Framework for Evaluating Water Quality of the New England Crystalline Rock Aquifers

By Philip T. Harte, Gilpin R. Robinson, Jr., Joseph D. Ayotte, and
Sarah M. Flanagan

National Water-Quality Assessment Program

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Foreword

National Water-Quality Assessment (NAWQA) Program

The U.S. Geological Survey (USGS) is committed to providing the Nation with credible scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov/). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). The NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991–2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html).

In the second decade of the Program (2001–2012), a major focus is on regional assessments of water-quality conditions and trends. These regional assessments are based on major river basins and principal aquifers, which encompass larger regions of the country than the Study Units. Regional assessments extend the findings in the Study Units by filling critical gaps in characterizing the quality of surface water and ground water, and by determining status and trends at sites that have been consistently monitored for more than a decade. In addition, the regional assessments continue to build an understanding of how natural features and human activities affect water quality. Many of the regional assessments employ modeling and other scientific tools, developed on the basis of data collected at individual sites, to help extend knowledge of water quality to unmonitored, yet comparable areas within the regions. The models thereby enhance the value of our existing data and our understanding of the hydrologic system. In addition, the models are useful in evaluating various resource-management scenarios and in predicting how our actions, such as reducing or managing nonpoint and point sources of contamination, land conversion, and altering flow and (or) pumping regimes, are likely to affect water conditions within a region.

Other activities planned during the second decade include continuing national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology; and continuing national topical studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on stream ecosystems, and transport of contaminants to public-supply wells.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Matthew C. Larsen
Associate Director for Water

Acknowledgments

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
	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)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Application rate	
pounds per acre per year [(lb/acre)/yr]	1.121	kilograms per hectare per year [(kg/ha)/yr]
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

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

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

*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.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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Abstract

Little information exists on regional ground-water-quality patterns for the New England crystalline rock aquifers (NECRA). A systematic approach to facilitate regional evaluation is needed for several reasons. First, the NECRA are vulnerable to anthropogenic and natural contaminants such as methyl *tert*-butyl ether (MTBE), arsenic, and radon gas. Second, the physical characteristics of the aquifers, termed "intrinsic susceptibility," can lead to variable and degraded water quality. A framework approach for characterizing the aquifer region into areas of similar hydrogeology is described in this report and is based on hypothesized relevant physical features and chemical conditions (collectively termed "variables") that affect regional patterns of ground-water quality.

A framework for comparison of water quality across the NECRA consists of a group of spatial variables related to aquifer properties, hydrologic conditions, and contaminant sources. These spatial variables are grouped under four general categories (features) that can be mapped across the aquifers: (1) geologic, (2) hydrophysiographic, (3) land-use land-cover, and (4) geochemical. On a regional scale, these variables represent indicators of natural and anthropogenic sources of contaminants, as well as generalized physical and chemical characteristics of the aquifer system that influence ground-water chemistry and flow. These variables can be used in varying combinations (depending on the contaminant) to categorize the aquifer into areas of similar hydrogeologic characteristics to evaluate variation in regional water quality through statistical testing.

Introduction

The New England crystalline rock aquifers (NECRA) are one of 19 principal aquifers selected by the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program for regional assessment of ground-water quality (Lapham and others, 2005). A principal aquifer is defined as a regionally extensive group of aquifers or an aquifer system that has the potential to be used as a source of potable water (U.S. Geological Survey, 2003). The NECRA is an important regional source of ground water. Irrigation, public supply, and self-supplied industrial water use from the NECRA total more than 96.3 Mgal/d in 2000 (Maupin and Barber, 2005). Domestic water usage may exceed that total (Hutson and others, 2004).

The NECRA are composed primarily of igneous and metamorphic rocks with little primary porosity and permeability. Ground-water flow and transport occurs mainly through fractures, joints, and faults (U.S. Geological Survey, 2003) formed during or after rock formation. Where glacial deposits are thin or nonexistent in the northeastern United States, crystalline rock is the primary source of ground water. The geochemistry of the NECRA is different from that of other bedrock aquifers in the Northeastern United States in that dissolved solids are relatively low and geochemical reactions are dominated by dissolved carbon dioxide (CO_2) reacting with feldspathic minerals (Rogers, 1989).

The NECRA are vulnerable to natural and anthropogenic sources of contaminants. Vulnerability of an aquifer incorporates the intrinsic susceptibility of the aquifer, the physical features of the aquifer, and the proximity and characteristics of the contaminant sources (Focazio and others, 2002).

The following are quotations from *Intrinsic Susceptibility and Vulnerability of Ground Water* (from Focazio and others, 2002):

> The intrinsic susceptibility of a ground-water system depends on the aquifer properties (hydraulic conductivity, porosity, hydraulic gradients) and the associated sources of water and stresses for the system (recharge, interactions with surface water, travel through the unsaturated zone, and well discharge). In this way, intrinsic susceptibility assessments do not target specific natural or anthropogenic sources of contamination but instead consider only the physical factors affecting the flow of water to, and through, the ground-water resource.
>
> The vulnerability of a ground-water resource to contamination depends on intrinsic susceptibility as well as the locations and types of sources of naturally occurring and anthropogenic contamination, relative locations of wells, and the fate and transport of the contaminant(s). Water-resource decision makers are often faced with a choice of deciding whether to manage a resource based on knowledge of intrinsic susceptibility or to target more comprehensive and contaminant-specific assessments of vulnerability.

Several carcinogenic contaminants have been measured at high (above U.S. Environmental Protection Agency Maximum Contaminant Level (MCL)) concentrations in ground water collected from the NECRA. For example, ground water collected from metasedimentary units and nearby granitic intrusions of the crystalline rock aquifers has been found to contain arsenic concentrations greater than 10 µg/L, the U.S. Environmental Protection Agency MCL (Ayotte and others, 2003; Lipfert and others, 2006; U.S. Environmental Protection Agency, 2006). Concentrations of ^{222}radon gas in excess of a U.S. Environmental Protection Agency proposed MCL of 300 pCi/L in water occurs in greater than 90 percent of domestic wells tapping crystalline rock aquifers of New Hampshire (Moore, 2004; Ayotte and others, 2007). Uranium concentrations in ground water from the NECRA also rank high compared to concentrations in other aquifers in northern parts of the United States (Ayotte and others, 2007). The relatively low permeability of bedrock in the NECRA has been hypothesized to make the aquifers susceptible to methyl *tert*-butyl ether (MTBE), a gasoline oxygenate because of relatively low amounts of dilution to source inputs (Ayotte and others, 2005, 2008).

This report summarizes regional ground-water-quality issues in the NECRA, categorizes some spatial patterns in regional ground-water quality that have been reported from regional and local studies, and proposes a methodology or “framework” on how a multicontaminant assessment of aquifer vulnerability to contamination can be evaluated on a regional scale. Regional ground-water quality is described in terms of natural and anthropogenic contaminants because of environmental concerns about their presence and variation in contaminant sources (termed “source input”). The framework for comparison of water quality across the NECRA consists of a group of spatial variables related to aquifer properties, hydrogeologic conditions, and contaminant sources. The framework is designed to characterize this large aquifer into areas of similar hydrogeologic characteristics and contaminant sources; the framework will be used in a planned study (2008–2011) of the regional ground-water quality of the NECRA (Kelly L. Warner, U.S. Geological Survey, written commun., 2007).

This study of the NECRA is part of the NAWQA Program’s regional assessment of ground-water-quality conditions and trends (Lapham and others, 2005). These regional assessments are based on spatial analysis and temporal trends in principal aquifers, such as the NECRA, which encompass large regions of the country. Several NAWQA studies have been completed in the region, and those study units overlap all or parts of the NECRA. Previous NAWQA studies in order of decreasing land area within the NECRA include the New England Coastal Basin (NECB) study; Connecticut, Housatonic, and Thames River Basins (CONN) study; and Long Island-New Jersey Drainage Basins (LINJ) study. The NECB and CONN study units overlap almost entirely within the NECRA study area, whereas the LINJ study lies primarily outside. Sampled wells in the NECRA from these previous NAWQA studies are shown in figure 1. The sampled wells were domestic bedrock wells chosen randomly using a random spatial generator selection process (Scott, 1990) for the CONN and LINJ, and a filtered (based on bedrock type and lithochemistry) random selection process for the NECB.

The distribution of wells sampled in the LINJ (northern New Jersey) is clustered into a small area (fig. 1). For these reasons, the planned regional study of the NECRA (Kelly L. Warner, U.S. Geological Survey, written commun., 2007) will focus primarily on the New England part of the NECRA.

Physical Setting

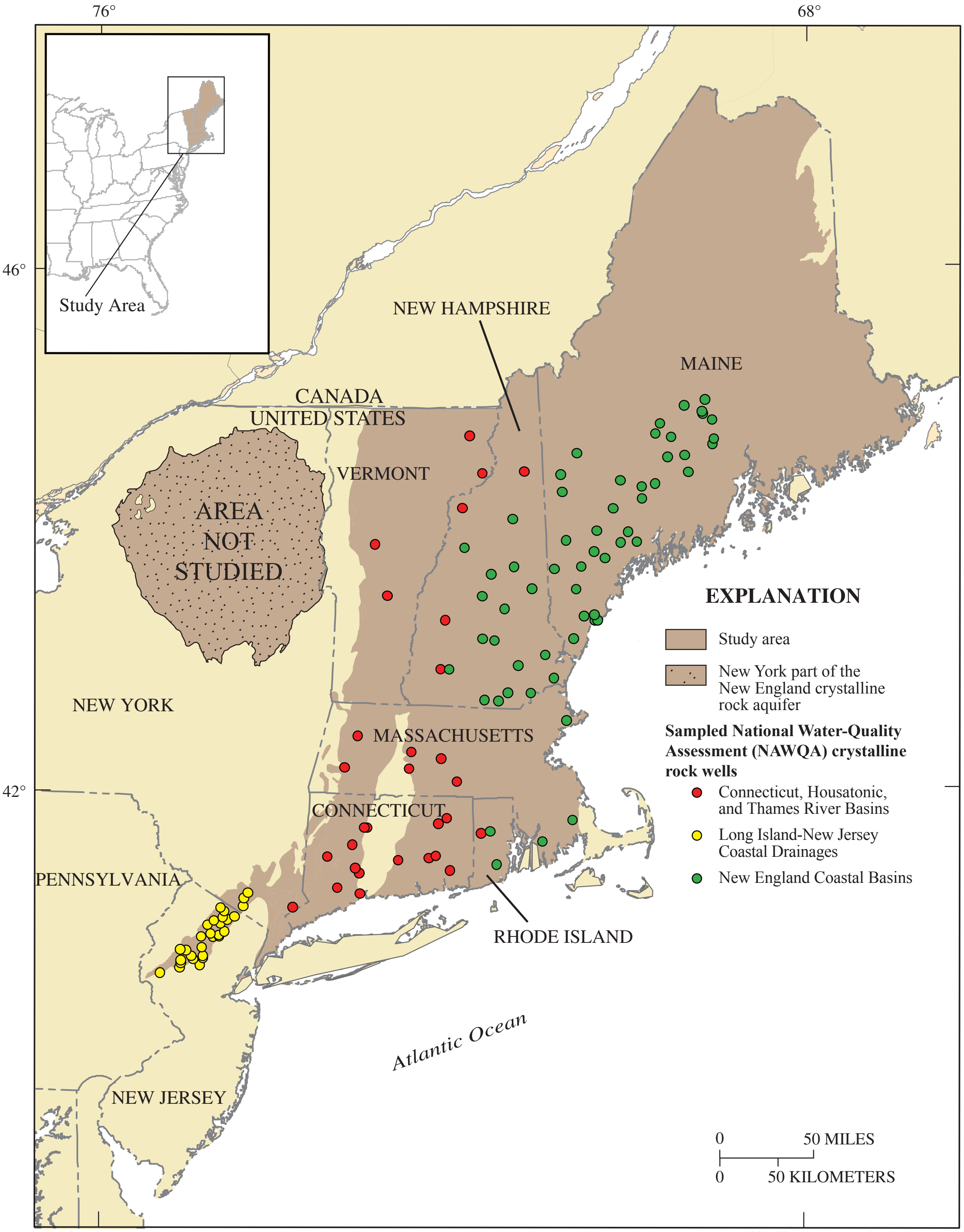
The NECRA underlie an area of approximately 72,000 mi^2. It includes small parts of northern New Jersey, a narrow band across southern New York, and the New England states of Connecticut, Massachusetts, Vermont, Rhode Island, New Hampshire, and Maine. For the most part, the aquifer is covered by glacial drift, and younger unconsolidated deposits and bedrock exposures are few and small. Overburden thickness can range from zero to more than 100 ft (Kontis and others, 2004). The entire aquifer is north of the Wisconsinan terminal moraine.

The terrain underlain by the NECRA has been divided by Fenneman (1938) from west to east into the Taconic Highlands, Green Mountains, New England Uplands, Seaboard Lowlands, and White Mountains (fig. 2). The largest peaks are in the White Mountains. Altitude of the terrain ranges from sea level to greater than 6,000 ft.

Land use ranges from urban to rural agricultural and forest, and it reflects population distribution and other cultural and physiographic features of the area (table 1). Population of the entire study area exceeds 15 million, and population density is greatest along the seacoast. Most urban centers are within the coastal high-population-density corridor (fig. 3). Agricultural areas make up 8.1 percent of the land area.

The study area can be divided into climatic regions based on proximity to the seacoast, orographic effects, and regional trends. Kontis and others (2004) show three climatic regions that trend northeast-southwest. Flanagan and others (1999) show a similar distribution of climatic regions that generally parallels the seacoast, based on data from the U.S. Department of Commerce (1977, 1982a, 1982b, 1982c) data. Mean annual air temperature ranges from 40 to 53°F (Kontis and others, 2004), with the coldest temperatures in the Adirondacks and northern Maine. Mean annual precipitation (1961–90) ranges from less than 34 to greater than 60 in/yr in high-relief areas of the Green Mountains, and White Mountains (fig. 2). Other high-precipitation areas include coastal areas of Connecticut and Maine.

