In cooperation with the
Maine Atlantic Salmon Commission

Trends in Timing, Magnitude, and Duration of Summer and Fall/Winter Streamflows for Unregulated Coastal River Basins in Maine During the 20th Century

Scientific Investigations Report 2005-5021

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

Cover Photograph: West Branch Sheepscot River, Maine, June 2003. (Photography by Tim Sargent, U.S. Geological Survey)

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Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.009290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]

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

$$°C = (°F - 32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) unless otherwise noted.

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

Trends in Timing, Magnitude, and Duration of Summer and Fall/Winter Streamflows for Unregulated Coastal River Basins in Maine During the 20th Century

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Abstract

The U.S. Geological Survey (USGS), in cooperation with the Maine Atlantic Salmon Commission (ASC), began a study in 2003 to examine the timing, magnitude, and duration of summer (June through October) and fall/early winter (September through January) seasonal streamflows of unregulated coastal river basins in Maine and to correlate them to meteorological variables and winter/spring (January through May) seasonal streamflows. This study overlapped the summer seasonal window with the fall/early winter seasonal window to completely bracket the low-streamflow period during July, August, and September between periods of high streamflows in June and October. The ASC is concerned with the impacts of potentially changing meteorological and hydrologic conditions on Atlantic salmon survival. Because winter/spring high streamflows appear to have trended toward earlier dates over the 20th century in coastal Maine, it was hypothesized that the spring/summer recession to low streamflows could have a similar trend toward earlier, and possibly lower, longer lasting, late summer/early fall low streamflows during the 20th century.

There were few statistically significant trends in the timing, magnitude, or duration of summer low streamflows for coastal river basins in Maine during the 20th century. The hypothesis that earlier winter/spring high streamflows may result in earlier or lower low streamflows is not supported by the data. No statistically significant trends in the magnitude of total runoff volume during the low-streamflow months of August and September were observed. The magnitude and timing of summer low streamflows correlated with the timing of fall/winter high streamflows and the amount of summer precipitation. The magnitude and timing of summer low streamflows did not correlate with the timing of spring snowmelt runoff. There were few correlations between the magnitude and timing of summer low streamflows and monthly mean surface air temperatures.

There were few statistically significant trends in the timing or duration of fall/winter high streamflows for coastal river basins in Maine during the 20th century. The timing of the bulk of fall/winter high streamflows correlated with seasonal precipitation. Earlier fall/winter center-of-volume dates correlated with higher September and October precipitation. In general, little evidence was observed of trends in the magnitude of seasonal runoff volume during fall/winter. The magnitude of fall/winter high streamflows positively correlated with November and December precipitation amounts. There were few correlations between the magnitude and timing of fall/winter high streamflows and monthly mean surface air temperatures.

Introduction

Combined land-surface air and sea-surface temperature data, presented in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2001), show an overall increasing trend in annual surface air temperature for New England for the period 1901-2000. Greatest seasonal warming rates for New England during 1976-2000 were during the winter months of December, January, and February (Intergovernmental Panel on Climate Change, 2001). Given these changes in air temperature and the demonstrated sensitivity of snowmelt to surface air temperature (Hartley and Dingman, 1993), the U.S. Geological Survey (USGS) and the Maine Atlantic Salmon Commission (ASC) did a cooperative study from 2001 to 2002 to determine whether there were statistically detectable changes in streamflow for unregulated coastal basins in Maine. The investigation revealed historical trends in streamflow, river ice, and snowpack consistent with a trend toward an earlier onset of spring conditions during the 20th century in coastal Maine (Dudley and Hodgkins, 2002). Dudley and Hodgkins (2002) documented a significant change in the timing of spring runoff toward earlier dates for an extended coastal streamflow record spanning 1906-1921 and 1929-2000. Coastal river streamflow-gaging stations showed, in general, significantly earlier last ice-off dates in the spring and a statistically significant decrease over time in the total number of days of ice-affected streamflow at most stations on coastal rivers in Maine. The longest, most complete snow records indicated an increase in snowpack density for the March 1 snow-survey date during 1938-2000.

Many studies of snowmelt-dominated river basins in western North America show seasonal shifts to greater winter streamflow and reduced summer streamflow (Cohen and

Miller, 2001). Similar changes in streamflow regime have been documented in historical river flows in southern British Columbia (Leith and Whitfield, 1998), and were modeled for four rivers in California (Lettenmaier and Gan, 1990) and for a river in Switzerland (Brubaker and Rango, 1996). These last three studies found lower summer low streamflows associated with increasing air temperatures.

The basins studied in British Columbia, California, and Switzerland have substantial summer snowmelt runoff, whereas snowmelt runoff in New England does not directly contribute appreciable quantities of water to summer streamflows. Spring snowmelt in northern New England, however, is important to ground-water recharge. Following spring recharge, ground water discharges into New England streams (as base flow) throughout the summer. Dudley (2004) found that the percentage of sand and gravel aquifers underlying Maine drainage basins is a significant explanatory variable for monthly mean streamflows for July through October (basins with more sand and gravel aquifers are associated with higher streamflows). This indicates the importance of base flow to summer and early fall streamflows. A base-flow recession from spring to late summer is typical in New England. With snowmelt occurring earlier (inferred from earlier high spring streamflows) (Dudley and Hodgkins, 2002), the base-flow recession may start earlier. This could lead to a longer period of low summer streamflow recession and lower minimum streamflows. Querner and others (1997), using a physically based model, found increased deficit volumes (the amount of water below a threshold streamflow) with increased air temperatures for a river that drains parts of southwestern Norway and for a river that drains parts of the Netherlands and Belgium.

The ASC is concerned with the impacts of potentially changing meteorological and hydrologic conditions on Atlantic salmon survival (Joan Trial, Maine Atlantic Salmon Commission, oral commun., 2002). To understand the potential effects of streamflow timing and quantity on survival of Atlantic salmon and other fish species in coastal Maine, it is important to characterize seasonal hydrologic conditions and whether they are (or not) changing over time. Low streamflows in the summer can result in high water temperatures and low concentrations of dissolved oxygen, stressing resident biota (Bradbury and others, 2002). Likewise, cold temperatures and ice formation during winter can be stressful to biota who reside in streams over winter. Surface ice can provide protective insulation between the stream and the air, but, in the absence of surface-ice cover, anchor ice can form. Anchor ice is an accumulation of ice crystals or slush adhering to riverbed material and can have serious effects on fish eggs developing within gravel beds (Prowse, 1994).

The U.S. Geological Survey (USGS), in cooperation with the Maine Atlantic Salmon Commission (ASC), began a study in 2003 to examine the timing, magnitude, and duration of summer (June through October) and fall/early winter (September through January) seasonal streamflows of unregulated coastal river basins in Maine and to correlate them to meteorological variables and winter/spring (January through May) seasonal streamflow. This study overlapped the summer seasonal window with the fall/early winter seasonal window to completely bracket the low-streamflow period during July, August, and September between periods of high streamflows in June and October.

Purpose and Scope

The purpose of this report is to specifically address the hypothesis that because winter/spring high streamflows appear to be occurring earlier in coastal Maine, base flow recessions could also be occurring earlier, resulting in a trend toward earlier, and possibly lower, longer lasting, summer low streamflows. This report presents the data and methods used to determine whether there are trends in the timing and (or) amount of streamflow during the summer and fall/winter for coastal river basins in Maine and whether these streamflow conditions are interseasonally correlated. The trend and correlation results presented in this report quantify whether seasonal changes observed in winter-spring hydrology relate to changes in summer low streamflows. The report also presents the data, methods, and results of correlation tests between seasonal streamflow statistics and meteorological data.

Description of the Study Area

The study area covers all unregulated coastal river basins in Maine that either currently are gaged or have been gaged by the USGS for more than 10 years (table 1, fig. 1). Six basins met these criteria; the basins are heavily forested and are characterized by low-relief rolling topography with little 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, fine- and coarse-grained glaciomarine deposits, ice-contact glaciofluvial deposits, eskers, and bedrock (Thompson and Borns, 1985).

The greatest changes in land use in Maine have been the replacement of agriculture and pasture lands by forest during the 20th century. The overall forest cover in Maine, estimated at 67 percent in 1900, increased to 90 percent by 1995 (Irland, 1998). Four of the six basins are in close proximity to each other in eastern coastal Maine (West Branch Union, Narraguagus, Machias, and East Machias, fig. 1)—a sparsely populated part of Maine. During the period 1880-1995, forested area in eastern coastal Maine increased from about 85-percent to 90-percent forested area (Irland, 1998). The remaining two river basins, Sheepscot and Royal, are in a

