant trends across nearly all flow frequencies.

Overall, the same trends in seasonal streamflows observed in the NER also are present in the six coastal rivers analyzed (tables 4 - 9); however, the trends are not as systematic across all river basins, and the overall trends exhibit less coherence than that observed in the longer record of the NER likely because of their shorter periods of record and variation in periods of time covered.

Four of the seven streamflow records have statistically significant trends for earlier spring SCVD (table 10, fig. 8). The advance in spring SCVD for the NER is highly significant with a p-value less than 0.0001. The advance of the spring SCVD over the NER period of record is approximately 20 days, moving from mid-April to late March (fig. 8). Although many of the trends over time do not appear to be linear, the trend in the spring SCVD for the NER is nearly so; thus, a rate of advance in the SCVD may be estimated at 2.1 days per decade. Only the Sheepscot River and the NER show statistically significant advances in spring peak-flow date (fig. 9). Trends in the fall peak-flow date and fall center-of-volume date are mixed. Two of three significant results indicate a trend toward later fall peak streamflows and center-of-volume dates (table 10).

Few of the trend test results for the magnitude of seasonal peak streamflows and the seasonal and annual runoff volumes are statistically significant (table 11).

Table 2. Snow-survey sites and survey dates analyzed for trends for coastal river basins in Maine

[Snow data through 2001; A, site analyzed for historical trends; *, not enough data for this site and survey date to do trend test; b1, dataset eliminated because of possible snow-condition sampling bias; b2, dataset eliminated because of possible sampling-date bias]

Site name	Latitude	Longitude	Altitude (feet)	First year of record	Status of survey-date dataset				
					15-Feb	1-Mar	15-Mar	1-Apr	15-Apr
Falmouth	43° 44'	70° 15'	141	1958	*	A	*	*	*
Auburn	44° 04'	70° 17'	289	1954	*	A	*	*	*
Topsham	44° 00'	69° 57'	200	1958	*	A	b2	*	*
Augusta	44° 17'	69° 42'	203	1923	*	b2	A	*	*
Bucksport	44° 33'	68° 48'	118	1956	*	A	*	*	*
Dedham	44° 38'	68° 33'	351	1959	*	A	b2	A	b1
Amherst	44° 50'	68° 27'	650	1930	A	A	A	A	b1
Franklin	44° 38'	68° 07'	249	1943	*	A	*	*	*
Whitneyville	44° 42'	67° 31'	98	1935	*	A	b2	*	*
Cooper Mtn.	44° 58'	67° 27'	505	1941	*	*	A	*	*
Baring	45° 07'	67° 20'	200	1956	*	b2	A	*	*

Table 3. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the Narraguagus Extended Record, coastal Maine, period of record: 1906-21, 1929-2000

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; *, censored data]

	Streamflow statistic/Trend direction											
	Minimum		75th Percentile		Median		Mean		25th Percentile		Maximum	
January	**0.0707**	+	**0.0997**	+	0.2714	+	**0.0525**	+	**0.0441**	+	**0.0707**	+
February	**.0020**	+	**.0008**	+	**.0014**	+	**.0002**	+	**.0008**	+	**.0003**	+
March	.1486	+	.1692	+	.1982	+	**.0320**	+	**.0235**	+	**.0931**	+
April	.4327	-	**.0350**	-	**.0226**	-	.1931	-	**.0910**	-	.7777	+
May	*		**.0003**	-	**.0001**	-	**.0001**	-	**.0001**	-	**.0003**	-
June	*		**.0101**	-	**.0059**	-	**.0015**	-	**.0040**	-	**.0092**	-
July	*		**.0722**	-	**.0511**	-	**.0606**	-	**.0283**	-	.2074	-
August	*		*		*		.2553	-	.1252	-	.9673	-
September	*		*		*		.8142	-	.7315	-	.7259	-
October	*		*		.4178	+	.9415	-	.8776	+	.3930	-
November	*		.1726	+	.1175	+	.1476	+	**.0882**	+	.5117	+
December	*		.1507	+	.1658	+	**.0696**	+	**.0538**	+	**.0822**	+
Annual	*		0.9815	-	0.5314	+	0.7099	-	0.7078	-	0.2777	+

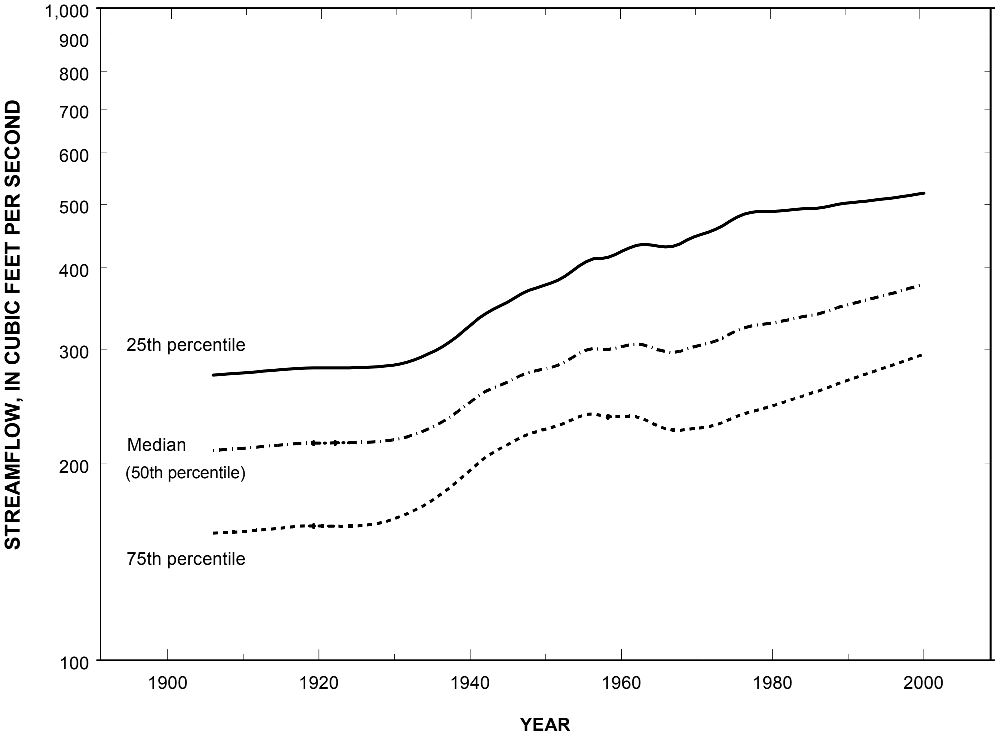


Figure 6. February daily mean streamflows for the Narraguagus Extended Record, coastal Maine. Loess regression lines are based on a 45-year weighting window.

