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Assessment of Ground-Water Resources in the Seacoast Region of New Hampshire

Scientific Investigations Report 2008–5222

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

Cover. Photograph shows Great Boar's Head, Hampton, N.H., and Atlantic Ocean surf as viewed looking south from the seawall at North Beach, Hampton, N.H. (Photograph by John Carden, Photographer, Hampton, N.H., and used with permission)

Assessment of Ground-Water Resources in the Seacoast Region of New Hampshire

By Thomas J. Mack

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to S

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per month (in/mo)	2.54	centimeter per month (cm/mo)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°C=(°F–32)/1.8$$

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

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.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

ACRONYMS AND ABBREVIATIONS USED IN REPORT

CFCs	chlorofluorocarbons
CWS	community water system
DEM	digital elevation model
EFH	equivalent freshwater head
EPM	equivalent porous medium (model)
ET	evapotranspiration
GCNE	Golf Club of New England
IGPCC	Intergovernmental Panel on Climate Change
NHCP	New Hampshire Coastal Program
NHDES	New Hampshire Department of Environmental Services
NHGS	New Hampshire Geological Survey
PAFB	Pease Air Force Base
RPC	Rockingham Planning Commission
TAZ	Transportation Analysis Zone
USGS	U.S. Geological Survey

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Assessment of Ground-Water Resources in the Seacoast Region of New Hampshire

By Thomas J. Mack

Abstract

Numerical ground-water-flow models were developed for a 160-square-mile area of coastal New Hampshire to provide insight into the recharge, discharge, and availability of ground water. Population growth and increasing water use prompted concern for the sustainability of the region's ground-water resources. Previously, the regional hydraulic characteristics of the fractured bedrock aquifer in the Seacoast region of New Hampshire were not well known. In the current study, the ground-water-flow system was assessed by using two different models developed and calibrated under steady-state seasonal low-flow and transient monthly conditions to ground-water heads and base-flow discharges. The models were, (1) a steady-state model representing current (2003–04) seasonal low-flow conditions used to simulate current and future projected water use during low-flow conditions; and (2) a transient model representing current average and estimated future monthly conditions over a 2-year period used to simulate current and future projected climate-change conditions.

The analysis by the ground-water-flow models indicates that the Seacoast aquifer system is a transient flow system with seasonal variations in ground-water flow. A pseudo-steady-state condition exists in the fall when the steady-state model was calibrated. The average annual recharge during the period analyzed, 2000–04, was approximately 51 percent of the annual precipitation. The average net monthly recharge rate between 2003 and 2004 varied from 5.5 inches per month in March, to zero in July, and to about 0.3 inches per month in August and September. Recharge normally increases to about 2 inches per month in late fall and early winter (November through December) and declines to about 1.5 inches per month in late winter (January and February). About 50 percent of the annual recharge coincides with snowmelt in the spring (March and April), and 20 percent occurs in the late fall and early winter (November through February). Net recharge, calculated as infiltration of precipitation minus evapotranspiration, can be negative during summer months (particularly July).

Regional bulk hydraulic conductivities of the bedrock aquifer were estimated to be about 0.1 to 1.0 feet per day. Estimated hydraulic conductivities in model areas representing the Rye Complex and the Kittery Formation were higher (0.5 to 1 foot per day) than in areas representing the Eliot Formation, the Exeter Diorite, and the Newburyport Complex, which have estimated hydraulic conductivities of 0.1 to 0.2 foot per day. A northeast-southwest regional anisotropy of about 5:1 was estimated in some areas of the model; this pattern is parallel to the regional structural trend and predominant fracture orientation. In areas of the model with more observation data, the upper and lower 95-percent confidence intervals for the estimated bedrock hydraulic conductivity were about half an order of magnitude above and below the parameter, respectively, and the estimated confidence intervals for estimated specific storage were within an order of magnitude of the parameter. In areas of the model with few data points, or few stresses, confidence intervals were several orders of magnitude. Estimated model parameters and their confidence intervals are a function of the conceptual model design, observation data, and the weights placed on the data.

The amount of recharge that enters the bedrock aquifer at a specific point depends on (1) the location of the point in the flow field; (2) the hydraulic conductivity of the bedrock (or the connectivity of fractures); and (3) the stresses within the bedrock aquifer. In addition, ground water stored in unconsolidated overburden sediments, including till and other fine-grained sediments, may constitute a large percentage of the water available from storage to the bedrock aquifer. Recharge into the bedrock aquifer at a point can range from zero to nearly all the recharge at the surface depending on regional hydrogeologic and anthropogenic factors. In a setting with few ground-water withdrawals, a larger portion of the recharge in the ground-water-flow system remains in the unconsolidated aquifers or upper bedrock than moves through the deeper bedrock aquifer, even in a setting with conductive bedrock, at any given time. With increased withdrawals in the bedrock aquifer, a larger proportion of the recharge in the aquifer system will move into the deeper areas of the aquifer system at any given time.

Ground-water residence time estimated by chlorofluorocarbon age-dating methods ranged from near zero (recently recharged) to more than 50 years. Ground water was oldest in areas with little water use, a low head gradient above the point of interest, and at a point of discharge in the flow system. At such locations, ground water may have flowed a considerable distance in the watershed. Where water use was high, or at an

area of recharge, the ground-water age may be younger. At large ground-water withdrawal points, ground water withdrawn includes a mix of water from recently recharged to that with residence times 30 years or more. The ground-water flow to large withdrawals includes ground water in the immediate area of the well and older water from greater distances. The age of water captured by recently installed large ground-water-withdrawal wells may become younger with time as the effects of the withdrawal on the flow system become established and the flow system reaches a new equilibrium.

Simulated effects to the Seacoast hydrologic system caused by increasing future water use include stream base flows declining by about 7 percent; fresh ground-water discharges to tidal bays, estuaries, and the ocean declining by about 2 percent; and lowered ground-water levels. Changes in ground-water levels were subtle but were greatest near large ground-water withdrawals with increasing demands and in developing rural areas. On the basis of the simulations, the hydrologic system will be most affected during periods of low flow, which may result in longer annual low-streamflow periods. Simulations show that the effects of increased demand will likely become apparent within the next 10 years (before 2017). Simulations of a hypothetical increase in sewering result in further declines in base flow (13 percent) and discharge to bays, estuaries, and the ocean (5 percent).

Climate change in New England is forecast to include more frequent and intense precipitation events, with a slight decrease to little change in total precipitation, and increasing temperatures. The effects of this potential future climate change on the Seacoast hydrologic system would likely include reduced base flows and fresh ground-water discharges to tidal areas and lowered ground-water levels. The effects of these climate changes by 2025 were estimated to be greater than the potential effects of increased water demands. The analyses indicated that there are potential issues of concern for future use of water resources in the Seacoast region. The models developed and demonstrated in this investigation can provide water-resource managers and planners tools with which to assess future water resources in this region. The findings regarding the effects of increasing water demand and potential climate change on ground-water availability may be transferrable to other regions of the Nation with similar hydrogeologic and climatic characteristics.

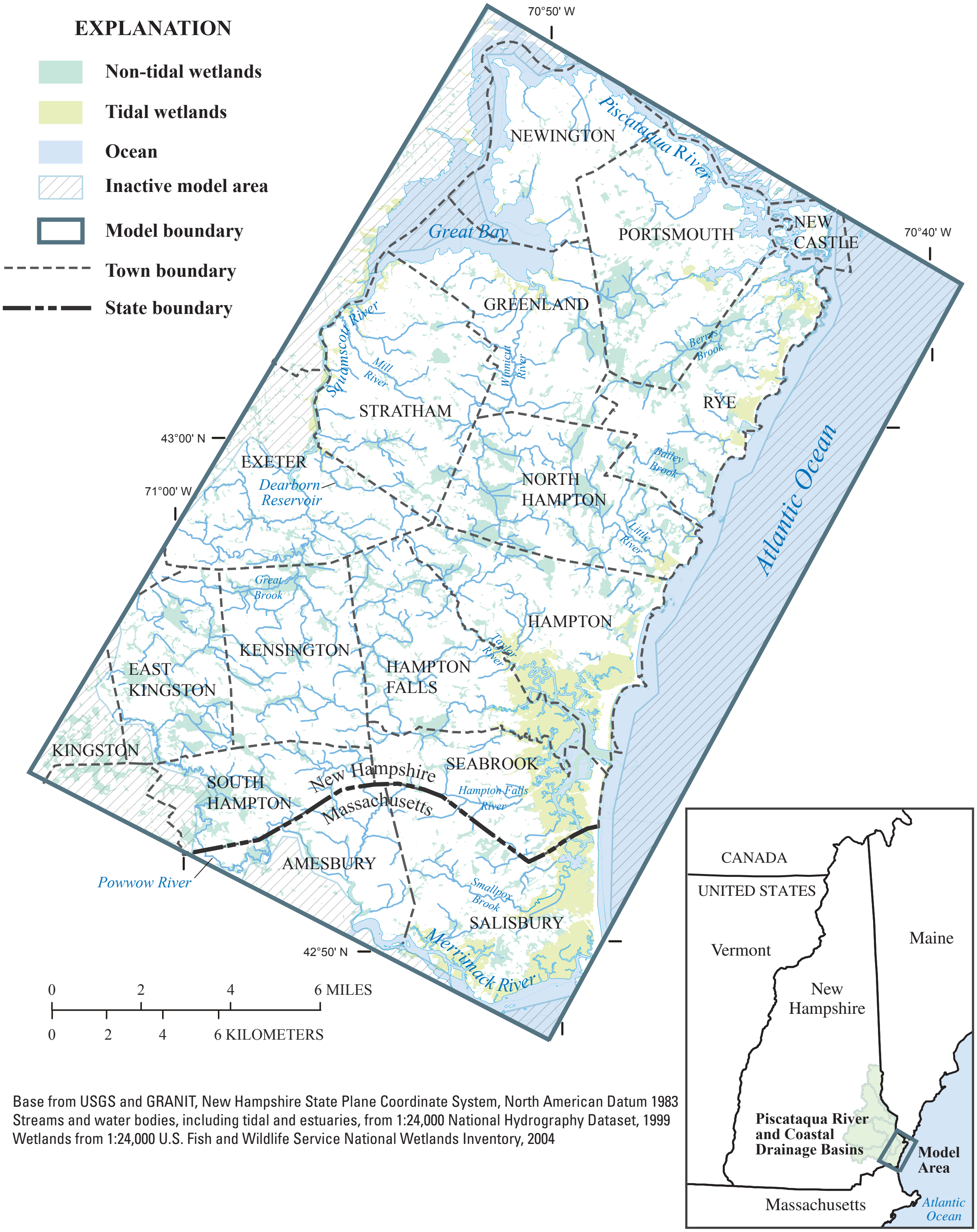
Introduction

The Seacoast region encompasses an area of southeastern New Hampshire bordering the Atlantic Ocean from Maine to Massachusetts (fig. 1). In 2004, the twelve towns that make up the Seacoast region (fig. 1) had a population of 80,000 that relied primarily on local ground-water resources for its water needs. The proximity of this region to the expanding area of metropolitan Boston has led to a 36-percent population increase over the past 20 years. This development has been accompanied by an increase in the use of ground water from both domestic and supply wells, nearly all of which are completed in the fractured-bedrock aquifer. Historically, the fractured-bedrock aquifer had not been considered a principal aquifer, and water-resource investigations of the 1970s (Anderson-Nichols, 1980; Cotton, 1977) and 1980s (Moore, 1990; Stekl and Flanagan, 1992) focused on stratified-drift aquifers to meet the increasing water demand. Currently (2003–04), the stratified-drift aquifers of the region are essentially fully utilized, and water levels have declined in some stratified-drift aquifers in southeastern New Hampshire over recent years. Consequently, the fractured-bedrock aquifers in the Seacoast and elsewhere in New Hampshire have become increasingly important for providing future ground-water resources.

In addition to use by a greater population in the region, individual usage has been increasing to meet the needs of modern appliances and landscaping. In addition, water may be distributed outside the source area or removed through sewering. In the Seacoast region, sewers eventually discharge to tidal water bodies, including local bays and the ocean, and sewering, therefore, removes freshwater from local aquifer systems.

These pressures on the Seacoast water resources became more apparent in 2001 and 2002 when an extensive drought affected the entire northeastern United States. In response to this drought, many Seacoast communities implemented water-use restrictions, and concern increased about the availability and sustainability of ground-water resources in the region. At the time of this drought, the potential effects of increasing demands, changes in water usages, and increased reliance on the fractured-bedrock aquifer on ground-water resources in the Seacoast region had not yet been quantified.

To address these concerns, cooperative investigations involving the New Hampshire Department of Environmental Services (NHDES) Coastal Program (NHCP) and Geological Survey (NHGS), the Seacoast communities, and the U.S. Geological Survey (USGS) were initiated in 2003 to assess water resources and needs for the Piscataqua River drainage basin and the coastal drainages of southeastern New Hampshire (fig. 1, inset map). Companion investigations by the NHGS provided geologic and well data for this investigation, and a companion investigation of water use in 44 towns within the Piscataqua River watershed in New Hampshire (Horn and others, 2007) provided water-use information. The current investigation developed a regional ground-water-flow model to evaluate ground-water availability in an approximately 160 mi^2 area of coastal New Hampshire, which includes 12 towns and is termed the Seacoast region (fig. 1). Although considerable data are collected on an on-going basis at sites of proposed large ground-water withdrawals, there was no comprehensive means for State, regional, and local interests to evaluate the cumulative hydrologic effects of additional withdrawals, in conjunction with existing water uses, on the water resources of the region. In this investigation, regional ground-water-



Base from USGS and GRANIT, New Hampshire State Plane Coordinate System, North American Datum 1983
Streams and water bodies, including tidal and estuaries, from 1:24,000 National Hydrography Dataset, 1999
Wetlands from 1:24,000 U.S. Fish and Wildlife Service National Wetlands Inventory, 2004

Figure 1. The Seacoast region, town boundaries, and major hydrologic features in the Seacoast model area, southeastern New Hampshire.

flow models were developed to provide an evaluation and a framework for understanding the present ground-water-flow system and a tool for evaluating the cumulative effects of increasing water demand on ground-water resources in the Seacoast region. The effects of increasing water demand and potential climate change are a National concern and many of the findings from the Seacoast region are transferrable to other regions, particularly in the glaciated northern United States, with similar hydrogeologic and climatic characteristics.

Purpose and Scope

This report describes an assessment of ground-water resources in the Seacoast region of coastal southeastern New Hampshire. The report includes documentation of the design and calibration of numerical ground-water-flow models and their use and limitations for evaluation of current and future ground-water availability. Current (2003–04) and projected (for 2017 and 2025) ground-water-resource conditions are described in the report.

The scope of this investigation is regional. The ground-water-flow models are designed for use in watershed- to sub-watershed-level planning and management of ground-water resources, not for site-specific hydrologic analyses. Evaluations of potential or future scenarios presented in this report are based on information available at the time of the study.

Description of the Study Area

The study area includes 160 mi^2 comprising all or parts of 12 towns in New Hampshire and a 30-mi^2 area comprising parts of 2 towns in northeastern Massachusetts. The two towns in Massachusetts were in the ground-water-flow model area but were not included in the ground-water-availability investigation. Study-area boundaries coincide with the boundaries of major hydrologic features, including tidal water bodies (Squamscott River, Great Bay, Atlantic Ocean, Piscataqua River, Merrimack River), the Powwow River (fig. 1), and Great Brook drainage divide (fig. 2) along the southwestern model-domain boundary. Altitudes range from 0 to about 300 ft, with most of the study area gently sloping and at altitudes less than 100 ft above North American Vertical Datum of 1988 (NAVD 88). All streams originate in and flow out of the study area (fig. 2). The exceptions are discharge areas in the Seacoast hydrologic system, and include the Powwow, Piscataqua, and Merrimack Rivers; the latter two are tidal water bodies in the study area. The climate of the Seacoast study area, including long-term precipitation data and trends, is described in appendix 1.

Geologic and Geographic Setting

The geographic setting of the study area was described by Bradley (1964) as part of the Seaboard Lowland section of the New England Physiographic Province. The area is covered by thin glacial and marine sediments (fig. 3) and the topography is generally low and reflects the shape of the bedrock surface. In the Seacoast area, ground water occurs in three major geologic units: glacial till, stratified-drift deposits, and bedrock. Glacial till is an unsorted mixture of clay, silt, sand, gravel, and cobbles deposited directly under glacial ice. Till is generally about 20 ft thick or less throughout the Seacoast. Stratified deposits consist of sorted and layered sand, gravel, silt, and clay of glacial or marine origin. Crystalline metasedimentary or intrusive bedrock underlies the surficial sediments, and is exposed at the surface in some areas.

Other geologic units in the Seacoast, which are less important with respect to ground-water resources, include beach alluvium, which forms the coastal shoreline in the southern half of the study area (Hampton, N.H., to Salisbury, Mass.); freshwater wetland deposits that dominate the central part of the study area, including some areas of the I-95 corridor; and marine wetland deposits, which particularly dominate the nearshore areas from Hampton, N.H., to Salisbury, Mass.

The bedrock in the study area consists of crystalline igneous rocks and metamorphic rocks of sedimentary origin (fig. 4). Crystalline bedrock is generally not considered a high-yielding ground-water resource; however, some of the highest-yielding bedrock wells in New Hampshire are in the Seacoast region (Moore and others, 2002). The geology of the Seacoast area has been the subject of numerous investigations including the work of Novotny (1969) and, more recently, Escamilla-Casas (2003), and mapping by Dr. Wallace Bothner (University of New Hampshire, oral commun., 2006). Bedrock structures of the Seacoast study area include the Rye anticline east of Great Bay; the Great Bay syncline, which coincides with the location of Great Bay; and the Portsmouth Fault (Lyons and others, 1997; Novotny, 1969, p. 4). These structures produce a northeast-southwest regional structural trend (approximately north 22 degrees east). The dominant rock types are metasedimentary rocks of the Rye Complex (fig. 4), which commonly consists of coarse-grained gneiss, quartzite, and schist; the Kittery Formation (fig. 4), primarily a phyllite, and schist; and the Eliot Formation, which is primarily slate, phyllite, and schist. The igneous rocks of the Breakfast Hill granite; the Exeter Diorite; and the Newburyport Complex, a quartz diorite, form lesser amounts of the bedrock in the study area (fig. 4). The geology of West Newbury, Mass., immediately adjacent and south of the study area, has been investigated by Walsh (2001) and includes bedrock of the Eliot Formation and Newburyport Complex. In terms of water resources, properties of the bedrock aquifer of the study area remain less well known than those of the surficial hydrogeologic units.

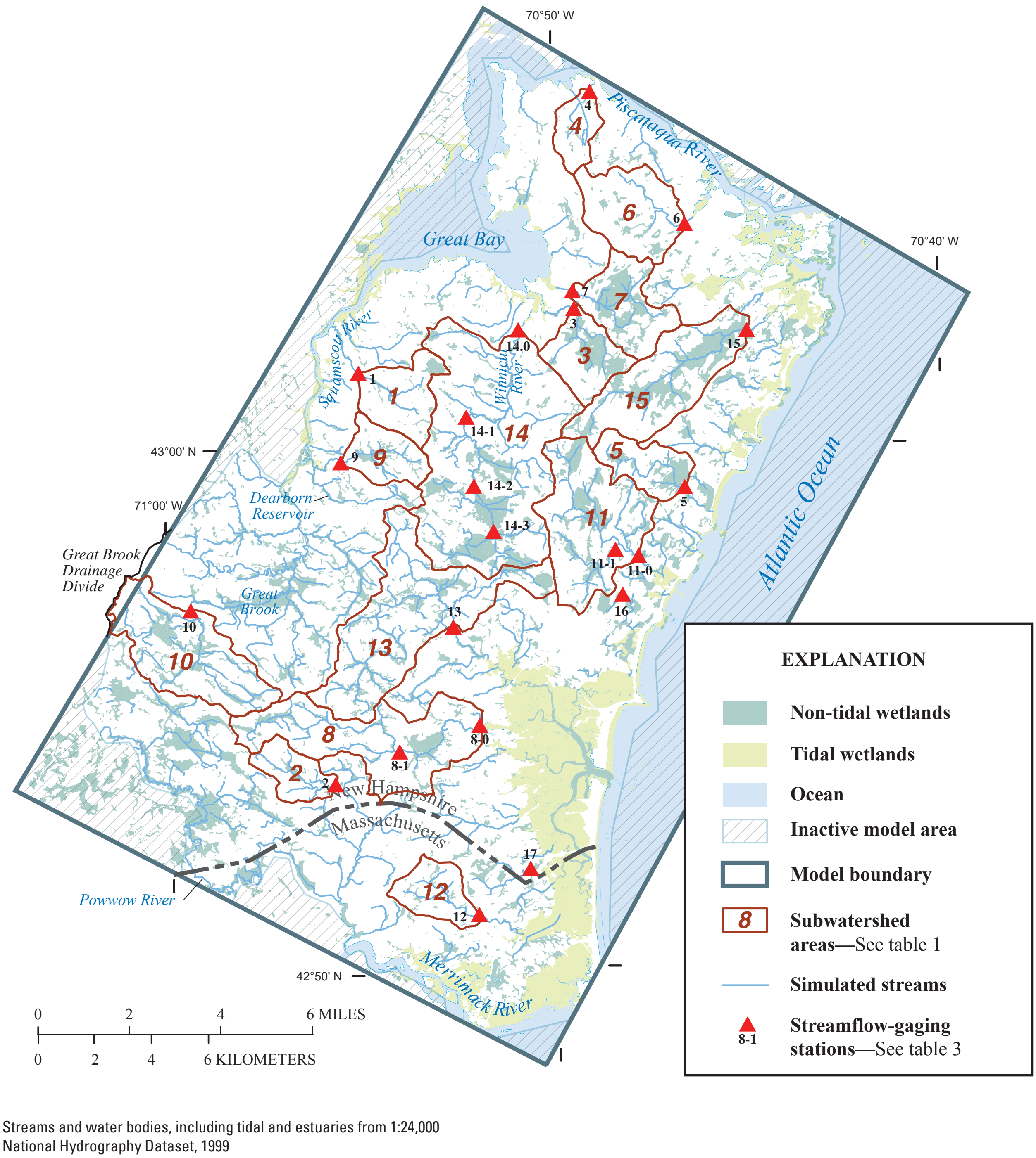
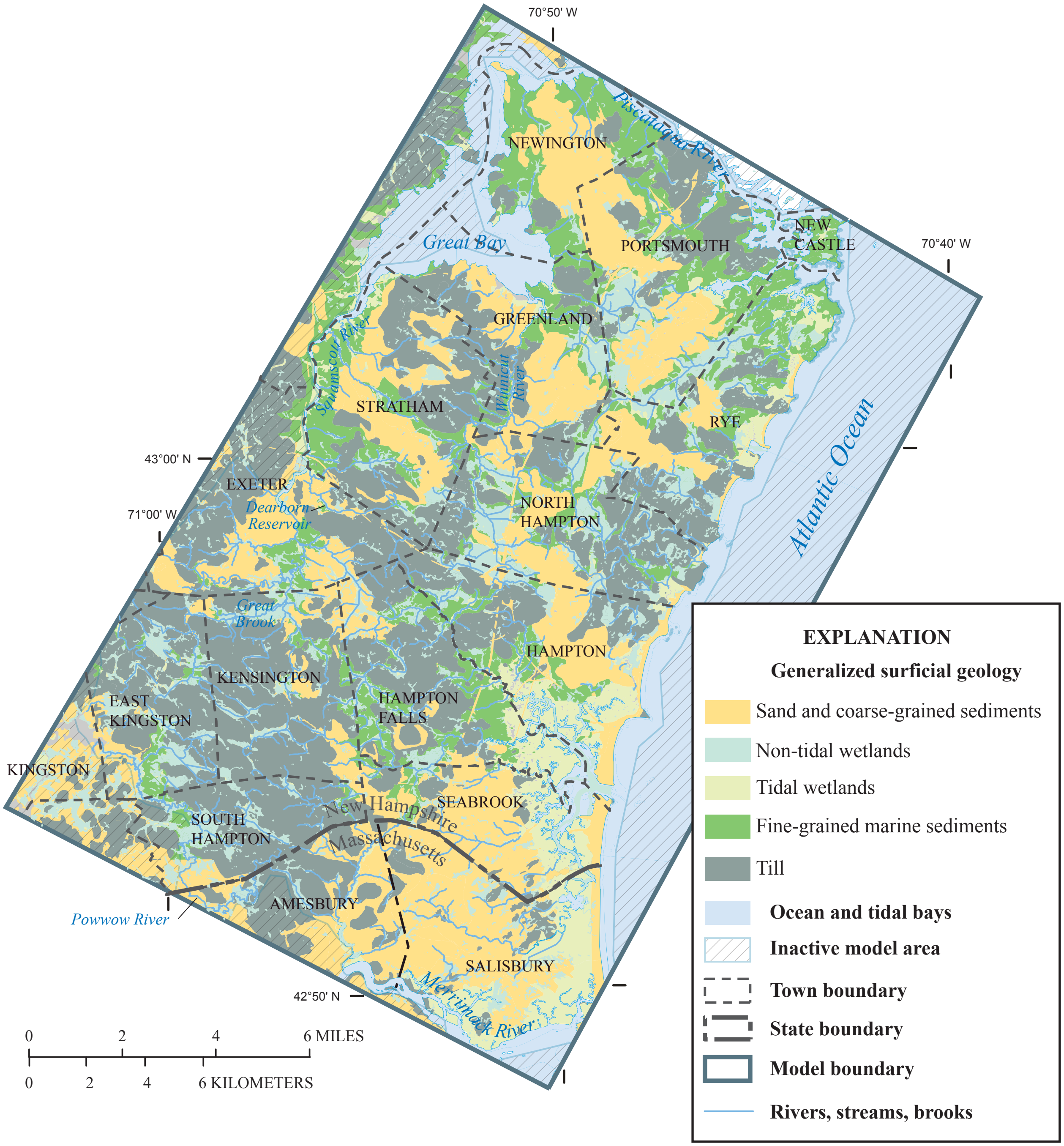


Figure 2. Watershed drainage divides, tidal areas, and streamflow-gaging stations in the Seacoast model area, southeastern New Hampshire.