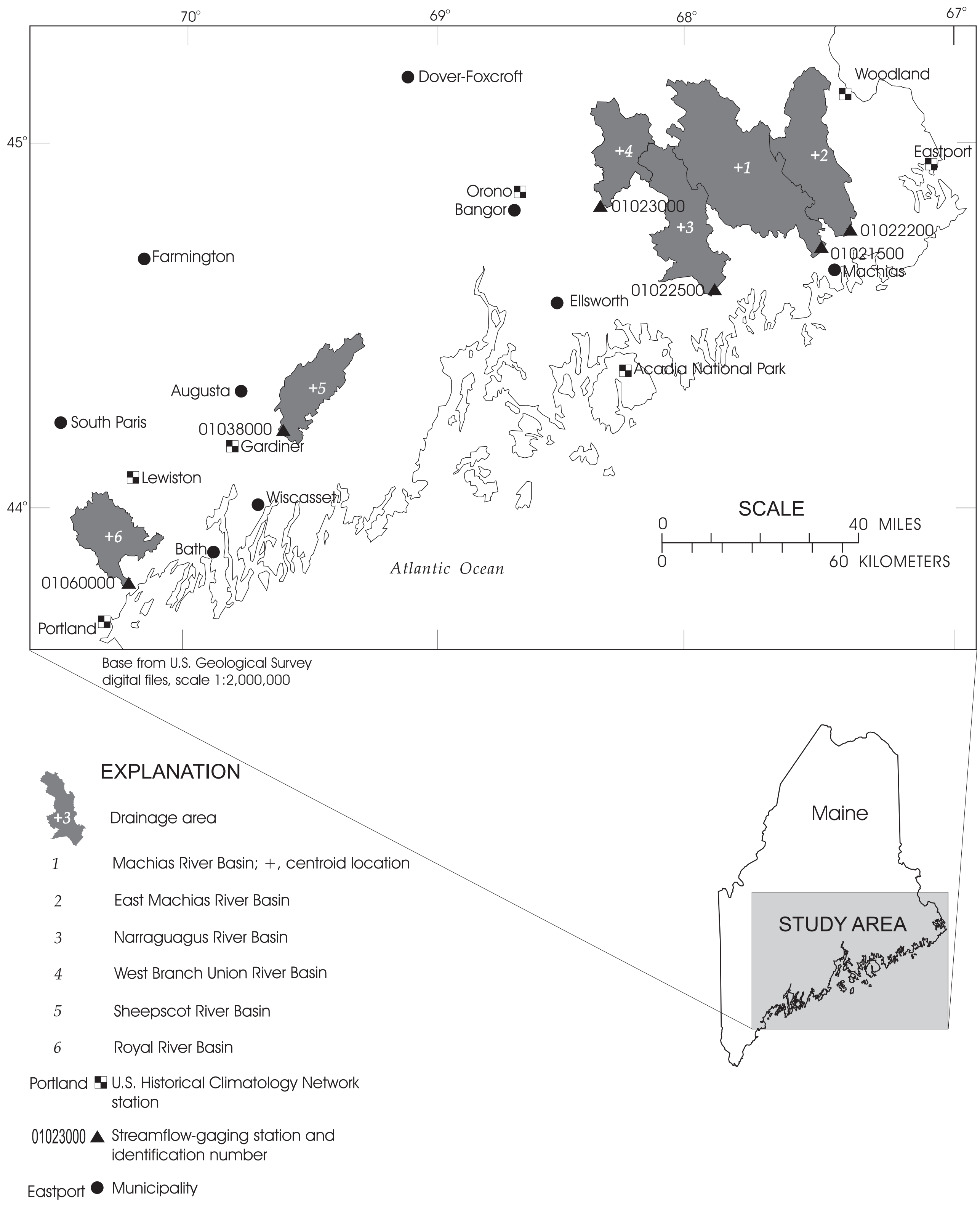

Figure 1. Locations of gaged coastal river basins, Maine.

Table 1. Coastal streamflow-gaging stations in Maine used in this investigation.

U.S. Geological Survey streamflow-gaging station		Latitude (north)	Longitude (west)	Drainage area (square miles)	Period of streamflow record used in this investigation[1]
Number	Name				
01021500	Machias River at Whitneyville	44°43’ 23”	67°31’ 15”	458	1906-21, 1930-77
01022000	East Machias River near East Machias	44°46’ 05”	67°24’ 30”	251	1927-58
01022500	Narraguagus River at Cherryfield	44°36’ 29”	67°56’ 10”	227	1948-2001
01023000	West Branch Union River at Amherst	44°50’ 25”	68°22’ 22”	148	1910-19, 1929-79
01038000	Sheepscot River at North Whitefield	44°13’ 23”	69°35’ 38”	145	1939-2001
01060000	Royal River at Yarmouth	43°47’ 57”	70°10’ 45”	141	1950-2001

[1] Period of streamflow record defined in water years; 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.

historically more populated part of Maine that was more heavily deforested during the late 19th and early 20th centuries. Since that time, forested area in the vicinity of the Sheepscot and Royal River Basins has increased from approximately 50-percent to 75-percent forested area (Irland, 1998).

The population of Maine in 2000 was about 1.3 million people—a 72-percent increase since 1910 (U.S. Census Bureau, 2002; University of Maine, 2004). Population in counties in eastern coastal Maine (vicinity of West Branch Union, Narraguagus, Machias, and East Machias River Basins, fig. 1) decreased 18 percent from 1910 to 1970, and increased 33 percent from 1970 to 2000, with a net population growth of 9 percent from 1910 to 2000. Population growth in the vicinity of the Sheepscot River Basin from 1910 to 2000 was about 68 percent; population growth during the period that streamflow gaging was done on the Sheepscot River (from 1940 to 2000) was about 87 percent. Population growth in the vicinity of the Royal River Basin from 1910 to 2000 was about 137 percent; population growth during the period that streamflow gaging was done on the Royal River (from 1950 to 2000) was about 57 percent (U.S. Census Bureau, 2002; University of Maine, 2004).

The climate of Maine’s coast is typified by mild summers and cold winters. Records from National Weather Service (NWS) stations indicate mean annual surface air temperatures from 1971 to 2000 of 45.7 °F in Portland and 44.1 °F in Eastport (fig. 1). Mean monthly surface air temperatures range from 21.7 °F in January to 68.7 °F in July in Portland, and from 22.1 °F in January to 64.0 °F in July in Eastport. The mean annual precipitation is 45.8 in. (inches) at Portland and 44.8 in. at Eastport and is fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 2002).

Proximity to the Gulf of Maine provides a moderating effect on surface air temperatures throughout the year. In general, coastal locations are warmer in the winter than inland locations. For comparison to the coastal locations of Portland and Eastport, mean annual surface air temperatures (for 1971-2000) at the inland towns of Dover-Foxcroft and Farmington (fig. 1) are 40.3 °F and 41.7 °F, respectively (fig. 1). Mean January surface air temperatures are 12.1 °F in Dover-Foxcroft and 14.4 °F in Farmington (National Oceanic and Atmospheric Administration, 2002). The distance of a river basin from the coast is a significant explanatory variable in regression equations used to estimate monthly streamflows in Maine (Dudley, 2004). During December, January, February, and March, the regression equations indicate that higher monthly streamflows, on a per unit-area basis, correspond with shorter distances from the coast. The relation reverses in May when higher streamflows occur in basins farther from the coast; this is consistent with colder, inland river basins storing more water in snowpack during the winter and releasing it later in the spring (Dudley, 2004).

The largest streamflows in coastal Maine typically occur in the late winter (March and April) and spring (May and June) when rain falls on a dense (ripe) snowpack or on saturated soils (fig. 2). Streamflows then recede as snowmelt ends and evapotranspiration increases. The recession typically persists into late summer (August-September) because of high evapotranspiration. Streamflow in late summer is dominated by ground-water discharge and is frequently augmented by runoff from rainfall events. As evapotranspiration decreases in the fall (October-November), streamflow increases. Repeated rainfall events and the occasional contribution of hurricane-related precipitation can result in high streamflows. Low streamflows can occur during the winter (December-February) if precipitation and surface water is frozen for extended periods of time.

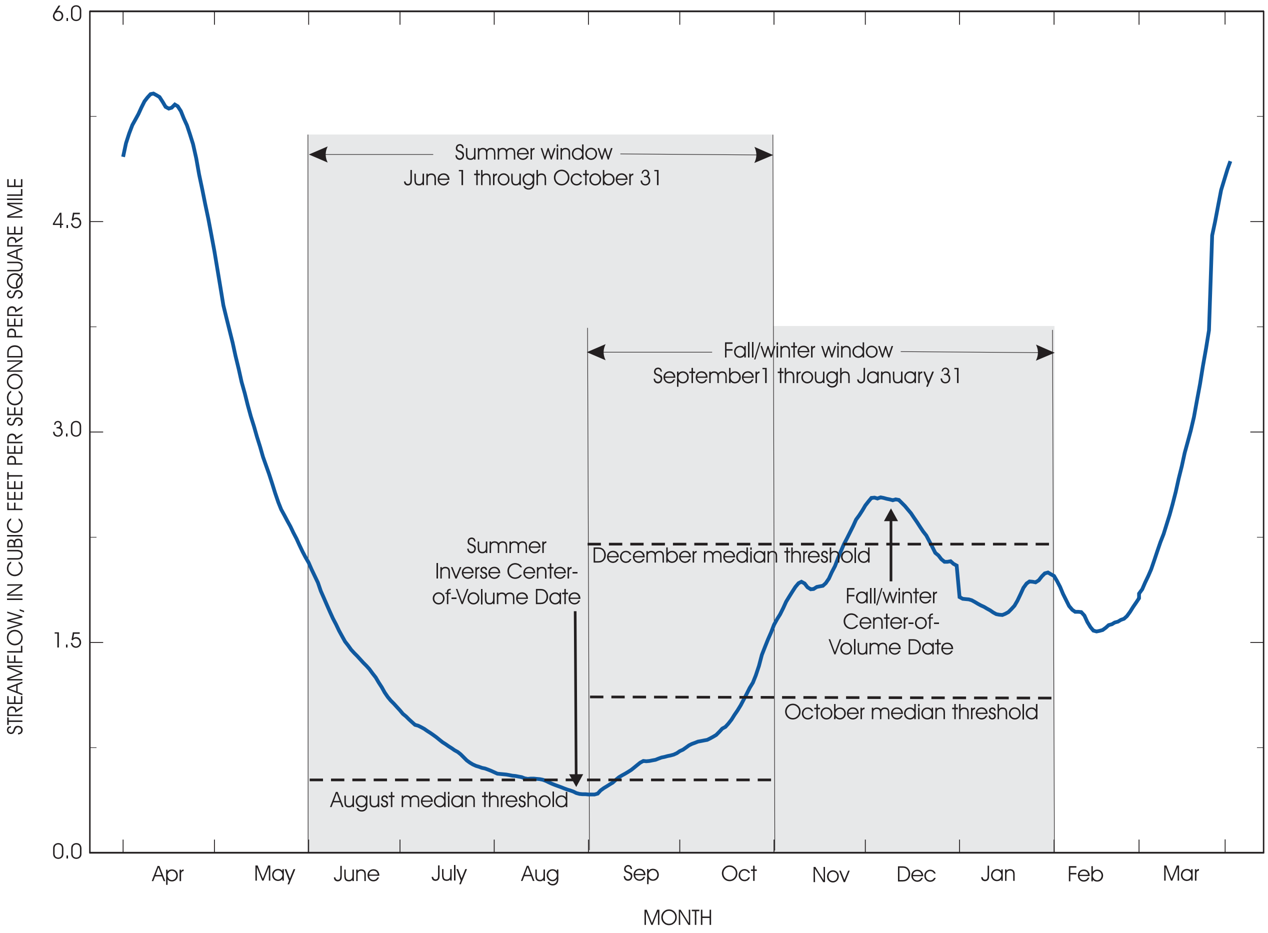

Figure 2. Average annual hydrograph for six rivers in coastal Maine. The rivers include Machias at Whitneyville, East Machias near East Machias, Narraguagus at Cherryfield, West Branch Union at Amherst, Sheepscot at North Whitefield, and Royal at Yarmouth.