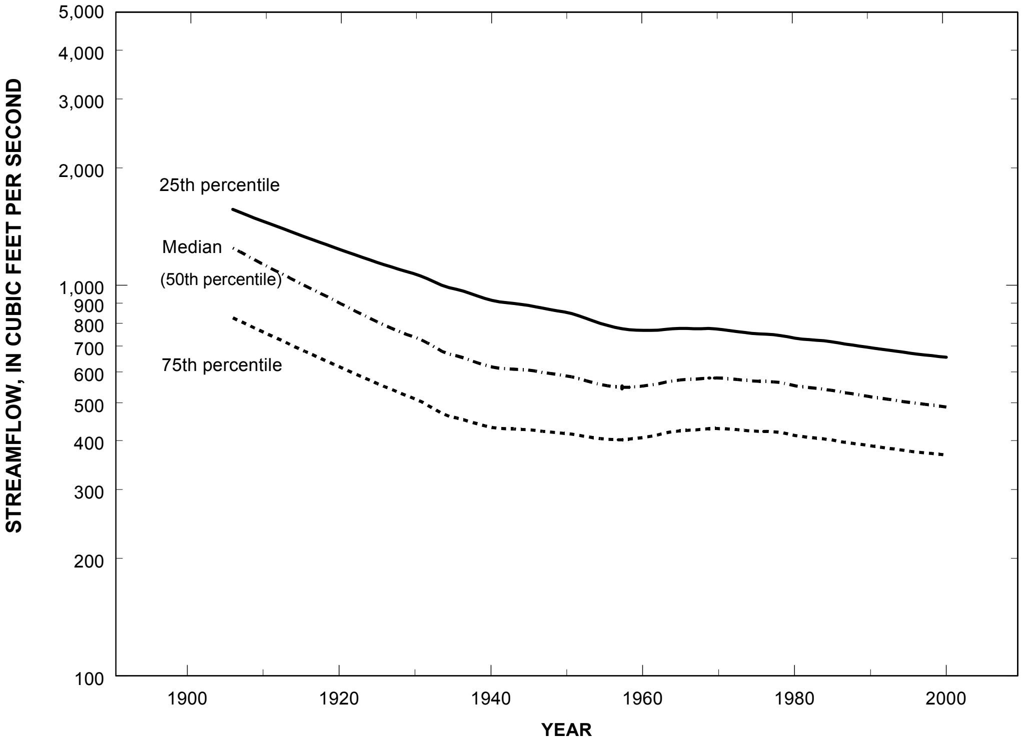


Figure 7. May daily mean streamflows for the Narraguagus Extended Record, coastal Maine. Loess regression lines are based on a 45-year weighting window.

Table 4. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the Machias River, coastal Maine, period of record: 1906-21, 1929-77

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; *, censored data]

	Streamflow statistic/Trend direction											
	Minimum		**75th Percentile**		**Median**		**Mean**		**25th Percentile**		**Maximum**	
January	*		0.7325	+	0.9446	+	0.5546	+	0.6979	+	0.4548	+
February	*		.1191	+	.1608	+	**.0574**	+	.1458	+	**.0134**	+
March	.7456	+	.8620	-	.4942	-	.9908	-	.6224	+	.5701	-
April	.9215	-	.6306	+	.7809	+	.7065	+	.8894	-	.7325	+
May	*		**.0071**	-	**.0307**	-	**.0907**	-	.1697	-	.3848	-
June	*		**.0080**	-	**.0023**	-	**.0006**	-	**.0031**	-	**.0055**	-
July	*		.6058	-	.2673	-	.1981	-	**.0327**	-	.3307	-
August	*		*		*		.7264	-	.3997	-	.7850	+
September	*		*		*		.8634	+	.8309	+	.4584	+
October	*		*		*		.3661	-	.3079	-	.4173	-
November	*		.7898	-	.9723	+	.4041	+	.2395	+	**.0559**	+
December	*		*		.1010	+	**.0294**	+	**.0285**	+	**.0088**	+
Annual	*		0.8034	-	0.1729	-	0.7089	-	0.4475	-	0.6950	+

Table 5. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the East Machias River, coastal Maine, period of record: 1927-58

[p-values in bold are significant at less than or equal to 0.10; +, upward trend over time; -, downward trend over time; *, censored data]

	Streamflow statistic/Trend direction											
	Minimum		**75th Percentile**		**Median**		**Mean**		**25th Percentile**		**Maximum**	
January	0.7726	+	0.9323	+	0.5983	+	0.5074	+	0.3677	+	0.3677	+
February	.1533	+	.1260	+	.2208	+	.2998	+	.2997	+	.2476	+
March	.2210	+	.3587	+	.3587	+	.2693	+	.3158	+	.2547	+
April	.4267	+	.2844	+	.5703	-	.8968	-	.8329	-	.8204	+
May	.5060	+	.3069	+	.1783	+	.3147	+	.4173	+	.4363	+
June	.5702	-	.5163	-	.6265	-	.4958	-	.7213	-	.6151	-
July	.2631	-	.1486	-	**.0195**	-	**.0252**	-	**.0222**	-	**.0556**	-
August	*		*		*		.9225	-	.7456	-	.5592	-
September	*		*		*		.6498	-	.5482	-	.4653	-
October	*		*		*		**.0517**	-	**.0693**	-	**.0125**	-
November	*		*		*		.2845	-	.6497	-	.9483	-
December	.2562	+	.5376	+	.2495	+	.3812	+	.4362	+	.3809	+
Annual	*		0.3535	-	0.9431	+	0.8166	+	**0.0970**	+	0.9858	+

Table 6. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the Narraguagus River, coastal Maine, period of record: 1948-2000

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time]

	Streamflow statistic/Trend direction											
	Minimum		**75th Percentile**		**Median**		**Mean**		**25th Percentile**		**Maximum**	
January	0.4208	-	0.5752	-	0.6189	-	0.6247	-	0.5486	-	0.6190	-
February	.7945	+	.8128	+	.7703	+	.6586	+	.5970	+	.9120	+
March	.5859	+	.4614	+	**.0702**	+	**.0496**	+	.1514	+	**.0057**	+
April	.4476	-	**.0690**	-	.2111	-	.4162	-	.7531	-	.4117	-
May	.9449	-	.8841	+	.6180	+	.9267	-	.9267	-	.6073	-
June	.6900	+	.2897	+	.3493	+	.3494	+	.3694	+	.3300	+
July	.1947	+	.1072	+	.1054	+	.1176	+	.1089	+	.2226	+
August	.6562	+	.4294	+	.4073	+	.3187	+	.4071	+	.2794	+
September	.9083	-	.9939	+	.9755	-	.3573	+	.5912	+	.7184	+
October	.2428	+	.1875	+	.1007	+	.1876	+	.1163	+	.4678	+
November	.4582	+	.4630	+	.9559	+	.4300	-	.5733	-	**.0637**	-
December	.4485	-	.2242	-	.1091	-	.1258	-	.1200	-	.1465	-
Annual	0.9223	-	0.2656	+	0.6846	+	0.8138	+	0.8837	+	0.4120	-

Table 7. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the West Branch Union River, coastal Maine, period of record: 1909-19, 1929-79

[p-values in bold are significant at less than or equal to 0.10; +, upward trend over time; -, downward trend over time]

	Streamflow statistic/Trend direction											
	Minimum		75th Percentile		Median		Mean		25th Percentile		Maximum	
January	**0.0909**	+	0.1258	+	0.1846	+	0.1424	+	0.1605	+	0.2483	+
February	**.0162**	+	**.0616**	+	**.0794**	+	**.0973**	+	.1011	+	**.0126**	+
March	.2509	+	.5071	+	.7937	+	.2671	+	.2754	+	.7161	+
April	.9695	+	.4253	-	.2020	-	.4517	-	.4478	-	.6460	-
May	.5487	+	.3927	+	.4252	+	.5488	+	.6831	+	.8233	+
June	.3820	-	.6324	-	.9035	-	.8483	-	.8934	+	.8184	-
July	.3961	-	.6736	-	.6460	-	.7402	-	.6278	-	1.0000	
August	.3968	-	.4041	-	.8567	-	.8034	-	.7699	+	.7415	+
September	.9503	+	.8567	-	.6185	+	.7747	+	.9901	+	.6676	+
October	.9542	-	.9491	-	.7546	+	.8433	-	.8733	-	.6279	-
November	.8783	-	.8483	+	.6691	+	.5660	+	.6972	+	.5531	+
December	**.0946**	+	**.0816**	+	.1274	+	**.0510**	+	**.0376**	+	**.0691**	+
Annual	0.6241	-	0.6433	+	0.5065	+	0.4093	+	**0.0486**	+	0.5868	+

