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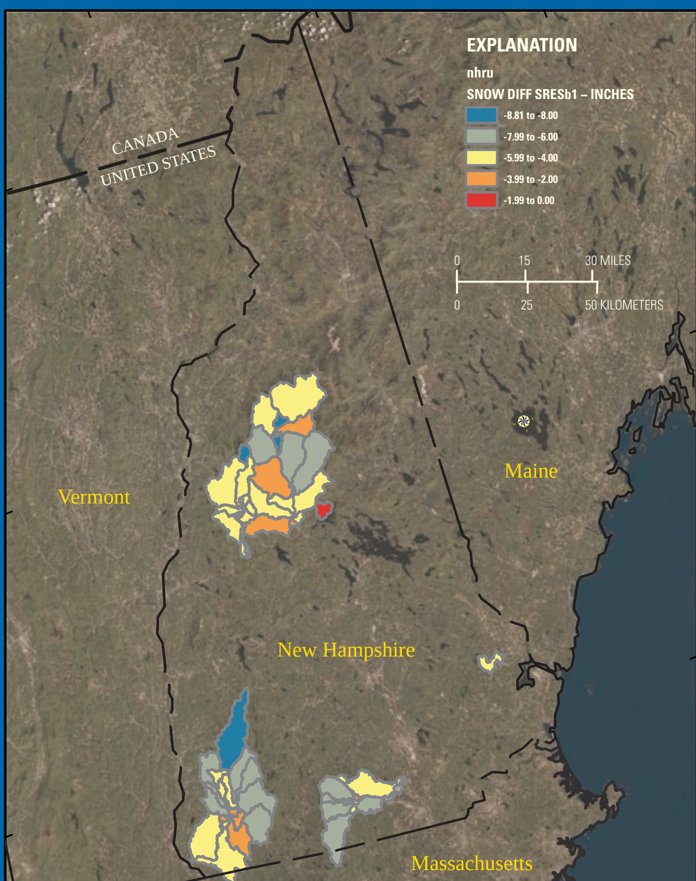
**Prepared in cooperation with the
New Hampshire Department of Health and Human Services**

Simulating Hydrologic Response to Climate Change Scenarios in Four Selected Watersheds of New Hampshire



Scientific Investigations Report 2015–5047

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

Front cover. Map showing projected pattern of change for snow melt, photograph of dry streambed in the upper Ammonoosuc River area, and photograph of U.S. Geological Survey streamgage on the Nonnewaug River during a flood.

Simulating Hydrologic Response to Climate Change Scenarios in Four Selected Watersheds of New Hampshire

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

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
section (640 acres or 1 square mile)	259.0	square hectometer (hm^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).

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

Abbreviations

CNRM	Centre National de Recherches Meteorologiques
ECHAM5	European Centre Hamburg Model version 5
GCM	general circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	geographic information system
GW DIFF CNRM SRESa2	difference between current (1981–2000) and future (2081–2100) simulated base flow using the CNRM global circulation model input for the SRESa2 emission scenario
GW DIFF CNRM SRESb1	difference between current (1981–2000) and future (2081–2100) simulated base flow using the CNRM global circulation model input for the SRESb1 emission scenario
HRU	hydrologic response unit
HUC	hydrologic unit code

IPCC	Intergovernmental Panel on Climate Change
N	number of observations
NRMSE	normalized root mean square error
NSE	Nash-Sutcliffe efficiency
PRCP DIFF CNRM SRESa2	difference between current (1981–2000) and future (2081–2100) daily precipitation output from the CNRM global circulation model for the SRESa2 emissions scenario
PRCP DIFF CNRM SRESb1	difference between current (1981–2000) and future (2081–2100) daily precipitation output from the CNRM global circulation model for the SRESb1 emissions scenario
PRCP DIFF ECHAM5 SRESa2	difference between current (1981–2000) and future (2081–2100) daily precipitation output from the ECHAM5 global circulation model for the SRESa2 emissions scenario
PRCP DIFF ECHAM5 SRESb1	difference between current (1981–2000) and future (2081–2100) daily precipitation output from the ECHAM5 global circulation model for the SRESb1 emissions scenario
PRMS	Precipitation Runoff Model System
R^2	coefficient of determination
SNOW DIFF CNRM SRESa2	difference between current (1981–2000) and future (2081–2100) simulated snowfall using the CNRM global circulation model input for the SRESa2 emissions scenario
SNOW DIFF SRESb1	difference between current (1981–2000) and future (2081–2100) simulated snowfall using the CNRM global circulation model input for the SRESb1 emissions scenario
SRES	IPCC designation for Special Report on Emissions Scenarios
SRESa2	SRES scenario A2
SRESb1	SRES scenario B1
TMAX DIFF CNRM SRESa2	difference between current (1981–2000) and future (2081–2100) daily maximum air temperature output from the CNRM global circulation model for the SRESb1 emissions scenario
TMAX DIFF CNRM SRESb1	difference between current (1981–2000) and future (2081–2100) daily maximum air temperature output from the CNRM global circulation model for the SRESb1 emissions scenario
TMAX DIFF ECHAM5 SRESa2	difference between current (1981–2000) and future (2081–2100) daily maximum air temperature output from the ECHAM5 global circulation model for the SRESa2 emissions scenario
TMAX DIFF ECHAM5 SRESb1	difference between current (1981–2000) and future (2081–2100) daily maximum air temperature output from the ECHAM5 global circulation model for the SRESb1 emissions scenario
USGS	U.S. Geological Survey

Simulating Hydrologic Response to Climate Change Scenarios in Four Selected Watersheds of New Hampshire

By David M. Bjerklie,[1] Joseph D. Ayotte,[1] and Matthew J. Cahillane[2]

Abstract

The State of New Hampshire has initiated a coordinated effort to proactively prepare for the effects of climate change on the natural and human resources of New Hampshire. An important aspect of this effort is to develop a vulnerability assessment of hydrologic response to climate change. The U.S. Geological Survey, in cooperation with the New Hampshire Department of Health and Human Services, is developing tools to predict how projected changes in temperature and precipitation will affect change in the hydrology of watersheds in the State. This study is a test case to assemble the information and create the tools to assess the hydrologic vulnerabilities in four specific watersheds.

The study uses output from general circulation models to drive hydrologic simulations of streamflow, groundwater base flow (hereafter referred to as base flow), and snowfall in four representative watersheds in New Hampshire during the 21st century, including the watersheds of the Ashuelot, Oyster, Pemigewasset, and Souhegan Rivers. Simulations show that on average, relative to current conditions, streamflow is likely to increase and base flow is likely to decrease, although this change is highly variable by geographic location and season. Streamflow variability will likely increase, with more high streamflows and more low streamflows. The largest increases in streamflow are in the winter, with small decreases in summer. Change in base flow varies across the State with the largest change in the northern Pemigewasset River watershed. Changes in snowfall are consistently decreasing for all watersheds on average, with the largest change also in the Pemigewasset. However, monthly snowfall totals during any given winter could be higher in the future than expected under current conditions.

Increasing frequency of floods (the largest seven floods expected to occur in 20 years) could be more significant than the size of the floods, except in the northern high altitude watersheds. In other words, the projections indicate a pattern of multiple floods that might not breach the riverbanks, yet the increased frequency could put additional strain on the existing river banks, infrastructure, and nearby human settlements. There is also likely to be an increase in high flows during the winter and spring months, which could result in more uncertainty in planning for the design, operation, and maintenance of infrastructure, including roads and utilities. Similarly, it is expected that, on average, there will be less base flow available and a wider range of seasonal fluctuation in base flow than experienced historically. These issues could necessitate more attention to planning and management of the resource. Based on past experience, the most important effects of climate change could be less certain planning options and a greater need for planning that accounts for the effects of larger streamflows than are currently available.

The effects of hydrologic change on human health and well-being could be most readily apparent with respect to changes in streamflow and the subsequent increase in the frequency of minor flooding and the frequency of summer and fall low streamflows. These changes could require the development of plans to adapt, protect, and upgrade infrastructure, such as bridges, culverts, roads, and other structures. The precipitation runoff modeling shows that rivers and watersheds in New Hampshire will likely change in response to climate change, and that this response varies with season and latitude. Although four representative areas were simulated in this study, additional models could be used to predict the response over the entire State.

Introduction and Background

There is a coordinated effort in New Hampshire to proactively prepare for the effects of climate change with a practical action plan (New Hampshire Climate Change Policy Task Force, 2009). A key component of the action plan is a vulnerability assessment of hydrologic responses to climate change. The U.S. Geological Survey (USGS) has been identified as a partner along with the New Hampshire Department of Health and Human Services and the University of New Hampshire in the development of tools and maps to

[1]U.S. Geological Survey.

[2]New Hampshire Department of Health and Human Services.

help assess the hydrologic effects from short- and long-term climate change. In this partnership, the USGS developed tools (1) to predict how climate change will affect streamflow, base flow, and snowfall and (2) to identify locations that are vulnerable to the effects of climate change in areas across the State. This report documents a test case to create the information and tools that will allow specific users to understand and assess the hydrologic vulnerabilities in four specific watersheds.

Vulnerability can be thought of as a measure of the degree to which a system is exposed to, susceptible to, and able to cope with and adapt to adverse effects (highlight 1). Hydrologic vulnerability as a result of climate change is defined for the purposes of this report as a measure of the degree to which a deleterious effect on the hydrologic system results from climate change. Deleterious effects include (1) depletion in reservoir storage, (2) depletion in groundwater storage, (3) decrease in snowpack, (4) decreases in base flow (the component of streamflow made entirely of base flow), (5) low streamflow, and (6) increases in flooding. Vulnerability can also incorporate an assessment of degraded conditions that result from quantitative changes in hydrology (O’Connor and others, 1999). These climatic effects could be exacerbated or alleviated by increased development through changes in land cover and water use. Each region will have differing vulnerabilities to climate change, and assessment of these vulnerabilities is the first step in considering potential adaptive strategies.

Hydrologic vulnerability from future climate scenarios has increasingly become a major point of research efforts in New Hampshire and the Northeastern United States (Neff and others, 2000). Mack (2009) assessed a future climate scenario for the seacoast region by simulating potential variations in groundwater recharge and water use. For this region of the State, Mack (2009) found that the potential effect of future climate change on groundwater by 2025 is likely to be more substantial on groundwater recharge than changes in water demand. Using a watershed runoff model to simulate groundwater recharge and snow in the Connecticut River Basin (western New Hampshire), Bjerklie and others (2010b) found that, during the more than five-decade period from 1960 to 2007, snowfall has generally decreased and base flow has generally increased. These changes have not been distributed uniformly in time or space and have marginally decreased or increased in some places in response to local conditions. Similarly, for the 50-year study period from 1961 to 2010, Dudley and Hodgkins (2013) found increasing groundwater levels and streamflow in northern New England. Hamilton and others (2010) reported climate trends in New Hampshire showing air temperature and precipitation increasing throughout the 20th century, with the increases accelerating since 1970. Hamilton and others (2010) also found indications of decreasing snowfall; however, they acknowledge that the trends in snowfall are more complicated with inconsistent trends. Jennifer Jacobs (University of New Hampshire, Durham, oral commun., March 2014) found evidence of consistently decreasing snowfall in New Hampshire.

Highlight 1
Hydrologic Hazards and Vulnerability

Hazard.—A hazard is a deleterious effect, source of potential danger, or condition that can cause harm, deprivation, and stress. The Federal Emergency Management Agency describes hazard identification as a process of *“defining and describing a hazard, including its physical characteristics, magnitude and severity, probability and frequency, causative factors, and locations/areas affected”* (Schwab and others, 1998).

Vulnerability.—How exposed and susceptible the hydrologic system is to deleterious effects from climate change, and how well the human and natural system can cope with and adapt to the deleterious effects. Important deleterious effects include: (1) depletion of groundwater availability and flow to streams in summer, (2) decrease in snowpack, (3) increased frequency and magnitude of flooding, and (4) increasing stream channel erosion and water quality degradation as a result of changes in water flow. Vulnerability will vary across the State and in different watersheds in relation to altitude and topography, geologic setting, land use and land cover change, and water use.

Wake and others (2014) indicate that the climate model consensus shows increasing air temperature and precipitation for New Hampshire in the future, at least into 2100. Bjerklie and others (2010b) project that, in response to this climate change, groundwater recharge (and subsequent base flow) will continue to increase and snowfall will decrease, but not everywhere, depending on the general circulation model (GCM, often referred to as a global climate model) emissions scenario. Similar projections are reported by the U.S. Geological Survey (2014) based on the Intergovernmental Panel on Climate Change (IPCC; 2014) and Melillo and others (2014).

Streamflow records for 400 sites in the conterminous United States, measured during a five-decade period from 1941 to 1999, indicate an increase in annual minimum daily and median daily streamflow beginning around 1970 (Lins and Slack, 1999; McCabe and Wolock, 2002), although there is a mixed pattern of increases and decreases in annual maximum daily streamflow across the United States. Annual streamflow in the eastern United States appears to increase as a step change and coincides with an increase in precipitation.

Past trends and GCM projections indicate that precipitation will continue to increase in the conterminous United States (Karl and Knight, 1998; Groisman and others, 2005). These trends have also been noted in more localized studies in parts of New England (Miller and others, 2002) and the State of New York (Burns and others, 2007). The measured step increase from about 1970 also coincides with changes in the timing of snowmelt peaks in New England (Hodgkins and others, 2003).

Deleterious effects of climate change could be exacerbated by human activities. This is particularly true in areas of high population, including areas within the Merrimack and Piscataqua River Basins in New Hampshire (fig. 1). Hydrologic models can be used to map and project climate change effects for these highly vulnerable areas that otherwise could be observed only from measurements made at discrete locations, often in more rural watersheds. The model provides a tool to extend trends observed at specific locations spatially and temporarily across a region.

Through the application of a New England-wide regional precipitation runoff model, this study is designed to assess potential changes in the hydrologic cycle that result from projected climate change in New Hampshire. The model is used to simulate the spatial and temporal distribution of air temperature, precipitation, snowfall and snowmelt, streamflow, and groundwater recharge across New Hampshire, with a focus on local watersheds in different physiographic regions of the State. Four watersheds, located in the Piscataqua and Merrimack River Basins in the White Mountain region and the Connecticut River Valley, have been chosen as representative pilot study watersheds. These include the Ashuelot River, Oyster River, Pemigewasset River, and Souhegan River watersheds (fig. 2). The study will also assess the relative effects of changes in human activities in combination with climate change on the water cycle.

Researchers are applying regional hydrologic models to map and assess the past and potential future trends in hydrologic variability as a result of climate change over large areas (Bjerklie and others, 2010b). Various types of hydrologic models have been used to couple simulated watershed processes with input data derived (downscaled) from GCMs (Hayhoe and others, 2006; Hayhoe and others, 2007). This project uses the USGS Precipitation Runoff Modeling System (PRMS; Leavesley and others, 1983; Markstrom and others, 2008). The PRMS lends itself to these goals because it can be parameterized at a wide range of scales with any scheme for subdividing the modeled area. The PRMS simulations are based on the spatial variation in measurable physical characteristics, including land cover, topography, soil, and geology, that can be quantified using geographic information systems (GISs). The PRMS simulates surface, soil, subsurface, groundwater storage flux, runoff, snow cover and snowmelt, and a large number of other hydrologic variables. The PRMS model computes these water balance variables for small watersheds (catchments) that comprise the watershed of interest. The catchment is referred to as the hydrologic response unit (HRU).

Purpose and Scope

The purpose of this report is to document a method that provides information and tools that will inform users on the potential effects of climate change on aspects of the hydrologic cycle in the State of New Hampshire. The report identifies large-scale hydrologic vulnerabilities of surface-water and groundwater systems of New Hampshire to potential climate change and presents development of a climate change hydrologic model in four selected areas of the State that can be used as a resource tool by State planners to assess near and distant future climate scenarios. The report documents a watershed scale hydrologic model that is used to assess the effects of climate change on hydrologic responses and vulnerability. The model simulates climate related watershed (hydrologic) changes in four sub-watersheds of New Hampshire that represent different physiographic and hydrologic areas of the State.

The model will provide information that can be used by the State of New Hampshire as adaptive management plans are developed for water resources. The report provides information on potential changes in streamflow, base flow to streams (and groundwater supply), and snowfall that serve as an initial indication of water resource management issues that the State could face in the future.

Description of Study Area

The State of New Hampshire can be divided into three broad physiographic regions, the White Mountains, the Connecticut River Valley and the New England Uplands, and the Seaboard Lowlands (Flanagan and others, 1999). The White Mountain region is dominated by mountain landscapes with altitudes (relative to the North American Vertical Datum of 1988 [NAVD 88]) ranging from less than 1,000 ft near the lakes region of central New Hampshire, to 6,300 ft at the top of Mount Washington. The Connecticut River Valley is a relatively narrow incised valley on either side of the Connecticut River, which forms the western boundary of New Hampshire. The valley flows through the White Mountain region and the New England Uplands, which are found south of the White Mountains in New Hampshire. The New England Uplands region consists of an area of undulating, hilly topography, ranging in altitude from below 1,000 ft to above 2,000 ft. The Seaboard Lowlands region is lower in altitude, below 500 ft, and less hilly than the New England Upland region. The four selected small study watersheds include the Ashuelot River, Oyster River, Pemigewasset River, and Souhegan River watersheds. The Pemigewasset River watershed is within the White Mountain region, the Oyster River watershed is within the coastal Seaboard Lowlands, and the Ashuelot River and Souhegan River watersheds are in the New England Uplands region with the Ashuelot River watershed being also within the Connecticut River Valley.

The climate in the study area is classified as continental because of prevailing westerly winds and is characterized by changeable weather, wide ranges in diurnal and annual temperatures, distinct seasonal trends that vary from year to year, and a fairly uniform distribution of precipitation throughout the year. Important local influences on the climate are terrain, altitude, and proximity to the Atlantic Ocean. The climate

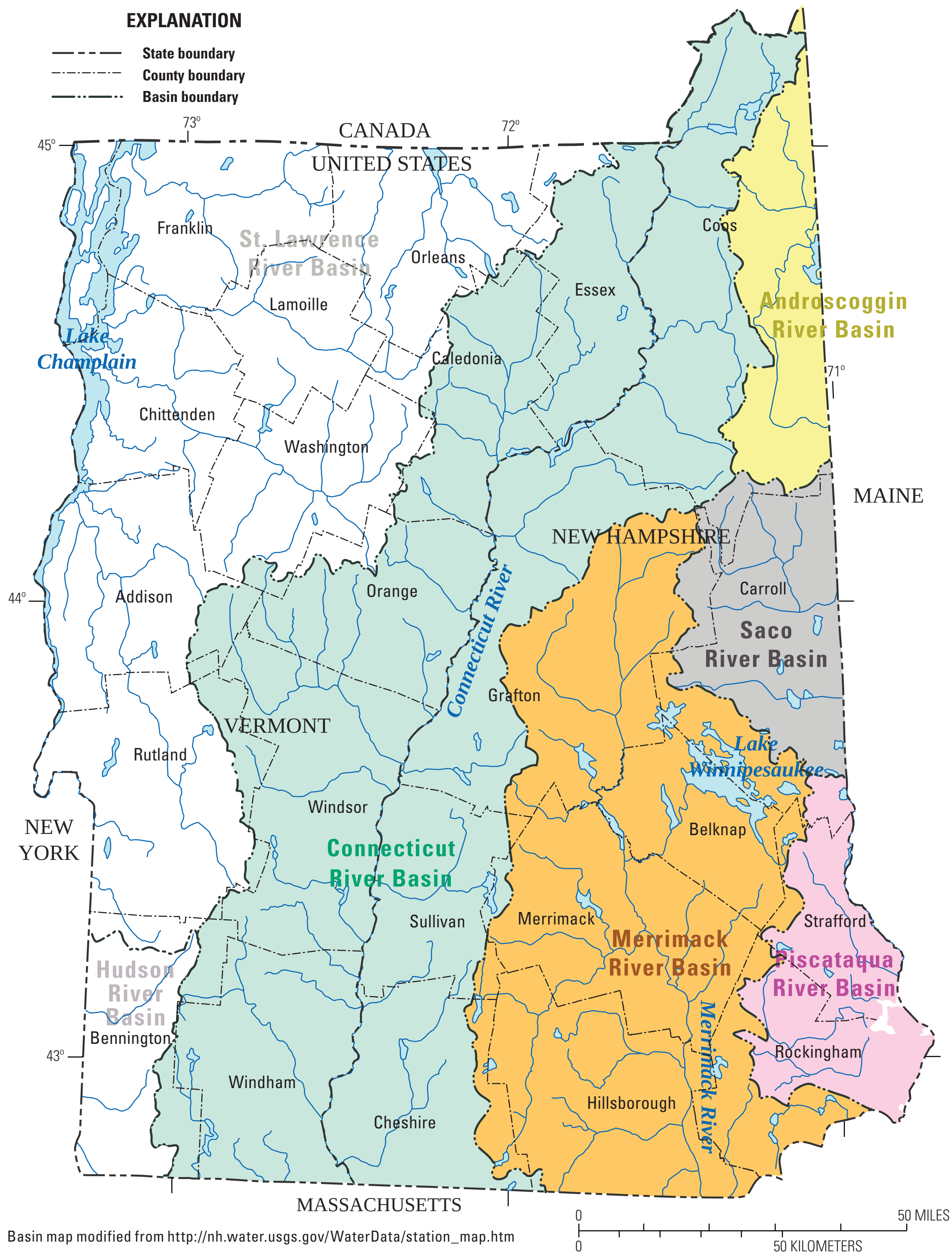

Figure 1. The major watersheds that encompass the State of New Hampshire.