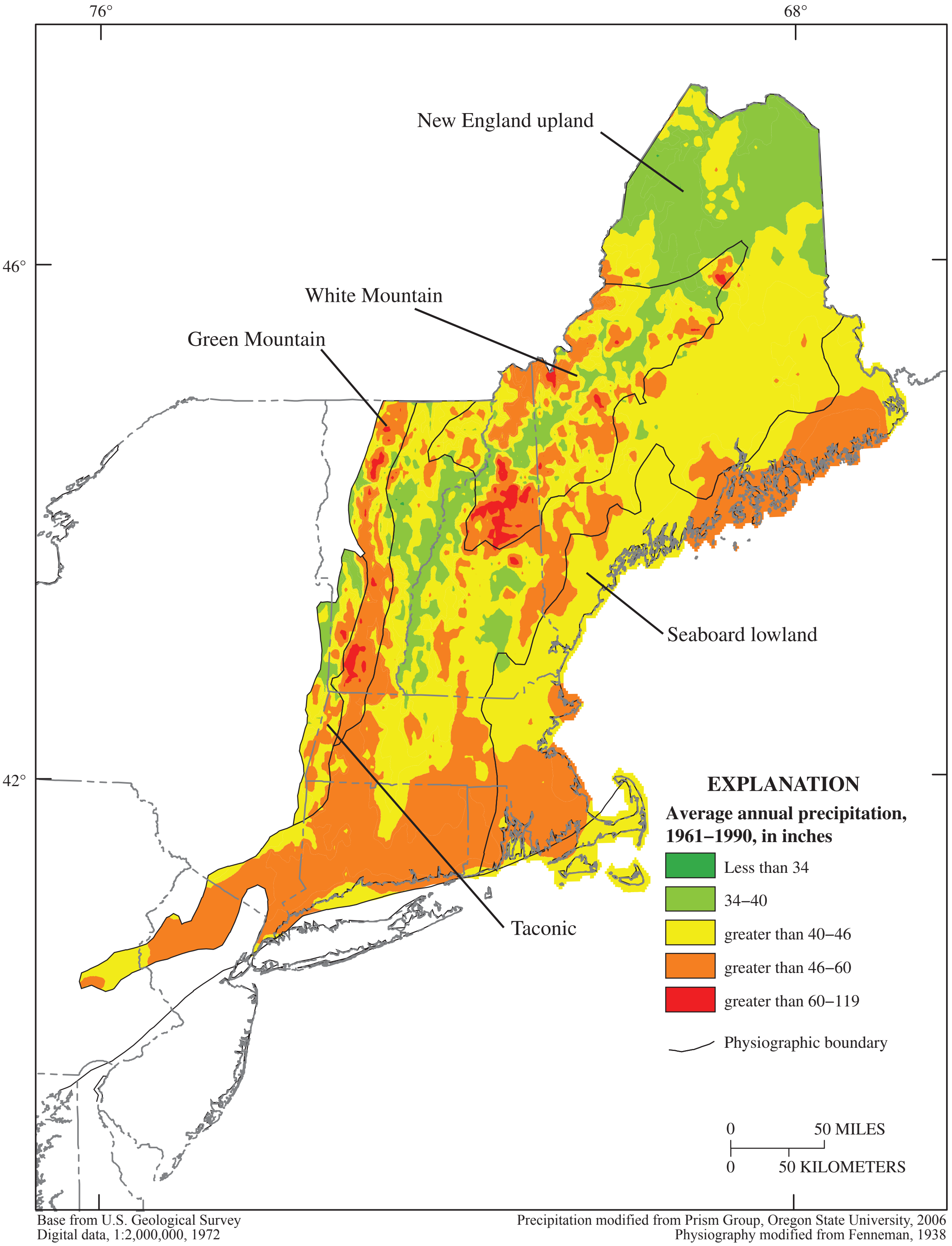
Mean annual runoff incorporates the effects of climate, precipitation, evapotranspiration, topography, soils, and other watershed characteristics (Kontis and others, 2004). A map of long-term mean annual runoff for the northeastern United



Base from U.S. Geological Survey
Digital data, 1:2,000,000, 1972

Modified from U.S. Geological Survey
Ground Water Atlas of the United States, 2000

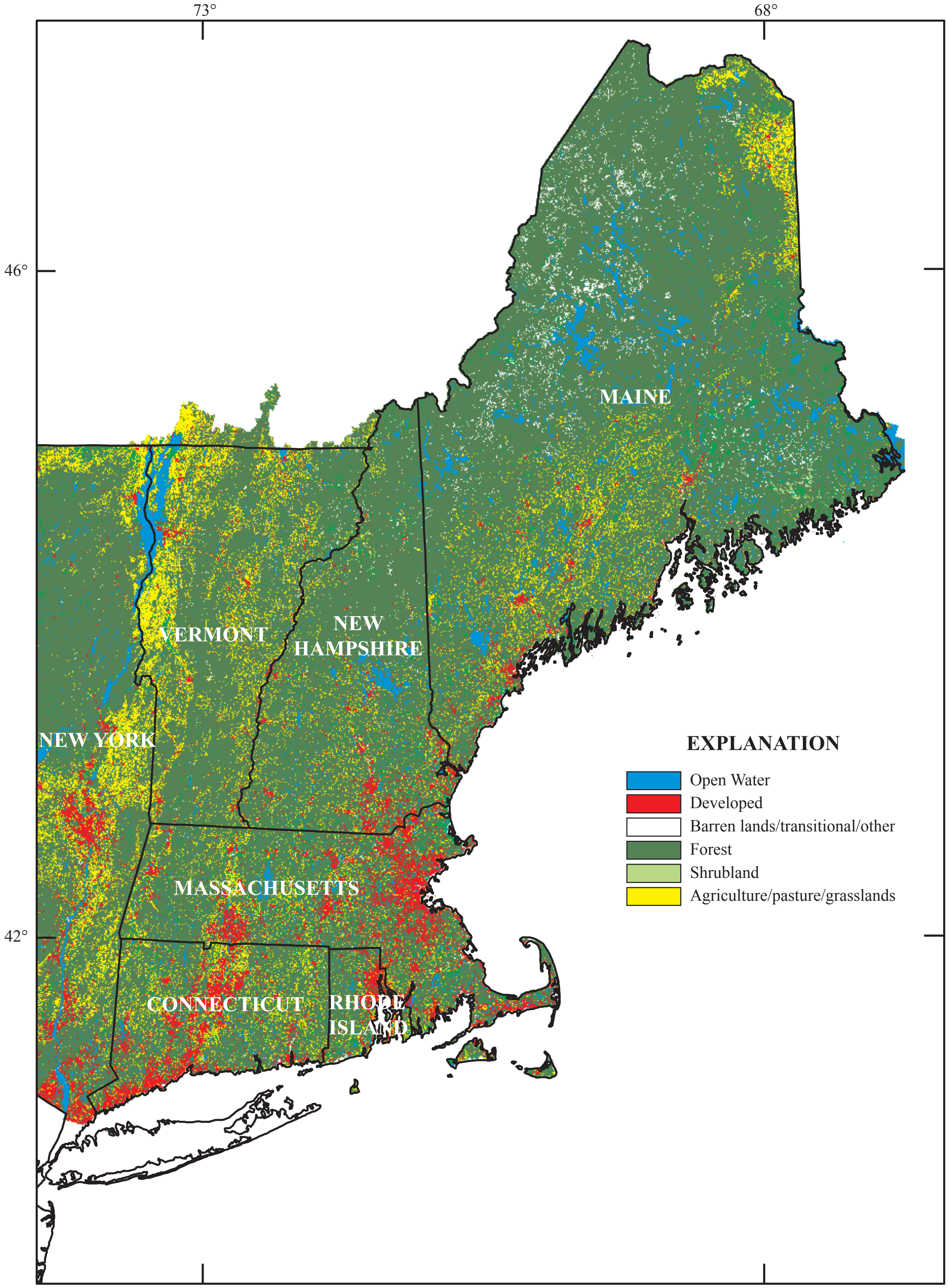
Figure 1. Location of the New England crystalline rock aquifers.



Base from U.S. Geological Survey
Digital data, 1:2,000,000, 1972

Precipitation modified from Prism Group, Oregon State University, 2006
Physiography modified from Fenneman, 1938

Figure 2. Long-term mean annual precipitation (1960–1991) and physiography for the northeastern United States.



Base from U.S. Geological Survey, 2006,
National Land Cover Dataset, 2001, digital data
accessed January 16, 2007, from http://www.mrlc.gov

From U.S. Geological Survey, 2006

Figure 3. Land use patterns in the New England area.

States is shown in Kontis and others (2004; fig. 2). High rates of runoff coincide with high topographic relief in areas of the Adirondacks, White Mountains, and northern Appalachians in Maine.

The NECRA are composed primarily of Proterozoic and Paleozoic igneous and metamorphic rocks (88 percent of the New England part of the aquifer). Major rock types also include variably deformed metasedimentary, metavolcanic, and plutonic rocks of various geologic ages and metamorphic grades (Robinson and Kapo, 2003). The most common crystalline igneous rocks are granite, rhyolite, diabase, pegmatite, and basalt (Sinnott, 1982). The most common metamorphic rocks are gneiss, schist, phyllite, slate, marble, quartzite, and argillite (Sinnott, 1982).

The NECRA are geologically complex with a structural fabric that generally trends northeast-southwest, perpendicular to the direction of collision during the Acadian Orogeny (Marvinney and Thompson, 2000). Lithologic and structural features of near-surface bedrock have been compiled from statewide maps of bedrock geology for Connecticut (Rogers, 1985), Maine (Osberg and others, 1985), Massachusetts (Zen and others, 1983), New Hampshire (Lyons and others, 1997), Rhode Island, (Hermes and others, 1994), and Vermont (Doll and others, 1961). The approximately 1,200 individual map units portrayed in these state bedrock-geology maps have been grouped into geologic provinces representing similar geologic setting and tectonic history (Robinson and Kapo, 2003). The province groups were defined with reference to lithostratigraphic explanations and correlation tables accompanying the state bedrock-geology maps (references above) and generally occur as north- to northeast-trending belts that follow the structural fabric of the Appalachian foldbelt and faults in New England (fig. 4). In the paragraphs that follow, the geologic-province categories are described in order of deformation or addition to North America (in the style of Cheney and Hepburn, 1993), generally from west to east across the New England States. These descriptions are based on information in Robinson and Kapo (2003).

The Grenville Belt province consists of Middle Proterozoic basement of the North American craton that was deformed and metamorphosed at high metamorphic grade during the Grenville orogeny approximately 1 billion years ago (fig. 4). Grenville Belt province rocks are exposed in areas of central Vermont, and western Massachusetts, and Connecticut. Some areas also were deformed, and retrograded, during younger orogenies.

The Eugeosynclinal Sequence province is mostly clastic and pelitic marine sedimentary rocks of Late Proterozoic to Ordovician age, including rift and arc volcanics and ultramafic blocks deposited in a continental slope or accretionary wedge setting. These rocks were deformed primarily during the Taconian and Acadian orogenies and are metamorphosed from low to high grade.

Table 1. Approximate land use distribution, by percent, in the New England crystalline rock aquifers.

Land-use distribution (percent)				
Agricultural	Urban developed	Forest	Surface water	Other
6.6	8.1	60.6	12.8	11.9

The Waits River-Gile Mountain province consists of metamorphosed clastic, calcareous, and semipelitic marine rocks, with lesser volcanics of Cambrian to Devonian age. These rocks were deformed and metamorphosed during the Acadian orogeny.

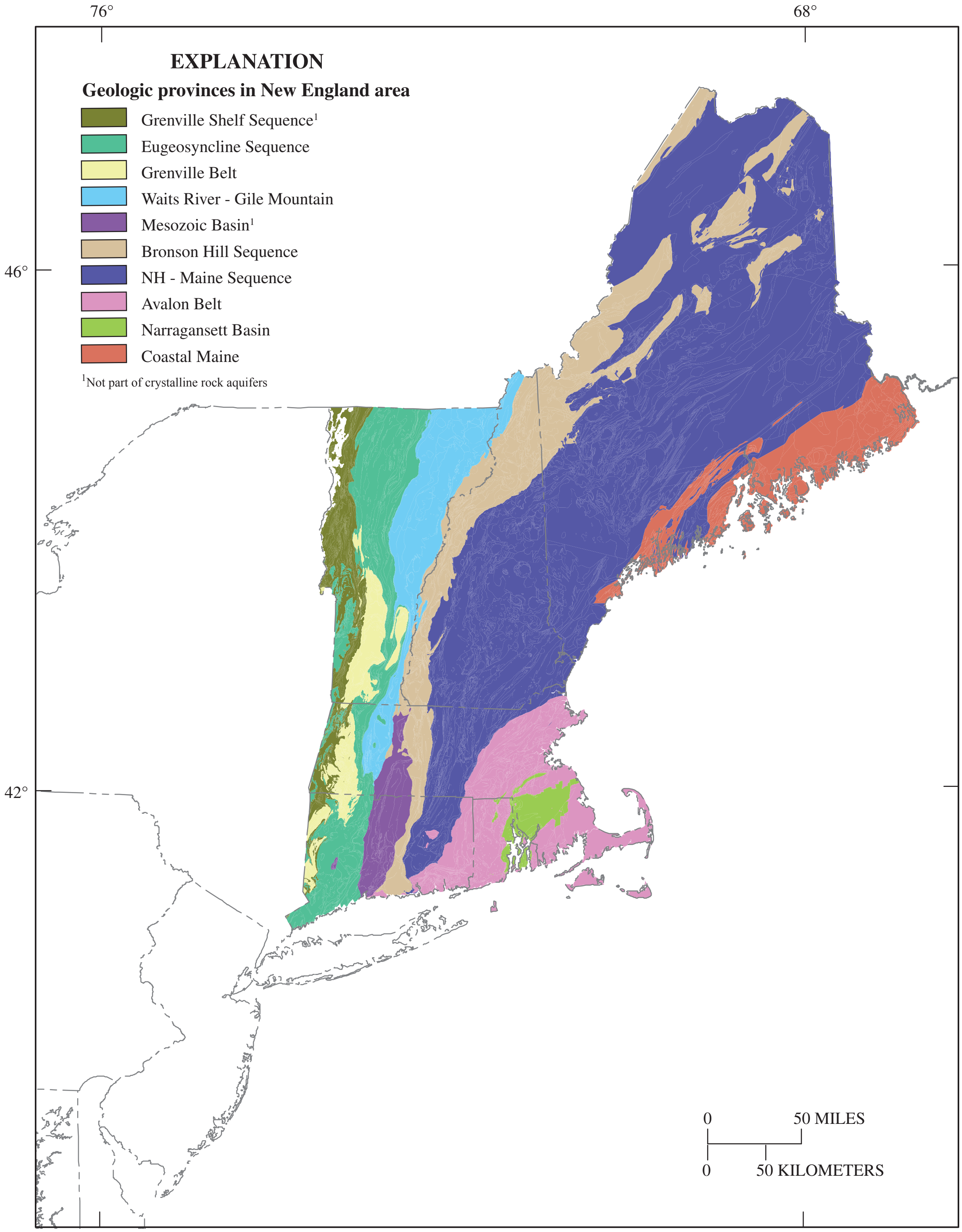
The Bronson Hill Sequence province consists of metamorphosed volcanic-island-arc rocks, associated marine sediments of Cambrian to Ordovician age, and exotic Proterozoic basement deformed by the Taconian and Acadian orogenies. Locally, deformation also occurred in Connecticut during the Alleghanian orogeny.

The New Hampshire-Central Maine Sequence includes metamorphosed marine sedimentary rocks and volcanics of Cambrian to Devonian age. These rocks were deformed primarily during the Acadian orogeny.