Table 8. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the Sheepscot River, coastal Maine, period of record: 1938-2000

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time]

	Streamflow statistic/Trend direction											
	Minimum		75th Percentile		Median		Mean		25th Percentile		Maximum	
January	0.8127	+	0.3558	+	0.9661	+	0.5118	+	0.8745	+	0.6930	+
February	.3816	+	.3340	+	.3017	+	.2663	+	.2021	+	.1606	+
March	.2849	+	.4660	+	.2386	+	**.0573**	+	**.0703**	+	**.0020**	+
April	.2769	-	.2742	-	.3133	-	.7292	-	.7155	-	.6707	+
May	.6662	-	1.0000		.9322	+	.9178	-	.6885	-	.9758	+
June	.9612	-	.6530	+	.6530	+	.6840	+	.4156	+	.6433	+
July	.8126	-	.5718	-	.8080	-	.9806	-	.8793	+	.6707	+
August	.5592	+	.9225	+	.7751	-	.8985	+	.9612	-	.8363	+
September	.6094	+	.8315	+	.3912	+	.2560	+	.4585	+	.1142	+
October	.2126	+	.1447	+	**.0682**	+	.1157	+	**.0366**	+	.1978	+
November	.2337	+	.5275	+	.6929	+	.7020	+	.5276	+	.9467	+
December	.5638	+	.5001	+	.7799	+	.7292	+	.9903	-	.4698	-
Annual	0.8565	+	0.2494	+	0.3473	+	0.1228	+	0.2321	+	0.2816	+

Table 9. Statistical significance (p-values) and trend direction for daily mean streamflow statistics for the Royal River, coastal Maine, period of record: 1949-2000

[p-values in bold are significant at less than or equal to 0.10; +, upward trend over time; -, downward trend over time]

	Streamflow statistic/Trend direction											
	Minimum		**75th Percentile**		**Median**		**Mean**		**25th Percentile**		**Maximum**	
January	0.9676	+	0.9870	+	0.3759	-	0.7887	-	0.6260	-	0.9611	-
February	.6725	-	.4259	-	.8264	-	.9935	-	.7886	+	.9935	+
March	.9676	+	.6609	+	.5210	+	.3673	+	.4403	+	**.0676**	+
April	.1622	-	**.0320**	-	**.0206**	-	**.0448**	-	**.0193**	-	.4899	-
May	.9935	-	.7886	+	.9611	+	.8582	+	.9353	+	.5316	+
June	.2197	-	.5156	-	.8454	+	.8138	+	.8012	+	.6434	+
July	.4594	-	.3932	-	.7948	-	.7638	+	.6609	+	.6727	+
August	.4111	-	.6141	-	.7267	-	.9288	-	.6726	-	.9611	+
September	.4995	-	.4115	-	.9029	-	.8391	+	.7823	+	.9288	-
October	.4496	+	.1799	+	**.0390**	+	.1482	+	**.0522**	+	.2910	+
November	.6786	+	.3378	+	.5211	+	.6089	-	.8327	-	.1855	-
December	.5918	+	.9546	+	.5862	-	.2325	-	.1801	-	.3983	-
Annual	0.2871	-	0.6878	+	0.8018	+	0.8737	-	0.9068	-	**0.0895**	+

Table 10. Statistical significance (p-values) and trend direction for Julian dates of spring and fall peak streamflows and centers-of-volume for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; <, less than; NER, Narraguagus Extended Record—see text]

Streamflow-gaging station	Spring center-of-volume		Spring peak flow		Fall center-of-volume		Fall peak flow	
Machias	**0.0928**	-	0.9338	-	**0.0529**	+	0.2498	+
East Machias	**0.0823**	-	0.2080	-	**0.0348**	+	**0.0464**	+
Narraguagus	0.4915	-	0.3764	-	0.2585	-	0.1623	-
West Branch Union	0.1757	-	0.2895	-	0.1286	+	**0.0029**	+
Sheepscot	**0.0309**	-	**0.0604**	-	**0.0896**	-	**0.0946**	-
Royal	0.1478	-	0.4744	-	0.1692	-	0.1574	-
NER	**<0.0001**	-	**0.0163**	-	0.2627	+	0.5555	+

Table 11. Statistical significance (p-values) and trend direction for spring and fall peak flow magnitudes and seasonal and annual runoff volumes for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; +, upward trend over time; -, downward trend over time; NER, Narraguagus Extended Record—see text]

Streamflow-gaging station	Spring peak streamflow		Fall peak streamflow		Spring total runoff volume		Summer total runoff volume		Fall total runoff volume		Total annual runoff volume	
Machias	0.6564	+	0.2379	+	0.8541	+	**0.0191**	-	0.2884	+	0.6999	-
East Machias	.9593	-	.6461	+	.4444	+	.5519	-	.8784	-	.9593	+
Narraguagus	.6585	-	.2273	-	.6816	+	.2096	+	.6135	-	.9246	-
West Branch Union	.5921	+	.3998	+	.2406	+	.9187	-	.3260	+	.1568	+
Sheepscot	.3046	+	.9467	-	.1335	+	.2362	+	.5639	+	**.0856**	+
Royal	.3061	+	.4747	+	.7887	-	.1600	+	.8391	+	.9935	+
NER	0.3727	+	0.6491	+	0.7797	+	**0.0207**	-	0.1328	+	0.8200	-

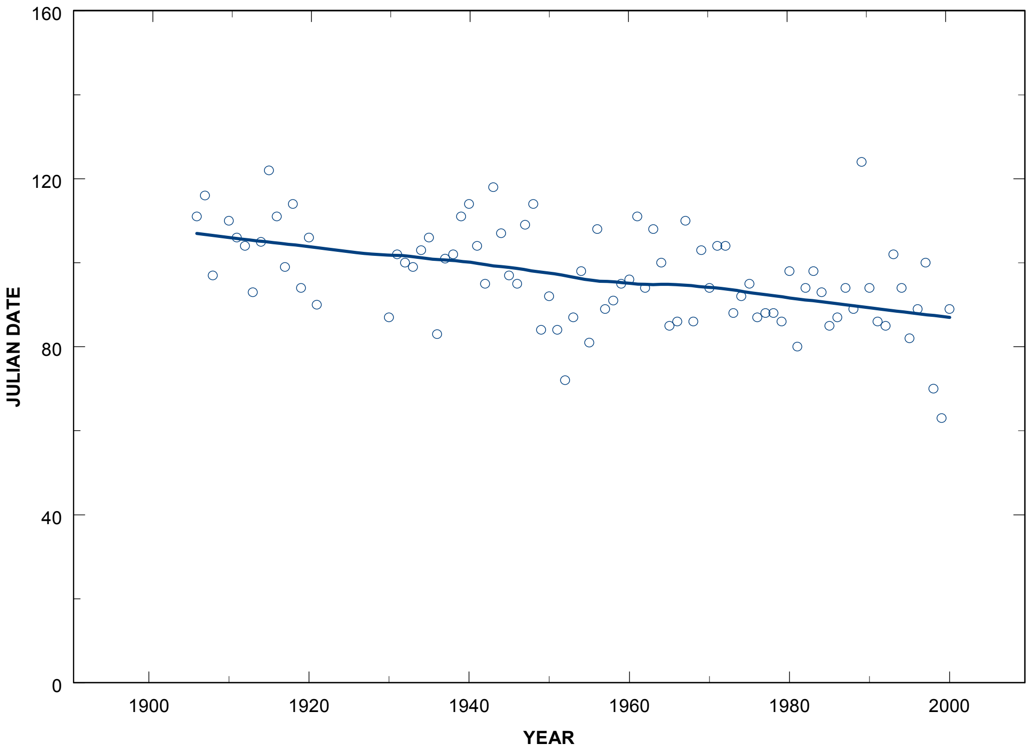


Figure 8. Trend in spring center-of-volume date for the Narraguagus Extended Record, coastal Maine. Loess regression line is based on a 45-year weighting window.