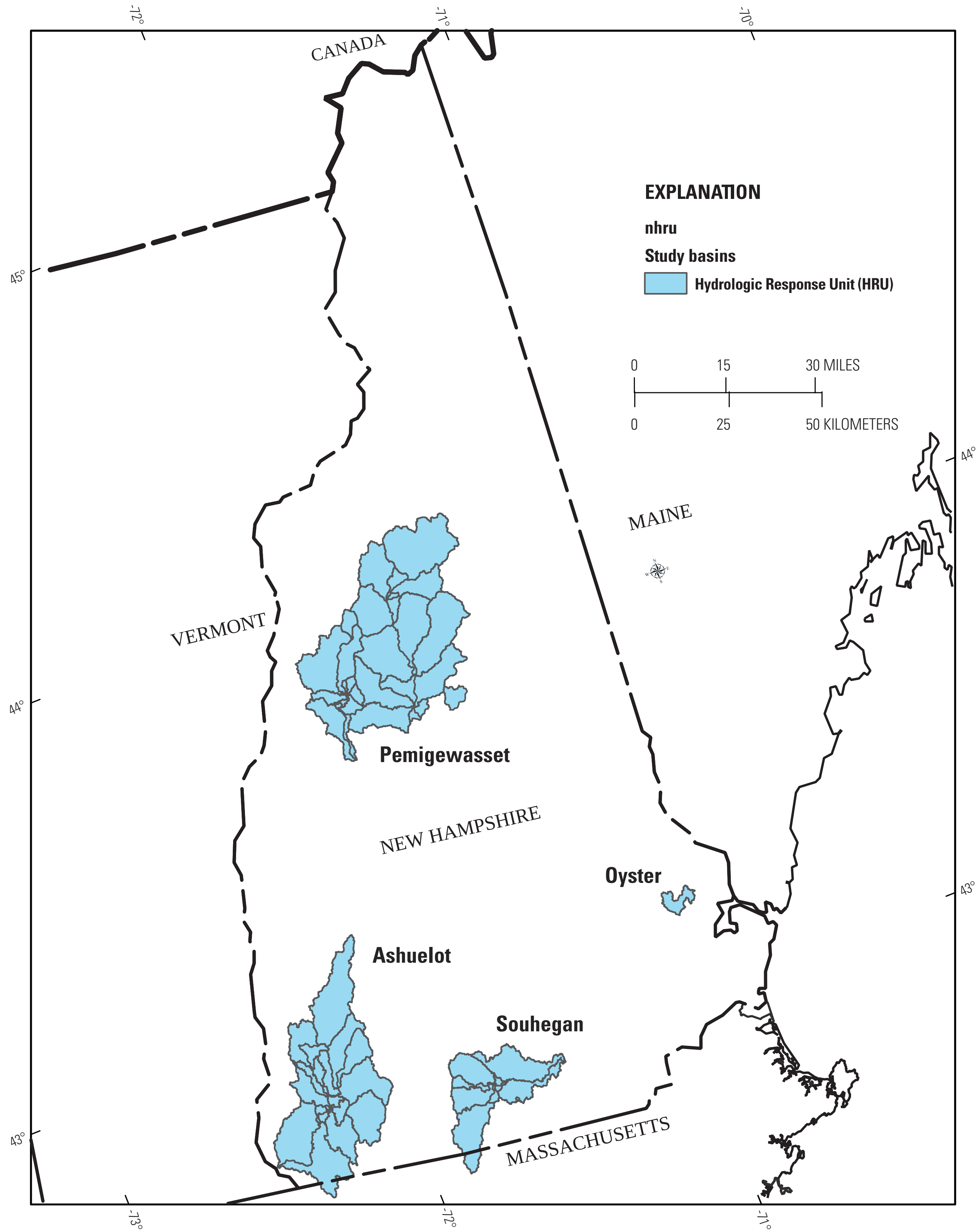

Figure 2. Watersheds in New Hampshire selected for detailed analysis of hydrologic change. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

varies between the physiographic regions and the four small study areas. Generally, precipitation is evenly distributed throughout the year across New Hampshire, yet there is variation in the average annual amount of precipitation because of the effects of terrain, altitude, and proximity to the ocean. The average amount of precipitation the study area receives is 40 to 50 inches per year (in/yr); however, average annual precipitation ranges from 42 in/yr in low-lying areas to greater than 60 in/yr near the summits of the White Mountains. The amount of frozen precipitation is dependent on altitude, terrain, and latitude. Snowfall amounts are generally greatest in January or February and are spatially variable ranging from 20 to 50 in/yr near the coast in the Seaboard Lowlands, from 30 to 70 in/yr in the Connecticut River Valley and the New England Uplands, and from 50 to 110 in/yr in the White Mountains. Snowmelt is a major source of water in streams during late winter and early spring. Temperatures vary widely on an annual basis. Temperature data from 1961 to 1990 indicate that the warmest month in the study area is July and the coldest month is January. On the basis of monthly average temperatures, winter temperatures are more variable across the study area than summer temperatures.

Methods and Data

An initial statewide hydrologic model was developed for the river basins of New Hampshire (fig. 1) using the Precipitation Runoff Modeling System (PRMS; U.S. Geological Survey, 2015). The PRMS generates daily runoff from daily input of air temperature and precipitation. The New Hampshire PRMS model is subdivided into small watersheds (catchments) that can be accumulated into river basins of interest. These catchments or HRUs are the basic computational unit of the model. The statewide model also includes several hundred river reaches that constitute the simulated river network that routes runoff generated from the HRUs downstream.

The calibration of the regional model that includes 45 sites in New Hampshire is based on period of record from 1981 to 2011. The model parameters for each HRU in the model were defined from GIS, defined as a model default (Steve Markstrom and Lauren Hay, U.S. Geological Survey, written commun., August 2013), or adjusted based on considerations developed by Bjerklie and others (2010a,b). The adjusted parameter includes the monthly Jensen-Haise potential evapotranspiration (PET) coefficient (Bjerklie and others, 2010b) which limits the amount of daily PET available each month. During calibration, the 45 sites in New Hampshire were evaluated based on a 32-year mean (1981–2011) of simulated daily flows compared with the USGS measured flows for each site. A detailed hydrologic evaluation was completed on four selected areas of the State (watersheds), which included basins representing different areas of the State, in areas of high density population, and where development is expected.

Future hydrologic conditions are simulated using daily simulated air temperature and precipitation from GCMs (Intergovernmental Panel on Climate Change, 2007). Given the uncertainty in climate modeling, it is desirable to use more than one GCM to obtain a range of potential future climatic conditions (Hay and others, 2011; Bjerklie and others, 2012). In this study, five GCMs were used to develop input data sets for PRMS that represent potential future climate conditions. Each GCM simulates a representative current conditions (1981–2000) dataset and two future scenarios based on IPCC low-emissions scenario (SRES1b) and high-emissions scenario (SRES2a). The timeframe for the projections includes two 20-year periods in the 21st century, 2046–2065 and 2081–2100. These are referred to as midcentury and end-of-century periods. The model also simulates a current reference period, spanning the 20-year period 1981–2000. The future time periods are compared with the current reference time period so that projected change can be evaluated in a self-consistent hydrologic framework described by the PRMS model. The output data include daily estimates of base flow, total river discharge, and snowfall for each HRU in the model.

Precipitation Runoff Model

The PRMS (http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html) is a USGS public access watershed runoff model (Leavesley and others, 1983; Markstrom and others, 2008) that has been developed into several updated versions. The model structure available as of August 2013 was used for the study in this report. The data and an automated method developed by Viger (2014) and Viger and Bock (2014) are used to develop the model spatial domain and to derive many of the parameters used in the model.

The daily water balance is simulated for each of the HRUs based on precipitation and temperature input data. The HRUs and the 12-digit hydrologic unit code (HUC) units, although at approximately the same scale, are not the same. The HRUs in the PRMS model include a wider range of sizes than the HUCs and could divide some HUCs into smaller subwatersheds. In some cases, more than one HUC could be lumped together. Although PRMS does not require HRUs to be delineated on watershed boundaries, the HRUs in the model developed in this study represent subwatersheds so that each HRU can represent a streamflow at its outlet. The parameterization, calibration, and evaluation of the PRMS model at the New Hampshire scale and detailed evaluation for four basins in New Hampshire are described in the following sections.

Modeling Considerations and Calibration Objectives

This modeling study compares possible future hydrologic changes for various climate change scenarios in New Hampshire. The scenarios were generated by different GCMs and different carbon emissions projections. Hydrologic effects of climate scenarios were simulated by use of the self-consistent regional hydrologic model (New England, including New Hampshire) PRMS. Hydrologic self-consistency is critical to enable direct comparisons between the different scenarios in time and space so that comparisons are “apples to apples,” so to speak. If different models were used or the model was calibrated using methods that are not consistent between different watersheds and for different locations, the model response to future scenarios would not be directly comparable.

Model calibration input data were obtained from DAYMET (Thornton and others, 2012; http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1219), which is a gridded digital dataset available on a daily time step for historical periods of record for the continental United States and includes daily precipitation and maximum and minimum air temperature. The DAYMET data are interpolated from station data, using physically based algorithms to a grid spacing of 1 kilometer (km) and are consistent with DAYMET data across the continental United States. Interpolation can cause smoothing of the data such that the timing and magnitude of local events are inaccurate; however, long-term averages are accurate (Thornton and others, 1997; Stahl and others, 2006; Oubeidillah and others, 2013; Di Vittoria and Miller, 2014). The future climate input data derived from GCMs are statistically downscaled from even larger grids, and the issues associated with the DAYMET data are also likely to be inherent in future simulations.

Data and calibration consistency are key to the regional model so that spatial comparisons can be made without differences in calibration and input that would complicate the comparison. The objective functions for the PRMS calibration include streamflow statistics measured at USGS streamgages, streamflow hydrograph characteristics, and the annual and seasonal water balance. To avoid the potential for comparatively variable and (or) exaggerated response to future input datasets between watersheds, the following modeling and calibration objectives are adopted for this study:

- Use of self-consistent input datasets for calibration and for future comparisons. The input datasets are derived from similar sources and developed using similar methods. The same GCMs used to derive future scenario input datasets are also used to derive the current scenario input datasets so that comparisons are not complicated by data differences.
- Use of consistent methods to assign parameter values for all regions in the model.
- Parameterization of the model uses methods based on physical features of watersheds. Parameters that cannot be assigned a value from data are left as default values to ensure that the values are physically realistic.
- Calibration is designed to achieve consistency and accuracy in reproducing water balances and hydrologic flow components (surface, subsurface, and groundwater) that result in representative hydrograph characteristics and flow regimes within the limitations of the input data.
- The model performance is evaluated by comparing streamflow statistics as measured by streamflow at the USGS streamgages of interest.

Input Data

The PRMS model uses mean daily precipitation and maximum and minimum daily air temperature as input. The daily precipitation and air temperature data used for this model were obtained through the USGS Geo Data Portal (http://cida.usgs.gov/gdp/) for a 32-year calibration period (1980–2011) and for future climate datasets consisting of 20-year time periods. The 32-year calibration and the 20-year simulation time periods (1) provide sufficient length of time series data to yield representative mean values and variability so that inferential statistics are meaningful, and (2) are of sufficient length to compare with regional projections of atmospheric climate change studies (Wake and others, 2014), as well as other regional climate change projects (U.S. Geological Survey, 2014).

The input time series of daily precipitation and minimum and maximum temperature used to calibrate the model is derived from DAYMET (Thornton and others, 1997; Thornton and others, 2012; DiVittoria and Miller, 2014), obtained through the USGS Geo Data Portal. The DAYMET data provide a consistent input dataset; however, smoothing of station data over the grid could result in damping of extreme and more intense precipitation events.

The DAYMET input data used for model calibration does not match the high precipitation events well in the higher altitudes in the Pemigewasset River watershed as evidenced by comparing the DAYMET input with station data for Pinkham Notch, the Benton 5 SW (station name) National Weather Service Cooperative Observer Program network station, and the U.S. Forest Service precipitation gage network station at the Hubbard Brook Experimental Forest (Campbell and Bailey, 2014). The comparison data (table 1) show that the mean precipitation and the number of daily precipitation events greater than 0.5 inch estimated from the DAYMET gridded data for four high altitude PRMS HRUs in the Pemigewasset River watershed (HRU numbers 1065, 1091, 1093, and 2337) are generally within 0 to 15 percent of the values from the data from the weather station for similar altitude, latitude, and longitude. However, the data from the weather stations show marked increases in the number of events greater than 1 inch (30–40 percent more days) and greater than 2 inches (60–80 percent more days). This is also expressed by a larger standard deviation of the daily data for the station data compared with that of the DAYMET data. Because of the differences between measured data from the weather stations and the gridded DAYMET data used as input

Table 1. Comparison of DAYMET and station precipitation data for four watersheds in New Hampshire from 1980 to 2008.

[Percent difference is the difference between the measurement at the station and the DAYMET average for the hydrologic response unit (HRU). PRMS, precipitation runoff modeling system; stdev, standard deviation]

HRU PRMS identifier number	Elevation, meters	Percent difference				
		Mean, inches	Stdev, inches	Number of days greater than 2 inches	Number of days greater than 1 inch	Number of days greater than 0.5 inches
HUBBARD						
1065	394	0.08	0.20	0.66	0.36	0.14
1091	578	0.08	0.23	0.73	0.41	0.14
1093	717	0.00	0.15	0.63	0.27	0.01
2337	708	0.06	0.21	0.81	0.42	0.12
Mean		0.05	0.20	0.71	0.37	0.10
NOAA						
1065	394	-0.20	-0.03	-0.36	-0.02	-0.17
1091	578	0.13	0.33	0.82	0.48	0.14
Mean		-0.03	0.15	0.23	0.23	-0.01

to PRMS, the PRMS will underpredict the magnitude, but not necessarily the frequency, of the largest runoff events in the Pemigewasset River watershed because the high-altitude precipitation is underrepresented in the model input. This same issue is expected to be present in the other watersheds considered in this study (Ashuelot, Oyster, and Souhegan Rivers) but to a lesser degree because the altitude ranges are smaller in these other watersheds.

U.S. Geological Survey streamflow records are used for calibration, along with independent estimates of evapotranspiration (movement of water not related to streamflow) where available. The PRMS model does not account for storage in lakes and reservoirs and the effects of dams and water diversions; therefore, streamgages used for calibration were selected so that influences of flow regulation by dams and diversions and storage effects from lakes were not important in streamflow characteristics. There were 45 streamgages in New Hampshire that were selected and used for calibration.

Future climate datasets were also obtained through the Geo Data Portal and are derived from downscaled GCM simulation data that are stored there. The Geo Data Portal hosts 13 different climate-change model datasets for three different climate change scenarios. For this study, five GCM datasets were chosen to represent the possible range of future outcomes. The GCMs that were chosen are listed in table 2 with their country of origin and the years of data used in this study. The future climate input data derived from GCMs are downscaled from large model grids, and the issues associated with the DAYMET data could be even greater in these datasets. Detailed information on the GCMs are available in Nakićenović and others (2000).

All the GCM projections show substantial temperature and precipitation increases during this century for watersheds in New Hampshire. Compatible datasets for the current (1981–2000) timeframe and the future (2081–2100) timeframe were derived for all GCMs, and additional midcentury (2046–2065) datasets derived for two of the GCMs (Centre National de Recherches Meteorologiques [CNRM] and Geophysical Fluid Dynamics Laboratory [GFDL]). These timeframes represent average climate conditions projected to occur for each 20-year climate period. Two IPCC special report emission scenarios (SRES) were chosen for each of the two time periods (four datasets)—one is the most optimistic with regards to future greenhouse gas emissions (SRESb1) and the other is less optimistic (SRESa2). The smallest projected changes in precipitation and temperature are associated with the SRESb1, and the largest projected changes and the largest uncertainties are associated with SRESa2. In general, the largest variability and uncertainty in the GCM projections are with precipitation. The SRESa2 scenario assumes a heterogeneous world with slow adaptive change to new energy technologies and increasing population (Intergovernmental Panel on Climate Change, 2007). The SRESb1 assumes a convergent world (one in which economies become more similar; Intergovernmental Panel on Climate Change, 2007) with a global population that peaks in midcentury and then declines with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and with the introduction of clean and resource-efficient technologies.

The three periods of downscaled data (1981–2000, 2046–2065, and 2081–2100, representing the current condition, midcentury, and the end-of-century, respectively) were used to calculate the difference between the simulated

Table 2. General circulation models used in the study of effects of climate change in four watersheds in New Hampshire.

[CNRM, Centre National de Recherches Meteorologiques; CSIRO, Commonwealth Scientific and Industrial Research Organisation; GFDL, Geophysical Fluid Dynamics Laboratory; ECHAM5, European Centre Hamburg Model version 5; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model]

Model identifier	Country of origin	Years of data
Cnrm _cm3_01, 02, 03 (CNRM)	France	1981–2000 (current) 2046–2065 (mid-century) 2081–2100 (end-of-century)
Csiro_mk3_0_01, 02, 03 (CSIRO)	Australia	1981–2000 (current) 2081–2100 (end-of-century)
Gfdl_cm2_01, 02, 03 (GFDL)	US National Oceanographic and Atmospheric Administration (NOAA)	1981–2000 (current) 2046–2065 (mid-century) 2081–2100 (end-of-century)
Mpi_echam5_01, 02, 03 (ECHAM5)	Germany	1981–2000 (current) 2081–2100 (end-of-century)
Mri_cgcm2_3_01, 02, 03 (CGCM)	Japan	1981–2000 (current) 2081–2100 (end-of-century)

current and future conditions under each of the two carbon emissions scenarios. The two midcentury future datasets (2046–2065) were obtained for the CNRM and GFDL GCMs for comparison with the end-of-century data. Figures 3*A–H* (in back of report) shows the distribution of change, by HRU, of mean maximum daily air temperature and precipitation between the current time period (1981–2000) and the end-of-century future time period (2081–2100) for the CNRM and the European Centre Hamburg Model version 5 (ECHAM5) GCM input data. The CNRM and ECHAM5 models were chosen as representative of the range of projected changes from the five GCM chosen for comparison. The GFDL and CNRM input data were used as indicators of the midcentury, because these data are considered representative of the group as a whole. The ECHAM5 and CNRM input data are used as indicators of the expected upper and lower range for the end-of-century results. The CNRM and the GFDL model input data are fairly representative of the mean values for all five of the GCMs, with GFDL considered as more or less in the middle of the group. The ECHAM5 input data generally were the most different relative to the others. For comparative purposes in this report and to show a range of results, simulations that use the GFDL and CNRM models are focused on the midcentury, and simulations that use the CNRM and ECHAM5 are focused on the end-of-century results, although simulations using input from all five models are summarized in tables for the end-of-century results.

Figures 3*A–H* (in back of report) shows the general pattern of change that is expected, based on the input data from the two GCMs. Both GCMs show that change in mean maximum daily air temperature (figs. 3*A–D*, in back of report) for the SRESa2 scenario (high-emissions scenario) will increase by about 7 to 10 degrees Fahrenheit (°F) between the current time period (1981–2000) and the end-of-century (2081–2100). However, the two GCMs show different patterns for the distribution of change in New England. The CNRM model shows the largest change in southern New England, including much of New Hampshire, whereas the ECHMA5 GCM shows the largest change in northern New England. In New Hampshire, however, both GCMs predict that maximum daily air temperature will increase about 8 to 9 °F. For the low-emissions scenario (SRESb1), the patterns of change for each of the GCMs shown are similar to the high-emissions scenario (SRESa2), however, the range of air temperature change is less. The CNRM model has a range of 3 to 5 °F, and the ECHAM5 GCM has a range of 5 to 7 °F.

The change maps of mean annual precipitation (figs. 3*E–H*, in back of report) show more difference (compared with changes in mean maximum daily air temperature) between the CNRM and ECHAM5 models, with the CNRM model showing an increase of precipitation across New England of 4 to 11 inches assuming the high-emissions (SRESa2) scenario and 2 to 9 inches assuming the low-emissions (SRESb1) scenario. The ECHAM5 model shows an increase of about 1 to 8 inches for both scenarios, with a more or less reverse spatial pattern compared with the CNRM model; the largest increases in precipitation were in northern New England, and the smallest increases were in southern New England. Both GCMs predict the full range of change in precipitation across New Hampshire, which indicates that the amount of change is dependent on location. Clearly, the choice of GCM and scenario used as input to the hydrologic is important to the hydrologic model predictions. The range of predictions for the five GCMs and two scenarios are presented as well as the averages for all of the models and scenarios.

Parameterization, Calibration, and Evaluation of New Hampshire-Scale Model

The New England regional PRMS model was initially parameterized using general GIS-based strategies (Steve Markstrom and Lauren Hay, U.S. Geological Survey, written commun., August 2013) and provided the starting point for the parameterization of the New Hampshire model. The New England model has not been published but was built initially parameterized and provided to this study by the U.S. Geological Modeling of Watershed Systems group which is part of the U.S. Geological Survey National Research Program (written comm., Lauren Hay and Steve Markstrom, U.S. Geological Survey, August 2013). The initial model parameters were based on physical attributes of the HRUs that comprise the model. The New England model includes 2,462 HRUs that are delineated at the approximate scale of the 12-digit-HUC subwatershed distribution (Seaber and others, 1994). Bjerklie and others (2010a) derived several other parameters pertaining to groundwater fluxes based on surficial geologic characteristics for several watersheds in Connecticut. These methods were applied for watersheds in New Hampshire for the model developed in this study and the model calibration was evaluated at the New Hampshire scale. The PRMS model for New Hampshire consists of 467 HRUs. The PRMS model used for this study was parameterized at the New Hampshire scale using methods that compute parameter values from GIS data sources or set default values within a range defined by physical limits (Markstrom and others, 2008). The GIS characteristics of each HRU are used to derive initial model parameters. Most of these parameters are not subject to calibration and represent physical properties that determine the parameter value. These GIS characteristics are obtained in October 2008 from national datasets that include the National Elevation Dataset (http://ned.usgs.gov/) for coordinates of the HRU centroid and topography, the Soil Survey Geographic Database (https://gdg.sc.egov.usda.gov/)for soils, the National Land Cover Database (http://www.mrlc.gov/nlcd2011.php) for land cover (Vogelmann and others, 2001) and the National Hydrography Dataset (http://nhd.usgs.gov/) for hydrography.

The model was calibrated to observed USGS streamgage records from 1980 to 2011. A previously developed PRMS model that included western New Hampshire (Bjerklie and others, 2010b) was used as the baseline calibration for this study. To achieve the best fit water balance for each HRU, the PET simulated by the model was optimized by comparing the long-term simulated streamflow against the long-term measured streamflow at the 45 USGS streamgages. This approach derives coefficients directly from the temperature records and basin altitude (Markstrom and others, 2008). The primary objective of the large area (statewide) calibration was to provide a reasonable representation of the annual water balance.

The PRMS model simulates unregulated natural streamflow and does not simulate the effects of dams, lake and reservoir storage, and groundwater and surface-water diversions. A method to adjust the monthly evapotranspiration coefficient in the model developed by Bjerklie and others (2010b) was used to calibrate the model-simulated evapotranspiration and general water balance at 45 New Hampshire basins. Other parameters that influence snow, snowmelt, and interception were adjusted to be comparable to Bjerklie and others (2010b) or were kept at their GIS derived values. The model default values for the groundwater base flow coefficient were adjusted by a method that links the surficial geologic characteristics of the model HRUs to the coefficient value that was used to adjust the groundwater routing (Bjerklie and others, 2010b). The default values for the subsurface routing coefficient, which represents the interflow component of groundwater runoff, were not adjusted in the model because there is insufficient regional information to assign values based on the GIS data. The value of the subsurface runoff coefficient affects groundwater recharge and the shape of the hydrograph recession.

The routing coefficients used in the model are linear functions, and the model would be expected to respond similarly to different input data of similar range. The current and future input datasets used for the simulations generally show a shift in the mean, maximum, and minimum that is in the same direction without a large change in the range of the data. As a consequence, the changes in model simulations will remain comparable between current and future timeframes as long as the input data sources and parameterization methods are self-consistent. Simulation errors (difference between the USGS streamflow data and the simulated streamflow) for the calibrated model, therefore, will be consistently carried over to future timeframes, and the magnitude and frequency of changes between simulated current and future conditions will be a product of the differences in the input datasets and the physical constraints of the modeled hydrologic system and will not be arbitrary.

New Hampshire exhibits a strong temperature gradient with latitude, and the PET coefficients were adjusted to account for this by uniquely fitting each coefficient to each HRU. The coefficient was adjusted up or down by a factor constant for all HRUs to match the long-term water balance so that precipitation minus actual evapotranspiration (AET) equals the mean annual streamflow (total runoff) for the calibration period (1980–2011) at each of the 45 streamgages. It is assumed that matching the long-term mean does not seriously bias the daily and seasonal water balance estimates. The effects of the long-term calibration on the seasonal and daily time scales are assessed for the four small-area (subset) models in the following section.

