USGS
science for a changing world

Framework for a Hydrologic Climate-Response Network in New England

Open-File Report 2015–1062

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

Framework for a Hydrologic Climate-Response Network in New England

By Robert M. Lent, Glenn A. Hodgkins, Robert W. Dudley, and Luther F. Schalk

Open-File Report 2015–1062

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

Suggested citation:
Lent, R.M., Hodgkins, G.A., Dudley, R.W., and Schalk, L.F., 2015, Framework for a hydrologic climate-response network in New England: U.S. Geological Survey Open-File Report 2015–1062, 34 p., http://dx.doi.org/10.3133/ofr20151062.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (F – 32) / 1.8.

Datum

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

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

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

Abbreviations

GAGES II	Geospatial Attributes of Gages for Evaluating Streamflow, version II
GCM	general circulation model
HCDN–2009	Hydro-Climatic Data Network 2009
MGS	Maine Geological Survey
PRMS	Precipitation-Runoff Modeling System
USGS	U.S. Geological Survey
USHCN	U.S. Historical Climatology Network
WSCV	winter-spring center of volume
WSV	winter-spring runoff volume

Framework for a Hydrologic Climate-Response Network in New England

By Robert M. Lent, Glenn A. Hodgkins, Robert W. Dudley, and Luther F. Schalk

Abstract

Many climate-related hydrologic variables in New England have changed in the past century, and many are expected to change during the next century. It is important to understand and monitor these changes because they can affect human water supply, hydroelectric power generation, transportation infrastructure, and stream and riparian ecology. This report describes a framework for hydrologic monitoring in New England by means of a climate-response network. The framework identifies specific inland hydrologic variables that are sensitive to climate variation; identifies geographic regions with similar hydrologic responses; proposes a fixed-station monitoring network composed of existing streamflow, groundwater, lake ice, snowpack, and meteorological data-collection stations for evaluation of hydrologic response to climate variation; and identifies streamflow basins for intensive, process-based studies and for estimates of future hydrologic conditions.

Introduction

Seasonal, annual, and longer term variations in precipitation and air temperature can affect the timing and magnitude of numerous hydrologic processes that, in turn, affect natural resources, ecosystems, and society. Recent investigations conclude that many different hydrologic processes in New England are sensitive to variations in precipitation and air temperature. Various hydrologic variables, such as peak flows and the timing of winter-spring streamflows, have changed during the last century and are expected to change in the future. Observed trends during winter and spring are largely related to changes in air temperature because of the sensitivity of snowpack to air temperature changes in New England. Trends during summer and fall are largely related to changes in precipitation.

The U.S. Geological Survey (USGS) published a framework for a hydrologic climate-response network in Maine (Hodgkins and others, 2009). The framework benefitted from a decade of climate-change-related investigations into many components of the water cycle in Maine and New England and demonstrated how relevant hydrologic data describing various components of the regional water cycle can be key indicators of climate change. This report expands the Maine framework to cover the New England region—a larger, more climatologically diverse area with a much greater population than Maine. The New England framework has four purposes:

- Identify specific hydrologic variables for inland areas that are sensitive to climate variation.
- Identify geographic regions with similar hydrologic responses.
- Propose a fixed-station monitoring network composed of existing streamflow, groundwater, lake ice, snowpack, and meteorological data-collection sites for evaluation of hydrologic response to climate variation.
- Establish basins for process-based studies and for estimates of future hydrologic conditions.

Although sea-level rise is an important climate-change-related issue, it is not directly addressed by this proposed climate-response network, which focuses on inland hydrologic response. Much of the "Climate and Hydrology of New England" section of this report is updated text from Hodgkins and others (2009).

Climate and Hydrology of New England

The climate of New England is complex and variable; latitude, proximity to the Atlantic coast, and variations in land-surface elevation exert determinative effects on the climate (New England Regional Assessment Group, 2001). New England is about halfway between the equator and the North Pole and is affected by warm, moist air from the south and cold, dry air from the north. The Atlantic Ocean moderates air temperatures in both winter and summer. In winter, the ocean variably affects the location of snow/rain boundaries. Despite the substantial effect of the ocean, the prevailing air flow is not from the Atlantic Ocean but from the drier North American continent. The mountainous topography of northern and western New England affects precipitation and air temperatures.

Precipitation is higher on the windward side of mountains than on the leeward side; however, because storm-track directions through the mountains are highly variable, the windward and leeward areas differ for different storms. Air temperature generally decreases with increasing elevation.

Streamflows in New England typically are highest in the spring, when rain falls on a ripe snowpack or on saturated soils. Streamflows recede as snowmelt ends and as evapotranspiration increases. This recession is frequently interrupted by runoff from rainstorms. Warm-season streamflows are usually lowest in August and September. In the fall, after evapotranspiration decreases substantially, repeated rains often saturate the soil and lead to high streamflows. Also in the fall, large amounts of rain can fall as a result of hurricanes, tropical storms, or their remnants. Winter streamflows are generally low in northern New England, where winter precipitation typically falls as snow. Winter streamflows in southern New England can be more variable than streamflows in northern New England because of more winter rain.

The snowpack in New England typically accumulates throughout the winter and reaches its maximum depth and water equivalent (the amount of water stored in the snowpack) in northern New England (where the snowpack is more substantial than in southern New England) in March or April. The median seasonal maximum depth of the snowpack from 1955 to 1992 varied from less than 8 inches (in.) in coastal Connecticut and Rhode Island to more than 32 in. in the mountains of western Maine and northern New Hampshire and in northern Maine (Cember and Wilks, 1993). Most historical field-based data for snow water equivalent in New England have been collected in Maine. The average water equivalent on or near March 1 ranged from 3 to 5 in. along the Maine coast to 7 to 9 in. in the western mountains and in northern Maine (Loiselle and Hodgkins, 2002). The 109 data-collection sites analyzed by Loiselle and Hodgkins (2002) had an average of 43 years of record through 2000. Almost all of the data-collection sites were lower than 2,000 feet (ft) in elevation and therefore do not represent the full range of average water equivalent in Maine, as many mountains have elevations higher than 2,000 ft.

Historical Climate and Hydrologic Changes in New England

Climate-related seasonal hydrologic changes have been documented in New England on the basis of data collected during the last 50 to 200 years. Many changes have been documented in winter and spring, whereas some changes have been found in summer and fall and for annual flow variables. Overall, there is strong regionally coherent evidence of changes consistent with increasing air temperatures in late winter and spring in the last 30 to 40 years in northern New England (Maine, New Hampshire, and Vermont).

Annual

Various changes in low to high annual streamflows in New England have been documented (Hodgkins and Dudley, 2005). Annual low streamflows significantly increased ($p < 0.1$) at several streamflow-gaging stations in northern New England from the early to mid-1900s through 2002. Annual peak flows have increased significantly during the last 50 to 100 years at several streamflow-gaging stations across New England (Hodgkins and Dudley, 2005; Collins, 2009; Hodgkins, 2010a; Armstrong and others, 2012). Annual maximum and minimum groundwater levels during the most recent 20 and 30 years have increased in northern New England (Dudley and Hodgkins, 2013); in general, increases in maximum levels have been greater than increases in minimum levels, resulting in trends toward an increasing annual range. Weider and Boutt (2010) found groundwater levels increasing overall in New England in the last decade. Precipitation has increased in New England across all seasons (Karl and Knight, 1998; Douglas and Fairbanks, 2011; Hodgkins and Dudley, 2011).

Sea level has been rising globally for the past 20,000 years largely because of melting continental ice sheets that accumulated during the last ice age (Poore and others, 2000). One of the projected effects of climate warming is a continued rise in sea level caused by a combination of melting glaciers and ice sheets (on land) and thermal expansion of the ocean, called eustatic sea-level rise (Frumhoff and others, 2007). Historical rates of relative sea-level rise (eustatic sea-level rise combined with the effects of land subsidence) measured along the coast of New England during the last century (48 to 101 years of data through 2013) range from 0.07 to 0.14 inches per year (in/yr; National Oceanic and Atmospheric Administration, 2014). Future estimated rates of eustatic sea-level rise range from 0.05 to 0.33 in/yr (Kirshen and others, 2008). The USGS, in cooperation with the National Park Service, recently conducted a study to estimate future inundation of salt marshes in response to sea-level rise in Acadia National Park, Maine, and the surrounding region (Nielsen and Dudley, 2013).

Winter and Spring

March mean streamflows increased significantly over time ($p < 0.1$) at 14 of 27 streamflow-gaging stations in New England; all of the significant increases were in northern New England. Flows increased 76 to 185 percent at the seven stations with the longest continuous records (1920s or 1930s through 2002) in northern New England (Hodgkins and Dudley, 2005). There were no stations with significant decreases. The streamflow changes in northern New England are likely related to changes in snowpack melt, though changes in precipitation patterns and other factors could also contribute to the changes in streamflow (Hodgkins and Dudley, 2006b). Increased air temperatures cause increased late-winter flows through earlier snowmelt and more precipitation falling as rain. Eighteen of 23 snow-measurement sites in northern New England with at least 50 years of records had a significant decrease ($p < 0.1$) in late-winter snowpack depth or an increase in snowpack density (Hodgkins and Dudley, 2006a). Increased snowpack density over time for a set late-winter date indicates that the snow has become more ready to melt by that date.

The ratio of December through March snowfall to total precipitation decreased significantly ($p = 0.043$) for the average of four U.S. Historical Climatology Network (USHCN) stations in northern New England from 1949 to 2000. The year-to-year ratio of snowfall to total precipitation in northern New England was correlated with air temperature ($r = –0.45$, $p = 0.008$) and total snowfall ($r = 0.48$, $p = 0.0003$) but not with total precipitation ($r = –0.078$, $p = 0.59$; Huntington and others, 2004). This supports the idea that winter snow and runoff in New England have been more sensitive to air temperature changes than to changes in precipitation amount.

Huntington and others (2003) found a significant decrease over time ($p = 0.0021$) in average ice thickness around February 28 on the Piscataquis River in central Maine. The ice thinned about 9 in. (45 percent) from 1912 to 2001. On average, for the nine rivers in northern New England with the longest records, river-ice occurrence (total number of winter days with ice-affected flow) decreased significantly ($p = 0.0013$) from 1936 to 2000 (Hodgkins, Dudley, and Huntington, 2005a). Most of the 20-day change in the total days of ice occurred from the 1960s to 2000. Year-to-year river-ice occurrence was highly correlated with winter air temperature ($r = –0.70$, $p < 0.0001$) and less highly correlated with winter precipitation ($r = -0.52$, $p < 0.0001$). More days of river ice were associated with colder temperatures and lower precipitation (Hodgkins, Dudley, and Huntington, 2005a).

Winter-spring streamflows became earlier at many rivers in New England during the 20th century; significant trends were mostly in northern New England. Most of the 1- to 2-week change in northern New England occurred in the most recent three decades through 2002 (Dudley and Hodgkins, 2002; Hodgkins and others, 2003; Hodgkins and Dudley, 2006b). Winter-spring streamflow timing is based on the center-of-volume date—the date, each year, on which half of the winter-spring streamflow volume passes a streamflow-gaging station. Historical winter-spring streamflow timing for the Piscataquis River in central Maine is shown in figure 1.

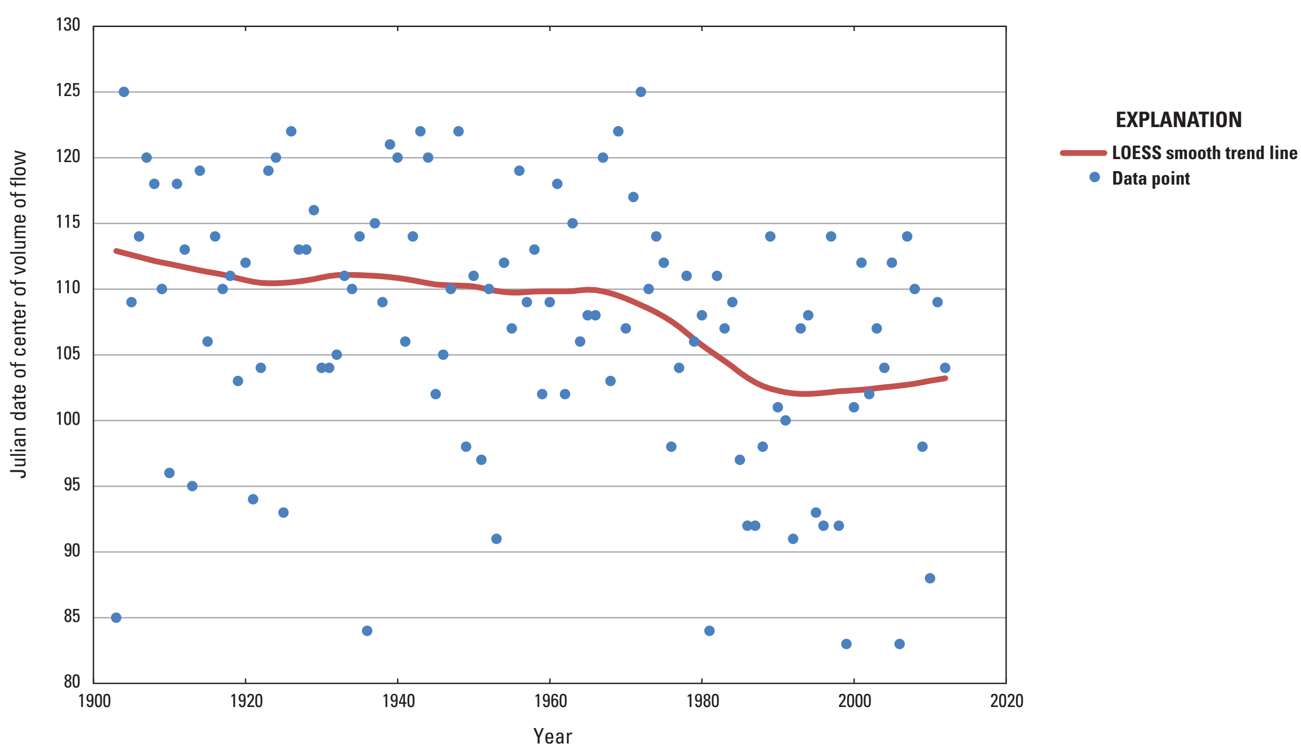

Figure 1. Historical winter-spring streamflow timing for the Piscataquis River in central Maine. The Julian date in is the sequential number of days in a year, with January 1 being day 1. (Julian date 90, for example, corresponds to March 31 in a nonleap year.) A local regression (LOESS) smoothing line is shown in red.

Year-to-year streamflow timing was highly correlated with March-through-April air temperature ($r = –0.72$, $p < 0.0001$; Hodgkins and others, 2003). Higher air temperatures were associated with earlier streamflows. The highest correlation coefficient between streamflow timing and precipitation was –0.37 ($p = 0.0018$) with January precipitation. May streamflows decreased significantly ($p < 0.1$) at 10 of 27 stations in New England; all of these decreases were in northern New England. Flows decreased 9 to 46 percent at the seven stations with the longest continuous records (Hodgkins and Dudley, 2005). No stations showed significant increases. Higher winter (December through March) precipitation is associated with higher April streamflows at many streamflow-gaging stations in northern and central New England (Hodgkins and others, 2012). This indicates that snowpack accumulation is an important mechanism for winter water storage and subsequently important for spring streamflows in this area. Higher March air temperatures are associated with lower April streamflows at many streamflow-gaging stations in central and southern New England, likely because the majority of snowmelt runoff occurs before April in warm years.

Dudley and Hodgkins (2013) documented increases in monthly groundwater levels in northern New England during the winter and spring during the past 30 years. The highest annual groundwater levels most commonly occur during spring or early summer (March through June), most frequently in April. April month-end levels correlate strongly with April mean streamflow and winter-spring runoff volume. While winter-spring streamflow timing in the Northeast has become earlier during the past century, this timing has not been observed to correlate with April groundwater levels or any other monthly groundwater levels (Dudley and Hodgkins, 2013).

On average, for the nine rivers in northern New England with the longest records, river-ice breakup dates (the annual last spring days of ice-affected flow) became significantly earlier ($p = 0.0037$) from 1936 to 2000. No appropriate river-ice data were available in southern New England. Most of the 11-day change in river-ice breakup in northern New England occurred from the 1960s to 2000 (Hodgkins, Dudley, and Huntington, 2005a). River-ice breakup was highly correlated with March-through-April air temperature ($r = –0.73$, $p < 0.0001$) and less highly correlated with precipitation (highest $r = –0.37$, $p = 0.0027$; Hodgkins, Dudley, and Huntington, 2005a).

Lake ice-out dates became significantly earlier at all five lakes in New England that had data from the mid-1800s to the early 2000s (Hodgkins and others, 2002; Benson and others, 2012; Hodgkins, 2013). Ice-out dates between 1859 and 2008 at representative lakes (Hodgkins and others, 2002), were 8.4 days earlier in northern/mountainous areas of northern New England and 13.5 days earlier in more southern areas of northern New England (Hodgkins, 2013). No long-term ice-out data are known from lakes in rural areas of southern New England. Historical ice-out dates for Damariscotta Lake in midcoastal Maine are shown in figure 2. The magnitude of trends over time depends on the length of the historical period considered. Lake ice-out dates during the last 50 years became earlier by 1.8 days per decade, based on the median change for all lakes with adequate data. This rate of change is much higher than those observed over longer historical periods; ice-outs became earlier by 0.6 days per decade during the last 75 years, 0.4 days per decade during the last 100 years, and 0.6 days per decade during the last 125 years (Hodgkins, 2013).

Summer and Fall

There is evidence of historical summer and fall hydrologic changes in New England. In summer, the lowest base flows increased from 1950 to 2006 at most streamflow-gaging stations in western New England (Hodgkins and Dudley, 2011). Many increases were greater than 20 percent, and some increases were greater than 50 percent in and near New Hampshire and Vermont. In contrast, some decreases were greater than 20 percent in the lowest base flows in northern and coastal areas of Maine. Summer air temperature in New England increased on average by 2.0 degrees Fahrenheit (°F) from 1950 to 2006 and may have played a role in the decreased base flows for streams in northern and coastal Maine by increasing evapotranspiration in areas with substantial wetlands and open-water bodies. Small decreases in precipitation in parts of this area may also have contributed to the base-flow decreases (Hodgkins and Dudley, 2011).