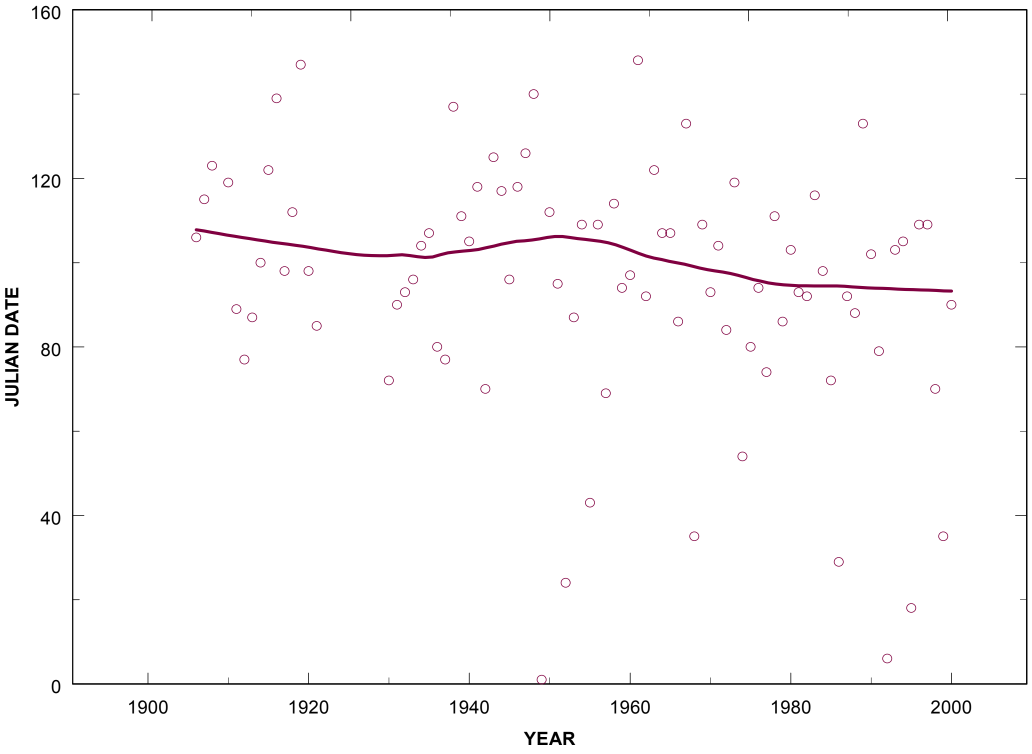


Figure 9. Trend in spring peak-flow date for the Narraguagus Extended Record, coastal Maine. Loess regression line is based on a 45-year weighting window.

Only the Machias River and the NER show statistically significant trends toward decreasing summer runoff volumes. The total summer runoff volume for the Machias River record decreased by 24 percent between Loess regression line end-point values in 1906 and 1977. The total summer runoff volume for the NER decreased 56 percent between 1906 and 2000.

The Sheepscot River is the only river that shows a statistically significant increasing trend in total annual runoff volume with a 20-percent increase over its period of record. Because this increase is not statistically significant for any single seasonal window, it is likely that this increase in annual runoff is distributed across multiple seasons.

Ice

Trend test results indicate, in general, fall ice-on is later, spring ice-off is earlier, and there are fewer days of total winter ice effect on the rivers in coastal Maine. The trends in later fall ice-on dates are significant at two of the five rivers (highly significant at the West Branch Union River), whereas trends for earlier spring ice-off are significant at four of five of the rivers. The combined effect of these trends yields statistically significant trends toward decreasing the total number of days of ice effect throughout the winter season at four of the five stations examined—highly significant trends at the Machias River.

Because the Loess regression line is sensitive to values at the beginning and end of the time period being plotted, the Narraguagus and Royal Rivers, both beginning around 1950, do not seem to follow the same trends as the rest of the rivers (fig. 10). Otherwise, all other river-ice trends are in agreement suggesting that trends in first fall ice-on date (fig. 10) are similar across the entire study area. The trend toward later first fall ice-on dates is statistically significant at the Machias River and highly significant at the West Branch Union River (table 12). Each river covers nearly the same time period with 48 years (1930-77) and 50 years (1930-79) of record, respectively. The average net change in ice-on date for the Machias and West Branch Union Rivers is 14 days.

The trend toward earlier last spring ice-off dates is statistically significant in all rivers except for the West Branch Union River (table 12). There was a period of particularly cold and (or) snowy weather evident during the 1960's (fig. 11). The net change in last spring ice-off date for the Machias River (1930-77) is 18 days. The Narraguagus (1950-00) and Royal Rivers (1949-00) are representative of the latter half of the 20th century. The average net change in last spring ice-off dates for the Narraguagus and Royal Rivers is 8.5 days. The Sheepscot River has 62 years (1939-2000) of record with a net change in last ice-off date of 12 days.

Table 12. Statistical significance (p-values) and trend direction for total number of days of ice, first ice-on date, and last ice-off date for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time]

Streamflow-gaging station	Period of record	First ice-on date		Last ice-off date		Total number of days of ice	
Machias	1929-77	**0.0293**	+	**0.0202**	-	<u>**0.0012**</u>	-
Narraguagus	1948-2000	.8931	-	**.0529**	-	**.0379**	-
West Branch Union	1929-79	<u>**.0041**</u>	+	.3611	-	**.0295**	-
Sheepscot	1938-2000	.1348	+	**.0534**	-	.1977	-
Royal	1949-2000	.2761	+	**.0773**	-	**.0849**	-

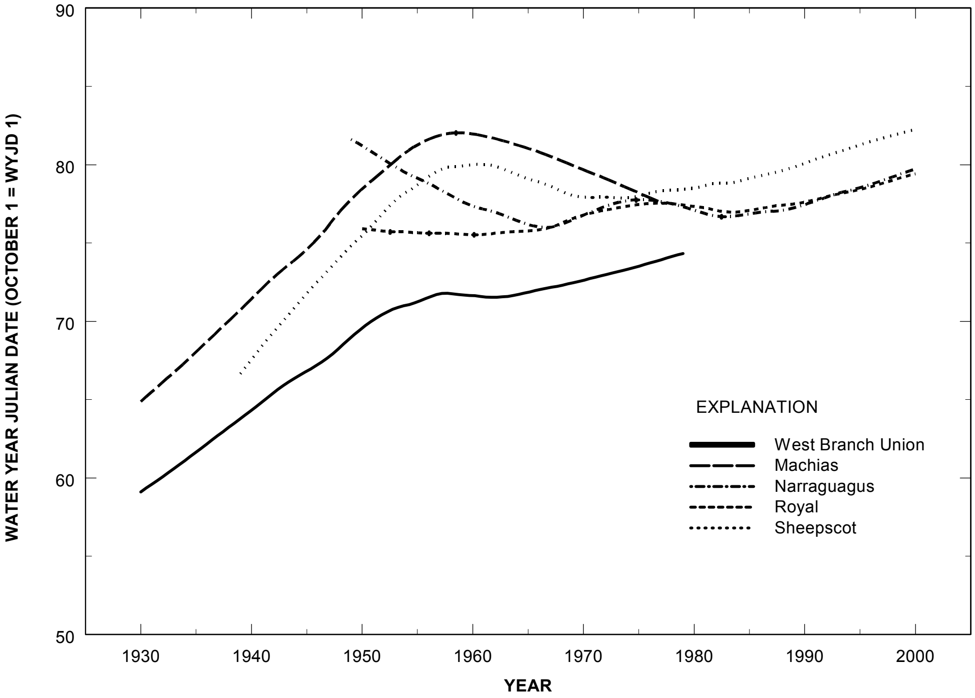


Figure 10. Trends in first ice-on date for coastal rivers in Maine. Loess regression lines are based on a 35-year weighting window.