The New Hampshire model showed very good simulation of the mean streamflow at all of the streamgages after statewide calibration (fig. 4). The mean error for the simulated daily streamflows for all 45 streamgages is 2.7 percent, which indicates that the regional water balance, on average, is well simulated. The mean error in the standard deviation of the simulated daily streamflows was 2.2 percent, which indicates that the variation in mean streamflows around the State was also well simulated.

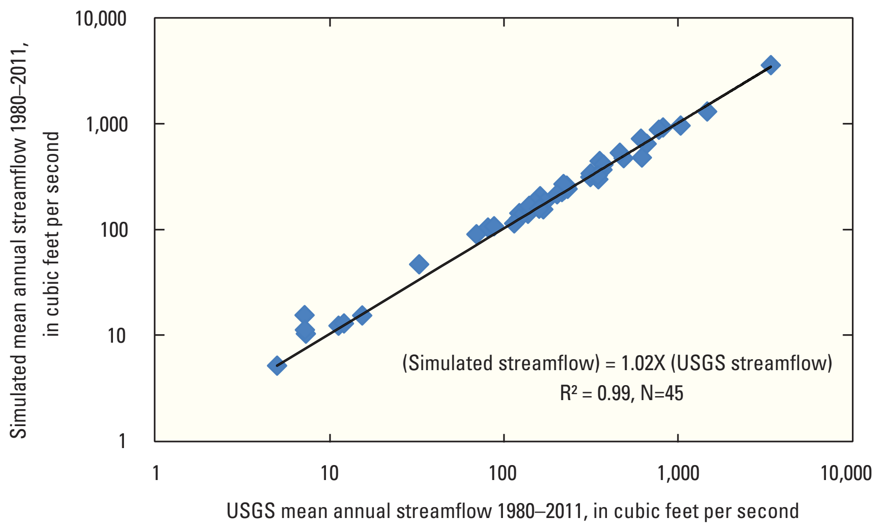

Figure 4. Simulated compared to mean annual streamflow at 45 calibration streamgages in New Hampshire.

Selection and Evaluation of Small-Area Models

Four small-area models were developed for more detailed analysis of the local effects of climate change on hydrology, (fig. 2) and to evaluate the performance of the calibrated New Hampshire model in more detail. The four watersheds (referred to as pilot study watersheds) chosen for detailed analysis, with HRUs at the same scale as the New Hampshire model, include the Ashuelot River watershed in southwestern New Hampshire in the Connecticut River Basin the Oyster River watershed in southeastern coastal New Hampshire in the Piscataqua River Basin, the Souhegan River watershed in south-central New Hampshire in the Merrimack River Basin, and the Pemigewasset River watershed in north-central New Hampshire in the southern White Mountain region. The Ashuelot River watershed is representative of a populated area of the State, but with less development than southern and coastal areas, and is also representative of the Connecticut Valley region. The population in the Oyster River and Souhegan River watersheds is rapidly increasing, and expansion of developed areas is likely to continue. The Pemigewasset River watershed is representative of an area of the State not expected to experience substantial increases in development. This watershed reflects the hydrology of high altitudes and mountainous terrain in the State.

The four pilot watersheds provide an initial look at the performance of the New Hampshire model in greater detail in four areas considered to be representative of physiographic environments in the State, including two areas (southeastern coastal and south-central) expected to grow in population during the coming decades. The evaluation results for the pilot watersheds are listed in tables 3 and 4 and shown on figure 5. The results are evaluated with the fractional percent error difference between the simulated and the measured streamflow (simulated minus measured divided by the measured) during the 31-year calibration period, the fractional percent difference between the standard deviation of the simulated and measured streamflow, the Nash-Sutcliffe efficiency (NSE) statistic (Nash and Sutcliffe, 1970), and the normalized root mean square error (NRMSE) between the simulated and measured streamflow (Goode and others, 2010). The percent difference provides information on how well the model simulates the mean and the standard deviation of measured data but does not account for the timing of the streamflow; differences can be overemphasized at the low end of the flow range and individual large errors can have a large affect even if the majority of the differences have small errors.

The NSE statistic and the NRMSE are measures of how well a simulated dynamic time series (streamflow hydrograph) fits the measured time series during the period of record. The NSE and the NRMSE statistics indicate how well the simulated hydrograph fits the dynamics of the measured hydrograph relative to the mean of the measured time series. A value of 1 for the NSE indicates that the simulated and measured time series are identical, and a value of 0 indicates that the simulated time series provides as much predictive information as the mean of the measured time series alone. Negative values for NSE indicate that the model simulation provides less predictive information than the mean value. The NRMSE provides a similar measure as the NSE with somewhat less emphasis on the highest streamflows, however, it is more difficult to interpret. An NRMSE value of 0 indicates a perfect fit between the simulated and observed time series, and a value of 1 indicates that the model simulation has the same predictive power as the mean (reverse of the interpretation of the NSE).

The statistics for the daily values during entire period are listed in table 3, and the statistics for the monthly aggregated values are listed in table 4. The comparison of the monthly simulated hydrographs and the measured hydrographs are

Table 3. Evaluation of daily statistics for four watersheds in New Hampshire.

[USGS, U.S. Geological Survey; No., number; ft^3/s, cubic feet per second; stdev, standard deviation; PRMS, precipitation runoff modeling system]

USGS streamflow gaging station	Data source	Mean (ft^3/s)	Standard deviation (ft^3/s)	Percent difference in mean	Percent difference in stdev	Normalized root mean square error	Nash-Sutcliffe coefficient
Ashuelot River at Hinsdale, N.H. 1161000	USGS Measured	772.0	831.5				
	Simulated	868.4	831.2	0.12	-0.00	0.61	0.63
Oyster River near Durham, N.H. 1073000	USGS Measured	21.6	37.1				
	Simulated	25.3	37.9	0.17	0.02	0.56	0.69
Pemigewasset River at Plymouth, N.H. 1076500	USGS Measured	1,464.9	2,027.6				
	Simulated	1,289.1	1,172.8	-0.12	-0.42	0.76	0.40
Souhegan River at Merrimack, N.H. 1094000	USGS Measured	373.2	471.7				
	Simulated	405.9	399.5	0.09	-0.15	0.58	0.67
Overall mean				0.06	-0.14	0.63	0.60

shown on figure 5. The results show that the mean simulated daily streamflow for the 31-year calibration period matches the USGS measured streamflows within -12 to 17 percent, with an average difference for all four basins of 6 percent. The difference in simulated standard deviations was less, from -15 to 0 percent for three rivers, but was -42 percent for the Pemigewasset River. The large difference for the Pemigewasset was a result of the poor representation of the highest precipitation events at the high altitudes in the input data and the resulting underprediction of the highest streamflow events. The large mean error (56 percent) for the Oyster River (table 3), could be associated with the large relative effect of groundwater pumping during low streamflow periods. Water use effects are not simulated in PRMS, and low streamflows are often not well simulated because of the simple linear reservoir representation of base flow that is used by PRMS. The mean percent differences and range of differences in this study are similar to the differences found in other calibrated PRMS models developed in complex terrain where the data were used to assess hydrologic change and to represent hydrologic conditions in unmeasured watersheds when comparative data were not available (Koczot, 2005; Chase, 2011).

The aggregated monthly differences (figs. 5 and 6; table 4) indicate that the largest percent errors occur during different months for each river; the largest overall error was in the Oyster River even though the absolute error (the difference between the measured and simulated discharge) in the Oyster River was less than 10 cubic feet per second (ft^3/s) for any given month. The range of percent errors are within those documented for monthly mean streamflow in other USGS PRMS studies designed to simulate streamflow in ungaged rivers as part of water resource planning efforts (Chase, 2011). Similar to the percent errors for the mean daily simulation during the calibration period, the errors associated with the standard deviation are less than those associated with only looking at the mean value. This indicates that the model is simulating the variability of monthly streamflow with greater accuracy than the mean. Inspection of the monthly and mean monthly hydrographs (figs. 5 and 6) demonstrates that the seasonal characteristics of the model simulation capture the seasonal water balance and unique hydrograph characteristics of each river reasonably well.

With the exception of the Pemigewasset River, the NSE values for the daily simulations are above typical values (0.5 or better) for well calibrated hydrologic models (Moriasi and others, 2007). The NSE for the Pemigewasset, although not as high as the other rivers, is acceptable considering that the input data does not represent the high precipitation events well in this basin. The NSE values for monthly streamflow are better than the daily streamflow, which indicates that the aggregation of the daily streamflow to monthly streamflow improves the predictive power of the simulation and is well above the acceptable level, even in the Pemigewasset River. The range of NSE values are similar to those from other regional and local PRMS studies (Viger and others, 2010; Dudley and Nielsen, 2011; LaFontaine and others, 2013). The NRMSE values track similarly to the NSE values, showing a range for the daily simulations similar to other regional studies (Goode and others, 2010) with marked improvement for the monthly streamflow time series during the daily streamflow time series.

Table 4. Evaluation of monthly statistics for four watersheds in New Hampshire.

[USGS, U.S. Geological Survey; NSE, Nash-Sutcliffe efficiency coeeficient (dimesionless); NRMSE, normalized root mean square error; stdev, standard deviation]

USGS streamflow gaging station	Difference	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Ashuelot River NSE = 0.82 NRMSE = 0.42	Mean percent Stdev percent	0.27 -0.18	0.29 0.05	0.07 -0.19	0.01 -0.13	0.16 0.01	0.05 -0.12	0.02 -0.36	-0.01 -0.14	0.12 0.23	0.12 0.18	0.19 -0.05	0.25 -0.14
Oyster River NSE = 0.81 NRMSE = 0.43	Mean percent Stdev percent	0.55 0.15	0.35 -0.15	-0.12 -0.18	-0.09 -0.30	0.10 -0.06	0.13 -0.29	0.70 -0.11	0.61 0.11	0.78 0.58	0.43 0.35	0.34 0.11	0.21 -0.11
Pemigewasset River NSE = 0.79 NRMSE = 0.46	Mean percent Stdev percent	0.11 -0.35	0.07 -0.18	-0.13 -0.10	-0.22 -0.35	-0.04 -0.05	-0.09 0.00	-0.34 -0.20	-0.46 -0.36	-0.42 -0.15	-0.17 -0.07	-0.01 -0.01	0.11 -0.24
Souhegan River NSE = 0.82 NRMSE = 0.42	Mean percent Stdev percent	0.22 -0.15	0.20 0.04	-0.14 -0.42	0.07 -0.23	0.09 -0.33	-0.01 -0.44	0.13 -0.46	0.31 0.03	0.20 0.04	0.37 0.23	0.18 -0.32	0.04 -0.37

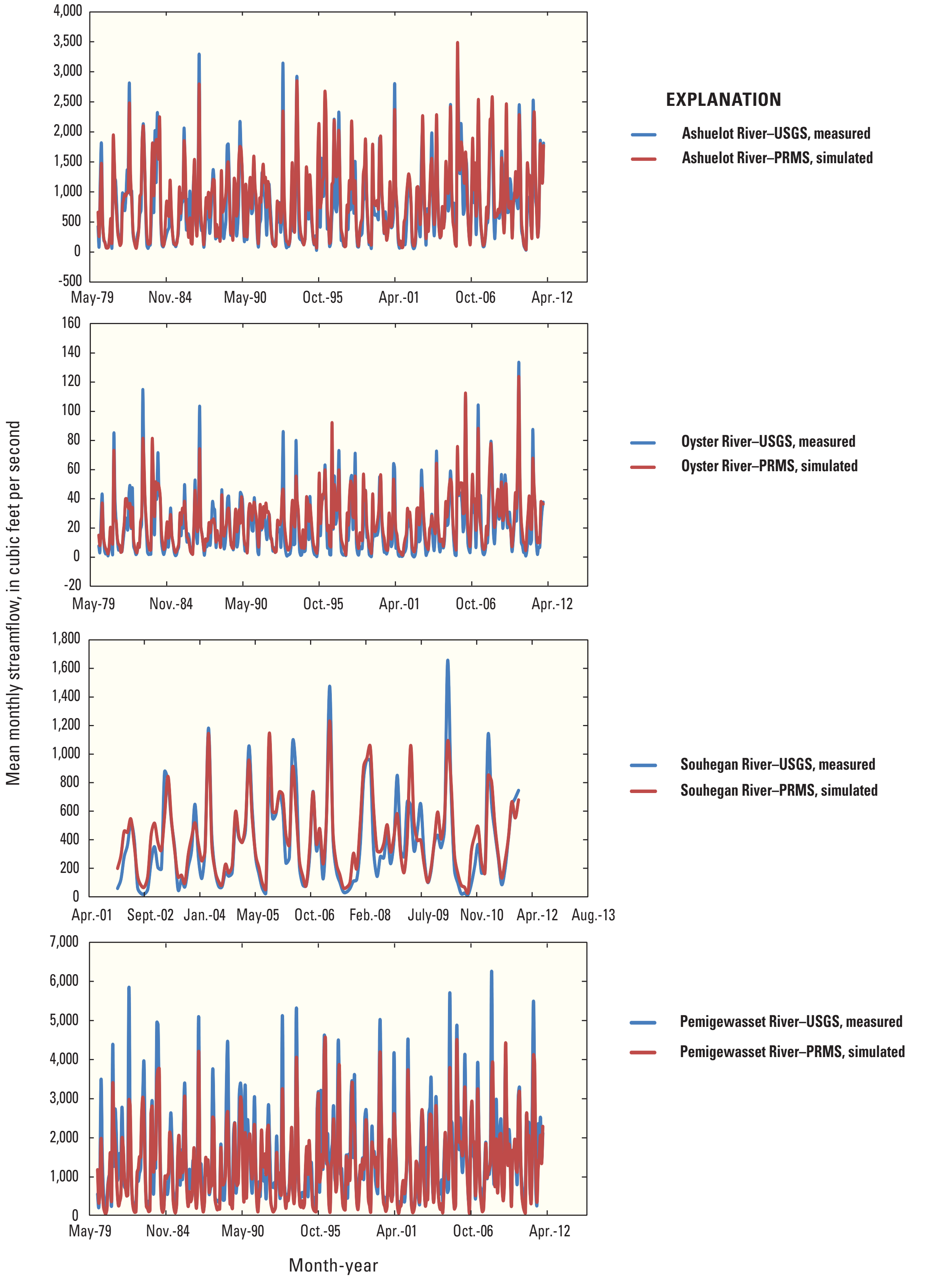

Figure 5. Monthly hydrographs for the calibration period from 1980 to 2011 for four pilot watersheds in New Hampshire. Note that the calibration period for the Souhegan River is from 2002 to 2011. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.

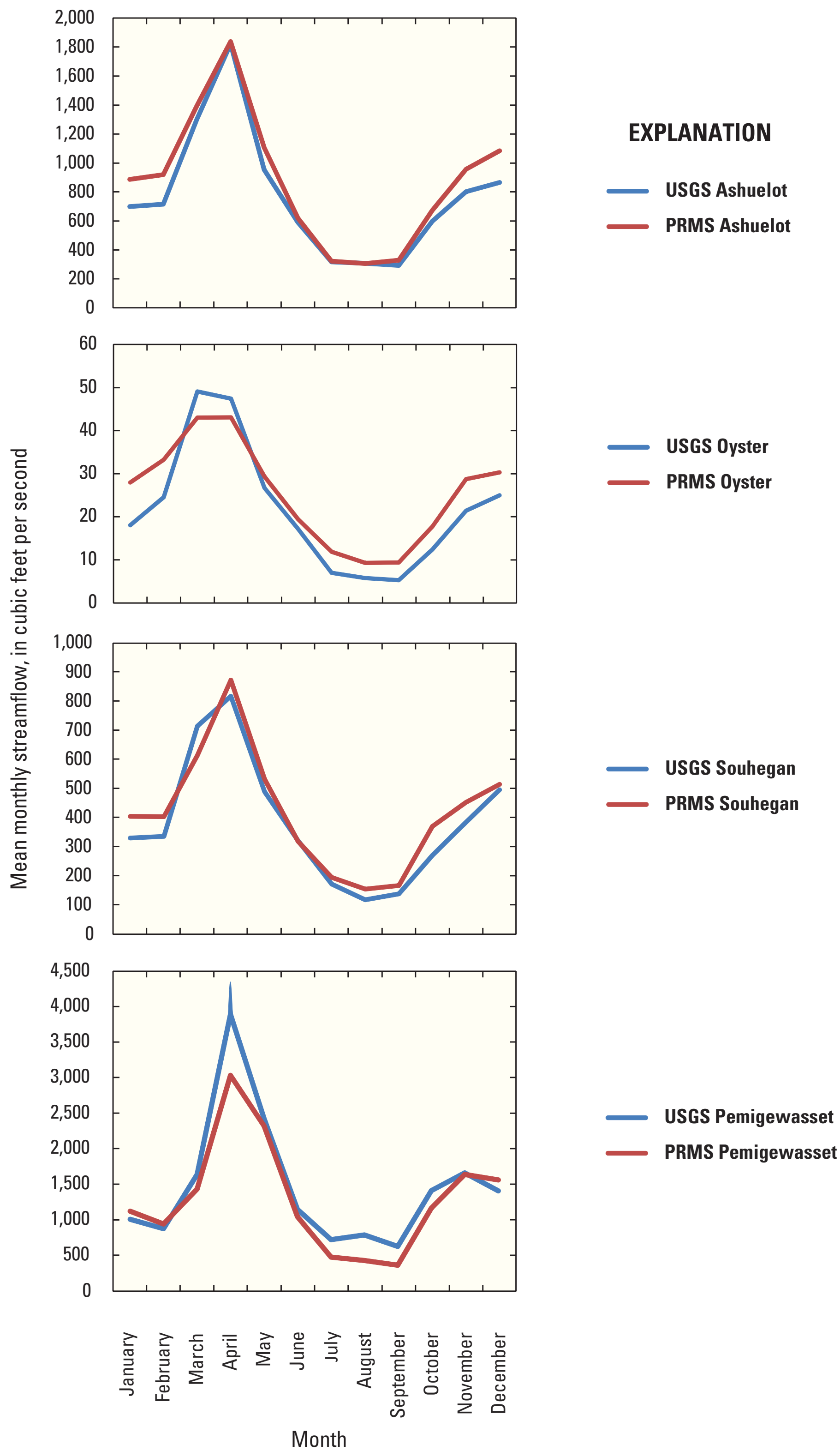

Figure 6. USGS-measured and PRMS-simulated mean monthly hydrographs for four pilot watersheds from 1981 to 2011. Note that the calibration period for the Souhegan River is from 2002 to 2011. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

The hydrologic simulations are generally adequate for analysis of potential future change from climate change, despite known issues with the input data in the Pemigewasset River watershed and groundwater withdrawals in the Oyster River watershed that are not accounted for in the model. This is evidenced by examining the hydrograph characteristics shown on figure 7. By inspection, the rate of rise for the rising limbs on the hydrographs and the rate of fall for the recessions on the hydrographs are similar for the measured and simulated hydrographs for all four basins, even if the magnitudes differ. This indicates that the routing processes are adequately simulated in the model. This is also evidenced by the NSE coefficients for the daily streamflows, which account for the flow timing and the magnitude. The comparisons between the simulated and measured streamflows for the calibration period support the usefulness of the models in simulating the hydrologic processes and the routing that occurs in the study watersheds even where the absolute magnitude could differ significantly. The future simulations using the PRMS model are expected to provide hydrologic responses to the future climate input datasets with similar behavior and accuracy for the daily streamflow and the seasonal variations. The focus of this study is to look at differences between current and future conditions, and as such, the future model results will only be compared with the current conditions using the same model parameters for each river. Therefore, the current and future comparisons will be evaluating change based on the same watershed characterization, and these comparisons are considered sufficiently valid as long as the water balance is represented well.

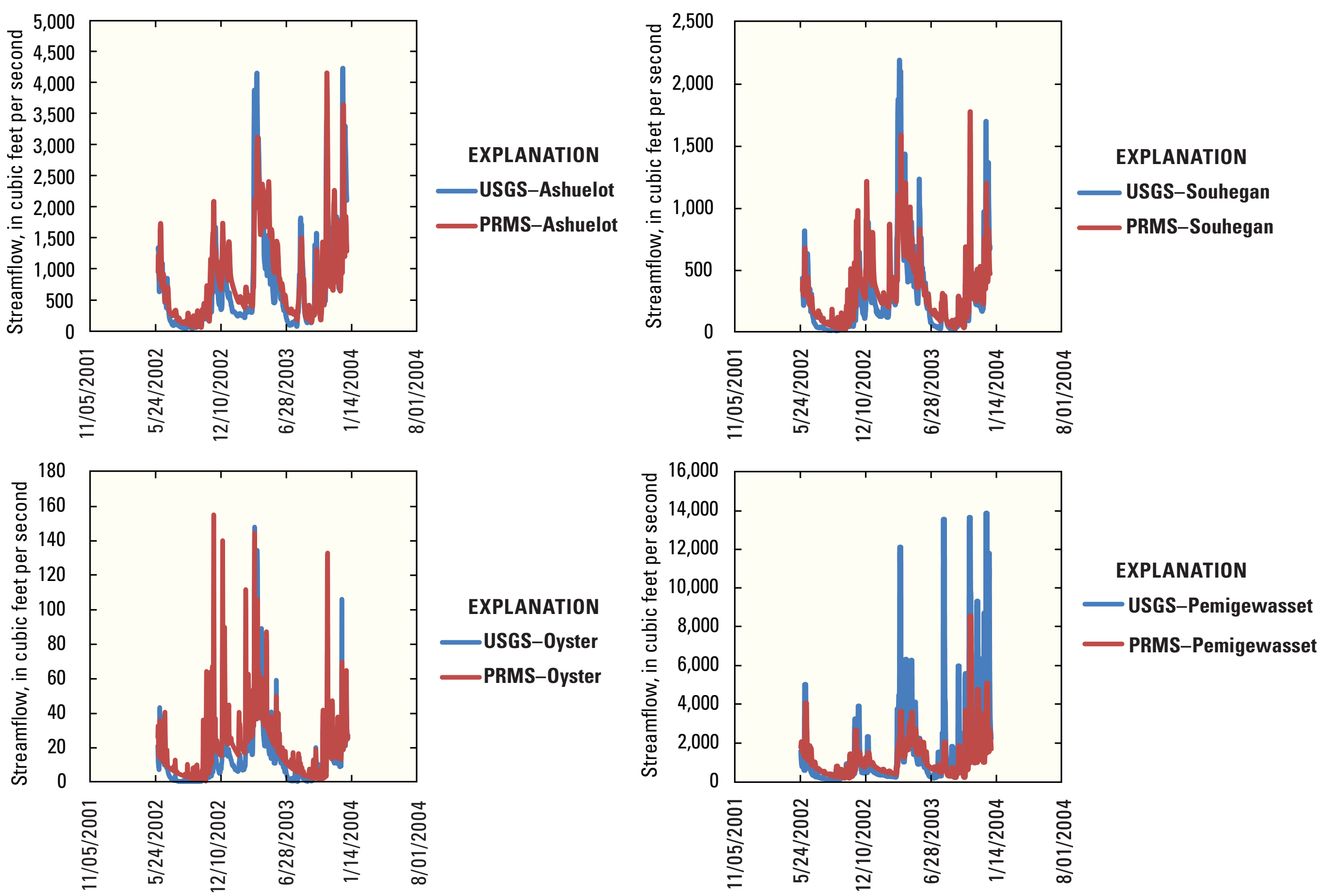

Figure 7. USGS-measured and PRMS-simulated streamflow spanning 1.5 years that show groundwater recession and rising limb characteristics for four pilot study rivers in New Hampshire. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.