Streamflow, Precipitation, and Surface Air Temperature Data

Streamflow, precipitation, and air temperature data sets were assembled for historical trend and correlation analyses as described below.

Streamflow Data

Streamflow data from six coastal streamflow-gaging stations in the study area (table 1, fig. 1) were retrieved from the National Water Information System (NWIS) (U.S. Geological Survey, 1998). Periods of record of streamflow data for the six stations range from 32 to 65 years in length, with a mean of 56 years. The earliest and latest dates for streamflow data used in this study are October 1, 1905, and September 30, 2001, respectively.

Because particular focus is placed on the analysis of low streamflows in this investigation, a careful evaluation of regulation during low-streamflow periods at each streamflow-gaging station was done. In order for trend analyses of continuous streamflows records to represent changes over time of natural conditions, it is important that the records represent unregulated streamflow. Unregulated streamflow is defined as streamflow substantially unaffected by diversions (such as pumping) and (or) regulation by dams or reservoirs, and is described in greater detail below.

The presence of regulation at each station is qualitatively documented in the annual USGS state Water-Data Reports and their predecessor Water-Supply Papers. Two stations, Machias River at Whitneyville (U.S. Geological Survey streamflow-gaging station number 01021500) and East Machias River near East Machias (01022000), have or historically have had some minor low-streamflow regulation. The low-streamflow regulation at these sites has been large enough as to have a transient effect on the magnitude of daily mean streamflows; however, the regulation at these sites is thought to be small enough as to have no effect on the computation of statistics (on the basis of daily mean streamflow) for monthly or longer timescales (such as the monthly mean) (Slack and Landwehr, 1992). On the basis of the above criteria, submonthly statistics for the Machias River (01023000) and East Machias River (01038000) were not computed. 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, in general, daily and longer averages of streamflow are thought to be representative of natural conditions (Slack and Landwehr, 1992).

Hydrograph plots of summer/fall and fall/winter streamflows during the periods of records at all the stations were examined to further evaluate the occurrence of substantial regulation. Substantial regulation was defined as regulation that caused the minimum or maximum daily streamflow for a season. If more than 10 percent of the period of record (3 to 6 years) for a station was suspected to be affected by regulation, the statistics based on timescales less than 1 month were not computed for that site (for example, the minimum daily streamflow, or the 7-day mean low streamflow). On the basis of the above criteria, submonthly statistics for the West Branch Union River (01023000) and Sheepscot River (01038000) were not computed. All statistics were computed for the Narraguagus River (01022500) and Royal River (01060000). Summer streamflow records in 1978 and 1985 were censored for the Narraguagus River (01022500) due to documented unusual regulation. Summer streamflow record in 1980 and winter streamflow record in 1956 were censored for the Royal River (01060000) due to suspected unusual regulation.

All six river basins are forested and rural, with little change in land use over the 20th century other than reforestation in the vicinity of the Sheepscot and Royal River Basins. The effects of reforestation on the timing and magnitude of streamflows for these basins are unknown.

Precipitation and Surface Air Temperature Data

Precipitation and surface air temperature time series used in this investigation were obtained from the U.S. Historical Climatology Network (USHCN) data set developed and maintained at the National Climatic Data Center (NCDC) (table 2, fig. 1) (Karl and others, 1990). The USHCN data have been subjected to quality control and homogeneity testing. Precipitation data have been adjusted for bias due to changes in station location and other station changes over time (Karl and Williams, 1987). Temperature data have been adjusted for bias originating from changes in observation time (Karl and others, 1986), instrumentation (Quayle and others, 1991), station location and other changes (Karl and Williams, 1987), and urban heat island effects (Karl and others, 1988). Only data from USHCN stations within 30 mi (miles) of any study basin centroid were used.

Analysis of Streamflow, Precipitation, and Surface Air Temperature Data

Temporal trends were analyzed for all data sets discussed in this section using the non-parametric Mann-Kendall test (Helsel and Hirsch, 1992). The data were smoothed for graphical presentation and serial correlation testing by use of locally weighted regression (LOESS) (Cleveland and Devlin, 1988) with local 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 data set with a significant temporal trend (p-value less than 0.10) 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.

Correlation tests were done using Pearson's product-moment correlation, which is a measure of the linear association between two variables (Helsel and Hirsch, 1992). The value of Pearson's “r” statistic lies between -1 and +1. An r-value greater than 0 indicates a positive linear relation between variables, and an r-value less than 0 indicates a negative linear relation between variables. The statistical significance of any Pearson's product-moment correlation is indicated by an associated p-value.

A modified Julian date system was used for all timing analyses in this investigation. The date-numbering system used in this investigation begins date numbering on April 1. This numbering system was used in order to capture the entire summer period (beginning in June) and subsequent fall/winter period (ending in January) in a single, sequentially numbered date system.

Table 2. U.S. Historical Climatology Network stations in Maine used in this investigation.

U.S. Historical Climatology Network station		Latitude (north)	Longitude (west)
Number	**Location**		
170100	Acadia National Park	44°21' 00”	68°16' 12”
172426	Eastport	44°55' 12”	67°00' 00”
173046	Gardiner	44°13' 12”	69°46' 48”
174566	Lewiston	44°06' 00”	70°13' 12”
176430	Orono	44°54' 00”	68°40' 12”
176905	Portland	43°39' 00”	70°18' 00”
179891	Woodland	45°09' 00”	67°24' 00”

Streamflow

Daily mean streamflows for individual USGS gaging stations are the original data used for this study. Each daily mean streamflow data set was used to construct 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 96-year period 1906-2001. 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, 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 2001. The Narraguagus Extended Record is referred to as NER in the remainder of this report.

The linear relation between the streamflow at the Machias and Narraguagus Rivers has an overall Pearson’s r correlation coefficient of 0.93 (fig. 3). It is suspected that the relation of low streamflows between the two rivers exhibits some non-linearity and greater variability than the relation at the higher range of streamflows (fig. 3) due to the minor regulation of low streamflows on the Machias River and the absence of regulation at Narraguagus. Statistics based on timescales less than 1 month were not computed for the NER because of the variability in the relation between the Machias and Narraguagus Rivers for low streamflows.

To examine trends over time in the timing, magnitude, and duration of summer and fall/winter streamflows, daily mean streamflow data were partitioned into two temporal windows. The summer window was defined as June 1 to October 31, and the fall/winter window was defined as September 1 to January 31. The dates June 1 and October 31 bracket the summer low-streamflow period between two periods of time that have characteristically high streamflows (fig. 2). The long-term daily mean streamflows for each station were normalized to their respective drainage areas (to yield daily mean cubic feet per second per square mile) and then arithmetically averaged across all stations to produce the graph shown in figure 2.

The fall/winter period was defined as September 1 to January 31. These dates bracket the fall/winter streamflow period between the period of lowest streamflow during the year (late August - early September) and the winter low-streamflow period that occurs roughly during January and February as precipitation and surface water freezes and substantial amounts of water are stored in snow pack (fig. 2). Although this is usually the period of lowest streamflow during the winter, Dudley and Hodgkins (2002) noted that, in general, low streamflows during December, January, and February have increased over the 20th century for coastal rivers in Maine.

Streamflow timing and magnitude statistics for the remainder of the year (February to May), during which the bulk of snowmelt runoff occurs, were not derived for this investigation. However, the winter/spring seasonal center-of-volume statistics for the timing of snowmelt runoff derived by Dudley and Hodgkins (2002) in an earlier study of coastal river basins in Maine were used in this investigation in correlation tests with summer low-streamflow statistics.

The winter/spring seasonal center-of-volume timing statistic, used by Dudley and Hodgkins (2002) and also applied by Hodgkins and others (2003), was computed by summing the daily streamflow volumes from the start to the end of the snowmelt runoff season. The seasonal center-of-volume date (CVD) is the first date, from the beginning of the season, on which at least half the total seasonal volume of water flows by a streamflow-gaging station. The winter/spring CVD is a useful variable for examining streamflow trends over time because it is more resistant to noise in the data than the peak-streamflow date and is thought to correspond more closely to the bulk of the spring snowmelt. The CVD also is more sensitive to changes in the timing of streamflow than is the percentage of streamflow occurring in one or more fixed months (Court, 1962). The winter/spring seasonal window used by Dudley and Hodgkins (2002) was January 1 to May 31. Because of the interest in describing the timing of the bulk of peak streamflows of the fall/winter time period for coastal river basins in Maine (fig. 2), the CVD was computed as a timing statistic for the fall/winter period, September 1 to January 31.

As part of this investigation into the timing of summer low streamflows, a timing statistic similar to the CVD was derived. In the case of characterizing the timing of the bulk of low streamflows, the inverse of all daily mean streamflow volumes from June 1 to October 31 was computed. By transforming the summer streamflow data in this manner, the summer hydrograph was effectively inverted and the timing of the new inverted peak streamflows corresponded to the timing of the bulk of low streamflows. The inverse volumes were summed, and the date by which half of this total inverse volume occurred was computed for each year at each streamflow-gaging station. This date is referred to as the inverse center-of-volume date (ICVD).