The timing and magnitude of low flows (which typically occur in the late summer and early fall in New England) are much more highly correlated with summer precipitation than with air temperature (Hodgkins, Dudley, and Huntington, 2005b). No strong relation was found between historical April streamflows and late-spring or summer streamflows in New England (Hodgkins and others, 2012). The lack of a strong relation implies that summer precipitation, rather than spring conditions, controls summer streamflows.

Dudley and Hodgkins (2013) documented increases in monthly groundwater levels in northern New England during the summer and fall during the past 30 years. The lowest groundwater levels most commonly occur during summer or fall (July through November), most frequently in September. September levels correlate strongly with August groundwater levels and August and September streamflows as well as with September base flow. Base flow from groundwater discharge typically supplies a large portion of streamflow during July, August, and September because of the relatively low amount of surface-water runoff in these months.

Summer stormflows increased from 1950 to 2006 by more than 50 percent at many stations in New England, particularly in and near New Hampshire and Vermont. Summer rainfall increased at most weather stations in New England from 1950 to 2006, with many increases of more than 20 percent in western New England (Hodgkins and Dudley, 2011).

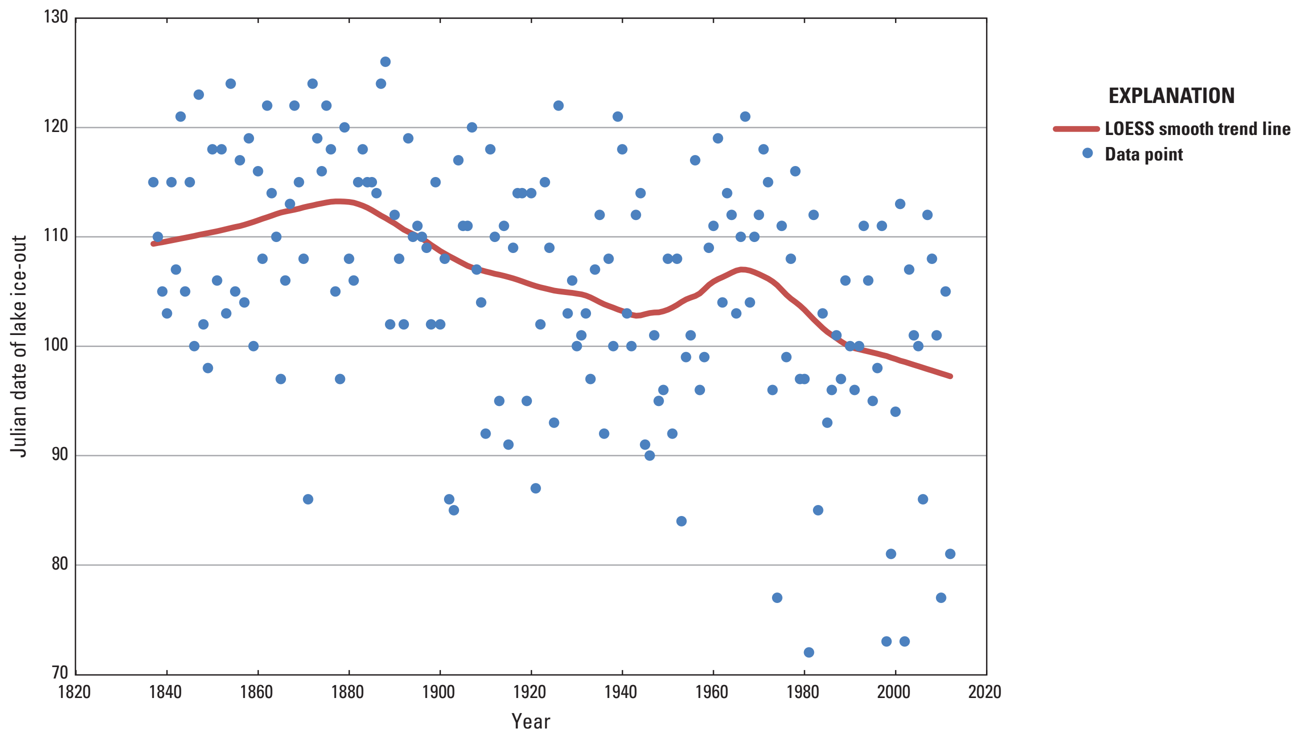

Figure 2. Historical ice-out dates for Damariscotta Lake in midcoastal Maine. The Julian date in is the sequential number of days in a year, with January 1 being day 1. A local regression (LOESS) smoothing line is shown in red.

Some consistent hydrologic changes during the fall in New England have been observed. Four of 16 rivers in northern New England had significantly later ($p < 0.1$) first fall days of river ice from the first half of the twentieth century to 2000; no rivers had significantly earlier first fall days of ice (Hodgkins, Dudley, and Huntington, 2005a). Some significant changes in the timing or magnitude of fall high flows have been found (Hodgkins and others, 2003; Dudley and Hodgkins, 2005; Hodgkins and Dudley, 2005). October streamflows significantly increased at five rivers in western New England through 2002; no rivers had significant decreases (Hodgkins and Dudley, 2005).

Drivers of Climate-Response Network Hydrologic Variables

Precipitation and (or) temperature variability typically drive the variability of hydrologic response. These meteorological drivers can differ by season. Organizing New England hydrologic climate-response variables by their important drivers increases understanding of which parts of the hydrologic cycle are expected to be affected by future temperature or precipitation change and whether the changes are expected to be caused by annual or seasonal changes (table 1).

Table 1. Annual and seasonal climatic drivers of hydrologic variability in New England.

[--, no variables included]

Climatic driver	Hydrologic climate-response variables		
	Annual	Winter and spring	Summer and fall
Temperature	Annual peak flow	Winter-spring runoff timing Lake ice-out dates	--
Precipitation	Annual peak flow	--	Groundwater levels Base-flow magnitude

Future Hydrologic Changes in New England

Output from recent modeling using multiple atmosphere-ocean general circulation models (GCMs) provides a range of climate projections for the northeastern United States. The GCMs were regionally downscaled and were forced with the low (B1), mid-high (A2), and high (A1FI) greenhouse-gas emission scenarios as described by Nakićenović and others (2000). Hayhoe and others (2007) used climate projections as input to the variable infiltration capacity (VIC) hydrologic model to simulate future hydrologic responses. Spring streamflow timing is expected to become earlier by 5 to 8 days, and annual 7-day low flows are expected to decrease by 1 to 4 percent between the periods 1961–90 and 2035–64 (Hayhoe and others, 2007). Projected low-flow changes by midcentury are small under the low- and mid-high-emissions scenarios; however, under the high-emissions scenario, larger decreases (11 percent) are projected by the period 2070–99. The number of short-term and long-term droughts (based on soil moisture deficits) is expected to increase by the period 2035–64. Total annual snow-water equivalent and the number of days with snow per month are expected to decrease. The central tendencies of general circulation model output indicate modest increases (about 10 percent) for New England annual precipitation and air temperature increases from about 1.8 to 5.4 °F (1 to 3 degrees Celsius [°C]) by the end of the century (Markstrom and others, 2012).

Cathance Stream Basin in Maine (Mastin and others, 2011; Dudley and others, 2012) and Pomperaug River Basin in Connecticut (Bjerklie and others, 2012) were 2 of 14 distributed-parameter Precipitation-Runoff Modeling System (PRMS) existing watershed models in the United States used to determine the sensitivity and potential effects of long-term climate change on freshwater resources across the United States (Markstrom and others, 2012). Regionally downscaled output from five GCMs and low (B1), medium (A1B), and mid-high (A2) greenhouse-gas emissions scenarios were used to estimate an ensemble of climate-change input scenarios for the basins. Projected increases in maximum and minimum daily air temperatures for all climate change scenarios for the 21st century result in projected decreases in the percentage of precipitation that falls as snow, snowpack water equivalent, and snowmelt. The projected changes in snowpack accumulation and melt would affect the seasonal amount and timing of streamflow. PRMS-modeled flows indicate that the projected changes in snowmelt timing will result in increases in streamflow for winter to early spring months (January through March) and decreases for spring months (April through June). The Cathance model indicates warmer winters will result in increased groundwater recharge during winter months (Pomperaug indicates future increases only for January) and decreases in recharge for all other times of the year. The Cathance and Pomperaug models indicate overall modest increases (about 10 percent) in precipitation over time, longer growing seasons, increases in evapotranspiration, and decreases in soil moisture (Markstrom and others, 2012).

Bjerklie and others (2011) estimated future changes in snowfall and groundwater recharge by using a regional watershed model for watersheds contributing to Long Island Sound, mostly from New England, including the Connecticut River Basin. GCM forecasted climate conditions were based on the B1 and A2 scenarios. Watershed model output for both scenarios for the end of the 21st century indicated increases in groundwater recharge over much of the region and substantial snowfall decreases across Massachusetts, Connecticut, southern Vermont, and southern New Hampshire relative to the beginning of the 21st century.

The USGS, in cooperation with the Maine Department of Transportation, studied changes in peak flows at four basins in coastal Maine on the basis of projected changes in air temperature and precipitation (Hodgkins and Dudley, 2013). The study used PRMS models to estimate future peak flows by way of a sensitivity analysis; a matrix of combinations that bracket probable future changes in precipitation and air temperature were applied to the historical meteorological input data for the models, and peak flows of specified annual exceedance probabilities (design flows) were computed from the PRMS model output for each basin. Air temperatures were adjusted by four different amounts, from –3.6 °F (–2 °C) to 10.8 °F (6 °C) of observed temperatures. Precipitation was adjusted by three different percentage values, from –15 percent to 30 percent of observed precipitation.

The study results indicated that increases in air temperature (with no changes in precipitation) lead to decreases in peak flows, a likely result of decreases in winter snowpack accumulation and thus decreases in snowmelt runoff. Increases in precipitation (with no changes in temperature) lead to increases in peak flows. For likely changes projected for the northeastern United States for the middle of the 21st century (combined temperature increase of 3.6 °F and precipitation increases of 0 to 15 percent), peak-flow changes at the four coastal Maine basins in this study were modeled to be evenly distributed between increases and decreases of less than 25 percent (Hodgkins and Dudley, 2013). Peak-flow increases caused by precipitation increases are largely balanced by peak-flow decreases caused by air temperature increases.

Potential Effects of Hydrologic Changes

Effects of climate change on hydrology could affect human water supply, hydroelectric power generation, transportation infrastructure, and stream and riparian ecology in the northeastern United States. Earlier snowmelt runoff could affect sensitive water systems by reducing water availability in the summer. Managers of storage reservoirs may need to modify operation schedules or increase reservoir storage earlier in the spring to allow for successful operation in a potentially longer summer low-flow season.

Changes in streamflow in the northeastern United States could also be important for other reasons; for example, increased winter flows can and have caused an increase in the frequency of midwinter ice jams (Beltaos, 2002). River ice jams can cause major flooding and damage river infrastructure. Ice jams played a major role in New England flooding in 1936 and 1991 (Grover, 1937; Wuebben and others, 1995).

Changes in the timing or magnitude of future streamflows will likely affect ecosystems. The ecological implications of changes in winter-spring streamflow timing in New England are not well understood. One possible effect is a greater challenge for the survival of Atlantic salmon. If the peak spring migration of juvenile salmon from freshwater rivers (which is controlled by photoperiod, temperature, and flow) becomes out of phase with optimal environmental conditions in rivers, estuaries, or the ocean, this could present a greater challenge to salmon survivability (McCormick and others, 1998). Changes in the timing of high spring flow and recession to summer low flows may be related to the observed altered timing of migration of Atlantic salmon (Huntington and others, 2003; Juanes and others, 2004).

Trends toward earlier snowmelt and increased summer evapotranspiration rates could shorten the annual periods of standing water used by amphibians for breeding in forested depressional wetlands (vernal pools; Brooks, 2009). Increases in summer evapotranspiration could decrease river base flows, which include surface water released naturally from storage in lakes, ponds, and wetlands (Hodgkins and Dudley, 2011). Lowered base flows could reduce available fish habitat during low-flow periods.

River ice causes many erosional and depositional features in river channels and on channel floodplains, especially in northern New England. Physical disturbances associated with ice-breakup scouring and flooding are important to nutrient and organic-matter dynamics, water chemistry, and the abundance and diversity of river biota (Prowse and Beltaos, 2002). The succession of riparian vegetation is directly linked to the scouring effects of ice (Prowse and Beltaos, 2002). River-ice breakup is likely to have important effects on primary producers, consumers, and food-web dynamics of river biota, although detailed information describing the magnitude of their effects is scarce (Scrimgeour and others, 1994). Mortality, emigration, or displacement of fishes at all life stages often results from severe ice conditions, through the actions of damming, scouring, associated flooding, or direct freezing (Power and others, 1993). Anchor ice, slush ice that adheres to streambeds, can have serious effects on fish eggs and embryos developing within gravel beds (Prowse, 1994). Anchor ice does not form when surface-ice cover is present, and therefore anchor ice could increase as surface-ice cover decreases.

Earlier lake ice-out dates are correlated with lower late-summer hypolimnion lake oxygen levels on the basis of limited data from northern New England (Hodgkins, 2013). Climatic warming has been shown in modeling studies to cause earlier lake ice-out dates, longer periods of summer stratification, and lower summer lake oxygen levels (Stefan and others, 1993; Elo and others, 1998). The lowering of hypolimnion oxygen levels could lead to enhancement of phosphorus release from sediments and increased lake eutrophication (Elo and others, 1998; Nõges and others, 2009). Trends toward earlier ice-outs and thus increased light availability, lake circulation, and water temperatures could lead to changes in spring and summer phytoplankton and zooplankton dynamics and benthic invertebrate abundance (Jassby and others, 1990; Porter and others, 1996; Blenckner, Omstedt, and Rummukainen, 2002; Blenckner, Pettersson, and Padisák, 2002).

In summary, historical climate-related seasonal hydrologic changes have been documented in New England in recent decades. Winter-spring hydrologic changes are related more to changes in air temperatures than to changes in precipitation; in contrast, summer-fall hydrologic changes are related more to changes in precipitation. Annual peak flows are affected by changes in both air temperature and precipitation. Future climatic changes will likely affect human infrastructure and stream ecology in New England.

Framework for a Hydrologic Climate-Response Network

The framework of a hydrologic climate-response network for New England has four major purposes:

- Identify specific hydrologic variables that are sensitive to climate change. This has been done in the "Climate and Hydrology of New England" section.
- Identify climate-response regions: geographic regions grouped by similar hydrologic responses.
- Propose a fixed-station monitoring network composed of existing streamflow, groundwater, lake ice, snowpack, and meteorological data-collection sites for evaluation of inland hydrologic response to climate variation.
- Establish basins for process-based studies and for estimates of future hydrologic conditions.

Climate-Response Regions

Hydrologic climate-response regions should have relatively homogeneous climates. New England's climate, as described in the "Climate and Hydrology of New England" section, is complex, with large north-to-south, coastal-to-inland, and sea-level-to-mountain-region gradients. New England would be divided into 14 regions (fig. 3, table 2) that follow major river-basin boundaries, have relatively homogeneous climates, and contain data-network sites with similar values or trends in key hydrologic variables. The 14 lower tier regions would be grouped into 4 upper tier regions according to similarities that are most evident at a coarse geographic scale. The upper tier regions would each be identified by a four-digit sequence, and the lower tier regions

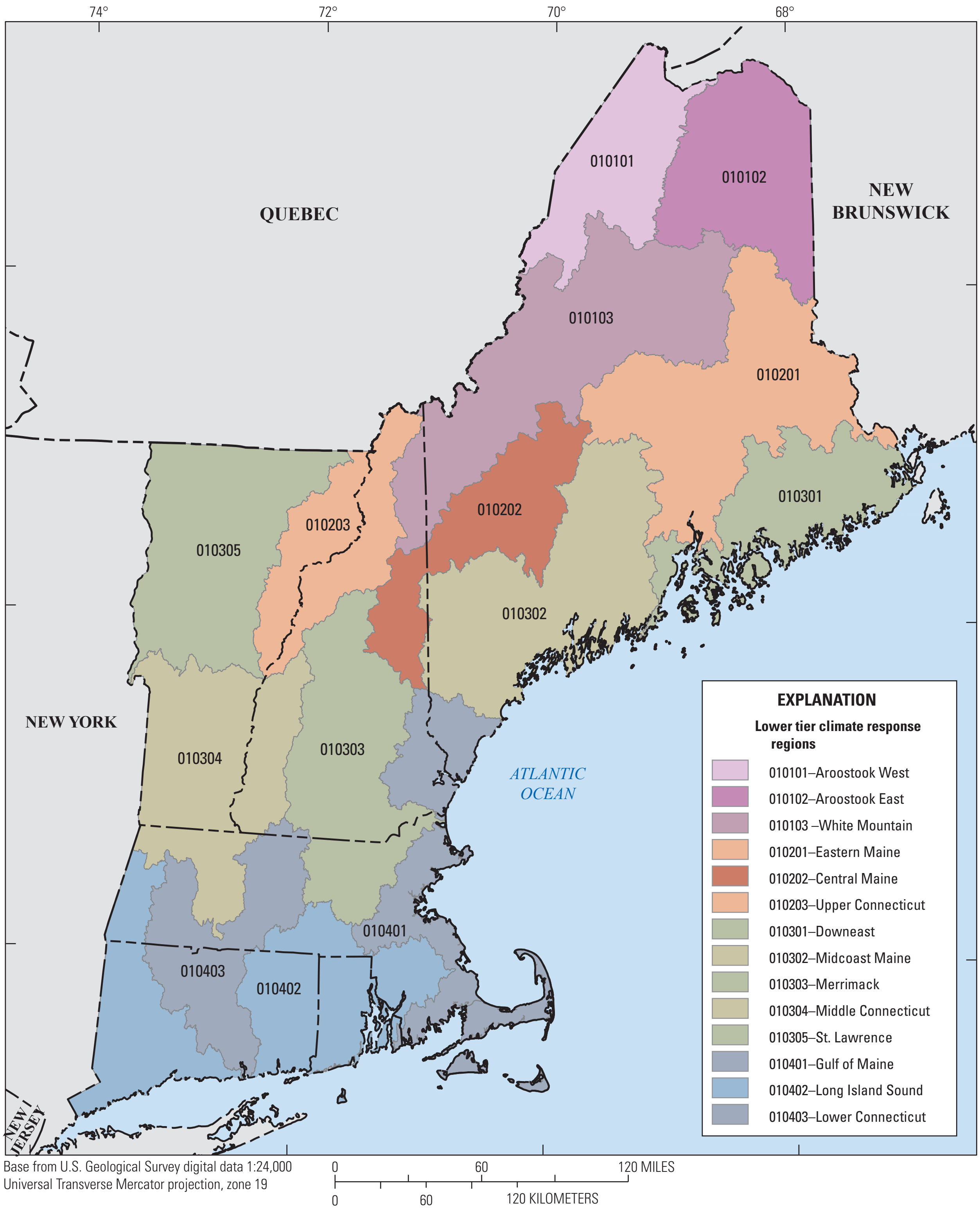

Figure 3. Hydrologic climate-response regions in New England.