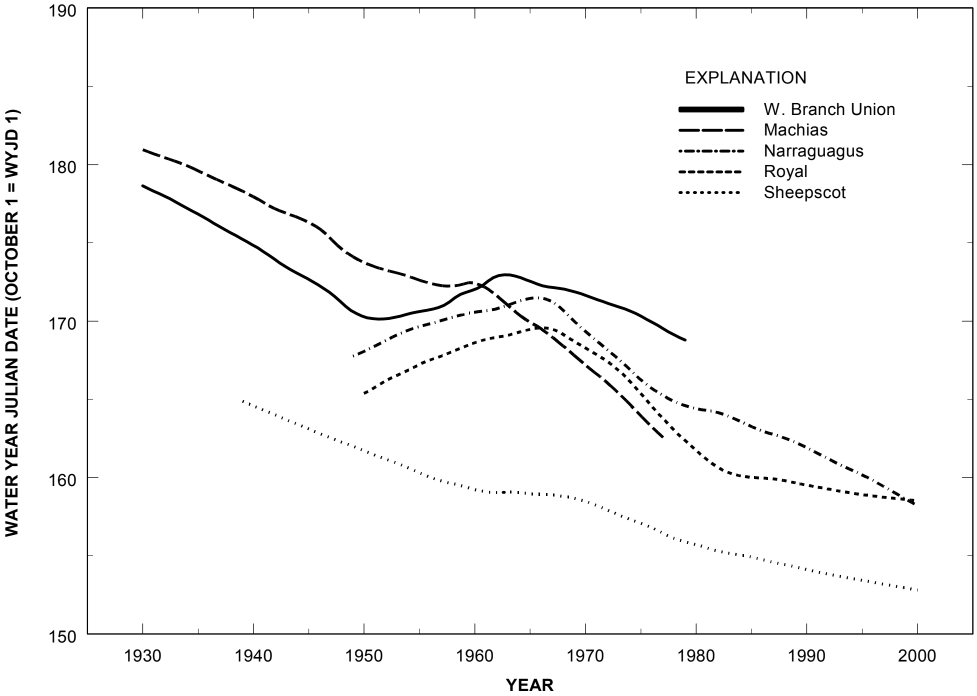


Figure 11. Trends in last ice-off date for coastal rivers in Maine. Loess regression lines are based on a 35-year weighting window.

The total number of days of ice-effect, also was affected by the anomalous weather during the 1960's (fig. 12). The trend toward fewer days of ice effect is statistically significant at all rivers except for the Sheepscot River (table 12). The net change in total days of ice-effect for the Machias and West Branch Union Rivers, representative of the mid-century (1930-77,79), is 37 days. The end of the Machias River regression line could be affected by the data values at the end of the time period being plotted. The net change in total days of ice-effect for the Narraguagus and Royal Rivers, representative of the latter half of the century (1949, 1950-00), is 15 days.

Snow

A straightforward histogram analysis of maximum values of snowpack water equivalent show the winters of 1963, 1966-67, 1969, and 1971 had large snowfalls, with 1963 and 1969 being most notable. In their analysis of historical snowpack in Maine, Loiselle and Hodgkins (2002) also found the winters of 1963 and 1969 to be heavy snow years. The effect of the particularly cold and (or) snowy winters during this decade can be seen not only in the snow data but in the trend plots of last ice-off date and total days of ice. This snowy period confounds the trend-test results for the snow data because much of the available snow data is sparse and of short duration. Most of the snow-survey sites have snow data beginning in the late 1950's, which places the beginning of these data sets in a time period of heavy snowfall. Because the trend test is sensitive to values at the beginning and end of the temporal window being tested, trends in snow depth and equivalent water for sites with data beginning in the late 1950's or early 1960's show highly significant decreasing trends, whereas snow sites with longer record show no significant trends.

For the February 15 survey date, only the snow-survey site at Amherst contained enough data to test for trends, and there were no significant trends in snow depth, equivalent water, or density.

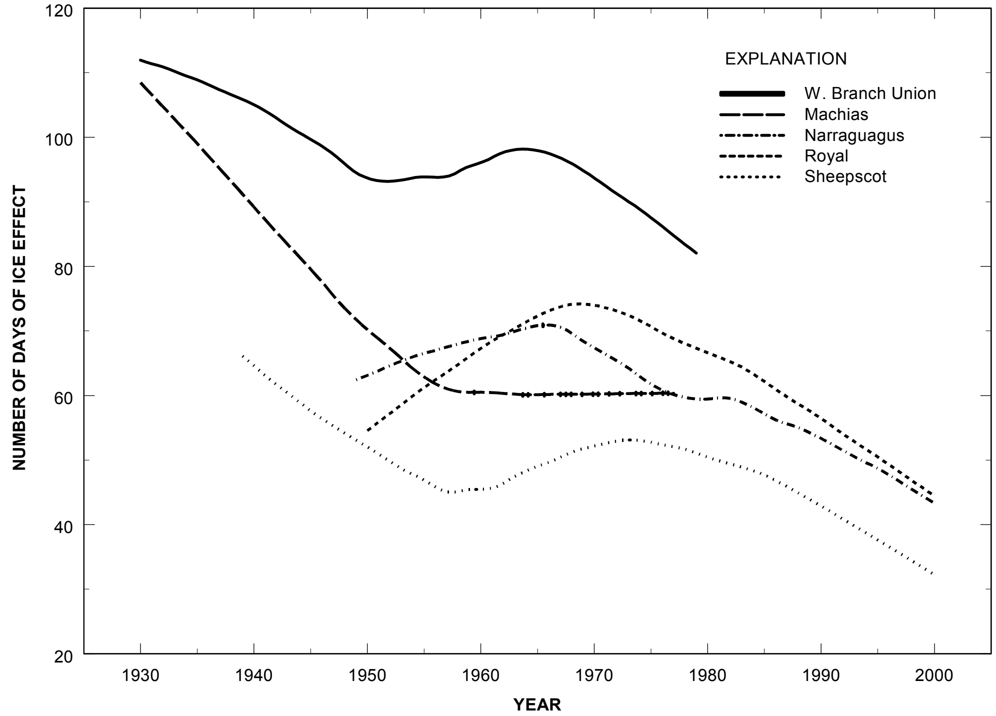


Figure 12. Trends in total number of days of ice effect for coastal rivers in Maine. Loess regression lines are based on a 35-year weighting window.

The March 1 survey date contained most of the available snow data with eight survey sites available for trend analyses. An analysis of water content in snowpack in Maine by Hayes (1972) showed that the average date of maximum water content of the snowpack along the coast occurs in early March. Only the stations with periods of record beginning in the late 1950's have statistically significant trends towards decreasing snow depth and equivalent water content (table 13) indicating that this trend is a product of heavy snowfall occurring in the early years of the temporal window.

For the March 1 survey date, two of the three stations with periods of record beginning before 1945 have statistically significant trends in increasing snow density (table 13). Amherst and Whitneyville, respectively, had net increases of 12 and 10 percent in snow density during their periods of record (fig. 13). Data for the Amherst site is shown on the figure because it has the longest and most complete snow data set of all the survey sites examined for this study.