Modeling of Future Streamflows

The parameterized and calibrated New Hampshire PRMS model was used to generate simulated daily estimates of streamflow for a 20-year period representing current hydrologic conditions (1981–2000) and future 20-year periods. The five GCMs chosen for this study each generated a 20-year end-of-century (2081–2100) time series of daily streamflow, snowfall, and base flow for each of two climate change scenarios (SRESa2 and SRESb1) and for the current conditions. Two of the models also generated midcentury time series (2046–2065) for comparison.

The comparative statistics for the results of the PRMS future simulations are provided in tables 5 through 8. The tables show the percent change in the mean and standard deviations for the simulated daily time series and the change in number of days greater than or less than the indicated streamflow exceedance threshold. In the tables, the number of days greater than 10 percent equals the number of daily streamflows during the 20-year record above the streamflow that exceeded 10 percent of the streamflows. The number of days less than 90 percent equals the number of days with streamflow less than the streamflow that exceeded 90 percent of all streamflows.

All the GCMs except the ECHAM5 model showed consistent increases in mean daily streamflow for each scenario and each river. In general, considering both emission scenarios, the CNRM and CGCM model input data estimated the largest increases in mean daily streamflow, and the ECHAM5 showed decreasing or very small increases in mean daily streamflow. All the rivers for each GCM showed increasing standard deviation of streamflow except the ECHAM5 SRESb1 scenario for the Oyster River. With few exceptions, all the GCMs for each of the four rivers showed an increasing number of high daily streamflows, exceeding the 10- and 1-percent high-streamflow value, and low streamflows below the 90- and 99-percent low-streamflow value. The increases in variability were similar in all the watersheds, with the greatest in the southern and coastal watersheds (Oyster River and Souhegan River). Use of input data from the CNRM model shows that changes in mean daily streamflow for the midcentury simulations are less than the changes for the end-of-century simulations, which indicates a graduated change from the present until 2100. This is also true using the GFDL input data for the SRESb1 scenario, however, by using the SRESa2 scenario GFDL input for all four rivers, the end-of-century mean streamflows are lower than midcentury streamflows. This indicates that using the GFDL model input for this scenario causes increases in evapotranspiration to overtake increases in precipitation, which alters the water balance and reduces streamflow.

The changes in streamflow also have a pronounced seasonal trend. The mean monthly change in streamflow for the simulations made with CNRM, GFDL, and ECHAM5 GCM scenarios are shown in figures 8 through 11. Most of the rivers show the largest increases in streamflow during the winter (December through February) and spring seasons (March through May) and the largest decreases in the summer (June through August), although the summer decreases are not large (less than 20 percent) for most of the GCM scenarios. A notable exception is that in the Ashuelot and Pemigewasset Rivers, using the ECHAM5 input data, the highest monthly streamflows occur earlier in the winter and spring with a smaller spring snowmelt volume. The climate change effects on streamflow are most pronounced relative to current conditions for the winter and spring months.

The change in the largest streamflows during the 20-year simulation period for all four rivers are compared by looking at the change in the number of days that the 0.1-percent exceedance streamflow occurs between current simulation periods and the future simulation periods. The 0.1-percent exceedance translates to the seven largest streamflows for the current (1981–2000) 20-year simulation period. Additionally, the average of the seven largest daily streamflow for the 20-year periods of future simulation were also compared with the current period simulation. These statistics are shown in table 9, and the results varied by river, GCM, and scenario. Generally, the largest streamflows increased in frequency for all of the rivers. However, the magnitudes of the largest streamflows (average of the seven largest daily streamflows during the 20-year period) did not generally increase for all rivers, GCMs, scenarios, and time frames with the exception of the Pemigewasset River which increased in all of the simulations. This suggests that, in much of New Hampshire with the exception of the White Mountain region where the Pemigewasset River watershed is located, flooding will increase in frequency but not necessarily in magnitude. The magnitude and frequency of peak streamflows increased by a relatively large amount in the Pemigewasset River and to a lesser, but still large, degree in the Ashuelot River compared with the Oyster and Souhegan Rivers.

The projected change in streamflows can be difficult to assess by looking at the hydrographs (figs. 7 through 11) and summary tables (tables 5 through 9). Plotting the daily streamflow data as a streamflow duration organizes the information so that statistical trends can be readily seen. The streamflow duration curves for the Oyster and Pemigewasset Rivers, simulated from the CNRM and GFDL GCMs, are shown on figures 12*A*–*D* (in back of report), with simulated streamflows for the 20-year current and future time periods ranked highest to lowest and plotted as a probability of exceedance. The lowest streamflow in the simulation record is the streamflow that is exceeded 100 percent of the time. Thus, the lowest streamflows have the highest probability of exceedance, and the highest streamflows have the lowest probability of exceedance, with the highest streamflow in the simulation record having a zero-percent chance of exceedance. The largest changes in predicted streamflow are observed at the extremes—the highest and lowest probabilities.

Table 5. Summary statistics for climate change simulations for the Oyster River watershed in New Hampshire.

[GCM, general circulation model; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1; CNRM, Centre National de Recherches Meteorologiques model; GFDL, Geophysical Fluid Dynamics Laboratory model; CSIRO, Commonwealth Scientific and Industrial Research Organisation model; ECHAM5, European Centre Hamburg Model version 5; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model; stdev, standard deviation]

GCM	Mean_diff[1]	Stdev_diff[2]	∆Days greater than 10 percent[3]	∆Days less than 90 percent[4]	∆Days greater than 1 percent[5]	∆Days less than 99 percent[6]
	Scenario SRESa2		Future simulation period 2081–2100			
CNRM	0.18	0.37	194	68	69	95
GFDL	0.12	0.45	88	90	65	43
CSIRO	0.11	0.71	49	152	52	19
ECHAM5	0.02	0.09	47	461	19	168
CGCM	0.22	0.47	191	-182	54	-59
Mean	0.13	0.42	113.80	117.80	51.80	53.20
Stdev	0.08	0.22	73.69	230.27	19.69	84.84
	Scenario SRESa2		Future simulation period 2046–2065			
CNRM	0.12	0.22	121	-12	61	36
GFDL	0.14	0.51	146	-29	64	58
	Scenario SRESb1		Future simulation period 2081–2100			
CNRM	0.12	0.11	129	-51	26	49
GFDL	0.17	0.48	200	-114	63	9
CSIRO	0.07	0.39	11	352	44	128
ECHAM5	-0.03	-0.01	0	442	10	84
CGCM	0.03	0.20	3	178	29	10
Mean	0.07	0.23	68.60	161.40	34.40	56.00
Stdev	0.08	0.20	91.16	243.05	20.03	50.85
	Scenario SRESb1		Future simulation period 2046–2065			
CNRM	0.08	0.04	137	72	19	65
GFDL	0.06	0.42	35	124	55	106

[1]Mean_diff is the difference between the mean of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[2]Stdev_diff is the difference between the standard deviation of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[3]∆Days greater than 10 percent is the number of days with streamflow greater than the streamflow exceeded 10 percent of the time (10th percentile).

[4]∆Days greater than 90 percent is the number of days with streamflow less than the streamflow exceeded 90 percent of the time (90th percentile).

[5]∆Days greater than 1 percent is the number of days with streamflow greater than the streamflow exceeded 1 percent of the time (1st percentile).

[6]∆Days less than 99 percent is the number of days with streamflow less than the streamflow exceeded 99 percent of the time (99th percentile).

Table 6. Summary statistics for climate change simulations for the Pemigewasset River watershed in New Hampshire.

[GCM, general circulation model; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1; CNRM, Centre National de Recherches Meteorologiques model; GFDL, Geophysical Fluid Dynamics Laboratory model; CSIRO, Commonwealth Scientific and Industrial Research Organisation model; ECHAM5, European Centre Hamburg Model version 5; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model; stdev, standard deviation]

GCM	Mean_diff[1]	Stdev_diff[2]	∆Days greater than 10 percent[3]	∆Days less than 90 percent[4]	∆Days greater than 1 percent[5]	∆Days less than 99 percent[6]
	Scenario SRESa2		Future simulation period 2081–2100			
CNRM	0.14	0.32	190	358	84	147
GFDL	0.01	0.39	111	844	63	457
CSIRO	0.09	0.60	110	579	155	164
ECHAM5	-0.00	0.16	21	576	49	129
CGCM	0.15	0.23	180	123	67	117
Mean	0.08	0.34	122.40	496.00	83.60	202.80
Stdev	0.07	0.17	67.92	270.45	41.82	143.22
	Scenario SRESa2		Future simulation period 2046–2065			
CNRM	0.09	0.26	129	65	66	27
GFDL	0.05	0.26	136	445	66	212
	Scenario SRESb1		Future simulation period 2081–2100			
CNRM	0.09	0.14	117	111	29	-12
GFDL	0.10	0.40	224	283	70	129
CSIRO	0.06	0.59	-27	653	106	167
ECHAM5	-0.01	0.13	-25	459	25	71
CGCM	0.03	0.13	2	327	30	176
Mean	0.05	0.28	58.20	366.60	52.00	106.20
Stdev	0.05	0.21	109.87	202.76	35.29	77.94
	Scenario SRESb1		Future simulation period 2046–2065			
CNRM	0.06	0.11	147	210	24	40
GFDL	-0.01	0.30	72	533	45	251

[1]Mean_diff is the difference between the mean of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[2]Stdev_diff is the difference between the standard deviation of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[3]∆Days greater than 10 percent is the number of days with streamflow greater than the streamflow exceeded 10 percent of the time (10th percentile).

[4]∆Days greater than 90 percent is the number of days with streamflow less than the streamflow exceeded 90 percent of the time (90th percentile).

[5]∆Days greater than 1 percent is the number of days with streamflow greater than the streamflow exceeded 1 percent of the time (1st percentile).

[6]∆Days less than 99 percent is the number of days with streamflow less than the streamflow exceeded 99 percent of the time (99th percentile).

Table 7. Summary statistics for climate change simulations for the Souhegan River watershed in New Hampshire.

[GCM, general circulation model; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1; CNRM, Centre National de Recherches Meteorologiques model; GFDL, Geophysical Fluid Dynamics Laboratory model; CSIRO, Commonwealth Scientific and Industrial Research Organisation model; ECHAM5, European Centre Hamburg Model version 5; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model; stdev, standard deviation]

GCM	Mean_diff[1]	Stdev_diff[2]	∆Days greater than 10 percent	∆Days less than 90 percent	∆Days greater than 1 percent	∆Days less than 99 percent
	Scenario SRESa2		Future simulation period 2081–2100			
CNRM	0.17	0.38	269	119	98	79
GFDL	0.08	0.44	108	233	85	118
CSIRO	0.06	0.69	34	303	86	4
ECHAM5	-0.02	0.11	96	665	5	356
CGCM	0.22	0.44	319	-66	82	-47
Mean	0.10	0.41	165.20	250.80	71.20	102.00
Stdev	0.10	0.21	122.17	270.34	37.51	155.81
	SRESa2		Future simulation period 2046–2065			
CNRM	0.11	0.27	159	-19	79	2
GFDL	0.11	0.39	139	50	59	17
	Scenario SRESb1		Future simulation period 2081–2100			
CNRM	0.09	0.12	141	-5	45	0
GFDL	0.16	0.52	221	-174	74	-5
CSIRO	0.04	0.40	2	420	75	125
ECHAM5	-0.01	0.09	45	529	8	187
CGCM	0.06	0.22	107	137	41	16
Mean	0.07	0.27	103.20	181.40	48.60	64.60
Stdev	0.06	0.19	85.07	291.88	27.66	86.62
	SRESb1		Future simulation period 2046–2065			
CNRM	0.06	0.03	173	137	23	50
GFDL	0.02	0.33	9	236	32	156

[1]Mean_diff is the difference between the mean of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[2]Stdev_diff is the difference between the standard deviation of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[3]∆Days greater than 10 percent is the number of days with streamflow greater than the streamflow exceeded 10 percent of the time (10th percentile).

[4]∆Days greater than 90 percent is the number of days with streamflow less than the streamflow exceeded 90 percent of the time (90th percentile).

[5]∆Days greater than 1 percent is the number of days with streamflow greater than the streamflow exceeded 1 percent of the time (1st percentile).

[6]∆Days less than 99 percent is the number of days with streamflow less than the streamflow exceeded 99 percent of the time (99th percentile).

Table 8. Summary statistics for climate change simulations for the Ashuelot River watershed in New Hampshire.

[GCM, general circulation model; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1; CNRM, Centre National de Recherches Meteorologiques model; GFDL, Geophysical Fluid Dynamics Laboratory model; CSIRO, Commonwealth Scientific and Industrial Research Organisation model; ECHAM5, European Centre Hamburg Model version 5; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model; stdev, standard deviation]

GCM	Mean_diff[1]	Stdev_diff[2]	ΔDays greater than 10 percent[3]	ΔDays less than 90 percent[4]	ΔDays greater than 1 percent[5]	ΔDays less than 99 percent[6]
	Scenario SRESa2		Future simulation period 2081–2100			
CNRM	0.16	0.39	263	109	122	74
GFDL	0.05	0.38	190	449	107	92
CSIRO	0.09	0.62	136	224	140	23
ECHAM5	-0.07	0.02	30	628	11	257
CGCM	0.19	0.34	334	12	83	-16
Mean	0.08	0.35	190.60	284.40	92.60	86.00
Stdev	0.10	0.21	116.81	251.88	50.17	104.64
	Scenario SRESa2		Future simulation period 2046–2065			
CNRM	0.11	0.29	157	-27	108	13
GFDL	0.10	0.29	227	109	93	0
	Scenario SRESb1		Future simulation period 2081–2100			
CNRM	0.08	0.22	72	82	54	15
GFDL	0.12	0.38	241	37	102	4
CSIRO	0.07	0.45	48	368	126	182
ECHAM5	-0.02	0.06	61	400	33	103
CGCM	0.06	0.22	149	165	38	7
Mean	0.06	0.26	114.20	210.40	70.60	62.20
Stdev	0.05	0.15	81.06	165.38	41.25	78.55
	Scenario SRESb1		Future simulation period 2046–2065			
CNRM	0.06	0.14	107	182	42	33
GFDL	0.03	0.24	105	323	65	89

[1]Mean_diff is the difference between the mean of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[2]Stdev_diff is the difference between the standard deviation of daily streamflows for the current period (1981–2000) and the future simulation period, in percent.

[3]ΔDays greater than 10 percent is the number of days with streamflow greater than the streamflow exceeded 10 percent of the time (10th percentile).

[4]ΔDays greater than 90 percent is the number of days with streamflow less than the streamflow exceeded 90 percent of the time (90th percentile).

[5]ΔDays greater than 1 percent is the number of days with streamflow greater than the streamflow exceeded 1 percent of the time (1st percentile).

[6]ΔDays less than 99 percent is the number of days with streamflow less than the streamflow exceeded 99 percent of the time (99th percentile).

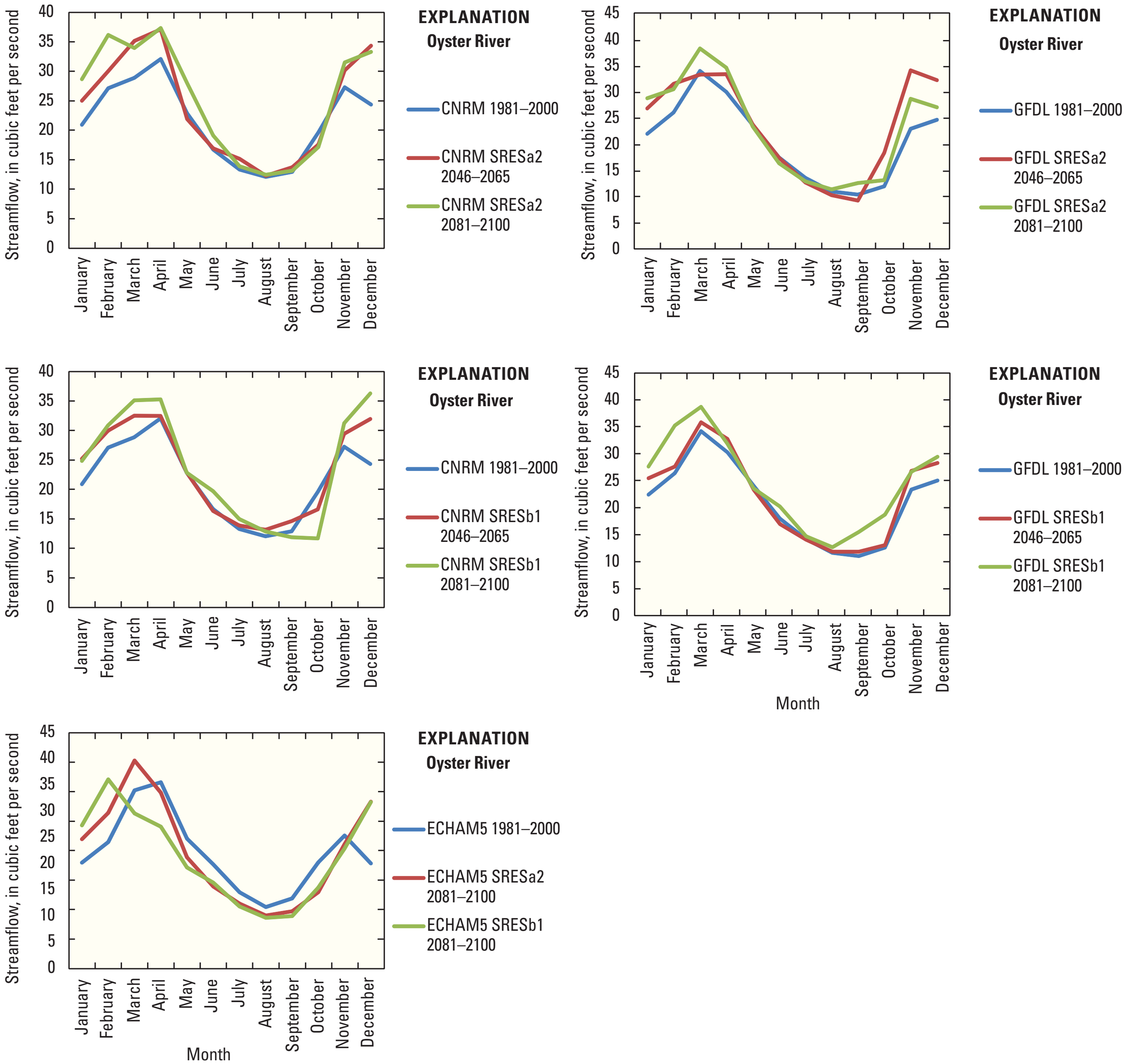

Figure 8. Mean monthly hydrographs for the simulated current and future streamflows in the Oyster River, New Hampshire, for the SRESa2 and SRESb1 scenarios, the midcentury and end-of-century simulations, respectively, using the CNRM and GFDL GCMs. The ECHAM5 simulations of end-of-century for the SRESa2 and SRESb1 scenarios are also shown for comparison. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.

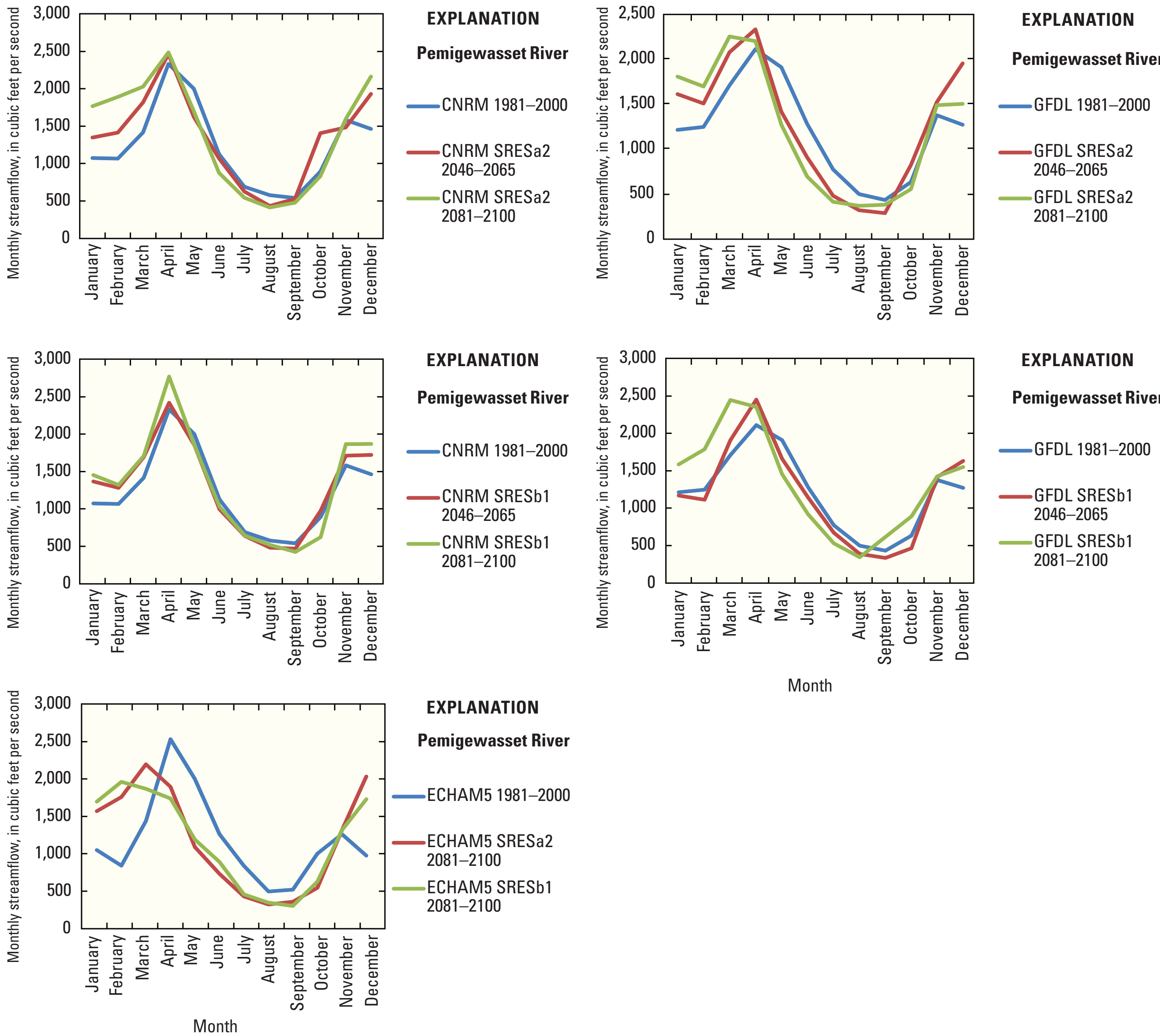

Figure 9. Mean monthly hydrographs for the simulated current and future streamflows in the Pemigewasset River, New Hampshire, for the SRESa2 and SRESb1 scenarios, the midcentury and end-of-century simulations, respectively, using the CNRM and GFDL GCMs. The ECHAM5 simulations of end-of-century for the SRESa2 and SRESb1 scenarios are also shown for comparison. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

