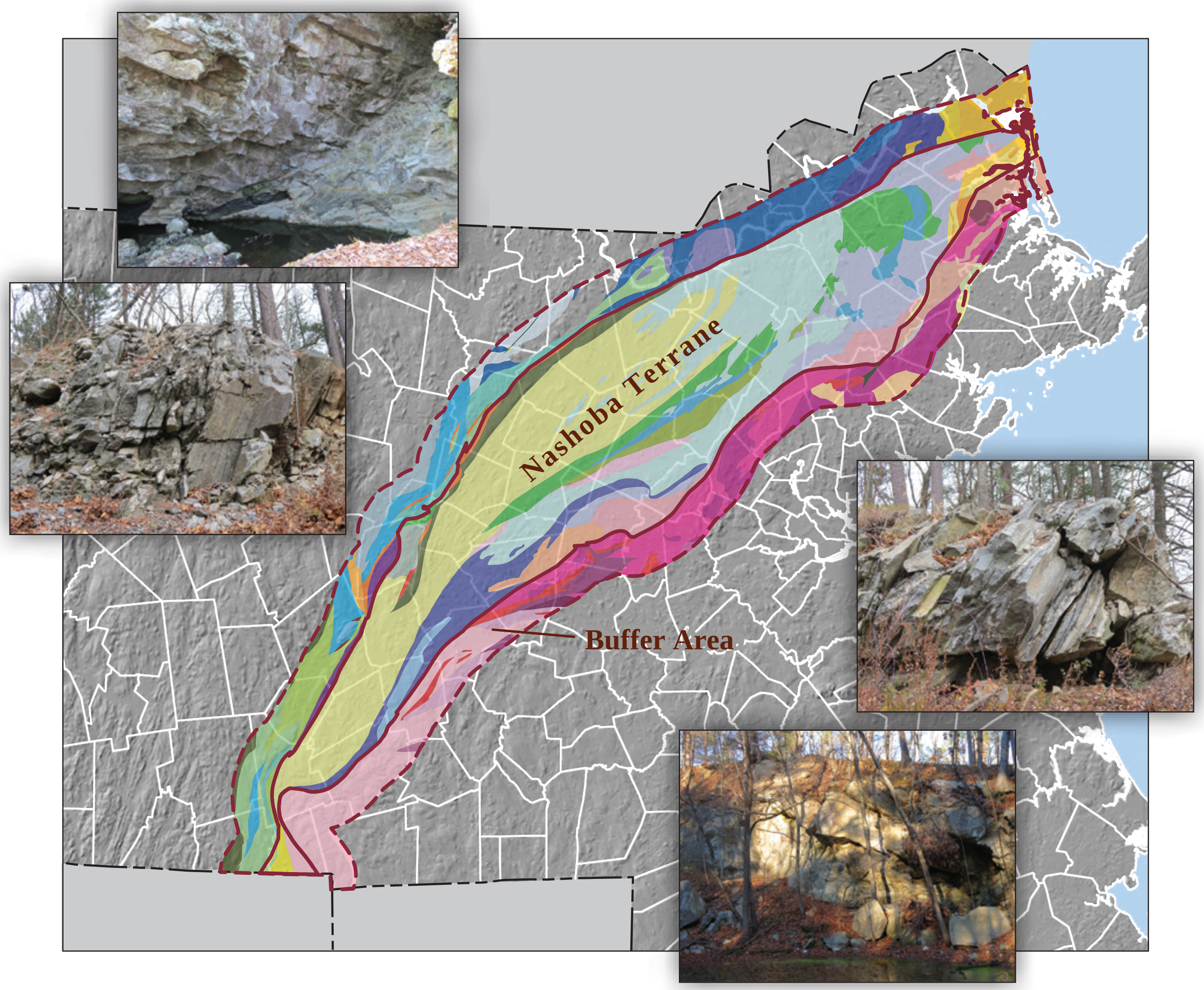
Prepared in cooperation with the Massachusetts Department of Environmental Protection

Yield of Bedrock Wells in the Nashoba Terrane, Central and Eastern Massachusetts



Scientific-Investigations Report 2012–5155

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

Cover. Figure shows bedrock geology in the Nashoba Terrane and surrounding area (Zen and others, 1983; Nicholson and others, 2006).