Table 2. Description of hydrologic climate-response regions in New England.

[See figure 3 for climate-response region locations. CRR, climate-response region; St., Saint; NH, New Hampshire]

CRR number	CRR name	Description
010101	Aroostook West	Includes all of the American side of the St. John River Basin above the Fish River
010102	Aroostook East	Includes all of the American side of the St. John River Basin below the Fish River
010103	White Mountain	Includes the upper Penobscot, upper Kennebec, and upper Androscoggin River Basins
010201	Eastern Maine	Includes the lower Penobscot River Basin and the American side of the St. Croix River Basin
010202	Central Maine	Includes the middle Kennebec, middle Androscoggin, and upper Saco River Basins
010203	Upper Connecticut	Includes all but one New Hampshire and Vermont basins emptying into the Connecticut River above Lebanon, NH
010301	Downeast	Includes all small, coastal drainage basins in the Downeast area
010302	Midcoast Maine	Includes the lower Kennebec, lower Androscoggin, and lower Saco River Basins
010303	Merrimack	Includes all basins draining into the Gulf of Maine through the Merrimack River
010304	Middle Connecticut	Includes all basins in New Hampshire, Vermont, and Massachusetts emptying into the Connecticut River between Lebanon and the lower Massachusetts border
010305	St. Lawrence	Includes all basins in Vermont emptying into the St. Lawrence River or Hudson River drainages, as well as one emptying into Canada
010401	Gulf of Maine	Includes all basins in New Hampshire and Vermont that empty into the Gulf of Maine except that of the Merrimack River
010402	Long Island Sound	Includes all drainages in Massachusetts, Connecticut, and Rhode Island basins that empty into Long Island Sound except those of the Connecticut River
010403	Lower Connecticut	Includes all Massachusetts and Connecticut basins emptying into the Connecticut River below the lower Massachusetts border

would be designated by the four-digit identifier of their parent higher tier region, followed by a two-digit suffix. Smoothed plots of winter-spring streamflow timing (fig. 4) and historical lake ice-out dates (fig. 5) in New England show that individual lakes and streams, for these variables, generally group well by upper tier climate-response region, particularly for winter-spring streamflow timing.

Major river-basin boundaries were followed for hydrologic climate-response-region boundaries. The current proposed configuration of the climate-response regions is optimized to best fit the spatial patterns in key hydrologic variables that have already been identified, but results of additional analyses of hydrologic variations could inform changes to the boundaries and (or) number of hydrologic climate-response regions in the future.

Primary Components and Associated Key Variables of a Hydrologic Climate-Response Network

Establishing a hydrologic climate-response network includes the identification of hydrologic components that include the major fluxes (such as streamflow) and storage compartments (such as groundwater storage) of the regional water cycle. Each component has one or more key variables that can be feasibly measured at data-collection sites. For example, streamflow has been identified as a component, with a key variable of streamflow being winter-spring streamflow timing. The key variables of components discussed in this section have been demonstrated to be responsive to climate change or are expected to be responsive to it in the next few decades, and are important for human water use or ecosystem function.

Three criteria were used to identify key variables to be included in a hydrologic climate-response data network: the existence of long-term historical data, the expectation that a variable will be responsive to changes in precipitation and (or) air temperature during the next few decades, and the human or ecological importance of the component variables. Long-term historical data allow a more complete perspective on future climate-related changes than short-term data because past decadal variability and longer term changes are better known. The "Climate and Hydrology of New England" section of this report lists known historical changes for variables of several hydrologic components and the known importance of these variables for humans and ecosystems. Many variables can be used to describe some of the components in a hydrologic climate-response data network. For example, streamflow variables could include annual peak flows, March mean flows, or many other measures. On the basis of extensive past work, some variables are more likely than others to be responsive to

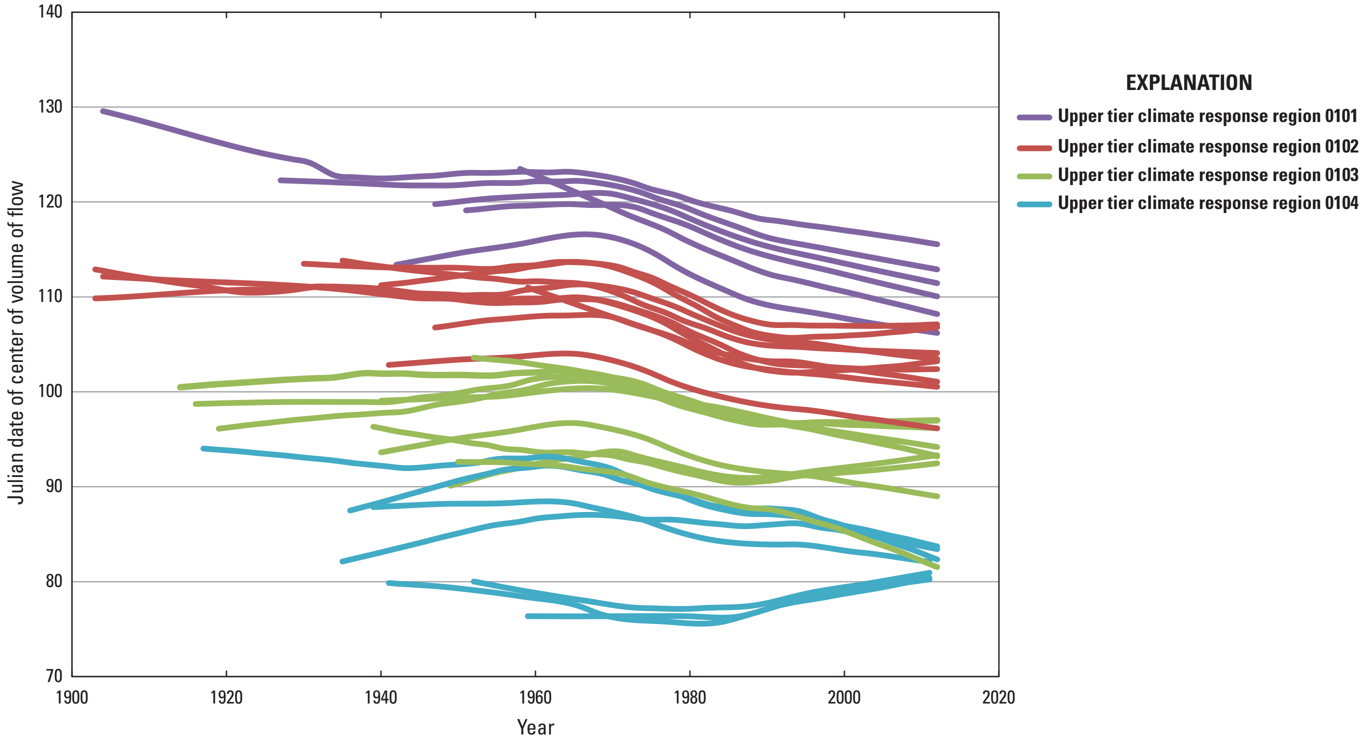

Figure 4. Winter-spring streamflow timing for streams in New England.

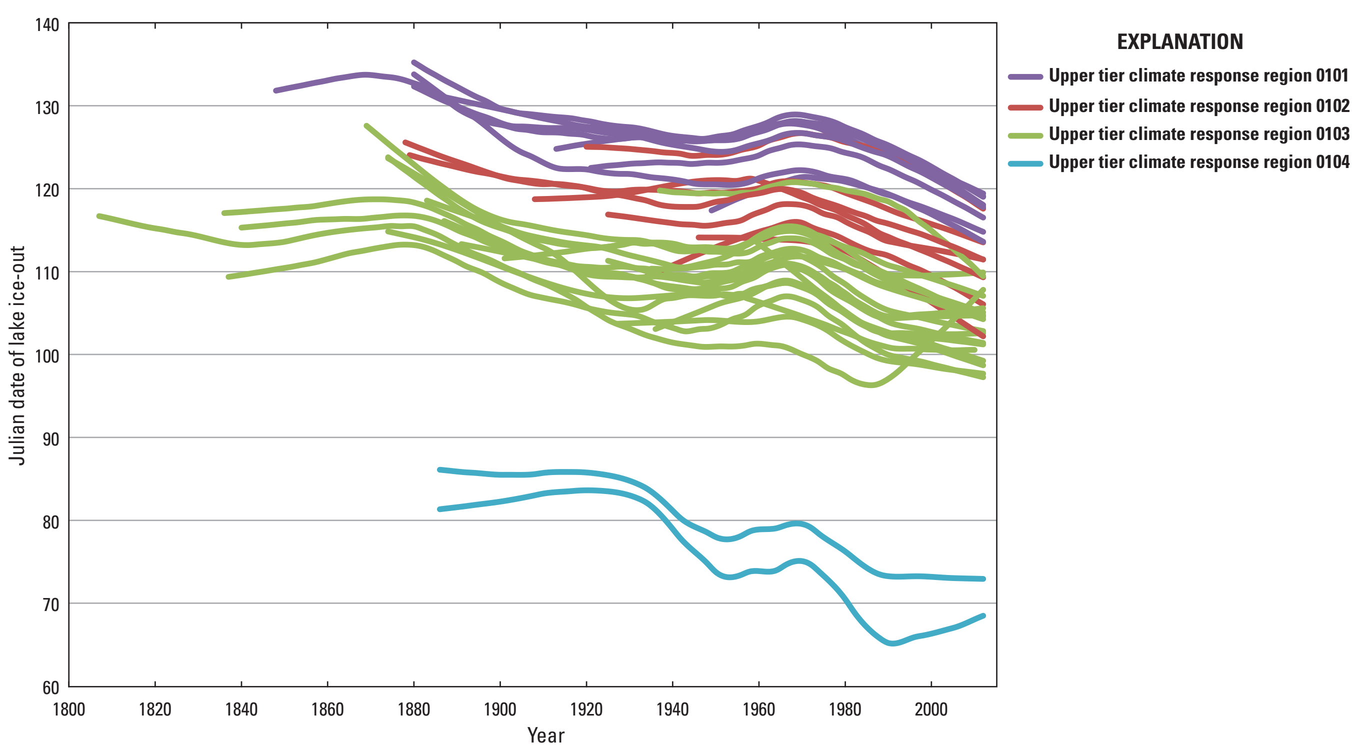

Figure 5. Historical lake ice-out dates in New England.

changes in precipitation and (or) air temperature (see "Climate and Hydrology of New England" section). Components proposed for inclusion in a hydrologic climate-response data network have at least one key variable with extensive historical data at multiple sites: streamflow, groundwater, lake ice, snowpack, and meteorological data. Other hydrologic components, such as water quality, are important to humans and (or) ecosystems but lack variables with extensive historical data. Key variables of primary components are listed in the following sections; additional components and (or) variables could be added as part of a larger network.

Streamflow

For the streamflow component, two key variables are proposed: winter-spring streamflow timing and the magnitude of the annual peak flow. Winter-spring streamflow timing is measured by the winter-spring center-of-volume (WSCV) date (Dudley and Hodgkins, 2002; Hodgkins and others, 2003; Hodgkins and Dudley, 2006b). The WSCV is a robust measure of streamflow timing. To compute the WSCV date, daily flow volumes from the start to the end of the annual winter-spring season are summed. The WSCV date is the date, in counting from the start of the season, by which half of the volume flows by a streamflow-gaging station. Another key variable derived from streamflow data—the magnitude of summer base flows—is discussed in the "Groundwater" section.

The USGS has been measuring and recording daily streamflow at some sites in New England for more than a century. More than 50 years of streamflow data are available for many rural, unregulated streams through the USGS National Water Information System (http://waterdata.usgs.gov/usa/nwis/sw). The streamflow data at these sites have been collected by the USGS using consistent, well-documented, high-quality methods (Corbett and others, 1943; Rantz and others, 1982). Therefore, historical changes in the data can be determined with confidence.

Streamflow data proposed for New England are from USGS streamflow-gaging stations that have streamflows which are minimally affected by direct human watershed changes such as reservoir regulation and urbanization. The streamflow-gaging stations come from the Hydro-Climatic Data Network 2009 (HCDN–2009) subset of the USGS Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES II), dataset (Falcone, 2011; Lins, 2012). The HCDN–2009 designation in GAGES II provides a determination of watersheds for potential study of climate-related streamflow trends; these watersheds represent hydrologic conditions least disturbed by human influences (relative to other watersheds within 12 major ecoregions in the United States) and have at least 20 years of complete and continuous data through 2009.

In some cases, stations that do not meet all of the criteria used for the HCDN–2009 network were added to the New England climate-response network. Some of the HCDN–2009 criteria were related to water-quality criteria, and stations with Canadian drainage were not included because of the lack of basin data consistent with United States data. Active stations were added if they have had no known regular alteration of natural daily mean streamflow (high and low flows) from streamflow regulation, flow diversion or augmentation, surface-water or groundwater withdrawals, or known substantial changes in basin land use such as urbanization. Some stations with short records were added if they met this criteria and filled in gaps in spatial coverage or were important for specific reasons—for example, basins that contain important resources such as Atlantic salmon habitat and (or) Native American or U.S. Department of Interior or Agriculture lands.

Active stations in New England with 80-percent data completeness for each decade from 1960 to 2012 (11 of 13 years for 2000 to 2012) would be used to examine long-term changes in streamflow variables. Thirty-one streamflow-gaging stations in New England met the criteria for minimal disturbance and long-term completeness (fig. 6; table 3). Another 30 stations in New England met the criteria for minimal disturbance and have shorter or less complete records; these stations are included in the network for short-term trend analysis (at least 30 years) and observation (less than 30 years) but are not used for long-term analysis until the criteria for long-term stations is met. It may be desirable for certain analyses to exclude nested watersheds in New England that have substantial shared watershed area. On the basis of minimally disturbed criteria, early years of data at two stations in Maine (Carrabassett River near North Anson prior to 1931 and Little Androscoggin River near South Paris prior to 1924) are not appropriate for inclusion in low-flow analyses, nor are data for a few days with unusual regulation at one station in Maine (Narraguagus River at Cherryfield in 1978 and 1985). Although the majority of the streamflow-gaging stations proposed for the network (fig. 6) are in the three northern New England states, efforts are being made by the USGS in southern New England, in partnership with cooperating agencies, to initiate or reactivate additional streamflow-gaging stations in minimally altered basins for eventual inclusion in the hydrologic climate-response network.

Groundwater

Groundwater is an important source of domestic water in northern New England, where more than 60 percent of domestic water comes from groundwater and 40 percent of the population is self-supplied by private wells (Kenny and others, 2009). Groundwater-level data have been collected by the USGS in New England for several decades; levels directly measure the availability of groundwater for human use and aquatic ecosystems. In general, the records are not as long or complete as those of streamflow. Historical groundwater records often exhibit monthly or longer sampling frequencies with fragmentary periods of record. As a consequence, it is challenging to meet record-completeness criteria necessary for long-term trend testing.