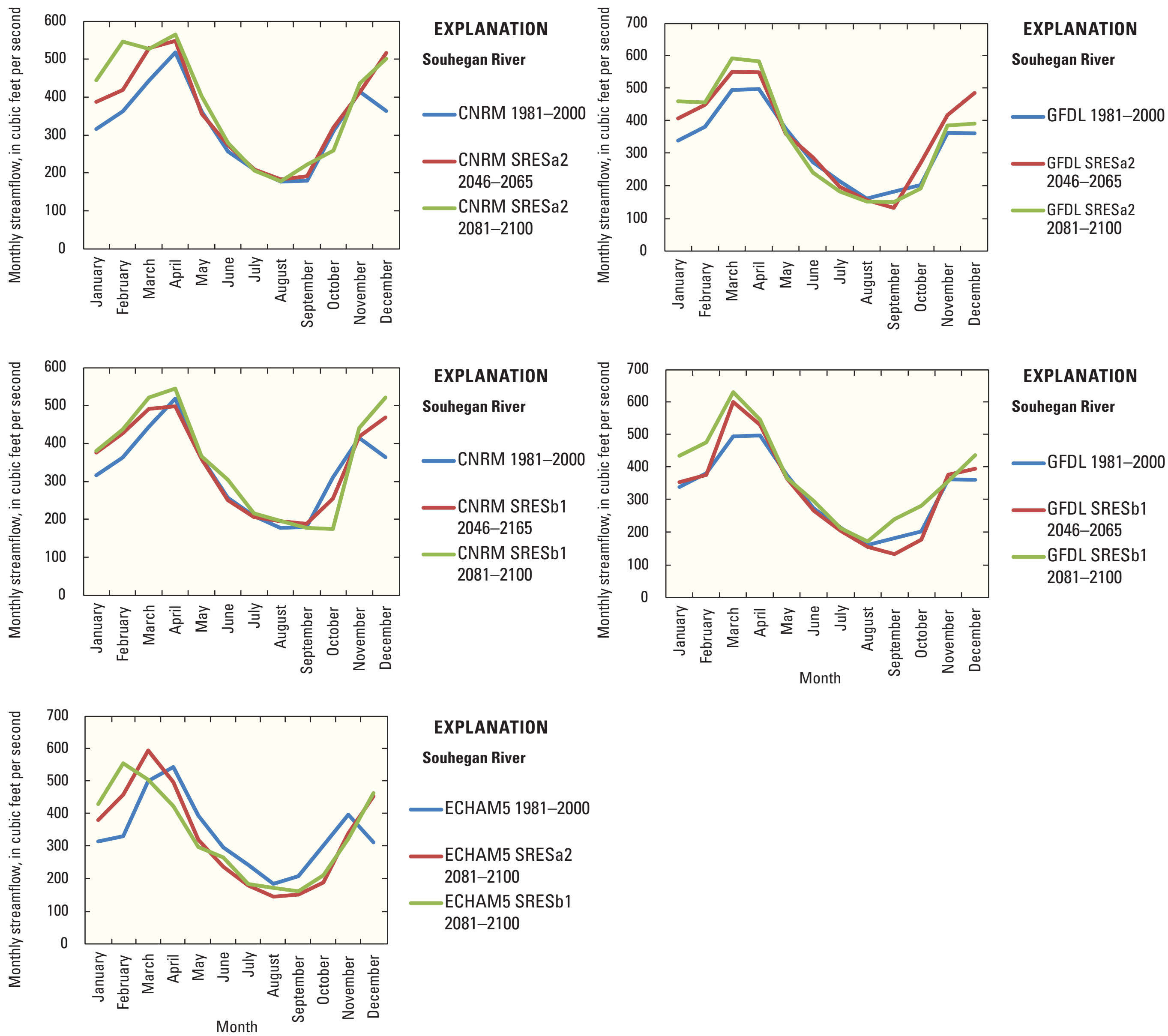

Figure 10. Mean monthly hydrographs for the simulated current and future streamflows in the Souhegan River, New Hampshire, for the SRESa2 and SRESb1 scenarios, the midcentury and end-of-century simulations, respectively, using the CNRM and GFDL GCMs. The ECHAM5 simulations of end-of-century for the SRESa2 and SRESb1 scenarios are also shown for comparison. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.

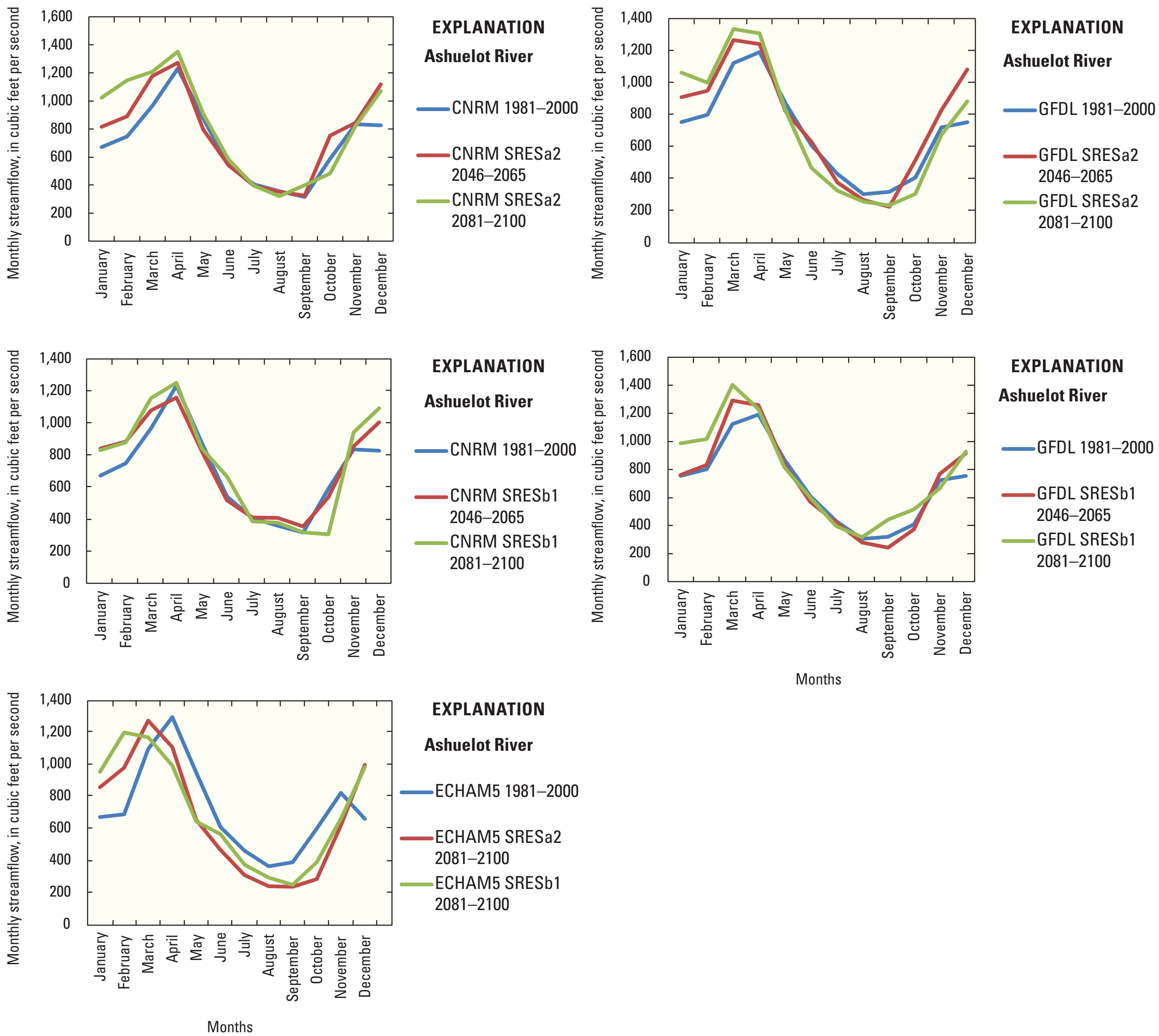

Figure 11. Mean monthly hydrographs for the simulated current and future streamflows in the Ashuelot River, New Hampshire, for the SRESa2 and SRESb1 scenarios, the midcentury and end-of-century simulations, using the CNRM and GFDL GCMs. The ECHAM5 simulations of end-of-century for the SRESa2 and b1 scenarios are also shown for comparison. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

Table 9. Comparison of the mean of the largest 0.1 percent of streamflows and 0.1 percent exceedance probability statistics for four watersheds in New Hampshire.

[Days > 0.1, the number of days with streamflow greater than the 0.1 percentile as defined by the current simulation period (1981–2000); the 0.1 percentile is that which is exceeded 0.1 percent of the time. Avg, average of seven largest streamflows in the model. ft³/s, cubic feet per second; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1]

Scenario, period of simulated record	Oyster River watershed		Pemigewasset River watershed		Souhegan River watershed		Ashuelot River watershed	
	Days > 0.1	Avg, in ft³/s	Days > 0.1	Avg, in ft³/s	Days > 0.1	Avg, in ft³/s	Days > 0.1	Avg, in ft³/s
Centre National de Recherches Meteorologiques general circulation model (GCM)								
Current, 1981–2000	7	5	7	13,266	7	5,325	7	6,720
SRESa2, 2046–2065	26	501	19	21,475	14	6,265	38	8,185
SRESa2, 2081–2100	28	587	26	16,135	20	5,410	53	8,929
SRESb1, 2046–2065	11	452	11	14,691	5	4,315	29	7,152
SRESb1, 2081–2100	16	469	15	15,113	7	4,221	41	8,419
Geophysical Fluid Dynamics Laboratory GCM								
Current, 1981–2000	7	323	7	11,695	7	3,038	7	6,334
SRESa2, 2046–2065	29	586	22	13,966	31	5,286	14	8,832
SRESa2, 2081–2100	31	463	29	18,912	36	4,804	26	9,066
SRESb1, 2046–2065	35	483	26	17,140	30	5,580	17	8,093
SRESb1, 2081–2100	32	528	36	19,374	46	5,583	28	9,477
[Japan Meteorological Agency] coupled ocean-atmosphere general circulation model								
Current, 1981–2000	7	417	7	17,130	7	4,390	7	7,106
SRESa2, 2081–2100	28	635	9	17,144	41	6,269	30	9,114
SRESb1, 2081–2100	15	536	11	19,332	14	6,331	17	9,418
Commonwealth Scientific and Industrial Research Organisation GCM								
Current, 1981–2000	7	346	7	12,583	7	3,527	7	5,619
SRESa2, 2081–2100	33	752	57	21,624	39	8,425	56	13,570
SRESb1, 2081–2100	15	520	58	23,752	29	5,177	56	9,393
European Centre Hamburg Model version 5 GCM								
Current, 1981–2000	7	530	7	14,451	7	4,862	7	8,541
SRESa2, 2081–2100	11	524	6	17,514	11	5,197	4	7,625
SRESb1, 2081–2100	5	536	12	19,332	8	6,331	8	9,418

The GFDL and the CNRM models show a similar overall pattern of the curve, which indicates both models are simulating similar mean flow patterns, but the GFDL model shows greater differences at the high and low end than does the CNRM model. Also note that both models show increasing highs and decreasing lows for the SRESa2 (high-emissions) scenario compared with the current condition for both time periods, but the SRESb1 (low-emissions) scenario does not show the same degree of change at the low streamflow end. The Oyster River is expected to experience smaller change at the low streamflow end and greater change at the high streamflow end, whereas there are large changes at the high and low ends of the streamflow range in the Pemigewasset River. Figures 12*E* and *F* (in back of report) represents an average of all the future simulations and scenarios for all five GCMs for the current, midcentury, and end-of-century time periods (representing the mean of all of the possible outcomes modeled). The average curves show similar trends. The Pemigewasset River shows the largest change relative to the current time period at the high and low streamflow ends of the curve, and the Oyster River shows change mostly at the high end of the streamflow range. It is interesting to note, however, that the average curve for the Pemigewasset River shows more change during the entire range of streamflow compared with the curves for the individual GCM models.

The simulated future changes in base flow and snowfall are predicted to vary by watershed and HRU location (figs. 13 and 14). This means that each area of the State could experience very different changes depending on topography or other factors. Therefore, different planning for infrastructure and public safety could need to be considered, depending on the location and the range of possible outcomes indicated by the various model inputs. The mean change in base flow and snowfall is computed by subtracting the 20-year mean for the future simulation from the 20-year mean for the current period simulation. The change statistics for each river's watershed by GCM and scenario are shown in table 10. The simulated changes in the mean indicate that snowfall is expected to decrease in all locations for all GCMs and scenarios, with the greatest decrease associated with the SRESa2 scenario and located in the Pemigewasset River watershed and the least change located in the Oyster River watershed (note that the model simulation estimates snowfall in inches of snow-water equivalent). To put the snowfall in a more familiar scale, the inches of water equivalent are multiplied by 10 to estimate an approximate amount of snow for a temperature range from 28 to 34 °F (National Oceanic and Atmospheric Administration, n.d.). The change in base flow varies widely by GCM, scenario, and HRU location, ranging from an increase in base flow (reported in inches of water) of about an inch, to a decrease by as much as 2 inches.

Taking all the GCM scenarios and watershed HRUs as a single statistical population, the mean decrease in snowfall is expected to range between 1 and 2 ft by the end of this century. Base flow (normalized by watershed area) is expected to decrease about 0.5 inch in the Ashuelot River and Souhegan River watersheds, 0.1 inch in the Oyster River watershed, and nearly 1 inch in the Pemigewasset River watershed.

There is a strong relation between the changes in base flow and snowfall and in geographic information for each HRU. Table 11 shows regression statistics that relate the mean changes in base flow and snowfall for each HRU with the altitude (feet above NAVD 88) and the latitude and longitude (relative to the North American Datum of 1983) for each HRU. Baseflow decreases with elevation and increases with latitude. Decrease of snowfall is inversely related to altitude (ranging from approximately 50 to 900 ft in the HRU population for the four watersheds) and latitude (ranging from 42 to 44 degrees north) and also inversely related to longitude (ranging from approximately 71.5 to 72.5 degrees west).

The simulated snowfall data, summarized by month and averaged during the 20-year simulation periods for all of the GCMs and scenarios (table 10), show decreases for each of the winter months. However, it is noted that the maximum monthly predicted snowfalls for the period of the simulations increase compared with the current condition. This indicates that, even though mean snowfall is decreasing from year to year, months of extreme snowfall can occur that exceed current conditions. Therefore, the snowfall from year to year and month to month is predicted to become more variable and the highs are predicted to be more extreme. This is because of the increased precipitation in months that remain below freezing in winter.

Potential Implications of Modeled Streamflow Changes

This study indicates a likelihood that climate change will alter flow regimes in rivers, snowfall amounts, and groundwater recharge both spatially and temporally. The direction of these changes, more frequent flooding and lower streamflows, increasing and decreasing groundwater recharge depending on location, and reduced snowfall but with continued chance of extreme snowfall during some years have implications for human and natural adaptations. For example, river channels will adjust to changing flow regimes over time (Leopold, 1994; Gibson and others, 2005), such that increasing flood frequency and magnitude would enlarge the river channel, and overbank flooding eventually will reach an equilibrium similar to the current condition. However, there will be a transition period that could be many years (Gibson and others, 2005). Similar to the natural environment, the developed environment—including roads, dams, river works, and recreational facilities—will also need to adapt to hydrologic change, which could take some time. It is recognized that hydrologic changes could not reach a static or even an equilibrium condition but could be in flux for a long period (Milly and others, 2008).

The implications of the hydrologic changes documented in this study for human health and well-being fall into multiple general categories (Backlund and others, 2008; Melillo and others, 2014). Although there will likely be economic effects resulting from climate change and effects on utilities including water and wastewater conveyance, and energy transmission, these are not directly assessed in this report.

The changes in hydrology discussed in this report are linked primarily to the potential for more rapid degradation of transportation infrastructure and attendant effects on public safety. Less predictable winter weather and more high streamflow events in the winter with attendant effects on water and transportation infrastructure could lead to adverse effects including increased frequency of road overtopping by high flows at stream crossings, less predictable winter driving conditions, and increased frequency of damage to culverts and bridges due to more frequent erosive high flows at stream crossings (Backlund and others, 2008; Melillo and others, 2014). The increased frequency of floods can also have large effects in low-lying areas and could have an important effect on stream geomorphology and erosion.

Changes in engineering practices, design, operation, and maintenance could be needed in the future to ensure that public safety does not decline. Planning for these changes will be challenging when estimating priority needs and balancing those needs with increasing costs (Melillo and others, 2014).

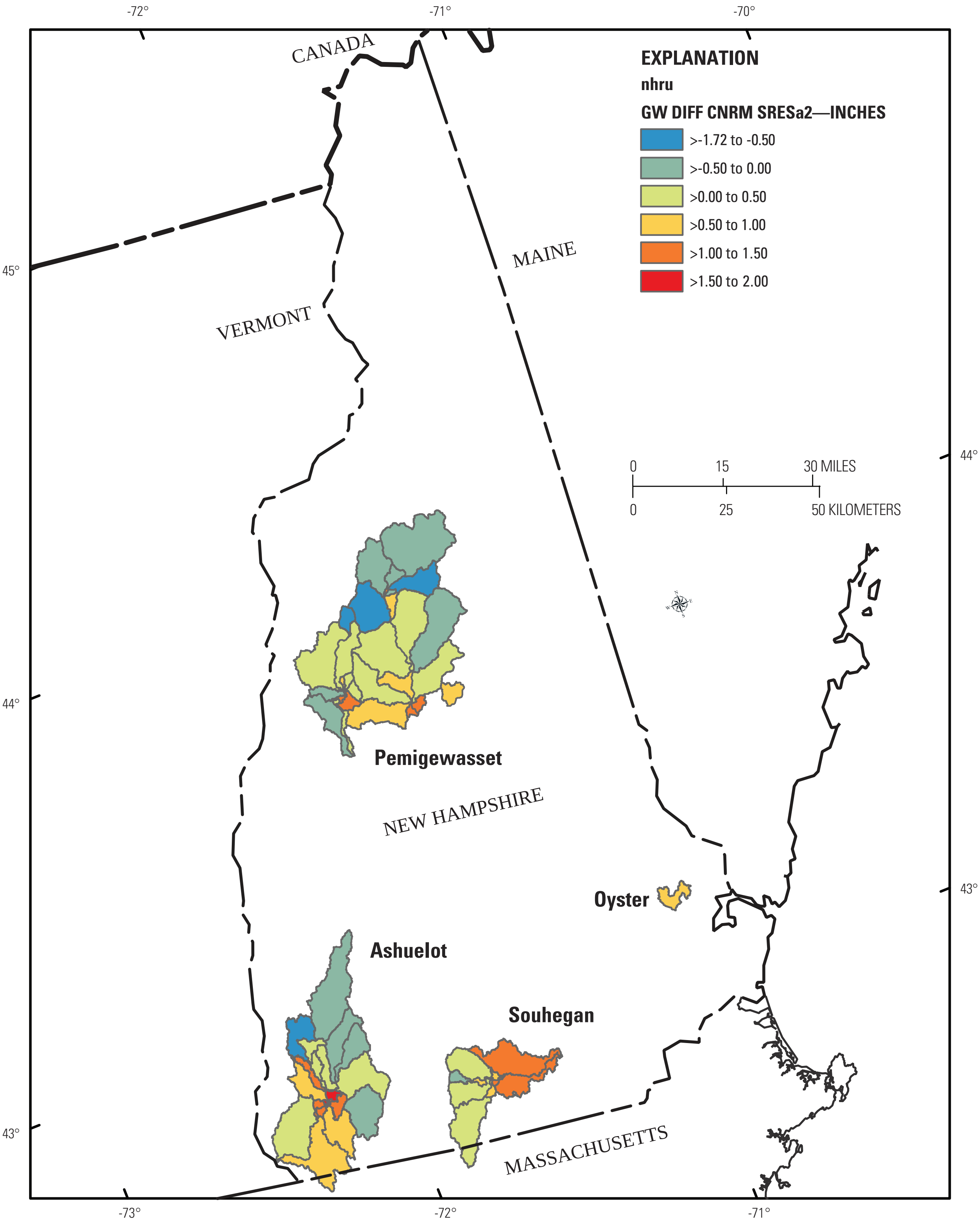

Figure 13. The simulated change in base flow between current (1981–2000) and end-of-century (2081–2100) periods using the CNRM model for the two scenarios mapped by hydrologic response unit in the four pilot river watersheds in New Hampshire. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

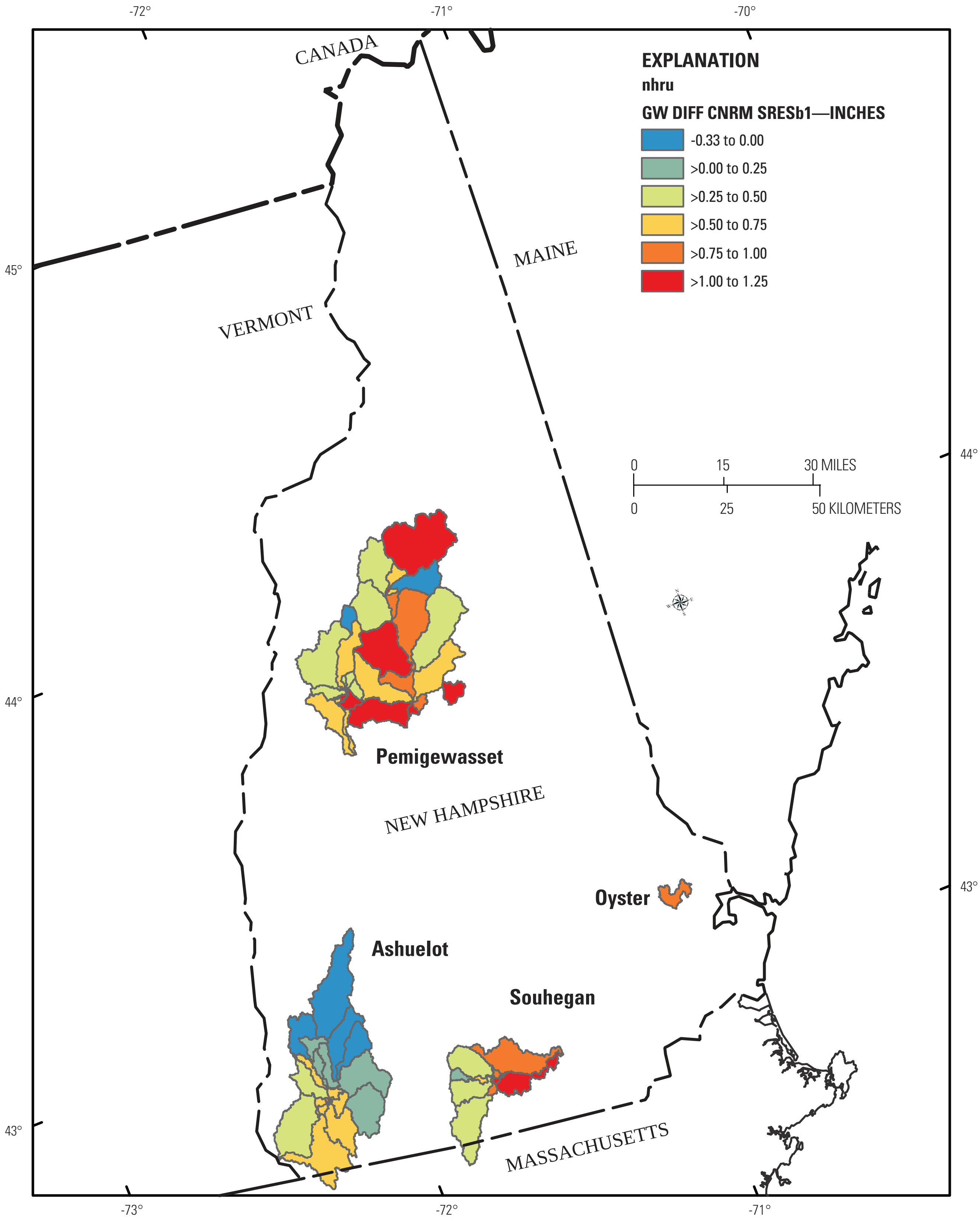

Figure 13. The simulated change in base flow between current (1981–2000) and end-of-century (2081–2100) periods using the CNRM model for the two scenarios mapped by hydrologic response unit in the four pilot river watersheds in New Hampshire. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.—Continued