Yield of Bedrock Wells in the Nashoba Terrane, Central and Eastern Massachusetts

By Leslie A. DeSimone and Jeffrey R. Barbaro

Prepared in cooperation with the
Massachusetts Department of Environmental Protection

Scientific-Investigations Report 2012–5155

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

Suggested citation:
DeSimone, L.A., and Barbaro, J.R., 2012, Yield of bedrock wells in the Nashoba terrane, central and eastern Massachusetts: U.S. Geological Survey Scientific Investigations Report 2012–5155, 74 p.,
(Also available at http://pubs.usgs.gov/sir/2012/5155.)

Acknowledgments

The authors are grateful to the Massachusetts Department of Conservation and Recreation (MDCR) and the Massachusetts Department of Environmental Protection (MDEP) for assistance with the compilation of well-yield data and to the Massachusetts Geological Survey (MGS) for providing geologic data and valuable advice to support this study. Specifically, the authors thank Joseph Kopera (MGS), Barbara Kickham (MDEP), Stephen Mabee (MGS), James Persky (MDEP), and Laurene Poland (MDCR) for assistance with these tasks.

The authors also thank and acknowledge the contributions of Stewart Clark and James Degnan, U.S. Geological Survey, who delineated the lineaments used in this study and of Frederick Day-Lewis, U.S. Geological Survey, who provided valuable advice on the geostatistical analyses.

Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

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)
	Flow rate	
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)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]

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

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

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

Abbreviations

α	acceptable statistical significance level
ANOVA	analysis of variance
CIR	color infrared
DEM	digital elevation model
GIS	geographic information system
log	base-10 logarithm
LOWESS	locally weighted scatterplot smoothing
MDCR	Massachusetts Department of Conservation and Recreation
MDEP	Massachusetts Department of Environmental Protection
MGS	Massachusetts Geological Survey
NWIS	National Water Information System
p	attained statistical significance level
R^2	coefficient of determination
USGS	U.S. Geological Survey

Yield of Bedrock Wells in the Nashoba Terrane, Central and Eastern Massachusetts

By Leslie A. DeSimone and Jeffrey R. Barbaro

Abstract

The yield of bedrock wells in the fractured-bedrock aquifers of the Nashoba terrane and surrounding area, central and eastern Massachusetts, was investigated with analyses of existing data. Reported well yield was compiled for 7,287 wells from Massachusetts Department of Environmental Protection and U.S. Geological Survey databases. Yield of these wells ranged from 0.04 to 625 gallons per minute. In a comparison with data from 103 supply wells, yield and specific capacity from aquifer tests were well correlated, indicating that reported well yield was a reasonable measure of aquifer characteristics in the study area.

Statistically significant relations were determined between well yield and a number of cultural and hydrogeologic factors. Cultural variables included intended water use, well depth, year of construction, and method of yield measurement. Bedrock geology, topography, surficial geology, and proximity to surface waters were statistically significant hydrogeologic factors. Yield of wells was higher in areas of granites, mafic intrusive rocks, and amphibolites than in areas of schists and gneisses or pelitic rocks; higher in valleys and low-slope areas than on hills, ridges, or high slopes; higher in areas overlain by stratified glacial deposits than in areas overlain by till; and higher in close proximity to streams, ponds, and wetlands than at greater distances from these surface-water features. Proximity to mapped faults and to lineaments from aerial photographs also were related to well yield by some measures in three quadrangles in the study area. Although the statistical significance of these relations was high, their predictive power was low, and these relations explained little of the variability in the well-yield data.

Similar results were determined from a multivariate regression analysis. Multivariate regression models for the Nashoba terrane and for a three-quadrangle subarea included, as significant variables, many of the cultural and hydrogeologic factors that were individually related to well yield, in ways that are consistent with conceptual understanding of their effects, but the models explained only 21 percent (regional model for the entire terrane) and 30 percent (quadrangle model) of the overall variance in yield. Moreover, most of the explained variance was due to well characteristics rather than hydrogeologic factors. Hydrogeologic factors such as topography and geology are likely important. However, the overall high variability in the well-yield data, which results from the high variability in aquifer hydraulic properties as well as from limitations of the dataset, would make it difficult to use hydrogeologic factors to predict well yield in the study area.

Geostatistical analysis (variograms), on the other hand, indicated that, although highly variable, the well-yield data are spatially correlated. The spatial continuity appears greater in the northeast-southwest direction and less in the southeast-northwest direction, directions that are parallel and perpendicular, respectively, to the regional geologic structural trends. Geostatistical analysis (kriging), used to estimate yield values throughout the study area, identified regional-scale areas of higher and lower yield that may be related to regional structural features—in particular, to a northeast-southwest trending regional fault zone within the Nashoba terrane. It also would be difficult to use kriging to predict yield at specific locations, however, because of the spatial variability in yield, particularly at small scales. The regional-scale analyses in this study, both with hydrogeologic variables and geostatistics, provide a context for understanding the variability in well yield, rather a basis for precise predictions, and site-specific information would be needed to understand local conditions.