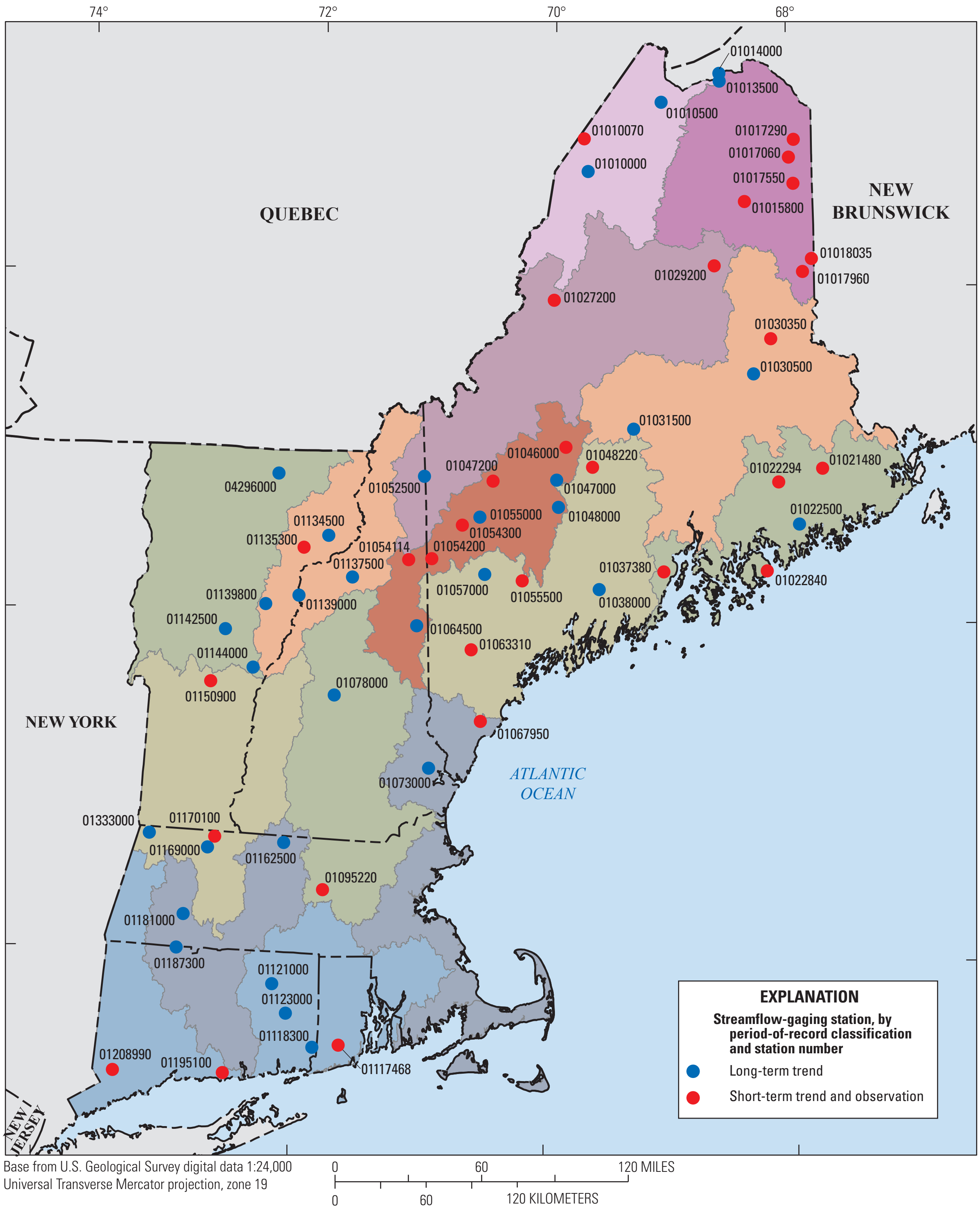

Figure 6. Streamflow-gaging stations in New England that drain relatively natural watersheds. Streamflow-gaging stations have at least 50 years of records for long-term trend testing, at least 30 years for short-term trend testing, and fewer than 30 years for observations. See figure 3 for climate-response regions by color.

Table 3. Streamflow-gaging stations in New England that drain relatively natural watersheds.

[See figure 6 for station locations. Green fill highlights "True" values. mi², square miles; ft, feet; HCDN-2009, Hydro-Climatic Data Network 2009; ME, Maine; NH, New Hampshire; MA, Massachusetts; RI, Rhode Island; CT, Connecticut; VT, Vermont]

Station number	Station name	Drainage area (mi²)	Elevation (ft)	HCDN-2009	Meets criteria of record length and completeness			
					30-year	50-year	70-year	90-year
01010000	St. John River at Ninemile Bridge, ME	1,341	931	No	True	True	False	False
01010070	Big Black River near Depot Mountain, ME	171	885	No	False	False	False	False
01010500	St. John River at Dickey, ME	2,680	590	No	True	True	False	False
01013500	Fish River near Fort Kent, ME	873	511	Yes	True	True	True	False
01014000	St. John River below Fish River at Fort Kent, ME	5,929	476	No	True	True	True	False
01015800	Aroostook River near Masardis, ME	892	530	No	True	True	False	False
01017060	Hardwood Brook below Glidden Brook near Caribou, ME	5.7	480	No	False	False	False	False
01017290	Little Madawaska River at Caribou, ME	234	420	No	False	False	False	False
01017550	Williams Brook at Phair, ME	3.82	580	No	False	False	False	False
01017960	Meduxnekeag River above South Branch Meduxnekeag River near Houlton, ME	88	355	No	False	False	False	False
01018035	Meduxnekeag River at Lowery Road near Houlton, ME	257	290	No	False	False	False	False
01021480	Old Stream near Wesley, ME	29.1	170	No	False	False	False	False
01022294	East Branch Bear Brook near Beddington, ME	0.042	907	No	False	False	False	False
01022500	Narraguagus River at Cherryfield, ME	227	44	Yes	True	True	False	False
01022840	Otter Creek near Bar Harbor, ME	1.35	90	No	False	False	False	False
01027200	North Branch Penobscot River near Pittston Farm, ME	232	1,086	No	False	False	False	False
01029200	Seboeis River near Shin Pond, ME	173	512	No	False	False	False	False
01030350	Wytopitlock Stream near Wytopitlock, ME	48.8	395	No	False	False	False	False
01030500	Mattawamkeag River near Mattawamkeag, ME	1,418	217	Yes	True	True	True	False
01031500	Piscataquis River near Dover-Foxcroft, ME	298	358	Yes	True	True	True	True
01037380	Ducktrap River near Lincolnville, ME	14.4	135	No	False	False	False	False
01038000	Sheepscot River at North Whitefield, ME	145	101	No	True	True	True	False
01046000	Austin Stream at Bingham, ME	90	350	No	False	False	False	False
01047000	Carrabassett River near North Anson, ME	353	303	Yes	True	True	True	False
01047200	Sandy River near Madrid, ME	25.3	930	No	False	False	False	False
01048000	Sandy River near Mercer, ME	516	197	No	False	False	False	False
01048220	East Branch Wesserunsett Stream near Athens, ME	19.5	500	No	False	False	False	False
01052500	Diamond River near Wentworth Location, NH	152	1,259	Yes	True	True	True	False
01054114	Peabody River at Gorham, NH	46.3	794	No	False	False	False	False
01054200	Wild River at Gilead, ME	69.6	683	Yes	True	False	False	False
01054300	Ellis River at South Andover, ME	130	620	No	False	False	False	False
01055000	Swift River near Roxbury, ME	96.9	616	Yes	True	True	True	False
01055500	Nezinscot River at Turner Center, ME	169	276	No	False	False	False	False
01057000	Little Androscoggin River near South Paris, ME	73.5	447	Yes	True	True	True	False
01063310	Stony Brook at East Sebago, ME	0.81	275	No	False	False	False	False
01064500	Saco River near Conway, NH	385	418	No	True	True	True	False
01067950	Kennebunk River near Kennebunk, ME	26.7	70	No	False	False	False	False
01073000	Oyster River near Durham, NH	12.1	65	Yes	True	True	True	False
01078000	Smith River near Bristol, NH	85.8	450	Yes	True	True	True	True

Table 3. Streamflow-gaging stations in New England that drain relatively natural watersheds.—Continued

[See figure 6 for station locations. Green fill highlights "True" values. mi², square miles; ft, feet; HCDN-2009, Hydro-Climatic Data Network 2009; ME, Maine; NH, New Hampshire; MA, Massachusetts; RI, Rhode Island; CT, Connecticut; VT, Vermont]

Station number	Station name	Drainage area (mi²)	Elevation (ft)	HCDN-2009	Meets criteria of record length and completeness			
					30-year	50-year	70-year	90-year
01095220	Stillwater River near Sterling, MA	29.1	400	No	False	False	False	False
01117468	Beaver River near Usquepaug, RI	8.87	108	Yes	True	False	False	False
01118300	Pendleton Hill Brook near Clarks Falls, CT	4.02	153	Yes	True	True	False	False
01121000	Mount Hope River near Warrenville, CT	28.6	336	Yes	True	True	True	False
01123000	Little River near Hanover, CT	30	221	Yes	True	True	False	False
01135300	Sleepers River (Site W-5) near St. Johnsbury, VT	42.9	642	No	False	False	False	False
01134500	Moose River at Victory, VT	75.2	1,104	Yes	True	True	False	False
01137500	Ammonoosuc River at Bethlehem Junction, NH	87.6	1,181	Yes	True	True	True	False
01139000	Wells River at Wells River, VT	98.4	506	Yes	True	True	True	False
01139800	East Orange Branch at East Orange, VT	8.95	1,180	Yes	True	True	False	False
01142500	Ayers Brook at Randolph, VT	30.5	630	Yes	True	True	True	False
01144000	White River at West Hartford, VT	690	375	Yes	True	True	True	True
01150900	Ottauquechee River near West Bridgewater, VT	23.4	1,149	Yes	False	False	False	False
01162500	Priest Brook near Winchendon, MA	19.4	850	Yes	True	True	True	True
01169000	North River at Shattuckville, MA	89	458	Yes	True	True	True	False
01170100	Green River near Colrain, MA	41.4	435	Yes	True	False	False	False
01181000	West Branch Westfield River at Huntington, MA	94	389	Yes	True	True	True	False
01187300	Hubbard River near West Hartland, CT	19.9	595	Yes	True	True	True	False
01195100	Indian River near Clinton, CT	5.68	35	Yes	True	False	False	False
01208990	Saugatuck River near Redding, CT	21	285	Yes	True	False	False	False
01333000	Green River at Williamstown, MA	42.6	615	Yes	True	True	False	False
04296000	Black River at Coventry, VT	122	710	Yes	True	True	False	False

A recent USGS study of groundwater-level trends in northern New England (Dudley and Hodgkins, 2013) identified wells in Maine, New Hampshire, and Vermont that are minimally affected by human disturbance and thus suitable for a climate-response network. Screening criteria involved the review of well data (time-series plots) and analysis summaries published in annual USGS State Water-Data Reports for non-climate-related effects such as substantial water-use withdrawals or proximity to regulated surface-water bodies. Local USGS groundwater hydrologists were also consulted on the appropriateness of wells. Wells with levels deemed not to be predominantly natural were excluded. In a few cases, clusters of unaffected wells were built close to each other in the same aquifer and had highly correlated ($R^2 > 0.80$) records; in these cases only the well with the longest and most complete record was included. Using a criterion of a minimum of 10 years of data (which could be nonconsecutive), Dudley and Hodgkins (2013) identified 77 wells in northern New England that would be suitable for a climate-response network. For the current report, USGS groundwater specialists in southern New England went through a similar process to identify appropriate wells. For New England groundwater wells, a completeness criterion of 80 percent per decade yields 70 and 12 wells appropriate for short-term (30-year) and long-term (50-year) trend testing, respectively (fig. 7; table 4).

Dudley and Hodgkins (2013) examined correlations of groundwater levels with precipitation and streamflow data and found that groundwater levels in May through August correlate strongly with annual (water year) streamflow (fig. 8, for example, from Dudley and Hodgkins, 2013); correlations of groundwater levels with monthly precipitation are less frequent and weaker. Correlations of groundwater levels with streamflow data suggest methods for leveraging the richness of historical streamflow data to extend the record of historical groundwater levels.

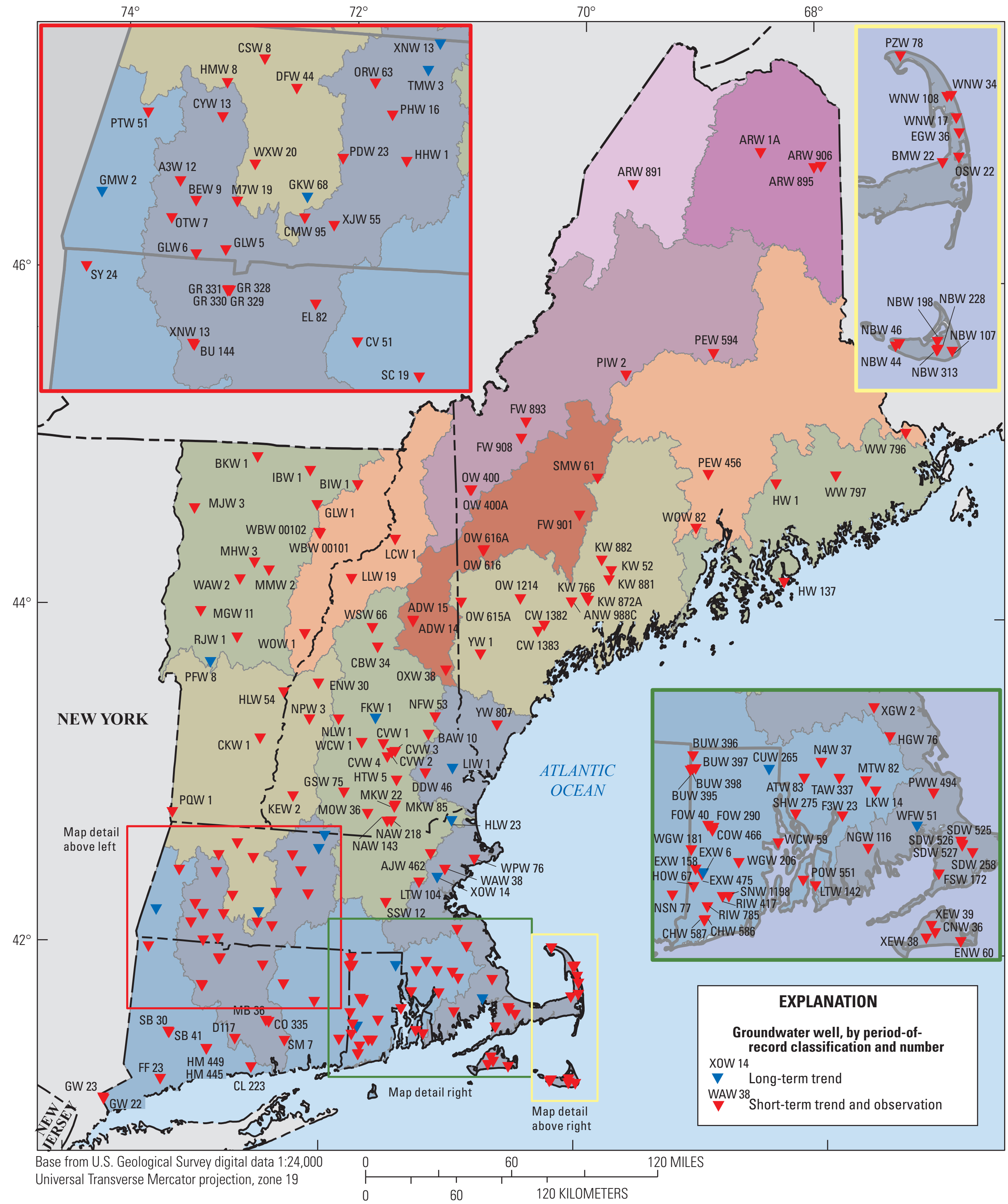

Figure 7. Groundwater wells in New England minimally affected by human disturbance. Wells have at least 50 years of records for long-term trend testing, at least 30 years for short-term trend testing, and fewer than 30 years for observations. See figure 3 for climate-response regions by color.

Table 4. Groundwater wells in northern New England that meet climate-network criteria.

[See figure 7 for well locations. Years of record, number of years (through water year 2013) when at least one datum point is present. Green fill highlights “TRUE” values. CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; RI, Rhode Island; VT, Vermont]

Well number	Well name	Years of record	Meets record completeness and length criteria	
			30-year	50-year
414704072580501	CT BU143	18	False	False
414649072574401	CT BU144	17	False	False
411832072325501	CT CL223	22	False	False
413457072252201	CT CO335	28	False	False
414833072190301	CT CV51	21	False	False
412825072410501	CT D117	28	False	False
415458072291901	CT EL82	21	False	False
411256073153101	CT FF23	48	True	False
415649072494801	CT GR328	31	False	False
415647072495901	CT GR329	30	False	False
415643072502201	CT GR330	30	False	False
415653072501701	CT GR331	23	False	False
410443073414101	CT GW22	12	False	False
410515073415901	CT GW23	12	False	False
412423072542801	CT HM445	22	False	False
412417072541901	CT HM449	21	False	False
413518072264501	CT MB36	21	False	False
412931071514201	CT NSN77	22	False	False
412954073125201	CT SB30	23	False	False
412935073122701	CT SB41	22	False	False
414243072040501	CT SC19	28	False	False
412824072173301	CT SM7	35	True	False
415956073241501	CT SY24	27	False	False
421550073025101	MA A3W12	28	False	False
423641071102501	MA AJW462	37	True	False
415447071155301	MA ATW83	50	True	False
421228072585301	MA BEW9	28	False	False
414630070014901	MA BMW22	51	True	False
421012072324501	MA CMW95	31	False	False
412154070404701	MA CNW36	22	False	False
423809072435601	MA CSW8	49	True	False
422733072532601	MA CYW13	28	False	False
423310072355801	MA DFW44	49	True	False
415125069581501	MA EGW36	39	True	False
412118070311001	MA ENW60	24	False	False
414705071045301	MA F3W23	50	True	False
413522070373601	MA FSW172	39	False	False
421355072322001	MA GKW68	60	True	True
420357072511601	MA GLW5	49	True	False
420259072581701	MA GLW6	49	True	False
421316073212801	MA GMW2	63	True	True
420353070520301	MA HGW76	50	True	False
422058072085501	MA HHW1	49	True	False
424841071004101	MA HLW23	54	True	True
423339072524101	MA HMW8	28	False	False
415228070554601	MA LKW14	50	True	False
422627071154002	MA LTW104	49	True	False
421240072490201	MA M7W19	28	False	False
415433070583302	MA MTW82	49	True	False
415812071111101	MA N4W37	50	True	False
411536069591301	MA NBW107	32	False	False
411712070022801	MA NBW198	33	False	False
411555070021901	MA NBW228	38	True	False
411542070023303	MA NBW313	32	False	False
411620070113201	MA NBW44	32	False	False
411645070104401	MA NBW46	35	True	False
414025070572801	MA NGW116	50	True	False
423441072170701	MA ORW63	29	False	False
414726069581601	MA OSW22	39	True	False
420912073043001	MA OTW7	49	True	False
422103072241102	MA PDW23	32	True	False
422103072241103	MA PDW24	31	False	False
422906072124301	MA PHW16	30	False	False
422745073112001	MA PTW51	51	True	False
415217070393102	MA PWW494	28	False	False
420355070112302	MA PZW78	39	True	False
413958070281801	MA SDW258	39	True	False
414219070313601	MA SDW525	12	False	False
414139070311501	MA SDW526	12	False	False
414124070311401	MA SDW527	12	False	False
414714071175901	MA SHW275	50	True	False
421851071312601	MA SSW12	25	False	False
415457071060101	MA TAW337	50	True	False
423717072043101	MA TMW3	56	True	True
423115071032001	MA WAW38	49	True	False
414518070435701	MA WFW51	55	True	True
415732070000401	MA WNW108	36	True	False
415353069585401	MA WNW17	51	True	False
415722070010001	MA WNW34	39	True	False
423505070491702	MA WPW76	49	True	False