New Hampshire surficial geology base from 1:24,000 N.H. State Geologist, 2005
Massachusetts base from 1:250,000 MassGIS, 1999

Figure 3. Distribution of surficial sediments, wetlands, and water bodies in the Seacoast model area, southeastern New Hampshire.

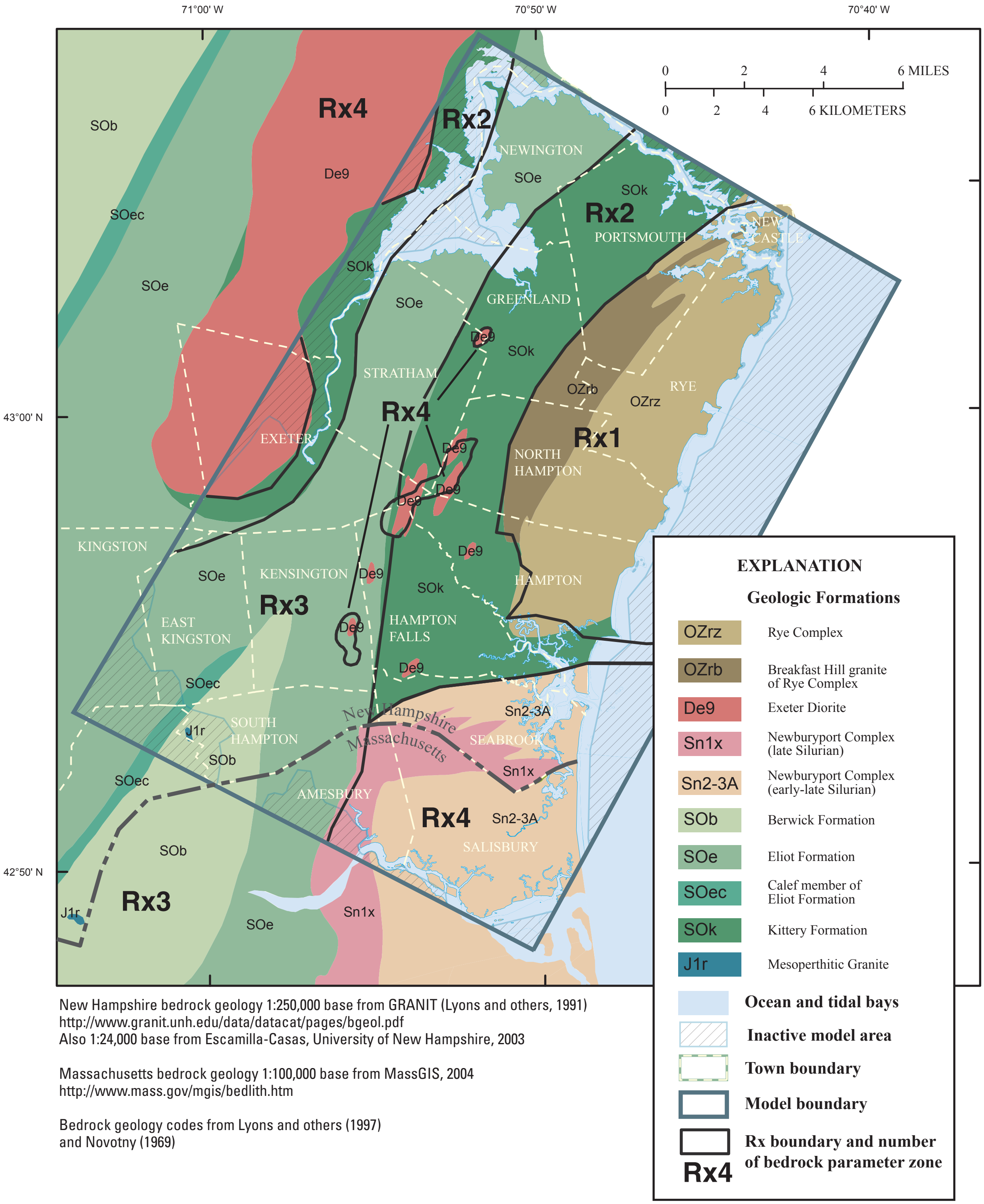


Figure 4. Dominant bedrock formations in the Seacoast area and bedrock parameter zones used in the Seacoast model, southeastern New Hampshire.

Background and Previous Studies

The first comprehensive assessment of the geology and ground-water resources of the study area was completed by Bradley (1964). In the 1980s, regional stratified-drift-aquifer assessments were completed in the study area in cooperation with the NHDES, and covered the coastal river basins (Stekl and Flanagan, 1992) and the Exeter River basin (Moore, 1990). These USGS investigations mapped the boundaries, saturated thickness, and transmissivity of stratified-drift aquifers, which were the aquifer resource with the greatest transmissivity and capacity for additional water supplies. Prior to the 1950s, many residents of the Seacoast relied on dug wells in glacial deposits. Although dug wells provide very little storage capacity, they generally were sufficient for domestic water needs at the time. Advances in drilling techniques and well pumps, after the 1950s, made bedrock wells easier to install and use. Bedrock wells have gained favor over time because of their storage capacity. The volume of water stored in a borehole can be a few times larger than that of a dug well during dry periods when water levels may be near the bottom of a dug well. Bedrock wells are also regarded as providing security against shallow contaminants such as septic inflows.

By the 1990s, stratified-drift aquifers in the Seacoast were either fully utilized, unavailable because of development, or in some localized areas contaminated by anthropogenic activities. Some water suppliers began installing supply wells in the bedrock aquifer in areas of the Seacoast to meet increasing demand. In response to an increasing demand for water resources and an interest in the State's bedrock aquifers, an assessment of factors related to well yield in the fractured-bedrock aquifer of New Hampshire was conducted by the USGS in cooperation with NHDES (Moore and others, 2002). A digital coverage of the bedrock geology of New Hampshire was provided by Lyons and others (1997) at a scale of 1:125,000. Detailed information about the geology of the Seacoast is provided by Novotny (1969), Escamilla-Casas (2003), and Dr. Wallace Bothner (University of New Hampshire, oral commun., 2005). Numerous site-specific water-supply investigations have been conducted by hydrogeologic consulting and engineering firms throughout the Seacoast area to identify new sources of ground water or describe aquifer characteristics.

Only within the past decade have ground-water-flow simulations been more widely used in the investigation of bedrock aquifers in the eastern United States. Two investigations of note were among the first regional ground-water-flow simulations in crystalline bedrock aquifers. Daniel and others (1997) used ground-water-flow simulation and flow-path analysis to investigate a 146-mi^2 hydrogeologic system in North Carolina's piedmont crystalline-bedrock aquifer. Tiedeman and others (1997) used ground-water-flow simulation and flow-path analysis to investigate the 4-mi^2 Mirror Lake watershed in northern New Hampshire.

Ground water in the crystalline-bedrock aquifer flows through discrete fractures and partings. At site-specific scales of tens to hundreds of feet, the location, orientation, and nature of individual fractures dominate the characteristics of ground-water flow; however, at larger scales—hundreds of feet or greater—the nature and location of individual fractures are not nearly as important in understanding the movement of ground water and fluxes (flow into or out of an aquifer) in the regional system. More important is understanding the large-scale properties of the rock, such as the regional connectivity of the individual fractures. This regional connectivity will determine the hydraulic conductivity of the rock at greater scales, or what can be termed "bulk hydraulic conductivity." This concept is analogous to ground-water flow in porous media; understanding the nature of individual pores, or the movement of ground water between pores, is not necessary for understanding and simulating ground-water flow in porous media. The bedrock aquifer can be treated as an equivalent porous medium (EPM) in some circumstances using a continuum approach, which is discussed with application to fractured bedrock by Hsieh (2002) and Hsieh and others (1999). The EPM approach has been used in an investigation of a limestone aquifer (Langevin, 2003a) in which solution fracture zones within the consolidated rock were not explicitly simulated but were represented as part of a continuum.

The scale of investigation is very important in the application of the EPM approach. It is assumed that bedrock at the scale of interest can be represented by zones of similar hydrologic characteristics. At larger scales, such as the watershed scale, the area of interest will be more homogenous. In the case of fractured-crystalline bedrock, zones of the bedrock aquifer with similar hydraulic properties, such as bulk hydraulic conductivity, are assumed to be identified by mapped geologic units. The EPM approach makes use of contrasts in fracture density, connectivity, yield, and possibly other properties between one rock formation and another. At small scales—for example, at the well-field scale—this approach may not be valid because the heterogeneity imposed by individual fractures, or a fracture zone, may dominate the flow system.

The EPM approach has been applied at the watershed scale to crystalline-bedrock aquifer systems in the eastern United States that are similar to that in the Seacoast study area. Examples include investigations by Lyford and others (2003) in Massachusetts; Harte (1992) and Tiedeman and others (1997, 1998) in northern New Hampshire; Daniel and others (1997) in North Carolina; and Starn and Stone (2005) in Connecticut. A preliminary simulation of regional ground-water flow in the Seacoast area was done by Mack and others (2002) and Mack (2003) for this investigation. Ground-water availability and use in fractured-rock settings elsewhere were investigated by Hunt and others (2001), Willey and Achmad (1986), and Vogel and Reif (1993). A helpful synthesis of fractured-bedrock investigations including ground-water-flow simulations and well yield is provided by Starn and Stone (2005).

Methods

This investigation provides a model of Seacoast ground-water resources through an integrated analysis of geohydrologic data including geologic information, water levels, streamflows, and water-use data. An assessment of ground-water sustainability requires an understanding and approximation of the complete hydrologic system and of the interaction of its components. These components depend upon the hydraulic properties of the surficial sediments and bedrock and upon the climate and topography of the area. Quantification of the hydrologic components also depends on the scale of investigation; these components were evaluated with respect to the regional ground-water-flow system.

Numerical ground-water-flow simulations were used to assess aquifer properties and surface- and ground-water interactions. A numerical model is a representation that describes the geometry, composition, and hydraulic properties of a ground-water-flow system and accounts for all known or estimated (conceptual) hydrologic processes included in ground-water flow. For calculating the availability of water over a watershed or regional setting, regionally varying bulk hydraulic properties that characterize different lithologic settings, as used in this investigation, are usually sufficient (Shapiro, 2002) to describe regional ground-water recharge, discharge, and storage. By constructing the numerical model and assigning known, estimated, or hypothetical properties to the flow components, it is possible to assess the conceptual understanding of the ground-water-flow system and its various components. The USGS modular finite-difference ground-water-flow model, MODFLOW-2000 (Harbaugh and others, 2000), was used as the computer code for this investigation. Digital coverages of topography, bathymetry, hydrography, and aquifer properties were used with preprocessing software (Winston, 2000) to construct MODFLOW-2000 data sets. The conceptual and numerical characteristics of these software packages are described later in this report. The model was designed and calibrated according to guidelines and methods described by Hill (1998) and the analysis techniques of Hill and others (2001).

Hydrogeologic Characteristics of the Seacoast Region

Hydraulic Properties

Hydraulic properties of aquifer materials include the horizontal and vertical hydraulic conductivity, specific yield, and specific storage. Surficial sediments and bedrock aquifers have contrasting hydraulic properties because of differences in the amount of consolidation that has occurred.

Surficial Deposits

The surficial geology of the Seacoast area (Bennett and others, 2004) was divided into four general groups of sediments with different origins and characteristics for the ground-water-flow simulation in this investigation. The hydraulic conductivites of the overburden aquifers, which affect ground-water-flow paths and residence times, differ considerably with the type of overburden deposit. The 4 groups are shown in figure 3; till; coarse-grained sediments, including sand and gravel, alluvium, and fill; fine-grained marine sediments, including fine-grained sand, silt, and clay; and wetland deposits, including freshwater and saltwater wetland deposits. The percentages of the study area and selected subwatersheds (fig. 2) covered by each of the four surficial sediment categories, surface water, and bedrock (fig. 3) are provided in table 1.

The most extensive surficial sediment is till, which covers about 39 percent of the study area. Till is generally a few feet to less than 20 feet thick and underlies most other sediments in the study area; the thickness generally can be inferred to be thin near large boulders or bedrock exposures. The hydraulic conductivity of till in New England has been measured at about 1 ft/d (Harte, 1997; Mack, 1995; Melvin and others, 1992). Till generally has similar horizontal and vertical hydraulic conductivities (Melvin and others, 1992) likely because it is an unsorted mixture of sediments. Before the mid-1900s, wells dug in till were typically about 20 ft deep and were adequate for domestic supply. Shallow till wells, which can still be found at many older homes in the Seacoast, generally do not meet the current water-supply needs of domestic users, particularly during dry periods.

The thickness and hydraulic properties of stratified-drift aquifers in the study area were determined by Moore (1990) and Stekl and Flanagan (1992). The horizontal hydraulic conductivity of stratified drift in New Hampshire ranges from about 2 to 15 ft/d for fine-grained sands, and from 50 to more than 200 ft/d for coarse-grained sands and gravel (Ayotte and Toppin, 1995; Medalie and Moore, 1995). The vertical hydraulic conductivity of stratified-drift sediments in New England is generally about one-tenth of the horizontal hydraulic conductivity (Randall, 2001). Most areas of the Seacoast have saturated thicknesses less than 40 ft. Notable exceptions include the stratified-drift aquifer underlying the Pease Tradeport, also known as the former Pease Air Force Base (PAFB), in Newington; an aquifer in Kensington at Great Brook Meadows; and thinner aquifers in Hampton.

Stratified-drift deposits cover about 24 percent of the study area. Only about 2 percent of the study area, however, is covered by stratified-drift aquifers with transmissivities of 1,000 ft^2/d or greater (Moore, 1990; Stekl and Flanagan, 1992). Less than 1 percent of the study area is covered by stratified-drift aquifers with transmissivities of 2,000 ft^2/d or greater. In some areas the stratified-drift aquifers support very high-yield supply wells. The most prominent stratified-drift aquifer in the study area is the plain covering parts of

Table 1. Subwatersheds and percentages of surficial geologic sediments, wetlands, surface-water bodies, and bedrock within each subwatershed, Seacoast model area, southeastern New Hampshire.

[All streams are in New Hampshire unless otherwise noted. Subwatershed areas shown on figure 2; mi², square miles; —, not available]

Sub-watershed number (fig. 2)	River or stream name	Area (mi²)	Stratified drift and other coarse-grained sediments	Marine sediments	Till	Wetland	Surface-water bodies	Bedrock
1	Mill Brook, Stratham	1.98	64.1	24.8	5.3	5.8	0.0	0.0
2	Back River, South Hampton	1.53	1.6	.0	94.1	4.0	.3	.0
3	Packer Brook, Greenland	2.31	49.2	27.0	7.3	14.8	1.7	.0
4	Pickering Brook, Newington	1.29	73.2	22.8	3.9	.0	.0	.0
5	Bailey Brook, Rye	1.95	39.5	10.1	43.0	7.1	.3	.0
6	Hodgson Brook, Portsmouth	3.52	49.4	26.4	23.0	.9	.3	.0
7	Pickering Brook, Greenland	2.97	43.5	11.8	15.8	28.1	.6	.1
8.0	Hampton Falls River, Route 1, Hampton Falls	6.66	22.3	21.7	52.0	3.2	.8	.0
8.1	Hampton Falls River, Mill Lane, Hampton Falls	3.61	10.4	.1	45.0	44.1	.4	.0
9	Parkman Brook, Stratham	1.89	23.8	33.8	42.1	.0	.3	.0
10	Great Brook, Kensington	5.45	1.1	6.8	81.3	10.6	.3	.0
11.0	Little River, North Hampton	6.12	22.9	23.2	46.1	7.4	.4	.0
12	Smallpox Brook, Salisbury, Mass.	1.83	95.0	5.0	—	—	—	—
13	Taylor River, Hampton	8.41	7.1	24.2	59.6	8.5	.6	.0
14.0	Winnicut River, Greenland	14.19	32.5	13.7	43.1	10.0	.6	.0
15	Berrys Brook, Rye	5.38	36.1	35.8	13.7	14.2	.1	.0
	Approximate total area and percentages of materials in the total area	230	24.3	17.6	39.1	7.7	11.1	.2

Newington and Portsmouth beneath the PAFB. This deposit is 4 mi long, 0.25 to 1 mi wide, and up to 70 ft thick (Bradley, 1964). The Haven Well, a water-supply well for the city of Portsmouth, is completed in this deposit and has a potential yield of more than 800 gal/min, although the permitted yield is limited to 300 gal/min to prevent drawing contaminated ground water into the well. The horizontal hydraulic conductivities of sands near the supply well were estimated to be approximately 210 to 260 ft/d (Montgomery Watson Harza, Inc., 2002). An extensive but thinner stratified-drift aquifer extends from western Rye to southern Portsmouth and northern Greenland. This aquifer includes the Greenland Well, which supplies more than 600,000 gal/d, and is generally less than 40 ft thick. Another notable but less extensive stratified-drift aquifer, with thicknesses of up to about 40 ft, is beneath central North Hampton (figs. 1 and 3). Stratified-drift deposits also cover parts of Seabrook and much of Salisbury, Mass., but these generally are thin discontinuous deposits.

Fine-grained marine sediments include fine-grained sand, silt, or clay. These sediments, deposited in estuaries and tidal areas during deglaciation, are in areas of lower elevation and cover about 18 percent of the study area (table 1). Fine-grained sediments typically have hydraulic conductivities of about 1 ft/d or less. Although some marine sediments (sands) may locally have higher horizontal hydraulic conductivity, the marine sediments typically have low horizontal hydraulic conductivities and very low vertical hydraulic conductivities; these sediments were considered as one unit for this regional investigation. Sediments beneath Great Bay, to the west, are primarily fine-grained sand, silts, and clays. Sediments beneath the Atlantic Ocean to the east were primarily coarse-grained sands and gravels (Poppe and others, 2003).

Wetland deposits cover approximately 8 percent of the study area (table 1). Large freshwater wetlands dominate the central areas of the Seacoast and smaller wetlands cover many low-lying areas (figs. 2 and 3). Coastal areas with prominent saltwater wetlands include Portsmouth, Hampton, Seabrook, and Salisbury. An investigation of a pond-dominated aquifer system in central Massachusetts (Carlson and Lyford, 2005) noted that wetland deposits likely have horizontal hydraulic conductivities of tens of feet per day and vertical conductivities of less than 1 ft/d.

The amount of water stored in unconsolidated sediments is typically about 25 to 50 percent per saturated volume for gravel, sand, and silt, and as much as 70 percent for clay (Freeze and Cherry, 1979). However, the water that can be released from gravity drainage per unit decline in the water table, termed specific yield, is less than the amount of water stored. The total amount of water available in the overburden aquifer is determined by the specific yield and thickness of the deposit. The specific yields of till, fine- and coarse-grained stratified drift are relatively similar, about 25 percent (Melvin and others, 1992). The specific yields of silt and clay may be on the order of 0.02 to 0.08 (DeSimone, 2004; Domenico and Schwartz, 1997; Kontis and others, 2004). Wetland deposits probably have specific yields greater than that of other surficial sediments; values of 0.4 have been reported (Domenico and Schwartz, 1997; Morris and Johnson, 1967).

Bedrock

Bedrock in the study area consists of crystalline metasedimentary and igneous rocks (Novotny, 1969) oriented in a northeast-southwest-trending structural pattern (fig. 4). Bedrock is exposed throughout the study area, particularly along the northern coastal shorelines; however, outcrop area makes up less than 1 percent of the study area (table 1). The hydraulic conductivity of the bedrock aquifer, which depends on the bedrock-fracture network and investigation scale, spans several orders of magnitude. Regionally, the hydraulic conductivity of the bedrock aquifer is defined by the small fractures of the pervasive fracture network (Tiedeman and others, 1997). The regional hydraulic conductivity estimated for crystalline rock in northern New Hampshire ranges from about 0.01 to 0.1 ft/d (Tiedeman and others, 1997).

The crystalline bedrock of the Seacoast effectively has little primary porosity for release of water from storage. Ground water is stored and transmitted in the secondary porosity provided by fracturing in the rock. The secondary porosity of crystalline bedrock aquifers due to fractures has been reported as 0 to 10 percent (Freeze and Cherry, 1979; Snow, 1968). However, very high well yields (more than 40 gal/min, appendix 2) and large ground-water supply wells (appendix 5) in some areas of the Seacoast, such as in the Kittery Formation and Rye Complex, indicate that the secondary porosity is likely to be great. Daniel (1989) found well yield and specific capacity to be correlated in the crystalline bedrock in North Carolina. Moore and others (2002) determined that the wells in the Rye Complex and the Kittery and Eliot Formations in the Seacoast area have a greater probability of a high yield compared to wells in the other bedrock types in New Hampshire. Additional discussion of bedrock well yields in the study area is provided in appendix 2.

Bedrock aquifers in the study area generally respond to stresses as a confined aquifer where the amount of water that can be released from the aquifer, from a decrease in hydraulic head, is defined by either a storage coefficient (S_c) or a specific storage (S_s). Specific storage is defined as the storage coefficient divided by the aquifer thickness (*b*).[1] Storage coefficients for fractured rock have been reported from 2×10^{-4} to 6×10^{-6} (Randall and others, 1988; Tiedeman and Hsieh, 2001; Paillet, 2001). Lyford and others (2003) calculated a storage coefficient of 9×10^{-4} based on an aquifer test at a high-yield supply well in the phyllite of the Eliot Formation less than 10 mi south of the study area. Analysis of earth-tide water-level fluctuations in the study area (appendix 3) indicates a bedrock-aquifer porosity of about 0.02 percent and a specific storage (S_s) of approximately 2×10^{-7}. Nielsen (2002) estimated porosities of 0.08 to 1.4 percent and 0.1 to 0.7 percent for schist and granitic rocks, based on geophysical analyses, in Bar Harbor, Maine.

Ground-Water Flow

Ground water flows toward water bodies from topographic highs to lows in the study area. The water table in the study area is generally 10 to 20 ft below the land surface, following the topography, except in wetlands and water bodies, where the water table is at the land surface. The ground-water system is recharged by precipitation at the land surface and discharges to streams or to tidal water bodies. Recharge is generally greatest in spring (March and April) and late fall (November and December). During summer months (July and August), evapotranspiration (ET) may cause the effective recharge to be zero or negative.

Recharge

Seasonal and average annual recharge rates (table 2) were estimated by Flynn and Tasker (2004) or calculated by Robert Flynn (U.S. Geological Survey, written commun., 2005) for watersheds of nearby stream-gaging stations (Keirstead and others, 2004) and for subwatersheds in the study area (fig. 2). Flynn and Tasker (2004) analyzed the historical streamflow records of more than 50 streams statewide with respect to climatic, topographic, land-cover, and surficial-geologic variables, using the techniques of Rutledge (1993, 1998) to estimate seasonal and annual recharge by hydrograph separation. Long-term average annual recharge at the Oyster River station (USGS number 01073000), which is

[1] Storage in the bedrock aquifer derived from an aquifer hydraulic test is commonly reported using the term storage coefficient (dimensionless) because the thickness (*b*) of the bedrock aquifer is generally unknown. The storage discussed in this report with respect to the ground-water-flow model is specific storage (with units of l^{-1}), which is applied to a prescribed aquifer (or layer) thickness.