Introduction

Historically, high-yielding public water supplies in Massachusetts have been located in the sand and gravel aquifers of glacial origin that lie close to the land surface. These aquifers can be readily mapped, and their water-yielding properties are well understood. The sand and gravel aquifers are typically of limited areal extent, however, and the rapid pace of growth and development in many communities in Massachusetts has left few areas where these aquifers remain available for future water supplies (Massachusetts Executive Office of Environmental Affairs, 2006). Because they are permeable and near land surface, the sand and gravel aquifers also are vulnerable to contamination. Moreover, existing public water supplies are in many cases strained to meet peak demands in summer months. Consequently, fractured bedrock, which underlies the glacial deposits and has been used for residential wells and small public supplies throughout most of Massachusetts, is increasingly being considered for public water supply. Use of fractured-bedrock aquifers is particularly of interest in the I–495 corridor in eastern Massachusetts, where sand and gravel aquifers are limited and population growth has been high in recent decades (Massachusetts Department of Environmental Protection, 2010).

Groundwater flow through fractured-bedrock aquifers is complex, and the hydraulic properties that influence the amount of water that can be produced by a well (well yield) are highly variable. There is little primary permeability (porosity in the rock matrix) in the crystalline rock that composes these aquifers. Most groundwater flow is through secondary permeability, which results from fractures in the consolidated rocks. The fractures vary considerably in number, size, orientation, and connectedness, which are characteristics that vary in ways that are difficult to determine over large areas. Consequently, unlike the areal extent of high-yielding sand and gravel aquifers, where sediment texture (gravel, sand, silt, or clay) serves as a fundamental, mappable surrogate for aquifer transmissivity, potential well yield in fractured-bedrock aquifers is not readily mapped. Moreover, the extreme heterogeneity of fracture characteristics can make well yield difficult to predict at any scale (Cederstrom, 1972).

Several approaches have been used for investigating the regional hydrogeologic properties and potential well yield in the fractured-bedrock aquifers in New England and elsewhere in the Appalachian provinces. Many studies have investigated the relations between well yield and geology, topographic setting, and other hydrogeologic factors, primarily by using existing well-yield data, to identify areas that might be expected to produce greater than average well yields (LeGrand, 1967; Siddiqui and Parizek, 1971; Daniel, 1989; Knopman, 1990; Hansen and Simcox, 1994; Mabee, 1999; Moore and others, 2002). More recently, several investigators used detailed information about fracture characteristics to better understand groundwater flow in fractured-bedrock aquifers at the regional scale (Mabee and Kopera, 2007; Manda and others, 2008; Starn and Stone, 2005). Geostatistical analysis is another more recently used approach to describe regional patterns of well yield (Drew and others, 1999; Cohen and others, 2007). In addition, numerous site-specific studies using borehole and surface geophysics, modeling, and hydraulic testing, including studies at the Mirror Lake research site in New Hampshire, have described the influences on groundwater flow to wells in the New England fractured-bedrock aquifers (for example, Loiselle and Evans, 1995; Tiedeman and others, 1997; Degnan and others, 2001; Lipfert and others, 2004; Boutt and others, 2010).

The present study of well yield in the Nashoba terrane, a cooperative study by the U.S. Geological Survey (USGS) and the Massachusetts Department of Environmental Protection (MDEP), was done to address the need for more information on the fractured-bedrock aquifers in eastern Massachusetts. The Nashoba terrane is a geologically defined area that extends from the Connecticut border in central Massachusetts to the New Hampshire border along the northern coast of Massachusetts (fig. 1). The area includes many of the towns in eastern Massachusetts that have experienced rapid growth in recent decades, or may grow rapidly in the future. The area also has been the subject of recent work by the Massachusetts Geological Survey and academic researchers, who have developed detailed geologic data for this region. The objective of this cooperative study was to characterize potential well yield in the Nashoba terrane, with the goal of providing information to assist communities and others in locating supply wells in this area.

The approach of the present study was based on the use of existing data on well yield, primarily yield reported by well drillers after well installation. The data are likely to have variable accuracy and precision and in some cases will overestimate aquifer hydraulic properties (Pierce, 1998; S.B. Mabee, Massachusetts Geological Survey, written commun., 2012). Cultural factors also introduce variability in the data that is unrelated to aquifer hydraulic properties. However, these disadvantages are offset by the large number of wells, spatial density, and areal extent of the existing well-yield data, characteristics that are important for an investigation of regional patterns in well yield at the scale of the Nashoba terrane.