The March 15 survey date only had four stations with data available for trend testing. The Augusta site has statistically significant trends toward decreasing snow depth and equivalent water with net decreases of 33 and 50 percent, respectively, during the period of record (table 14). The Baring site has a statistically significant trend in decreasing snow density (table 14); however, the period of record for the snow density trend begins in 1962 so the trend also could be a product of the large snowfall occurring in the early years of the temporal window analyzed. The effects of the anomalous winter weather in the 1960's are conspicuous for the Amherst snow-survey site for this survey date (fig. 14).

The April 1 survey date only had two stations with data available for trend testing. Both stations have highly significant trends in decreasing snow depth and equivalent water (table 15). Although these trends in early-spring decreasing snowpack agree with a significant linear trend toward earlier initiation of frost-free conditions for New England for the period 1961-90 (Cooter and LeDuc, 1995), these trends likely are a product of the anomalous winter weather occurring in the early years of the temporal window being examined, with both snow records beginning in the late 1950's (fig. 15).

SYNTHESIS OF TRENDS IN STREAMFLOW, RIVER ICE, AND SNOWPACK

Long periods of record are of great value when examining historical trends. Effects that are not discernable in a short period of record (decades) can become clearer as a longer period of time (century or more) is examined. For example, a recent USGS investigation of trends in lake ice-off dates in New England showed statistically significant ($p<0.10$) trends towards earlier (advancing) lake-ice out dates at 4 of 13 lakes with 100 years or less of record; statistically significant ($p<0.10$) advancing trends at 10 of 11 lakes with 101-150 years of record; and highly significant (in this case, $p<0.0001$) advancing trends in 5 of 5 lakes with more than 150 years of record (Hodgkins and others, 2002). The same is the case with records examined in this study—trends in daily mean streamflow are more evident with the longer record of the NER and are not as clear in the shorter, temporally disparate streamflow records of the other sites.

The trends over time in streamflow statistics, timing and magnitude of runoff, ice occurrence, and snowpack data corroborate the hydroclimatological scenario of a temporal shift towards earlier spring snowmelt runoff. The NER shows a significant trend toward increasing streamflows in February and trends toward decreasing streamflows in May and June across all flow-frequencies analyzed. This result is supported by the highly significant trend in earlier spring SCVD for the NER. Trends in river-ice data also show shorter ice-effect periods with earlier ice-off dates in the spring. The significant trends observed in the ice-off data for these coastal rivers could result, in large part, because of trends in spring streamflow. Magnuson and others (2000) noted that whereas freeze and breakup dates were strongly correlated to air temperature, the mechanisms for ice breakup on rivers can be dominated by the timing, magnitude, and rate of spring runoff.

Trends toward increased snowpack density at sites with the longest snowpack record for March 1 is consistent with earlier snowpack melt. Analyzing a data set of historical and reconstructed snow-cover data from stations in Canada, the United States, the former Soviet Union, and the People's Republic of China, Brown (2000) found a rapidly decreasing trend in North American spring snow cover during the 1980's and early 1990's and a significant long-term (since the early 1900's) decrease in water equivalent of April snowpack. Brown (2000) also observed that a signifi-

Table 13. Statistical significance (p-values) and trend direction for snow data for the March 1 survey date for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; *, no trend test because of lack of data]

Snow-survey station location	Snow depth	Equivalent water content	Snow density	Beginning of period of record
Falmouth	**0.0318** -	**0.0504** -	**0.0390** +	1958
Auburn	**.0559** -	**.0962** -	.5190 +	1954
Topsham	**.0182** -	**.0171** -	**.0567** +	1959
Augusta	*	*	*	*
Bucksport	**.0100** -	**.0233** -	.1584 +	1956
Dedham	**.0378** -	**.0587** -	.4028 +	1959
Amherst	.2427 -	.4254 -	**.0780** +	1938
Franklin	.2548 -	.2324 -	.3523 +	1943
Whitneyville	.2906 -	.9645 -	**.0344** +	1941
Cooper Mountain	*	*	*	*
Baring	*	*	*	*

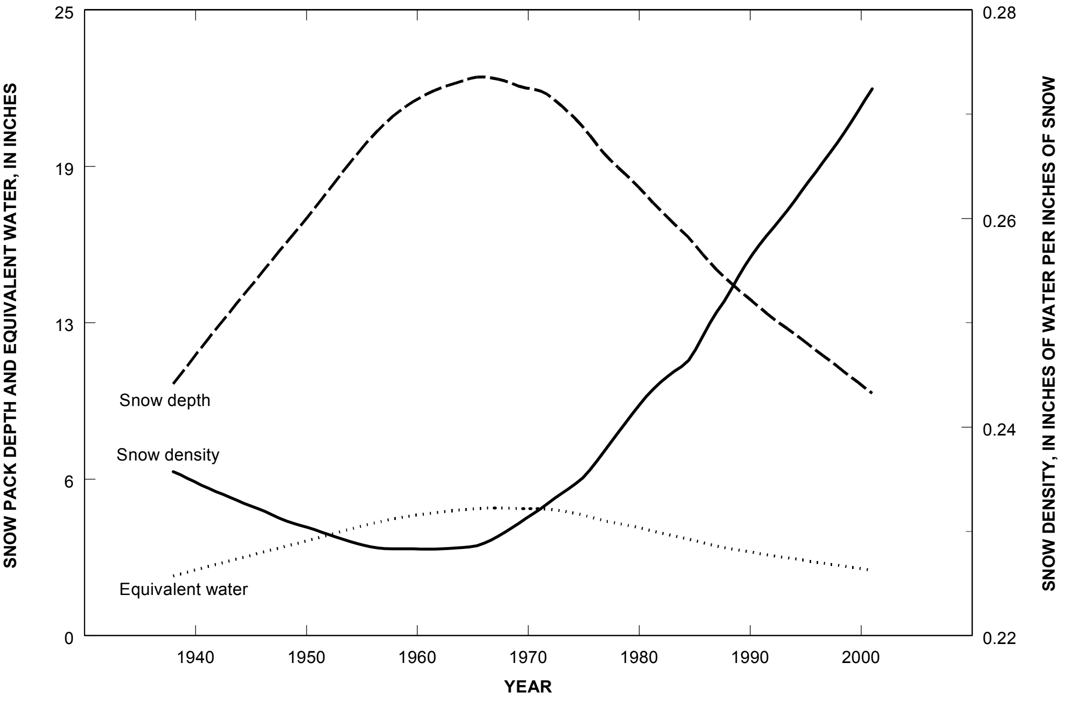


Figure 13. Trends in snow depth, equivalent water, and snow density at the Amherst snow-survey site for the March 1 survey date, coastal Maine. Loess regression lines based on a 35-year weighting window.