The Coastal Maine province consists of Late Proterozoic to Silurian-Devonian volcanic and marine sedimentary rocks. These rocks were deformed and attached to North America during the Acadian orogeny and during the Alleghanian orogeny.

The Avalon Belt province includes granite and associated volcanic rock of Late Proterozoic age overlain by clastic continental platform and marine rocks with a fossil assemblage similar to West Africa. This province was deformed during the Alleghanian orogeny

The Narragansett Basin contains coarse to fine clastic sedimentary rocks deposited in basins that formed after attachment of the Avalon Belt province to North America. The basins were created, filled, and deformed during a transgressional phase of the Alleghanian orogeny. The rocks range from low to high metamorphic grade.



Base from U.S. Geological Survey
Digital data, 1:2,000,000, 1972

From Robinson and Kapo, 2003

Figure 4. Geologic provinces in the New England crystalline rock aquifers.

Geohydrology

Flow of water through the crystalline rocks is dependent on the presence of secondary openings. Spaces between the individual mineral crystals (primary openings) of the crystalline rocks are few, microscopically small, and generally unconnected. Consequently, the intergranular porosity of crystalline rocks is small, usually about 1 to 2 percent (Wood and others, 2004). Nonfractured sections of crystalline rocks have low hydraulic conductivity ranging from 0.000003 to 0.0001 ft/d (U.S. Geological Survey, 2003). For almost all wells completed in crystalline rocks, water reaches the wells through secondary openings other than intergranular pore spaces. Virtually all bulk movement of water in crystalline rocks is through fractures or joints in the rocks.

Fractures form in crystalline rocks as a result of the cooling and deformation of igneous and metamorphic rocks, faulting, jointing, and weathering. Openings commonly are present along relict bedding planes, cleavage planes, foliation, and other zones of weakness in the rocks; these openings typically are heterogeneous in spacing, orientation, size, and degree of interconnection. Generally, openings in the rocks are most prevalent near land surface and decrease in number and size with depth. Thus, wells in New England commonly are not drilled past depths of 300 to 600 ft but some deeper wells have intersected deep water-yielding fractures. In a study evaluating bedrock yields in Massachusetts, bedrock yield was found to decrease with depth in the upper 400 ft but some larger yields (median value greater than 20 gal/min) were found at depths greater than 400 ft (Hansen and Simcox, 1994). Deep wells (greater than 300 ft) installed in crystalline rock of the Blue Ridge Mountains adjacent to deep thrust faults have yielded several hundred gallons per minute of ground water (Seaton and Burbey, 2005).

The types of fractures in crystalline rock of the study area are similar to fractures in other geologic settings, in that highly permeable zones of subhorizontal fractures are embedded within a network of less permeable fractures (Shapiro, 2003). This highly variable pattern can be viewed as scale-dependent, where permeability variations decrease with increasing scale from the well field to watershed size.

Ground water in the upper 600 ft of crystalline rocks is recharged from precipitation through the fracture system either directly at outcrop areas or indirectly through overlying glacial deposits (Harte, 1992). Recharge occurs primarily in the uplands (Harte, 1992); the water moves down a hydraulic gradient to stream valleys where it discharges either to the valley fill or to streams or other surface-water bodies, except where intercepted by ground-water withdrawals from wells. The rate of recharge to crystalline rock aquifers in the Mirror Lake area of New Hampshire was estimated to be 1–4 in/yr (Harte 1992; Tiedeman and others, 1998). Higher rates of recharge are possible in areas underlain by more fractured, permeable rock and where rates of ground-water withdrawals are high (exceeding 100 gal/min) (T.J. Mack, U.S. Geological Survey, oral commun., 2007).

Although the crystalline rocks transmit water, the volume of water stored in the fracture system of these rocks generally is small, and drawdown is large in some pumped wells that produce only small quantities (less than 10 gal/min) of water. Water that is stored in overlying glacial deposits or water in nearby streams or other surface-water bodies, however, commonly is hydraulically connected with the bedrock fracture system. This surficial water can provide large quantities of water as recharge to crystalline rock from inducement during pumping of wells completed in the crystalline rocks.

A summary of well characteristics for crystalline rock in New England as of 1985 is given in table 2. The typical range of well yields is less than 5 gal/min, but yields from some wells may exceed 500 gal/min. Recent trends (1994–2005) suggest wells have been drilled progressively deeper over time (Brandon Kernen, New Hampshire Department of Environmental Services, written commun., 2007).

In a study of bedrock wells in Massachusetts (Hansen and Simcox, 1994), a strong relation was found between well yields and topographic position. The median yield from wells in valleys and lowlands exceeded yields from hillside and hilltops by 25 to 100 percent. Furthermore, within valleys and lowlands, yields increased with increasing overburden thickness. In a study of well yields in central Vermont, well yields were highest in certain bedrock formations in lowlands (Kim and others, 2006). Similarly, bedrock type and topographic position explained 34 and 31 percent of observed variation in transmissivity, respectively, in Maine (Mabee, 1999). Mabee (1999) further identified the importance of regional geologic setting in controlling ground-water yield and suggested that bedrock type and topography may be more important attributes in controlling yield in the crystalline rock aquifers of New England than unglaciated areas underlain by crystalline rock in Maryland, and sedimentary rocks in Pennsylvania.

Table 2. Summary of well characteristics in crystalline rock aquifers in New England, by State.

[From U.S. Geological Survey, 1985; ft, feet; gal/min, gallons per minute; --, no information]

State	Well characteristics			
	Depth (ft)		Yield (gal/min)	
	Common range	May exceed	Common range	May exceed
Connecticut	100–300	500	1–25	200
Maine	20–800	--	2–10	500
Massachusetts	100–400	1,000	1–20	300
New Hampshire	100–600	800	1–10	100
Rhode Island	100–300	500	1–20	50
Vermont	100–600	800	1–10	100

A multidisciplinary geologic framework approach was used to evaluate ground-water yields in watersheds surrounding the southern Worcester Mountains in central Vermont (Kim and others, 2006). The Worcester Mountains are a north-northeast trending, south-plunging anticlinorial ridge with a core of resistant schist; this lithology forms the steepest slopes. The flanks and surrounding valleys are composed of generally less resistant amphibolites, phyllites, and granofels. Kim and others (2006) evaluated the relations between well yields and (l) lithologic and surficial units, (2) proximity to topographic lineaments, (3) surficial material thickness and permeability, (4) proximity to surface-water sources, (5) major bedrock structures, (6) slope and other topographic indices, and (7) drainage area. The two most significant variables that were found to correlate with well yield were bedrock lithology and topography.

In a regional study on bedrock well yield in New Hampshire, more than 400 explanatory variables were examined with respect to the natural log of the reported well yield[1] by means of multivariate regression (Moore and others, 2002a, b). Results indicate that well yield is generally lower in wells on steep hill slopes and hilltops and at a greater distance from surface-water bodies. Yields were found to be greater in wells in valleys, at sites with large upgradient topographic drainage areas, and within 100 ft of some types of mapped lineaments. Well yields also correlated with 29 mapped geologic units from the New Hampshire State Geologic Map (Lyons and others, 1997).

Identification of Regional Water-Quality Issues

Limited information is available on regional ground-water-quality patterns relative to hydrogeologic or land-use features other than summaries of ground-water constituent concentrations by major geologic unit (bedrock and unconsolidated), and geography (watershed and land use). Therefore, spatial trends for many regional water-quality constituents have not been identified.

Appendix 1 is a summary of contaminants as reported by State agencies in the New England area. This information was generated from reports (section 305(b) and section 303(d)) submitted by the States to the U.S. Environmental Protection Agency as required in the Clean Water Act. Ground-water-quality information largely is derived from water-quality tests by regulated community and non-transient public-water-supply systems that serve more than 25 people. The source of the water samples may be from a variety of measurement locations (for example, near the well or from the distribution system) and treatment options (treated and untreated water samples). Other regional water quality issues may be unreported and not reflected in the (section 305(b) and section 303(d)) reports. Thus, these data should be viewed only as a screening tool for identification of potential regional water-quality issues.

Natural contaminants, such as radon and heavy metals from minerals in the rock, were reported to have generally low concentrations in ground water in Rhode Island http://www.dem.ri.gov/pubs/305b/four.pdf and Vermont (Vermont Department of Environmental Conservation, 2004). In other states, little information exists on natural-contaminant occurrence as reported by State agencies. In New Hampshire, bedrock water quality is affected by high concentrations (above regulated limits) of fluoride, arsenic, and radioactive elements (appendix 1).

Anthropogenic contaminants such as bacteria, some volatile organic compounds (VOCs), and road deicers were detected in public-supply wells and monitoring networks in several states (appendix 1). Bacterial contamination in the form of total coliforms and *Escherichia coli* has been a particular problem in Vermont. Human and animal wastes are a primary source of bacteria in water and originate from feedlots, pastures, dog runs, urban and suburban yards, and other land areas where domestic-animal wastes are deposited, as well as forested and agricultural-edge areas where wild-animal wastes are deposited. Additional sources include seepage or discharge from septic tanks, sewage-treatment facilities, and natural soil/plant bacteria. Bacteria from these sources can enter wells that are open at the land surface or do not have watertight casings or well caps http://www.water-research.net/bacteria.htm. Of the VOCs measured, MTBE was the most commonly detected in several states (appendix 1). Several states had no information on road-deicer-related chloride concentrations in ground water; where they were reported, as in Maine and Rhode Island, high sodium (greater than 100 mg/L) and (or) chloride (greater than 250 mg/L) concentrations were found in approximately 10 percent of public-supply wells (appendix 1).

A compilation of regional water-quality issues reported from the NAWQA study units (NECB, CONN, and LINJ) is provided in table 3 from sampled wells shown in figure 1. Water samples were analyzed for major ions, trace elements, pesticides, and VOCs. No biological (bacteria) analyses were done. VOCs were the most frequently detected anthropogenic class of contaminants whereas radon and arsenic were the most frequently detected natural contaminant as reported by NAWQA study units (table 3). High radon concentrations above the proposed MCL of 300 pCi/L (U.S. Environmental Protection Agency, 2006) were prevalent in samples from the NECB and CONN study units, indicating widespread detection of high radon in New England (Ayotte and others, 2007).

In crystalline rock aquifers in northern Europe (Norway and United Kingdom), natural contaminants with high concentrations include radon, fluoride, sodium, uranium, barium, iron, and manganese (Banks and others, 1998; Banks and Robins, 2002). The hydrogeologic environment in northern Europe is similar to that of New England, and northern European studies on regional water quality may provide insight into potential issues in New England. A Finnish study found

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[1] Although reported well yields from installation reports can provide an exaggerated well yield estimate because nonequilibrium conditions and borehole depletion are unaccounted for during testing, some general relations can be discerned from the large number of reported tests.

Table 3. Summary of regional ground-water quality issues in the New England crystalline rock aquifers as reported by previous NAWQA studies.

[Wells shown in figure 1. VOCs, volatile organic compounds; MCLs, Maximum Contaminant Levels; USEPA, U.S. Environmental Protection Agency; pCi/L, picocuries per liter; mg/L, milligrams per liter; MTBE, methyl *tert*-butyl ether; μg/L, micrograms per liter]

NAWQA study unit name	States in study unit	Study unit abbreviation/source of information	Number and type of crystalline bedrock wells sampled	Water-quality constituents sampled	Anthropogenic contaminants detected	Natural contaminants detected
New England Coastal Basins	ME, MA, NH, RI	NECB/Flanagan and others (1999); Robinson and others (2004); Coakley and others (1999, 2000)	58; domestic water-supply wells	Major ions, nutrients, trace elements, pesticides, VOCs, ground-water age	VOCs detected in 30 percent of water samples but all at concentrations below USEPA MCLs.	Radon concentrations exceeded 300 pCi/L in 98 percent of water samples. Arsenic concentrations exceeded USEPA MCL of 10 μg/L in 17 percent of water samples. Lead concentrations detected in 30 percent of water samples but all concentrations below USEPA MCL of 15 μg/L. Fluoride concentrations highest in this study unit but only 2 out of 58 samples above USEPA MCL of 4 mg/L.
Connecticut, Housatonic, and Thames River Basins	CT, MA, NH, NY, RI, VT	CONN/Grady (1997)	30; domestic water-supply wells	Major ions, nutrients, selected trace elements (radon, uranium, and arsenic only), pesticides, VOCs	VOCs detected in 30 percent of water samples but all at concentrations below USEPA MCLs.	Radon concentrations exceeded the proposed USEPA MCL of 300 pCi/L in 97 percent of water samples. Arsenic concentrations exceeded USEPA MCL of 10 μg/L in 10 percent of water samples.
Long Island-New Jersey Coastal Drainages	NJ, NY	LINJ/Ayers and others (2000)	30; domestic water-supply wells	Major ions, nutrients, trace elements, pesticides, VOCs	VOCs and pesticides detected more frequently in this study unit than NECB and CONN but concentrations generally below USEPA MCLs. Highest MTBE concentration of 30 μg/L found in this study unit. Nitrate concentrations all below USEPA MCL of 10 μg/L but concentrations generally higher in this study unit than NECB and CONN study units.	Radon, arsenic, and lead contaminant concentrations lower in this study unit than in the NECB and CONN study units.

a strong correlation (Spearman's rho = 0.74, $p < 0.0001$) between ^{222}radon and ^{210}lead in wells completed in crystalline aquifers (Vesterbacka, 2005; Vesterbacka and others, 2005). A similar contaminant relation between ^{222}radon and total lead (rho = 0.52, $p = 0.004$) was identified in domestic well samples from the granitic and metamorphic crystalline aquifers of the NECB study unit (fig. 1) in eastern New England (Ayotte and others, 2007).

Factors Affecting Water Quality

Factors and representative variables affecting water quality can be divided into two basic categories: physical and chemical. The division is arbitrary because physical and chemical processes are interdependent. For example, chemical reactions in ground water along fracture faces are partly a function of the reaction time of the ground water and the structure of the rock, which in turn are dependent on the physical characteristics of the rock, secondary fracture distribution, connectivity, aperture size, and the ground-water-flow field. The initial chemistry of the ground water may be related to the source of water; that is, whether it is recharged from overlying sediments, distant sources, or the atmosphere.

In a study of bedrock yield and ground-water quality in Maine, Mabee (1992) found that ground-water-flow processes in the bedrock affected ground-water quality. Ground-water quality correlated with bedrock type, topographic position, structural position relative to folds and faults, and the presence, thickness, and type of overlying unconsolidated deposits. For a constituent such as fluoride, for example, concentrations more highly correlated with the type and thickness of overlying unconsolidated deposits than with bedrock type suggest that ground-water recharge and the chemical quality of recharge water is an important explanatory variable.

Physical Processes

The small amount of storage and relatively high velocity (compared to porous media) of ground-water flow through fractures in crystalline rock may promote variable and potentially degraded ground-water quality. Therefore, the intrinsic susceptibility of the crystalline rock can be a major factor in occurrence of natural and anthropogenic contamination.