Purpose and Scope

This report describes analyses of well yield for the fractured-bedrock aquifers of the Nashoba terrane and a surrounding buffer area in central and eastern Massachusetts. The analyses include a description of well-yield data, development and analysis of factors potentially affecting well yield, and geostatistical analysis. Data from approximately 7,200 wells are included.

Description of the Study Area

The study area encompasses the area of the Nashoba terrane, which is a lithotectonic geologic unit, and a buffer area extending about 2.8 miles (mi) [4.5 kilometers (km)] from the unit boundaries (fig. 1). The area extends northeastwards across central and eastern Massachusetts from the towns of Webster and Dudley along the Connecticut border to Newbury, Rowley, and Salisbury along the Massachusetts northern coast (appendix 1). Topography varies from gently rolling to hilly, with elevations generally decreasing from west to east and ranging from about 900 feet (ft) to sea level. A number of major surface-water drainage basins are located partly or wholly in the Nashoba terrane, including those of the Sudbury, Assabet, Concord, Blackstone, Ipswich, Parker, and French Rivers. All or substantial parts of 74 towns are in the study area (appendix 1), and these towns include more than one-half of the total population of Massachusetts. Water supplies

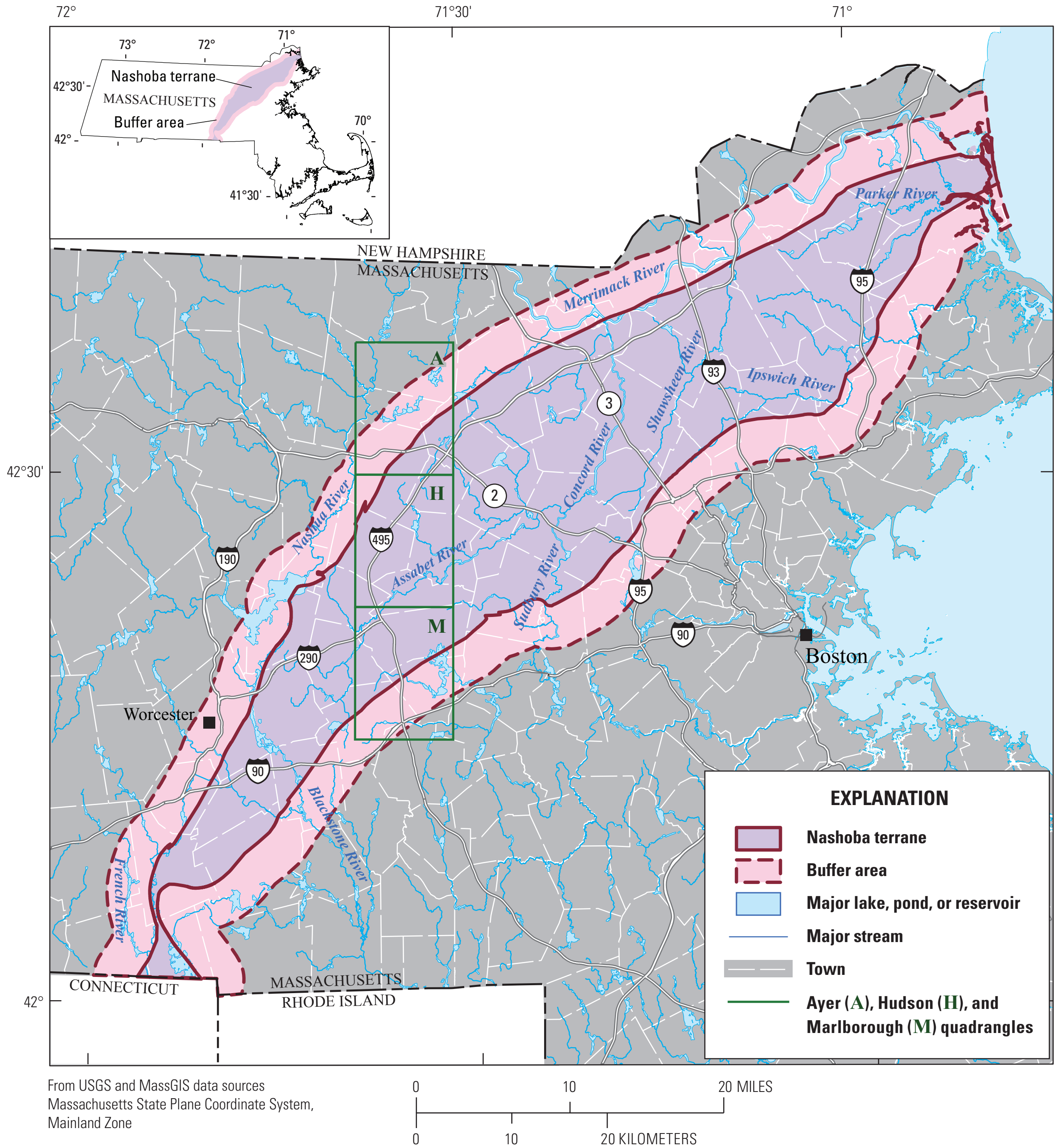


Figure 1. Location of the Nashoba terrane in central and eastern Massachusetts.

for these towns include a mix of public and privately owned community wells, private household wells, community-owned surface-water reservoirs, and a large regional water authority with water sources outside of the study area.

Geologic Setting

The Nashoba terrane is a zone of high-grade metamorphic and intrusive rocks that is bounded by two regional fault zones, the Clinton-Newbury fault on the west and the Bloody Bluff fault on the east (Goldsmith, 1991a, Skehan, 2001). It differs from the adjacent Avalon (Milford-Dedham) terrane to the east and Merrimack terrane to the west in terms of rock units, metamorphic grade, and in the composition and age of some of its intrusive rocks (Zen and others, 1983; fig. 2). The rocks of the Nashoba terrane and of the adjacent terranes are considered exotic in that they were accreted to the North American craton through a series of tectonic collisions during closure of the pre-Atlantic Iapetus Ocean in the Paleozoic Era (Acaster and Bickford, 1999; Skehan, 2001). The tectonic history and interrelations of these three terranes in eastern Massachusetts, as well as other nearby rock units in central Massachusetts, have long been subjects of study and are still not entirely understood (Wintsch and others, 1992; Acaster and Bickford, 1999; Watts and others, 2000).