Table 14. Statistical significance (p-values) and trend direction for snow data for the March 15 survey date for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; o, no trend over time; *, no trend test because of lack of data]

Snow-survey station location	Snow depth	Equivalent water content	Snow density	Beginning of period of record
Falmouth	*	*	*	*
Auburn	*	*	*	*
Topsham	*	*	*	*
Augusta	**0.0842** -	**0.0340** -	0.3041 -	1945
Bucksport	*	*	*	*
Dedham	*	*	*	*
Amherst	.8683 -	.6414 -	.8496 -	1930
Franklin	*	*	*	*
Whitneyville	*	*	*	*
Cooper Mountain	.4629 -	.3371 -	.8202 -	1947
Baring	1.0000 o	.4159 -	**.0643** -	1962

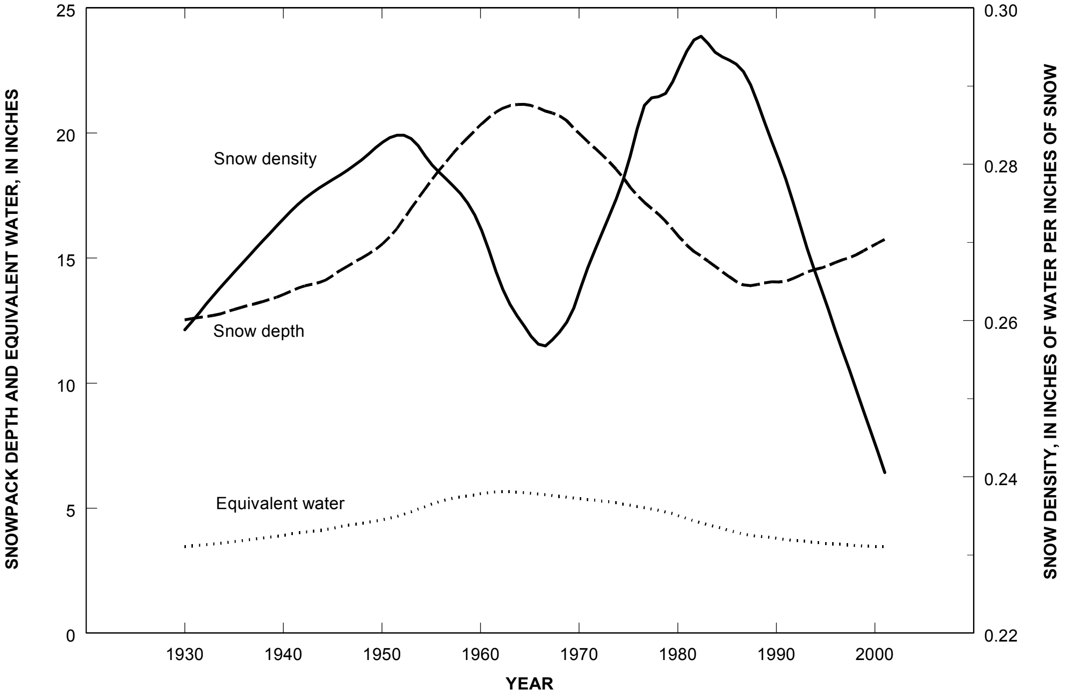


Figure 14. Trends in snow depth, equivalent water, and snow density at the Amherst snow-survey site for the March 15 survey date, coastal Maine. Loess regression lines based on a 35-year weighting window.

Table 15. Statistical significance (p-values) and trend direction for snow data for the April 1 survey date for coastal river basins in Maine

[p-values in bold are significant at less than or equal to 0.10; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, upward trend over time; -, downward trend over time; *, no trend test because of lack of data]

Snow-survey station location	Snow depth	Equivalent water content	Snow density	Beginning of period of record
Falmouth	*	*	*	*
Auburn	*	*	*	*
Topsham	*	*	*	*
Augusta	*	*	*	*
Bucksport	*	*	*	*
Dedham	**0.0065** -	**0.0057** -	0.2968 -	1959
Amherst	**.0004** -	**.0003** -	.8457 -	1956
Franklin	*	*	*	*
Whitneyville	*	*	*	*
Cooper Mountain	*	*	*	*
Baring	*	*	*	*

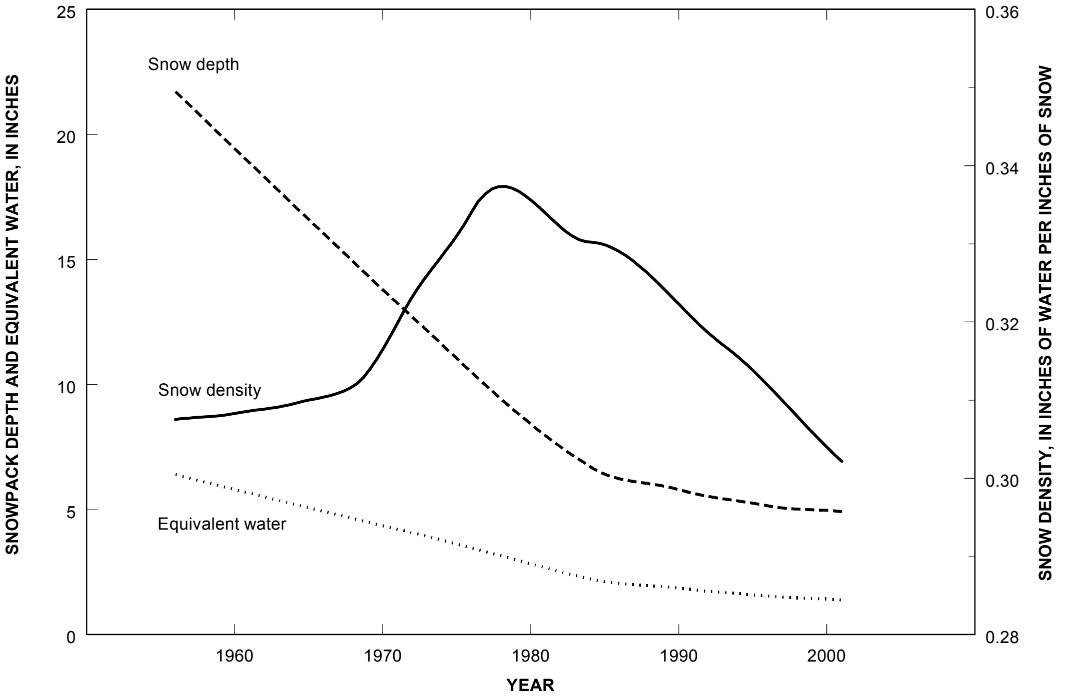


Figure 15. Trends in snow depth, equivalent water, and snow density at the Amherst snow-survey site for the April 1 survey date, coastal Maine. Loess regression lines based on a 35-year weighting window.

cant hemispheric-scale reduction in snow-cover extent was associated with warming over the Northern Hemisphere mid-latitude areas, with the largest warming during the November-April snow season in March.

The statistically significant decreasing trend in the NER summer runoff volume is consistent with findings of an earlier spring snowmelt runoff that would contribute less water in the late spring and summer months. Zhang and others (2001) generally found trends that were not significant for starting dates of the spring high-flow season (both earlier and later) from 1947 to 1996 in areas of Canada to the northwest and northeast of Maine. This result could indicate that the mechanisms controlling the timing of Canadian streamflows did not change in the same way as the mechanisms in Maine, that their measure of timing is not as sensitive as the spring SCVD, or that the additional years of streamflow data from 1997 to 2000 used in this study strengthen the trend test results. Throughout Canada, with the exception of the Atlantic region, Zhang (2001) observed increases in March and April mean monthly streamflows and decreases in streamflow for June through September, attributing the trends to an earlier snowmelt resulting in less water remaining in the basin later in the year. In the Atlantic region of Canada, where the trends are more mixed and less significant, Zhang attributes the trends to increasing total spring precipitation and decreasing spring temperatures related to the North Atlantic Oscillation (NAO).

Directions of trends in the fall peak-flow date and fall center-of-volume date with any statistical significance are mixed, although two of three significant results indicate a trend to later fall peak streamflows and center-of-volume. Statistically significant trends over time in river ice-on data for the late fall and early winter are for later ice-on dates, even though this trend is significant at fewer sites than the statistically significant trends in ice-off data.