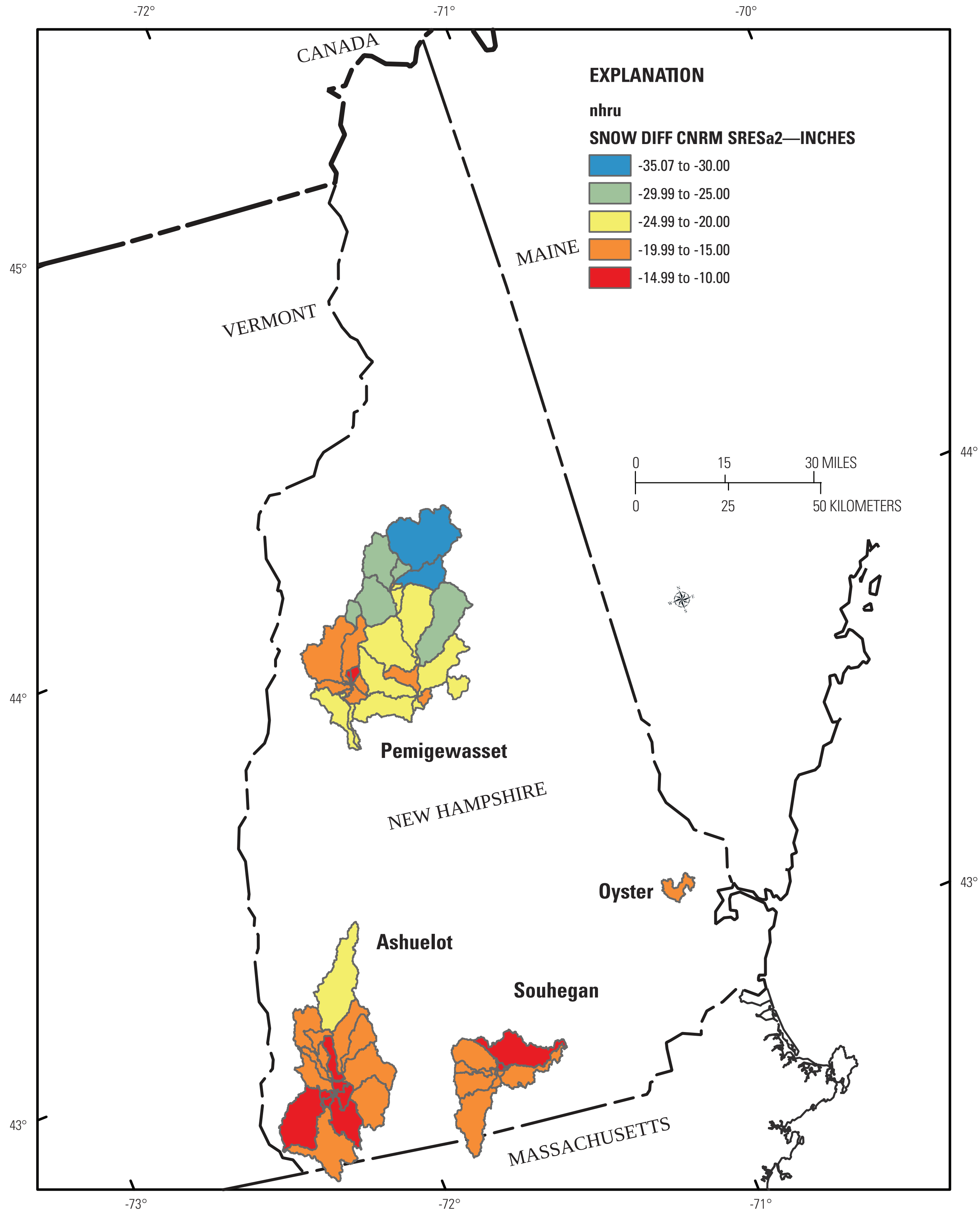

Figure 14. The simulated change in snowfall between current (1981–2000) and end-of-century (2081–2100) time periods using the CNRM model for the two scenarios mapped by hydrologic response unit in the four pilot river watersheds in New Hampshire. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.

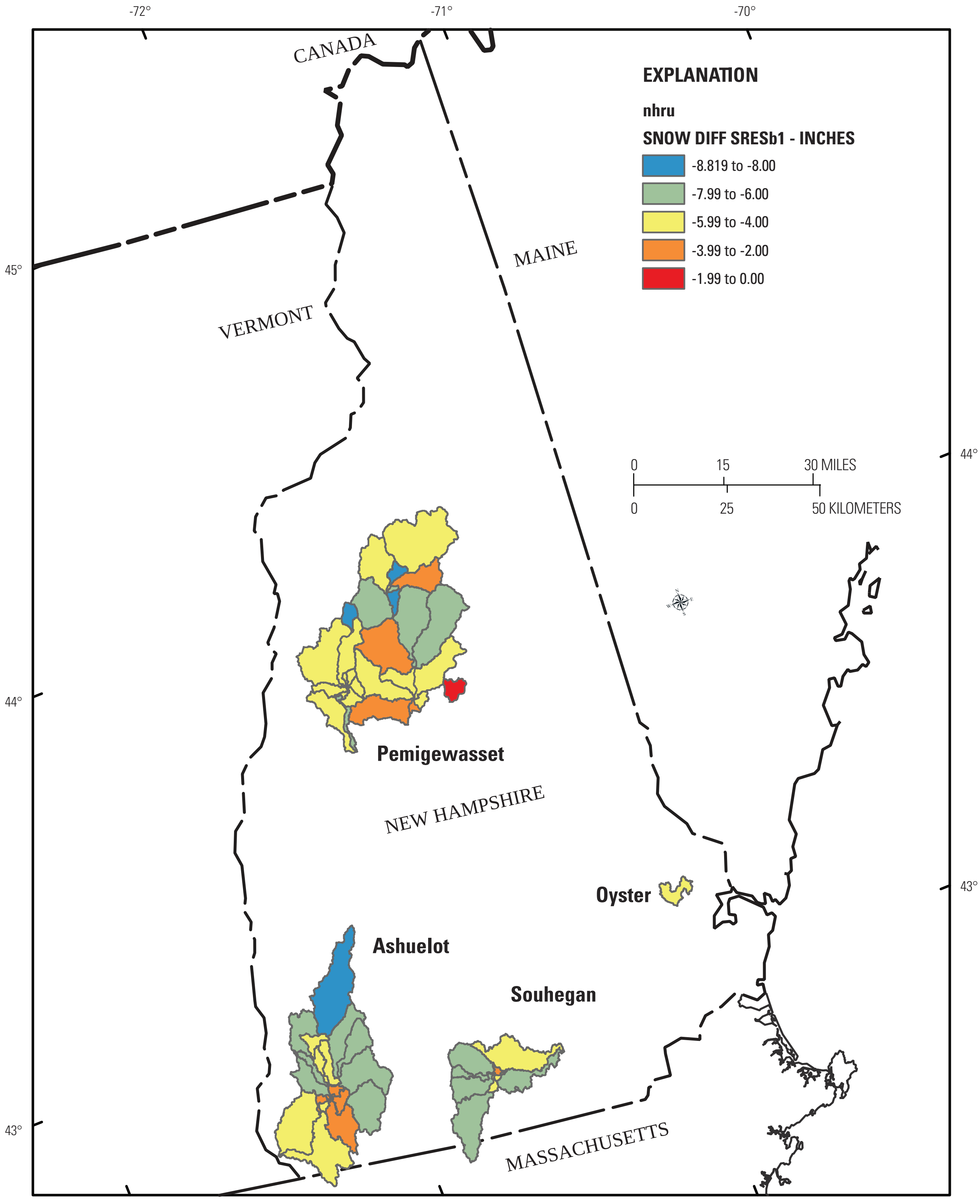

Figure 14. The simulated change in snowfall between current (1981–2000) and end-of-century (2081–2100) time periods using the CNRM model for the two scenarios mapped by hydrologic response unit in the four pilot river watersheds in New Hampshire. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.—Continued

Table 10. Mean change in base flow and snowfall in New Hampshire.

[Snowflow is estimated from the simulated snow-water equivalent times 10. GCM, global circulation model; ECHAM5, European Centre Hamburg Model version 5; SRESa2, Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000) scenario A2; SRESb1, IPCC SRES scenario B1; CNRM, Centre National de Recherches Meteorologiques model; CGCM, [Japan Meteorological Agency] coupled ocean-atmosphere general circulation model; CSIRO, Commonwealth Scientific and Industrial Research Organisation model; GFDL, Geophysical Fluid Dynamics Laboratory model]

GCM and scenario	Groundwater baseflow change, inches				Snowfall change, inches of snow-water equivalent times ten			
	Oyster River	Pemigewasset River	Souhegan River	Ashuelot River	Oyster River	Pemigewasset River	Souhegan River	Ashuelot River
ECHAM5SRESa2	-0.77	-1.89	-1.47	-1.92	-18.35	-30.92	-23.73	-20.38
ECHAM5SRESb1	-0.97	-1.47	-1.02	-1.02	-12.58	-21.14	-16.48	-12.55
CNRMSRESa2	0.64	0.17	0.57	0.61	-15.20	-22.56	-16.95	-15.17
CNRMSRESb1	0.85	0.67	0.66	0.34	-5.60	-5.60	-5.74	-5.37
CGCMSRESa2	0.97	0.03	1.21	0.65	-20.19	-33.42	-23.88	-21.12
CGCMSRESb1	-0.77	-1.10	-0.54	-0.35	-15.44	-28.75	-19.53	-15.79
CSIROSRESa2	-0.90	-1.88	-1.82	-1.19	-16.75	-32.77	-27.08	-20.95
CSIROSRESb1	-0.67	-1.31	-1.41	-0.95	-12.98	-17.64	-19.32	-14.83
GFDLSRESa2	-0.12	-1.98	-0.82	-0.94	-16.66	-28.13	-19.00	-17.42
GFDLSRESb1	0.97	-0.03	0.75	0.28	-11.43	-18.43	-10.78	-10.51
Mean for all GCMs and scenarios	-0.08	-0.88	-0.39	-0.45	-14.52	-23.94	-18.25	-15.41

Model Limitations

This study emphasizes the importance of understanding predicted trends in streamflow, snowmelt, soil moisture, and base flow through the hydrologic responses to models of climate change. Episodic events such as floods, which are affected by hourly and finer time-scale precipitation events, are not addressed in this study. Other limitations include the following:

- Increases in groundwater or reservoir withdrawals are not simulated;
- Interbasin transfers are not simulated from return flow from withdrawals;
- Land use changes are not simulated; and
- The effect of frozen ground on runoff is not explicitly simulated (the version of PRMS used in this study does not account for this process).

Complexities associated with land use, and change in land cover and vegetation could be important in trends of possible future change and could be a more important driver to hydrologic change than the climate in some areas. The climate scenarios simulated in this study are only possibilities; however, the reality could be expected within the range of GCMs and scenarios modeled. Although not a limitation, it is important to note that according to the IPCC report (Intergovernmental Panel on Climate Change, 2007), the modeled scenarios are more likely to occur than a return to the norm of our past experiences during the reference period of the past few decades.

Table 11. Regression statistics relating change in groundwater base flow and snowfall to geographic variables.

[R, coefficient of multiple correlation; R^2, coefficient of determination; t Stat, ratio of the departure of the parameter from its notional value and its standard error; P-value, threshold value]

Regression statistics for change in groundwater base flow						
Multiple R	0.88					
R^2	0.78					
Adjusted R^2	0.77					
Standard error	0.32					
Observations	62					
	Coefficients	**Standard error**	**t Stat**	***P*-value**	**Lower 95 percent**	**Upper 95 percent**
Intercept	-10.11	4.42	-2.29	0.03	-18.96	-1.26
HRU_ELEVATION	-0.004	0.00	-12.42	0.00	-0.00	-0.00
HRU_LATITUDE	0.25	0.10	2.39	0.02	0.04	0.45
Regression statistics for change in snowfall						
Multiple R	0.90					
R^2	0.81					
Adjusted R^2	0.80					
Standard error	2.40					
Observations	62					
	Coefficients	**Standard error**	**t Stat**	***P*-value**	**Lower 95 percent**	**Upper 95 percent**
Intercept	-348.31	113.49	-3.07	0.00	-575.49	-121.14
HRU_ELEVATION	-0.02	0.00	-7.71	0.00	-0.02	-0.01
HRU_LONGITUDE	-6.04	1.23	-4.92	0.00	-8.50	-3.58
HRU_LATITUDE	-2.30	0.91	-2.54	0.01	-4.12	-0.49

Regression equation:
ΔSNOW is -0.177 × (HRU_ELEVATION/10) – 6.04 × (HRU_LONGITUDE) – 2.30 × (HRU_LATITUDE) – 348.31.

ΔGW is mean annual change in groundwater base flow, inches.

ΔSNOW is mean annual change in snowfall, snow-water equivalent, in inches times 10.

HRU_ELEVATION/10 is mean Hydrologic Response Unit (HRU) elevation, in feet above North American Vertical Datum 88 (NAVD 88).

HRU_LONGITUDE is longitude of the HRU centroid, in decimal degrees (Note that the longitude is negative for the Western Hemisphere).

HRU_LATITUDE is latitude of the HRU centroid, in decimal degrees.

Summary and Conclusions

Based on evidence from the five models used to evaluate hydrologic change in four representative watersheds, streamflow is likely to increase in New Hampshire. Variability of streamflow is likely to increase, with an increased number of highs and lows. Streamflow will probably have the largest increases in winter and will decrease in summer, although summer decreases are small (less than 20 percent). The models demonstrate that the change in base flow and snowfall would vary by location. Base flow change ranges from reductions by as much as 2 inches to increases of a similar amount depending on the scenario and the global climate model (GCM). The change is highly dependent on altitude, latitude, and the GCM used for the future simulations. The largest change is in the northern Pemigewasset River watershed. Changes in snowfall are consistently decreasing for all models and all scenarios and are spatially variable with reductions as much as 2 feet in the Pemigewasset River watershed in northern New Hampshire and less change in the watersheds in southern New Hampshire. Similar to the change in groundwater, the change in snowfall is dependent on altitude and latitude and also on longitude.

The most significant effects of increasing flooding could be on the frequency of large events (the largest seven floods expected in 20 years) rather than the size of the floods, except in the watershed in northern New Hampshire. There is likely to be less snowfall on average, but large snow events could still occur in any given winter. There is likely to be an increase in high flows during winter and spring months that could result in more uncertainty in the planning of infrastructure design, operation, and maintenance (including roads and utilities). Similarly, less groundwater base flow is expected to be available on average in some areas, whereas in other areas, base flow may increase; additionally a wider range of seasonal fluctuation in base flow is expected than currently observed.

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Figures 3 and 12

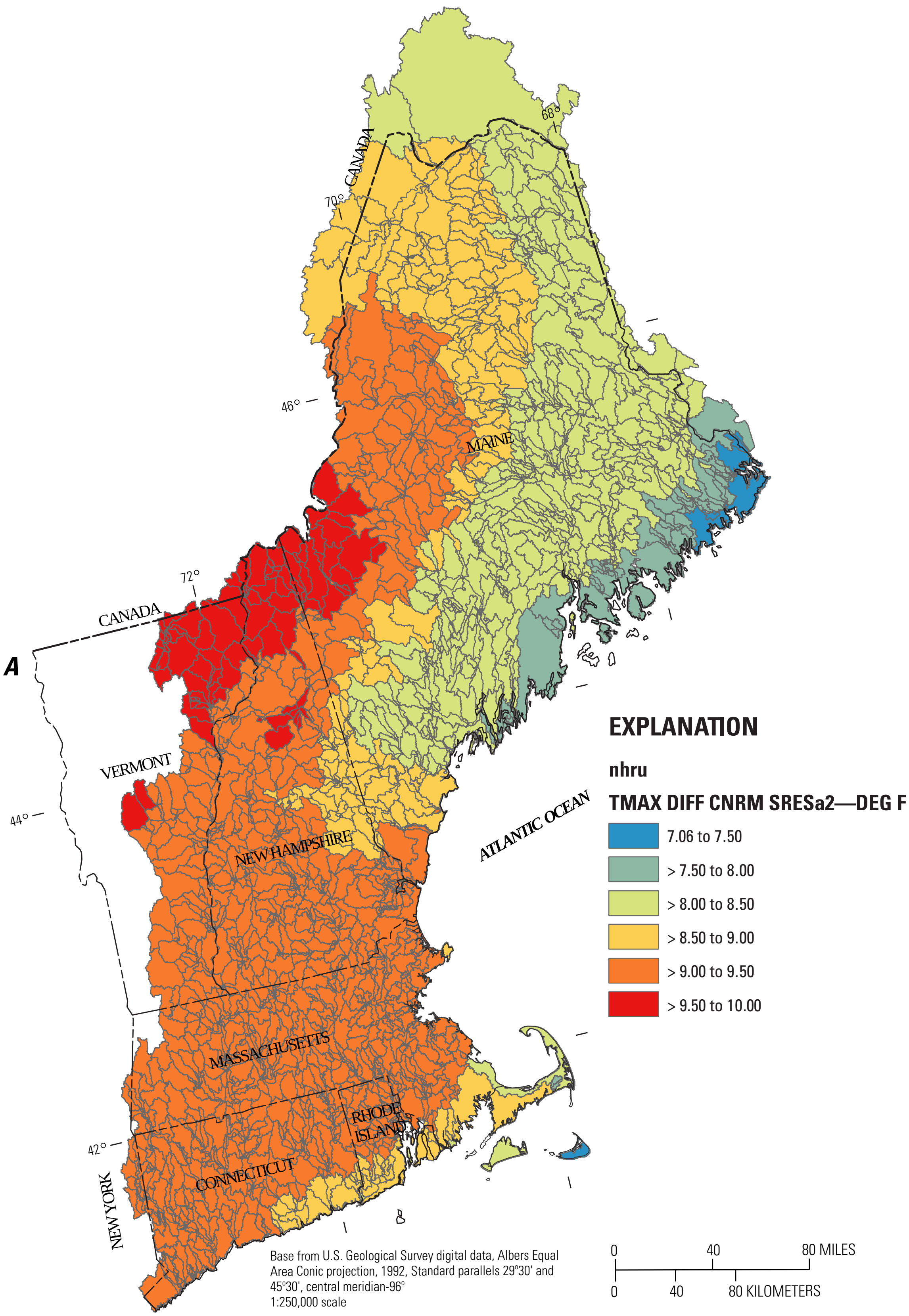
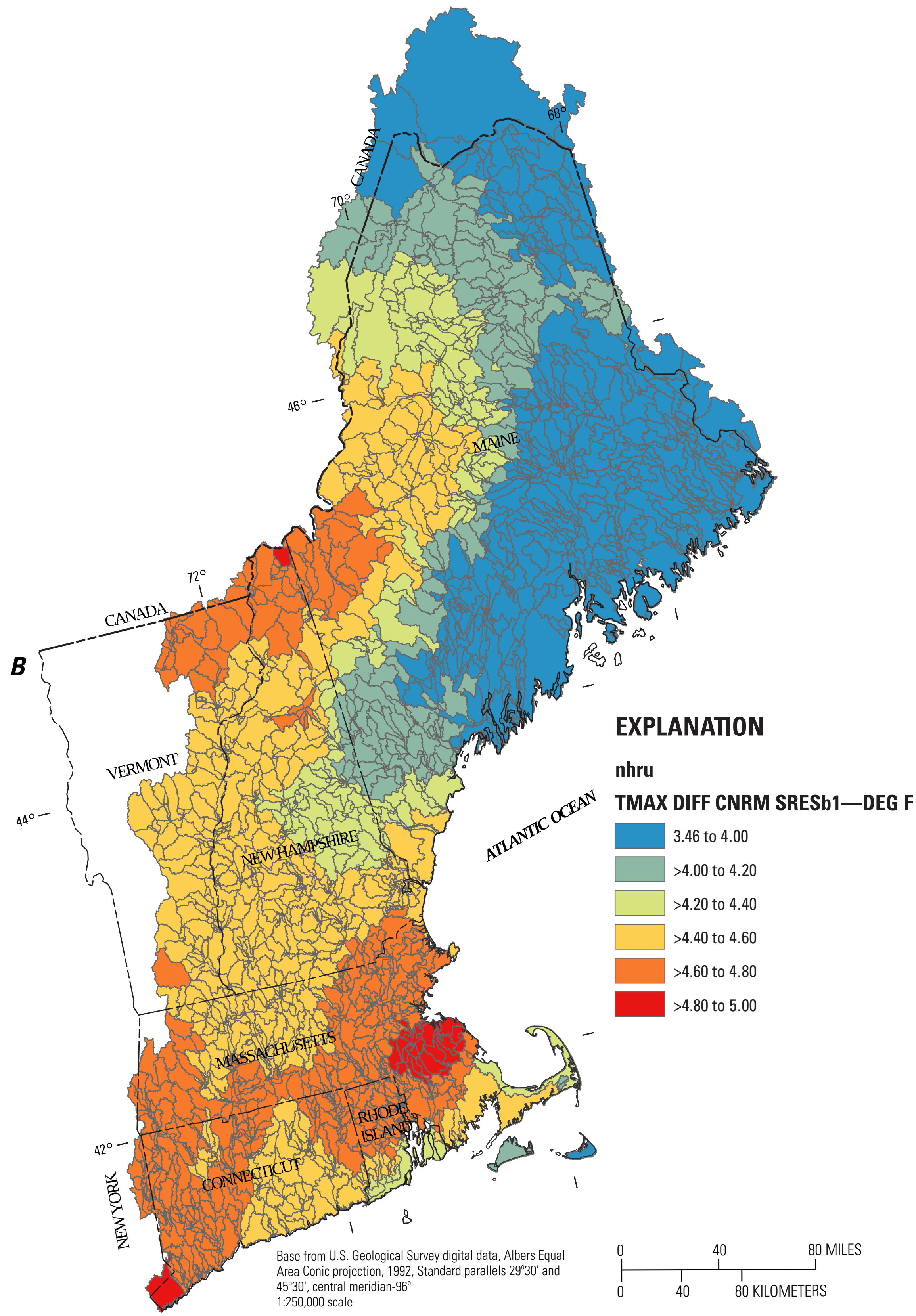


Figure 3. *A–H,* distribution of predicted change in mean daily maximum air temperature and change in mean annual precipitation projected for New Hampshire from 2081 to 2100 between current conditions and future climate conditions for the CNRM and ECHAM5 GCMs and the two scenarios SRESa2 and SRESb1. Definitions of abbreviations are listed in the “Abbreviations” section, p. ix.