Bedrock units of the Nashoba terrane are metasedimentary, metavolcanic, and intrusive plutonic rocks that are thought to have formed in a volcanic island arc or marginal basin geologic setting in the early Paleozoic (Goldsmith, 1991a; Hepburn and others, 1993; Robinson and others, 1993). The Tadmuck Brook Schist, Nashoba Formation, Fish Brook Gneiss, Shawsheen Gneiss, and Marlboro Formation compose the metasedimentary and metavolcanic rock formations (table 1). The Nashoba Formation, primarily metasedimentary schists and gneisses, and the Marlboro Formation, primarily metavolcanic amphibolites and gneiss, are the most areally extensive of the metamorphic rock units (fig. 2). Intrusive plutonic rocks include the Andover Granite, several more mafic rock units—the Sharpners Pond Diorite, Assabet Quartz Diorite, Straw Hollow Diorite—and several unnamed units. The Andover Granite is thought to have originated, at least in part, from melting of the Nashoba Formation (Hill and others, 1984; Wones and Goldsmith, 1991). The more mafic intrusive rocks include gabbros, diorites, and tonalites, and are consistent with an origin at a subduction zone such as would be present at a convergent plate boundary (Hill and others 1984; Skehan, 2001). Regional metamorphism and deformation of Nashoba terrane rocks, mostly to high-temperature sillimanite grade, occurred when the Nashoba terrane collided with the Merrimack terrane in the early to mid-Paleozoic (Acaster and Bickford, 1999; Hepburn and others, 1993).

Rocks near the eastern margin of the Merrimack terrane and near the western margin of the Avalon terrane are included in the study area in the buffer area around the Nashoba terrane. Merrimack rock units in the study area are low-grade metasedimentary rocks—calcareous metasiltstones, metapelites, and quartzites—and intrusive rocks, mostly granites, but also include some more mafic rock types (table 1). The metasedimentary rocks are thought to have originated as turbidite and submarine fan sediments/deposits (Robinson and Goldsmith, 1991). Rocks of the Avalon terrane (Milford-Dedham Zone; Zen and others, 1983) in the study area include extensive, Precambrian granitic plutons and the metasedimentary Westboro Formation (table 1). Avalon terrane rocks in eastern Massachusetts can be correlated with similar rocks in Great Britain; they are thought to have formed as volcanic and plutonic islands that were accreted on to the North American craton and later split during the opening of the Atlantic Ocean (Rast and Skehan, 1983; Goldsmith, 1991b). Unmetamorphosed sedimentary and volcanic rocks of the Newbury Volcanic Complex (included on the statewide geologic map with the Avalon terrane rocks) occur in fault-bounded blocks adjacent to the Avalon and Nashoba terranes and may be volcanic expressions of the intrusive rocks of intermediate composition in the Nashoba terrane (Goldsmith, 1991b; Hepburn and others, 1993).