One example of degraded water quality because of low storage and high ground-water velocities is illustrated by a study of induced recharge caused by withdrawal of ground water in underlying fractured crystalline rock of a forested catchment area in Sweden. In this study, the induced recharge negatively effected ground-water quality in the crystalline rock by increasing vertical transport of shallow oxidized recharge water to the bedrock (Mossmark and others, 2007). The oxidized water altered the chemistry of the ground water in the crystalline rock. The withdrawals also caused increases in dissolved organic carbon and sulfate, thus, lowering the pH of the ground water. As a result, cations such as calcium, which were bound to bedrock fractures, became soluble in ground water.

Apparent residence times of ground water in fractured crystalline rock measured by age-dating tracers can vary due to mixing of ground water from different sources and, as noted above, the susceptibility to mixing is high given the low storage capacity and high velocity of flow in fractures. For example, in a study of fractured crystalline rock aquifers in Virginia, apparent residence times determined from environmental tracers (chloroflourocarbons (CFCs), tritium and tritium/helium, and sulfur hexafluoride (SF_6)) in ground-water samples collected in bedrock wells showed a high percentage of young waters (less than 5 years old) and high likelihood of a binary sample from mixing of young and old waters (Nelms and others, 2003). Further, the heterogeneous nature of fracture distributions and velocity fields results in a seemingly spatially random distribution of residence times. Nelms and others (2003) found that residence times of waters from crystalline rock did not correlate with total well depth.

CFC analysis and subsequent age-dating of ground-water samples collected in 58 domestic rock wells from crystalline rock aquifers as part of the NECB NAWQA study also showed no correlation with total well depth. The lack of correlation (Spearman correlation rho of 0.154) between total depth and apparent residence time is partly a function of several factors including (1) well-construction techniques in crystalline rock, (2) number of water-bearing fractures intersected by the borehole, (3) mixing of ground water outside of and inside of the borehole, (4) fracture connectivity of individual fractures, and (5) sampling method. For example, in domestic wells, which are actively withdrawing water, the ground-water sample represents an integrated water sample from the entire well borehole. The integrated water sample is derived from the flux-averaged contribution of the water-bearing capability of the individual fractures intersecting the well borehole (Shapiro, 2002).

Drilled wells in crystalline rock are generally constructed of long (median depth approximately 300 ft) open boreholes. In some cases, wells are drilled to a depth where enough fractures yielding sufficient supply are encountered. In other cases, wells may be drilled deeper to increase borehole storage. Even when a single fracture is intercepted by a well, variability in residence times can be large within a single fracture given that transport is controlled by fracture connectivity (intersection of other fractures with the single fracture). In some cases, mixing within a single fracture may exceed mixing in the borehole from multiple fractures if the fracture connectivity of the individual fracture is high. Cook and others (2005) conclude that residence times in low grade metamorphic fractured crystalline rock of Australia are controlled by the type and number of horizontal fractures intersecting the well borehole and the vertical connectivity of each horizontal fracture. Whereas the low grade metamorphic crystalline rock are characterized by planar fractures, which may not be applicable to the high grade metamorphic rock of New England, the conceptual analogy could be valid for the NECRA.

A schematic diagram (fig. 5) illustrates the potential variability of residence time of ground water in crystalline rock from fracture patterns relative to depth-to-bottom of the well and length of open borehole. Two hypothetical end members are shown, the first from a relatively short open borehole (shallow depth) that is intersected by multiple horizontal fractures with little vertical connectivity (fig. 5A). The second from a long open borehole (deep well) that is intersected by few but vertically well-connected fractures (fig. 5B). The residence time and chemistry of ground water from these two end members can be quite different given the fracture distribution. The shallow well depicted (fig. 5A) can have residence times older than the deep well (fig. 5B) because the travel time within the horizontal fractures are greater than the travel times from the fractures connected vertically in the deep well. Associated with these fracture patterns are chemical differences in the ground water. If travel and reaction time are assumed equal, the shallow well depicted will have chemically more mature water than the deep well.

Although overall patterns in residence time of ground water are not readily discernible as a function of well depth, residence times correlate with variables that indirectly measure gross transport properties and infer residence time. For example, Ayotte and others (2003) found a positive correlation (Spearman correlation rho of 0.71) between pH and age of recharge water (fig. 6A). The pH of ground water in crystalline rock was hypothesized to be a surrogate for residence time because one of the primary factors affecting pH, in addition to the amount of carbonate minerals, is hydrolysis of silicate minerals in crystalline rock. This reaction, which increases pH, is a slow reaction so higher pH tends to indicate older ground water. The concentration of dissolved oxygen (D.O.) also was inversely correlated (Spearman correlation rho of -0.71) with apparent age (fig. 6B). The high D.O. concentrations in some crystalline rock aquifer ground-water samples suggest the possibility of relatively rapid recharge from overlying sources as the reason for young ground water. In contrast, high concentrations of arsenic are not directly related to the apparent residence time of the water (fig. 6C) (Ayotte and others, 2003). The relation of pH and dissolved oxygen to apparent ground water age is largely expected because these parameters are expected to be a function of ground water residence time. Thus, any mixing of waters of different ages is ultimately represented by the integrated water sample values for pH and dissolved oxygen.

The pH and dissolved oxygen of ground water is a good indicator of apparent ground-water age partly because of the ubiquitous nature of source inputs for these parameters in the NECRA. The inputs (dissolved oxygen and pH of recharge water) and processes affecting dissolved oxygen and pH are fairly uniform throughout the NECRA. While calcite concentrations may vary in certain rock types (Robinson and Kapo, 2003), which will affect pH, the variability of calcite overall in the NECRA is small compared to the variability of trace elements such as arsenic.

Source input variability of arsenic or other similar trace element contaminants is high within the NECRA, thus their concentration is a poor indicator of apparent residence time (fig. 6C). For example, if arsenic in a well water sample from a deep well enters the well at some shallow depth, representing only a small fraction of the water entering the well, the concentration may not relate to the apparent age of the sample. Alternatively, if the source of arsenic in solution is desorption from iron oxides on the aquifer materials, there may be a threshold residence time that is coincident with iron reducing conditions and high arsenic concentrations. Further decreases in redox state, if associated with residence time, may not be related to further increases in arsenic concentration. Further, solute concentrations produced by a fracture source may vary due to the amount of arsenic available for desorption, irrespective of apparent residence time.

Occurrence of anthropogenic contaminants in ground water in crystalline rock is affected by the physical processes of vertical flow, recharge, dilution, and reactive and nonreactive chemical transport. Anthropogenic contaminants are often closely related to land use and recharge waters because these contaminants require external source inputs to the aquifer and include VOCs, such as MTBE and chloroform; road-deicing chemicals; pesticides; and nitrate (Gilliom and others, 2007; Zogorski and others, 2006; Ayotte and others, 2008).

MTBE concentrations in samples from private bedrock wells in New Hampshire and Maine have been related to several urban factors including population density, housing density, and the percentages of urban land use and roads within 1,640 ft (500 m) of the well (State of Maine, 1998; Ayotte and others, 2004). MTBE concentrations, for example, declined with increasing distance from underground gasoline storage tanks. In addition, MTBE concentrations were related to the specific conductance of the water sample. Because specific conductance may increase in response to chloride from road deicers and septic systems, it also is an indicator of urbanization. MTBE concentrations were significantly higher in water samples that were more acidic (lower pH). The implication is that recently recharged (low pH) ground water is more directly connected to the land surface and, thus, to sources of MTBE. Conversely, ground water with high pH may be relatively old and, in some cases, could predate the introduction of MTBE into the local ground-water system (Ayotte and others, 2004).

MTBE concentrations positively correlated with increasing depth of wells (Ayotte and others, 2004). Given drilling practices in the bedrock, deep wells in some cases indicate insufficient or low yield because long open holes are required to provide adequate storage for water supply. Consequently, deep wells are generally low yielding, and the high occurrence rates and concentrations of MTBE in deep wells could result from several processes. For example, in low-yield wells, a major proportion of the water and MTBE contamination may be derived from leakage of shallow ground water, either through fractures near the bedrock surface or along the well casing, because insufficient yield is provided in

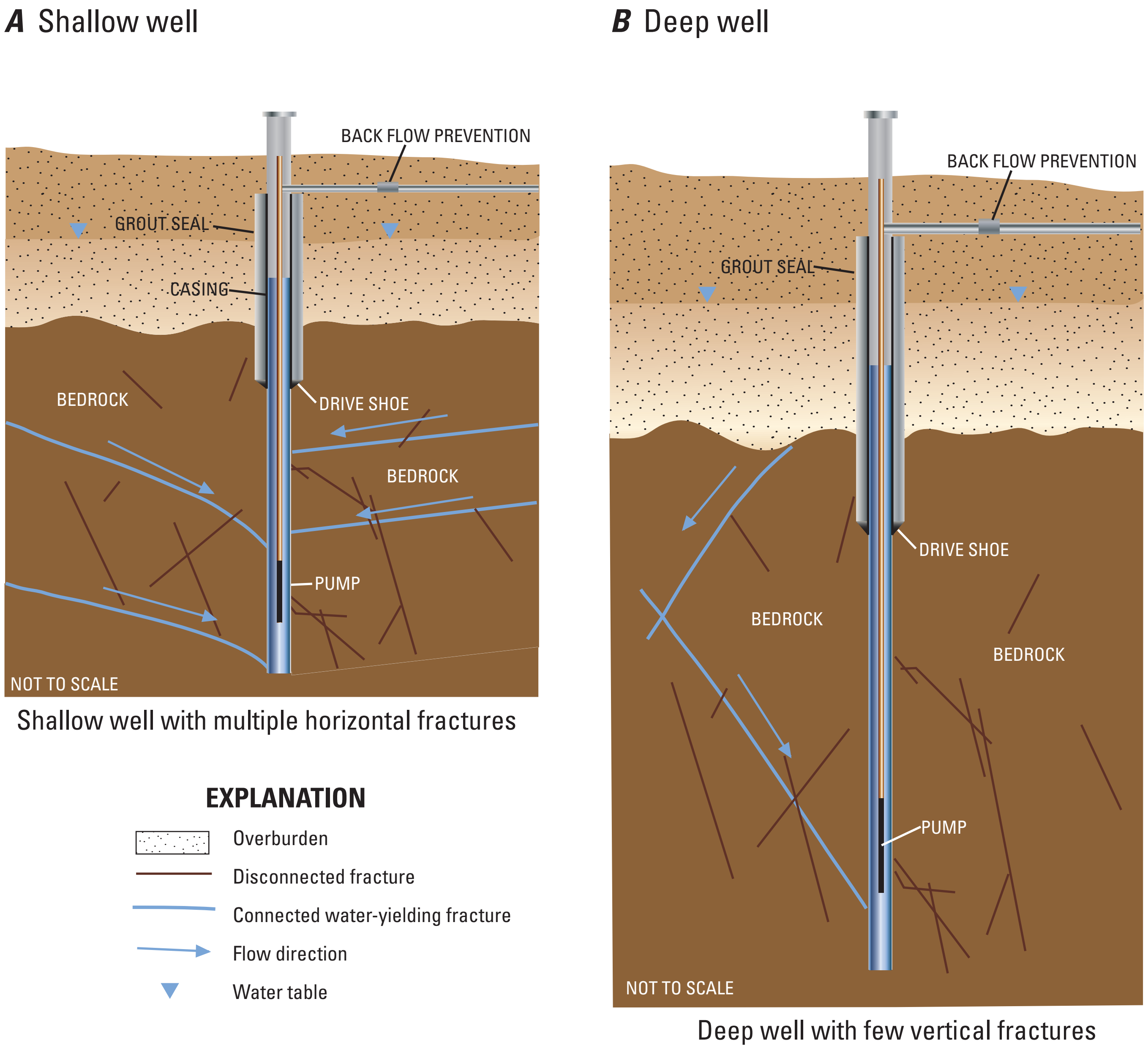


Figure 5. Hypothetical depth of well and fracture patterns in *(A)* shallow wells and *(B)* deep wells in the New England crystalline rock aquifers.

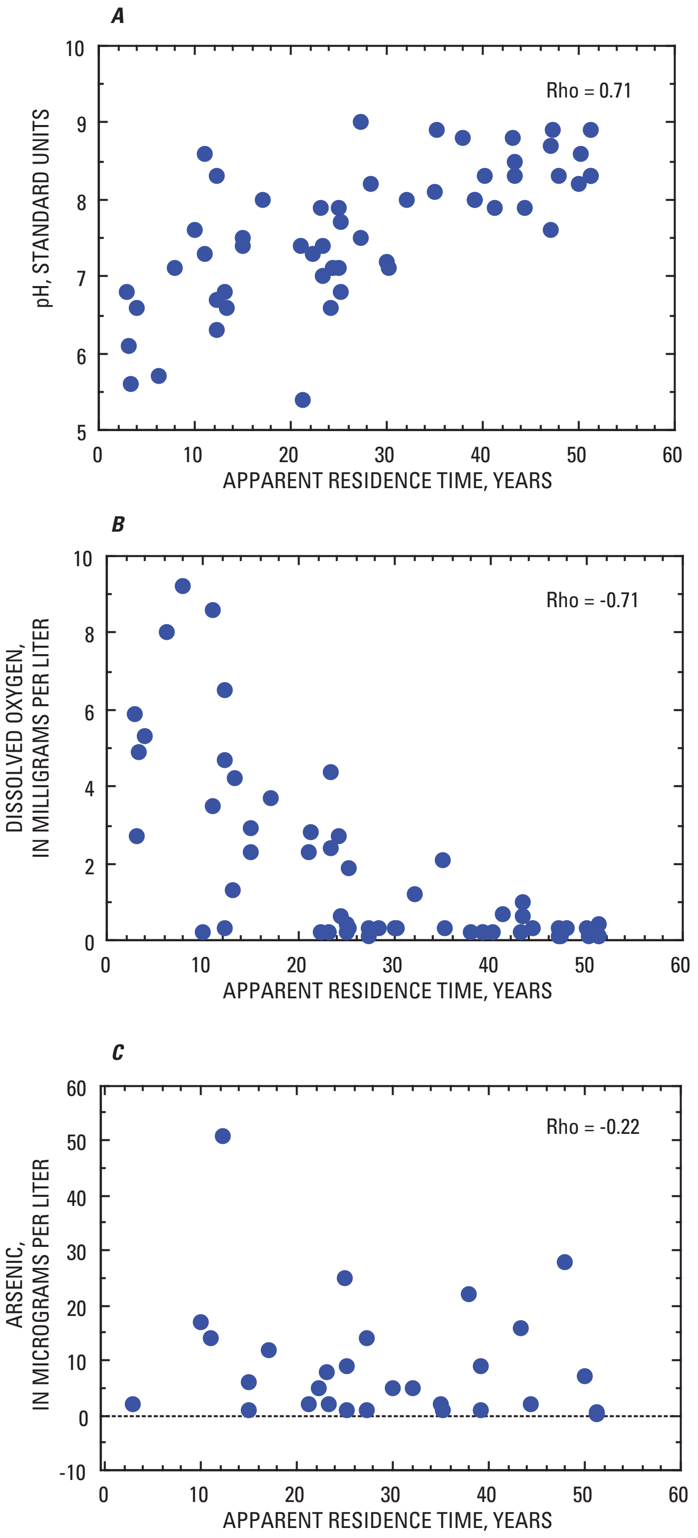


Figure 6. Relation between residence time and *(A)* pH, *(B)* dissolved oxygen, and *(C)* arsenic from crystalline rock ground water of the New England Coastal Basins. (From data presented by Ayotte and others, 2003)

the deeper bedrock. Alternatively, low-yield wells with little or no surface leakage may be less affected by dilution. Einarson and Mackay (2001) indicate that contaminant concentrations in wells under constant pumping decrease with increasing pumping rate because the ratio of clean water to contaminated water increases. Thus, for deep, low-yield bedrock wells, MTBE that enters the well is less likely to be diluted than in high-yield wells.