Table 2. Recharge estimates calculated for streams in southeastern New Hampshire and northern Massachusetts, and estimated for selected watersheds in the Seacoast model area, southeastern New Hampshire.

[Areas of stratified drift from Flynn and Tasker (2004), based on areal coverages published earlier than the extents listed in table 1; mi², square miles; in., inches; —, not available]

Stream	Record length (years)	Drainage area (mi²)	Stratified drift (percent)	Average annual recharge (in.)	Normalized average annual recharge (in.)	Winter[1] (in.)	Spring[1] (in.)	Summer[1] (in.)	Fall[1] (in.)
Mohawk Brook[2]	11	7.5	0	18.7	23.9	5.4	7.6	1.6	4.2
Oyster River[2]	50	12.1	7	19.5	20.7	5.9	7.6	2.8	4
Dudley Brook[2]	23	5.8	25	—	—	3.9	5.2	1.4	2.4
Parker River, Mass.[2]	50	21.2	4	23.1	26.1	7.8	8.8	3.9	4.8
Mill Brook[3]	Estimation	2.5	64	21.8	—	6.0	7.3	2.5	4.3
Winnicut River[3]	Estimation	14.2	35	22.0	—	6.1	7.3	2.5	4.3
Berrys Brook[3]	Estimation	5.4	36	22.2	—	6.1	7.3	2.5	4.4
Little River[3]	Estimation	6.1	23	20.5	—	5.8	7.0	2.4	3.9
Taylor River[3]	Estimation	8.4	7	20.1	—	5.8	7.1	2.5	3.8
Hampton Falls River[3]	Estimation	3.6	10	22.2	—	6.3	7.5	2.4	4.3
Great Brook[3]	Estimation	5.5	1	22.0	—	6.2	7.5	2.5	4.3

[1]Seasons as used by Flynn and Tasker (2004): Winter is January 1 through March 15; Spring is March 16 through May 31; Summer is June 1 through October 31; and Fall is November 1 through December 31.

[2]Analysis of historical streamflow records from Flynn and Tasker (2004).

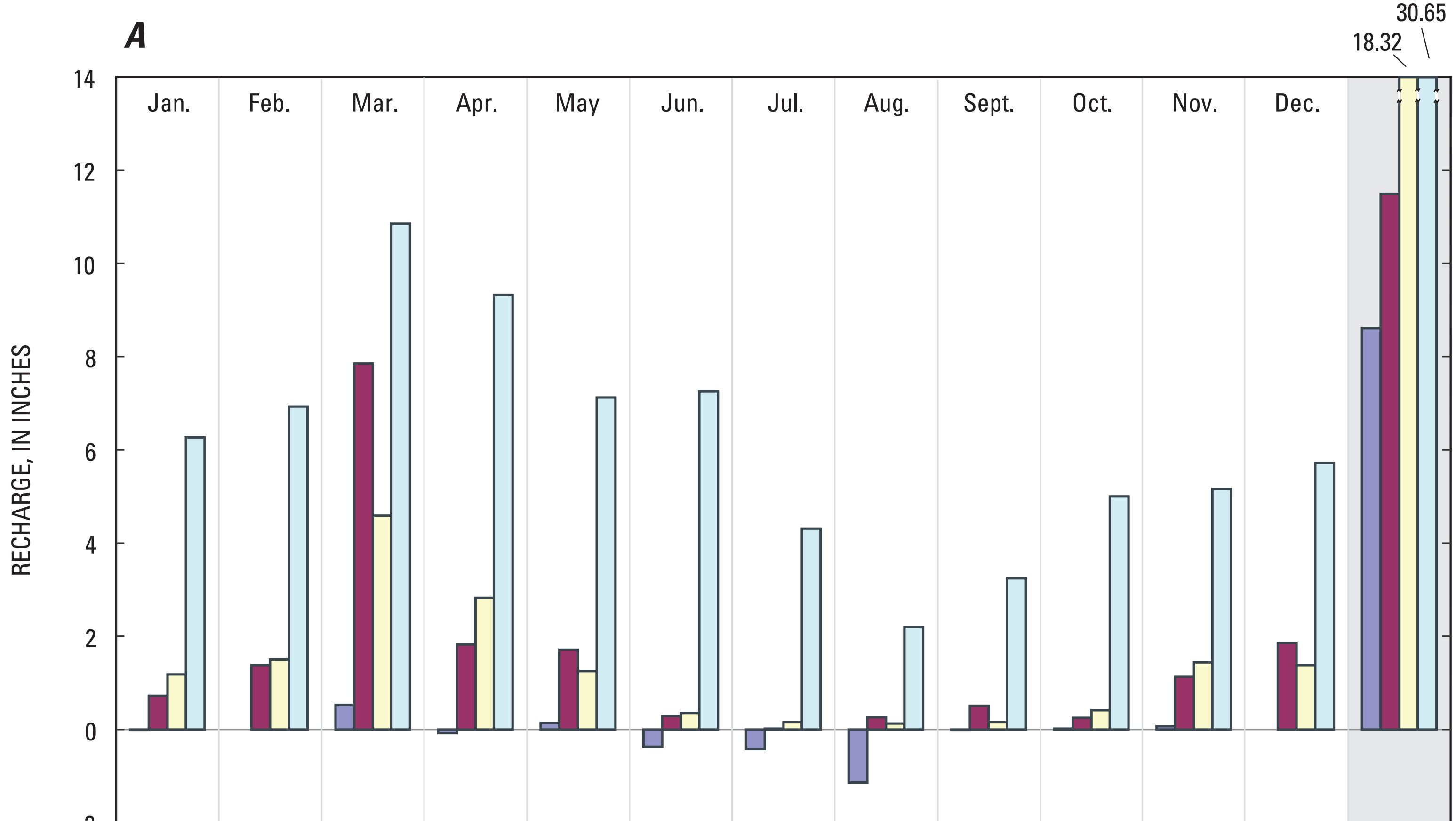
[3]Calculations based on watershed characteristics (Robert H. Flynn, U.S. Geological Survey, written commun., 2005).

approximately 5 mi northwest of the study area, was estimated to be approximately 19 in/yr. The area of the Oyster River watershed is approximately 12 mi², and 7 percent of it is covered by stratified drift. Estimated average annual recharge in the Mohawk River watershed in Strafford, N.H., a 7.5 mi² watershed consisting entirely of till-covered bedrock, is about 19 in/yr (Flynn and Tasker, 2004).

Recharge in the glaciated Northeast is commonly thought to be a function of sediment type with higher recharge rates attributed to coarse-grained sand and gravel and lower rates attributed to fine-grained sediments and tills. Many investigations in New England refer to a relation between sediment type and recharge. Weiss and others (1982) present a curve indicating increasing streamflow per square mile with increasingly coarse-grained sediment in Connecticut. This work may more appropriately indicate increased storage in coarse-grained sediments and not necessarily an increased amount of recharge. Recharge rates in till-covered areas and areas covered by stratified drift were found to be similar by recent investigations in Massachusetts (Bent, 1999), New Hampshire and Vermont (Flynn and Tasker, 2004), and Michigan (Hotschlag, 1997). Recharge rates in coarse-grained sediments are not necessarily higher than in till, but a well completed in coarse-grained sediments can capture water from a larger area with less drawdown.

Long-term recharge trends were assessed by analyzing monthly total recharge estimated by hydrograph separation (RORA method) (Rutledge, 1998, 2000) of daily streamflows at the Oyster River station between 1935 and 2003 (fig. 5). The median monthly total recharge is less than 1 in. from June to October, about 0.14 in. from July to September, and a high of 4.6 in. in March. The median monthly recharge was 0.9 in. (exceeded 50 percent of the time), whereas the mean monthly recharge was 1.6 in. (exceeded 35 percent of the time). Hydrograph separation results in negative recharge during some months, when there can be a net loss due to ET.

Monthly recharge was estimated for the continuous streamflow-gaging stations in the study area (fig. 2) for the period of investigation (fig. 6). Recharge estimated for the Oyster River station was similar to that estimated for other stations in the model area. Recharge varied monthly with the amount of precipitation. Little or no recharge was estimated for July and August of each year and for January 2004 (0.60-in. precipitation). Peaks were estimated for March 2003 and April 2004; however, monthly total recharge estimates for March 2003 at the Oyster, Winnicut, and Hampton Falls stations were not realistic in that they were greater than the precipitation total for the month. Hydrograph-separation techniques are not always appropriate at small time scales, such as monthly intervals, and must be used with caution



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
MINIMUM	-0.01	0.00	0.53	-0.08	0.14	-0.37	-0.42	-1.14	-0.01	0.02	0.07	0.00	8.61
MEAN	0.72	1.38	7.85	1.82	1.71	0.29	0.02	0.26	0.51	0.25	1.13	1.85	11.49
MEDIAN	1.18	1.50	4.59	2.82	1.25	0.35	0.15	0.13	0.15	0.41	1.44	1.38	18.32
MAXIMUM	6.27	6.93	10.85	9.32	7.12	7.25	4.31	2.20	3.24	5.00	5.16	5.72	30.65

Figure 5. *(A)* Long-term monthly recharge statistics on the basis of 69 years of record.

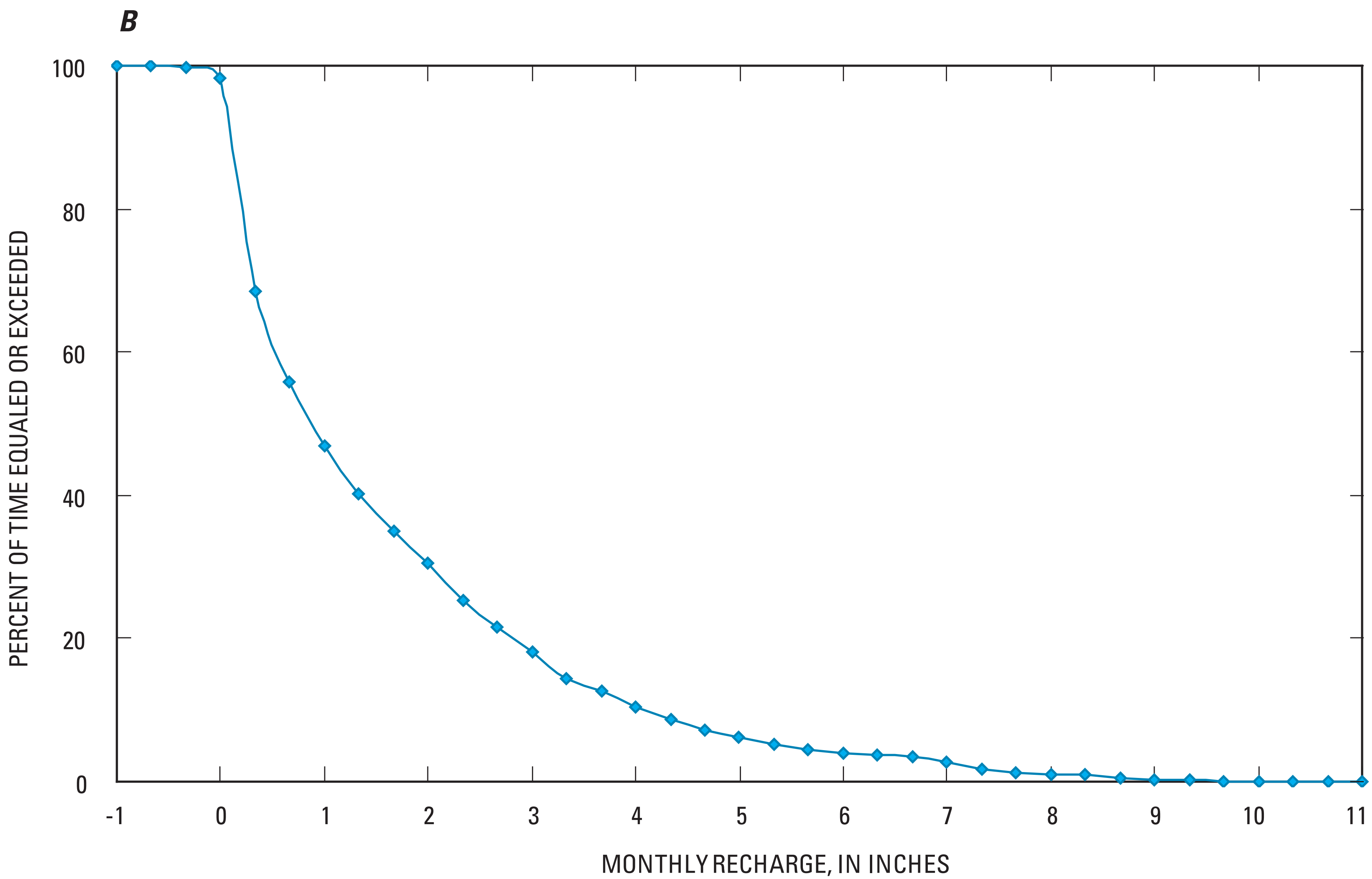


Figure 5. *(B)* Monthly recharge-duration probabilities estimated for the drainage area to the Oyster River streamflow-gaging station, New Hampshire, on the basis of 69 years of record.—Continued

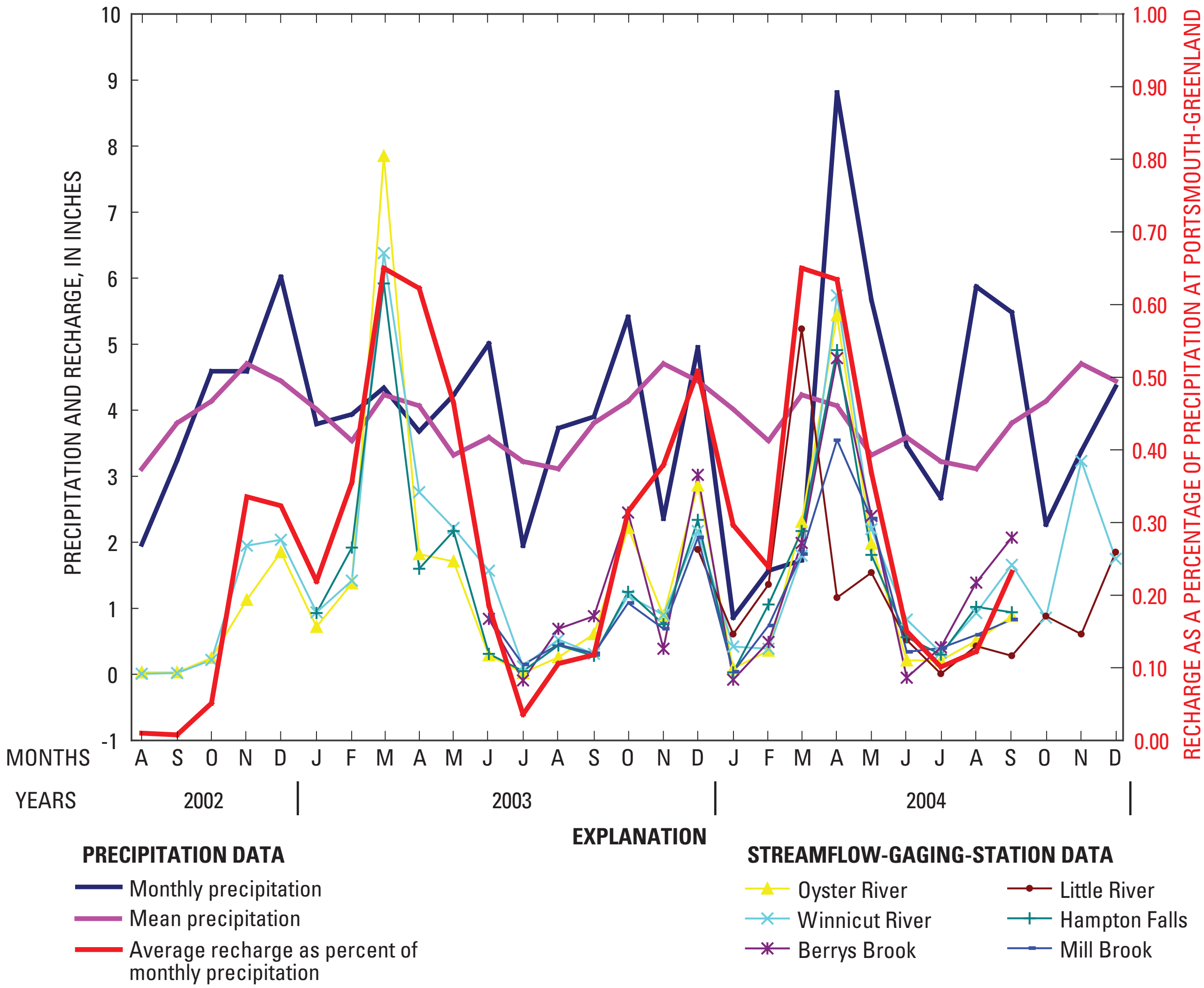


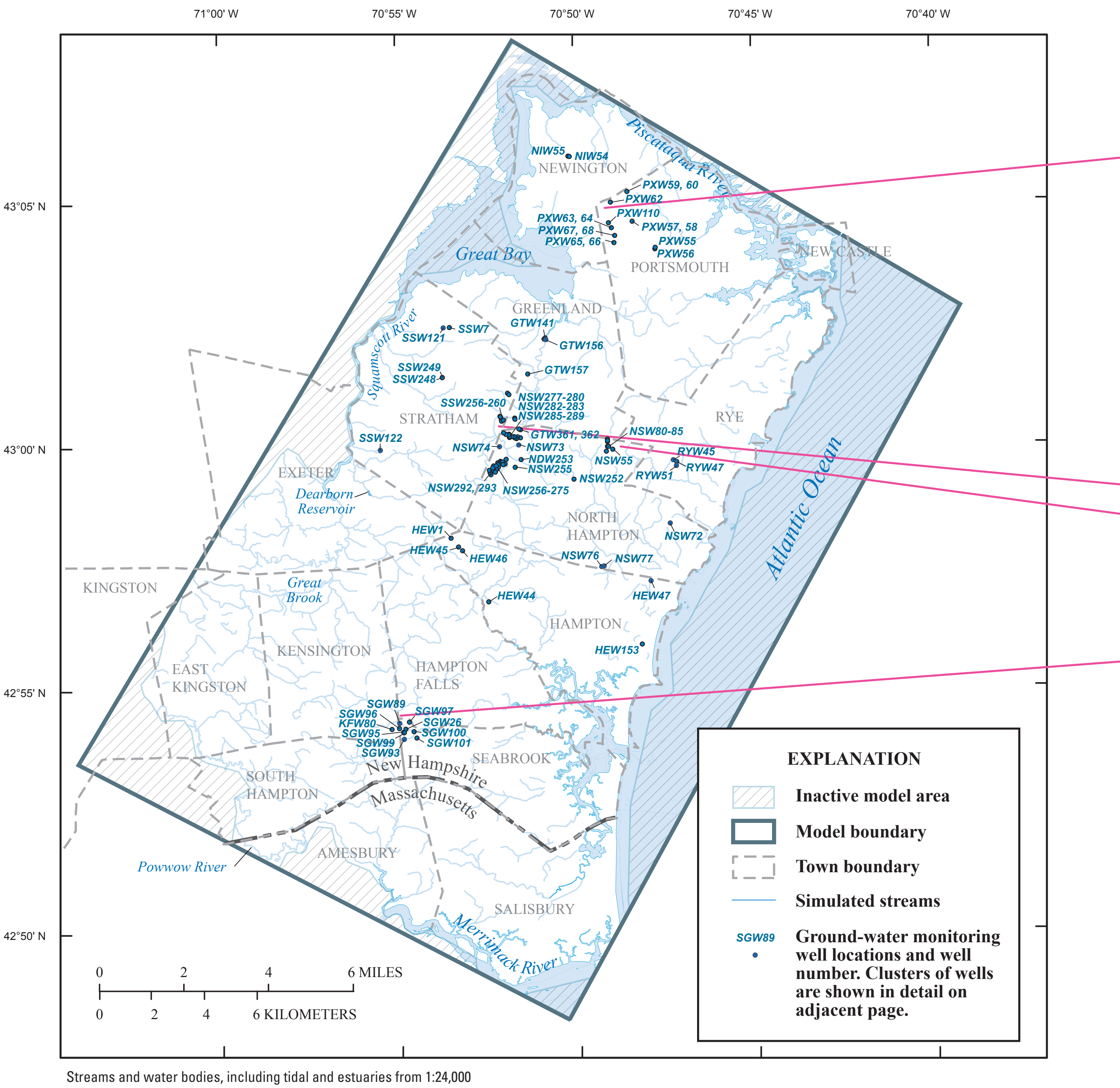
Figure 6. August 2002 to December 2004 monthly recharge estimated for Seacoast and Oyster River streamflow-gaging stations and precipitation in New Hampshire.

(Rutledge, 2000). It was assumed that recharge is not greater than 65 percent of precipitation for these months. Monthly recharge was estimated to be a few percent of precipitation in the summer months, about 30 to 50 percent in the fall, and about 65 percent of precipitation in April.

Water Levels

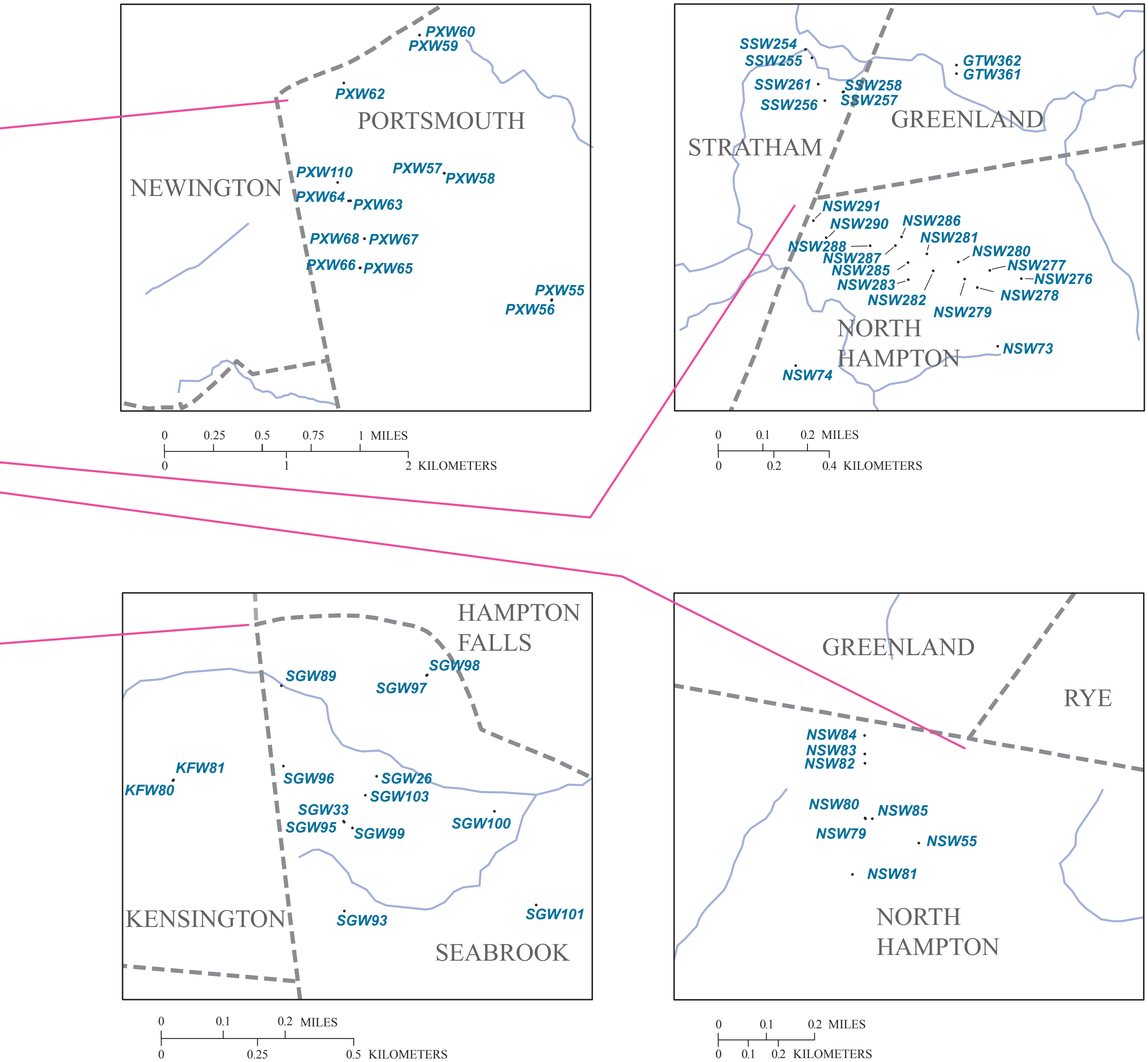
Ground-water levels were measured at selected stratified-drift, till, and bedrock monitoring wells in the study area (fig. 7). Water levels also were available from Aquarion Water Company (Raymond Talkington, Geosphere Environmental, written commun., 2005) Golf Club of New England (Timothy Warr, Exeter Environmental, written commun., 2005), and the former Pease Air Force Base (Peter Forbes, U.S. Air Force, written commun., 2004; William Pepe, Montgomery Watson Herza, written commun., 2005). Historical water levels were obtained from drilling completion reports and a waste-site inventory of well information (GEOLOGS); both databases were maintained by the NHGS (Frederick Chormann, New Hampshire Geological Survey, written commun., 2004).