Table 4. Groundwater wells in northern New England that meet climate-network criteria.—Continued

[See figure 7 for well locations. Years of record, number of years (through water year 2013) when at least one datum point is present. Green fill highlights "TRUE" values. CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; RI, Rhode Island; VT, Vermont]

Well number	Well name	Years of record	Meets record completeness and length criteria	
			30-year	50-year
421923072451001	MA WXW20	27	False	False
412304070382001	MA XEW38	22	False	False
412434070392601	MA XEW39	22	False	False
420954070564501	MA XGW2	49	True	False
420905072254001	MA XJW55	49	True	False
424204072015201	MA XNW13	74	True	True
424752071315202	MA XNW13	27	False	False
424800071295301	MA XNW13	50	True	False
424810073160401	MA XNW13	49	True	False
422819071065701	MA XOW14	74	True	True
440730070035304	ME ANW988C	14	False	False
464807068284401	ME ARW1A	15	False	False
463642069344601	ME ARW891	26	False	False
464234068010401	ME ARW895	15	False	False
464259067572901	ME ARW906	25	False	False
435902070171301	ME CW1382	11	False	False
435653070201801	ME CW1383	11	False	False
451128070280301	ME FW893	15	False	False
443831070002601	ME FW901	14	False	False
450539070301301	ME FW908	12	False	False
444950068220601	ME HW1	16	False	False
441440068182701	ME HW137	20	False	False
441849069442001	ME KW52	45	False	False
440918069564001	ME KW766	37	True	False
440810069553601	ME KW872A	35	True	False
441533069452401	ME KW881	13	False	False
442233069490701	ME KW882	11	False	False
440823070291501	ME OW1214	34	True	False
444637070552301	ME OW400	52	False	False
443647070552302	ME OW400A	24	False	False
440642070583402	ME OW615A	11	False	False
442515070481001	ME OW616	14	False	False
442515070481002	ME OW616A	11	False	False
445319068560101	ME PEW456	36	True	False
453629068531801	ME PEW594	21	False	False
452829069322101	ME PIW2	13	False	False
445148069513301	ME SMW61	24	False	False
443407069020901	ME WOW82	11	False	False
450713067162801	ME WW796	34	True	False
445227067520101	ME WW797	28	False	False

Table 4. Groundwater wells in northern New England that meet climate-network criteria.—Continued

[See figure 7 for well locations. Years of record, number of years (through water year 2013) when at least one datum point is present. Green fill highlights "TRUE" values. CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; RI, Rhode Island; VT, Vermont]

Well number	Well name	Years of record	Meets record completeness and length criteria	
			30-year	50-year
434822070482501	ME YW1	23	False	False
432310070393301	ME YW807	26	False	False
435948071220301	NH ADW14	19	False	False
435948071220302	NH ADW15	20	False	False
431916071125901	NH BAW10	18	False	False
434952071390901	NH CBW34	21	False	False
431526071345501	NH CVW1	26	False	False
431224071303601	NH CVW2	50	True	False
431248071290201	NH CVW3	22	False	False
431049071324301	NH CVW4	47	True	False
430527071140101	NH DDW46	22	False	False
433616072074001	NH ENW30	20	False	False
432428071390701	NH FKW1	47	True	False
425744071532001	NH GSW75	19	False	False
430235071275501	NH HTW5	49	True	False
425543072175801	NH KEW2	51	True	False
442830071321001	NH LCW1	47	True	False
430721071005001	NH LIW1	58	True	True
441401071531501	NH LLW19	21	False	False
425303071283701	NH MKW22	28	False	False
425339071281501	NH MKW85	17	False	False
425024071413001	NH MOW36	48	False	False
432534071095601	NH NFW53	22	False	False
432343071570901	NH NLW1	66	True	True
432322072112401	NH NPW3	20	False	False
434221071051501	NH OXW38	20	False	False
431540071452801	NH WCW1	48	True	False
435645071420520	NH WSW66	19	False	False
415546071474701	RI BUW395	22	False	False
415847071471401	RI BUW396	22	False	False
415606071462201	RI BUW397	21	False	False
415559071471201	RI BUW398	21	False	False
412434071422401	RI CHW586	22	False	False
412424071423601	RI CHW587	21	False	False
414315071410701	RI COW466	22	False	False
415626071254601	RI CUW265	68	True	True
413505071452801	RI EXW158	30	False	False
413358071433801	RI EXW475	33	True	False
413423071431901	RI EXW6	66	True	True
414357071405101	RI FOW290	22	False	False

Table 4. Groundwater wells in northern New England that meet climate-network criteria.—Continued

[See figure 7 for well locations. Years of record, number of years (through water year 2013) when at least one datum point is present. Green fill highlights "TRUE" values. CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; RI, Rhode Island; VT, Vermont]

Well number	Well name	Years of record	Meets record completeness and length criteria	
			30-year	50-year
414420071422301	RI FOW40	30	False	False
413126071455501	RI HOW67	30	False	False
413220071115501	RI LTW142	21	False	False
413325071152401	RI POW551	22	False	False
412932071374302	RI RIW417	38	True	False
412718071415201	RI RIW785	24	False	False
412935071355701	RI SNW1198	21	False	False
414106071223901	RI WCW59	31	False	False
413907071465001	RI WGW181	46	True	False
413645071332901	RI WGW206	31	False	False
444731071514701	VT BIW1	47	True	False
445603072422901	VT BKW1	42	False	False
431551072350601	VT CKW1	47	True	False
443952072114001	VT GLW1	46	True	False
433240072242901	VT HLW54	44	True	False
445158072155001	VT IBW1	13	False	False
440016073070901	VT MGW11	33	True	False
441829072413901	VT MHW3	25	False	False
443646073124901	VT MJW3	52	False	False
441552072341901	VT MMW2	29	False	False
434217073010601	VT PFW8	55	True	True
435129072483301	VT RJW1	42	False	False
441215072483101	VT WAW2	35	False	False
442939072093701	VT WBW00101	18	False	False
442939072093702	VT WBW00102	18	False	False
435343072151801	VT WOW1	46	True	False

Key variables for a groundwater network include the annual highest and lowest levels. The annual maximum groundwater level (most common in April) is a measure of recharge to the groundwater system and correlates strongly with April mean streamflow and winter-spring runoff volume (WSV); April mean streamflow and WSV are measures of water available for aquifer recharge in the spring from snowpack melt and rain. Dudley and Hodgkins (2013) used monthly data and did not observe a correlation between winter-spring runoff timing (WSCV date) and annual peak groundwater level. However, it is possible that analysis of groundwater-level data with a finer temporal resolution (for example, daily data) would show that the timing of the annual peak groundwater level correlates with the winter-spring runoff timing.

During the lowest groundwater conditions of the year, municipalities, individuals, and industries can encounter groundwater-supply challenges. The annual minimum groundwater level (most common in September) correlates strongly with August levels and August and September streamflows as well as with September base flow (Dudley and Hodgkins, 2013). These are all related metrics, as base flow from groundwater discharge typically composes a large portion of streamflow during July, August, and September.

The base-flow component of streamflow comes from groundwater and other delayed sources. Base flow is important to fish and other aquatic species. The USGS streamflow-gaging stations identified for potential inclusion in a hydrologic climate-response data network and appropriate for the analysis of low flows (table 3) would be appropriate to use as input to an automated technique, such as HYSEP (Sloto and Crouse, 1996), for separating base flow from total streamflow.

Lake Ice

The key historical measure of lake ice (and the only commonly available measure of lake ice in New England) is lake ice-out date—the annual date in spring when winter ice cover leaves a lake (Hodgkins and others, 2002; Hodgkins, 2013). This is normally defined as the date at which substantial ice is no longer visible for a lake or the date at which a boat can traverse between set points. In Northern Hemisphere mid-latitude areas such as New England, ice-out dates can serve as useful indicators of late-winter and early-spring climate change. A remarkable amount of lake ice-out data has been recorded and saved in New England during the past two centuries, mostly in northern New England. Lake ice-out dates for many lakes in New England have been compiled (Hodgkins and James, 2002; Hodgkins, 2010b) and analyzed (Hodgkins and others, 2002; Hodgkins, 2013); data from additional lakes have been recently compiled. There are 37 lakes that have at least 80-percent data completeness for each decade from 1960 to 2013 (11 of 13 years for 2000 to 2012). As of 2012, 5 lakes have 165 years or more of data, and another 14 have more than 110 years of data. Long-term lake ice-out data for many lakes in New England represent a unique

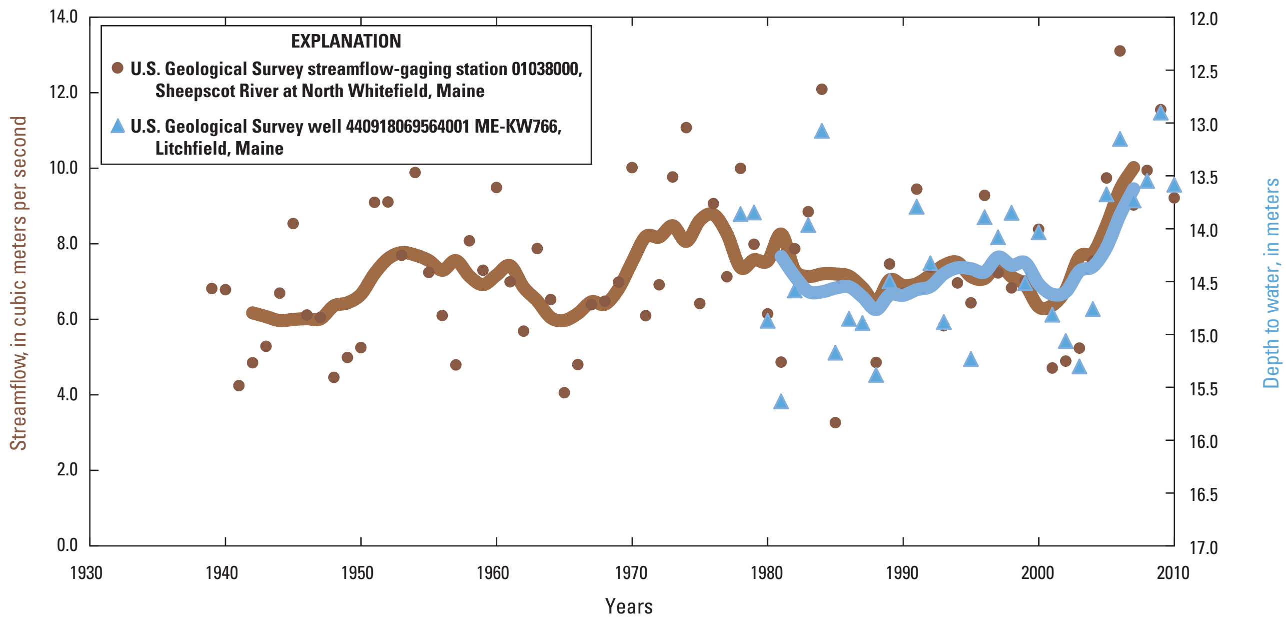

Figure 8. Relation of August groundwater levels and annual mean streamflows; modified from Dudley and Hodgkins (2013, fig. 7). Curves are 7-year moving averages.

hydroclimatic dataset that is useful for continued monitoring of hydrologic response to regional climate change. These lakes would be used in a hydrologic climate-response data network. An additional seven lakes with 30 to 50 years of record would augment the network for short-term trend analysis (fig. 9; table 5). These lakes are appropriate for inclusion in the network on the basis of 80-percent data completeness for each decade from 1980 to 2013 (11 of 13 years for 2000–2012). Many more lakes in northern New England have short records or records with large gaps. These lakes could also be included in the network when their records approach useful lengths (and meet completeness criteria).

Most of the lakes in this study are in rural areas (Hodgkins and others, 2002). Lakes in the northern parts of Maine, New Hampshire, and Vermont generally drain remote, undeveloped forests. Lakes in more southerly areas of northern New England generally drain rural areas with forests, some low-density residential development, and small towns. Lake Auburn is near a relatively small urban area (Auburn, Maine); Houghtons and Ponkapoag Ponds outside Boston, Massachusetts, are near a large urban area. There are no lakes currently known with substantial amounts (more than 10 years) of ice-out data from nonurban lakes in southern New England. The ice-out dates for lakes near urban areas could be affected by urban heat-island temperature effects.

Ice-out definitions for individual lakes can vary over time and among observers (Hodgkins and others, 2002). Twenty years or more of overlapping data from independent observers were available for six lakes. On the basis of this limited dataset, Hodgkins and others (2002) concluded that observer biases (different people on the same lake recording different ice-out dates for the same year) of more than 1 day are unlikely on relatively round lakes. In contrast, 3- to 4-day biases can occur on long, narrow lakes if the observation locations are on opposite ends of the lake. On two long, narrow lakes with north-south axes, the observer of later ice-out dates was located at the northern end of the lakes. These observational biases could result in large biases in ice-out trends over time at individual lakes. At a large number of lakes, however, it is unlikely that observer-location biases would tend to bias trend tests in any one direction. For example, for a large number of lakes there is no reason to expect that people observed less recent ice-outs at the southern end of lakes and more recent ice-outs at the northern end of lakes.

Snowpack

Long-term snowpack data are mostly limited to Maine, but given its importance in New England hydrology, snowpack is included as a variable in the New England hydrologic climate-response network. The following text is from Hodgkins and others (2009, p. 13):

> “Key snowpack variables are the magnitude of late-winter water equivalent, depth, and density for selected dates. Emergency management and response agencies, flood-forecasting agencies,

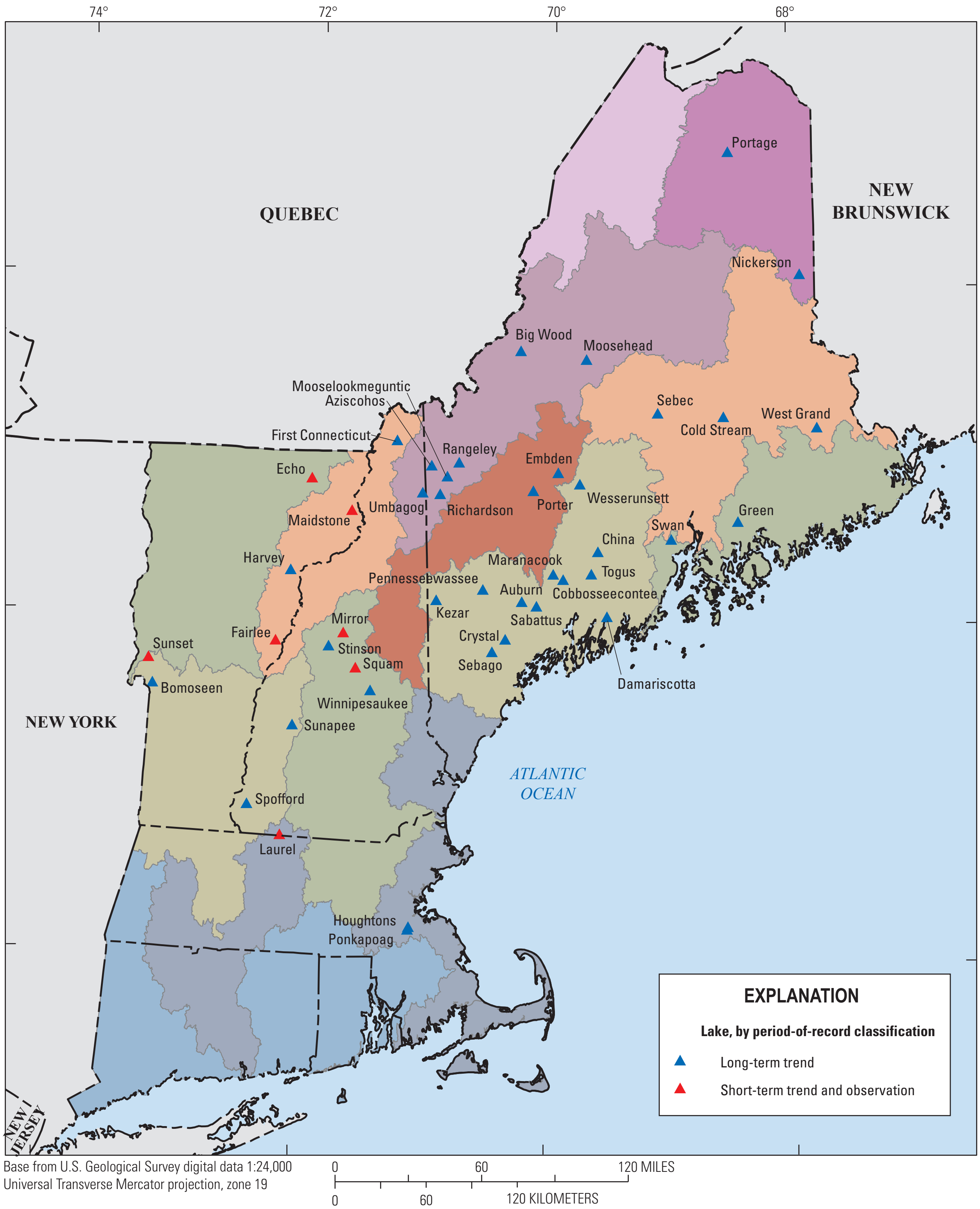

Figure 9. Lakes in New England with substantial amounts of ice-out data. Sites have at least 50 years of records for long-term trend testing, at least 30 years for short-term trend testing, and fewer than 30 years for observations. See figure 3 for climate-response regions by color. See table 5 for full lake names.

Table 5. Lakes in New England with substantial amounts of ice-out data.