Rocks of the Nashoba, Merrimack, and Avalon terranes in the study area are fractured and faulted. The two regional fault zones, the Clinton-Newbury and Bloody Bluff zones, define the terrane boundaries and thus likely coincide with the former locations of the tectonic features associated with terrane accretion, presumably subduction zones (Skehan, 2001). Both fault zones have complex histories, with multiple episodes of movement (Hepburn and others, 1993). Within the Nashoba terrane, faulting and fracturing also is complex (Barosh, 1984; Goldsmith, 1991c). Two regional faults, the Assabet River and Spencer Brook faults, extend in a northeast-southwest direction through parts of the terrane (fig. 2).

Hydrogeologic Setting

Groundwater in the crystalline rocks of the Nashoba terrane flows primarily through secondary porosity: joints, faults, fractures, and other openings (henceforth, collectively called “fractures”) in otherwise relatively impermeable competent rock. Groundwater recharge is from infiltration of precipitation, either directly in areas where bedrock is exposed or indirectly as leakage from saturated overlying unconsolidated deposits; water also may infiltrate the bedrock aquifer directly from surface waters. Discharge is to streams, lakes and ponds, wetlands, directly to the ocean in coastal areas, to overlying unconsolidated deposits, and to supply wells. Flow systems typically follow topography, especially where steeply dipping fractures provide for close connection between the bedrock aquifer and overlying unconsolidated deposits and surface waters (Daniel, 1989; Lyford and others, 2003; Starn and Stone, 2005; Mack, 2009). The complex geometry of interconnected fracture zones, however, can result in flow systems that extend substantially beyond surface-water divides; these conditions may be prevalent in rocks with moderately or shallow dipping fractures (Tiedeman and others, 1997; Williams and others, 2005; Mabee and Salamoff, 2006).