The longest water-level record within the model area was provided by Aquarion Water Company in support of a NHDES ground-water-withdrawal compliance program. Water levels have been measured at an overburden (stratified-drift) and bedrock-well pair since July 1997 (fig. 8). Water levels reach their annual peaks in the spring between late March and early May, and are low in the late fall and occasionally in the winter



Streams and water bodies, including tidal and estuaries from 1:24,000
National Hydrography Dataset, 1999

Figure 7. *(A)* Ground-water monitoring wells in the study area.


PXW60
PXW59
PXW62
PORTSMOUTH
NEWINGTON
PXW110
PXW57
PXW58
PXW64
PXW63
PXW68
PXW67
PXW66
PXW65
PXW55
PXW56
0 0.25 0.5 0.75 1 MILES
0 1 2 KILOMETERS
SSW254
SSW255
SSW261
SSW256
SSW258
SSW257
GTW362
GTW361
GREENLAND
STRATHAM
NSW291
NSW290
NSW286
NSW288
NSW281
NSW287
NSW280
NSW285
NSW277
NSW283
NSW276
NSW282
NSW278
NSW279
NORTH HAMPTON
NSW73
NSW74
0 0.1 0.2 MILES
0 0.2 0.4 KILOMETERS
HAMPTON FALLS
SGW98
SGW89
SGW97
KFW81
KFW80
SGW96
SGW26
SGW103
SGW33
SGW95
SGW99
SGW100
KENSINGTON
SGW93
SGW101
SEABROOK
0 0.1 0.2 MILES
0 0.25 0.5 KILOMETERS
GREENLAND
RYE
NSW84
NSW83
NSW82
NSW80
NSW85
NSW79
NSW55
NSW81
NORTH HAMPTON
0 0.1 0.2 MILES
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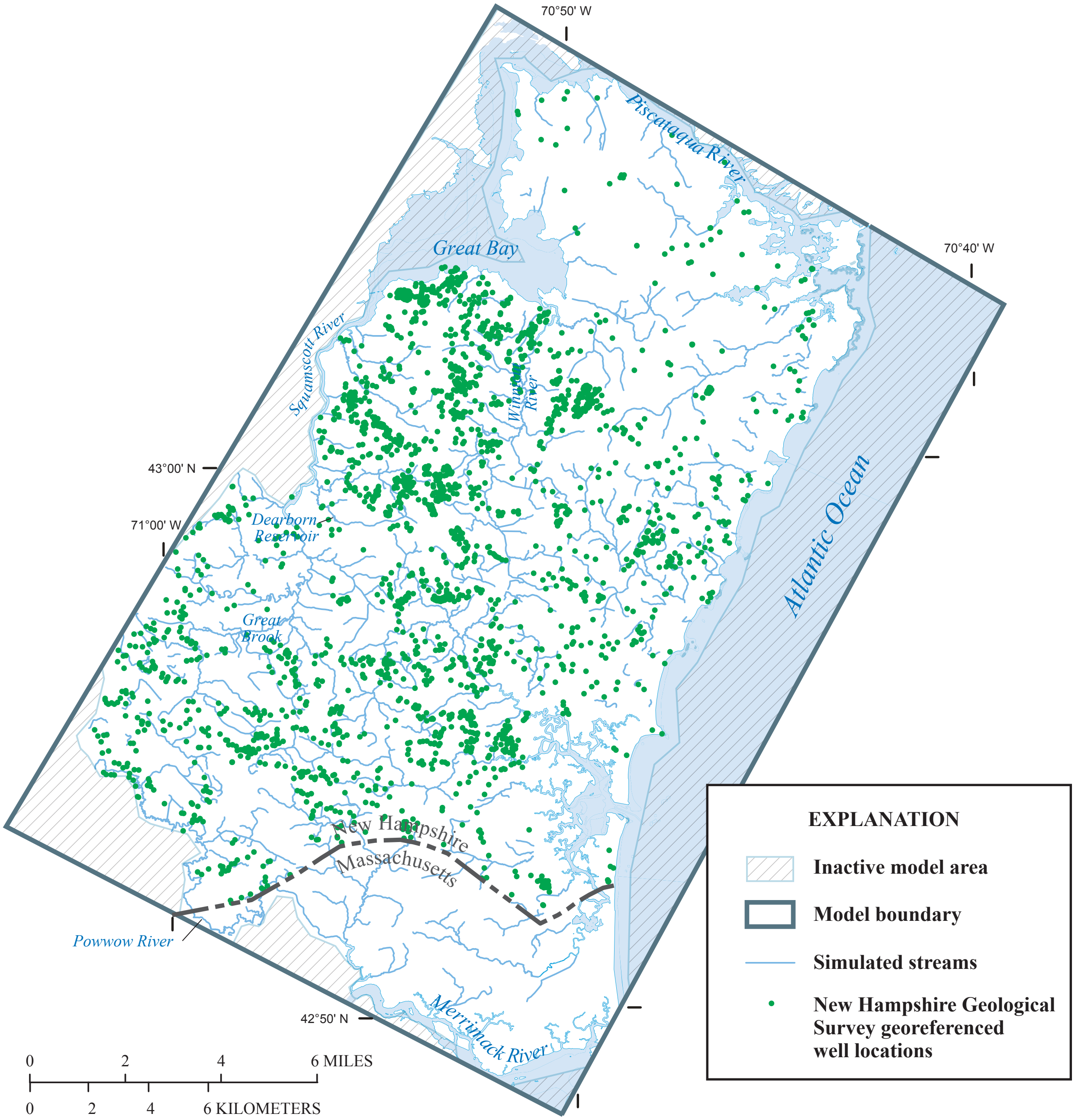
B



Streams and water bodies, including tidal and estuaries from 1:24,000
National Hydrography Dataset, 1999

Figure 7. *(B)* Georeferenced wells in the study area.—Continued

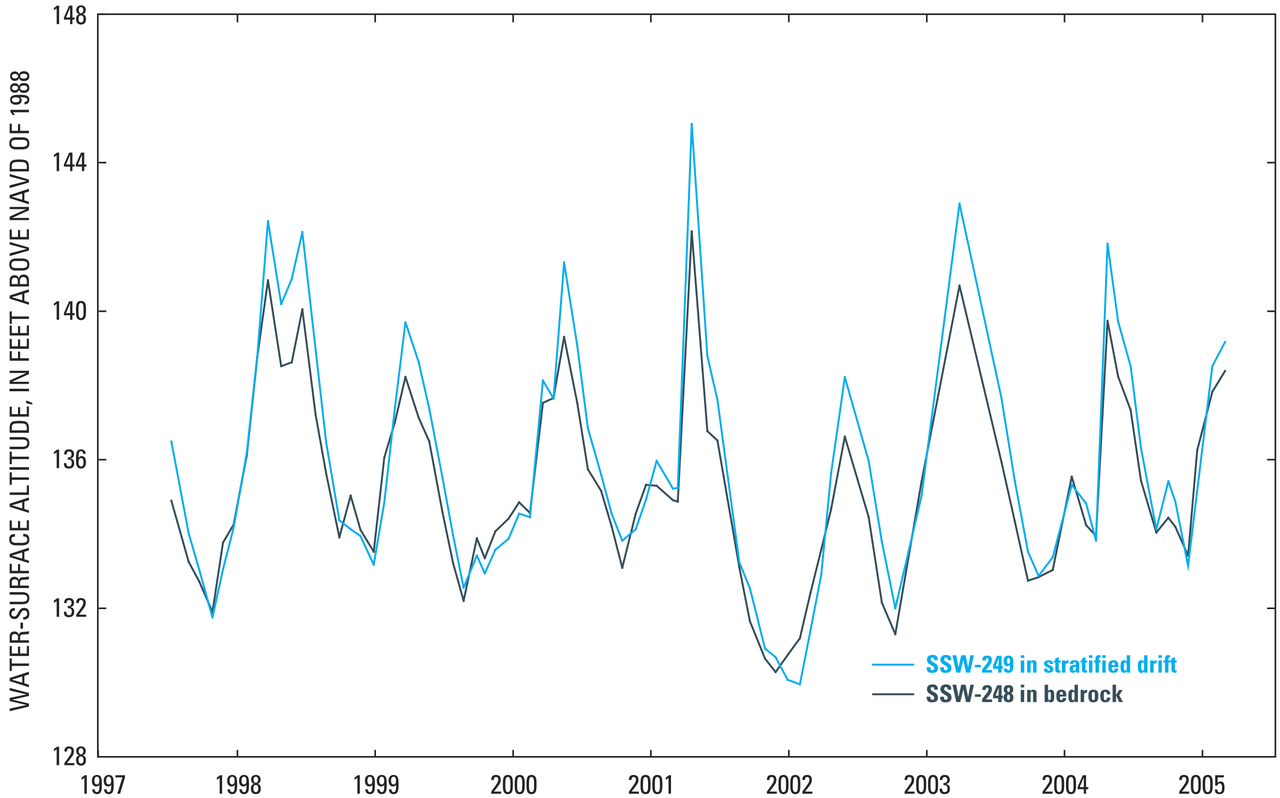


Figure 8. Monthly ground-water levels at an overburden (SSW-249) and bedrock (SSW-248) well pair in Stratham, New Hampshire. (Location of wells shown in figure 7)

during periods of low precipitation. The historical total ranges in water levels in these wells, the difference between maxima and minima, are about 12 ft in the bedrock and 15 ft in the overburden aquifer. The typical annual range is about 8–10 ft in either the stratified drift or bedrock, and therefore, water levels generally vary to about 4 to 5 ft above or below median values. The overburden- and bedrock-well hydrographs reflect seasonal hydraulic gradients. During high water levels, the overburden head is typically higher than the bedrock head, and ground water is moving downward into the bedrock. During periods of low recharge, the head in the overburden may be similar to the bedrock head or below it, indicating that water may have drained from the overburden aquifer. At nearby long-term (1953–2004) monitoring well NH-LIW 1 in Lee, N.H., less than 10 mi northwest of the study area, water levels in a coarse-grained deltaic deposit situated above other deposits have followed a similar pattern but with about a 2-ft annual water-level fluctuation (Keirstead and others, 2004, 2005).

Ground-water levels in 3 till and 3 bedrock wells were collected continuously in the study area during the investigation (fig. 9). In general, water levels at the wells show similar rises and falls in response to precipitation events. Wells completed in till (SSW-7, HEW-45, and GTW-156) show a greater natural range in water-level fluctuations. Well SSW7 shows about a 13-ft range in water levels during the period of investigation. A 10-ft range was observed in periodic measurements made at SSW-7 in the mid-1950s (Bradley and Peterson, 1962). It is interesting to note that a decline in water level of more than 3 ft occurred from July 28 to August 4, 2004, and July 28 to August 5, 2005, when the well went dry (not shown). These periods coincide with the high water demands of the Stratham Fair, which was supplied by a bedrock well less than 100 ft away from well SSW-7. The hydrograph for well GTW-156 shows a smaller range in water levels (about 8 ft) for a till well; however, it is near a dam on the Winnicut River, and the water-table fluctuations were likely to be somewhat damped by the pond formed by the dam. The water-level fluctuation at till well HEW-45 also is about 10 ft annually. A domestic bedrock well is less than 50 ft from HEW-45, but its use is relatively low and it likely imposes a small stress on the overlying till aquifer. Historical water levels measured at HEW-1, a dug till well approximately

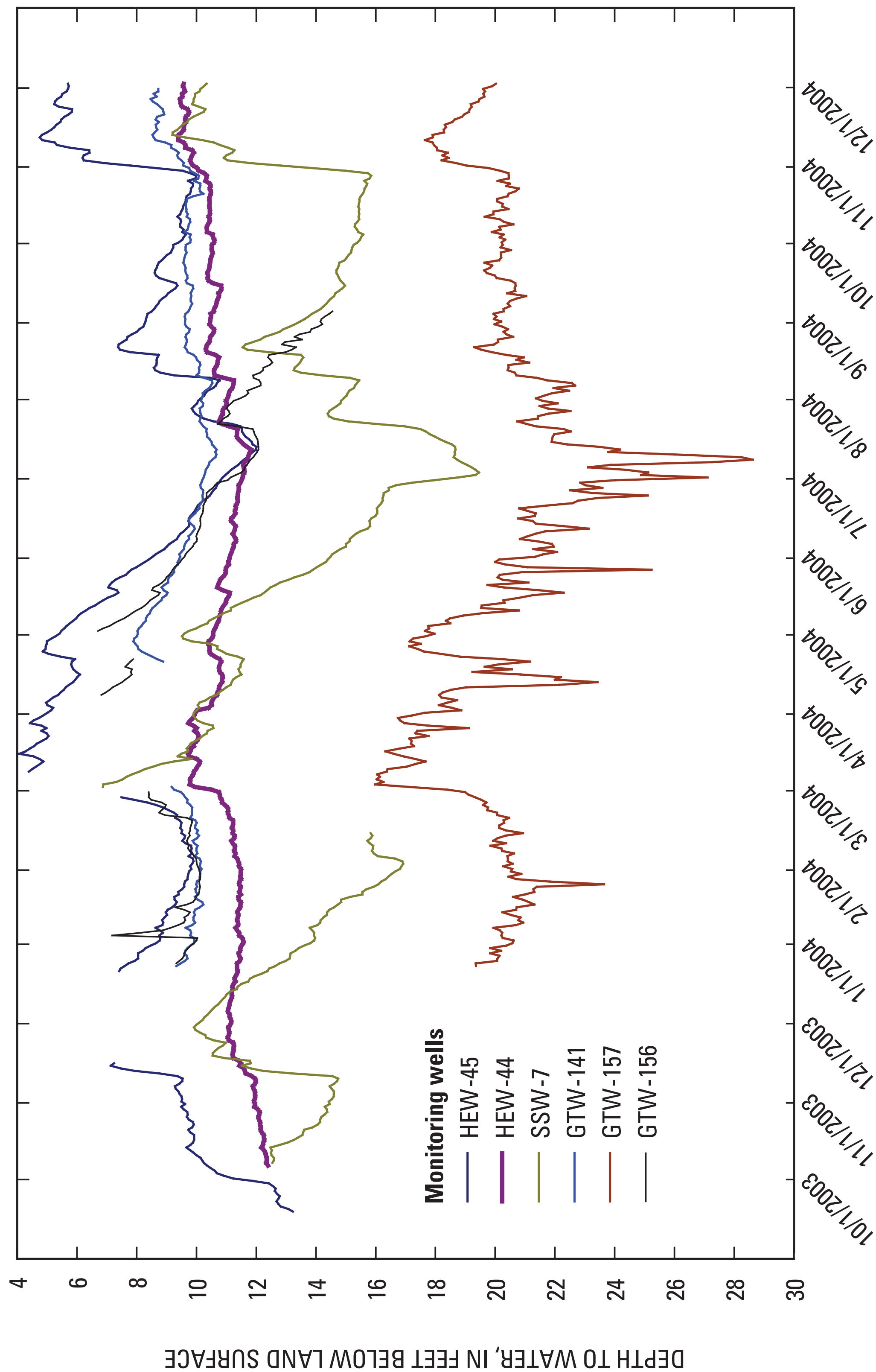


Figure 9. Daily mean depth to ground water in six monitoring wells in the Seacoast model area, southeastern New Hampshire, between October 2003 and January 2004. Areas of no data (data gaps) are missing record. (Well locations shown in figure 7)

1,000 ft west of HEW-45, show a 20-ft range from December 1953 to December 1957 (Bradley and Peterson, 1962). This well was used for domestic supply at the time, and it is likely that during periods of greater depths to water on the hydrograph, the well was actually dry. Although till has a specific yield similar to stratified drift (about 0.25 percent), till aquifers have low hydraulic conductivity, cannot readily transmit ground water to nearby drainage areas (or to sources of stress), and show a greater water-level response to precipitation than a coarse-grained aquifer. As observed at well SSW-7 (fig. 9), saturated till deposits provide some storage of ground water to underlying aquifers. Lyford and others (2003) found that a till aquifer in Newbury, Mass., provided a source of water for withdrawals in the underlying bedrock aquifer. Because of low hydraulic conductivity in a till aquifer, the water stored in it is only readily transmitted to nearby sources of stress.

The effects of residential development and associated domestic water use on ground-water levels were observed in some monitoring wells during the study period. Without anthropogenic stresses, such as nearby withdrawals, the annual range in bedrock ground-water levels is typically less than 3 ft. For example, the range in the water levels at two bedrock wells monitored in the study area—HEW-44, a high-yield (50 gal/min) bedrock well, and GTW-141, a moderate-yield (5 gal/min) bedrock well—were slightly less than 3 ft during the period of study. Near the end of the study (2005), a residential development was constructed within 500 ft of bedrock monitoring well HEW-44. The installation of domestic wells by rotary drilling with a yield test upon completion caused anomalous rapid water-level declines in HEW-44 that corresponded with the timing of well installations. During this same period, the range in water levels at USGS monitoring well NH-PBW-148 (about 35 mi to the west) was about 2.5 ft. Hydrographs for the well pair SSW-248 and SSW-249, located in a rural neighborhood in Stratham, N.H. (fig. 8) (Raymond Talkington, Geosphere, Inc., written commun., 2005), showed a maximum range of about 16 ft, and a typical annual range of about 8–10 ft, between 1997 and 2004. The annual range in water levels at the Stratham well pair may be influenced by domestic water use at nearby wells. The mean-daily water level in well GTW-157, an unused bedrock well in a neighborhood with nearby domestic wells, showed a range of over 12 ft. Instantaneous water-level measurements at GTW-157 indicated an even greater range in water-level changes likely caused by nearby well interference. The peaks of the GTW-157 hydrograph, which does not show the instantaneous responses, show an annual water-level range of about 6 ft. The rapid response to precipitation indicates that the bedrock aquifer receives rapid recharge because it is in good hydraulic connection with surficial deposits. A pronounced drawdown pattern (fig. 10) was measured at a well pair consisting of an active domestic bedrock supply well and unused overburden (till) well (Timothy Warr, written commun., 2006). Drawdowns in the bedrock well were commonly between 5 and 15 ft, but the water level recovered daily and showed seasonal trends even with daily use of the well. Water levels from the nearby till well (fig. 10) showed seasonal trends and the effects of the domestic withdrawals. Head differences observed at the wells during stressed periods, summer and fall, indicate that the overburden aquifer is likely supplying water to the underlying bedrock in the early summer (indicated by overburden heads above bedrock heads) and may become depleted late in the summer or early fall (indicated by overburden heads below bedrock heads). During less-stressed periods of the year, with higher water levels, heads in the aquifers were generally nearly equal. The coincidence between the flat part of the till water-level record in September 2003 and the maximum water depth indicates that the till well was dry.

The long-term monthly record for LIW-1, a dug well in stratified drift 8 mi west of the study area in Lee, N.H. (Keirstead and others, 2005), indicates that the water level in this well rose and fell in the same manner as the water levels in the Stratham well pair. The range in water levels at LIW-1, however, was less than 1 ft annually because of the coarse-grained and well-drained nature of the aquifer. Because the aquifer can drain rapidly through good connections to nearby sinks (drainages), the head in LIW-1 fluctuates little with recharge. If there were no other stresses, the head in the aquifer would seek the altitude of the sink, the nearby streams. In contrast, the water level in the Stratham surficial aquifer closely paralleled the bedrock water level (correlation coefficient of 0.97). The stratified drift mapped at this location is not well connected to drainages, and the natural drainage of ground water in this aquifer system is through the adjacent till and bedrock aquifers.

Water levels measured periodically since 1994 in bedrock monitoring wells near a municipal well field in northwest Seabrook (Douglass DeNatalie, Earth Tech, written commun., 2005) show that water levels declined from approximately 1996 until about 2002 (fig. 11) as a result of increased withdrawals combined with several years of low precipitation (appendix 1). Ground-water levels rose with increased precipitation at the end of a drought (2002) and possibly also because of changes in withdrawal amounts or locations. Water levels in well SGW-26 in the stratified-drift aquifer showed some withdrawal-related changes of more than 30 ft. Although there were too few observations to show seasonal trends, water levels in the surficial aquifer usually recovered to high levels during non-summer seasons and other low-stress periods. In general, water levels in the surficial and bedrock aquifers recovered rapidly—within a few months—with reduced withdrawals and increased precipitation.

Surface Water

The study area consists of many small watersheds that drain directly to tidal water bodies (fig. 2). The Winnicut River watershed, in the center of the study area, is the largest watershed (14.2 mi^2), followed by the Taylor River (8.41 mi^2) and Hampton Falls River (6.7 mi^2) watersheds (table 1). Because of the low relief (generally less than 60 ft) and extensive

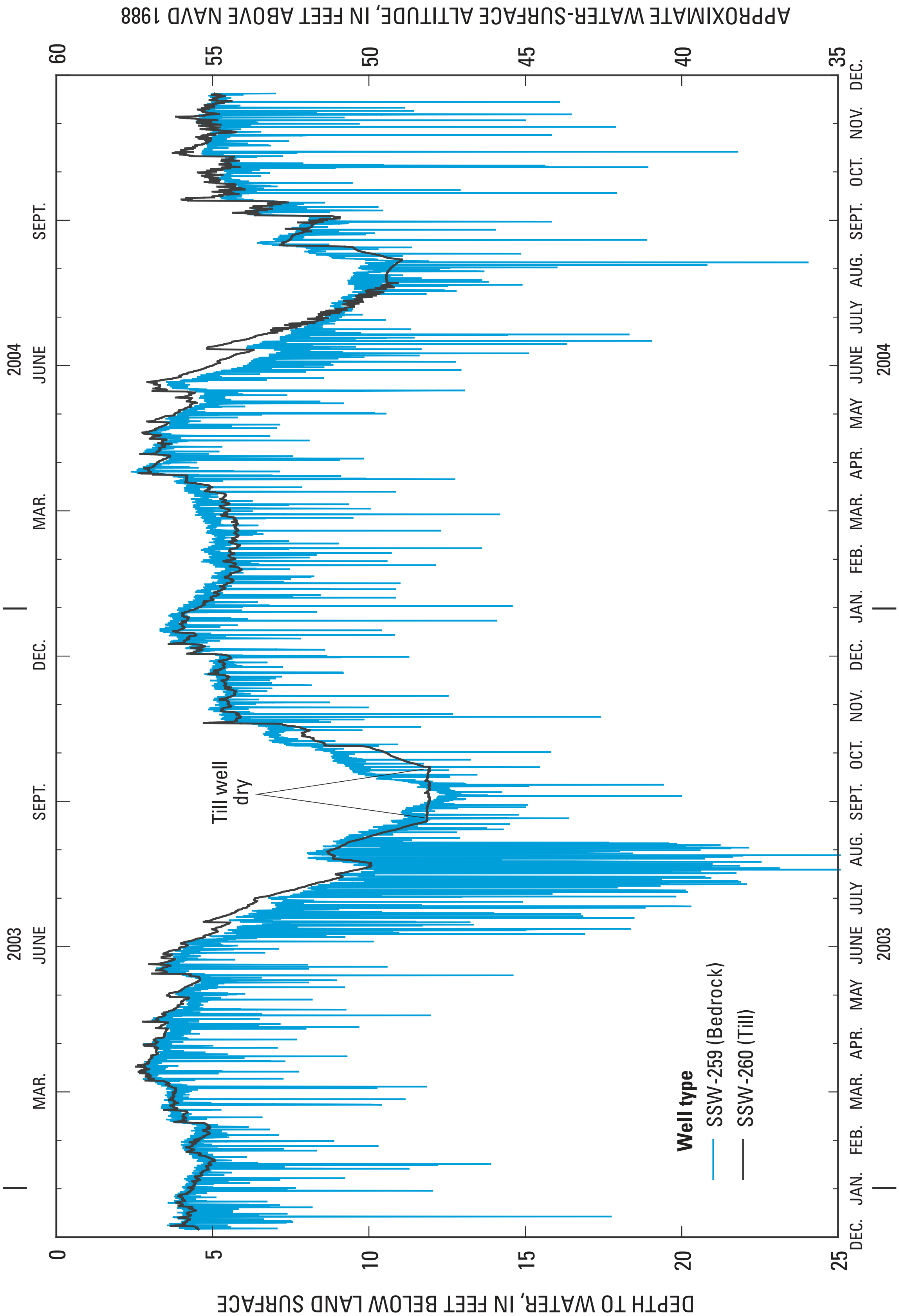


Figure 10. Daily water levels at a domestic bedrock (SSW-259) and till (SSW-260) well pair, Stratham, New Hampshire. (Location of wells shown in figure 7)