[See figure 9 for lake locations. ft, feet; MA, Massachusetts; ME, Maine; NH, New Hampshire; VT, Vermont]

Lake name and location	Elevation (ft)	Period of record (years)
Houghton's Pond near Ponkapoag, MA	161	126
Ponkapoag Pond at Ponkapoag, MA	161	126
Aziscohos Lake at Aziscohos Dam, ME	1,513	97
Big Wood Pond at Jackman, ME	1,161	92
China Lake at East Vassalboro, ME	194	86
Cobbosseecontee Lake near Winthrop Center, ME	164	171
Cold Stream Pond near Enfield, ME	190	67
Crystal Lake at Dry Mills, ME	308	53
Damariscotta Lake at Damariscotta Mills, ME	46	175
Embden Pond near North Anson, ME	413	88
Green Lake at Lakewood, ME	167	78
Kezar Lake near Lovell, ME	374	112
Lake Auburn at East Auburn, ME	259	170
Lake Wesserunsett at East Madison, ME	335	125
Maranacook Lake at Winthrop, ME	210	88
Moosehead Lake at Moosehead, ME	1,011	165
Mooselookmeguntic Lake at Upper Dam, ME	1,453	111
Nickerson Lake near Carys Mills, ME	377	64
Pennesseewassee Lake at Norway, ME	394	137
Portage Lake near Portage, ME	610	87
Porter Lake near New Vineyard, ME	633	74
Rangeley Lake at Oquossoc, ME	1,519	133
Richardson Lakes at Middle Dam, ME	1,444	131
Sabattus Pond at Sabattus, ME	236	87
Sebago Lake near North Windham, ME	266	172
Sebec Lake at Sebec, ME	305	130
Swan Lake at Swanville, ME	203	122
Togus Pond near West Windsor, ME	180	71
Umbagog Lake near Upton, ME	1,240	122
West Grand Lake at Grand Lake Stream, ME	303	135
First Connecticut Lake near Pittsburg, NH	1,636	92
Lake Winnipesaukee at Interlaken Park, NH	515	126
Laurel Lake near Fitzwilliam Depot, NH	1,099	50
Mirror Lake at Hubbard Brook Experimental Forest at West Thornton, NH	705	41
Spofford Lake at Spofford, NH	748	70
Squam Lake at Holderness, NH	597	35
Stinson Lake at Stinson Lake, NH	1,355	76
Sunapee Lake at Sunapee, NH	1,090	144
Echo Lake at East Charleston, VT	1,253	43
Harvey Lake at West Barnet, VT	892	62
Lake Bomoseen near Fair Haven, VT	427	54
Lake Fairlee near West Fairlee, VT	705	37
Maidstone Lake at Bullthroat, VT	1,302	39
Sunset Lake near Hortonia, VT	508	37

people who live near streams, and many water-dependent industries need to know how much water to expect each year from snowmelt. Primarily for this reason, the Maine Cooperative Snow Survey Program, run jointly by the Maine Geological Survey (MGS) and the USGS, compiles snowpack data collected by the USGS, the MGS, the National Weather Service, electric-power utilities, water-power companies, pulp and paper companies, and others on a regular basis (currently weekly, historically biweekly) in late winter and spring (Hodgkins and Dudley, 2006a).

“The depth and water equivalent (the depth of water that would result if the snowpack were melted) of the snowpack have been measured at selected sites in Maine since the early part of the 20th century [Hodgkins, Dudley, and Loiselle, 2005]. Most of the sites are in flat or gently sloping areas of mixed hardwood and conifer forest. Measurements are not made near conifers. Most data are collected at locations with an elevation of less than 2,000 ft. Historical site information for the sites in this report is extremely limited. Some sites have been moved away from the local effects of development, extensive logging, or unacceptable amounts of conifer growth.

“Snowpack depth and water-equivalent data were analyzed for those sites with data spanning at least 50 years through 2004 (Hodgkins and Dudley, 2006a). The exact date of sampling at a site varies from year to year. Data for a site commonly are not available for every year for a given sampling window. Sampling windows were defined as 15-day windows centered on February 15, March 1, March 15, April 1, April 15, and May 1. To be included for analysis, the sites were required to have at least 50-percent complete data for the first and second halves of their record for at least one sampling window. Thirty-seven sites in and near Maine met the described criteria. Historical snow depth and water-equivalent data for these sites are reported in [Hodgkins, Dudley, and Loiselle (2005)] as follows:

“Because sampling windows were used, it is possible to have biased sampling over time at sites (Hodgkins and Dudley, 2006a). If sampling tends to be earlier or later over time, any significant trends in the snowpack data could be the result of sampling bias. All data sets (individual sites for each applicable sampling window) that met the criteria for inclusion were tested for significant changes over time in the date of sampling. Data from many sites sampled during the March 1 sampling window were found to be biased, with many sampling dates prior to March 1 early in the record and many dates after March 1 later in the record. Fourteen sites were eliminated because of significant bias in the date of sampling. Data from 23 sites with data for at least one sampling window did not show significant sampling bias and were considered appropriate for use in computing climate-related trends over time [fig. 10; table 6]. These sites would be the starting point for sites to be included in a hydrologic climate-response data network.”

It would be desirable to add shorter-term snowpack sites, but this requires an amount of analysis beyond the scope of this report. It would also be desirable to have additional snowpack sites outside of Maine, particularly in areas of regular substantial snowpack.

Meteorological Stations

Precipitation and air temperature trends and variability are important to streamflow, groundwater, lake ice-out, and snowpack trends and variability. The relative influence of precipitation and air temperature varies by season. Many recent climate-change-related studies have made use of the U.S. Historical Climatology Network (USHCN) monthly dataset to analyze meteorological trends; the most recent dataset available is version 2 (Quinlan and others, 1987; Menne and others, 2009). The USHCN data are quality-assured and evaluated on the basis of record length and completeness; data are subject to time-of-observation bias adjustments (Karl and others 1986; Vose and others, 2003), homogeneity testing, and adjustment procedures to account for non-climate-related changes in the record such as instrument and station location changes (Menne and Williams, 2009). Missing data are estimated by using weighted averages of highly correlated neighboring data. The 44 USHCN stations in New England are shown in table 7 and figure 11; stations have a minimum of 99 years of record through 2012 and are appropriate for the analysis of long-term trends.

Process-Based Studies

An important part of establishing a hydrologic climate-response network in New England would be to identify basins that are appropriate for use in process-based studies designed to improve understanding of and predict hydrologic and ecosystem change. The combination of extensive historical hydrologic data, ecological data, and deterministic watershed modeling would greatly increase our understanding of the effects of climate change on hydrologic components and ecosystem health.

For each of the 14 lower tier regions in the proposed hydrologic climate-response network, a representative basin (in geology, land cover, and other characteristics) that has extensive historical data for multiple hydrologic components would be identified; potential sites are indicated in table 8 and

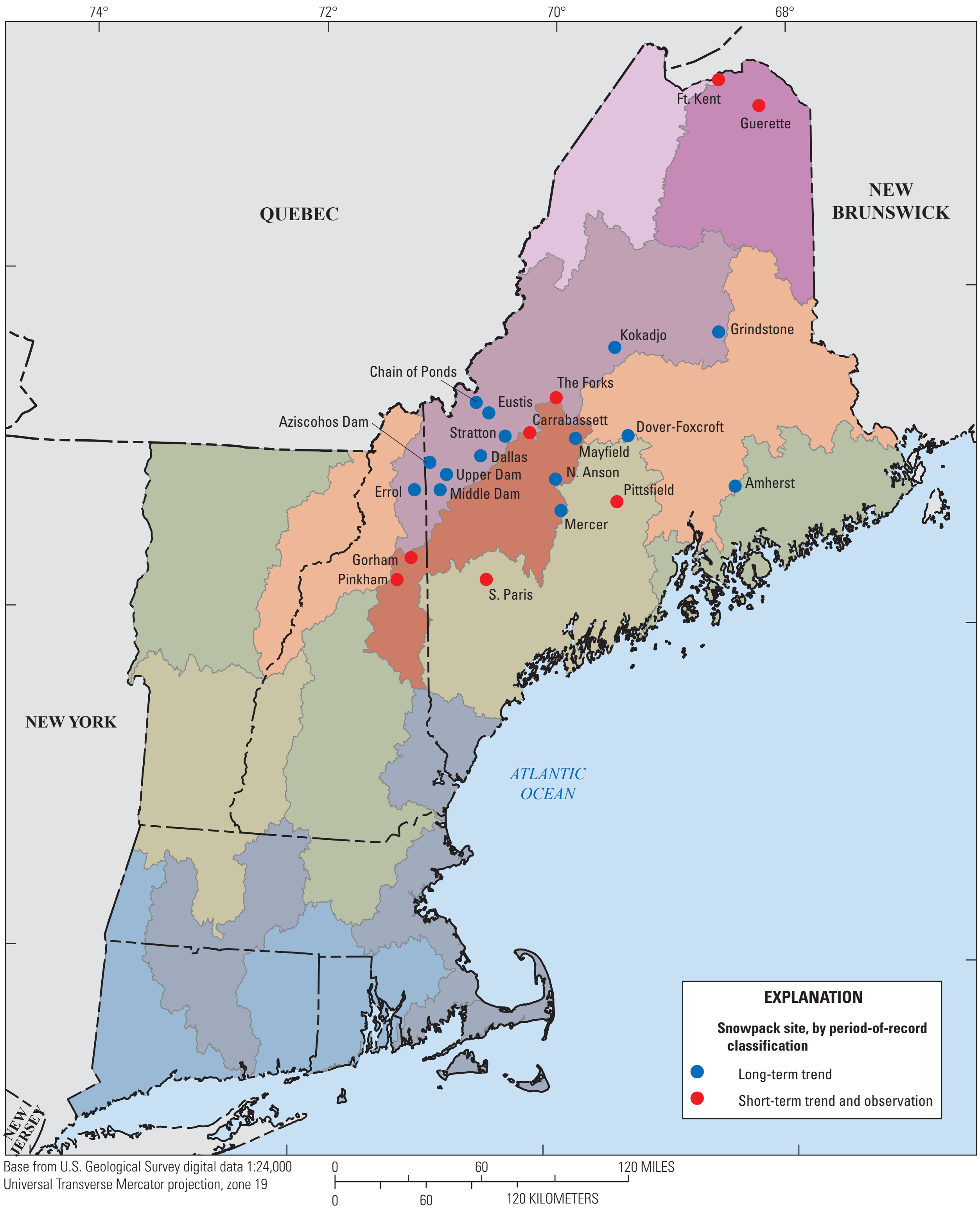

Figure 10. Location of long-term snowpack sites in New England. Sites have at least 50 years of records for long-term trend testing, at least 30 years for short-term trend testing, and fewer than 30 years for observations. See figure 3 for climate-response regions by color. See table 6 for full site names.

Table 6. Long-term snowpack sites in New England.

[See figure 10 for site locations. Abbreviations in site name are part of the official name. All sites are in Maine, unless otherwise noted. A sampling window is defined as a 15-day period centered on the date shown. NH, New Hampshire]

Site number	Site name	Map name (in fig. 10)	Sampling window
1002	The Forks	The Forks	1-Mar
1004	Grindstone	Grindstone	1-Mar
1015	Mercer	Mercer	1-Mar
1020	Dover-Foxcroft (B)	Dover-Foxcroft	1-Mar
1024	North Anson	N. Anson	1-Mar
1044	Pinkham Notch (UWP), NH	Pinkham	1-Mar
1050	Pittsfield (B)	Pittsfield	1-Mar
1053	Gorham, NH	Gorham	1-Mar
1066	Mayfield (Bingham Upper)	Mayfield	1-Mar
1292	Kokadjo (KWP)	Kokadjo	1-Mar
1002	The Forks	The Forks	15-Mar
1018	Amherst (BH)	Amherst	15-Mar
1022	Fort Kent	Ft. Kent	15-Mar
1024	North Anson	N. Anson	15-Mar
1027	Errol/Errol Dam (UWP), NH	Errol	15-Mar
1028	Aziscohos/Aziscohos Dam (UWP)	Aziscohos	15-Mar
1030	Middle Dam (UWP)	Middle Dam	15-Mar
1031	Upper Dam (UWP)	Upper Dam	15-Mar
1046	South Paris	S. Paris	15-Mar
1061	Guerrette	Guerrette	15-Mar
1100	Eustis (KWP)	Eustis	15-Mar
1246	Stratton (KWP)	Stratton	15-Mar
1288	Carrabassett (KWP)	Carrabassett	15-Mar
1289	Dallas (KWP)	Dallas	15-Mar
1290	Chain of Ponds (KWP)	Chain of Ponds	15-Mar
1027	Errol/Errol Dam (UWP), NH	Errol	1-Apr
1028	Aziscohos/Aziscohos Dam (UWP)	Aziscohos	1-Apr
1030	Middle Dam (UWP)	Middle Dam	1-Apr
1031	Upper Dam (UWP)	Upper Dam	1-Apr

Table 7. Long-term meteorological stations in New England.

[See figure 11 for station locations. Location of meteorological stations shown in figure 8. Abbreviations in site name are part of the official name. ft, feet; PPOR, years of precipitation record through 2012; TPOR, years of air temperature record through 2012; CT, Connecticut; ME, Maine; MA, Massachusetts; NH, New Hampshire; RI, Rhode Island; VT, Vermont]

Meteorological station		Elevation (ft)	PPOR (years)	TPOR (years)
Number	Name			
062658	CT 062658 FALLS VILLAGE	550	117	117
063207	CT 063207 GROTON	40	117	117
067970	CT 067970 STAMFORD 5 N	190	107	117
068138	CT 068138 STORRS	650	117	117
170100	ME 170100 ACADIA NP	470	117	117
170814	ME 170814 BRASSUA DAM	1,060	113	115
171628	ME 171628 CORINNA	297	117	117
172426	ME 172426 EASTPORT	85	117	117
172765	ME 172765 FARMINGTON	420	117	117
173046	ME 173046 GARDINER	140	117	117
173944	ME 173944 HOULTON 5N	390	109	117
174566	ME 174566 LEWISTON	180	117	117
175304	ME 175304 MILLINOCKET	360	117	117
176905	ME 176905 PORTLAND JETPORT	45	117	117
176937	ME 176937 PRESQUE ISLE	599	117	114
179891	ME 179891 WOODLAND	140	117	117
190120	MA 190120 AMHERST	150	117	117
190535	MA 190535 BEDFORD	160	117	117
190736	MA 190736 BLUE HILL	630	117	117
193213	MA 193213 GREAT BARRINGTON 5 SW	817	99	117
194105	MA 194105 LAWRENCE	50	117	117
195246	MA 195246 NEW BEDFORD	70	117	117
196486	MA 196486 PLYMOUTH-KINGSTON	45	117	117
196681	MA 196681 PROVINCETOWN	20	117	117
196783	MA 196783 READING	90	117	117
198367	MA 198367 TAUNTON	20	117	117
198757	MA 198757 WALPOLE 2	165	117	117
199316	MA 199316 WEST MEDWAY	210	117	117
270706	NH 270706 BETHLEHEM 2	1,180	117	117
272174	NH 272174 DURHAM	80	117	117
272999	NH 272999 FIRST CONNECTICUT LAKE	1,660	117	110
273850	NH 273850 HANOVER	603	117	117
274399	NH 274399 KEENE	520	117	117
370896	RI 370896 BLOCK ISLAND STATE AP	110	117	117
374266	RI 374266 KINGSTON	114	117	117
376698	RI 376698 PROVIDENCE WSO AP	51	117	117
431081	VT 431081 BURLINGTON WSO AP	330	117	117
431243	VT 431243 CAVENDISH	842	117	117
431360	VT 431360 CHELSEA	800	117	117
431580	VT 431580 CORNWALL	345	117	117
432769	VT 432769 ENOSBURG FALLS	420	117	117
437054	VT 437054 SAINT JOHNSBURY	700	117	117
437607	VT 437607 SOUTH HERO	110	117	117
437612	VT 437612 SOUTH LINCOLN	1,341	117	117

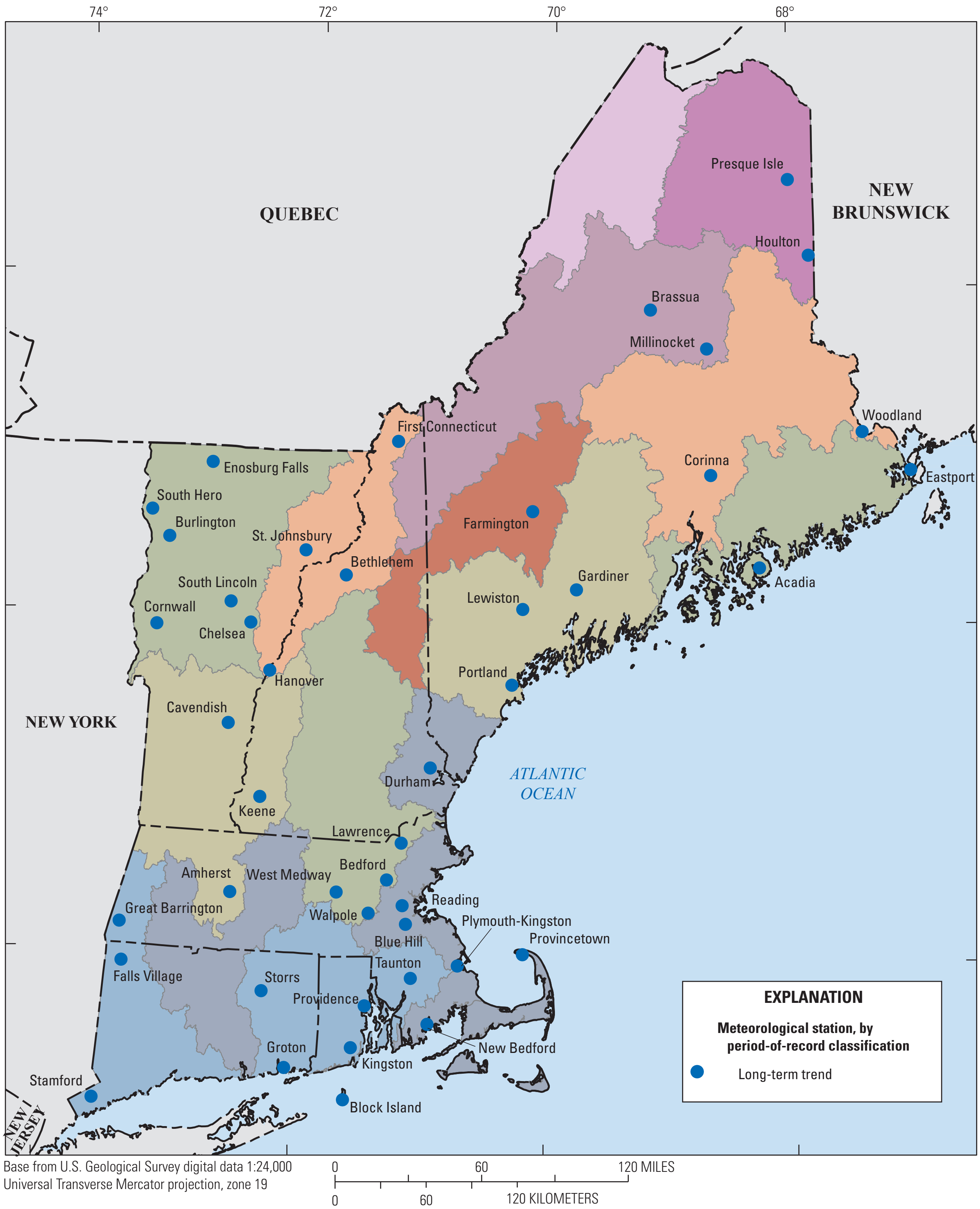

Figure 11. U.S. Historical Climatology Network meteorological stations in New England. Stations have at least 50 years of records for long-term trend testing. See figure 3 for climate-response regions by color. See table 7 for full station names.