The relation between vertical fracture patterns in the bedrock and the geohydrologic characteristics of the overburden is an important factor in crystalline-rock yield and ground-water quality. Lyford and Walsh (2004) showed that high-angle vertical fracturing facilitated vertical flow from the overburden and that this condition enhanced well yield from crystalline rock at several sites in Massachusetts where overburden was thick. In addition to yield, increased vertical flow can enhance vertical transport. Contiguous vertical fractures have been shown to facilitate nitrate transport (Taylor and others, 2001) in crystalline rock. For example, nitrate concentrations in ground-water samples from vertical fractures intersecting the Metrowest Water Supply Tunnel in Boston were highest in areas underlying a pond, suggesting vertical recharge from the pond and transport of nitrate.

Chemical Processes

Bedrock lithology and the chemistry and mineralogy of the host rock material are important factors in bedrock water quality. For example, regional assessments of arsenic concentrations in crystalline rock of New England have identified lithology as an important explanatory variable in predicting arsenic concentrations (Ayotte and others, 2006). High arsenic concentrations have been associated with a lithostratigraphic belt of calcareous metasedimentary rocks (Ayotte and others, 1999). These rocks contain higher arsenic concentrations (median value >1 mg/kg) in whole-rock samples than some other rock types in the region (Robinson and Ayotte, 2006). Felsic volcanic rocks and sulfidic metamorphic rock types sampled by Robinson and Ayotte (2006) also had elevated whole-rock arsenic concentrations.

The solubility and mobility of chemicals in source parent material depend on geochemical conditions (pH, redox, and activity coefficient) and transport mechanisms. For example, arsenic concentrations in ground water in the crystalline rock tend to correlate with certain pH, Eh, and dissolved oxygen levels. High arsenic concentrations (>10 µg/L) generally corresponded to high pH (7.0–8.5) in ground-water samples from crystalline rock of New England (Ayotte and others, 2003). Furthermore, high arsenic concentrations were associated with low dissolved oxygen concentrations (<1 mg/L). Aqueous arsenic in ground water exists primarily as the oxyanions arsenate (AS^{5+}) and arsenite (AS^{3+}). Arsenate predominates in oxic waters whereas arsenite is in sulfidic and methanic waters (Welch and others, 2000). Arsenic desorbs from iron hydroxyoxides and some clays at high pH; thus, desorption may be an important mechanism leading to elevated arsenic concentrations in ground water (Welch and others, 2000). Arsenic associated with sulfide minerals in rock can be released by the weathering effects of oxygen-rich environments, whereas arsenic bound to iron oxides can be released by iron-reducing bacteria in low-oxygen conditions.

In addition to geochemical conditions, dissolved organic carbon can affect arsenic concentrations because of its control on redox state. Landfill leachate with low dissolved-oxygen concentrations (<1 mg/L) has been shown to facilitate reductive dissolution of hydrous ferric oxides and associated arsenic (Stollenwerk and Colman, 2004).

Microbial conditions can indirectly and directly affect arsenic concentrations. Available dissolved oxygen will enhance microbial activity, resulting in lowering redox potential and subsequent release of arsenate via reductive dissolution. During microbial arsenate respiration, arsenate is reduced to arsenite by arsenate reductase (Oremland and Stolz, 2003).

Whereas bulk movement of ground water relies on flow through secondary openings, ground-water chemistry can be affected by interaction of water with the rock matrix through rock-matrix diffusion. Matrix diffusion was hypothesized to affect ^{222}radon concentrations in crystalline rock at the Mirror Lake research site in New Hampshire by diffusion of parent compound, radium^{226}, through the rock matrix and accumulation onto weathered fracture faces (Wood and others, 2004). Thus, water-rock chemistry can be affected by a combination of rock-matrix diffusion and fracture-face weathering.

Ground-water quality may be influenced by regional and local bedrock structure and mineral segregation that develop in response to stress-strain fields. For example, structural features in a given rock can affect flow patterns and rates, residence time, and dilution. From a chemical standpoint, rock deformation can produce mineral segregations that are preferentially located along structural features, such as faults, shear zones, and fractures. These mineral segregations can influence water chemistry through secondary mineral precipitation, enhanced weathering, and chemical exchange reactions during water-rock interactions. For example, shear zones that form mylonites sometimes have bulk compositions that differ from the unsheared rock (Veeger and Ruderman, 1998). Ground water from shear zones can have elevated arsenic concentrations relative to ground water from similar unsheared rock (Veeger and Ruderman, 1998).

Considerations for Development of Regional Framework

This report considers studies that investigate yield and water quality because of the relation between ground-water-flow characteristics and water quality. Specifically, flow in crystalline rock affects residence time, recharge, dilution, and mixing of ground water and therefore, flow can affect water quality.

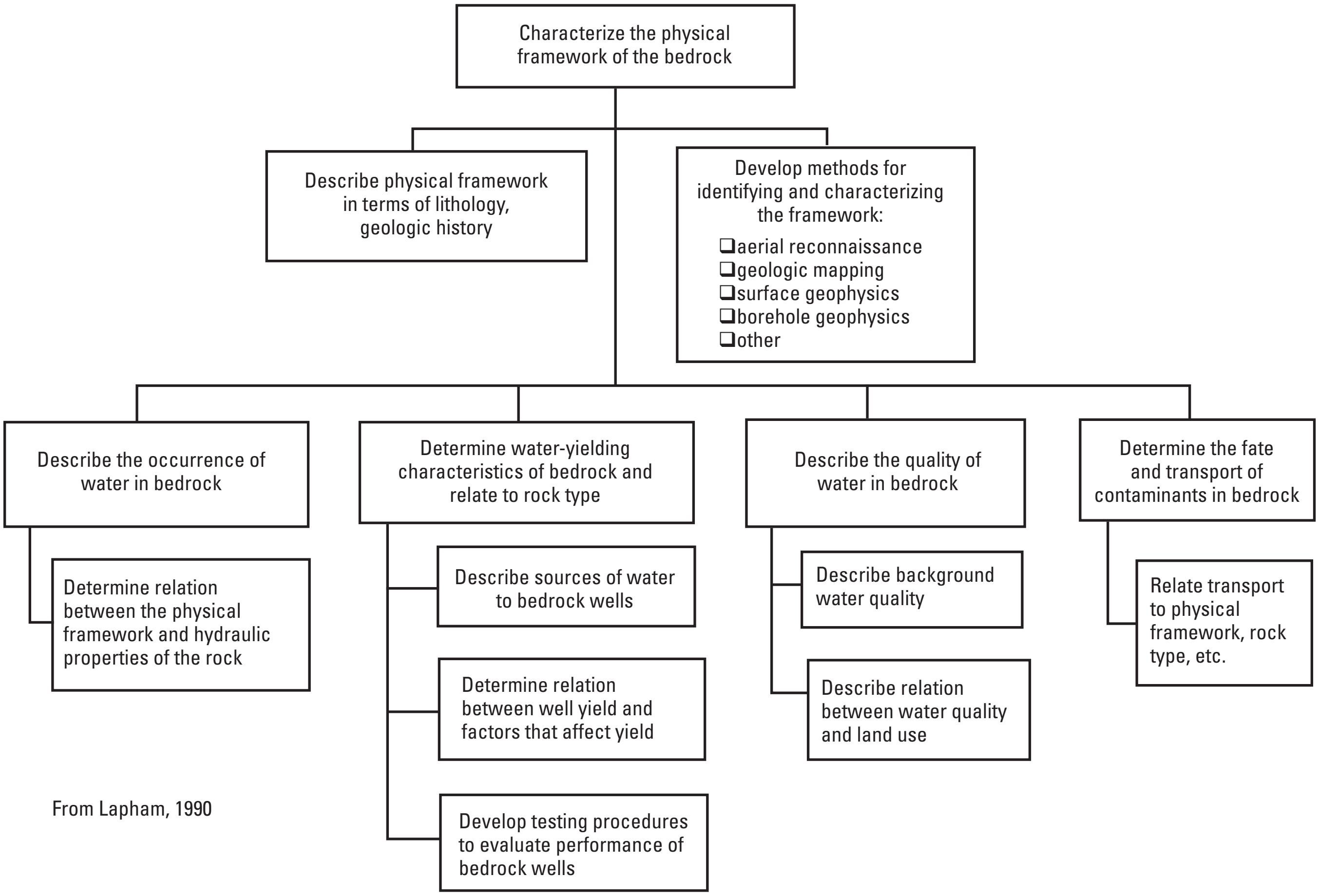
A common theme in the characterization of regional variability of natural contaminants in crystalline rock aquifers of New England is the importance of the mineralogic and lithologic composition of the rock type (table 4, in back of report). This appears to be a primary explanatory variable in most studies. However, geologic structure and fracture patterns have been shown to control ground-water flow and therefore, transport processes related to flow such as dilution, and the chemical composition of the rock through mineralogic segregation along structural features (Veeger and Ruderman, 1998). For anthropogenic and natural contaminants, ground-water flow, geochemistry, and land use are all important influences (table 4, in back of report). Although the source of contaminant is from near-surface inputs for anthropogenic contaminants, natural sources or contaminants indigenous to the rock and soil may also be affected by geochemical processes induced from anthropogenic practices.

Review of Other Framework Approaches

Lapham (1990) proposed an approach to characterize the hydrogeologic framework for the bedrock of New England (fig. 7) and the comparison of features such as water quality to the framework. As stated by Lapham (1990), “Characterization of the bedrock framework consists of a description of the following physical properties of the rock: (1) the primary porosity of the rock; (2) the types of rock fracture systems (joints, faults, shear zones) that contribute to the rock’s secondary porosity; and (3) the characteristics of these fracture systems, including the areal and vertical geometry, orientation, size of openings, spacing, density, and fracture interconnection.” Lithologies in geologic provinces with differing geologic, tectonic, and deformation histories may develop different patterns of fault and fracture systems in response to differing stress regimes. As such, hydrologic properties may differ based on lithology, geologic province, or terrane features.

Regional analysis of anthropogenic contamination from nitrogen loading (fertilizer land application and sewage) have been studied primarily for areas dominated by contiguous (areally extensive) surficial aquifers (Navulur and Engel, 1998) as well as other areas of the United States (Lindsey and others, 2006). These regional studies provide insight into how one might apply similar methods to understand the occurrence of anthropogenic contaminants in crystalline rock aquifers.

The vulnerability of ground-water systems in Indiana to nitrate contamination was assessed by use of soil information from the National Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO) (Navulur and Engel, 1998). This information proved useful in predicting areas of elevated nitrate concentrations and the regional distribution of nitrate in ground water. Vulnerability was further assessed by use of the U.S. Environmental Protection Agency model DRASTIC (Aller and others, 1987), which characterizes hydrogeologic settings based on features that control ground-water flow, including depth to water, net recharge,



From Lapham, 1990

Figure 7. Objectives from a proposed 1990 study of the hydrogeology of bedrock of New England.

aquifer media, soil media, topography, impact of the vadose-zone media, and hydraulic conductivity of the underlying aquifer. The vulnerability of the aquifer to contamination can then be spatially mapped with the DRASTIC model. Navulur and Engel (1998) showed that this approach was effective in identifying areas of nitrate contamination in Indiana. Eighty-one percent of nitrate detections in Indiana occurred within the area ranked most vulnerable to contamination although the land area represented only 25 percent of the State.

Nonlinear-regression models have been developed to assess nitrate concentrations across the United States, including crystalline rock aquifers of the New England area (Nolan and Hitt, 2006). A mechanistic structure was applied in model development that segregates nitrogen sources and physical factors that enhance or restrict nitrate transport in ground water. Results indicate that areas with high nitrogen application, high recharge, well-drained soils, fractured rocks or aquifers with high effective porosity, and lack of attenuation processes have the highest predicted nitrate concentration.

Crystalline rock aquifers in the southern Appalachian Mountains (Lindsey and others, 2006) were examined for selected contaminants including nitrate, pesticides, volatile organic compounds (VOCs), and radon. Linear regression and logistic regression models were developed to identify variables important in estimating concentrations. For nitrate, the percentage of agricultural land use, the input of nitrogen from all sources, and dissolved oxygen were the most significant variables affecting increased concentrations of nitrate. For VOCs, detections were related to land use and well depth. The analysis indicated a significant positive correlation between chloroform concentration and urban land use, leaking underground storage tanks, and population density. MTBE concentrations also were positively correlated to the same variables. Both chloroform and MTBE were inversely related to well depth and shallower wells had higher concentrations than studies in New England (Ayotte and others, 2004) that show a positive correlation with well depth. These differences in results point to potential variations in source input and flow processes between crystalline rock in the New England region and elsewhere. For ^{222}radon, crystalline rock aquifers with felsic mineralogy had the highest concentrations, and the lowest concentrations were in areas with mafic mineralogy.

MTBE concentrations in public- and private-supply wells in crystalline rock aquifers of New Hampshire were analyzed by use of logistic regression models (Ayotte and others, 2008). Important variables in predicting concentrations included source terms (distance from potential fuel sources) as well as certain variables related to transport and dilution. Proxy variables such as low pH correlated with MTBE concentrations suggesting residence time is an important variable, with low pH indicative of young immature waters.