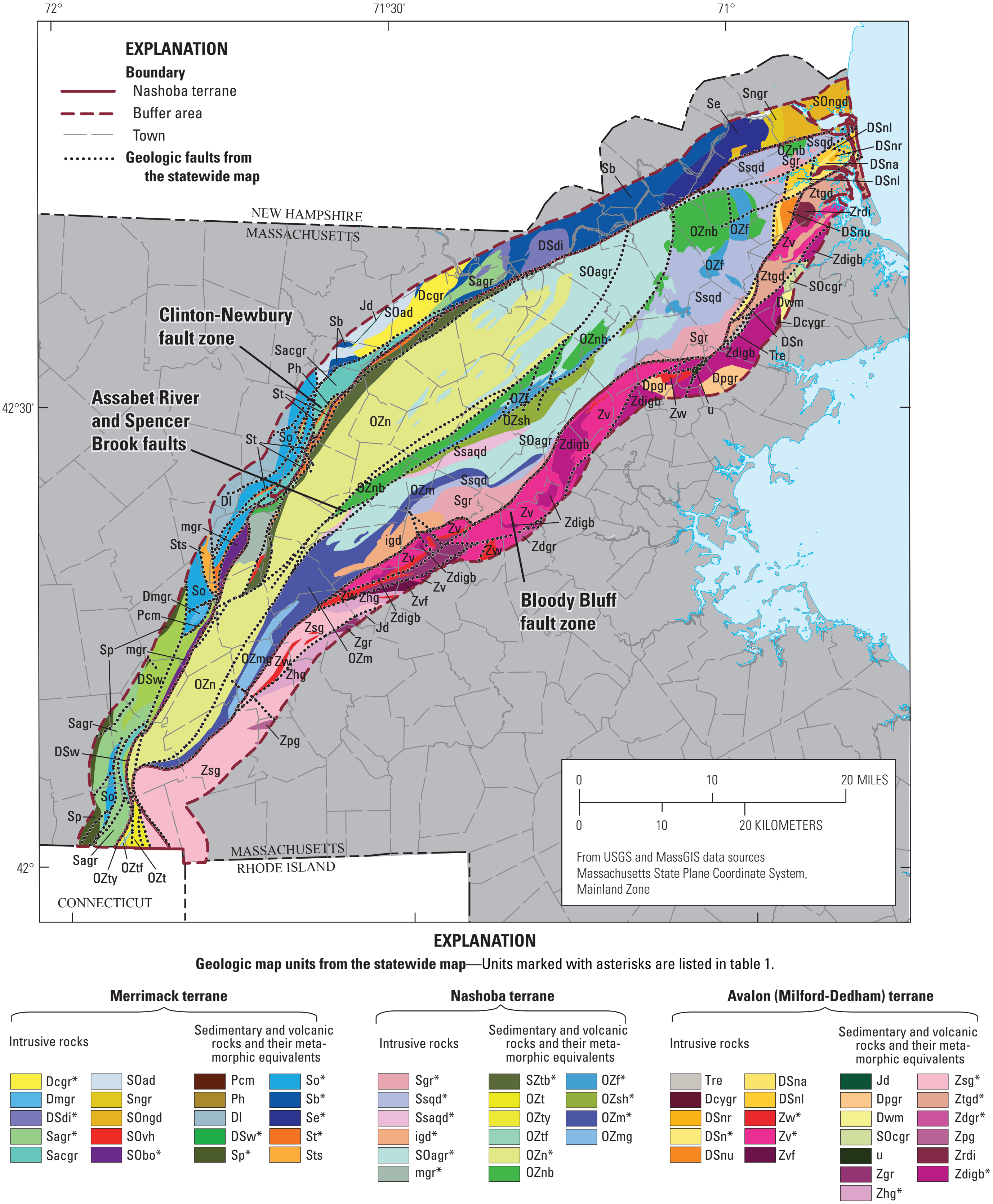


Figure 2. Bedrock geology in the Nashoba terrane and surrounding area. Data are from Zen and others (1983) and Nicholson and others (2006). Geologic map units are listed in table 1 and (or) appendix 2.

Table 1. Major geologic map units in the Nashoba terrane and surrounding area.

[Description from the statewide geologic map for Massachusetts, Zen and others (1983). See Zen and others (1983), figure 2, and appendix 1 for a complete list of rock units shown on the statewide bedrock map]

Bedrock formation	Map symbol	Generalized rock type	Description
			Nashoba terrane
Andover Granite	SOagr	granite	Light to medium grey, foliated, medium to coarse-grained muscovite-biotite granite, with pegmatite common. Includes the Acton Granite.
Assabet Quartz Diorite	Ssaqd	diorite, gabbro, and other mafic intrusive rocks	Gray, medium-grained, slightly foliated biotite-hornblende diorite and quartz diorite*
Fish Brook Gneiss	OZf	schist and gneiss	Light grey, biotite-plagioclase quartz gneiss, with a distinctive swirl-form foliation
Granodiorite of the Indian Head pluton	igd	granite	Gray, fine- to medium-grained biotite granodiorite, and gray fine-grained hornblende-biotite tonalite
Marlboro Formation	OZm	amphibolite	Thinly layered amphibolite, biotite schist and gneiss, minor calc-silicate granofels, and felsic granofels
Nashoba Formation	OZn	schist and gneiss	Sillimanite schist and gneiss, partly sulfidic, amphibolite, biotite gneiss, calc-silicate gneiss, and marble
Sharpners Pond Diorite	Ssqd	diorite, gabbro, and other mafic intrusive rocks	Nonfoliated, medium-grained equigranular biotite-hornblende tonalite and diorite
Shawsheen Gneiss	OZsh	schist and gneiss	Sillimanite gneiss, sulfidic at base, with minor amphibolite
Straw Hollow Diorite	Ssaqd	diorite, gabbro, and other mafic intrusive rocks	Gray, medium-grained, slightly foliated biotite-hornblende diorite and quartz diorite*
Tadmuck Brook Schist	SZtb	pelitic rocks	Andalusite phyllite and sillimanite schist, partly sulfidic, with local quartzite in upper part
Unnamed	mgr	granite	Light-gray muscovite granite
Unnamed	Sgr	granite	Orange-pink, rusty weathering, medium-to coarse-grained biotite granite to granodiorite
			Merrimack terrane
Ayer Granite	Sagr	granite	Granite to tonalite, partly porphyritic; locally gneissic; locally muscovitic
Berwick Formation	Sb	pelitic rocks	Thin- to thick-bedded metamorphosed calcareous sandstone, siltstone, and minor muscovite schist
Boylston Schist	SObo	pelitic rocks	Carbonaceous phyllite and schist; locally sulfidic; quartzite; calc-silicate beds
Eliot Formation	Se	pelitic rocks	Phyllite and calcareous phyllite
Oakdale Formation	So	pelitic rocks	Metamorphosed thin-bedded pelitic and calcareous siltstone and muscovite schist
Paxton Formation	Sp	schist and gneiss	Biotite granofels, calc-silicate granofels, and sulfidic schist
Tower Hill Quartzite	St	quartzite	Quartzite and phyllite
Worcester Formation	DSw	pelitic rocks	Carbonaceous slate and phyllite and minor metagraywacke
Chelmsford Granite	Dcgr	granite	Light gray, even and medium-grained, muscovite-biotite granite; locally foliated
Unnamed	DSdi	diorite, gabbro, and other mafic intrusive rocks	Diorite and tonalite
			Avalon (Milford-Dedham) terrane
Newbury Volcanic Complex	DSn	volcanics	Sedimentary and volcanic rocks, including rhyolite, porphyritic andesite, basalt, tuff, mudstone, and siltstone
Westboro Formation	Zw	pelitic rocks	Quartzite, schist, calc-silicate quartzite, and amphibolite
Unnamed	Zv	volcanics	Metamorphosed mafic to felsic flow, and volcaniclastic and hypabyssal intrusive rocks
Dedham Granite	Zdgr	granite	Light grayish-pink to greenish-gray, equigranular to slightly porphyritic granite
Hope Valley Alaskite Gneiss	Zhg	granite	Mafic-poor gneissic granite, locally muscovitic
Scituate Granite Gneiss	Zsg	granite	Gneissic granite containing biotite in small clots
Topsfield Granodiorite	Ztgd	granite	Gray to gray-green, porphyritic granodiorite containing blue quartz; usually cataclastically foliated and altered
Unnamed	Zdigb	diorite, gabbro, and other mafic intrusive rocks	Diorite and gabbro