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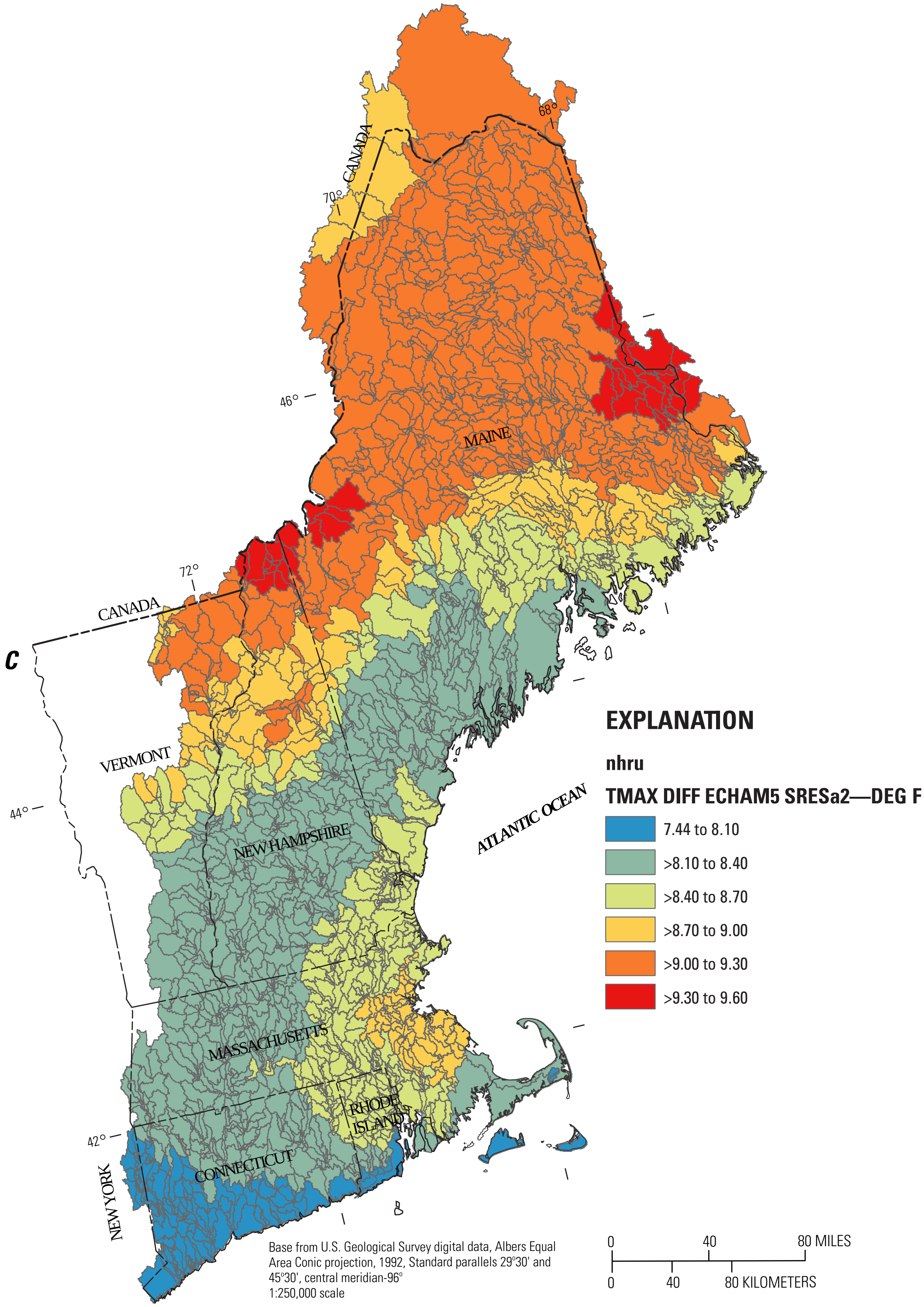

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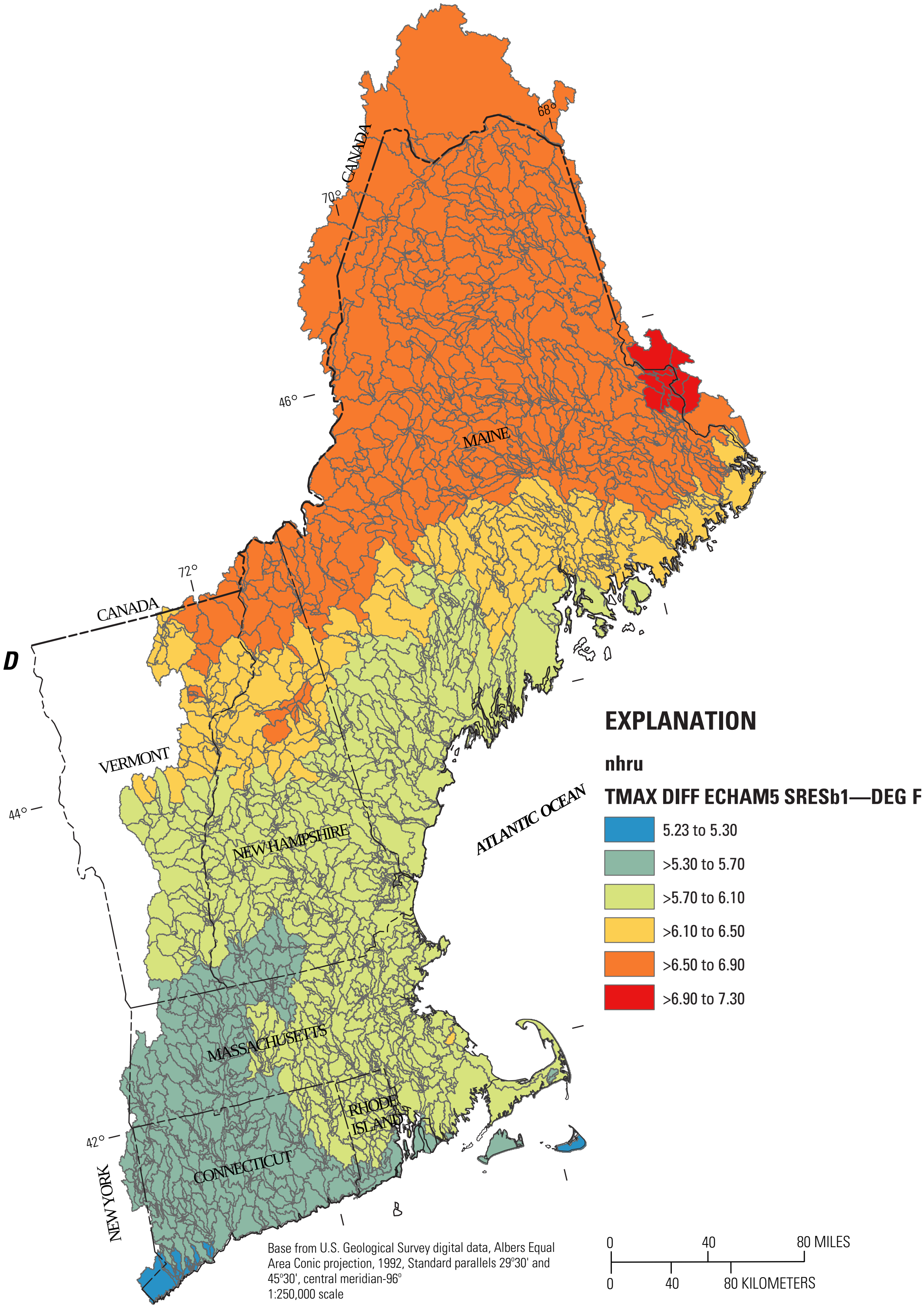

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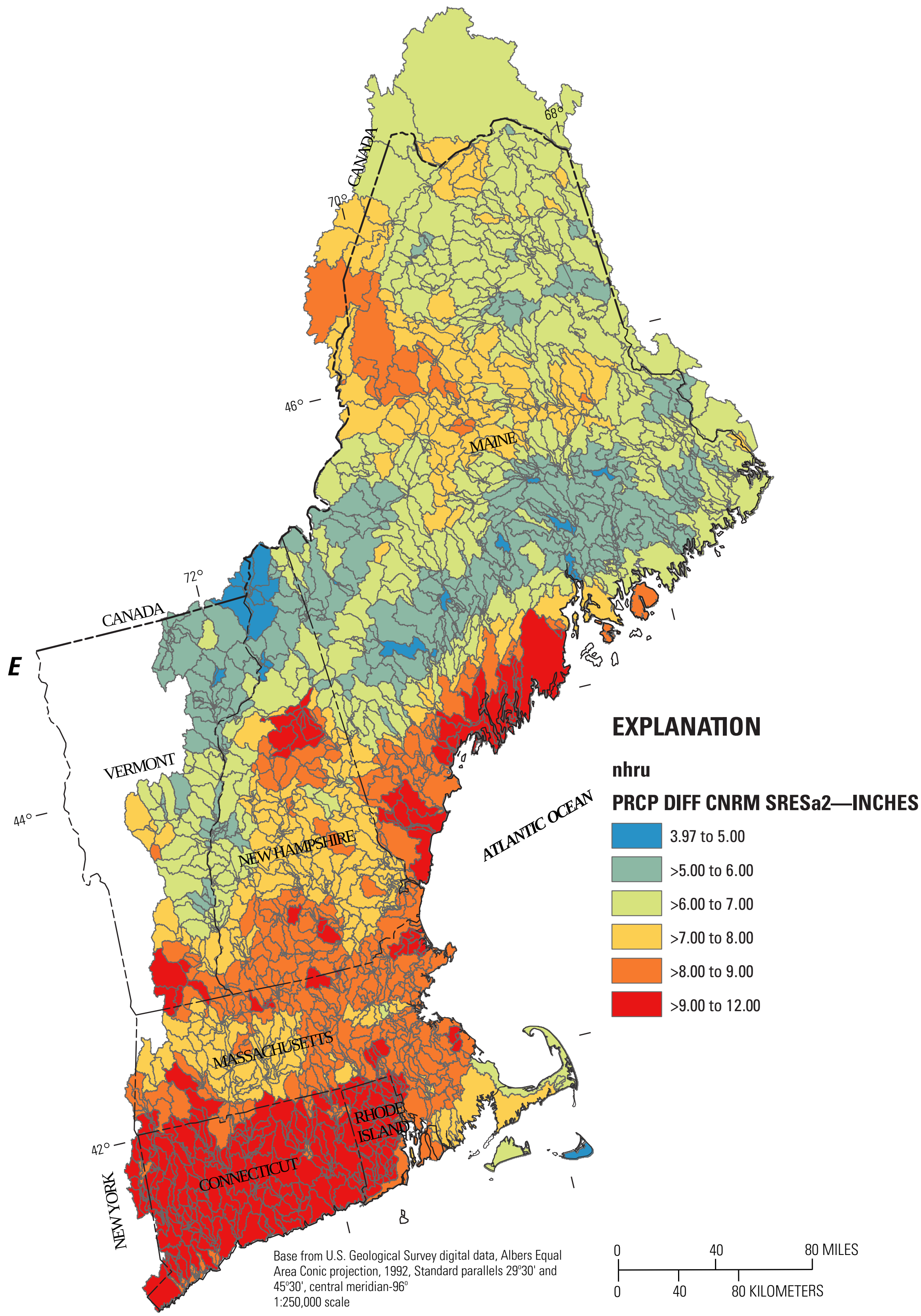

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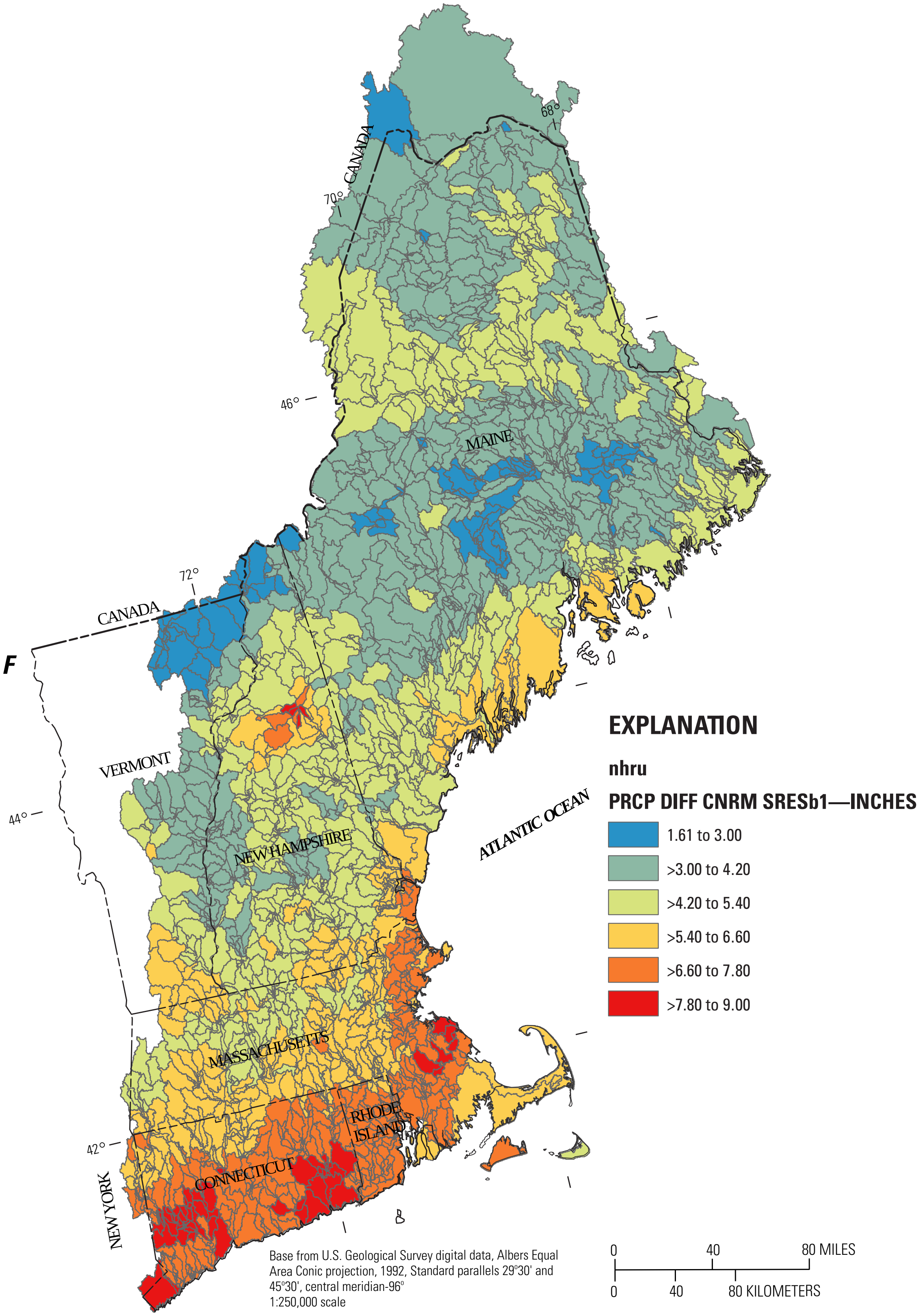

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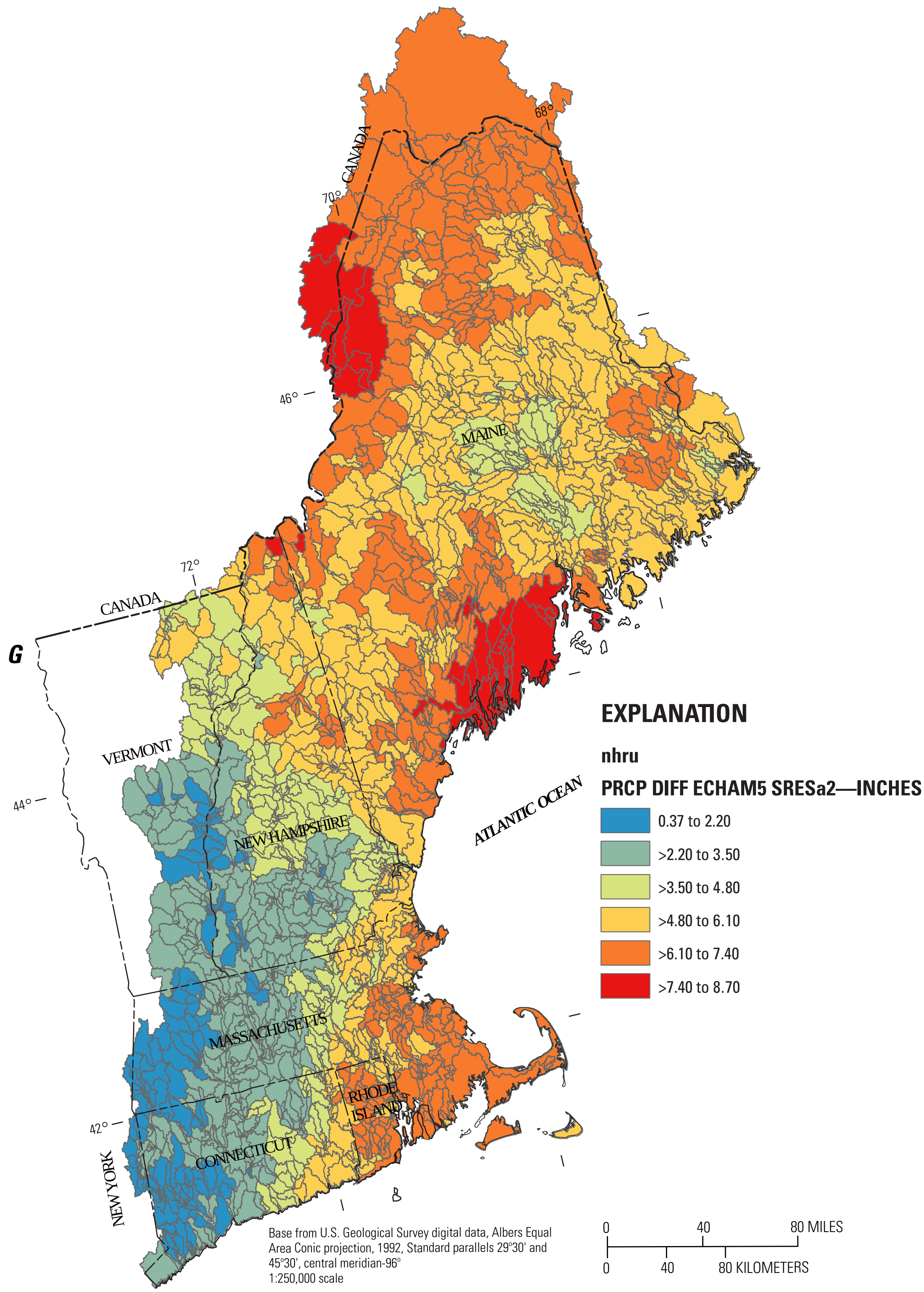

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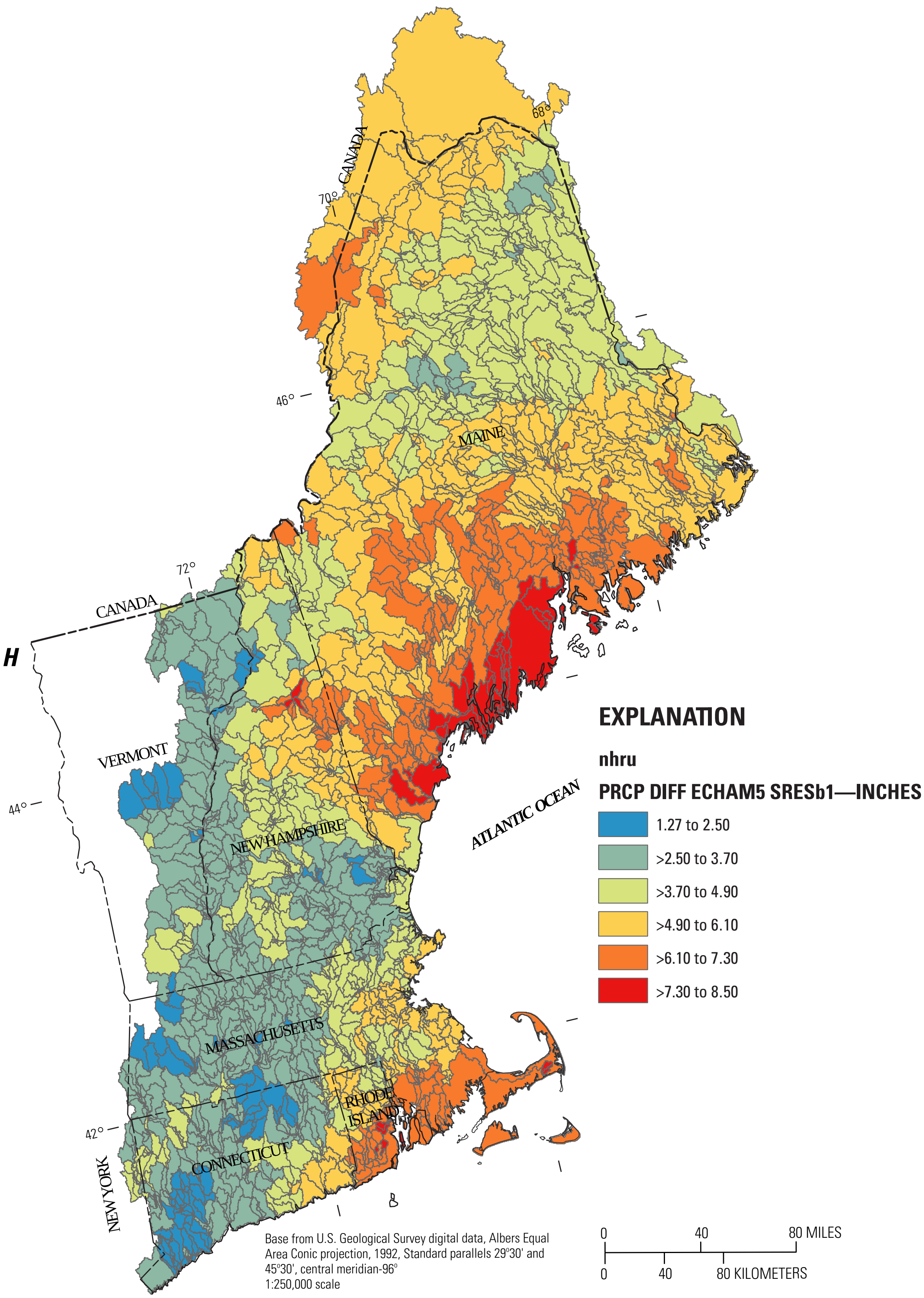