Other timing and streamflow-magnitude statistics derived for this investigation involved the averaging of daily mean streamflows over time scales of various lengths. For example, the 7-day-low streamflow is the lowest mean streamflow arithmetically averaged over a consecutive 7-day period within a given seasonal window. The date of the 7-day-low streamflow is the date at the center of the 7-day period—that is, day 4 of 7. The dates and mean streamflow magnitudes of the 1-day, 7-day, 15-day, 31-day, and 45-day low streamflows were computed for each summer period, for each year, for each station. Due to the mean shape of the fall/winter hydrograph for coastal river basins in Maine (fig. 2), the dates and streamflow magnitudes of the 1-day, 7-day, 15-day,

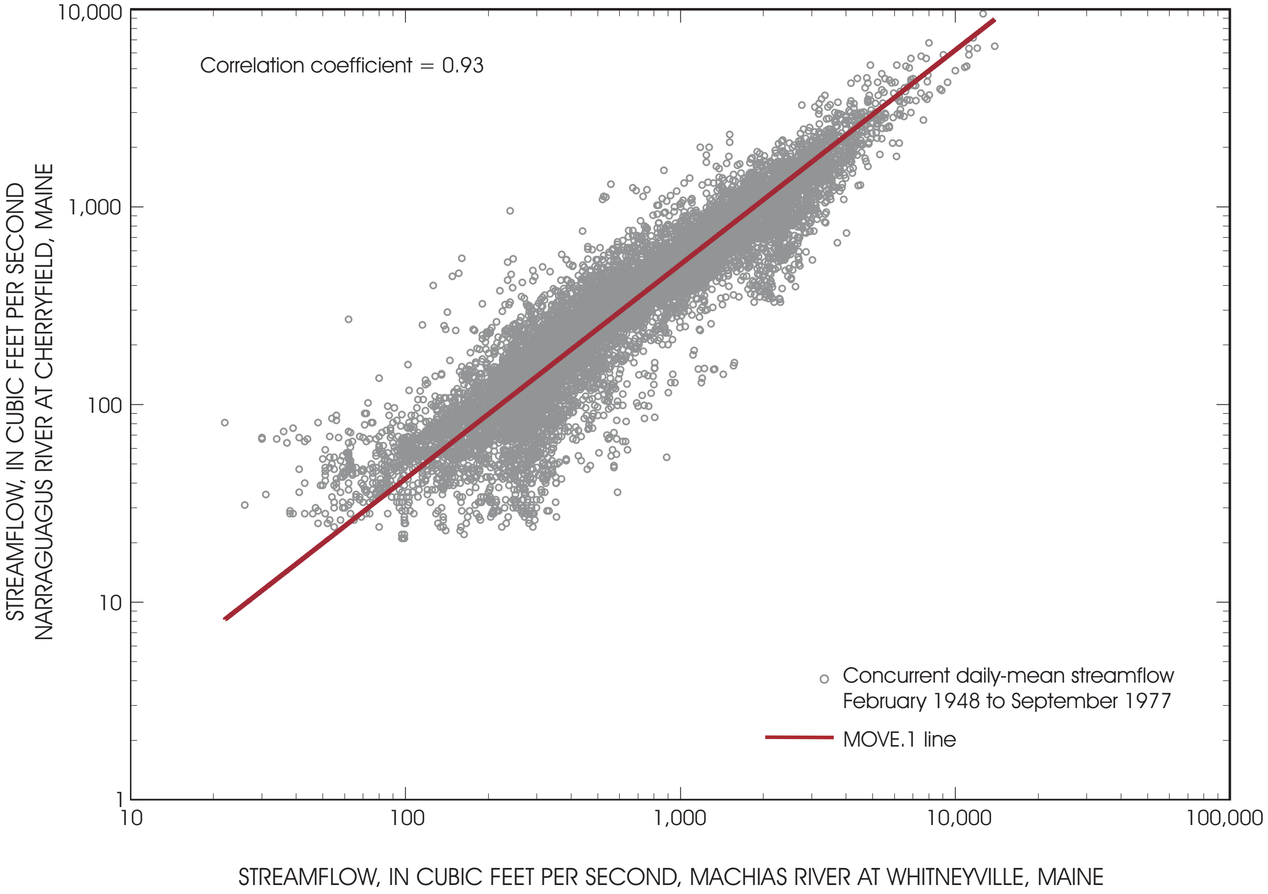

Figure 3. Maintenance of Variance Extension, type 1 (MOVE.1) relation between the streamflow at Machias and Narraguagus Rivers, Maine.

31-day, and 45-day peak streamflows were computed for each fall/winter period, for each year, for each station. As mentioned previously, statistics for time periods less than 31 days were not computed for stations with more than 10-percent of their record containing unusual regulation during low- or high-streamflow periods. Results of trend tests on streamflow statistics computed over timescales of 1, 7, and 15 days were intended to provide mutual corroboration; it was also hypothesized that longer timescales (7 and 15 days) may be more resistant to variability in the data. Streamflow statistics computed over timescales of 31 and 45 days were intended to provide common magnitude and timing statistics for all sites, providing a basis for comparison for sites for which submonthly statistics were censored.

Threshold statistics also were used as a measure of seasonal timing of streamflow. For the summer seasonal window, the long-term August median streamflow was used as a threshold statistic. The following threshold timing statistics were derived: the first date streamflow was equal to or less than the threshold; the last date streamflow was equal to or less than the threshold; the cumulative number of days that streamflow was equal to or less than the threshold; and the number of days between the first and last threshold dates, inclusive of those dates. For the purposes of trend testing, if streamflow was never equal to or less than the threshold streamflow during a given season in a given year, the first date was given a value of one day later than the latest first date for that station; the last date was given a value of one day earlier than the earliest last date for that station; the number of days between the first and last threshold dates was computed as usual; and the cumulative number of days that streamflow was equal to or less than the threshold was zero.

Similarly, the long-term December median was used as a threshold statistic for the fall-winter period because streamflows generally peak in December within this seasonal window (fig. 2). Fall/winter threshold timing statistics included the first date streamflow was equal to or greater than the threshold; the last date streamflow was equal to or greater than the threshold; the cumulative number of days that streamflow was equal to or greater than the threshold; and the number of days between the first and last threshold dates, inclusive of those dates. For years when streamflow was never equal to or greater than the threshold streamflow during a given year, statistics were handled similarly to those for the summer season described above.

A single fall-season October threshold statistic was computed to investigate a possible lengthening of the late-summer/early-fall low-streamflow period. The first date within the fall/winter seasonal window on which the streamflow exceeded the long-term October median was used as an indicator for the end of the late-summer/early-fall low-streamflow period.

Finally, total seasonal runoff volumes were computed to investigate trends in total seasonal streamflow. The fall/winter seasonal volume was computed by summing the daily mean streamflow volumes from the start to the end of the fall/winter seasonal window (September 1 to January 31). The summer seasonal volume was computed by summing the daily mean streamflow volumes from August 1 to September 30 only. The abbreviated seasonal window for summer total volume was used because high streamflows at the beginning and end of the summer seasonal window (fig. 2) would otherwise dominate the magnitude of the runoff volume, masking variability in low streamflows.

The Mann-Kendall trend test was used to test for significant changes over time in all of the aforementioned variables. Correlation tests between timing and total runoff volumes between seasons were done to investigate interseasonal relations of streamflow.

Precipitation and Surface Air Temperature

Monthly precipitation and surface air temperature data from the U.S. Historical Climatology Network (USHCN) stations were tested for correlation with streamflow timing and magnitudes for all streamflow-gaging stations. Only meteorological data from USHCN stations within 30 mi of a coastal river drainage-basin centroid were correlated with streamflow data for the corresponding USGS streamflow-gaging station (table 3). If more than one USHCN station was

Table 3. Pairing of U.S. Geological Survey coastal streamflow-gaging stations and U.S. Historical Climatology Network stations for correlation testing.

U.S. Geological Survey streamflow-gaging station		U.S. Historical Climatology Network station(s)	
Number	Name	Number(s)	Location(s)
01021500	Machias River at Whitneyville	179891	Woodland
01022000	East Machias River near East Machias	179891, 172426	Woodland, Eastport
01022500	Narraguagus River at Cherryfield	176430, 170100	Orono, Acadia National Park
01023000	West Branch Union River at Amherst	176430	Orono
01038000	Sheepscot River at North Whitefield	173046	Gardiner
01060000	Royal River at Yarmouth	174566, 176905	Lewiston, Portland
--	Narraguagus Extended Record (NER)	176430, 170100	Orono, Acadia National Park

within 30 mi of the drainage-basin centroid, the meteorological data were aggregated using a distance-weighted algorithm with the nearby stations having more weight than more distant stations (equation 1, fig. 1).

The algorithm for aggregating meteorological data weighted the data such that the sum of the weights for all of the aggregated stations was equal to one:

$$W_1 + W_2 + \ldots + W_n = 1 \qquad (1)$$

Where,

W_n is the weight for station n, and is a function of the inverse square of the station distance from the basin centroid.

Trends in Timing, Magnitude, and Duration of Summer and Fall/Winter Streamflows for Unregulated Coastal River Basins in Maine During the 20th Century

Trend test results and correlation results are presented and discussed in the following sections for each data set in this investigation. Trend test results calculated on the basis of individual streamflow records are referenced on a site-by-site basis. Generalizations about overall trends or hydrologic mechanisms rely primarily on the Narraguagus Extended Record (NER), with individual stations providing supporting information for the time period(s) they cover.

Trends in Summer Streamflows

Only one statistically significant trend in the timing or duration of summer low streamflows for coastal rivers in Maine was observed in this investigation (tables 4 and 5). The date of the 31-day low streamflow for the West Branch Union River had a statistically significant trend toward earlier dates with a p-value of 0.046 (table 4). Trend test results indicate the duration of the summer low-streamflow period has not changed significantly for coastal river basins in Maine during the 20th century, and no statistically significant trends were observed in the first date, last date, and cumulative number of days streamflow has been less than or equal to the long-term August median streamflow (table 5).

No statistically significant trends in total summer runoff volume for the months of August and September were observed (table 6). LOESS smooth plots illustrate the general pattern over time in August-September runoff volumes and indicate runoff volumes reached their lowest during the period 1945-65 (fig. 4). Only one statistically significant trend in the magnitude of summer low streamflows for coastal rivers in Maine was observed in this investigation (table 6). Although nearly all trend test results indicate negative trends (toward lower streamflows), only the trend in the magnitude of the 7-

Table 4. Statistical significance (p-values) and trend direction for summer (June 1 to October 31) streamflow timing statistics for coastal river basins in Maine.

[ICVD, inverse center-of-volume date; Low1D, date of the low 1-day mean streamflow; Low7D, date of the low 7-day mean streamflow; Low15D, date of the low 15-day mean streamflow; Low31D, date of the low 31-day mean streamflow; Low45D, date of the low 45-day mean streamflow; 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; +, trend over time toward later dates; -, trend over time toward earlier dates; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station							
Number	**Name**	**ICVD**	**Low1D**	**Low7D**	**Low15D**	**Low31D**	**Low45D**
01021500	Machias River at Whitneyville	0.903 +	*	*	*	0.893 -	0.566 +
01022000	East Machias River near East Machias	0.268 +	*	*	*	0.404 +	0.496 +
01022500	Narraguagus River at Cherryfield	0.467 +	0.740 -	0.716 +	0.597 +	0.664 +	0.710 +
01023000	West Branch Union River at Amherst	0.311 -	*	*	*	**0.046** -	0.260 -
01038000	Sheepscot River at North Whitefield	0.156 -	*	*	*	0.322 -	0.176 -
01060000	Royal River at Yarmouth	0.337 +	0.490 +	0.935 +	0.490 -	0.150 +	0.480 +
--	Narraguagus Extended Record (NER)	0.360 -	*	*	*	0.370 -	0.253 -

Table 5. Statistical significance (p-values) and trend direction for summer (June 1 to October 31) streamflow threshold statistics for coastal river basins in Maine.