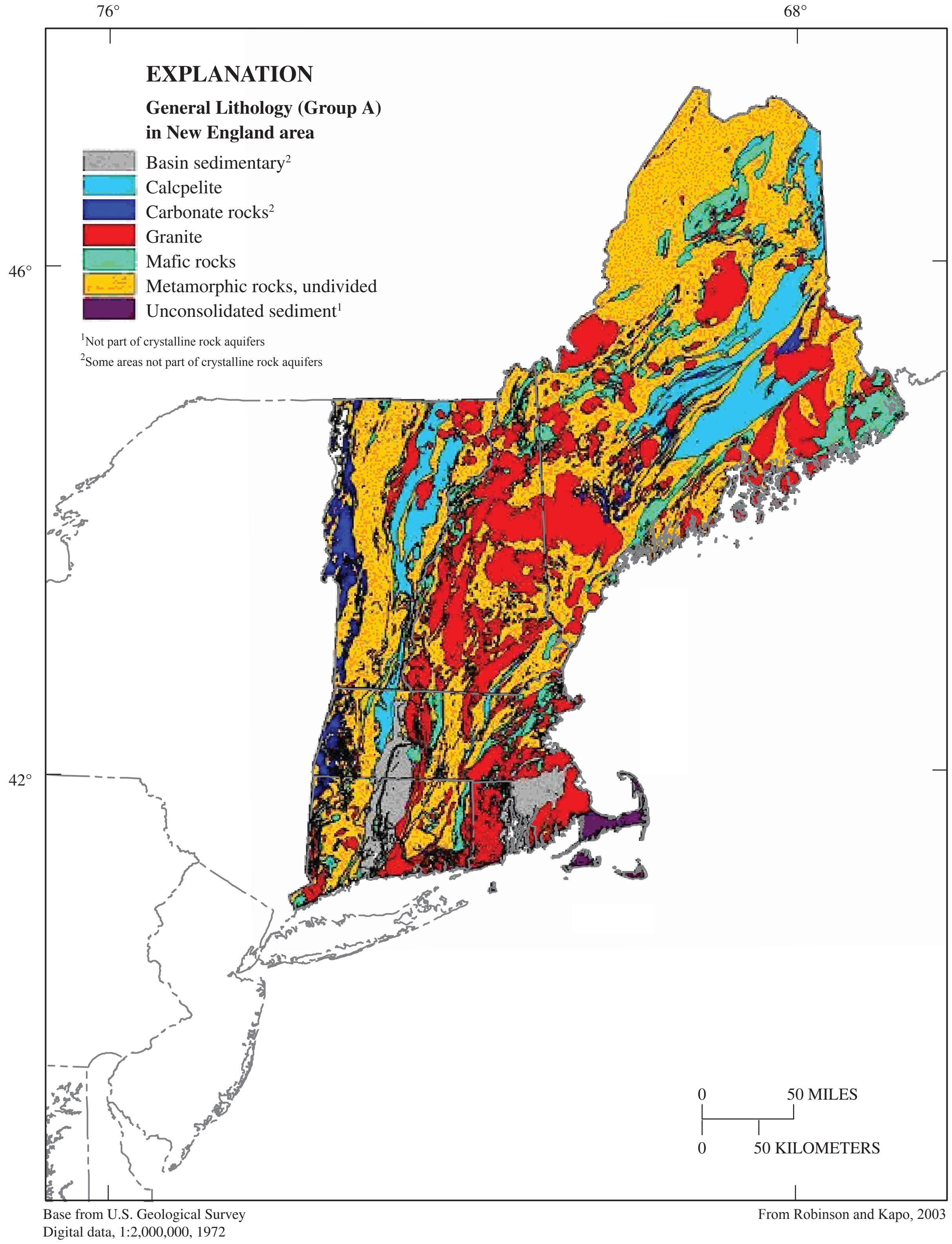
Assessments of regional ground-water quality in fractured crystalline rock of New England have utilized the lithochemical approach developed by Robinson (1997). This approach is predicated on the relation that the general reactivity of the crystalline rock controls regional ground-water quality patterns. The lithochemical approach has been shown to be a powerful tool in evaluating regional ground-water quality for some common (pH, hardness, iron, manganese, fluoride, arsenic, and radon) water-quality constituents (Moore, 2004) and for specific trace constituents such as arsenic (Ayotte and others, 1999, 2003, 2006; Robinson and Ayotte, 2006). The rock types in the crystalline rock aquifers of New England have been categorized into lithology groups that likely have similar effects on ground-water quality (Robinson, 1997). These characteristics are based on mineralogical and chemical characteristics relevant to water quality, which include the reactivity of constituent minerals to dissolution and the presence of carbonate or sulfide minerals (Robinson and others, 2002; Montgomery and others, 2002). When integrated with landscape variables, the lithochemical approach can be used to evaluate regional ground-water quality for a variety of natural and anthropogenic contaminants (Ayotte and others, 1999, 2003, 2006; Robinson and Ayotte, 2006).

The lithochemical classification (groups) for the New England part of the NECRA is shown in figures 8 and 9. The rock groups are derived from rock group categories A and B as reported in Robinson and Kapo (2003). Lithochemical classification is unavailable for the New York and New Jersey part of the NECRA.

The general lithology groups shown in figure 8 are (1) calcareous rock types containing carbonate minerals (Carbonate rocks and Calcpelite), (2) mafic rock types with abundant ferromagnesian and calcsilicate minerals (Mafic rocks), (3) granitic rock types predominantly made up of alkali feldspar and quartz (Granite rocks), and (4) other metamorphic rock types that include subgroups such as sulfidic schists and dominantly pelitic (mica-rich) metasedimentary rocks (Metamorphic rocks, undivided). In figure 8, the granitic and metamorphic rock categories in rock group A are subdivided into additional subcategories based on general differences in mineralogy and (or) rock geochemistry.

As is evident in figures 8 and 9, the lithologic framework of the New England part of the NECRA is heterogeneous and complex. Table 5 lists the area fractions of the various lithology groups in the New England part of the NECRA.

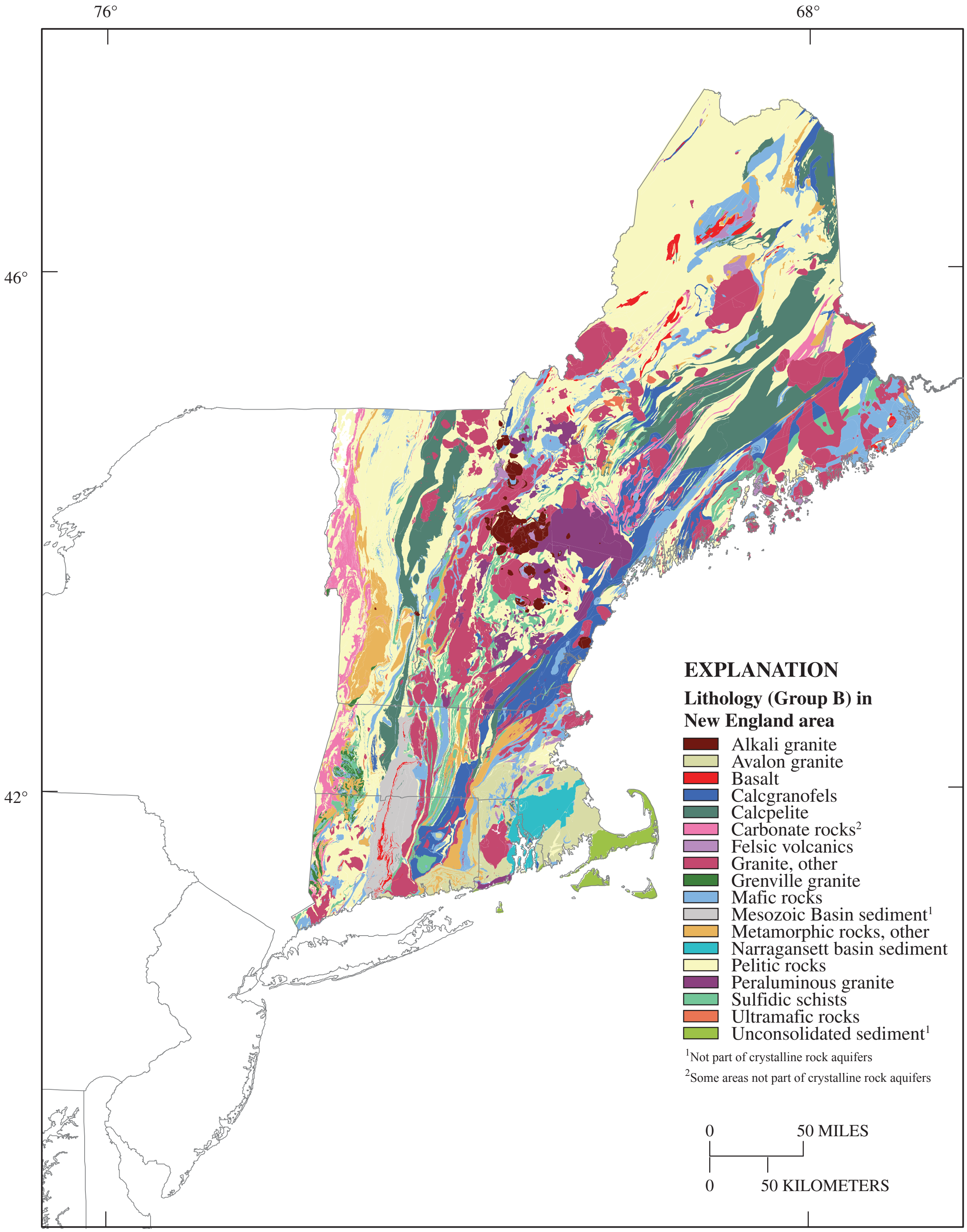
Ground-water flow characteristics of the fractured crystalline rock have been noted as a potentially important factor in the assessment of regional water quality and techniques that can discern regional patterns in flow should be considered as part of the framework approach. Ground-water flow characteristics of parts of the fractured crystalline rock of New England area have been examined by use of the hydrostructural domain approach (Mabee and Kopera, 2005; Manda and others, 2005, 2006). This approach maps rocks based on hydrostructural domains, which are regionally grouped physical attributes including rock type, number and distribution of fracture sets, type of fractures present or absent, degree of fracture development, fracture spacing, and nature of fracture termination (Manda and others, 2006). Together with the surficial geologic setting (overburden characteristics), the hydrostructural domain controls ground-water flow and source of water to



Base from U.S. Geological Survey
Digital data, 1:2,000,000, 1972

From Robinson and Kapo, 2003

Figure 8. General lithology distribution of rock group A in the New England crystalline rock aquifers.



Base from U.S. Geological Survey
Digital data, 1:2,000,000, 1972

From Robinson and Kapo, 2003

Figure 9. Lithology distribution of rock group B in the New England crystalline rock aquifers.

Table 5. Lithology groups and their respective area fractions for the New England crystalline rock aquifers.

[Rounding in area fraction may not add up to 1.0]

Lithology group A	Area fraction	Lithology group B	Area fraction
Mafic rocks	0.085	Mafic rocks	0.084
		Ultramafic rocks	.001
Granite	.253	Alkali granite	.013
		Peraluminous granite	.036
		Avalon granite	.031
		Grenville granite	.004
		Granite, other	.160
		Felsic volcanics	.009
Calcpelite	.095	Calcpelite	.095
Metamorphic rocks, undivided	.521	Calcgranofels	.068
		Pelitic rocks	.368
		Sulfidic schists	.041
		Metamorphic rocks, other	.044
Basin metasedimentary	.013	Narragansett Basin	.013

crystalline rock aquifers. Conceptually, in its simplest explanation, the physical characteristics of the fractured rock impart preferred flow patterns. For example, regions with units of rocks that have only one fracture-set orientation will exhibit anisotropic flow trending parallel to the strike set.

Areas of potential enhanced vertical flow and transport can be ascertained from the hydrostructural domain approach. Conversely, areas with primarily horizontal sheeting fractures have less vertical flow and dilution from the overburden (Lyford and Walsh, 2004); these areas also can be identified. In particular, foliated rock with fractures parallel to foliation exhibit high connectivity and enhanced rates of ground-water recharge (Manda and others, 2007). Thus, these rocks may have identifiable patterns of ground-water quality due to dilution, recharge, and vertical transport of contaminants.

Discussion of Regional Framework Factors

A framework for analysis of water quality across the NECRA consists of a group of spatial variables representing features related to aquifer properties, hydrologic conditions, and contaminant sources. These variables can be used in varying combinations (depending on the contaminant) to categorize the aquifer region into areas of similar hydrogeologic characteristics to evaluate variation in water quality. For consideration as a spatial variable, information must be available across the study area, such as degree of rock foliation.

The framework includes variables grouped under four categories (features; table 6) that can be mapped over the aquifer. The categories are (1) geologic, (2) geochemical, (3) hydrophysiographic, and (4) land use-land cover spatial features. On a regional scale, these features represent indicators of natural and anthropogenic sources of contaminants, as well as generalized physical characteristics of the aquifer system that influence ground-water chemistry and flow. The incorporation of these features into a regional evaluation will help characterize this large region into areas of similar hydrologic characteristics and contaminant sources in which water quality can be compared. Variables associated with these features, sources of information, and proposed contaminants to be evaluated for this study are listed in table 6.

Contaminant chemistry in crystalline-rock ground water also depends on source inputs of contaminants (types of contaminants and water chemistry), aquifer

Table 6. Categories of spatial features, associated explanatory variables, sources of information, and ground-water contaminants to be evaluated for the regional study of the New England crystalline rock aquifers.

[MTBE, methyl *tert*-butyl ether; NaCl, sodium chloride; N, nitrogen; As, arsenic; U, uranium; Ra, radium; Rn, radon; STATSGO, State Soil Geographic Database (Source of data is at Oregon State University in Corvallis, Oreg., at http//www.ocs.oregonstate.edu/prism/index.phtml); PRISM, Parameter-elevation Regressions on Independent Slopes Model climate mapping system; USGS, U.S. Geological Survey; NLCD, National Land Cover Data; TIGER, Topologically Integrated Geographic Encoding and Referencing; salt refers to sodium, chloride and trace contaminants]

Spatial feature	Variable	Source	Contaminants to evaluate
Geologic	Geologic province, bedrock lithochemistry, bedrock geologic unit	Compiled at 1:125,000- to 1:500,000-scale state geologic maps	All
	Proximity to faults	Nicholson and others (2006) Dicken and others (2005)	MTBE, NaCl, N
	Proximity to intrusive granite contacts	State geologic maps Peters and others (1999)	As, U
	Overlying surficial sediments	NLCD (2001) Vogelman and others (2001) Randall (2001) Stone and others (1992) Cain and Hamidzada (1993) Koteff (1993) Marvinney and Walters (1993) Stone and Beinikis (1993) Dudley (1993)	All
	Pleistocene marine inundation	Ayotte and others (2006)	As, U, Ra (?)
Geochemical	Stream-sediment chemistry	Robinson and others, 2004; National Uranium Evaluation Program data	As, U, Rn
	Soil survey data	STATSGO; Wollock (1997)	Rn, Ra
	Stream pH	National Uranium Evaluation Program stream pH data	As, U, Rn
	Stream alkalinity	National Uranium Evaluation Program stream alkalinity data	As, U, Ra (?)
Hydrogeologic	Ground-water recharge	Recharge from base-flow index model	All
	Precipitation	PRISM	All
	Elevation, slope, slope change	USGS Digital Elevation Model	All
	Hydrologic landscape	Wollock (2003)	All
	Well depth	Source well data	All
Land use/land cover	Land use polygon and grid data	2001 multiple resolution land cover; refined 1970 land use data and NLCD land use data	All
	Population density	TIGER census tract data	MTBE, NaCl, N
	Proximity to roads	National Transportation Network	MTBE, NaCl
	Proximity to gas stations		MTBE, NaCl

chemistry, and physiochemical conditions such as pH, redox state, and ground-water age. Ground water physiochemical conditions have not been mapped at a regional scale, so measurement of water quality at individual wells are used as an indicator of conditions. The framework, therefore, uses geologic and other landscape features, in part, as a surrogate for the general patterns and regional variation in these physiochemical conditions.