Table 8. Basin sites appropriate for process-based studies.

[See figure 12 for basin locations. ME, Maine; NH, New Hampshire; MA, Massachusetts; RI, Rhode Island; CT, Connecticut; VT, Vermont]

Station number	Station name
01010000	St. John River at Ninemile Bridge, ME
01013500	Fish River near Fort Kent, ME
01017060	Hardwood Brook below Glidden Brook near Caribou, ME
01018035	Meduxnekeag River at Lowery Road near Houlton, ME
01022500	Narraguagus River at Cherryfield, ME
01027200	North Branch Penobscot River near Pittston Farm, ME
01030500	Mattawamkeag River near Mattawamkeag, ME
01031500	Piscataquis River near Dover-Foxcroft, ME
01037380	Ducktrap River near Lincolnville, ME
01038000	Sheepscot River at North Whitefield, ME
01047000	Carrabassett River near North Anson, ME
01052500	Diamond River near Wentworth Location, NH
01054200	Wild River at Gilead, ME
01064500	Saco River near Conway, NH
01067950	Kennebunk River near Kennebunk, ME
01073000	Oyster River near Durham, NH
01078000	Smith River near Bristol, NH
01095220	Stillwater River near Sterling, MA
01117468	Beaver River near Usquepaug, RI
01121000	Mount Hope River near Warrenville, CT
01135300	Sleepers River (Site W-5) near St. Johnsbury, VT
01137500	Ammonoosuc River at Bethlehem Junction, NH
01142500	Ayers Brook at Randolph, VT
01150900	Ottauquechee River near West Bridgewater, VT
01162500	Priest Brook near Winchendon, MA
01181000	West Branch Westfield River at Huntington, MA
01208990	Saugatuck River near Redding, CT
01333000	Green River at Williamstown, MA
04296000	Black River at Coventry, VT

figure 12. Specific effort would be made to select candidate basins that have existing watershed models and ones that contain important resources such as Atlantic salmon habitat and (or) Native American and U.S. Department of Interior or Agriculture lands. A deterministic watershed model would then be developed for each of these basins (if not already completed) to improve understanding of basin hydrologic processes. The watershed models would use numerical methods to describe the physical processes that control the movement of water throughout a basin. Runoff processes simulated by the models would include overland flow, shallow subsurface flow, and groundwater flow.

The watershed models would be constructed by using the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983; Markstrom and others, 2008). PRMS is well suited for simulating runoff from rural basins and has been applied to many basins in the United States. PRMS is a deterministic, distributed-parameter modeling system. The model is deterministic in that it computationally incorporates multiple components of the hydrologic cycle as understood through known physical laws or empirical relations in hydrologic science. The modeled hydrologic relations are typically governed by quantifiable physical characteristics of the basin. Parameters describing the physical basin characteristics are assigned in a distributed fashion, representing the spatial variation (heterogeneity) in basin characteristics. In this manner, the model is designed to simulate the hydrologic system as realistically as possible.

The models would be calibrated to historical records. Calibrated watershed models provide simulated time series of daily streamflow for many locations throughout a basin. The models leverage limited streamflow-gaging-station data and provide a method for characterizing subbasin hydrology. An example of rainfall-runoff-model subareas for two basins in eastern coastal Maine (Dudley, 2008) is shown in figure 13. The model explicitly simulates the physical processes of surface runoff, subsurface flow, and groundwater flow and processes affecting soil moisture, snowpack accumulation and melt, and evapotranspiration. This information would enable natural-resource managers to characterize the timing and quantity of water moving through the basin to support many endeavors, including geochemical calculations, water-use assessment, river biota population dynamics modeling, and habitat modeling and assessment. It would also allow scenario testing for interactions between climate change and changes in water use and land use.

Additional research would be conducted to improve understanding of processes such as soil moisture dynamics, groundwater/surface-water interactions, ice dynamics, and hydrologic/ecological interactions that are important to habitats and species. For example, with improved availability of groundwater data, PRMS could be integrated with the USGS groundwater model MODFLOW in an application called GSFLOW (Markstrom and others, 2008) to support investigations of basin-scale groundwater and surface-water resources. Using models to characterize the relative contributions of surface water and groundwater to streamflow throughout the basin would lead to an improved understanding of water quantity and quality and the effects of future hydrologic changes on ecosystems in the basin.

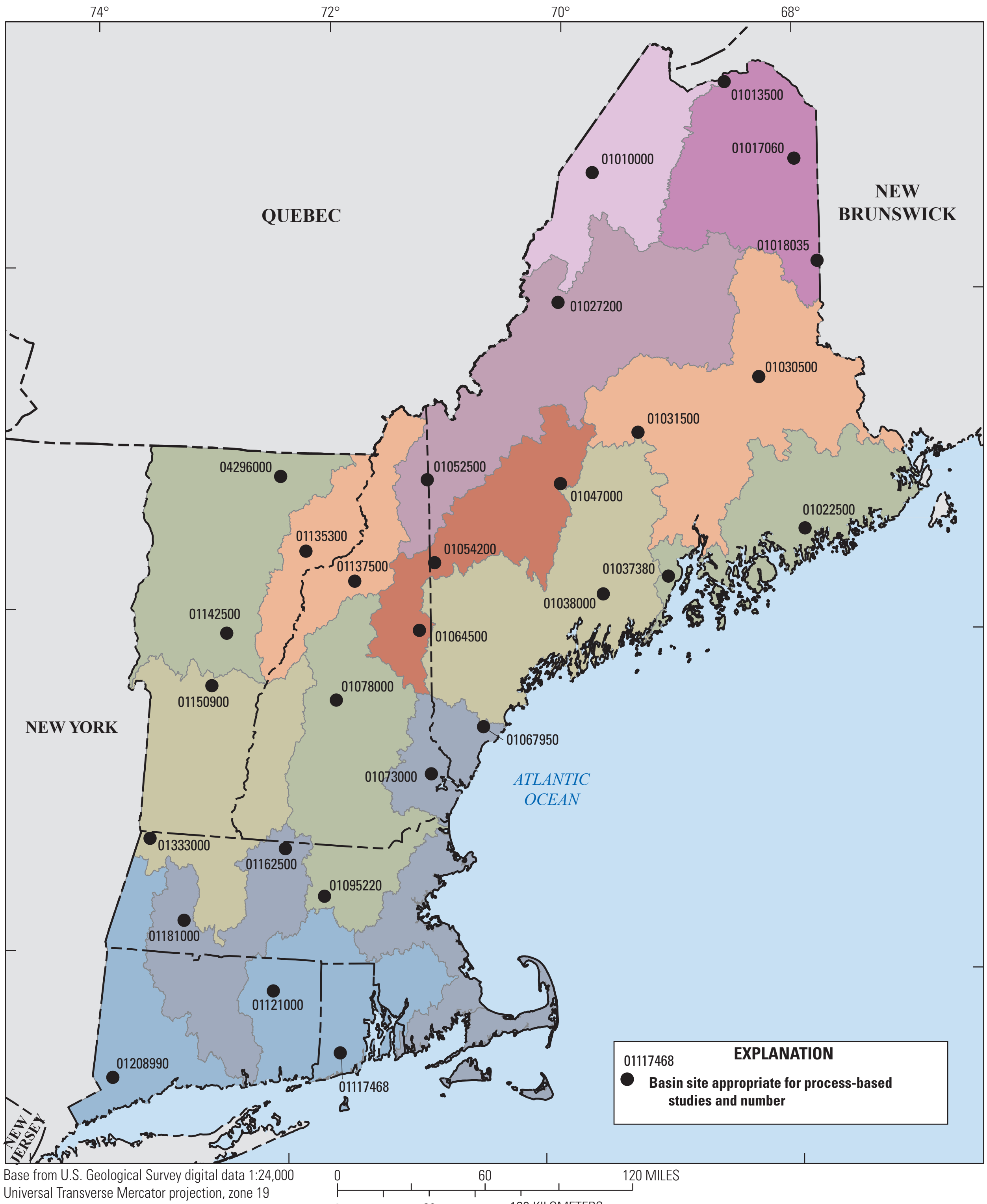

Figure 12. Basin sites appropriate for process-based studies. See figure 3 for climate-response regions by color.

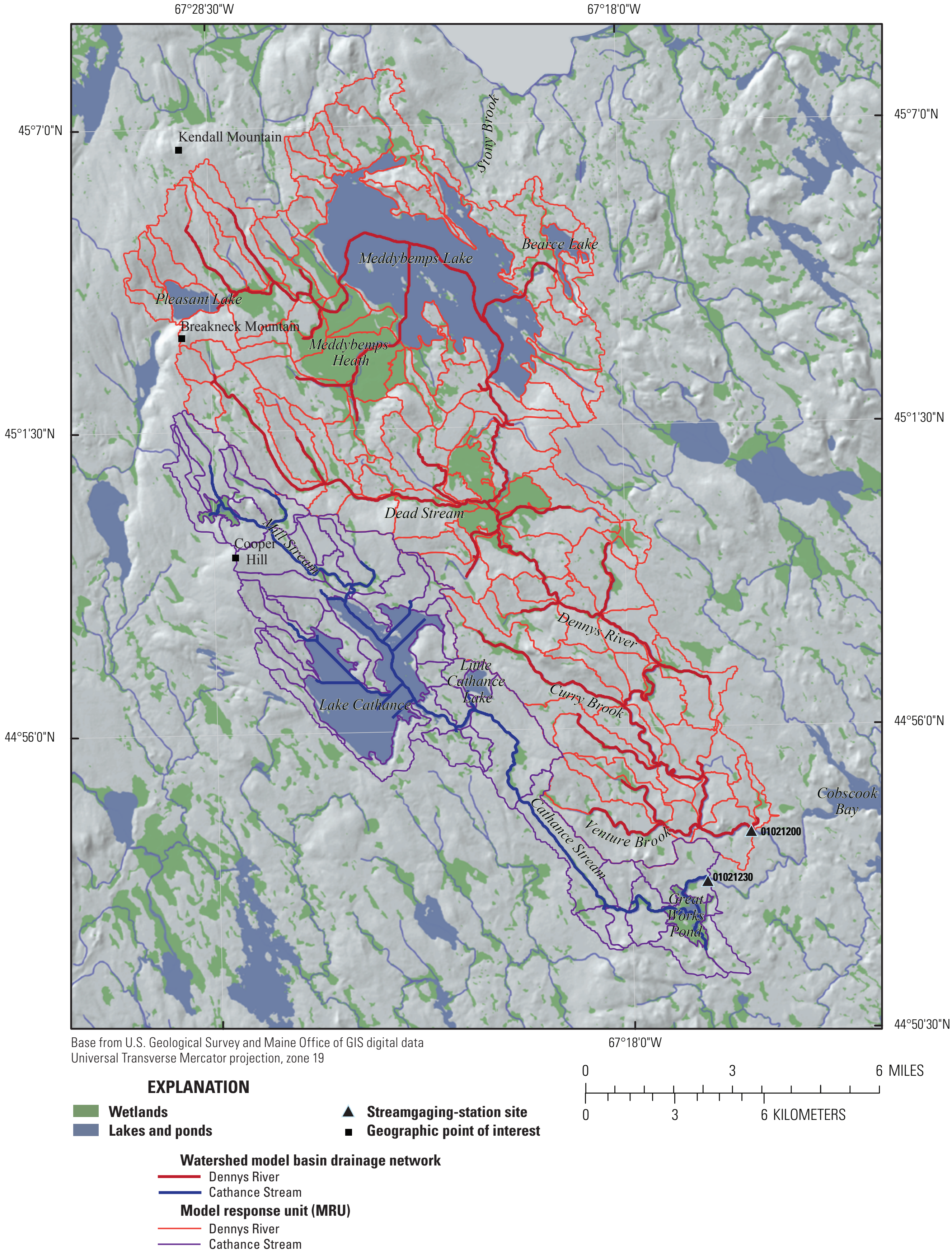

Figure 13. An example of rainfall-runoff-model subareas for two basins in eastern coastal Maine; modified from Dudley (2008, fig. 5).

Summary

Seasonal, annual, and longer term variations in precipitation and air temperature can affect the timing and magnitudes of numerous hydrologic processes that, in turn, can affect human water supply, hydroelectric power generation, transportation infrastructure, and stream and riparian ecology. Recent investigations conclude that many different hydrologic processes in New England are sensitive to variations in precipitation and air temperature. Hydrologic variables such as peak flows, the timing of winter-spring flows, lake ice-out dates, snowpack, and groundwater levels have changed during the last century and are expected to change in the future. Many changes in winter and spring have been documented, and some changes in summer and fall and for annual flow variables have also been found. Observed trends during winter and spring are largely related to changes in air temperature because of the sensitivity of snowpack to air temperature changes in New England. Trends during summer and fall are largely related to changes in precipitation.

The framework for the New England climate-response network described in this report identifies specific inland hydrologic variables that are sensitive to climate variation; identifies geographic regions with similar hydrologic responses; proposes a fixed-station monitoring network that includes existing streamflow, groundwater, lake ice, snowpack, and meteorological data-collection networks for evaluation of hydrologic response to climate variation; and establishes potential streamflow basins for intensive process-based studies and for estimates of future hydrologic conditions.

The framework proposes that New England be divided into 14 regions that follow major river-basin boundaries, have relatively homogeneous climates, and contain network sites with similar values or trends in key hydrologic variables. Establishing the proposed network would require the identification of hydrologic components of interest (fluxes and storage compartments), the key variables that characterize each component, and a set of data-collection sites. Three criteria were used to identify key variables: the existence of long-term historical data, the expectation that a variable will be responsive to changes in precipitation and (or) air temperature during the next several decades, and the human or ecological importance of the component variables.

For the streamflow component, two key variables are proposed: winter-spring streamflow timing and the magnitude of the annual peak flow. Streamflow data proposed for New England are from rivers, monitored by U.S. Geological Survey streamflow-gaging stations, with streamflows minimally affected by direct changes to the watershed from human activities such as reservoir regulation and urbanization. Thirty-one streamflow-gaging stations in New England meet the criteria for minimal disturbance and long-term completeness (at least 80-percent data completeness for each decade from 1960 to 2013 (11 of 13 years for 2000 to 2012). Another 30 stations in New England meet the criteria for minimal disturbance and have shorter or less complete records.

Key variables for a groundwater network include the annual highest and lowest levels. For New England groundwater wells, a completeness criterion of 80 percent per decade yields 70 and 12 wells appropriate for short-term (30-year) and long-term (50-year) trend testing, respectively.

The key (and only commonly available in New England) historical measure of lake ice is lake ice-out date—the annual date in spring when winter ice cover leaves a lake. There are 37 lakes that meet long-term-completeness criteria (as defined in the previous paragraph). As of 2012, 5 lakes have 165 years or more of data, and another 14 have more than 110 years of data.

Key snowpack variables are the magnitude of late-winter water equivalent, depth, and density for selected dates. Twenty-three sites with long-term data for at least one late-winter sampling window were considered appropriate for a New England hydrologic climate-response network; data from these sites did not show significant sampling bias over time. It would be desirable to have additional snowpack sites outside of Maine, particularly in areas of regular substantial snowpack.

Precipitation and air temperature trends and variability are important to streamflow, groundwater, lake ice-out, and snowpack trends and variability. The relative influence of precipitation and air temperature varies by season. A network of 44 meteorological stations have a minimum of 99 years of record through 2012 and are appropriate for analyzing long-term trends.

An important part of establishing a hydrologic climate-response network in New England is identifying basins that are appropriate for use in process-based studies designed to improve understanding of and predict hydrologic and ecosystem change. For each region in the proposed hydrologic climate-response network, a representative basin (in geology, land cover, and other characteristics) that has extensive historical data for multiple hydrologic components would be identified. A deterministic watershed model would then be developed for each of these basins (if not already completed). The models would then be used to improve understanding of hydrologic processes in basins (fluxes and storages), make streamflow projections, and provide input to ecological models.

This proposed framework for a New England climate-response network lays a foundation for the organization of data-collection networks and climate-response regions and for the identification of key climate-related hydrologic variables. Ongoing and future analyses of hydrologic data are expected to inform improvements to the proposed framework.

References Cited

Armstrong, W.H., Collins, M.J., and Snyder, N.P., 2012, Increased frequency of low-magnitude floods in New England: Journal of the American Water Resources Association, v. 48, no. 2, p. 306–320.

Beltaos, Spyros, 2002, Effects of climate on mid-winter ice jams: Hydrological Processes, v. 16, no. 4, p. 789–804.