[Threshold streamflow for each station is the long-term August median; FD, first date streamflow is at or below the threshold; LD, last date streamflow is at or below threshold; DD, number of days between the FD and LD, inclusive; Cum, cumulative number days in the season streamflow is at or below the threshold; p-values in bold and underlined are highly significant at less than or equal to 0.01; +, trend over time toward later dates; -, trend over time toward earlier dates; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station					
Number	**Name**	**FD**	**LD**	**DD**	**Cum**
01022500	Narraguagus River at Cherryfield	0.613 +	0.692 -	0.312 -	0.630 -
01060000	Royal River at Yarmouth	0.295 -	0.974 -	0.764 +	0.431 +

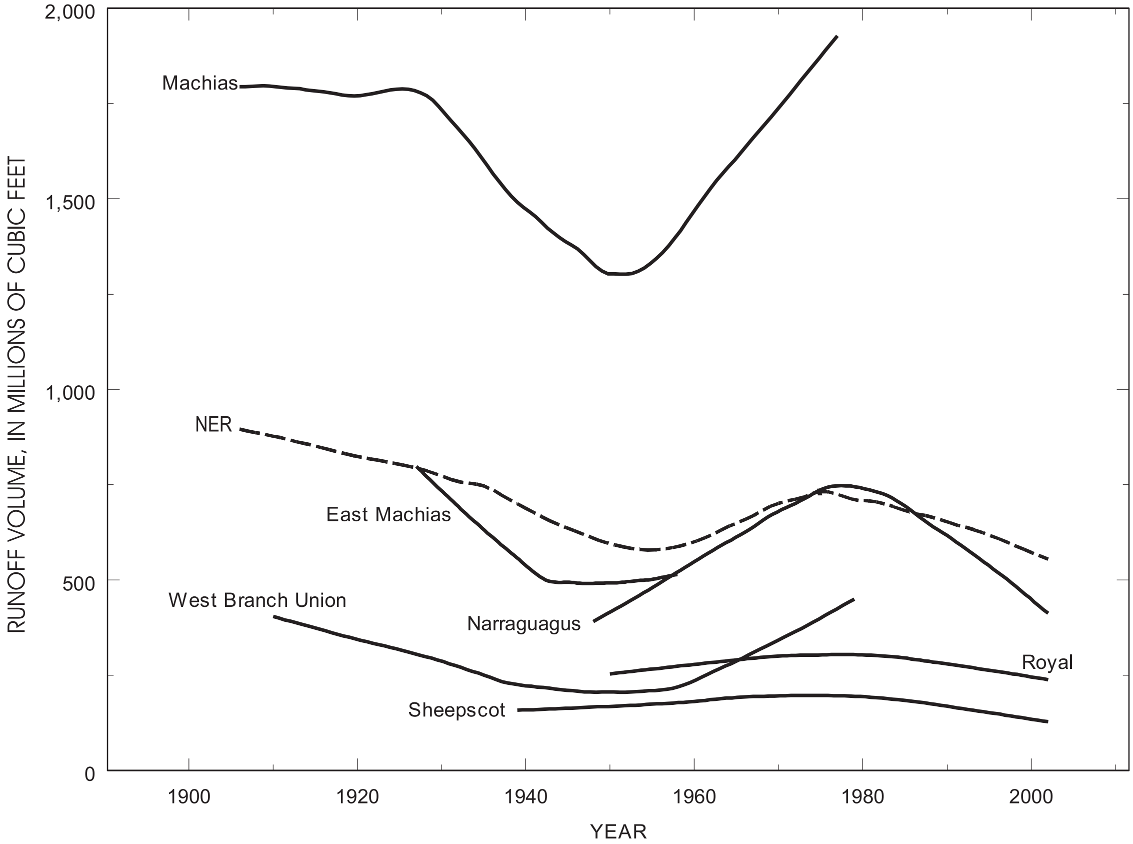

Figure 4. Trends in total runoff volume (August 1 to September 30) for six coastal rivers in Maine and the Narraguagus Extended Record (NER) (dashed line). LOESS regression lines are based on a 45-year weighting window.

Table 6. Statistical significance (p-values) and trend direction for summer (June 1 to October 31) streamflow magnitude statistics for coastal river basins in Maine.

[TotVol, total runoff volume from August 1 to September 30; Low1Q, low 1-day mean streamflow; Low7Q, low 7-day mean streamflow; Low15Q, low 15-day mean streamflow; Low31Q, low 31-day mean streamflow; Low45Q, low 45-day mean streamflow; 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; +, trend over time toward higher flows; -, trend over time toward lower flows; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station							
Number	**Name**	**TotVol**	**Low1Q**	**Low7Q**	**Low15Q**	**Low31Q**	**Low45Q**
01021500	Machias River at Whitneyville	0.948 -	*	*	*	0.789 +	0.944 -
01022000	East Machias River near East Machias	0.721 -	*	*	*	0.386 -	0.465 -
01022500	Narraguagus River at Cherryfield	0.747 +	0.794 -	0.956 -	0.758 -	0.636 -	0.813 -
01023000	West Branch Union River at Amherst	0.896 +	*	*	*	0.702 -	0.697 -
01038000	Sheepscot River at North Whitefield	0.698 +	*	*	*	0.831 -	0.776 -
01060000	Royal River at Yarmouth	0.937 -	0.145 -	**0.096** -	0.155 -	0.139 -	0.151 -
--	Narraguagus Extended Record (NER)	0.288 -	*	*	*	0.243 -	0.248 -

day low streamflow for the Royal River had a statistically significant result (p-value of 0.096).

Trends in Fall/Winter Streamflows

The October median streamflow threshold date was used as a measure of the onset of fall high-streamflow conditions as streamflows transition from summer low streamflows to fall high streamflows. Later or earlier October threshold dates could indicate changes in the length of the summer low-streamflow period. No statistically significant trends in the first date within the fall/winter seasonal window (September 1 to January 31) on which the streamflow exceeded the long-term October median were observed (table 7). Five out of the seven statistically insignificant trend test results indicate trends toward earlier dates, and two indicated later dates.

Little evidence of statistically significant trends in the timing or duration of fall/winter high streamflows for coastal river basins in Maine during the 20th century was observed, with only two statistically significant trend results (tables 8 and 9). The date of the 1-day peak streamflow for the East Machias River (1927-1958) had a statistically significant trend toward later dates with a p-value of 0.038 (table 8). Of the statistically insignificant results, 77 percent indicate trends toward later dates, 23 percent toward earlier dates. The Machias River (1906-21, 1930-77) had a statistically significant trend toward increasing difference between the first and last dates of streamflow equal to or exceeding the long-term December median (p-value of 0.079); however, trends for both the first threshold data and last threshold date for this site were statistically insignificant (table 9). These results are consistent with those presented in Hodgkins and others (2003), who demonstrated few statistically significant changes in the timing of fall high streamflows for 27 rural rivers in New England.

In general, little evidence of trends in total seasonal runoff volume during fall/winter was observed (table 10). Only the West Branch Union River (1910-19, 1929-79) had statistically significant trends toward higher total fall/winter runoff volume (table 10, fig. 5). Nine of 12 statistically

Table 7. Statistical significance (p-values) and trend direction for the October median threshold timing statistic for coastal river basins in Maine (September 1 to January 31).

[FD, first date that fall streamflow exceeds the long-term October median; 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; +, trend over time toward later dates; -, trend over time toward earlier dates; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station		
Number	**Name**	**FD**
01021500	Machias River at Whitneyville	0.740 -
01022000	East Machias River near East Machias	0.102 +
01022500	Narraguagus River at Cherryfield	0.722 +
01023000	West Branch Union River at Amherst	0.107 -
01038000	Sheepscot River at North Whitefield	0.124 -
01060000	Royal River at Yarmouth	0.961 -
--	Narraguagus Extended Record (NER)	0.147 -