The geologic categorical features are based on information derived from statewide maps of bedrock geology for Connecticut (Rogers, 1985), Maine (Osberg and others, 1985), Massachusetts (Zen and others, 1983), New Hampshire (Lyons and others, 1997), Rhode Island (Hermes and others, 1994), and Vermont (Doll and others, 1961). The geologic features include individual geologic map units and groups of geologic map units that have been generalized into geologic province (regional scale) and lithologic group categories. The province groups were defined by use of lithostratigraphic information and correlation tables accompanying the state bedrock geologic maps (referenced above), and they generally occur as north- to northeast-trending belts that share common features of lithology, age of formation, geologic setting, and tectonic history (Robinson and Kapo, 2003; fig. 1). The lithology group categories generalize the geologic map units according to their lithochemistry that relates to the generalized geochemical and mineralogical composition of the rocks and the signature that they would impart to the ground water flowing within them (Robinson and Kapo, 2003). Because this feature is based on chemical composition and mineralogy, it is useful in the regional analysis of constituents that are sensitive to rock-water interactions (Robinson and others, 2002). The individual geologic map units represent the most local-scale variability related to physiochemical properties of the aquifer and contaminant occurrence and distribution.

Other geologic features that may be used as a surrogate for variation in physiochemical conditions of the aquifer include proximity to geologic structures and contacts and overlying surficial geologic units (table 6). Proximity to faults and lineaments (which may be bedrock fracture zones) is a geologic framework variable that may relate to features such as ground-water recharge rates, dilution, flow rates, and ground-water residence time. Proximity to intrusive granite contacts with associated hydrothermal alteration may be a useful geologic variable because such controls may delineate mineralized areas varying in natural-contaminant source concentrations, as well as physiochemical properties. An example of an overlying surficial geologic variable is information on soil characteristics (STATSGO) including permeability, percentage of organic matter, and texture. Soil characteristics are factors in contaminant occurrence and distribution in other parts of the world (Smedley and Kinniburgh, 2002). Pleistocene marine inundation is another surficial geologic feature that may affect regional ground-water quality. Pleistocene marine inundation can affect chemistry of overlying sediments through residual pore waters with increased salinity and enhanced cation exchange, alteration in clay chemistry, and increased ground-water pH (Ayotte and others, 2006). These pore waters may recharge underlying crystalline rock aquifers and interact with rock mineralogy and influence ground-water chemistry in the bedrock.

The geochemical features, some of which are listed in table 6, can be considered as surrogates for variation in natural contaminant sources and influences on geochemical processes in the aquifer. Hydrogeologic features influence hydrologic recharge, flow conditions, and residence time. Land-use and land-cover features are considered surrogates for anthropogenic contaminant sources and potential influences on mobilization of natural contaminants.

Table 7 lists proposed natural and anthropogenic constituents to be examined in regional evaluation of the NECRA. It includes a list of explanatory variables, related measurable characteristics, and related interpretation (effect). For example, nitrogen, a primarily anthropogenic contaminant, is related to land use and particularly to agricultural practices as well as to atmospheric sources through precipitation.

Table 7. Ground-water contaminants in relation to explanatory variables in regional studies in the New England crystalline rock aquifers.

[As, arsenic; U, uranium; Ca, calcium; Rn, radon; Th, thorium; N, nitrogen; MTBE, methyl *tert*-butyl ether; Cl, chloride; Na, sodium; salt, sodium, chloride, and trace contaminants]

Ground-water contaminant		Explanatory variables	Measure	Interpretation
Natural	**As**	Rock chemistry	As	Elevated as source
		Sediment chemistry	As	Proxy for elevated as rock source
		Lithology group	Sulfidic schist	Elevated as source
			Calcpelite	Elevated as source/pH influence
		Geologic province/unit	Various	Elevated as source/pH influence
		Proximity to granite contact	Distance	Elevated as in contact zone
		Granite pegmatite	Well colocation	Elevated as source
		Proximity to serpentine	Colocation/distance	Elevated as source/pH influence
		Proximity to landfill	Redox	Reductive dissolution in landfill groundwater plume
		Water chemistry	pH	Desorption at high pH
			Redox	Dissolution/desorption under reducing conditions
	U	Aeroradioactivity	U	Elevated U source
		Sediment chemistry	U	Elevated U source
		Lithology group	Peraluminous granite	Elevated U source
		Water chemistry	Redox	Oxidizing conditions solubilize U from source
			Ca, bicarbonate	Complexing agent
			Rn	Co-occurrence
	Rn	Aeroradioactivity	U, Th	Source
		Sediment chemistry	U, Th	Source
		Lithology group	Various	Source, transport
Anthropogenic	**N**	Land use	Agriculture	Source
		Population density	Septic density	Source
		Well depth	Depth	Susceptibility to surface contamination
		Nonfoliated vs. foliated		
		Proximity to high-angle fault	Distance	Susceptibility to surface contamination
	MTBE	Road density		Source
		Population density		Source
		Proximity to gas stations	Distance	Source
		Nonfoliated vs. foliated		
		Proximity to high-angle fault	Distance	Susceptibility to surface contamination
	Cl, Na	Road density		Source
		Population density		Source
		Marine inundation	Absence/presence	Source
		Nonfoliated vs. foliated		
		Proximity to high-angle fault	Distance	Susceptibility to surface contamination

Framework Approach

The relation between physical and chemical processes in controlling ground-water quality in the crystalline rock aquifers suggests that a linked physical and chemical approach may be useful for the analysis of anthropogenic and natural contaminants. This approach contained herein incorporates the hypothesized most relevant explanatory variables from the hydrostructural domain and lithochemical approaches as well as variables identified from previous investigations of water quality. The framework can be used to characterize the aquifer region into areas of similar hydrologic characteristics and contaminant sources for which water quality can be compared.

The proposed framework approach is diagrammed in a flowchart shown in figure 10. The flowchart is structured under three main factors (source, intrinsic susceptibility, and vulnerability) that likely affect the distribution of contaminants on a regional scale. Under each of the three factors is a set of features (geologic, hydrophysiographic, etc). Within each feature there are set of subcategories, such as bedrock, and a listing of relevant explanatory variables under each subcategory, such as lithologic group. The listing of explanatory variables in this way follows the general approach developed by Warner and Arnold (2006) and groups the variables under source, susceptibility, and vulnerability factors. Although some variables are listed as a source or susceptibility factor, all variables fall under the vulnerability factor.

The result of the application of the framework approach will be a vulnerability assessment to the contaminant of interest and an indication of potential factors that affect the occurrence, distribution, and fate of contaminants. The main benefits to the use of the framework approach are that it lists relevant explanatory variables and it specifies a systematic, structured approach to test potential relations between variables and regional water quality.

An important criterion in the framework approach is whether the contaminant (or constituent) is anthropogenic or naturally derived (source factor). However, many of the same explanatory variables are used in evaluating vulnerability because of the interdependence between physical and chemical processes. For example, an anthropogenic contaminant like MTBE may correlate to land-use practices, but it is also possible that land use can affect general chemical conditions that in turn affect mobilization of certain metals. Thus, land use is listed as a source factor but also listed as a vulnerability factor (fig. 9).

Variables listed under intrinsic susceptibility factors incorporate generalized physical characteristics of the aquifer system that influence ground-water chemistry and flow. For example, the variable ground-water recharge, a hydrophysiographic feature listed under the hydrologic category, is an intrinsic susceptibility factor that affects dilution and water chemistry. Some variables are both a source and susceptibility factor and are connected, such as bedrock geology. Water-chemistry explanatory variables incorporate the effect of source, intrinsic susceptibility, and vulnerability factors and are listed at the bottom of the framework. Variables related to well characteristics of individual wells and water samples are listed near the end of the vulnerability assessment. Well characteristics provide information on the location and source of the water sample and may provide insight into factors such as degree of mixing of the water sample and vulnerability of the sample to contamination.

All data on explanatory variables are readily available for regional spatial analysis. For example, regional fault information is available at a 1:250,000 scale from USGS sources (Nicholson and others, 2006; Dicken and others, 2005). Soil cover is available from STATSGO (state soil surveys from NRCS). Soil cover will include features such as surface-water bodies and wetlands. Although surficial geologic maps may provide more detail than soil surveys on the characteristics of overburden sediments, detailed surficial geologic maps are unavailable on a regional scale.

Several variables are proxies for other important variables. Regional structural and fracture trends are unavailable; therefore, proximity to geologic faults, geologic province, lithology group, and geologic map unit variables are used as proxies for variation in structural features. For example, an important variable in the study of bedrock yield and recharge is the presence of steeply sloping (near vertical) foliations and partings. If these characteristics are present, they can transmit vertical flow from overlying sources and thus have the potential for increased yield (Lyford and Walsh, 2004; Manda and others, 2007). Therefore, although specific fracture information is unavailable locally, the presence or absence of foliated rock can be used to identify areas with the potential for vertical fractures.

Natural and anthropogenic constituent concentrations can be evaluated with variables shown in figure 10 by means of a variety of statistical methods such as univariate analysis or multivariate analysis (correlations, regression, principal component analysis, logistic regression, cluster analysis, and multivariate analysis of variance). Additional information on these statistical methods is available in Alley (1993) and in a more recent article by Woocay and Walton (2008).

The likelihood of variables affecting regional water quality can be further assessed by use of geochemical models. Forward geochemical models can be used to determine the water chemistry (output) in the rock aquifer if the recharge water chemistry (input) and the lithochemistry of the rock are known (Parkhurst and others, 1999). The output results of the forward model can be compared to the actual water quality of the aquifer to identify the effect of various input water chemistry on the overall water quality of the aquifer. Inverse geochemical models can be used to identify the lithochemical reactions controlling the rock water chemistry (Plummer and others, 1994) and, therefore, identify important mineral reactions. A case example of geochemical modeling to identify flowpath reactions in the NECRA of the Mirror Lake area is presented in Harte and Winter (1996).

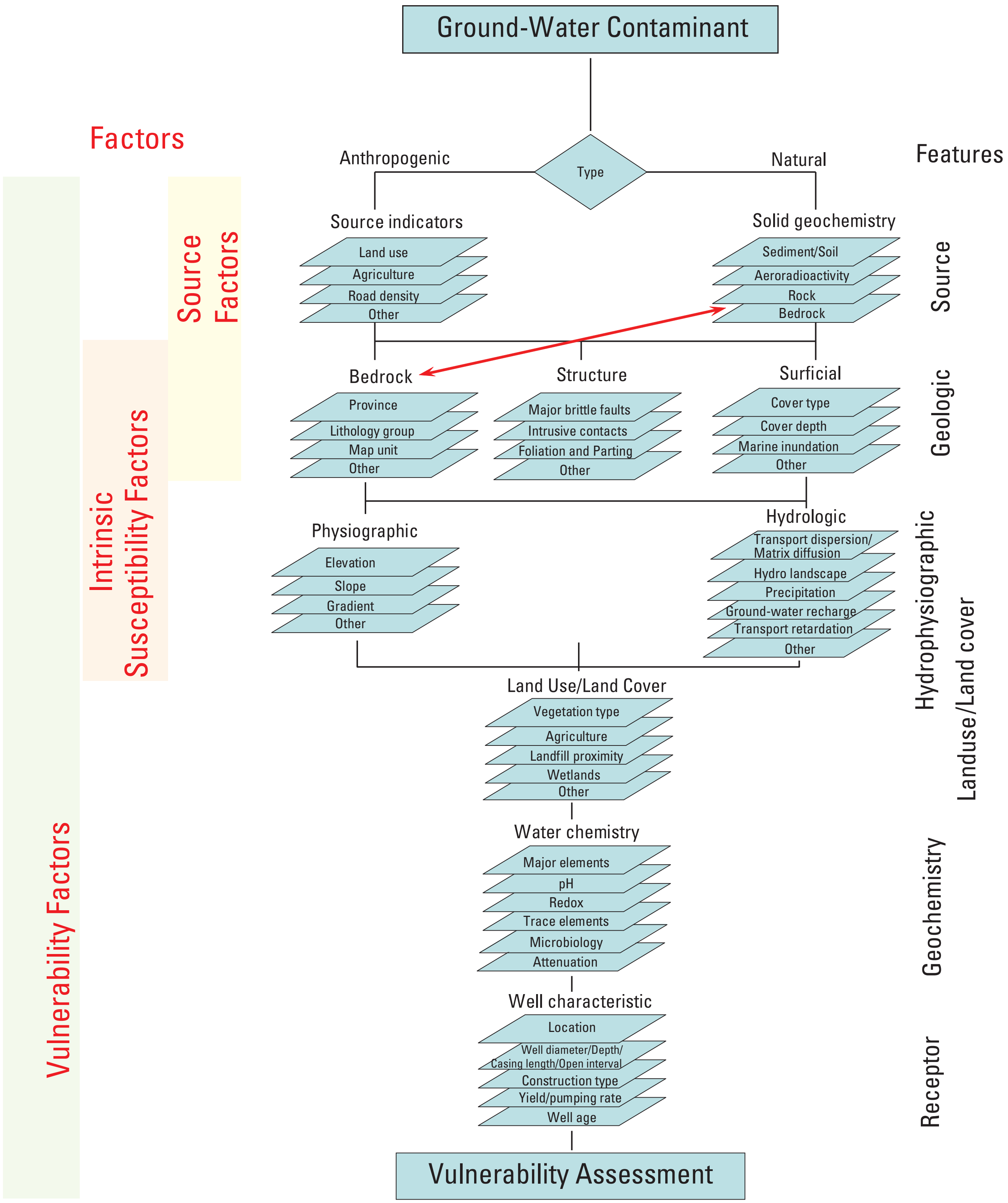


Figure 10. Preliminary framework approach for the evaluation of regional ground-water quality in the New England crystalline rock aquifers.

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Table 4. Summary of factors affecting regional water quality in crystalline rocks of the New England area.