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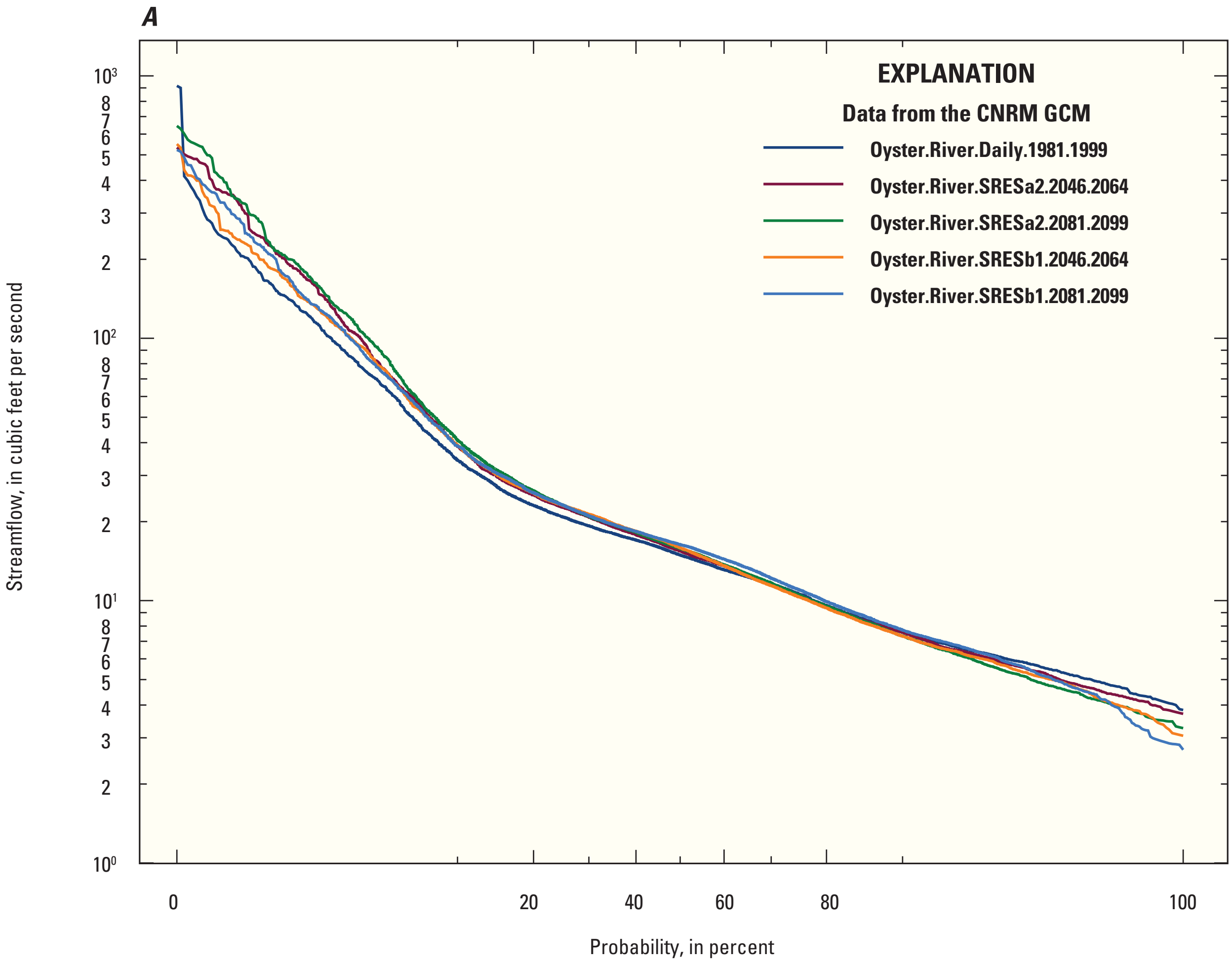
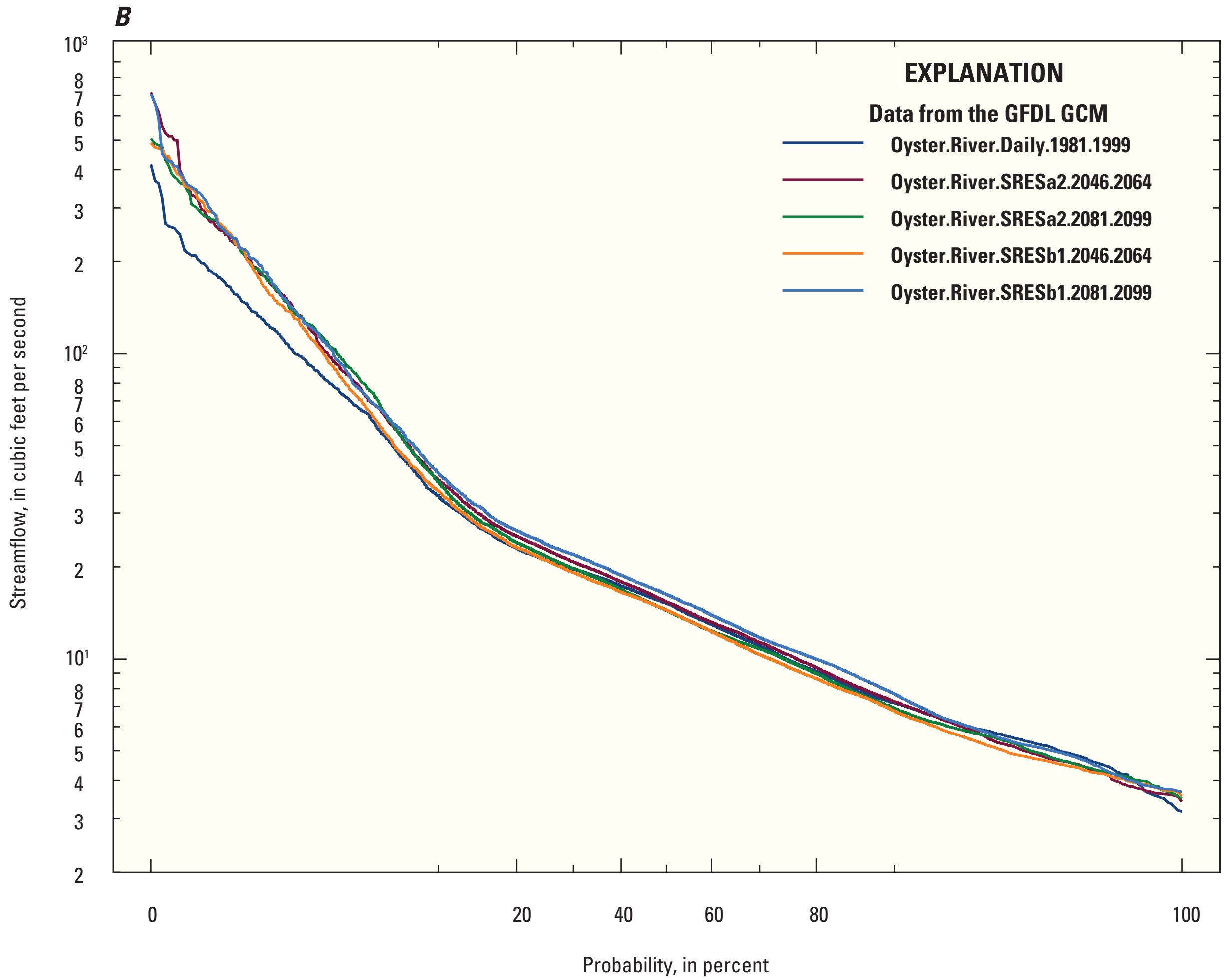


Figure 12. *A–D, s*treamflow duration curves for the Oyster River and Pemigewasset River watersheds in New Hampshire for the two emissions scenarios for midcentury (SRESa2) and end-of-century (SRESb1) for the CNRM and GFDL models, two of the five GCMs; and *E–F,* average streamflow duration curves that average all five GCM predictions and the two emission scenarios. Definitions of abbreviations are listed in the "Abbreviations" section, p. ix.



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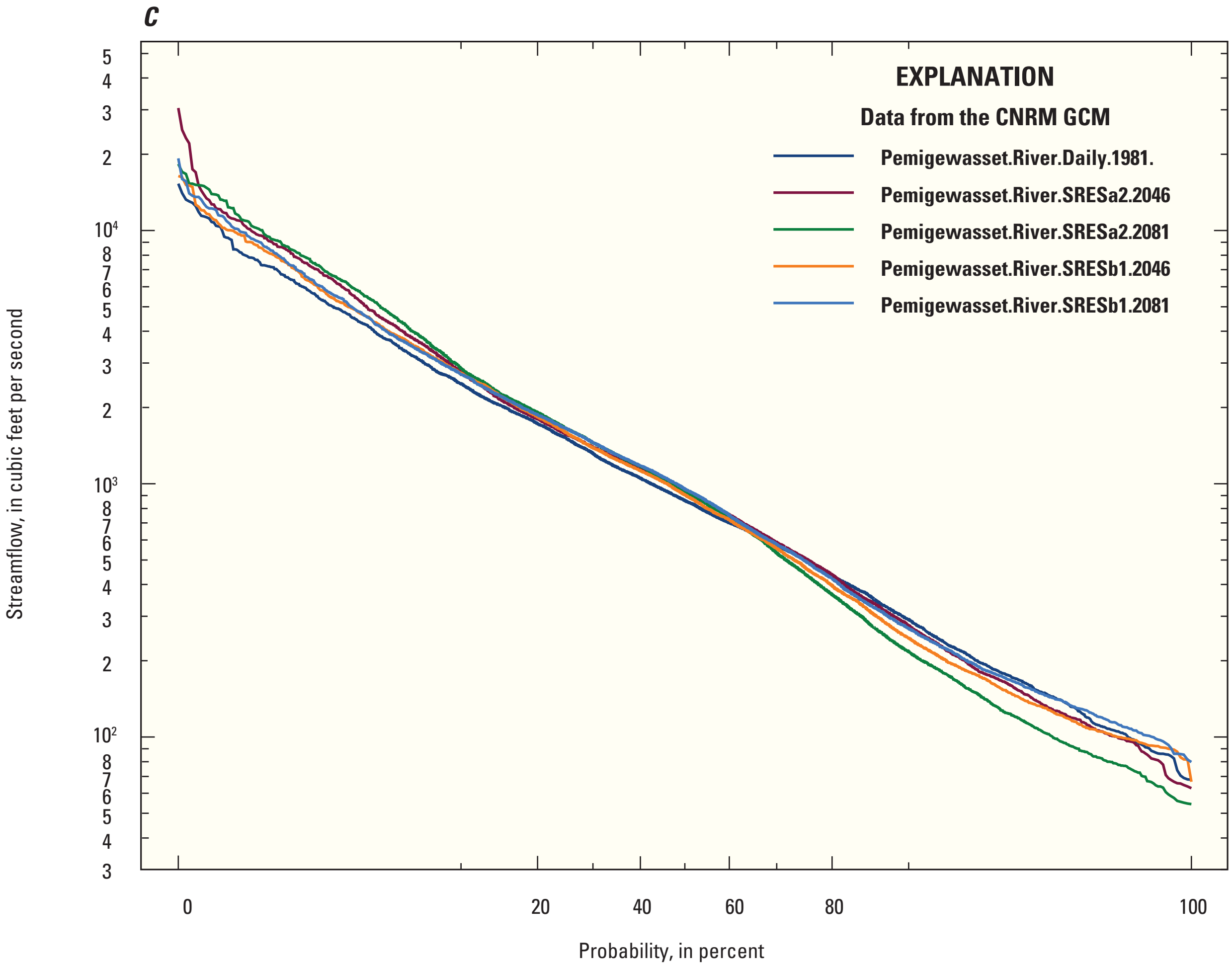

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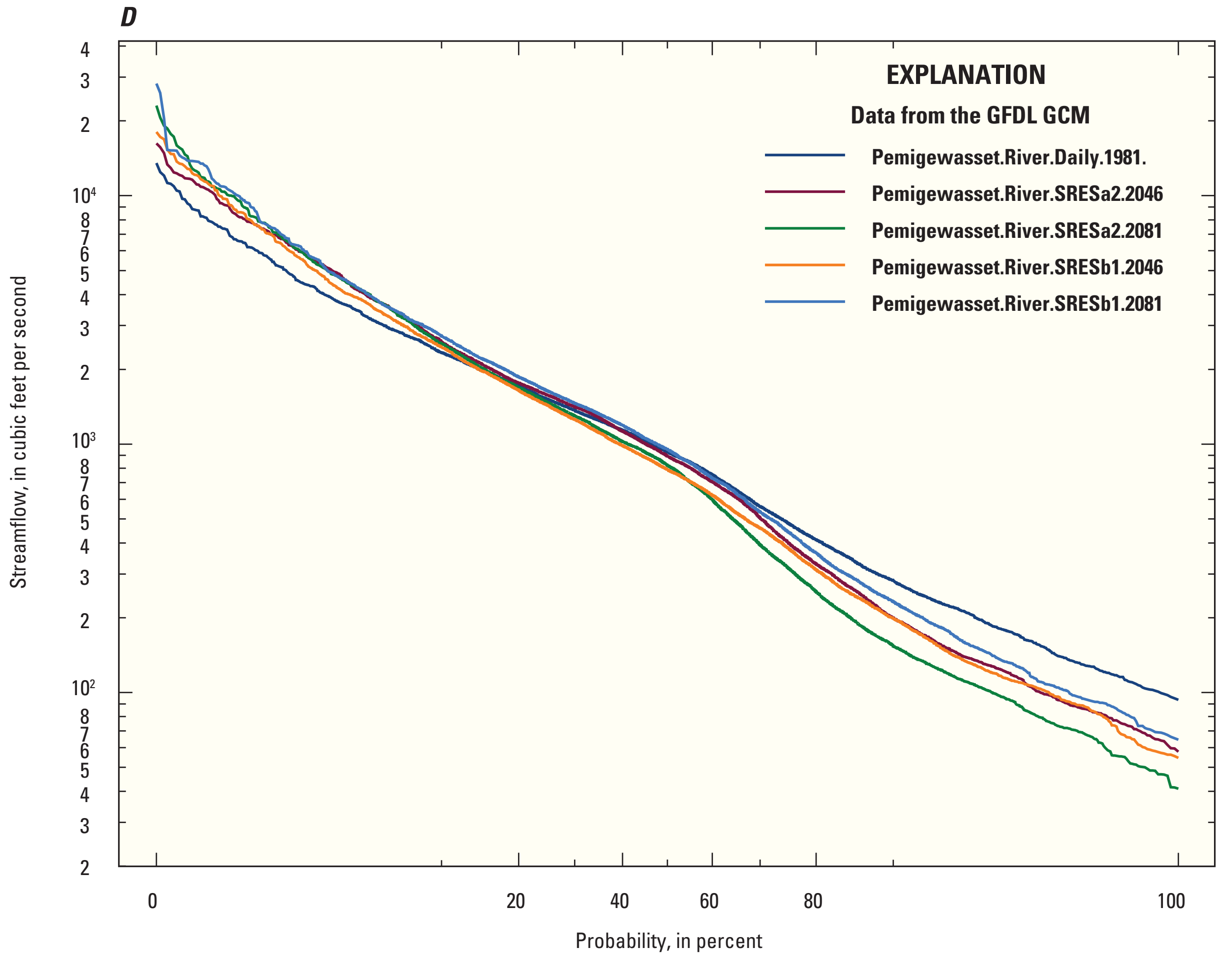

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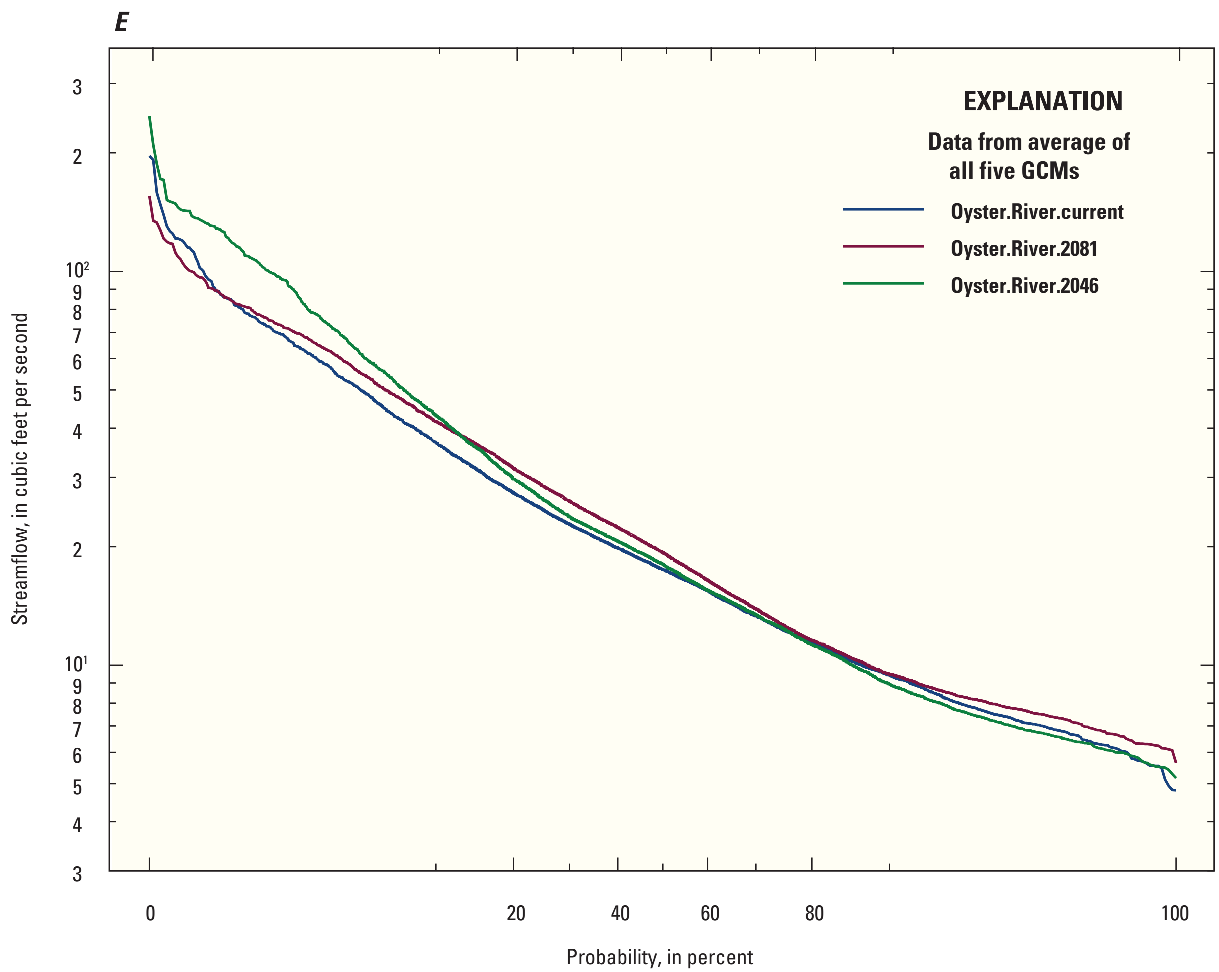

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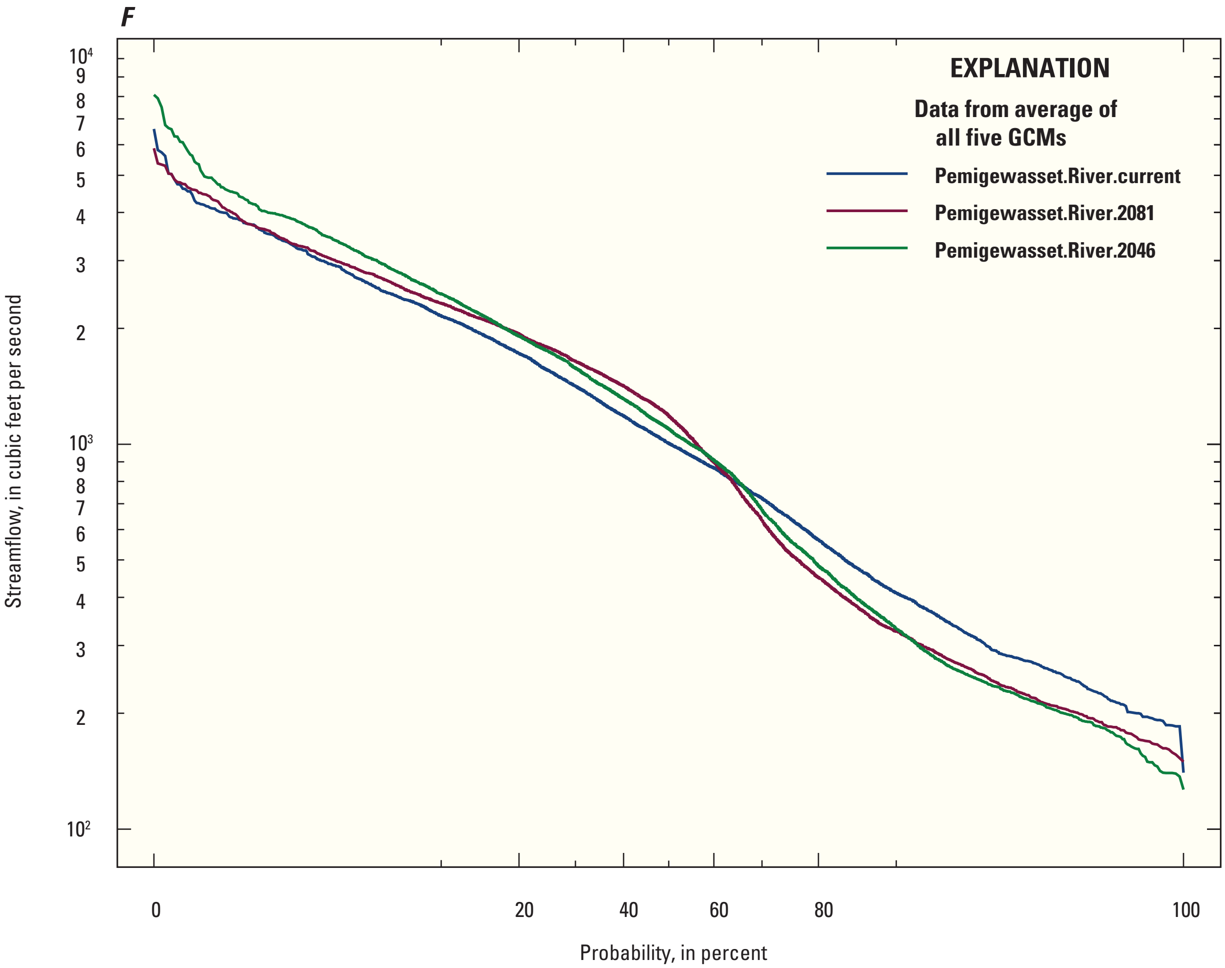

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