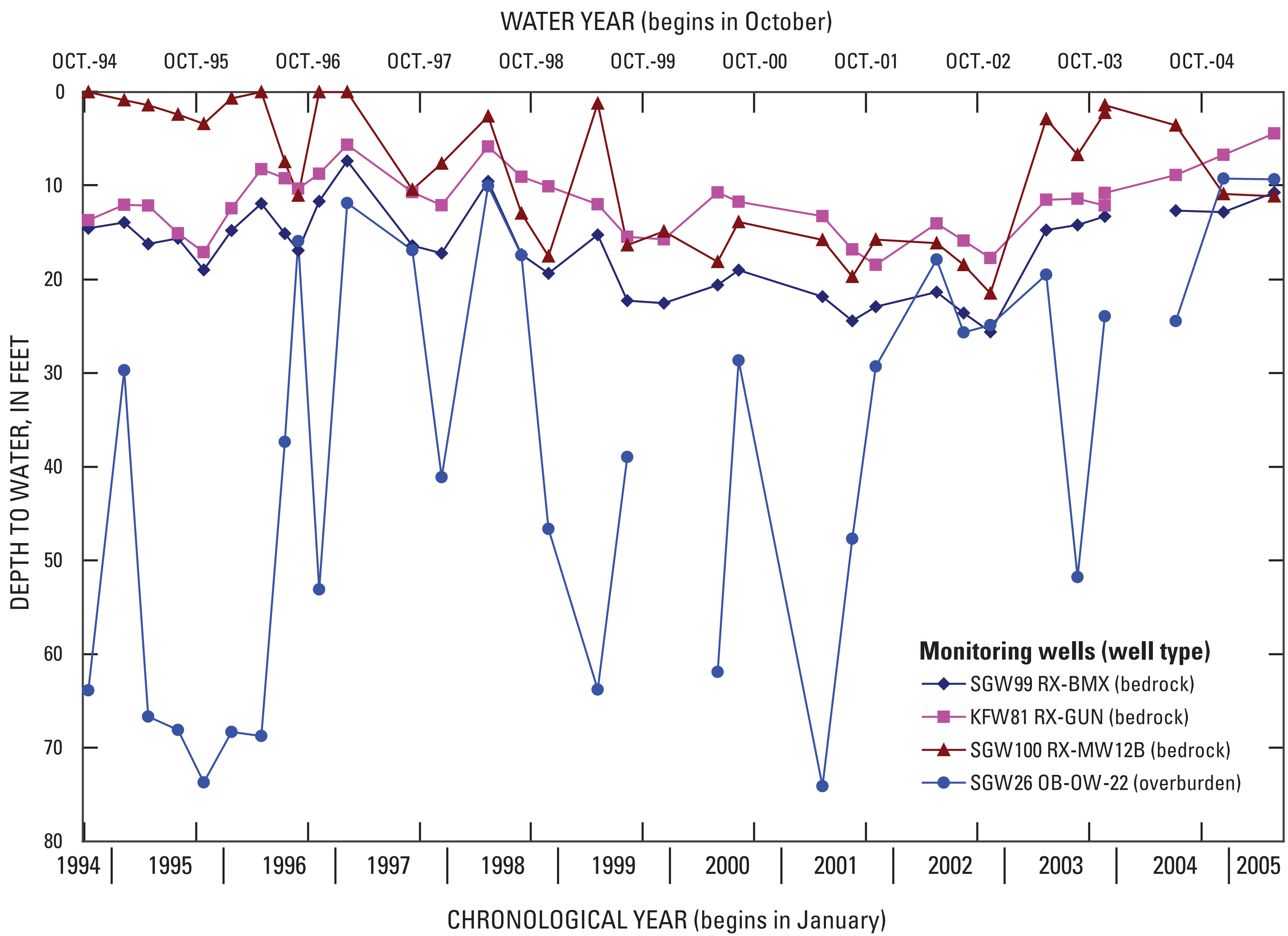


Figure 11. Water levels in selected bedrock and overburden wells near supply wells in Seabrook, New Hampshire. (Location of wells shown in figure 7)

wetlands in the center of the study area, the drainage divide between some adjacent watersheds, such as the Winnicut and Taylor River watersheds, is difficult to distinguish. Streamflow was measured at 6 continuous streamflow-gaging stations selected to represent the larger watersheds in the study area, and miscellaneous streamflow measurements were collected at 17 partial record stations (fig. 2, table 3). Few locations provide suitable hydraulic conditions for stream gaging. The locations suitable for continuous streamflow gaging, particularly Berry's Brook and Little River, also were favored by beavers and were difficult to keep clear of beaver dams and debris.

Average flow in the Winnicut River for water years 2002–2004 is 22.3 ft^3/s or 1.65 $ft^3/s/mi^2$. The 90-percent flow duration for this period was 2.2 ft^3/s. The lowest daily mean flow was 0.30 ft^3/s and occurred on 9 days in August and September 2002 (Keirstead and others, 2004). Mean annual and monthly (table 3) base flows at streamflow-gaging stations in the study area were calculated by using the automated hydrograph-separation method PART (Rutledge, 1993, 1998). Annual base flows calculated for 1934 to the present for the long-term Oyster River streamflow-gaging station are shown for comparison. An investigation of streamflows in Maine indicated a trend of earlier spring peak flows during the 20th century over the period of record but generally no change in total annual flow (Dudley and Hodgkins, 2002). Figure 12 shows monthly mean base flows calculated for 2002–04 for the study area.

There are few freshwater bodies in the model area, and most are small ponds. An impoundment near the outlet of one water body, Dearborn Brook in Exeter (fig. 2), forms a small (about 0.01-mi^2) surface-water reservoir. Wetlands (fig. 3) extend throughout the center of the model area, particularly in the Winnicut, Taylor, Pickering, Packer, and Berry's River watersheds. Large ponds and wetlands represent a surface expression of the regional water table. Where withdrawals in a well field lowered the water table, some wetlands were perched above the water table (Geosphere, 2003). Small ponds and wetlands, representing a more localized drainage feature, were more likely to be perched above the water table than more extensive wetlands or water bodies. For example, streamflow measurements at Nilus Brook and an unnamed tributary to Little River in Hampton in October 2004 (table 3) likely represent drainage from a seasonally perched pond and wetland.

Ground-Water-Flow Simulation

Ground-water flow was simulated by a numerical ground-water-flow model to assess regional ground-water availability by accounting for, and providing a means to quantify, all components of flow in the aquifer system. To assess the components of the ground-water-flow system, models were developed and calibrated under steady-state seasonal low-flow and transient monthly conditions. The development and calibration of these two models are discussed in the report sections Steady-State Model and Transient Model. Two model scenarios are then discussed, in the report sections indicated, to simulate current and future projected water use (Potential Future Water Use) and current and future projected climate change conditions (Potential Climate Change).

A summary of the models developed for calibration, parameter estimation, and various simulations is provided in table 4. The models include (1) simulation of current and future water use by a steady-state model representing seasonal low-flow conditions; (2) simulation of current and future climate change by a transient model representing estimated future monthly conditions for a 2-year cycle; and (3) simulation of historical ground-water flow and residence time by a transient model representing annual average conditions over a 55-year period.

The three-dimensional finite-difference ground-water flow program MODFLOW-2000 (Harbaugh and others, 2000) was used to simulate ground-water flow. By this technique, the ground-water-flow system is subdivided into a grid consisting of layers of cells with unique hydrologic properties. Physical processes in the natural system, such as recharge, streamflows, and wells, were represented numerically as boundary conditions in the model. Parameters (Hill and others, 2000) were used to describe recharge and the hydraulic conductivity, or a multiplier of conductivity, of specific geologic units or zones of similar surficial materials; riverbed conductivity; and constant-head cells.

Model Design and Spatial Discretization

The regional ground-water-flow system is one of thin and discontinuous surficial aquifers underlain by a fractured crystalline-bedrock aquifer. Figure 13 provides a conceptual and numerical representation of the ground-water flow system of the study area.

The lateral boundaries of the model were selected to coincide with major hydrologic features, primarily tidal water bodies, of the Seacoast (figs. 1, 2). The area of the model domain was approximately 190 mi^2 (160 mi^2 in New Hampshire and 30 mi^2 in Massachusetts) and was surrounded by a no-flow boundary. Model grid-cell sizes were determined by trial and error. Determining the optimum grid-cell size required evaluating the resolution of the simulated hydrologic features with respect to the time required for data-set development and simulation computation time, both which increase dramatically with small cell size. The model was simulated with a grid-cell size of 200 by 200 ft. Smaller grid spacing was tested, primarily to provide finer stream discretization but resulted in greatly increased computer storage and simulation time with little improvement in the regional simulation.

The model is subdivided vertically into five layers (fig. 13). Model grid-cell elevations were interpreted with respect to 30-meter Digital Elevation Model (DEM) point elevations. The upper surface of the model (layer 1) corresponds

Table 3. Streamflow characteristics for streams in the Seacoast model area and for Oyster River, southeastern New Hampshire.

[Site numbers shown on figure 2 unless otherwise indicated; C, continuous-record streamflow-gaging station; P, partial-record streamflow-gaging station; mi^2, square miles; ft^3/s, cubic feet per second; —, not available]

Site number	Station number	Stream	Location	Area (mi^2)	Station code	Mean flow 2004 (ft^3/s)	Calculated annual base flow 2004 (ft^3/s)	Streamflow measured October 7–8, 2004 (ft^3/s)	Streamflow measured January 4, 2004 (ft^3/s)	Base flow estimated January 4, 2004 (ft^3/s)	Base flow estimated January 27, 2004 (ft^3/s)
	01073000	Oyster River	Durham (not in model area)	12.1	C	19.4	16	4.1	24	10.6	3.5
9		Parkman Brook	Portsmouth	1.91	P	—	—	[1] 1	—	—	—
1	01073750	Mill Brook	Route 108, Stratham	2.48	C	—	2.5	1.00	4.9	2.3	.37
4		Pickering Brook	Shattuck Way, Newington	—	P	—	—	.095	—	—	—
6		Hodgson Brook	Cate Street, Portsmouth	3.52	P	—	—	1.18	—	—	—
3		Packer Brook	Ports Avenue, Greenland	2.25	P	—	—	.56	—	—	—
7		Pickering Brook	Ports Avenue, Greenland	2.97	P	—	—	.61	—	—	—
14-1	01073785	Winnicut River	Route 33, Greenland	14.19	C	22.3	19.3	7.3	27	10.3	2.4
14-2		Winnicut River	Winnicut Road, Stratham	—	P	—	—	4.94	—	—	—
14-3		Winnicut River	Walnut Road, North Hampton	—	P	—	—	3.47	—	—	—
14-4		Winnicut River	Route 111, North Hampton	—	P	—	—	1.71	—	—	—
15	01073810	Berrys Brook	Sagamore Road, Rye	5.38	C	9.8	7.6	3.1	8.1	6	.75
5		Bailey Brook	Love Lane, Rye	1.73	P	—	—	1.09	—	—	—
11-0	01073822	Little River	Woodbury Road, North Hampton	6.12	C	8.5	5.9	2.5	8.5	4.4	.4
11-1		Little River	Unnamed tribuary, North Hampton	—	P	—	—	.30	—	—	—
16		Nilus Brook	North Shore Road, Hampton	1.5	P	—	—	.61	—	—	—
13		Taylor River	Old Stage Road, Hampton	8.41	P	—	—	4.83	—	—	—
10		Great Brook	Giles Road, Brentwood	5.5	P	—	—	1.82	—	—	—
8-0		Hampton Falls	Route 1, Hampton Falls	6.66	P	—	—	3.68	—	—	—
8-1	01073848	Hampton Falls	Mill Lane, Hampton Falls	3.61	C	6	4.6	1.72	8	3.3	.72
2		Back River	Amesbury Road, South Hampton	1.53	P	—	—	.535	—	—	—
17		Cains Brook	Route 1, Seabrook	—	P	—	—	[1] 1	—	—	—
12		Smallpox Brook	True Road, Salisbury, Mass.	1.83	P	—	—	1.00	—	—	—

[1] Flow estimated on the basis of previous measurements or qualitative information.

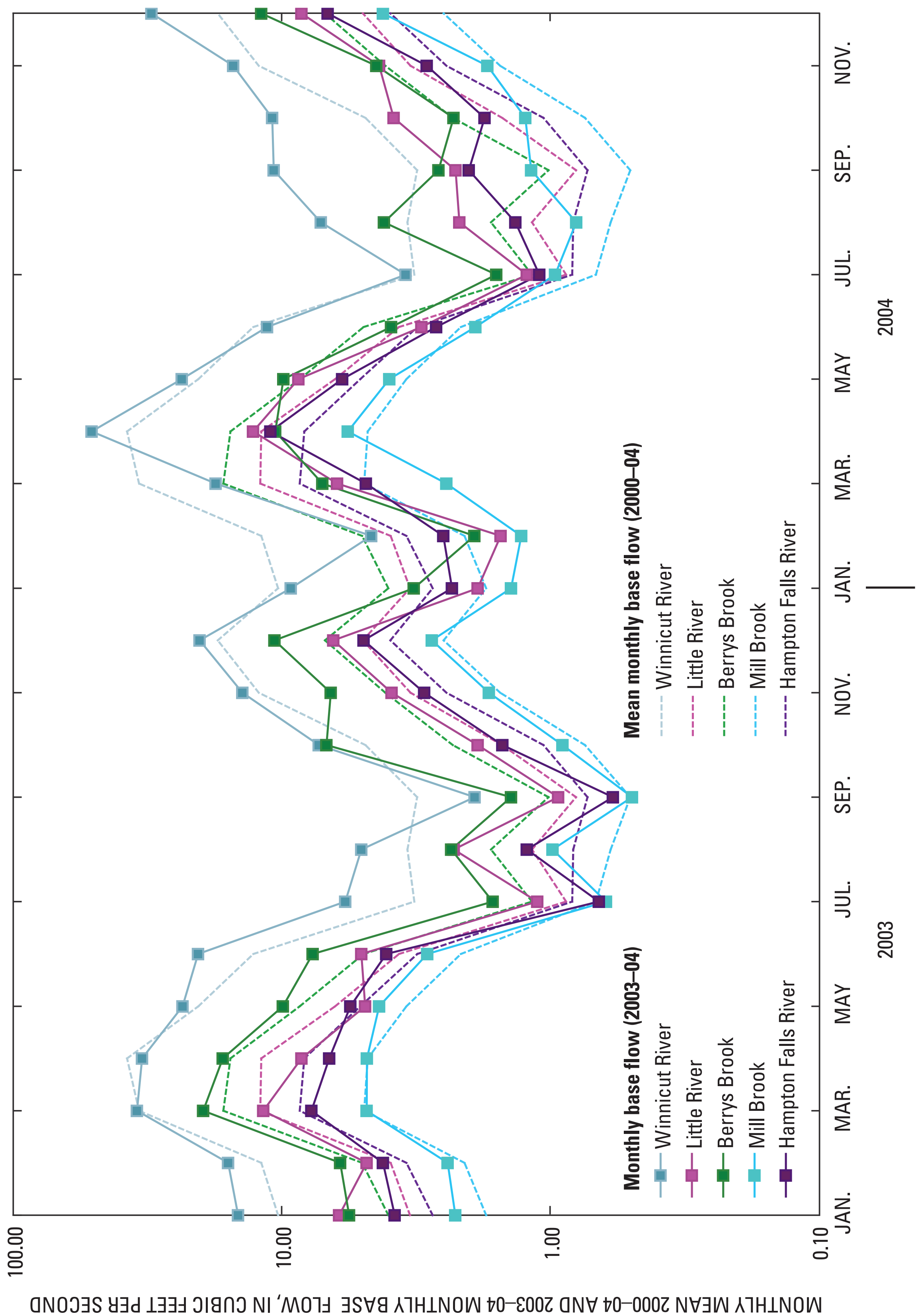


Figure 12. Monthly mean 2003–04 and mean 2000–04 base flows calculated for streams in the Seacoast model area, southeastern New Hampshire.

Table 4. Ground-water-flow models developed and scenarios simulated in the Seacoast study area, New Hampshire.

[Code: C, calibration; SS, steady state; T, transient]

Report section	Models or scenarios	Code	General purpose	Conditions or base scenario	State and simulation length	Detailed stress period
			Simulation of current and future ground-water availability			
Potential future water use	1. Future water use A) 2004 B) 2017 C) 2025	SS	Potential water-use conditions	Base conditions are annual low flow using 2004 fall recharge rates	Steady state, daily	Average daily.
Potential future climate change	2. Climate change A) Winter precipitation increased 5 percent B) No change in winter precipitation C) Winter precipitation decreased 5 percent	T	Potential future climate conditions	Base conditions include increased air temperature causing a modification of current monthly recharge rates, an earlier spring melt, and longer evapotranspiration season	Transient, 2 years	24 months using average monthly rates.
			Model development and calibration			
Appendix 5—Steady-state model	Development and calibration	C, SS	Development, parameter estimation, and calibration	Average daily rates for October 2004	Steady state, daily	Average daily, October 2004.
Appendix 7—Transient model	Development and calibration	C, T	Development, parameter estimation, and calibration	Recent average monthly conditions for 2001–04 and specific months 2003–04	Transient, 4 years	24 periods with 12 periods using average monthly rates repeated twice, and 24 periods using specific monthly rates.
			Simulation of historical regional ground-water flow			
Appendix 9—Historical model	3. Historical ground-water flow	SS	Historical	Historical water use, approximated over past 55 years	6 steady state periods, 55 years	Annual rates; 5, 10-year averaged periods; and 1, 5-year averaged period.

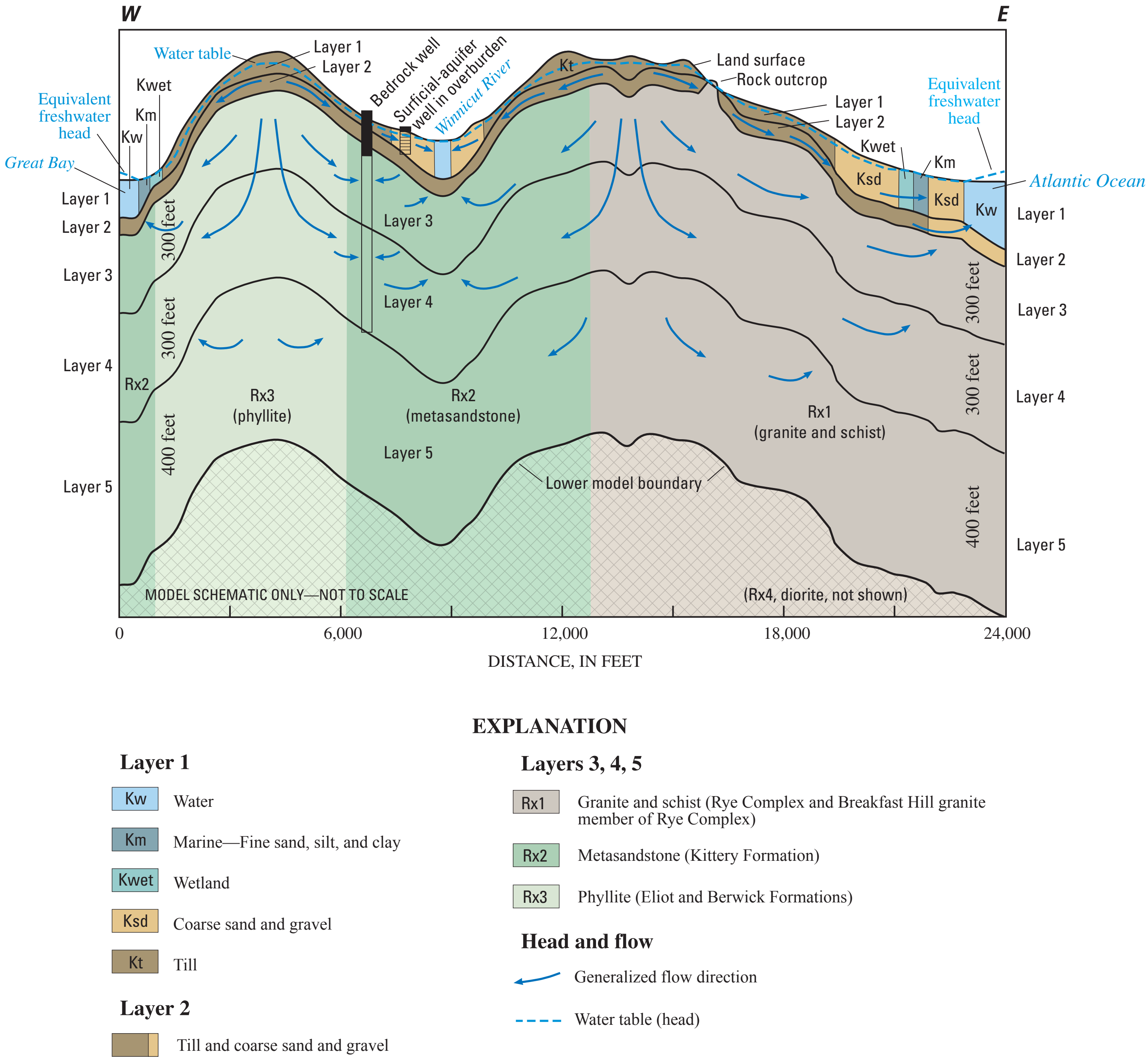


Figure 13. Schematic cross section of the ground-water-flow model for the Seacoast model area, southeastern New Hampshire.

to the nearest DEM 30-meter grid-cell elevation. All other elevations used in the model were calculated from the surface elevation interpreted for each individual grid cell. Layer thicknesses and extent were chosen to represent both hydrogeologic characteristics and numerical considerations. Layers 1 and 2 represent primarily surficial deposits or water bodies. The thickness of layer 1 in marine areas was equal to the surface-water depth provided by bathymetric data for areas including Great Bay, Piscataqua River, and the Atlantic Ocean. On land, the thickness of layer 1 was determined from contours representing thickness of the stratified-drift aquifer (Moore, 1990; Stekl and Flanagan, 1992), bedrock well casing lengths and boring data, and thicknesses inferred from surficial mapping. Model layers 3 and 4 were each 300 ft thick, following the base of layer 2, and model layer 5 was 400 ft thick following the base of layer 4 (fig. 13).

The conceptual model of the ground-water-flow system is one of a fractured crystalline-bedrock aquifer with a range of regional hydraulic conductivities and an overlying layer of thin unconsolidated glacial sediments and discontinuous stratified-drift aquifers. The stratified-drift aquifers cover about 24 percent of the total model area (table 1); however, the high-yielding stratified-drift aquifers cover much smaller areas. A continuum approach, in which the fractured bedrock network is represented as an equivalent porous medium (Hsieh, 2002), was used in the simulation of ground-water flow. For this purpose, bulk hydraulic properties are usually sufficient to describe regional ground-water recharge, discharge, and storage (Shapiro, 2002). Bulk hydraulic properties in this case refer to aquifer properties such as hydraulic conductivity, which can be assumed to be constant at a particular scale for a specific geologic material or unit. For example, in the Seacoast model area, a specific gneiss generally has a greater hydraulic conductivity, as indicated by well yields, than that of a nearby schist. Despite local variations in the hydraulic conductivity of both rocks, the bulk hydraulic conductivity of the gneiss is greater than that of the schist at the regional scale. Through the use of the continuum approach, regional variations in hydraulic conductivity and other hydraulic properties were incorporated into the model to account for heterogeneity in aquifer properties at the regional scale.

The ground-water models developed herein were designed to represent ground-water flow in the regional aquifer system. Although the models incorporate specific large ground-water withdrawals in the surficial and bedrock aquifers, they cannot be used to accurately characterize ground-water levels near withdrawal wells or specific ground-water flow paths at the cell level of precision. The models can be used to calculate regional- or subwatershed-level ground-water balances, regional changes in ground-water levels, and general flowpaths. Data sets for the Seacoast ground-water-flow models are available on the DVD at the back of the report and at http://pubs.usgs.gov/sir/2008/5222/.