These seasonal trends in streamflow, river ice, and snowpack for coastal rivers in Maine could be the result of changes over time in air temperature, seasonal distribution, amount of precipitation, and (or) land use. Increased air temperatures could contribute to earlier melting of the snowpack. The winter air temperature also could affect the nature of winter precipitation causing wetter and denser snowfall. The effect of air temperature on ice formation and breakup can be substantial; for example, the length of the river-ice season in the Atlantic region of Canada has increased during the past 45 years with the greatest rates of change observed in Cape Breton and Newfoundland, Canada in response to colder air temperatures (Prowse and Beltaos, 2002). Prowse and Beltaos (2002) point out that other than this North Atlantic anomaly and certain rivers in central and eastern Siberia, the overall trend elsewhere is toward shorter river-ice seasons. Although the system of explanatory mechanisms is complex, the North Atlantic anomaly appears to be linked to winter ocean currents that have become colder as a result of the intensity of the NAO (Brimley and Freeman, 1997). Magnuson and others (2000) have found that later freeze and earlier breakup dates of lake and river ice during the past 150 years (1846-1995) correspond to an increase in air temperature of approximately 2.2 ^{O}F per century, with freeze and breakup dates correlating most strongly with air temperatures 1 to 2 months preceding the event.

Although the seasonal distribution of precipitation was not specifically examined in this study, trends over time for more rain in the spring and less in summer could contribute to the monthly and seasonal trends observed in the streamflow record. Although this study did not find any significant trends in minimum daily streamflow on an annual basis, Lins and Slack (1999) report trends toward increasing annual minimum daily streamflow at various central and northern Maine streamflow-gaging stations possibly associated with NAO-affected precipitation patterns.

Reforestation has been the greatest change in land use in Maine during the last century with increases in forest area ranging from 18- to 186-percent in various areas throughout the State. Reforestation contributes to greater evapotranspiration during the growing season of summer and early fall. Fall runoff volumes can be decreased further by an extended length of the growing season caused by warmer temperatures. Given the large amount of reforestation that has occurred in these coastal basins over the last century, however, none of the coastal rivers show statistically significant trends toward decreasing total annual runoff. The Sheepscot River basin has experienced a large increase in forest area with estimates ranging from 100- up to 186-percent, whereas the streamflow data show a statistically significant trend toward increasing annual runoff volume. These results suggest an increase in precipitation and (or) a decrease in evapotranspiration.

Because of the uncertainty regarding the causes of these trends in streamflow, river ice, and snowpack for coastal rivers in Maine, additional studies could be done to investigate the relation of the trends to changes in regional air temperature, NAO index, Gulf of Maine ocean temperature, and the frequency, distribution, magnitude, and ratio of snow to rain for coastal precipitation.

SUMMARY

Air temperature and precipitation have increased in New England during the past century. Because a major component of the hydrology of river basins in New England involves snow-pack and the timing of snowmelt, the hydrologic response of the region to warmer winters may be significant. This report, by the U.S. Geological Survey, in cooperation with the Maine Atlantic Salmon Commission, presents the data and methods used to determine if any statistically detectable changes in streamflow, river ice, and snowpack have taken place in coastal river basins in Maine in response to observed changes in climate. Specific data evaluated include the timing and magnitude of annual, monthly, and seasonal streamflows; the occurrence and duration of river ice; and changes in snowpack depth, equivalent water content, and snow density for coastal river basins in Maine.

Historical trends in streamflow, ice, and snow are all consistent with an earlier onset of spring conditions in coastal Maine. There has been a significant trend in the timing of spring runoff toward earlier dates for extended streamflow record spanning 1906-21 and 1929-2000. Only one of the coastal rivers (Sheepscot) had a significant trend in annual runoff volume. River-ice occurrence at coastal river streamflow-gaging stations show, in general, earlier last ice-off dates in the spring. Later initial onset of ice also is evident, although significant at fewer stations than the number for earlier ice-off dates. Later ice-on in the winter and earlier ice-off in the spring contribute to a statistically significant decrease over time in the total number days of ice-effect at most gages on coastal rivers in Maine. The longest, most complete snow records indicate an increase in snow density for the March 1 snow-survey date during the last 60 years; however, trends in snowpack depth, equivalent water content, and snow density generally are inconclusive because of missing data and short periods of available record.

REFERENCES CITED

Brimley, W.A., and Freeman, C.N., 1997, Trends in river ice cover in Atlantic Canada, in Proceedings of the Ninth Workshop on River Ice, September 24-26, 1997: Fredricton, New Brunswick, Canadian Committee on River Ice Processes and the Environment, Canadian Geophysical Union, p. 335-349.

Brown, R.D., 2000, Northern Hemisphere snow cover variability and change, 1915-97: Journal of Climate, v. 13, p. 2339-2355.

Cleveland, W.S., Devlin, S.J., 1988, Locally weighted regression: an approach to regression analysis by local fitting: Journal of the American Statistical Association, v. 83, p. 596-610.

Cooter, E.J., and LeDuc, S.K., 1995, Recent frost date trends in the North-Eastern USA: International Journal of Climatology, v. 15, p. 65-75.

Court, A., 1962, Measures of streamflow timing: Journal of Geophysical Research. v. 67, p. 4335-4339.

Hartley, S., and Dingman, S.L., 1993, Effects of climatic variability on winter-spring runoff in New England river basins: Physical Geography, v. 14, p. 379-393.

Hayes, G.S., 1972, Average water content of snowpack in Maine: U.S. Geological Survey Hydrologic Investigations Atlas HA-452, scale 1:1,000,000.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier, 529 p.

Hodgkins, G.A., James, I.C., and Huntington, T.G., 2002, Historical changes in lake ice-out dates as indicators of climate change in New England, 1850-2000: International Journal of Climatology, Volume 22, Issue 15, p. 1819-1827.

Intergovernmental Panel on Climate Change, 2001, Climate change 2001, the scientific basis: Cambridge, Cambridge University Press, 881 p.

Irland, L.C., 1998, Maine's forest area, 1600-1995-Review of available estimates-College of Natural Sciences, Forestry, and Agriculture, University of Maine, Maine Agricultural and Forest Experiment Station Miscellaneous Publication 736, February 1998, 12 p.

Lins, H.F., and Slack, J.R., 1999, Streamflow trends in the United States: Geophysical Research Letters, v. 26, p. 227-230.

Loiselle, M.C., and Hodgkins, G.A., 2002, Snowpack in Maine-Maximum observed and March 1 mean equivalent water content: U.S. Geological Survey Water-Resources Investigations Report 01-4258, 19 p.

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M., and Vuglinski, V.S., 2000, Trends in lake and river ice cover in the Northern Hemisphere: Science, v. 289, p. 1743-1746.

Prowse, T.D., and Beltaos, S., 2002, Climatic control of river-ice hydrology-A review: Hydrologic Processes, v. 16 p. 805-822.

Randall, A.D., 2000, Hydrogeologic framework of stratified-drift aquifers in the glaciated northeastern United States: U.S. Geological Survey Professional Paper 1415-B, 179 p. (1 plate showing hydrophysiographic regions in the glaciated northeastern United States, scale 1:2,500,000).

Rantz, S.E., 1982, Measurement and computation of streamflow: vol. 1 & 2: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Sagarin, R., 2001, False estimates of the advance of spring: Nature, v. 414, p. 600.

Slack, J.R., and Landwehr, J.M., 1992, Hydro-climatic data network (HCDN)-A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874-1988: U.S. Geological Survey Open-File Report 92-129, 193 p.

Thompson, W.B., and Borns, H.W., 1985, Surficial geologic map of Maine: Maine Geological Survey, Department of Conservation, scale 1:5000,000.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 2000, Climatological data annual summary, New England: v. 112, no. 13.

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R., 2001, Trends in Canadian streamflow: Water Resources Research, v. 37, p. 987-998.

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