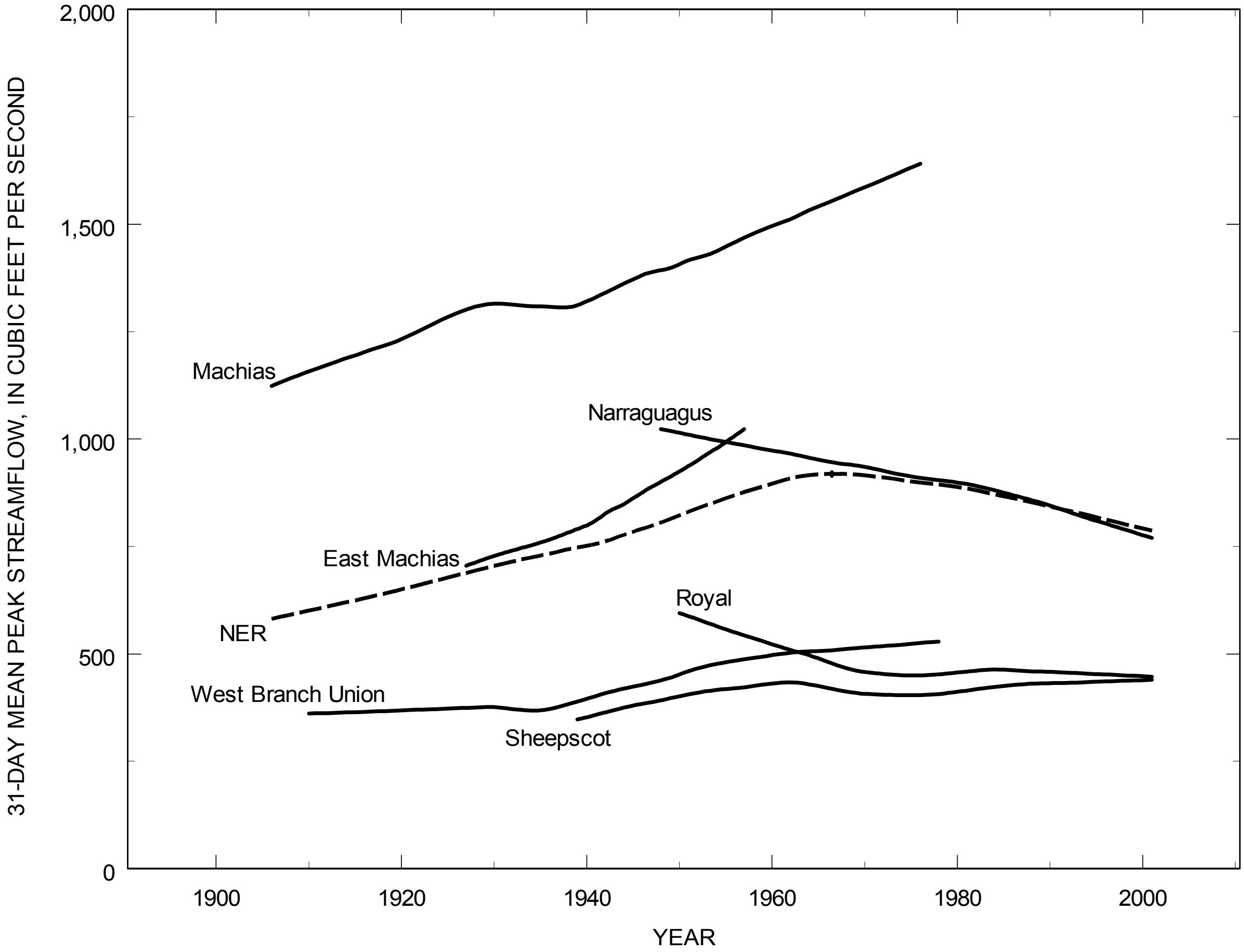

Figure 5. Trends in the magnitude of 31-day mean peak streamflow (September 1 to January 31) for six coastal rivers in Maine and the Narraguagus Extended Record (NER) (dashed line). LOESS regression lines are based on a 45-year weighting window.

Table 8. Statistical significance (p-values) and trend direction for fall/winter (September 1 to January 31) streamflow timing statistics for coastal river basins in Maine.

[CVD, center-of-volume date; High1D, date of the high 1-day mean streamflow; High7D, date of the high 7-day mean streamflow; High15D, date of the high 15-day mean streamflow; High31D, date of the high 31-day mean streamflow; High45D, date of the high 45-day mean streamflow; 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; +, trend over time toward later dates; -, trend over time toward earlier dates; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station							
Number	**Name**	**CVD**	**High1D**	**High7D**	**High15D**	**High31D**	**High45D**
01021500	Machias River at Whitneyville	0.229 +	*	*	*	0.429 +	0.145 +
01022000	East Machias River near East Machias	0.205 +	**0.038** +	0.149 +	0.138 +	0.192 +	0.148 +
01022500	Narraguagus River at Cherryfield	0.530 -	0.777 +	0.464 +	0.952 +	0.823 -	0.595 -
01023000	West Branch Union River at Amherst	0.581 +	0.615 +	0.762 -	0.491 +	0.432 +	0.127 +
01038000	Sheepscot River at North Whitefield	0.798 +	0.129 +	0.571 +	0.709 +	0.667 +	0.449 +
01060000	Royal River at Yarmouth	0.826 -	0.807 -	0.445 -	0.974 -	0.884 +	0.832 +
--	Narraguagus Extended Record (NER)	0.131 +	*	*	*	0.265 +	0.258 +

Table 9. Statistical significance (p-values) and trend direction for fall/winter (September 1 to January 31) streamflow threshold statistics for coastal river basins in Maine.

[Threshold streamflow for each station is the long-term December median; FD, first date streamflow is at or above threshold; LD, last date streamflow is at or above threshold; DD, number of days between the FD and LD, inclusive; Cum, cumulative number days in the season streamflow is at or above the threshold; 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; +, trend over time toward later dates; -, trend over time toward earlier dates; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station					
Number	**Name**	**FD**	**LD**	**DD**	**Cum**
01021500	Machias River at Whitneyville	0.230 -	0.191 +	**0.079** +	0.960 -
01022000	East Machias River near East Machias	0.323 +	0.810 +	0.452 -	0.984 -
01022500	Narraguagus River at Cherryfield	0.483 +	0.518 -	0.660 -	0.152 -
01023000	West Branch Union River at Amherst	0.130 -	0.340 +	0.152 +	0.318 +
01038000	Sheepscot River at North Whitefield	0.852 -	0.884 -	0.945 -	0.891 +
01060000	Royal River at Yarmouth	0.864 +	0.824 -	0.948 -	0.727 -
--	Narraguagus Extended Record (NER)	0.731 +	0.102 +	0.698 +	0.644 +

Table 10. Statistical significance (p-values) and trend direction for fall/winter (September 1 to January 31) streamflow magnitude statistics for coastal river basins in Maine.

[TotVol, total runoff volume from September 1 to January 31; High1Q, high 1-day mean streamflow; High7Q, high 7-day mean streamflow; High15Q, high 15-day mean streamflow; High31Q, high 31-day mean streamflow; High45Q, high 45-day mean streamflow; 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; *, statistic not tested]

U.S. Geological Survey streamflow-gaging station							
Number	**Name**	**TotVol**	**High1Q**	**High7Q**	**High15Q**	**High31Q**	**High45Q**
01021500	Machias River at Whitneyville	0.370 +	*	*	*	**0.071** +	**0.084** +
01022000	East Machias River near East Machias	0.693 +	0.220 +	0.167 +	0.179 +	0.186 +	0.155 +
01022500	Narraguagus River at Cherryfield	0.266 -	**0.072** -	**0.093** -	**0.075** -	0.159 -	0.134 -
01023000	West Branch Union River at Amherst	**0.083** +	**0.042** +	**0.027** +	**0.046** +	**0.051** +	**0.035** +
01038000	Sheepscot River at North Whitefield	0.654 +	0.360 +	0.494 +	0.575 +	0.486 +	0.654 +
01060000	Royal River at Yarmouth	0.564 -	0.655 -	0.350 -	0.252 -	0.287 -	0.232 -
--	Narraguagus Extended Record (NER)	0.228 +	*	*	*	**0.037** +	**0.039** +

significant trends in the magnitude of high fall/winter streamflows were toward higher streamflows, for the Machias (1906-21, 1929-77) and West Branch Union (1909-19, 1929-79) Rivers, and the NER (1906-21, 1929-2002). The Narraguagus River (1948-2002) had three statistically significant trends toward lower peak fall/winter streamflows (table 10). The mixed statistically significant trends in the magnitude of high fall/winter streamflows might be a result of the differences in time periods tested with a trend toward lower streamflows only appearing in the contemporary record (fig. 5). The mixed statistically significant trends also might be explained by correlations with seasonal precipitation and surface air temperature discussed later.

Correlations Among Seasonal Streamflows

The timing of summer low streamflows was not significantly correlated with the timing of spring snowmelt runoff (table 11), but later summer low streamflows correlated with later fall/winter high streamflows, with statistically significant correlations at all six stations. In general, later summer low streamflows correlated with later October median streamflow threshold dates, with statistically significant correlations at three of six stations.

The magnitude of summer low streamflows was not significantly correlated to the timing of spring snowmelt runoff (table 12), but lower summer 31-day mean low streamflows correlated with later fall/winter high streamflows, with statistically significant correlations at four of six stations. In general, lower summer low streamflows correlated with later October median streamflow threshold dates, with statistically significant correlations at two of six stations.

Correlations of Seasonal Streamflow with Precipitation and Surface Air Temperature

Overall, seasonal streamflows correlated more strongly with monthly mean precipitation than with monthly mean air temperatures (tables 13-16). Later summer low streamflows correlated with lower mean monthly precipitation in August (four of six stations had statistically significant correlations) and September (all six) (table 13). The correlation between later summer low streamflows, later fall/winter high streamflows, and later October threshold dates is supported by correlation results between the timing of summer low streamflows and late summer/early fall precipitation. Later fall/winter high streamflows correlated with lower mean monthly precipitation in September (4 of 6) and October (3 of 6) (table 13). There were few significant correlations between streamflow timing statistics and monthly mean surface air temperatures (table 14); later summer low streamflows correlated with higher mean July air temperatures (2 of 6).

Streamflow magnitude statistics correlate with monthly mean precipitation. The magnitude of summer low streamflows was correlated with mid-summer precipitation; lower summer low streamflows correlated with lower July (4

Table 11. Interseasonal correlations of summer (June 1 to September 30) low-streamflow timing (ICVD) to spring (January 1 to May 31) and to fall/winter (September 1 to January 31) high-streamflow timings (CVD) and to the October median threshold date for coastal river basins in Maine.

[ICVD, inverse center-of-volume date; CVD, center-of-volume date; October median threshold date, the first date within the fall/winter seasonal window on which the streamflow exceeds the long-term October median; Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station		Spring CVD	Fall/Winter CVD	October median threshold date
Number	Name			
01021500	Machias River at Whitneyville	-0.025	**0.347**	**0.376**
01022000	East Machias River near East Machias	-0.108	**0.731**	**0.499**
01022500	Narraguagus River at Cherryfield	0.022	**0.547**	0.290
01023000	West Branch Union River at Amherst	-0.092	**0.499**	0.331
01038000	Sheepscot River at North Whitefield	0.055	**0.556**	**0.580**
01060000	Royal River at Yarmouth	0.169	**0.478**	0.318

Table 12. Interseasonal correlations of the magnitude of summer (June 1 to September 30) 31-day mean low-streamflow (Low31Q) to fall/winter (September 1 to January 31) and to spring (January 1 to May 31) high-streamflow timings (CVD) and to the October median threshold date for coastal river basins in Maine.