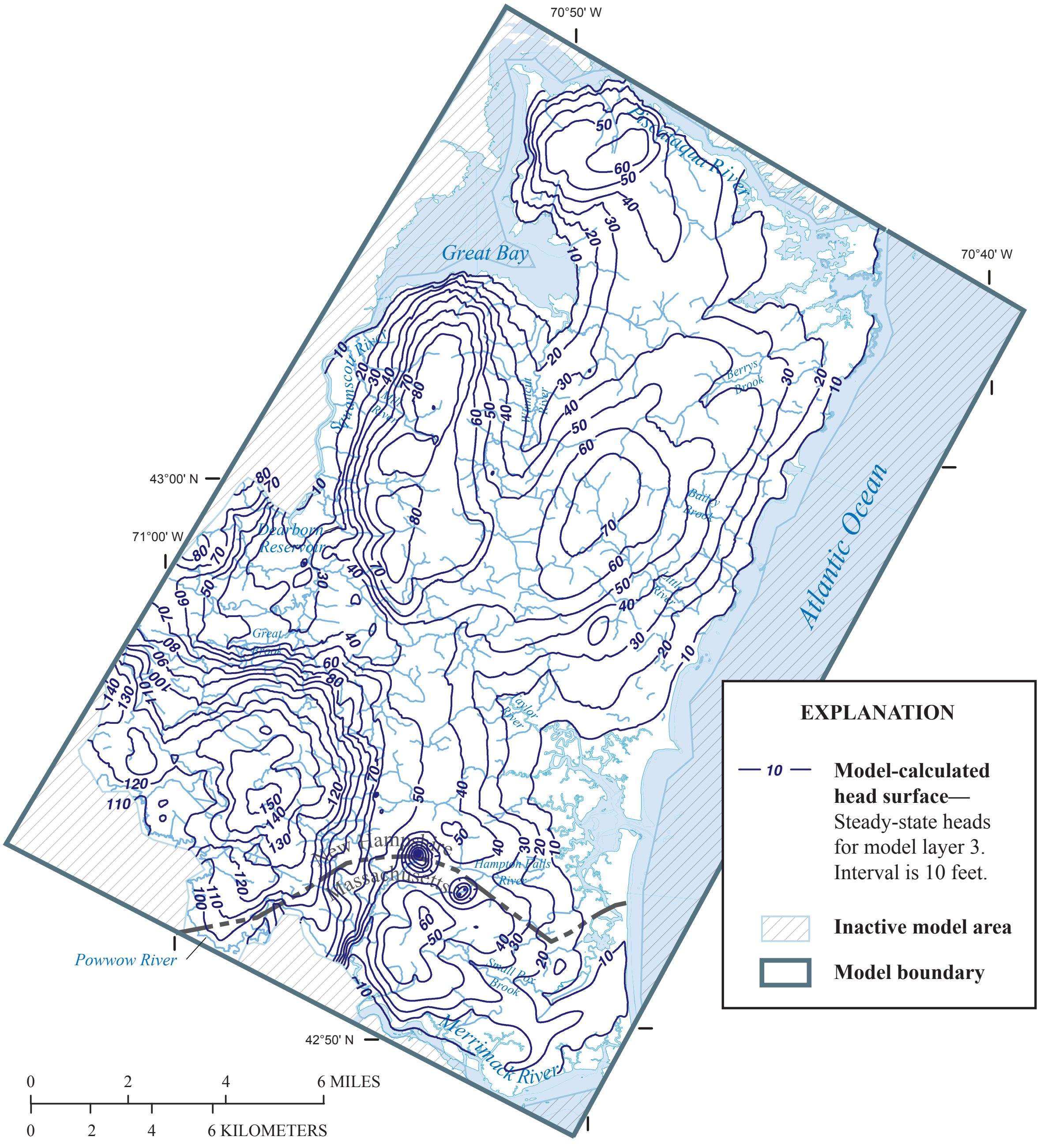
Simulated Recharge, Discharge, and Storage

The regional ground-water-flow models (described above and in appendixes 5 and 7) were used to assess ground-water availability in the Seacoast area. Model analyses indicate that the Seacoast aquifer system is a transient flow system with seasonal ground-water flow variations. Seasonal high flows are in March and April, and low flows occur from July through October. The fall is generally a more stable period and can be termed a pseudo-steady state; fluxes are lower, and inflows and outflows are approximately balanced. Figure 14 provides a simulated-head surface representing a seasonal low-flow condition in October 2004.

The transient ground-water-flow model was used to assess average monthly and specific monthly recharge rates for 2003 and 2004 (appendix 7). The average annual recharge during the study period (22 in/yr) was approximately 51 percent of the annual precipitation (table 7–1). The average monthly rate of recharge between 2000 and 2004 ranged from 5.5 in/mo in March to net recharge rates of zero in July and about 0.3 in/mo in August and September (fig. 15). Average recharge increases to about 2 in/mo in late fall and early winter and declines to about 1.5 in/mo in late winter. In general, about 50 percent of the annual recharge occurs in the spring and 20 percent occurs in the late fall and early winter. Although monthly precipitation is typically between 3 and 5 in/mo (fig. 6), monthly recharge can be greater than the actual precipitation during snowmelt periods, and net recharge (recharge minus ET) can be negative during the summer.

Streamflows in the Seacoast aquifer system originate from recharge within the study area. Ground water in the bedrock aquifer system may follow a short or long flow path because of factors such as position in the flow system and local stresses. In general, ground water in the bedrock aquifer near the coastal boundary has followed a relatively long flow path from its source of recharge, compared to other areas, and may have recharged the aquifer over 30 years ago. With the addition of withdrawal stresses, the natural flow system would be altered and ground-water-flow paths may become shorter and the withdrawn water younger. Some of the ground water contributing to a withdrawal well is generally a mix with short and long residence times. The water may have traveled a relatively short distance, on the order of hundreds of feet, and may have recharged the aquifer within months to a few years. The withdrawal also may include water that has traveled farther through the flow system and has a residence time of decades.

The amount of ground water that could flow into the Seacoast area from inland areas to the west (from outside the model area) is likely to be insignificant. Some ground water may flow thousands of feet deep in the bedrock aquifer, following regional paths, in accordance with flow concepts described by Toth (1963). The nature of the bedrock aquifer itself and of the hydrologic boundaries between the Seacoast model area and the inland areas to the west of Great Bay



Base from USGS and GRANIT, New Hampshire State Plane Coordinate System, North American Datum 1983
Model-calculated head surface from steady-state model layer 3

Figure 14. Surface representing calculated steady-state heads for model layer 3, October 2004, Seacoast model area, southeastern New Hampshire.

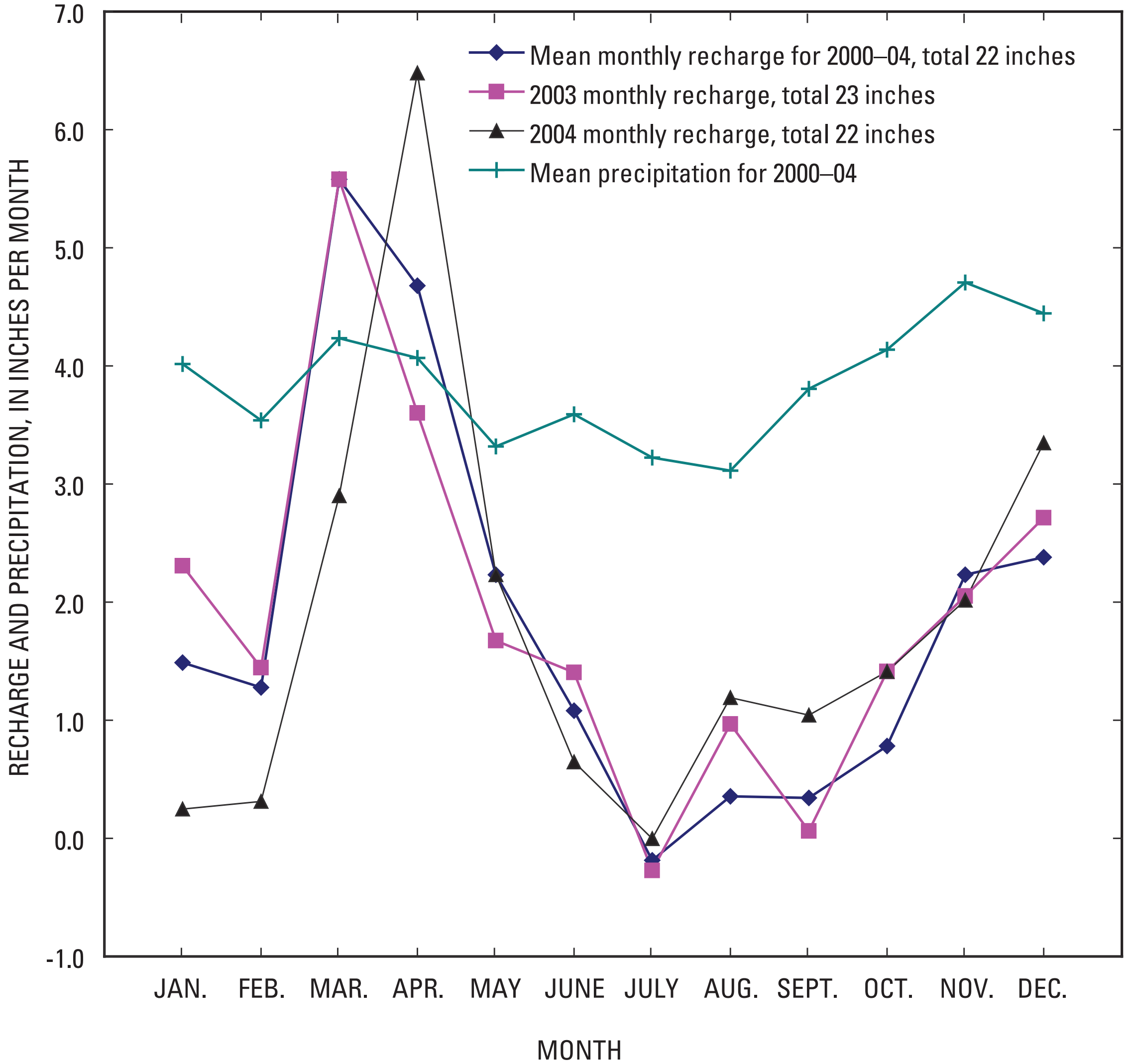


Figure 15. Average monthly recharge for 2000–04, monthly recharge for 2003 and 2004, and mean precipitation for 2003–04 for the Seacoast model area, southeastern New Hampshire.

(a high equivalent freshwater-head boundary), the shorelines and the Squamscott River (low heads at points of discharge), and the low hydraulic conductivities of the bedrock aquifers prevent regional ground-water inflows from the inland areas from being a significant component of the Seacoast water balance. Such flow, if present, would consist of slow-moving ground water in low-yielding deep bedrock areas and would not be a sustainable supply source.

Storage

Ground water is stored in the Seacoast area in the pore space of unconsolidated overburden sediments as primary porosity and in fractures in the crystalline bedrock as secondary porosity. The total volume of water stored in the Seacoast aquifer system was estimated on the basis of model-cell thicknesses and assumed bulk hydraulic properties. See the Hydraulic Properties section of the report for a discussion of these properties. Approximately 560,000 Mgal may be stored in the Seacoast model area aquifer system (table 5), although storage may range from 260,000 to 1,600,000 Mgal for the sediment or rock porosities assumed to be present. The estimated ranges for water storage in the unconsolidated sediments in table 5A were calculated by adding or subtracting 10 percent from the assumed primary porosities or specific yields. The estimated range in water stored in the bedrock aquifers were calculated by varying the secondary porosity one order of magnitude lower, and one-half an order of magnitude greater, than the assumed porosities (table 5B).

Estimates of the total volumes of water stored in the aquifer system (table 5) are useful for comparing the relative storage volumes for different geohydrologic zones and their contribution to the entire Seacoast aquifer system. Noteworthy is the amount of water stored in unconsolidated till and fine-grained sediments; these sediments are generally not considered primary aquifers; however, they do contribute water directly to the underlying bedrock aquifer. In the model area (fig. 3), these sediments store more than twice as much water as the coarse-grained unconsolidated-sediments (table 5A). The bedrock aquifers associated with model zones Rx1 (Rye Complex and Breakfast Hill granite of the Rye Complex) and Rx2 (Kittery Formation) (fig. 4) are estimated to have the most water in storage, about 77,000 to 99,000 Mgal, respectively, as a result of their areal extent (fig. 4) and assumed bulk secondary porosities (table 5B). Model bedrock zone Rx3 (the Eliot and Berwick Formations) was estimated to have nearly as much water in storage (58,000 Mgal) as each of the model bedrock zones Rx1 and Rx2. Model bedrock zone Rx4, representing the Newburyport Complex and Exeter Diorite, was estimated to have less water in storage as a result of its smaller areal extent (fig. 4) and lower assumed secondary porosity than the other zones (table 5B).

Theoretical volumes of water that could be released by the Seacoast area aquifer system also were estimated (table 5). Total volumes and the amounts that could be released by 3- and 10-foot water-level (head) declines are provided. The range in water volumes that could be released from the unconsolidated aquifers was estimated by adding and subtracting 10 percent from the assumed specific yield. The range in water volumes that could be released from the bedrock aquifer was calculated by varying the specific storage by plus and minus one order of magnitude. Many variables used in the transient flow models to generate the estimates in table 5 were approximated at a regional scale; therefore, the volumes of water stored should be considered gross estimates.

Numerous qualifications and limitations are associated with the storage estimates in table 5. For instance, the secondary porosity and specific storage of bedrock aquifers are not well known, and the specific storage, in particular, may differ from estimates by orders of magnitude. Table 5 indicates that a considerable volume of water is stored in the bedrock aquifer. However, a much smaller volume of water can theoretically be released from the aquifer system and most of the water released would be from overburden aquifers. The volume of water that can be released from the bulk storage of an aquifer is limited by the hydraulic properties of the aquifer. The volume of water that could potentially be released, or drained, from the unconfined surficial aquifer is limited by specific yield, which is less than the porosity of the aquifer. At least 10 percent of the bulk water in the surficial aquifers will be retained in the pore spaces after water drainage or withdrawal. Under confined conditions in the bedrock aquifers, the amount of water that can be released, determined by the specific storage, is orders of magnitude less than the bulk water estimated by the secondary porosity (table 5B). Where the bedrock aquifer actually dewaters and becomes unconfined (not calculated in table 5), the water released by drainage would be the water stored in the secondary porosity, or less than 1 percent of the volume of the rock drained.

Additional limitations include the well efficiencies and effectiveness and spatial constraints of well placement and aquifer setting. For example, releasing the total volume of water stored in an aquifer would require lowering the water level to the base of the aquifer. This would not be realistic; closely-spaced wells, tens to hundreds of feet apart, would have to be installed throughout the entire aquifer area. An estimated 85,000 Mgal of water would be released from storage by a 10-ft decline in the water table (table 5A,B). Such a large decline, however, is also not realistic for the entire model area because of limitations on well placement. In highly developed, restricted, or peripheral areas of the flow system, installing as many wells as would be needed to capture water is not practical. Greater head declines (tens to hundreds of feet) are known to occur locally in response to ground-water withdrawals. Such large head declines, however, generally do not propagate far in the bedrock aquifer because of the low bulk hydraulic conductivities.

A more realistic scenario was based on a smaller, 3-ft head decline, which may occur over the course of a year in most of the study area. Given this condition, it was estimated that relatively little water would be released from the bedrock

Table 5. Estimated bulk water in storage by *(A)* unconsolidated aquifer sediments and *(B)* bedrock aquifers in geohydrologic zones of the Seacoast model area in southeastern New Hampshire.

[Model zones shown on figures 3 and 4; ft, feet; ft^3, cubic feet; Mgal, million gallons; Sy, specific yield (dimensionless); Ss, specific storage (dimensionless); —, not applicable]

Model zone	General sediment group or bedrock group-formation names	Median model-cell thickness (ft)	Approximate sediment or rock volume (ft^3 x 1,000,000)	Primary porosity (percent)		Bulk volume of water in storage; range is for ±10 percent of the primary porosity (Mgal)	Bulk specific yield (Sy)	Theoretical amount of water that could be released for ±10 percent of the assumed specific yield (Sy) (Mgal)	Water released by a 3-ft head decline over the entire model area[2] (Mgal)	Water released by a 10-ft head decline over the entire model area[3] (Mgal)
					A. Unconsolidated aquifer sediments[1]					
Ksd	Coarse-grained sand, gravel, and fill	29	33,000	35	Median	85,000		61,000	6,200	21,000
					Range	61,000–110,000	0.25	37,000–86,000	3,700–8,700	12,000–29,000
					Median	105,000		65,000	4,900	16,000
Km	Fine-grained sand, silt, and clay	40	35,000	40	Range	79,000–131,000	.25	39,000–92,000	2,900–6,800	9,700–23,000
					Median	99,000		71,000	13,000	43,000
Ktill	Till	17	38,000	35	Range	71,000–128,000	.25	43,000–100,000	7,700–18,000	26,000–60,000
					Median	31,000		23,000	1,600	5,400
Kwet[4]	Wetland and underlying undifferentiated glacial sediments	43	10,000	40	Range	23,000–39,000	.30	16,000–31,000	1,000–2,000	3,600–7,300
	Subtotals				Median	320,000		220,000	25,700	85,400
		—	116,000	—	Range	235,000–409,000	—	134,000–308,000	15,000–36,000	52,000–119,000
Model zone	**General sediment group or bedrock unit**	**Total model cell thickness (ft)**	**Approximate sediment or rock volume (ft^3 x 1,000,000)**	**Secondary porosity (percent)**		**Static volume of water in storage; range is for -10 to 5 times the assumed secondary porosity (Mgal)**	**Bulk specific storage (Ss)**	**Theoretical amount of water that could be released for ±10 times the assumed specific storage (Mgal)**	**Water released by a 3-ft head decline over the entire model area[2] (Mgal)**	**Water released by a 10-ft head decline over the entire model area[3] (Mgal)**
					B. Bedrock aquifers[5]					
Rx1	Rye Complex and Breakfast Hill Granite	1,000	1,000,000	1.00	Median	77,000		6.2	0.02	0.06
					Range	8,000–390,000	8.E-07	0.6–60	.002–.2	.006–.6
					Median	99,000		30	.09	.30
Rx2	Kittery Formation	1,000	1,330,000	1.00	Range	10,000–500,000	3.E-06	3–300	.009–.9	.03–3
					Median	58,000		1.2	.004	.012
Rx3	Eliot and Berwick Formations	1,000	1,560,000	0.05	Range	6,000–290,000	1.E-07	.1–10	.0004–.04	.001–.1
					Median	6,000		.6	.002	.006
Rx4	Newburyport Complex and Exeter Diorite	1,000	860,000	.01	Range	600–30,000	1.E-07	.06–6	.0002–.02	.0006–.06
	Subtotals				Median	240,000		38	.113	.378
		—	4,750,000	—	Range	24,000–1,210,000	—	3–376	.01–1.1	.04–4
	Totals				Median	560,000		220,000	25,700	85,400
			4,866,000	—	Range	260,000–1,600,000	—	134,000–308,000	15,000–36,000	52,000–119,000

[1] Based on extent of surficial sediments shown in figure 3.
[2] Water released from storage is based on the assumption of a theoretical head decline at all model cells such as may occur on an annual basis.
[3] Water released from storage is based on the assumption of a theoretical head decline at all model cells; hypothetical extreme scenario.
[4] Wetland sediment group includes underlying unconsolidated glacial sediments.
[5] Based on extent of bedrock zones shown in figure 4.

aquifer (0.11 Mgal), but a much greater amount would be released from the overburden sediments (25,700 Mgal). Because the bedrock aquifer and the overlying unconsolidated aquifers in the study area are hydraulically well connected, the water released from the overburden aquifers would contribute to the water available from the bedrock aquifer. Thus, sediments that generally are not considered primary aquifers, such as till or fine-grained sediments, have an important role in contributing a considerable amount of water to the underlying bedrock aquifer.

The 25,700 Mgal associated with a 3-ft head decline also corresponds to the amount of water released annually due to seasonal drainage. This water is not available for use but is released from the aquifer system to streams and other water bodies such as tidal estuaries. On the basis of simulated recharge rate of 22 in/yr (appendix 7, Transient Model), an estimated 35,000 Mgal/yr moves through the entire aquifer system. The transient-model analysis indicates that a larger volume of water moves through the bedrock aquifer on a daily basis; this larger volume highlights the importance of recharge and hydraulic connectivity in the bedrock-aquifer system. Both the bulk water in the aquifer system and the water moving through the system are about an order of magnitude larger than the approximate 3,800 Mgal/yr currently being extracted. In addition, the amount of water available for use at a location depends on many local factors, including the amount of water that can physically be extracted without exceeding drawdown limitations at the well and the ability for water to flow to a supply well; these factors are governed by the hydraulic properties of the aquifer. Finally, where water can be extracted, the resultant stress on the aquifer system must be evaluated with respect to declines in ground-water levels elsewhere and discharges to streams or other water bodies.

Future Water Availability

In the evaluation of future water availability, two factors were of primary concern: increased use of water associated with projected population growth, and potential changes in precipitation and ET that may be associated with climate change. The future population growth in the Seacoast area has been projected by the Rockingham Planning Commission (RPC) for the years 2017 and 2025 (Tom Falk, Rockingham Planning Commission, written commun., 2006), whereas the Union of Concerned Scientists has forecast climate change globally, including New Hampshire (Ekwurzel, 2006). Detailed coefficients for water use and projected future water use, based on population projections for Rockingham County, N.H., have been developed by Horn and others (2007) for the study area. Increases in future water demand in the model area of approximately 20 and 33 percent have been projected for 2017 and 2025, respectively, and were used in this investigation as the basis for future simulated water demands.

Along with increasing water use, potential climate change may affect future water availability. An objective of the study was to assess the effect of adverse climate conditions on the hydrology of the Seacoast area. Discussion of climate change within this century includes projections of increasing temperatures and changing precipitation patterns; some researchers indicate that climate changes are currently occurring (Hayhoe and others, 2006; Hodgkins and others, 2003, 2005; Hodgkins and Dudley, 2006; Huntington and others, 2004). A similar ground-water-flow simulation was conducted by Scibek and Allen (2006) to assess the effect of climate change on ground water in British Columbia, Canada. The Intergovernmental Panel on Climate Change (IGPCC) forecasts that the projected increasing temperature in the northern United States will lead to earlier spring snowmelts and patterns of reduced summer runoff (Intergovernmental Panel on Climate Change, 2001). Increases in temperature and changes in ET and precipitation patterns in New England presented by Hayhoe and others (2006) were interpolated and used as a basis for climate change in this investigation. The effects of increasing future water use and potential climate changes on the Seacoast ground-water resources were evaluated with respect to changes in base flows and ground-water heads.

Potential Future Water Use

A steady-state ground-water-flow model, described above and in appendix E, was used as the basis for calculating the effect of future water demands and uses on the water balance in the study area. The steady-state model represents a seasonal low-flow condition (October 2004) to provide an analysis of water demand during critical periods of low water availability. During high-flow periods, seasonal water demands generally are less critical for human or biotic needs. Projected water demands were based on the RPC’s Transportation Analysis Zone (TAZ) regional growth model and water-use coefficients developed by the Seacoast water-use investigation (Horn and others, 2007). Projected water-use demands were calculated for the years 2017 and 2025 for TAZ areas. The TAZ areas are subdivisions of town areas and were larger than the census block areas used in model calibration (appendix 5) but TAZ area water-use projections were distributed in a consistent manner. The future demands (2017 and 2025) were compared to ground-water flow and water-use simulations based on 2003 TAZ data to provide current and future simulations with consistent water-use and planning methodology. Because of differences in population-projection zones used in the future water-use analysis, the water-use compilation used in the future water-use scenarios is slightly different from the water-use compilation used in the monthly transient model calibration (discussed in detail in appendix 7). Although the water-use compilation used in the transient model is more precise for current (2003–04) water uses, a base scenario calculated on the basis of generalized 2004 water-use information, but in the same manner as the scenarios of future water uses, was used to provide a consistent water-use compilation for simulation comparisons.

The distribution of current and future withdrawals and returns was determined on the basis of existing large ground-water withdrawals, water and sewer distribution systems, wetlands, and protected areas. Rates of existing registered withdrawals were increased to projected withdrawal rates by the percentage of change calculated for the TAZ projections for 2003 to 2017 and 2003 to 2025. Areas currently supplied by water sources external to the model area were assumed to continue to be externally supplied and were not included in the areas for which withdrawals were simulated. The percentages of change in the current and future TAZ projected withdrawals were assigned to the wells that supply areas that have water-distribution systems. In the model, existing overburden or bedrock wells were represented by simulated wells in model layers 1 or 3. The changes in TAZ withdrawals for areas served by water-distribution systems were compared to determine the relative changes in withdrawals over time. Current (2004) total withdrawals, registered and distributed, in the model area were approximately 10 Mgal/d. Factors of 1.20 and 1.33 were applied to withdrawal rates at existing water system withdrawal wells to simulate 2017 and 2025 withdrawals, respectively. In areas without water-distribution systems, current and future withdrawals were distributed over simulated withdrawal areas (appendix 5, fig.5–5A) according to the percentage of change in water use in the TAZ areas.