Benson, B.J., Magnuson, J.J., Jensen, O.P., Card, V.M., Hodgkins, G.A., Korhonen, Johanna, Livingstone, D.M., Stewart, K.M., Weyhenmeyer, G.A., and Granin, N.G., 2012, Extreme events, trends and variability in Northern Hemisphere lake ice phenology (1855–2005): Climatic Change, v. 112, p. 299–323.

Bjerklie, D.M., Hay, L.E., and Markstrom, S.L., 2012, Watershed scale response to climate change—Pomperaug River watershed, Connecticut: U.S. Geological Survey Fact Sheet 2011–3122, 6 p. [Also available at http://pubs.usgs.gov/fs/2011/3122/.]

Bjerklie, D.M., Trombley, T.J., and Viger, R.J., 2011, Simulations of historical and future trends in snowfall and groundwater recharge for basins draining to Long Island Sound: Earth Interactions, v. 15, no. 34, p. 1–35.

Blenckner, Thorsten, Omstedt, Anders, and Rummukainen, Markku, 2002, A Swedish case study of contemporary and possible future consequences of climate change on lake function: Aquatic Sciences, v. 64, no. 2, p. 171–184.

Blenckner, Thorsten, Pettersson, Kurt, and Padisák, Judit, 2002, Lake plankton as a tracer to discover climate signals: Verhandlungen des Internationalen Verein Limnologie, v. 28, p. 1324–1327.

Brooks, R.T., 2009, Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the northeastern United States: Climatic Change, v. 95, p. 469–483.

Cember, R.P., and Wilks, D.S., 1993, Climatological atlas of snowfall and snow depth for the northeastern United States and southeastern Canada: Northeast Regional Climate Center Research Publication RR 93–1, 213 p.

Collins, M.J., 2009, Evidence for changing flood risk in New England since the late 20th century: Journal of the American Water Resources Association, v. 45, no. 2, p. 279–290.

Corbett, D.M., and others, 1943, Stream-gaging procedure—A manual describing methods and practices of the Geological Survey: U.S. Geological Survey Water-Supply Paper 888, 245 p. [Also available at http://pubs.er.usgs.gov/publication/wsp888.]

Douglas, E.M., and Fairbanks, C.A., 2011, Is precipitation in northern New England becoming more extreme?—Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm: Journal of Hydrologic Engineering, v. 16, no. 3, p. 203–217.

Dudley, R.W., 2008, Simulation of the quantity, variability, and timing of streamflow in the Dennys River Basin, Maine, by use of a precipitation-runoff watershed model: U.S. Geological Survey Scientific Investigations Report 2008–5100, 44 p. [Also available at http://pubs.usgs.gov/sir/2008/5100/.]

Dudley, R.W., Hay, L.E., Markstrom, S.L., and Hodgkins, G.A., 2012, Watershed scale response to climate change—Cathance Stream Basin, Maine: U.S. Geological Survey Fact Sheet 2011–3128, 6 p. [Also available at http://pubs.usgs.gov/fs/2011/3128/.]

Dudley, R.W., and Hodgkins, G.A., 2002, Trends in streamflow, river ice, and snowpack for coastal river basins in Maine during the 20th century: U.S. Geological Survey Water-Resources Investigations Report 02–4245, 26 p. [Also available at http://me.water.usgs.gov/reports/wrir02-4245.pdf.]

Dudley, R.W., and Hodgkins, G.A., 2005, Trends in timing, magnitude, and duration of summer and fall/winter streamflows for unregulated coastal river basins in Maine during the 20th century: U.S. Geological Survey Scientific Investigations Report 2005–5021, 26 p. [Also available at http://pubs.usgs.gov/sir/2005/5021/.]

Dudley, R.W., and Hodgkins, G.A., 2013, Historical groundwater trends in northern New England and relations with streamflow and climatic variables: Journal of the American Water Resources Association, v. 49, no. 5, p. 1198–1212.

Elo Aija-Riitta, Huttula, Timo, Peltonen, Anu, and Virta, Juhani, 1998, The effects of climate change on the temperature conditions of lakes: Boreal Environment Research, v. 3, p. 137–150.

Falcone, J.A., 2011, GAGES-II—Geospatial attributes of gages for evaluating streamflow: U.S. Geological Survey Web page, accessed August 5, 2014, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml.

Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.C., and Wuebbles, D.J., 2007, Confronting climate change in the U.S. northeast—Science, impacts, and solutions: Cambridge, Mass., Union of Concerned Scientists, 146 p. [Also available at http://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/pdf/confronting-climate-change-in-the-u-s-northeast.pdf.]

Grover, N.C., 1937, The floods of March 1936—Part 1. New England rivers: U.S. Geological Survey Water-Supply Paper 798, 466 p. [Also available at http://pubs.usgs.gov/wsp/0798/report.pdf.]

Hayhoe, Katharine, Wake, C.P., Huntington, T.G., Luo, Lifeng, Schwartz, M.D., Sheffield, Justin, Wood, Eric, Anderson, Bruce, Bradbury, James, DeGaetano, Art, Troy, T.J., and Wolfe, David, 2007, Past and future changes in climate and hydrological indicators in the US northeast: Climate Dynamics, v. 28, no. 4, p. 381–407.

Hodgkins, G.A., 2010a, Historical changes in annual peak flows in Maine and implications for flood-frequency analyses: U.S. Geological Survey Scientific Investigations Report 2010–5094, 38 p. [Also available at http://pubs.usgs.gov/sir/2010/5094/.]

Hodgkins, G.A., 2010b, Historical ice-out dates for 29 lakes in New England, 1807–2008: U.S. Geological Survey Open-File Report 2010–1214, 32 p. [Also available at http://pubs.usgs.gov/of/2010/1214/.]

Hodgkins, G.A., 2013, The importance of record length in estimating the magnitude of climatic changes—An example using 175 years of lake ice-out dates in New England: Climatic Change, v. 119, nos. 3–4, p. 705–718.

Hodgkins, G.A., and Dudley, R.W., 2005, Changes in the magnitude of annual and monthly streamflows in New England, 1902–2002: U. S. Geological Survey Scientific Investigations Report 2005–5135, 37 p. [Also available at http://pubs.usgs.gov/sir/2005/5135/.]

Hodgkins, G.A., and Dudley, R.W., 2006a, Changes in late-winter snowpack depth, water equivalent, and density in Maine, 1926–2004: Hydrological Processes, v. 20, no. 4, p. 741–751.

Hodgkins, G.A., and Dudley, R.W., 2006b, Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002: Geophysical Research Letters, v. 33, no. 6, L06402, 5 p., http://dx.doi.org/10.1029/2005GL025593.

Hodgkins, G.A., and Dudley, R.W., 2011, Historical summer base flow and stormflow trends for New England rivers: Water Resources Research, v. 47, no. 7, W07528, 16 p., http://dx.doi.org/10.1029/2010WR009109.

Hodgkins, G.A., and Dudley, R.W., 2013, Modeled future peak streamflows in four coastal Maine rivers: U.S. Geological Survey Scientific Investigations Report 2013–5080, 18 p. [Also available at http://pubs.usgs.gov/sir/2013/5080/.]

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G., 2003, Changes in the timing of high river flows in New England over the 20th century: Journal of Hydrology, v. 278, p. 244–252.

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G., 2005a, Changes in the number and timing of days of ice-affected flow on northern New England rivers, 1930–2000: Climatic Change, v. 71, no. 3, p. 319–340.

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G., 2005b, Summer low flows in New England during the 20th century: Journal of the American Water Resources Association, v. 41, no. 2, p. 403–412.

Hodgkins, G.A., Dudley, R.W., and Loiselle, M.C., 2005, Historical late-winter and spring snowpack depth and equivalent water-content data for Maine: U.S. Geological Survey Open-File Report 2005–1259, 80 p. [Also available at http://pubs.usgs.gov/of/2005/1259/.]

Hodgkins, G.A., Dudley, R.W., and Schalk, L.F., 2012, Relations between winter climatic variables and April streamflows in New England and implications for summer streamflows: U.S. Geological Survey Scientific Investigations Report 2012–5092, 11 p. [Also available at http://pubs.usgs.gov/sir/2012/5092/.]

Hodgkins, G.A., and James, I.C., II, 2002, Historical ice-out dates for 29 lakes in New England: U.S. Geological Survey Open-File Report 02–34, 32 p. [Also available at http://me.water.usgs.gov/reports/OFR02-34.pdf.]

Hodgkins, G.A., James, I.C., II, 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, v. 22, no. 15, p. 1819–1827.

Hodgkins, G.A., Lent, R.M., Dudley, R.W., and Schalk, C.W., 2009, Framework for a U.S. Geological Survey hydrologic climate-response program in Maine: U.S. Geological Survey Open-File Report 2009–1115, 23 p. [Also available at http://pubs.usgs.gov/of/2009/1115/.]

Huntington, T.G., Hodgkins, G.A., and Dudley, R.W., 2003, Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine: Climatic Change, v. 61, nos. 1–2, p. 217–236.

Huntington, T.G., Hodgkins, G.A., Keim, B.D., and Dudley, R.W., 2004: Changes in the proportion of precipitation occurring as snow in New England (1949–2000). Journal of Climate, v. 17, no. 13, p. 2626–2636.

Jassby, A.D., Powell, T.M., and Goldman, C.R., 1990, Interannual fluctuations in primary production—Direct physical effects and the trophic cascade at Castle Lake, California: Limnology and Oceanography, v. 35, no. 5, p. 1021–1038.

Juanes, Francis, Gephard, Stephen, and Beland, K.F., 2004, Long-term changes in migration timing of adult Atlantic salmon (*Salmo salar*) at the southern edge of the species distribution: Canadian Journal of Fisheries and Aquatic Sciences, v. 61, p. 2392–2400.

Karl, T.R., and Knight, R.W., 1998, Secular trends of precipitation amount, frequency, and intensity in the United States: Bulletin of the American Meteorological Society, v. 79, p. 231–241.

Karl, T.R., Williams, C.N., Jr., Young, P.J., and Wendland, W.M., 1986, A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States: Journal of Climate and Applied Meteorology, v. 25, p. 145–160.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p. [Also available at http://pubs.usgs.gov/circ/1344/.]

Kirshen, Paul, Watson, Chris, Douglas, Ellen, Gontz, Allen, Lee, Jawon, and Tian, Yong, 2008, Coastal flooding in the northeastern United States due to climate change: Mitigation and Adaptation Strategies for Global Change, v. 13, nos. 5–6, p. 437–451.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system—User's manual: U.S. Geological Survey Water-Resources Investigations Report 83–4238, 207 p. [Also available at http://pubs.usgs.gov/wri/1983/4238/report.pdf.]

Lins, H.F., 2012, USGS hydro-climatic data network 2009 (HCDN–2009): U.S. Geological Survey Fact Sheet 2012–3047, 4 p. [Also available at http://pubs.usgs.gov/fs/2012/3047/.]

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. [Also available at http://me.water.usgs.gov/reports/WRIR01-4258.pdf.]

Markstrom, S.L., Hay, L.E., Ward-Garrison, C.D., Risley, J.C., Battaglin, W.A., Bjerklie, D.M., Chase, K.J., Christiansen, D.E., Dudley, R.W., Hunt, R.J., Koczot, K.M., Mastin, M.C., Regan, R.S., Viger, R.J., Vining, K.C., and Walker, J.F., 2012, Integrated watershed-scale response to climate change for selected basins across the United States: U.S. Geological Survey Scientific Investigations Report 2011–5077, 143 p. [Also available at http://pubs.usgs.gov/sir/2011/5077/.]

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008, GSFLOW—Coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW–2005): U.S. Geological Survey Techniques and Methods, book 6, chap. D1, 240 p. [Also available at http://pubs.usgs.gov/tm/tm6d1/.]

Mastin, M.C., Chase, K.J., and Dudley, R.W., 2011, Changes in spring snowpack for selected basins in the United States for different climate-change scenarios: Earth Interactions, v. 15, p. 1–18.

McCormick, S.D., Hansen, L.P., Quinn, T.P., and Saunders, R.L., 1998, Movement, migration, and smolting of Atlantic salmon (*Salmo salar*): Canadian Journal of Fisheries and Aquatic Sciences, v. 55, supplement 1, p. 77–92.

Menne, M.J., and Williams, C.N., Jr., 2009, Homogenization of temperature series via pairwise comparisons: Journal of Climate, v. 22, p. 1700–1717.

Menne, M.J., Williams, C.N., Jr., and Vose, R.S., 2009, The United States historical climatology network monthly temperature data, version 2: Bulletin of the American Meteorological Society, v. 90, p. 993–1007.

Nakićenović, Nebojša, Alcamo, Joseph, Davis, Gerald, de Vries, Bert, Fenhann, Joergen, Gaffin, Stuart, Gregory, Kenneth, Grübler, Arnulf, Jung, T.Y., Kram, Tom, La Rovere, E.L., Michaelis, Laurie, Mori, Shunsuke, Morita, Tsuneyuki, Pepper, William, Pitcher, Hugh, Price, Lynn, Riahi, Keywan, Roehrl, Alexander, Rogner, H.H., Sankovski, Alexei, Schlesinger, Michael, Shukla, Priyararshi, Smith, Steven, Swart, Robert, van Rooijen, Sascha, Victor, Nadejda, and Zhou Dadi, 2000, Special report on emissions scenarios; A special report of Working Group III of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom, Cambridge University Press, 599 p. [Also available at http://www.grida.no/publications/other/ipcc%5Fsr/?src=/climate/ipcc/emission/index.htm.]

National Oceanic and Atmospheric Administration, 2014, Mean sea level trends for northern Atlantic stations: National Oceanic and Atmospheric Administration data, accessed October 27, 2014, at http://tidesandcurrents.noaa.gov/sltrends/northatlantictrends.htm.

New England Regional Assessment Group, 2001, Preparing for a changing climate—The potential consequences of climate variability and change—The New England regional assessment overview: Durham, N.H., U.S. Global Change Research Program, 96 p. [Also available at http://downloads.globalchange.gov/nca/nca1/NCA1-New-England-Assessment-Report.pdf.]

Nielsen, M.G., and Dudley, R.W., 2013, Estimates of future inundation of salt marshes in response to sea–level rise in and around Acadia National Park, Maine: U.S. Geological Survey Scientific Investigations Report 2012–5290, 20 p. [Also available at http://pubs.usgs.gov/sir/2012/5290/.]

Nõges, Tiina, Nõges, Peeter, Jolma, Ari, and Kaitaranta, Joni, 2009, Impacts of climate change on physical characteristics of lakes in Europe: Luxembourg, European Commission Joint Research Centre Report EUR 24064 EN, 56 p. [Also available at http://bookshop.europa.eu/en/impacts-of-climate-change-on-physical-characteristics-of-lakes-in-europe-pbLBNA24064/.]

Poore, R.Z., Williams, R.S., Jr., and Tracey, Christopher, 2000, Sea level and climate: U.S. Geological Survey Fact Sheet 2000–002, 2 p. [Also available at http://pubs.usgs.gov/fs/fs2-00/.]

Porter, K.G., Saunders, P.A., Haberyan, K.A., Macubbin, A.E., Jacobsen, T.R., and Hodson, R.E., 1996, Annual cycle of autotrophic and heterotrophic production in a small, monomictic Piedmont Lake (Lake Oglethorpe)—Analog for the effects of climatic warming on dimictic lakes: Limnology and Oceanography, v. 41, no. 5, p. 1041–1051.

Power, G., Cunjak, R.A., Flannagan, J.F., and Katopodis, C., 1993, Biological effects of river ice, chap. 4 *of* Prowse, T.D., and Gridley, N.C., eds., Environmental aspects of river ice: Saskatoon, Saskatchewan, Environment Canada, National Hydrology Research Institute, p. 97–119.

Prowse, T.D., 1994, Environmental significance of ice to streamflow in cold regions: Freshwater Biology, v. 32, no. 2, p. 241–259.

Prowse, T.D., and Beltaos, Spyros, 2002, Climatic control of river-ice hydrology—A review: Hydrological Processes, v. 16, no. 4, p. 805–822.

Quinlan, F.T., Karl, T.R., and Williams, C.N., Jr., 1987, United States historical climatology network (HCN) serial temperature and precipitation data: Oak Ridge, Tenn., U.S. Department of Energy, Oak Ridge National Laboratory, NDP–019.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 v. [Also available at http://pubs.usgs.gov/wsp/wsp2175/.]

Scrimgeour, G.J., Prowse, T.D., Culp, J.M., and Chambers, P.A., 1994, Ecological effects of river ice breakup—A review and perspective: Freshwater Biology, v. 32, no. 2, p. 261–275.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP—A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96–4040, 46 p. [Also available at http://pubs.er.usgs.gov/publication/wri964040.]

Stefan, H.G., Hondzo, Midhat, and Fang, Xing, 1993, Lake water quality modeling for projected future climate scenarios: Journal of Environmental Quality, v. 22, no. 3, p. 417–431.

Vose, R.S., Williams, C.N., Jr., Peterson, T.C., Karl, T.R., and Easterling, D.R., 2003. An evaluation of the time of observation bias adjustment in the U.S. historical climatology network: Geophysical Research Letters, v. 30, no. 20, p. CLM–3–1—CLM–3–4.

Weider, Kaitlyn, and Boutt, D.F., 2010, Heterogeneous water table response to climate revealed by 60 years of ground water data: Geophysical Research Letters, v. 37, no. 24, p. 1–6.

Wuebben, J.L., Deck, D.S., Zufelt, J.E., and Tatinclaux, J-C., 1995, Ice jam flood assessment for the St. John River Basin, Aroostook County, Maine: U.S. Army Corps of Engineers Special Report 95–15, 22 p. [Also available at http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA295607.]

For more information concerning this report, contact:
Director, New England Water Science Center
U.S. Geological Survey
196 Whitten Road
Augusta, ME 04330
dc_nweng@usgs.gov
or visit our Web site at:
http://me.water.usgs.gov

Publishing support by:
The Pembroke Publishing Service Center.

Lent and others—**Framework for a Hydrologic Climate-Response Network in New England**—Open-File Report 2015–1062

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20151062