[CVD, center-of-volume date; October median threshold date, the first date within the fall/winter seasonal window on which the streamflow exceeds the long-term October median; Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station		Spring CVD	Fall/Winter CVD	October median threshold date
Number	Name			
01021500	Machias River at Whitneyville	0.085	**-0.401**	-0.318
01022000	East Machias River near East Machias	0.013	**-0.532**	-0.376
01022500	Narraguagus River at Cherryfield	0.011	**-0.414**	-0.312
01023000	West Branch Union River at Amherst	-0.038	-0.324	**-0.366**
01038000	Sheepscot River at North Whitefield	0.050	**-0.430**	**-0.593**
01060000	Royal River at Yarmouth	0.108	-0.286	-0.341

Table 13. Correlations of summer low-streamflow timing (ICVD) and fall/winter high-streamflow timing (CVD) with monthly mean precipitation for coastal river basins in Maine.

[ICVD, summer inverse center-of-volume date; CVD, fall/winter center-of-volume date; Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station		Timing												
Number	Name	statistic	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
01021500	Machias River at Whitneyville	ICVD	-0.063	0.020	0.029	0.060	-0.002	-0.048	-0.281	-0.151	**-0.610**	-0.330	0.060	-0.079
		CVD	0.189	0.059	-0.091	0.081	0.055	-0.294	0.009	-0.053	**-0.386**	**-0.438**	0.037	0.320
01022000	East Machias River near East Machias	ICVD	0.018	0.089	0.009	-0.306	0.040	-0.251	0.028	**-0.457**	**-0.577**	**-0.660**	0.014	-0.019
		CVD	0.187	0.132	-0.088	-0.151	0.157	-0.390	0.075	-0.252	**-0.548**	**-0.680**	-0.017	0.047
01022500	Narraguagus River at Cherryfield	ICVD	-0.046	0.099	-0.046	-0.039	0.067	0.104	-0.315	**-0.494**	**-0.497**	-0.254	-0.015	-0.076
		CVD	0.029	-0.072	0.090	-0.064	-0.119	0.014	**-0.374**	-0.339	-0.322	-0.277	-0.178	-0.013
01023000	West Branch Union River at Amherst	ICVD	0.151	-0.014	0.207	-0.073	0.131	-0.021	-0.049	-0.281	**-0.388**	-0.231	-0.062	-0.143
		CVD	0.168	-0.036	-0.032	-0.126	-0.027	-0.108	**-0.386**	-0.266	-0.322	**-0.440**	0.021	0.049
01038000	Sheepscot River at North Whitefield	ICVD	-0.239	0.186	-0.115	-0.048	0.165	0.180	0.097	**-0.342**	**-0.618**	-0.223	-0.059	0.073
		CVD	-0.199	0.044	-0.067	-0.194	-0.112	0.195	-0.212	-0.168	**-0.453**	-0.281	-0.214	-0.042
01060000	Royal River at Yarmouth	ICVD	-0.080	0.118	-0.046	0.141	0.251	**0.410**	-0.068	**-0.576**	**-0.533**	-0.228	-0.064	0.127
		CVD	-0.093	-0.114	0.063	0.062	-0.170	0.041	-0.234	-0.224	**-0.461**	-0.336	-0.042	0.205

Table 14. Correlations of summer low-streamflow timing (ICVD) and fall/winter high-streamflow timing (CVD) with monthly mean surface air temperature for coastal river basins in Maine.

[ICVD, inverse center-of-volume date; CVD, center-of-volume date; Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station		Timing statistic	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Number	Name													
01021500	Machias River at Whitneyville	ICVD	-0.168	0.001	-0.043	-0.071	0.144	0.099	**0.418**	0.101	0.135	0.215	-0.001	0.070
		CVD	-0.057	-0.012	-0.045	0.151	0.021	0.121	0.143	0.033	0.035	-0.089	0.191	**0.424**
01022000	East Machias River near East Machias	ICVD	-0.151	-0.120	0.032	-0.194	-0.050	0.067	0.263	0.235	0.057	0.168	0.125	0.129
		CVD	-0.203	-0.059	0.017	0.029	-0.136	0.102	0.240	0.092	-0.129	0.015	0.174	0.230
01022500	Narraguagus River at Cherryfield	ICVD	0.001	0.042	-0.272	-0.153	-0.100	0.136	0.149	0.282	0.183	0.055	-0.012	0.142
		CVD	-0.016	0.064	-0.129	0.083	0.072	0.005	0.220	0.207	0.096	-0.003	0.056	0.298
01023000	West Branch Union River at Amherst	ICVD	0.024	0.260	0.034	0.202	0.126	0.168	**0.406**	0.307	0.282	0.133	0.129	0.147
		CVD	0.049	0.171	0.037	0.205	0.183	0.282	0.239	0.113	0.200	-0.148	0.007	0.195
01038000	Sheepscot River at North Whitefield	ICVD	-0.110	0.157	-0.193	0.010	-0.101	-0.089	0.050	0.106	0.174	0.127	-0.173	0.100
		CVD	-0.056	0.010	-0.132	0.055	0.083	-0.153	0.118	0.171	0.136	0.096	-0.008	0.253
01060000	Royal River at Yarmouth	ICVD	0.101	-0.038	-0.281	-0.115	-0.223	-0.098	-0.037	0.119	0.113	0.029	-0.245	0.067
		CVD	-0.089	-0.195	-0.184	-0.100	-0.030	-0.129	0.134	0.037	-0.080	0.172	-0.012	0.131

Table 15. Correlations of the summer 31-day mean low-streamflow magnitude and fall/winter 31-day mean high-streamflow magnitude with monthly mean precipitation for coastal river basins in Maine.

[Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station		Magnitude statistic	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Number	Name													
01021500	Machias River at Whitneyville	31-day low	0.122	0.227	0.169	0.268	0.189	0.226	0.224	**0.442**	0.298	**0.430**	-0.057	0.243
		31-day high	0.073	0.021	0.048	0.309	-0.188	0.191	0.210	**0.623**	0.067	0.208	**0.625**	**0.517**
01022000	East Machias River near East Machias	31-day low	0.003	0.069	-0.180	0.221	0.141	0.139	0.310	**0.740**	0.100	**0.624**	-0.007	0.197
		31-day high	0.084	0.110	-0.081	0.420	-0.211	0.066	0.171	**0.682**	-0.030	0.194	**0.726**	**0.618**
01022500	Narraguagus River at Cherryfield	31-day low	0.046	0.147	-0.049	**0.419**	0.187	0.238	**0.626**	**0.419**	0.270	0.244	-0.049	0.306
		31-day high	0.025	-0.091	0.080	0.209	-0.015	0.158	0.245	0.065	0.181	0.286	**0.546**	**0.534**
01023000	West Branch Union River at Amherst	31-day low	-0.019	0.213	-0.039	0.235	0.196	0.318	**0.571**	**0.497**	0.325	0.194	-0.053	0.261
		31-day high	0.017	-0.052	0.119	-0.020	-0.154	0.172	0.104	0.112	0.243	0.193	**0.526**	**0.445**
01038000	Sheepscot River at North Whitefield	31-day low	0.182	0.143	-0.090	**0.329**	0.153	0.198	**0.394**	0.193	0.284	0.148	-0.006	**0.399**
		31-day high	0.151	-0.037	0.112	0.280	0.061	0.122	0.030	0.076	0.055	0.287	**0.447**	**0.571**
01060000	Royal River at Yarmouth	31-day low	0.105	0.265	0.042	**0.411**	0.332	0.146	**0.497**	0.232	0.263	0.138	-0.001	**0.374**
		31-day high	0.043	-0.005	0.164	0.258	0.081	0.044	0.203	0.271	0.068	0.271	**0.501**	**0.622**

Table 16. Correlations of summer 31-day mean low-streamflow magnitude and fall/winter 31-day mean high-streamflow magnitude with monthly mean surface air temperature for coastal river basins in Maine.

[Pearson r-values in bold are statistically significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station														
Number	**Name**	**Magnitude statistic**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
01021500	Machias River at Whitneyville	31-day low	0.129	0.056	0.036	0.051	-0.091	-0.100	-0.170	-0.111	-0.071	0.156	-0.031	-0.072
		31-day high	0.244	-0.086	-0.142	-0.051	0.089	-0.108	-0.022	-0.037	-0.180	-0.041	0.336	0.407
01022000	East Machias River near East Machias	31-day low	0.186	0.189	0.052	0.185	-0.103	-0.244	-0.224	-0.313	-0.025	0.229	0.069	0.047
		31-day high	0.144	0.036	-0.017	0.093	0.090	-0.043	-0.170	-0.149	-0.257	-0.130	0.332	0.411
01022500	Narraguagus River at Cherryfield	31-day low	-0.004	0.176	0.282	0.294	-0.004	-0.168	-0.014	-0.042	0.015	-0.051	-0.096	-0.015
		31-day high	0.326	-0.138	0.146	0.101	0.053	-0.083	0.112	0.091	0.015	-0.005	0.234	0.176
01023000	West Branch Union River at Amherst	31-day low	0.123	0.185	0.125	0.250	-0.174	-0.112	-0.161	0.027	-0.070	0.003	0.029	0.116
		31-day high	0.215	0.050	-0.040	-0.075	0.092	-0.045	-0.044	-0.052	-0.197	-0.056	0.255	0.273
01038000	Sheepscot River at North Whitefield	31-day low	0.139	0.052	0.102	0.116	-0.201	-0.209	-0.142	-0.069	0.056	-0.144	-0.101	-0.003
		31-day high	0.310	-0.022	0.287	0.116	-0.006	-0.027	0.043	0.085	-0.072	0.010	0.265	0.199
01060000	Royal River at Yarmouth	31-day low	0.033	0.184	0.143	0.236	-0.174	-0.258	-0.091	0.030	-0.023	0.050	-0.070	0.034
		31-day high	0.164	0.065	**0.407**	0.335	-0.027	-0.104	0.275	0.118	-0.003	0.152	0.135	0.132

of 6) and August (4 of 6) monthly mean precipitation (table 15). Lower summer low streamflows also correlated with lower spring/early summer precipitation during April (3 of 6) (table 15) suggesting either spring recharge of ground water or seasonal weather patterns that produce covarying precipitation during spring and summer. Higher fall/winter high streamflows correlated with higher November and December mean monthly precipitation at all six stations for both months (table 15). The mixed statistically significant trends in the magnitude of high fall/winter streamflows might be explained by changes in November and December monthly mean precipitation over time. There were few significant correlations between streamflow magnitude statistics and monthly mean surface air temperatures (table 16).