Estimated withdrawals for some areas could be greater than what could probably be obtained from the surficial or bedrock aquifer at that location. For example, obtaining a high yield from a bedrock well requires locating fracture zones that intersect sufficient fractures to access ground water stored in the regional aquifer system. Such fracture zones may not exist or they may not yet have been identified. This study did not assess the locations of potential fracture zones or supply wells. Evaluation of the potential yield of an individual well can only be done with site-specific investigations. This study evaluated the potential hydrologic impacts of such withdrawals within the regional aquifer.

Distributed withdrawals (aggregated non-registered uses) were simulated using the Flow and Head Boundary (FHB) package (Leake and Lilly, 1997) by TAZ area. Return flows were distributed in areas not served by an external water supply and not served by an existing sewer system. Returns were estimated to be 85 percent (assuming a 15-percent loss) of the total water used (Horn and others, 2007) and were distributed over simulated return areas (appendix 5, fig.5–5) according to the percentage of change in water use in the TAZ areas. Returns were simulated using the FHB package as a source in model layer 2.

The effects of increased water use include increased consumptive use and water transfers. Because treated sewer returns in the Seacoast model area are water transfers that are discharged to tidal water bodies, these transfers represent a loss of water from the hydrologic system. In some areas, supplied water is returned to leach fields and may result in a water input to the local hydrologic system. In the Seacoast aquifer system, almost all recharge enters the aquifer system through surficial sediments. Impervious surfaces cover about 7.5 percent of the larger Seacoast region (Justice and Rubin, 2005). Precipitation on bedrock and impervious surfaces generally flows to nearby surficial sediments. Precipitation on impervious surfaces that drain to a sewer system is transferred to another area in the aquifer or out of the area through a sewer, representing a loss of potential recharge; thus, recharge at an impervious surface is effectively zero. If the impervious surface does not drain to a sewer system or stream network but drains to surficial sediments, there is no change in recharge from the impervious surface. This was found to be the case for a 20-mi^2 watershed in Maine where impervious surfaces doubled (to 3.5 percent) over 35 years but little statistical change was detected in streamflow peaks or recessions (Dudley and others, 2001). Changes in base flow caused by sewering associated with urbanization are well documented for other areas (Simmons and Reynolds, 1982; Spinello and Simmons, 1992). To assess the potential effect of the loss of return flows due to sewering, a second set of simulations was conducted in which the entire model area was assumed to be fully sewered and withdrawals were not returned to the aquifer.

Calculated water balances (recharge, outflows, and consumptive use) with respect to increased future water use are presented in figure 16 for the model area. For the Seacoast hydrologic system, future water-use scenarios projected decreases in fresh ground-water discharge to tidal water bodies of approximately 1 and 2 percent and decreased base flows of 5 and 7 percent for 2017 and 2025, respectively (fig. 16). With a fully sewered scenario, projected decreases in fresh ground-water discharge to tidal water bodies were approximately 3 and 5 percent and decreased base flows of 9 and 13 percent for 2017 and 2025, respectively. The reduced discharges effectively lengthen the low-flow periods in the annual flow cycle.

Changes in ground-water heads differed by watershed and were larger in areas of greater demand and use (fig. 17). Regional changes in ground-water levels were subtle but were greatest near large ground-water withdrawals with increasing demands and in developing rural areas (fig. 17). In some areas of the model, simulated head contours moved inland with increased water use, particularly in areas with increased use and shallow head gradients (areas with less topographic relief). In addition, larger ground-water withdrawals in the system were typically in areas with less relief. Reduced freshwater discharge to tidal areas and lower heads in lowlying coastal areas could cause the interface between fresh and saline ground water to move inland.

Potential Climate Change

Potential changes in ground-water conditions caused by climate change were simulated for a 2025 climate-change scenario. Interpolation of climate-change conditions projected for the end of this century to near-term (2017) conditions

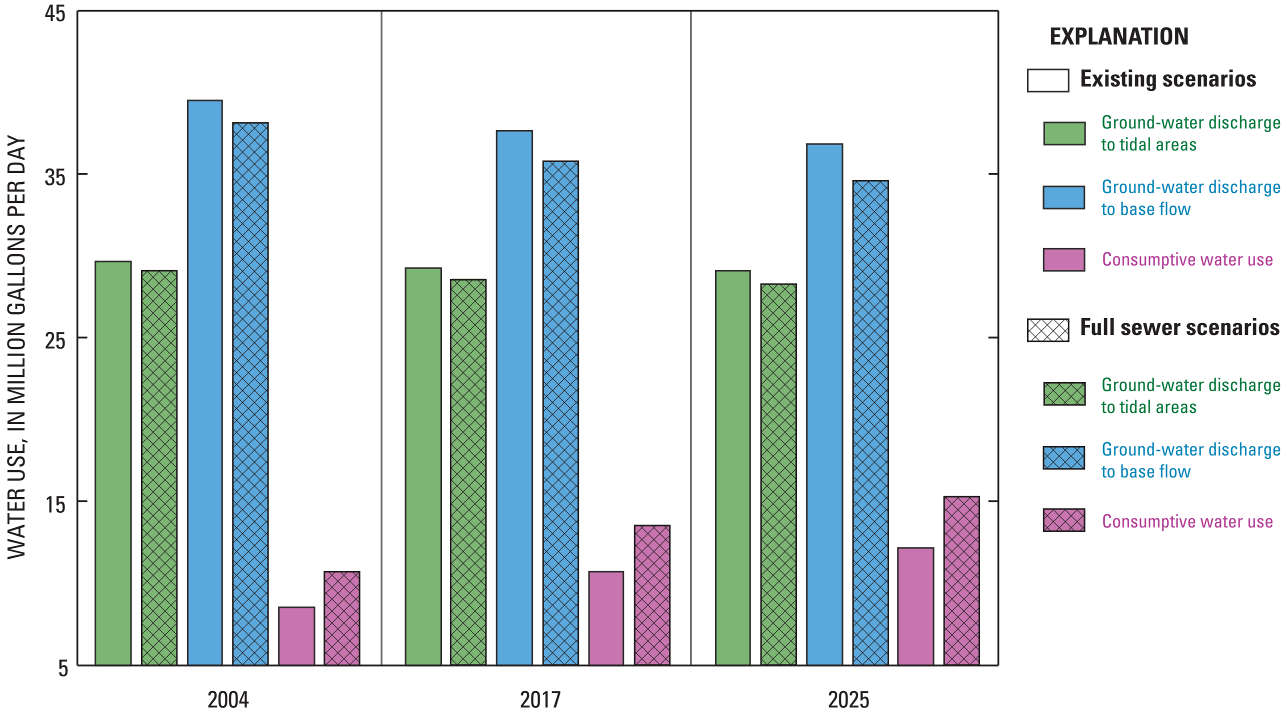


Figure 16. Simulated current (2004) and future (2017 and 2025) ground-water discharge and consumptive use for the Seacoast model area, southeastern New Hampshire.

would not be realistic. Potential climate changes may affect both the total annual recharge to the Seacoast hydrologic system and the timing of recharge during the year; therefore, a transient monthly ground-water-flow simulation was selected. All model parameters, with the exception of net recharge, were the same as those used for the transient monthly model. Although water demand for the year 2025 is projected to increase, the simulated climate change for 2025 was evaluated on the basis of the current (2003–04) water-use conditions to isolate the effects of only climate change without the influence of other variables.

Hayhoe and others (2006) present meteorological, hydrological, and biological observations of recent climate change and estimates of potential future climate change for the northeastern United States. Projected climate conditions of interest to this investigation include changes in precipitation amounts and patterns, and changes in ET rates and growing-season lengths caused by rising temperatures. Hayhoe and others (2006) indicate that, by the end of the century, average precipitation is projected to increase 11 to 14 percent during the winter and not to change or slightly decrease in the summer. Slight changes in precipitation patterns in these directions have been observed since 1970. Interpolating projections given by Hayhoe and others (table 3, 2006) to 2025, winter precipitation may increase by 5 percent, but not change during other seasons. Increasing winter precipitation has also been accompanied by intensification of storms (Huntington, 2006; Wake and Markholm, 2005). This trend of intensification is projected to continue with an increase in both high and low streamflow events (Hayhoe and others, 2006). In this investigation, analysis of monthly precipitation totals and base flows indicates that periods with intense storms increase the total precipitation but may not proportionately increase the base flow and, therefore, the effective recharge. Intense precipitation produces more runoff, and therefore, less recharge relative to the amount of precipitation, than recharge caused by less intense precipitation events. Thus, intensified precipitation is likely to lead to little increase, or even a decrease, in winter recharge. Increased temperatures would increase ET in spring and fall and thus would lead to a decrease in net recharge. Therefore, it is likely that the effect of more intense future storms on recharge in the future would be negative.

In addition to changing precipitation amounts and patterns, two other likely effects of increasing temperatures were of primary interest to the Seacoast water-availability

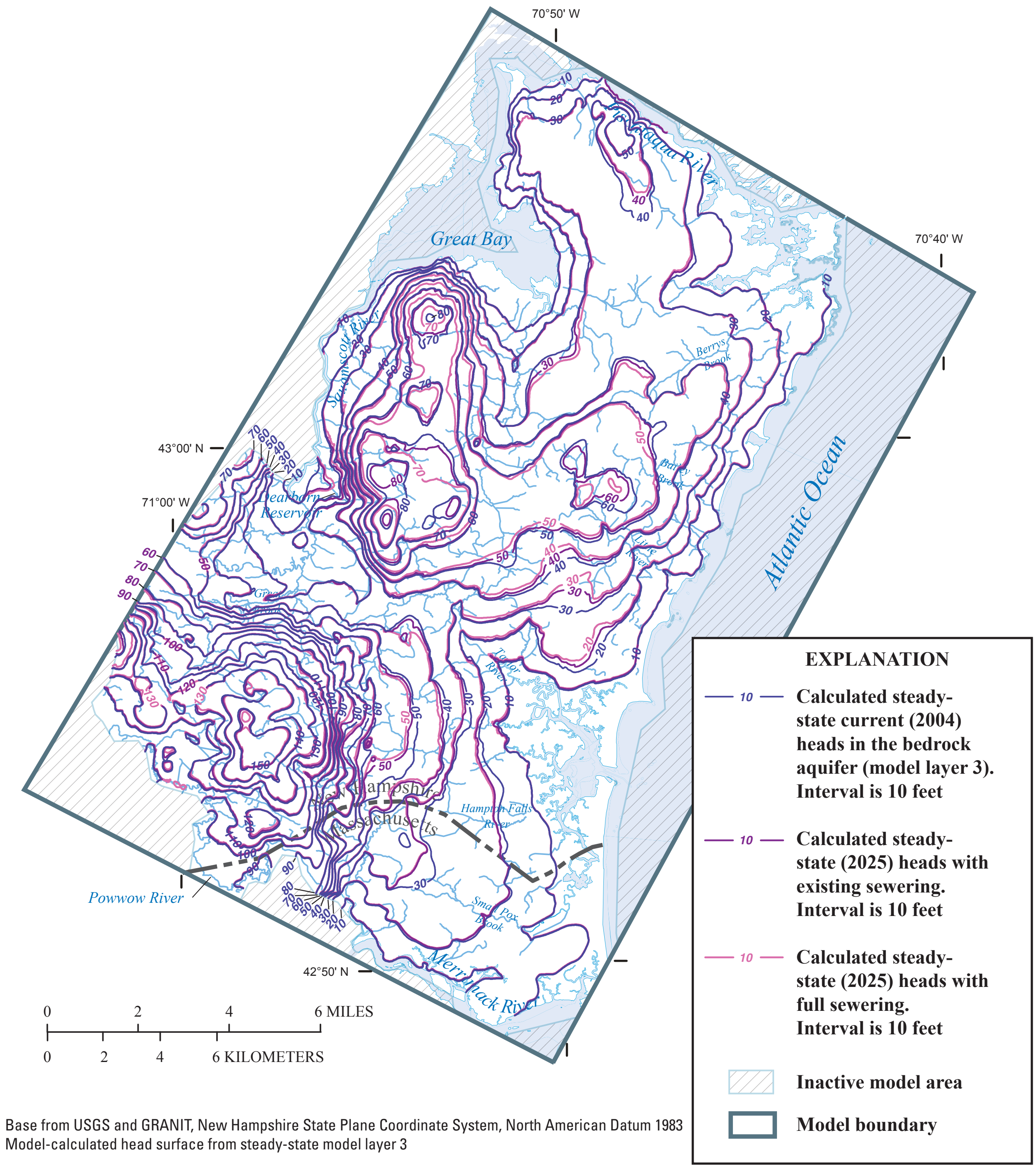


Figure 17. Calculated steady-state current (2004) and future (2025) heads in the bedrock aquifer (model layer 3) under existing and fully sewered conditions for the Seacoast model area, southeastern New Hampshire.

study; runoff from spring snowmelt may occur earlier in the winter, and a longer growing season may extend ET earlier in the spring and later in the fall. Hodgkins and others (2005) and Hodgkins and Dudley (2006) have noted a trend of increasingly earlier spring runoff that is correlated with increasing temperatures. During the current investigation, the period of greatest recharge was March through April. If the growing-season length described by Hayhoe and others (2006) is interpolated to 2025, the growing season is predicted to extend 1 to 2 weeks longer into October in 2025 than currently (2004). ET is forecast to increase by 4 to 16 percent by the end of the century with most change occurring in the spring and summer (Hayhoe and others, 2006). For this investigation, it was assumed that the growing season in 2025 will begin two weeks earlier than present (2004).

Figure 18 presents effective recharge (recharge minus ET) estimated for average monthly 2000–04 conditions (fig. 15) and recharge changes used in the ground-water-flow simulations for three likely future climate scenarios based on interpretation of future climate predictions by Hayhoe and others (2006). All future (2025) scenarios incorporated the effect of increasing temperatures on the Seacoast hydrologic system by simulating an earlier spring snowmelt and a longer ET season. In the first scenario, winter precipitation and the peak spring recharge were increased by 5 percent, and the effective recharge was calculated on the basis of current monthly precipitation-to-recharge ratios. The second scenario simulated no change in the winter-precipitation and peak-recharge rates. The third scenario simulated a 5-percent decrease in winter recharge as may be caused by intensification of precipitation and a reduction in effective recharge. All scenarios were initiated by using heads from the end of the 2000–04 scenario (end of December) as initial boundary conditions. Two 2-year cycles of each future scenario were run to remove the effects of the initial boundary condition on the simulations.

Future scenarios were characterized by earlier peak recharge in late winter and a longer low-recharge period (fig. 18). The first future scenario, the base scenario, simulates a spring snowmelt that is shifted from March and

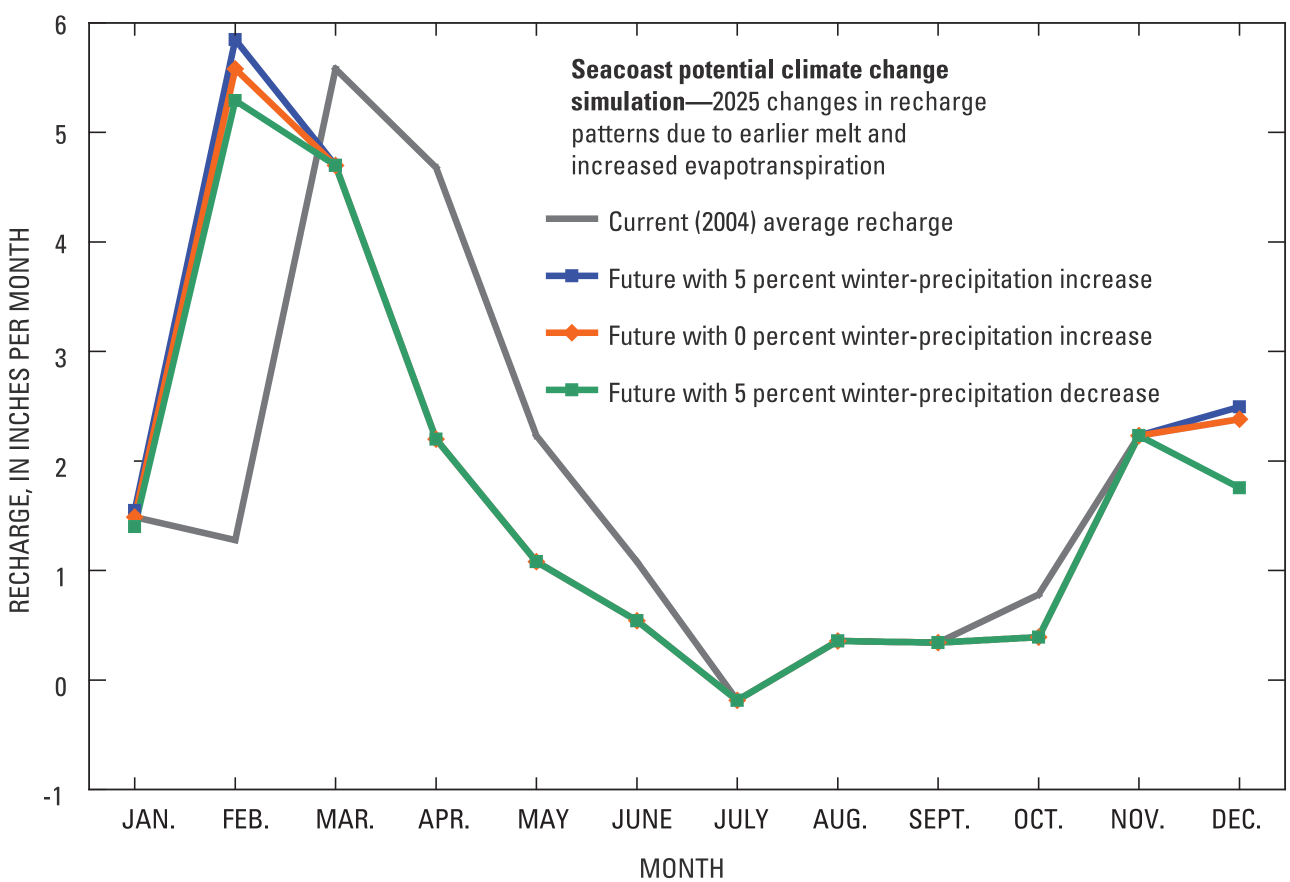


Figure 18. Simulated current (2004) and future (2025) effective recharge rates caused by three different climate-change scenarios for the Seacoast model area, southeastern New Hampshire.

April into February and March. In addition, the estimated average monthly recharge rates for May and June were shifted one month earlier to April and May. Because of increased temperature and an earlier onset of ET, the spring net recharge would increase. In the current simulation, the net recharge for July was slightly negative (-0.2 in.), representing fully effective ET. On the basis of the assumption that the ET rate in the future June may be between the current June and July rates, the future June recharge rate was conservatively simulated at half the current June rate, or 0.5 in. The October recharge rate also was reduced by half to 0.4 in. to account for an increased ET rate. The winter rates for December and January (54 and 42 percent of precipitation, respectively) were 5 percent higher than present rates at 2.2 and 2.5 in., respectively. The future simulation was also assessed with winter recharge rates equal to present rates and with recharge 5 percent lower than present rates (fig. 18).

Base flows simulated for future climate conditions were compared to current average monthly base flows. The Winnicut River, the largest watershed in the study area, was used for this comparison (fig. 19). Because there is little storage in the Seacoast hydrologic system, changes in recharge result in similar changes in base flows. The simulations indicated increases in winter base flows but decreases in spring and summer base flows. Similar to recharge (fig. 18), the peak base flow may be slightly greater but will likely occur earlier in the winter. An increase in the growing-season length (and consequently increased ET) would result in reduced net recharge and decreased water availability through the summer months.

The effects of changes in the simulated net recharge (fig. 18) on regional ground-water heads in the bedrock aquifer are shown in figure 20. The effects of the three scenarios on heads were similar at the regional scale. October heads in the bedrock aquifer were calculated for layer 3, for the second climate-change scenario (no change in winter precipitation), and were compared to the current average recharge scenario (fig. 20). Simulated changes were greater than the changes caused by increased water use. Apparent impacts were observed in all areas of the model but were greatest in low relief, high water-use areas.

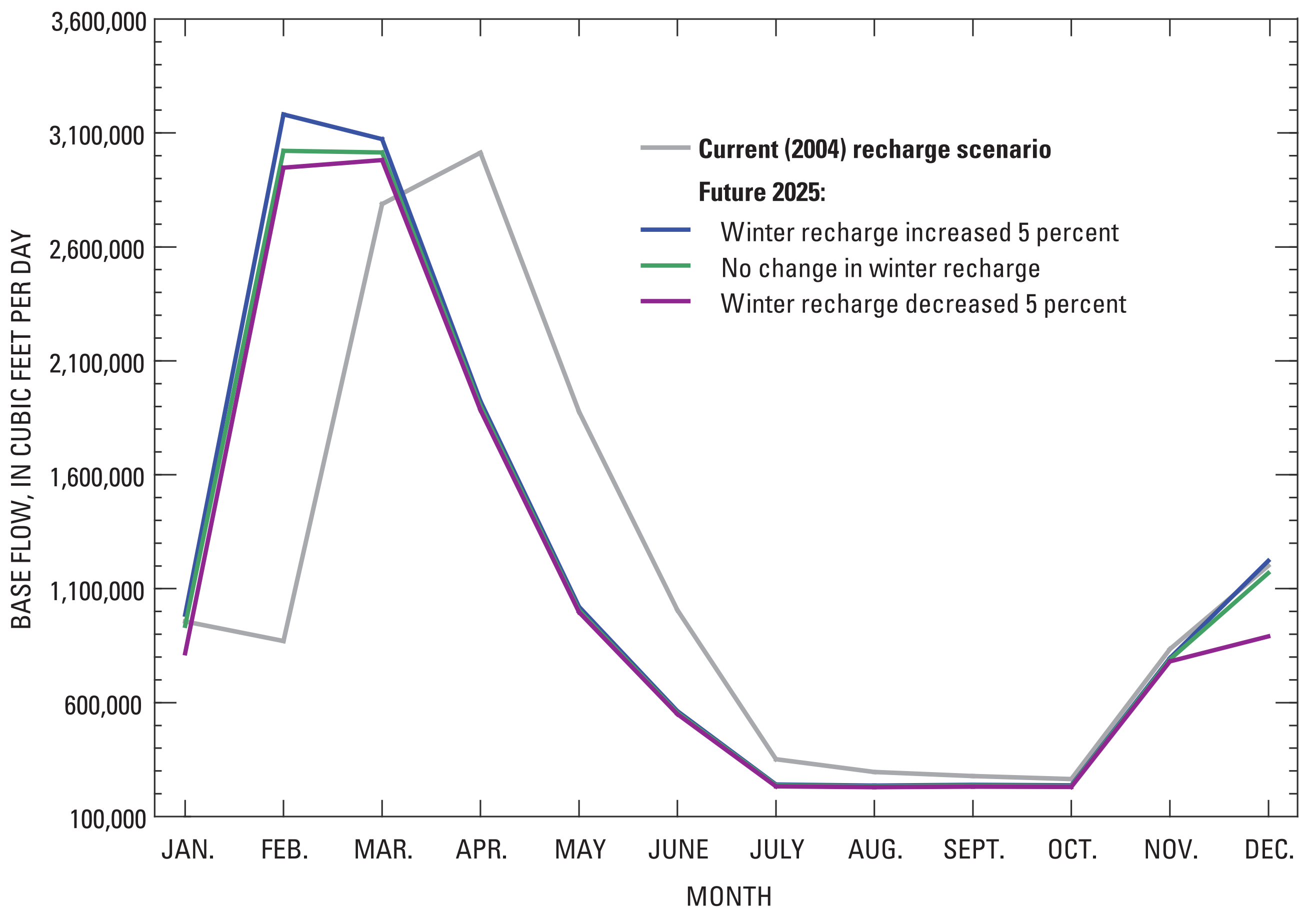
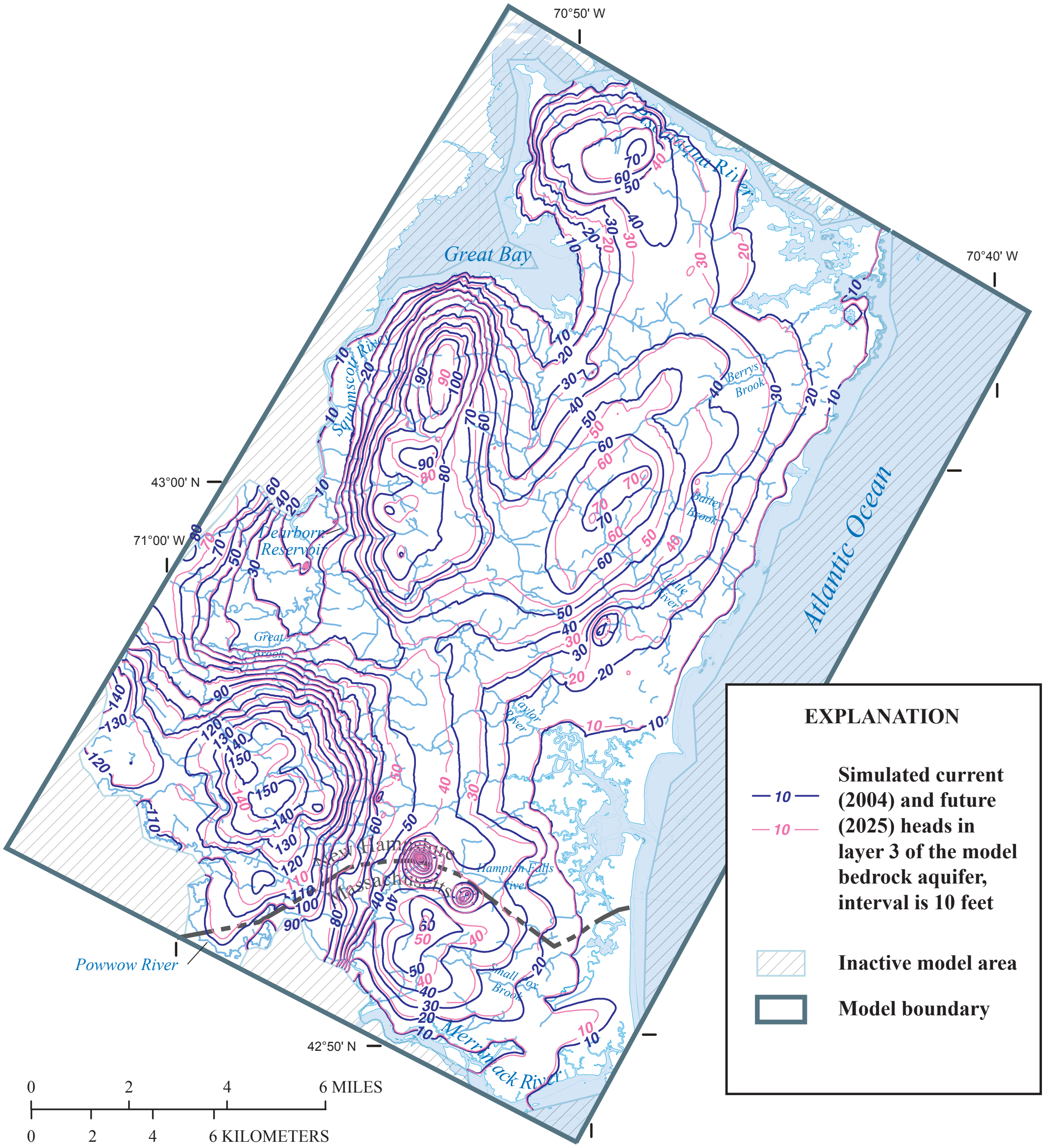


Figure 19. Simulated current (2004) and future (2025) base flows in the Winnicut River as a result of climate changes simulated for the Seacoast model area, southeastern New Hampshire.