[N/A, not applicable; mg/kg, milligrams per kilograms; As, arsenic; U, uranium; ppm, parts per million; MTBE, methyl *tert*-butyl ether; VOCs, volatile organic

Study	Type of study	Major constituent type	Water-quality constituents examined	Major findings
Yields of bedrock wells in Massachusetts.	Water supply	N/A	None	Major bedrock type, topographic setting, and well construction all appeared to affect yields of wells. Highest yields were found in wells in valleys with thick overburden deposits, suggesting recharge from overburden is a source of water to bedrock wells. Bedrock included three major types: crystalline, carbonate, and noncarbonate sedimentary (typically low-grade metamorphosed sedimentary units). Crystalline rock primarily consisted of granite, gneiss, and schist.
Geologic framework for ground-water resources in Central Vermont.	Water supply	N/A	None	Analyzed relations between well yield and (l) lithologic and surficial units, (2) proximity to topographic lineaments, (3) surficial material thickness and permeability, (4) surface-water proximity, (5) major bedrock structures, (6) slope and other topographic indices, and (7) drainage area. Found bedrock type and topography related to well yield. Other factors were less important.
Fracture characterization for Nashoba Terrane, Massachusetts.	Water supply	N/A	None	Mapping of crystalline rock based on hydrostructural domain to quantify hydraulic properties and generate regional conceptual models of flow. The mapping of hydrostructural domains include rock type, number of distribution of fracture sets, type of fractures present or absent, degree of fracture development, fracture spacing, and nature of fracture termination. Information is compiled at the regional, quadrangle, and local well-field scales.
Factors related to well yields in New Hampshire.	Water supply	N/A	None	Well depth, proximity to lineaments, plutons, slope of land, and some rock types were found to correlate with well yields. Many of the intrusive rocks positively correlated with high well yield. Fine-grained metasediments negatively correlated with well yield including phyllites, metapelite, and some schist. Foliated plutons negatively correlated, whereas nonfoliated plutons positively correlated with yield.
Water sources to public supply wells in fractured bedrock.	Water supply	N/A	None	Characteristics of ductile features (foliation and folds) were used to build conceptual models of flow and input into numerical models. In areas where foliation produces high-angle faults, leakage rates from overlying surficial material is important in controlling sources of water to pumped wells.
Geochemical comparison of ground water in the Northeast.	Water quality	Natural contaminant	Major ions	Calcite undersaturated with regard to crystalline rock ground water of the New England area. Water chemistry suggests water reacting with feldspathic minerals.
Water quality in New Hampshire.	Water quality	Natural contaminant	pH, hardness, iron, manganese, fluoride, arsenic, radon.	Bedrock water quality varied by lithochemical groupings. Bedrock units are grouped by lithochemical characteristics based on mineralogic and chemical properties that include reactivity of minerals to dissolution and presence of carbonate and sulfide minerals. Radon potential was grouped separately on the basis of lithology and mineralogy of uranium content, including two-mica granite and pegmatites.
Water quality in New England.	Water quality	Natural contaminant	Arsenic	Bedrock water quality positively correlated with bedrock whole-rock arsenic concentrations. The distribution of bedrock geology features at the geologic-province, lithology-group, and map-unit level closely correlate with areas of elevated arsenic in ground water.
Water quality in New England.	Water quality	Natural contaminant	Arsenic	Bedrock water quality positively correlated with bedrock geology. Bedrock ground-water quality samples from wells located in rocks grouped under calcareous metasedimentary were found to contain the highest arsenic concentrations.

compounds; mg/L, milligrams per liter]

Factors assessed (X = ASSESSED; XX = MEANS IMPORTANT EXPLANATORY VARIABLE)												
Structure (R = Regional, L = Local)	Fracture patterns (R = Regional, L = Local)	Bed-rock type	Geo-chemical con-ditions	Land use	Well depth	Well diam-eter	Well yield	Topo-graphic setting	Thick-ness of over-burden	Type of over-burden material	Year of con-struction	Author
		X	N/A		X	X	X	XX	X		X	Hansen and Simcox (1994)
X	X	XX	N/A		X		X	X	X	X		http://www.anr.state.vt.us/dec/geo/grndwaterWorc.htm
X	X	X	N/A				X	X	X	X		http://water.usgs.gov/wrri/02-03grants_new/prog-compl-reports/2003MA19G.pdf
XX	XX	XX	N/A	N/A	XX	N/A	XX	XX	X	X		Moore and others (2002a)
XX	XX						XX					Lyford and others (2003)
		XX										Rogers (1989)
		XX										Moore (2004)
		XX		X								Robinson and Ayotte (2006)
		XX			X		X		X	X		Ayotte and others (2003)

Table 4. Summary of factors affecting regional water quality in crystalline rocks of the New England area.—Continued

[N/A, not applicable; mg/kg, milligrams per kilograms; As, arsenic; U, uranium; ppm, parts per million; MTBE, methyl *tert*-butyl ether; VOCs, volatile organic

Study	Type of study	Major constituent type	Water-quality constituents examined	Major findings
Geochemical patterns of arsenic enriched ground water in Northport, Maine.	Geochemistry	Natural contaminant	Arsenic	Found that mineralogic differences in fractured rock is an important factor in high arsenic on the basis of the association of high silica and arsenic concentrations, which suggest dissolution of clays from granite intrusions. The adsorption and dissolution of arsenic from iron oxhydroxides, although a factor, is not a primary cause given the lack of a strong correlation with pH. The bedrock water with the highest arsenic was surmised to be of intermediate evolution between a calcium-bicarbonate water type (modern recharge) and a sodium-bicarbonate (old) water type. Sodium-bicarbonate water type can be from silicate hydrolysis when longer residence time allows for the dissolution of sodium-feldspar or from exchange of calcium for sodium.
Mineralogy of arsenic in New Hampshire.	Geochemistry	Natural contaminant	Arsenic	Pegmatite dike intruded into the Silurian lower Rangeley Formation, a metapelite, in central New Hampshire, found to contain high concentration (59 mg/kg) of As in the form of arsenopyrite and scorodite. The exposure to oxidizing conditions is believed to have initiated the dissolution of arsenopyrite into scorodite and release of As into ground water.
Hydrogeologic controls on radon-222 in fractured bedrock aquifer, Rhode Island.	Geochemistry	Natural contaminant	Radon, Uranium	Although U content of one granite and two gneiss rocks were not that different (ranging from 1.9 to 4.1 ppm), large differences occurred in ground-water samples for radon that suggest emination differences in the rock. Fluoride and alkalinity were found to be markers of suggesting increased weathering of fracture faces that facilitated the release of U and production of radon-222. Zones of elevated bedrock U may be associated with shear zones and formation of mylonites. Shear zones create foliation and preferential concentration of U.
Water quality in New England.	Water quality	Anthropogenic contaminant	MTBE	An analysis of MTBE concentrations in ground water from crystalline rock of southeastern New Hampshire showed that land use and population density were important factors to detection of MTBE. Well yield was inversely related to MTBE concentrations, whereas low-yield wells showed higher MTBE concentrations. Bedrock type did not correlate with MTBE, indicating no significant relation between well yield and bedrock type for this area.
National occurrence of VOCs.	Water quality	Anthropogenic contaminant	VOCs	Crystalline rock aquifers from the New England area showed a high frequency of VOC detection compared to other principal aquifers throughout the U.S. Factors such as source, transport, and geochemical conditions (oxygen levels in aquifer) affected occurrence.
Water quality in New England Coastal Basins.	Water quality	Anthropogenic contaminant	VOCs, pesticides, nitrates	One detection of VOC contaminant occurred in 30 percent of 58 domestic bedrock wells. The most common contaminants were MTBE, chloroform, 1,1,1-trichloroethane, TAME (*tert*-amyl-methyl ether), and PCE (tetrachloroethylene). Pesticides were detected in only 10 percent of 56 wells. Nitrate concentration was low in domestic bedrock wells—less than 0.05 mg/L in nearly 60 percent of 58 domestic bedrock wells.
Road salt in bedrock wells in Maine.	Water quality	Anthropogenic contaminant	Road salt	Negative correlations between low water levels and high chloride concentrations in bedrock wells in Maine suggest chloride sequestering (accumulation of chloride in dead-end fractures or fractures that contribute flow during low-flow periods).
Geochemical conditions around Augusta, Maine.	Water quality	Anthropogenic contaminant	Nitrate	Collection of geochemical data showed that, although several trace elements were at high concentrations, including arsenic, concentrations of nitrate from 600 wells generally were low, about 1.1 mg/L.

compounds; mg/L, milligrams per liter]

Factors assessed (X = ASSESSED; XX = MEANS IMPORTANT EXPLANATORY VARIABLE)												
Structure (R = Regional, L = Local)	**Fracture patterns (R = Regional, L = Local)**	**Bed-rock type**	**Geo-chemical con-ditions**	**Land use**	**Well depth**	**Well diam-eter**	**Well yield**	**Topo-graphic setting**	**Thick-ness of over-burden**	**Type of over-burden material**	**Year of con-struction**	**Author**
		XX	XX	X				X				Lipert and others (2006)
		XX	XX									Utsunomiya and others (2003)
XX		X	XX		X		X	X	X	X		Veeger and Ruderman (1998)
		X		XX	XX		XX					Ayotte and others (2004)
			XX	XX	X							Zogorski and others (2006)
				X	X							Robinson and others (2004)
				XX								Katz (2007)
		XX										Yang and others (2006)

Appendix 1. Summary of regional ground-water-quality issues in ground water of the New England area, by state, as reported by state

[VOCs, volatile organic compounds; MCLs, Maximum Contaminant Levels, U.S. Environmental Protection Agency standards unless otherwise specified;
Protection Agency Health Advisory Level; Sb, antimony; As, arsenic; Cd, cadmium; Pb, lead; Mn, manganese; Fe, iron; Be, beryllium; MTBE, methyl *tert*-butyl ether;

State	Type of study	Major findings	Water-quality issues		
			Anthropogenic		
			VOCs	Nutrients	Bacteria
Vermont	Regional water quality monitoring of public community and non-transient systems. Not differentiated with regard to rock type. Second study on agricultural activities includes 1,294 monitoring wells; also not differentiated by rock type. Limited data from private wells (80 percent set in bedrock).	Bacteria problems were reported for many public supply wells in state.	Twenty-eight public systems out of unknown number had VOCs above MCLs of 5 µg/L.	Nine public systems out of an unknown number had nitrate concentrations above 5 µg/L (10 µg/L is MCL). Seventy-eight (6 percent) agricultural wells exceed of the MCL (10 mg/L) for nitrate.	One hundred thirteen public systems out of unknown number tested positive for bacteria contamination.
New York	Regional water-quality monitoring of public community and non-transient systems.	None reported for crystalline rock for large systems (more than 100,000 served).			
Massachusetts	Regional water-quality monitoring of public community and non-transient systems. Not differentiated with regard to rock type.	Sixty-nine percent of regional water quality supplies rely on ground water. Major problem was coliform bacteria. No other detailed information provided.	Not reported.	Not reported.	Not reported.
Rhode Island	Regional water-quality monitoring of public community and non-transient systems. Not differentiated with regard to rock type.	Bacteria from septic systems identified as a problem.	MTBE and solvent organics detected the most.	Median concentration of nitrate was 2 mg/L out of unknown number of samples.	Common problem.
New Hampshire	Ground water from private wells. Not differentiated with regard to rock type but generally set in crystalline rock aquifers.	Bedrock well-water quality is sometimes affected by naturally occurring contaminants including fluoride, arsenic, mineral radioactivity, and radon gas.	Nineteen of 65 wells had levels exceeding MCLs of 5 µg/L.	Seventeen of 1999 wells had levels above MCL.	Not reported.
Maine	Ambient ground-water-quality monitoring-well data. Generally differentiated by rock type.	No detections above MCL of 5 µg/L for VOCs were measured out of 1,196 public water supply wells sampled in crystalline rock. Nitrate concentrations were below MCL of 10 µg/L. Chloride concentrations high in many wells.	Below MCLs.	Generally below MCL of 10 µg/L for nitrate.	Fourteen percent of wells tested positive for total coliform or *E. coli*.
New Jersey	Ambient ground-water-quality monitoring-well data (150 total wells). Not differentiated by rock type but region—northern and southern New Jersey—and by land use-agricultural, urban, and undeveloped.	In northern New Jersey, Sb, As, Cd, Pb, and Mn, appear to be mostly natural in origin. Fe and Be have an urban association.	Thirty-eight out of 148 network wells had detectable concentrations of MTBE.	Generally concentrations are low, below MCLs.	Not reported.
Connecticut	Reports from 600 non-community ground-water systems. Not differentiated by rock type.	MTBE, heating oils, and VOCs most common contaminants.	MTBE, heating oils, and VOCs most common contaminants.	Unknown number of violations exceeded for nitrate MCL.	One hundred eighty six systems out of 600 tested positive for bacteria contamination.

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environmental agencies.

µg/L, micrograms per liter; mg/L, milligrams per liter; N/A, not applicable; pCi/L, picocuries per liter; ppb, parts per billion; EPA HAL, U.S. Environmental TDS, total dissolved solids; *E. coli*, *Escherichia coli*]

Water-quality issues						
Anthropogenic				Natural		
Pesticides	Emerging contaminants	Road salt	Salt-water intrusion	Metals	Radionuclides	Other source of information
One well out of 1,294 agricultural wells tested above MCL for herbicides.	N/A	Not reported.	N/A	Five public systems above MCL (10 µg/L) for arsenic.	Nine public systems with gross alpha above 10 pCi/L (15 pCi/L is the MCL).	Vermont Department of Environmental Conservation (2004)
	N/A		N/A			http://www.health.state.ny.us/environmental/water/drinking/water_quality_report_links.htm
Not reported.	N/A	Not reported.	Not reported.	None reported.	None reported.	http://www.epa.gov/305b/2000report/chp6.pdf
Not typically detected in samples.	N/A	An unknown number of municipal wells reported to have sodium concentrations exceeding 20 mg/L.	Not reported.	None reported.	Out of 101 samples in Pawcatuck River Basin, only two samples had radon concentrations below 500 pCi/L.	http://www.dem.ri.gov/pubs/305b/four.pdf
Not reported.	N/A	Sodium contamination is of concern from road salting.	Not reported.	None reported.	None reported.	New Hampshire Department of Environmental Science (2000, 2006)
Median concentrations of hexazinone, a pesticide, in 49 wells tested in Maine, was 0.43 ppb. The EPA HAL is 400 ppb.	N/A	One hundred fifty drinking-water wells with chloride concentrations exceeding 250 mg/L (State secondary drinking water level).	Common on coastal peninsulas and offshore islands of Maine.	None reported.	None reported.	http://www.maine.gov/dep/blwqdocmonitoring/305b/2006/2006_Draft_305b_Report_Section3.pdf
Concentrations low in all land use categories.	N/A	Higher TDS reported for wells in urban (550 mg/L median value) and agricultural areas (269 mg/L median value).	N/A	See major findings.	Concentrations of radium-224 have been shown to be affected by land use and that agricultural and lawn-chemical products can compete with naturally occurring radium and mobilize radium.	http://www.state.nj.us/dep/wms/bwqsa/docs/2006AppendixI AmbientGWQMN.pdf
Not reported.	Not reported.	Not reported.	Not reported.	None reported.	Unknown number of violations exceeded for radionuclide MCLs.	Connecticut Department of Environmental Protection (2006)

and 303(d): State of Connecticut Department of Environmental Protection Bureau of Waste Management, Hartford, Conn.

Conservation: Waterbury, Vt.