The number of days that streamflow is equal to or below the long-term August median streamflow was negatively correlated with precipitation throughout late spring and summer (table 17); fewer days below the August median streamflow threshold correlated with greater amounts of precipitation in July (2 of 2) and August (1 of 2). Higher spring precipitation during April (2 of 2) and May (1 of 2) correlates to fewer days of streamflow equal to or below the long-term August median, suggesting either spring recharge of ground water or seasonal weather patterns that produce covarying precipitation during spring and summer. The number of days that streamflow is equal to or above the long-term December median streamflow was positively correlated with precipitation in late summer, fall, and early winter (table 18); more days above the December median streamflow threshold correlated with greater amounts of precipitation in August (3 of 6), September (5 of 6), October (6 of 6), and December (5 of 6).

Conclusions

It was hypothesized that summer low streamflows could be occurring earlier and that a longer period of low-streamflow recession could result in a decrease in the magnitude of low streamflows for coastal river basins in Maine. As discussed earlier, these hypothesized changes have been documented in historical streamflow records in southern British Columbia (Leith and Whitfield, 1989) and modeled for rivers in California (Lettenmaier and Gan, 1990) and Switzerland (Brubaker and Rango, 1996). The basins studied in British Columbia, California, and Switzerland have substantial summer snowmelt runoff, whereas most snow in Maine has melted by mid-May; in the spring, much of the snowmelt in Maine recharges ground water, which is later discharged to streams over the summer. However, a change in the timing of snowmelt runoff could still be important to the timing and magnitude of summer low streamflows in Maine. Querner and others (1997) found lower streamflows associated with increased air temperatures for a river in southwestern Norway and a river in the Netherlands and Belgium.

The results in this report indicate little evidence of trends over the 20th century in the timing, magnitude, or duration of summer low streamflows in coastal Maine. Correlation results indicate that summer low streamflows are more sensitive to precipitation than temperature. Statistically significant results indicate, in general, later timing of the bulk of summer low streamflows is correlated with decreasing August and September precipitation and later timing of the bulk of fall/winter high streamflows; lower magnitude summer low streamflows are correlated with lower April, July and August precipitation and later timing of the bulk of fall/winter high streamflows; and longer duration summer low-streamflows are correlated with lower amounts of April and July precipitation (table 19).

There is little evidence of trends over the 20th century in the timing or duration of fall/winter high streamflows in coastal Maine. There were statistically significant trends in the magnitude of high fall/winter streamflows at four of the six rivers tested. Seventy-five percent of the statistically significant results were toward higher peak fall/winter streamflows; the remaining trends toward lower peak fall/winter streamflows. The mixed trends in the magnitude of high fall/winter streamflows might be a result of the differences in time periods tested with a trend toward lower streamflows only appearing in the contemporary record. The mixed statistically significant trends also might be explained by correlations with seasonal precipitation and surface air temperature. Correlation results indicate that fall/winter high streamflows are more sensitive to precipitation than temperature. Statistically significant results indicate, in general, later timing of the bulk of fall/winter high streamflows is correlated with decreasing September and October precipitation; lower magnitude fall/winter high streamflows are correlated with lower November and December precipitation; and longer duration fall/winter high streamflows are correlated with higher amounts of August, September, October, and December precipitation (table 19).

There were few statistically significant correlations of mean monthly air temperature with the timing, magnitude, or duration of summer or fall/winter streamflows. The relatively abundant precipitation in coastal Maine may mask any strong temperature-dependent signal in streamflows examined in this report. Future changes in summer low streamflows and fall/winter high streamflows in coastal Maine may depend more on future changes in seasonal precipitation than changes in air temperature.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Maine Atlantic Salmon Commission (ASC), began a study in 2003 to examine the timing, magnitude, and duration of summer (June through October) and fall/early winter (September through January) seasonal streamflows of

Table 17. Correlations of cumulative number of days below the long-term August median streamflow threshold with monthly mean precipitation for coastal river basins in Maine.

[Pearson r-values in bold are significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station													
Number	**Name**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
01022500	Narraguagus River at Cherryfield	-0.135	-0.096	-0.076	**-0.401**	-0.221	-0.310	**-0.650**	**-0.355**	-0.319	-0.314	0.012	-0.258
01060000	Royal River at Yarmouth	-0.205	-0.238	-0.028	**-0.377**	**-0.428**	-0.261	**-0.476**	-0.270	-0.195	-0.240	0.150	-0.339

Table 18. Correlations of cumulative number of days above the long-term December median streamflow threshold with monthly mean precipitation for coastal river basins in Maine.

[Pearson r-values in bold are significant with p-values less than 0.01; Pearson r-values in bold and underlined are statistically significant with p-values less than 0.0001]

U.S. Geological Survey streamflow-gaging station													
Number	**Name**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
01021500	Machias River at Whitneyville	0.098	0.060	0.130	0.346	-0.037	0.329	0.082	**0.447**	**0.459**	**0.443**	0.317	**0.404**
01022000	East Machias River near East Machias	-0.016	0.028	-0.210	0.281	-0.123	0.201	0.027	**0.559**	0.391	**0.516**	0.422	0.430
01022500	Narraguagus River at Cherryfield	0.058	-0.030	0.082	0.214	0.127	0.228	**0.351**	0.216	**0.516**	**0.435**	0.254	**0.477**
01023000	West Branch Union River at Amherst	0.022	0.018	0.050	0.183	-0.003	0.296	0.326	0.176	**0.482**	**0.359**	0.239	**0.436**
01038000	Sheepscot River at North Whitefield	0.232	-0.097	0.163	0.167	0.009	-0.006	0.102	0.232	**0.473**	**0.427**	**0.345**	**0.387**
01060000	Royal River at Yarmouth	0.098	0.050	0.140	0.117	0.073	0.016	0.245	**0.425**	**0.427**	**0.426**	0.298	**0.476**

unregulated coastal river basins in Maine and to correlate them to meteorological variables and winter/spring (January through May) seasonal streamflow. This study overlapped the summer seasonal window with the fall/early winter seasonal window to completely bracket the low-streamflow period during July, August, and September between periods of high streamflows in June and October. The ASC is concerned with the impacts of potentially changing meteorological and hydrologic conditions on Atlantic salmon survival. Because winter/spring high streamflows appear to have trended toward earlier dates over the 20th century in coastal Maine, it was hypothesized that the spring/summer recession to low streamflows could have a similar trend toward earlier, and possibly lower, longer lasting, late summer/early fall low streamflows during the 20th century.

Streamflow data from six streamflow-gaging stations in coastal Maine were retrieved from the USGS National Water Information System (NWIS). Periods of record of streamflow data for the six stations range from 32 to 65 years, with a mean of 56 years. 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 1906-2002. To examine trends over time in the timing, magnitude, and duration of summer and fall/winter streamflows, daily mean streamflow data were partitioned into two seasonal windows. The summer window was defined as June 1 to October 31, and the fall/winter window was defined as September 1 to January 31. Streamflow timing and magnitude statistics for the remainder of the year (February to May), during which most snowmelt runoff occurs, were not derived for this investigation. The winter/spring seasonal center-of-volume statistics for the timing of snowmelt runoff derived in an earlier study of coastal river basins in Maine were used in this investigation in correlation tests with summer low-streamflow statistics.

Surface air temperature and precipitation time series used in this investigation were obtained from the U.S. Historical Climatology Network (USHCN) data set developed and maintained at the National Climatic Data Center. Only meteorological data from USHCN stations within 30 miles of coastal river drainage-basin centroids were correlated with streamflow data for the corresponding USGS streamflow-gaging station.

Little evidence of statistically significant trends in the timing, duration, or magnitude of summer low streamflows for coastal river basins in Maine during the 20th century was observed; the hypothesis that earlier winter/spring high streamflows may result in earlier and lower summer low streamflows is not supported by the data. Trend test results indicate the duration of the summer low-streamflow period has not changed significantly for coastal river basins in Maine over the 20th century. There also were no statistically significant trends in total runoff volume during the combined low-streamflow months of August and September.

Although little evidence of trends in the timing and magnitude of summer low streamflows for coastal river basins in Maine during the 20th century was observed, the magnitude and timing of summer low streamflows correlated with the timing of fall/winter high streamflows and with seasonal precipitation. Notably, the magnitude and timing of summer low streamflows were not correlated with the spring snowmelt runoff; however, later summer low streamflows did correlate with later fall/winter high streamflows. This is supported by correlation results between the timing of summer low streamflows and late summer/early fall precipitation—in particular, earlier summer low streamflows correlated with higher September precipitation. Lower summer low streamflows were also correlated with later fall/winter high streamflows. The magnitude of summer low streamflows correlated with mid-summer precipitation; higher precipitation amounts correlated with higher low streamflows. The correlation with precipitation is much stronger than that with monthly mean surface air temperatures. In general, summer low streamflow was positively correlated most strongly with July and August monthly mean precipitation. The cumulative number of days of streamflow at or below the long-term August median streamflow, at the two streamflow-gaging stations tested, was negatively correlated with summer precipitation (particularly July), indicating higher summer precipitation resulted in fewer days of streamflow below the long-term August median.

The October median streamflow threshold date was used as a measure of the onset of fall high-streamflow conditions as streamflows transition from summer low streamflows to fall high streamflows. Later or earlier October threshold dates could indicate changes in the length of the summer low-streamflow period. No statistically significant trends were observed in the occurrence of the first date during late summer/early fall on which the streamflow exceeded the long-term October median.

Little evidence of statistically significant trends in the timing or duration of fall/winter high streamflows for coastal river basins in Maine during the 20th century was observed. In general, there was little evidence of trends in the magnitude of total seasonal runoff volume during fall/winter. The timing of fall/winter high streamflows was correlated with seasonal precipitation. Earlier fall/winter high streamflows correlated with higher September and October precipitation. The magnitude of fall/winter high streamflows was positively correlated with November and December precipitation. Correlations with monthly mean precipitation amounts were stronger than those with monthly mean surface air temperature.

Table 19. General summary of correlation results.
[+, positive correlation; -, negative correlation]

Streamflow statistic	Fall/winter high-flow timing	April precipitation	July precipitation	August precipitation	September precipitation	October precipitation	November precipitation	December precipitation
Summer low-flow timing	+			-	-			
Summer low-flow magnitude	-	+	+	+				
Summer low-flow duration		-	-					
Fall/winter high-flow timing					-	-		
Fall/winter high-flow magnitude							+	+
Fall/winter high-flow duration				+	+	+		+

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