Base from USGS and GRANIT, New Hampshire State Plane Coordinate System, North American Datum 1983
Model-calculated head surface from steady-state model layer 3

Figure 20. Simulated current (2004) and future (2025) heads in layer 3 of the model of the bedrock aquifer under climate changes simulated for the Seacoast model area, southeastern New Hampshire.

Another potential effect of climate change is sea-level rise. Ward and Adams (2001) estimate a 2-ft rise in sea level and inundation of low-lying areas of New Hampshire's coast by the year 2100. The implications of such a change on Seacoast water resources would be two fold: (1) an increase in the potential-head surface in tidal areas would cause the fresh ground-water/saltwater interface to move inland, and (2) additional areas of New Hampshire's coastline would be inundated with saltwater, causing a landward movement of the interface closer to existing fresh ground-water aquifers. The effects of these changes would take time, possibly years, to propagate inland and achieve a new dynamic steady state between the aquifers and sea water. The effects of sea-level rise on ground-water resources were not simulated; however, the effects would be greatest in low-lying areas adjacent to the coast and less in interior areas of the Seacoast aquifer system. Ground-water resources immediately adjacent to the tidal areas, and primarily used for domestic supply, would be affected first and most strongly by a sea-level rise.

Discussion

The October synoptic measurement conditions, and associated steady-state simulation, were representative of seasonal low-flow rates but would not represent long-term average conditions; flow rates would be too low. The October steady-state simulation is useful for simulation of a quasi-steady state, seasonal low-flow condition such as that investigated with the future water-use scenarios. Depending on the objective of the model, an average of the monthly recharge rates or a specified annual recharge rate, such as that derived from the transient analysis, may be appropriate for use in steady-state simulations representing a multiyear or long-term ground-water-flow scenario as described in appendix 9. Anderson and Evans (2007) similarly found that calibrating a steady-state model to low-flow conditions may estimate recharge correctly for that period but would underestimate annual recharge. Similarly, they found that steady-state average-recharge conditions can provide a representation of annual transient conditions. The seasonal and annual recharge rates calculated by Flynn and Tasker (2004) were comparable to those developed in this investigation despite differences in time discretization (seasonal compared to monthly) and analysis period (decades compared to recent years). These considerations indicate that regional simulations by the Seacoast ground-water-flow model may be most appropriate at longer time scales, such as seasonal or annual stress periods based on seasonal or annual average rates rather than on monthly or shorter stress periods. The spatial and temporal design of a simulation, however, also depends on the purpose and objectives of the investigation.

Because it is largely bounded by tidal water bodies, the Seacoast aquifer system may be affected by salt-water intrusion. Salt-water intrusion is not believed to be widespread but has been reported in some domestic supply wells adjacent to salt-water bodies. The orientation of the regional bedrock structure (northeast/southwest, parallel to the coast), and the estimated anisotropy of the hydraulic conductivity may limit the potential for salt-water intrusion to the larger ground-water supply wells for much of the Seacoast bedrock aquifer. Lineaments oriented orthogonal to the regional structure (Ferguson and others, 1997a, b; Johnson and others, 1999) however, could represent important bedrock-fracture zones and a potential pathway for salt-water intrusion. A linear pattern orthogonal to the regional structure is apparent in the orientation of the major rivers within and along the boundaries of the study area; these rivers include the Merrimack and Piscataqua Rivers, and sections of the Taylor River, Little River, and Bailey Brook (fig. 1). Hypothesis tests were conducted to assess the potential for salt-water intrusion in large ground-water-withdrawal well fields between 1 and 2 mi from the coastline (Mack, 2004). Hypothetical orthogonal fracture zones were simulated with a hydraulic conductivity 1,000 times the bulk-matrix conductivity and oriented from the well fields directly to the ocean. Ground-water-flow simulations indicated that salt-water intrusion near the shoreline is unlikely to migrate into the interior areas of the Seacoast model area under current climate conditions.

Sustained large ground-water withdrawals alter the natural ground-water-flow system by causing younger water to flow deeper into the aquifer, some of which is captured by the well, than would occur at that same location if there were little or no withdrawal. This probably occurs in the more developed parts of the Seacoast model area. Large ground-water withdrawals in the Seacoast aquifer are only possible in areas of high transmissivity, such as in highly fractured areas of the Kittery Formation and Rye Complex or in some fracture zones in other bedrock units. Any ground-water withdrawal, however, is balanced by a reduction in flow or a short-term removal of water from storage elsewhere in the ground-water-flow system. The reduction will affect ground-water flow to a hydraulic boundary, such as a stream or other water body, or another area of the aquifer. Highly fractured bedrock generally has a greater storage capacity than less fractured, lower-yielding bedrock and can, therefore, buffer the effect of withdrawals to some extent. Projected future water uses for the years 2017 and 2025 were simulated to result in reduced base flows and freshwater discharges to tidal areas. Such changes will be most apparent during low-flow periods, as assessed; for example, some streams that have historically gone dry may go dry for longer periods of the year. If future development scenarios include additional consumptive water uses, such as regional sewering that does not return water to the aquifer, the combined effect may result in further decreases in base flows and tidal discharges.

The projections of Hayhoe and others (2006) were approximately interpolated in this investigation to provide near-term (2025) potential future climate conditions for the Seacoast ground-water-availability assessment. Potential climate changes include higher temperatures, longer growing seasons, increased ET, and precipitation changes. Although the climate-change interpolations used in the present investigation were speculative, recent climate-change research indicates that increasing temperatures are highly likely during this century (Hayhoe and others, 2006). Rising temperatures will result in reduced annual recharge caused by a longer ET period during the year. Temperature increases, however, also may result in less of the winter precipitation stored in the annual snowpack and less water released during the snowmelt recharge period in March and April. This period may shift to a time earlier in the year and farther from the period of peak summer demand. The climate forecasts (Hayhoe and others, 2006) include a potential slight increase in winter precipitation and more frequent occurrences of intense precipitation events. Slight (5 percent) increases in winter precipitation had little effect on the annual water balance. More frequent and intense precipitation events are expected to decrease the potential for long-term droughts (Hayhoe and others, 2006); however, increasingly intense storms may result in an effective net decrease in recharge because of increased surface runoff as has been observed by this investigation.

Projected future increases in water use would affect the hydrologic system by decreasing base flows, tidal discharges, and ground-water levels. Based on projected estimates of growth (Horn and others, 2007), most of these effects will most likely occur by the year 2017. The potential effects of climate change simulated for the Seacoast hydrologic system will likely exacerbate the same effects. The effects of these changes by 2025 were estimated to be greater than the potential effect of increased water demands. Although simulation of the effects of near-term (2025) climate changes on the hydrology of the Seacoast are speculative, climate change is expected to continue and be more severe later in this century (Hayhoe and others, 2006). Future water demand and potential climate-change scenarios were investigated independently to allow for assessment of the separate effects of each scenario. These scenarios are not likely to occur independently; however, potential climate changes will likely exacerbate the effects of increasing water demand. Additionally, increasing temperatures and longer growing seasons would likely result in greater water demands than the estimates used in this analysis.

The analyses indicate potential issues of concern in terms of future water availability in the Seacoast region. Development associated with growth may result in increases in water use, the addition of sewered areas that discharge to tidal waters, or the construction of new connections from impervious areas to sewer systems. All of these changes would alter the water balance of the Seacoast aquifer system. Any change in one component of the hydrologic system—surface water or ground water—is balanced by changes in another part of the system (Alley and others, 1999; Winter and others, 1998). For example, increased consumptive water use or increased water transfers out of the system (sewering) will result in lower ground-water levels and reductions in base flow to streams or in ground-water discharges to tidal areas. The concept of a "water budget" or "safe yield" of an aquifer system, defined as an amount of water that can be withdrawn without affecting the system, is not considered valid by some researchers (Bredehoft, 1997; Bredehoft and others, 1982; Sophocleous, 1997, 2000). A withdrawal will have an effect at some level on the aquifer system. The magnitude of the effect may need to be evaluated to determine whether the yield of the withdrawal well can be considered safe in a hydrologic or ecological context. Although the yield of one well at a specified rate may have little effect on the hydrologic system, the cumulative effect of multiple independent withdrawals at the same rate may have a measurable hydrologic or ecologic effect on the environment. The amount of water stored in and recharging the aquifer system can be calculated, as in this investigation; however, the amount of water that can be withdrawn without affecting the system, called the "sustainable use," needs to be assessed by water-resource planners and is not addressed by this investigation.

The sustainable use can be determined by hydrologic properties and by the amount of change in the water balance that is considered acceptable by planners, water-resource managers, regulators, and the community (Sophocleous, 2000). Ground-water and surface-water systems are generally connected (Winter and others, 1998), especially on a regional scale. Ground-water withdrawals can have complex interactions with surface-water and aquifer systems. For this reason, water-management decisions generally require the use of a model and assessment by a hydrologist (Bredehoft, 2002). The models developed and demonstrated in this investigation are intended to provide water-resource managers and planners with tools with which to assess future water resources in the Seacoast region.

Model Limitations

The ground-water-flow models developed for the Seacoast area provide a regional-scale simulation of ground-water flow specifically for simulation of water-balance issues, but not for analysis on a site-specific scale. For example, the ground-water-flow models may be used to investigate the effects of water-use changes resulting from development on regional ground-water levels, heads, and discharges to streams. Site-specific scales of analysis might include calculations of the drawdown in a well field, the sustainable yield of a well, the head at a specific location, or the flow path to a withdrawal point.

Ground-water-flow models are a numerical representation of the physical flow system and require simplifications and assumptions. Limitations are inherent in the practical application of ground-water-flow models, and the assumptions and simplifications incorporated in a model depend to some extent on the intended use of that model. A discussion of the adequacy of models for their intended use is provided by Reilly and Harbaugh (2004). Several model limitations that are discussed by DeSimone (2004) for a similar investigation in eastern Massachusetts also apply to the Seacoast models. For example, the Seacoast ground-water-flow models do not simulate unsaturated-zone flow processes (ground-water flow above the water table), or the direct, or overland, component of streamflow; instead, the models simulate the base-flow component of streamflow, or ground-water discharge. Evapotranspiration also is not specifically simulated but is accounted for within a net (or effective) recharge.

Simplifications include the parameterization of hydrogeologic properties and characteristics into homogenous units and the assignment of these parameters to groups of cells with areas of 200 by 200 ft and thicknesses that depend on the model layer. Simplification also includes the temporal grouping of recharge, streamflow, and ground-water-flow characteristics into monthly and annual periods.

An important limitation of the Seacoast models is that they do not specifically simulate ground-water flow in bedrock fractures, but rather the bulk flow of ground water in the regional-flow system. Thus, the model accounts for the overall movement of ground water through the aquifer system, incorporating regional bedrock anisotropy, but not through specific fractures. The detailed configuration of fracture networks is generally known only at few research sites and then generally only at scales on the order of tens to hundreds of feet, the cell-size scale in the Seacoast model. Incorporation of detailed fracture characteristics into the ground-water-flow model is not possible at the scale of investigation used and it is not necessary for simulation of regional ground-water flow. Simulation of site-specific conditions would require additional hydrogeologic data and possibly the use of local grid refinement techniques (Mehl and Hill, 2005).

Limitations resulting from not incorporating detailed fracture information include inaccurate calculation of flow or heads that are influenced by individual fractures and fracture zones, and poor model performance in the immediate vicinity of ground-water withdrawals. The model underestimates model-cell hydraulic conductivity in areas where the bedrock aquifer is highly fractured and does not account for the anisotropy of individual fractures or fracture zones. As a result, in the vicinity of ground-water withdrawals, simulated water-level drawdowns will be greater than actual drawdowns, and ground-water flow paths, which locally are controlled by the fracture network, may differ from the simulated direction of flow imposed by the regional hydraulic gradient. Such limitations apply to the vicinity of a well field and indicate that the models cannot be used to simulate ground-water flow at a well-field scale. The size of the area affected by these limitations may be hundreds of feet; the actual size depends on multiple hydrogeologic factors and is directly related to the magnitude of the ground-water withdrawal. However, the models simulate the regional ground-water flow to or from such well fields and can be used to account for the effects of ground-water withdrawals on the regional hydrologic system. The ground-water-flow models also can be used to provide boundary conditions, including hydrologic properties and fluxes, to models designed to be used in small-scale or site-specific studies.

Summary and Conclusions

Ground-water availability in the Seacoast region was analyzed between 2003 and 2004 though a cooperative investigation among the Seacoast's communities, the New Hampshire Department of Environmental Services' Coastal Program and Geological Survey, and the U.S. Geological Survey. The investigation was completed by developing ground-water-flow models for a 160-square mile area of coastal New Hampshire to provide insight into the recharge, discharge, and availability of ground water in the study area. Population growth and increasing water use have prompted concern about the sustainability of regional ground-water resources. New supply wells are installed almost exclusively in the region's bedrock aquifer. The bedrock aquifer has recently become more important for water supply than it has in the past because local high-yielding stratified-drift aquifers are either fully utilized or not available because of development or other restrictions. Previously, the regional characteristics of the fractured-bedrock aquifer in the Seacoast area of New Hampshire were not well known. Increasing reliance on the bedrock aquifer, increasing ground-water withdrawals, and potential changes in patterns of use have increased concern about the sustainability of the region's ground-water resources.

Components of the ground-water-flow system were assessed by developing and calibrating models for steady-state seasonal low-flow and transient monthly conditions. A steady-state model was used to simulate current and future projected water use during low-flow conditions, and a transient model was used to simulate the hydrologic effects of current average and estimated future monthly climate conditions over a 2-year period.

The finite-difference ground-water-flow models were based on MODFLOW-2000 and auxiliary packages for inverse parameter-estimation. Surficial sediments and surface-water bodies were simulated in the first model layer, which ranged in thickness from near zero to about 100 feet (ft). The second model layer had a uniform thickness of 6 ft and represented a lower saturated sediment layer representing till in most areas. Model layers 3 and 4 were both 300 ft thick and represented the underlying bedrock aquifer and withdrawals from it. The fifth model layer was 400 ft thick and represented a deeper bedrock aquifer. Nearly three quarters of the lateral uppermost boundary of the model consisted of salt-water bays, estuaries, and the ocean; these water bodies were simulated as an equivalent fresh-water constant-head boundary.

The ground-water-flow simulations indicated that the Seacoast aquifer system is a transient flow system with seasonal ground-water-flow variations. The aquifer system has seasonal high flows in March and April, and seasonal low flows occur from July through October. The fall (September and October) is generally a more stable period during which inflow and outflow fluxes are lower and are approximately balanced. The average annual recharge during the study period was approximately 51 percent of the annual precipitation. The average monthly rate of recharge to the aquifer (or effective recharge, which is recharge minus evapotranspiration) between 2000 and 2004 ranged from 5.5 inches per month (in/mo) in March to 0.0 in/mo in July and about 0.3 in/mo in August and September. Recharge increased to about 2 in/mo in late fall and early winter and declined to about 1.5 in/mo in late winter. In general, about 50 percent of the annual recharge occurs in the spring (March and April), and 20 percent occurs in the late fall and early winter (November through January). Recharge can be greater than the actual precipitation during snowmelt periods and effective recharge can be negative during summer months (July and August).

Regional hydraulic conductivities of the bedrock aquifer were estimated to be about 0.1 to 1.0 foot per day (ft/d), with a regional horizontal anisotropy of 2.5:1 to 5:1 in some areas. Model areas representing the Rye Complex and the Kittery Formation were assigned higher estimated hydraulic conductivities (0.5 to 1 ft/d) than areas representing the Eliot Formation, the Exeter Diorite, or Newburyport Complex (0.1 to 0.2 ft/d). A northeast-southwest anisotropy was estimated (2.5 to 5:1) that follows the regional structural trend and predominant fracture orientation. Higher confidence was calculated for parameters assigned to areas with greater amounts of data, such as the central and eastern areas, than to other areas such as the south and western areas representing the Exeter Diorite and Newburyport Complex. In these areas of the model, the upper and lower 95-percent confidence intervals for the estimated bedrock hydraulic conductivity were about half an order of magnitude above and below the estimate, and the 95-percent confidence intervals for specific storage were several orders of magnitude above and below the estimate. The uncertainty in estimated model parameters in this part of the model is higher for areas with less observational data and fewer withdrawal stresses.

Recharge enters the Seacoast aquifer system almost entirely through surficial aquifer sediments. Precipitation on bedrock and impervious surfaces generally flows to nearby surficial sediments. Precipitation that drains from impervious surfaces to a sewer system is transferred to another area in the aquifer system or out of the system altogether; in the latter situation, potential recharge is lost. The majority of the recharge, about 90 percent, enters the bedrock aquifer. The amount of recharge that flows into the lower bedrock aquifer is considerably lower (regionally about 17 percent) and at any given point depends on the location of the point in the flow field, the hydraulic conductivity of the bedrock, connectivity of fractures, and the stresses within the bedrock aquifer. Therefore, depending on these regional and anthropogenic factors, the recharge that flows into the bedrock aquifer at a specific location can range from zero to nearly all the recharge at the surface.

Regionally, a considerable amount of water (approximately 240,000 million gallons (Mgal)) may be stored in the secondary porosity provided by fractures in bedrock aquifers in the Seacoast model area. The bedrock in the eastern area of the model likely stores more water than bedrock in the southwestern area of the model. The estimated hydraulic properties of the bedrock aquifers, however, indicate that the amount of water available for release from storage in the bedrock may be less than 1 Mgal on an annual basis. A much larger volume of water (320,000 Mgal) may be stored in the pore space of unconsolidated overburden sediments. Of that water, about 25,000 Mgal may be released from storage seasonally. About half of that water is stored in till and other fine-grained sediments, which are generally not considered primary aquifers; about one quarter is stored in coarse-grained (sand and gravel) sediments; and one quarter is stored in wetlands and underlying glacial sediments. Stresses on the aquifer system resulting from water extracted from storage, however, must be evaluated with respect to declines in ground-water levels and discharges to streams or other water bodies.

In a natural setting with few withdrawal stresses, more recharge in the ground-water-flow system remains in the unconsolidated aquifers or upper bedrock than moves through the deeper bedrock aquifer. With increased withdrawals, more of the recharge in the aquifer system will move into the deeper areas of the aquifer. The residence time of ground water in the bedrock aquifer was investigated by chlorofluorocarbon age-dating at locations of high and low water use and at different areas of the flow system. Ground-water ages ranged from near zero (recently recharged water) to more than 30 years old. Ground water is oldest in areas with little water use, a low head gradient above the point of interest, and at discharge areas in the flow system. In areas where water use is high, or from shallow depths in the flow system, the residence time of ground water may be nearly zero (very recent). Water sampled from high-use supply wells sampled in the model area included a mixture of recently recharged water to water 30 years old or more. Some residence times may be longer because of diffusion of water from fractures in the rock matrix. Some of the supply wells sampled were installed within the past few years, or within the past decade. The residence time of ground water withdrawn from such wells may become less with time as the effects of the withdrawal on the flow system become established and less older water diffuses from the fractured rock.

Model parameters, including hydraulic conductivity, storage, and porosity, were estimated for the regional aquifer system and do not incorporate local heterogeneities in the aquifer such as fracture zones. The hydraulic conductivity measured at a specific site may be orders of magnitude greater or smaller than the regional value. The regionally estimated geohydrologic characteristics, however, can be used to provide general boundary conditions and aquifer properties for use in site-specific investigations. Although the models were not designed to accurately calculate heads or flows at specific points in the aquifer, they can be used to describe the general ground-water-flow system and to assess differences in ground-water flow in the study area.

Simulated effects on the Seacoast hydrologic system from projected increased future water use include declining base flows; declining fresh ground-water discharges to tidal bays, estuaries, and the ocean; and lowered ground-water levels. The hydrologic system will be affected most during periods of low flow and annual low-streamflow periods may be longer. Simulations of the hydrologic effects of increased water demand for the years 2017 and 2025 indicated that these effects will likely be apparent within the next 10 years (by 2017). By 2025, increased demand may result in a reduction in ground-water discharge to streams of about 7 percent and a slight reduction, about 2 percent, in freshwater discharge to tidal areas. With additional sewering in the Seacoast, the reduction in flows would be greater. The potential future effects of climate change on the Seacoast hydrologic system will also likely include reduced base flows and fresh ground-water discharges to tidal areas, and lowered ground-water levels. By 2025, these effects were estimated to be greater than the potential effects of increased water demands. The effects of increased demands on the hydrologic system were exacerbated by simulations with a hypothetical regional sewer system. The declines in ground-water levels in these simulations were most pronounced in low-lying areas with higher rates of water use; these are also the areas with many of the Seacoast's extra large ground-water supply systems.

The simulations based on future water demands and climate changes provide an indication of potential effects on the Seacoast hydrologic system later in this century (2025). These predicted effects pose a potential concern for future water resources in the Seacoast region. The models developed in this investigation can provide tools with which water-resource managers and planners can assess future water resources in the Seacoast region of New Hampshire.

Although the ground-water-flow models were developed for a specific area, many of the findings of this investigation regarding ground-water availability in glacial and fractured bedrock aquifer systems may be transferrable to other areas of the Nation with similar hydrogeologic or climatic characteristics, particularly in the glaciated northern United States. For example, findings related to seasonal recharge may be applicable to regions with similar climates and precipitation patterns. Likewise, findings regarding the effect of increasing water demand and future climate change on ground-water availability may be applicable to other regions of the Nation with similar hydrogeologic and climatic conditions.

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