*Assabet Quartz Diorite and Straw Hollow Diorite are undifferentiated on the statewide geologic map (Zen and others, 1983).

Hydraulic properties of fractured-bedrock aquifers such as those of the Nashoba terrane are typically extremely variable; reported ranges of hydraulic conductivity or aquifer transmissivity at sites in fractured-bedrock aquifers in New England extend over six orders of magnitude (Shapiro and Hsieh, 1998; Johnson, 1999; Lyford and others, 1999, 2003). Research at the Mirror Lake site and elsewhere in fractured igneous- and metamorphic-rock aquifers indicates that this heterogeneity is structured with zones of highly transmissive fractures that are connected through networks of less transmissive fractures (Day-Lewis and others, 2000; Shapiro and Hsieh, 2001). At the regional scale, the hydraulic properties of the less transmissive fractures control groundwater-flow rates (Shapiro, 2003); locally, high-yielding wells intersect the more transmissive zones, with sustained yield, in some cases, supported by hydraulic connections to surface waters or thick overlying unconsolidated deposits (Cederstrom, 1972; Caswell, 1979). The heterogeneous nature of fracture networks also leads to abrupt changes in hydraulic properties over short distances (Shapiro, 2003). Pervasive patterns of fracture orientation can impart a pronounced anisotropy to hydraulic properties and to the areal extent of locally transmissive zones (Singhal and Gupta, 2010).

Several recent studies provide information about fractures and groundwater flow in the Nashoba terrane rocks that is based on measurements of fractures at bedrock outcrops and in boreholes (Mabee, 2005; Kopera and others, 2006b; Mabee and Salamoff, 2006; Manda and others, 2008; and Boutt and others, 2010); similar characteristics are described for bedrock wells in Connecticut (Starn and Stone, 2005). Three main types of fractures were identified—tectonic joints, foliation-parallel fractures, and sheeting joints (Boutt and others, 2010).

Major sets of tectonic joints in the Nashoba terrane are steeply dipping and are in the northeast-southwest (azimuth of 30 degrees) and northwest-southeast (azimuth of 130 degrees) directions (Manda and others, 2008). The directions of major tectonic joints are roughly parallel and perpendicular to the regional tectonic fabric; no relation to rock type was found (Manda and others, 2008). Minor sets of steeply dipping fractures in north-south and east-west directions also occur (Mabee, 2005; Kopera and others, 2006b; Mabee and Salamoff, 2006). Steeply dipping fractures are expected to provide connections between the bedrock aquifer and overburden, as well as connections between subhorizontal fracture sets (Starn and Stone, 2005; Boutt and others, 2010).

The directions of foliation-parallel fractures tracks the central directional trend of the Nashoba terrane area (north-northeast in the south changing to north-east in the north), with azimuth values ranging from 30 to 70 degrees. The vertical orientation of foliation-parallel fractures varies. Foliation-parallel fractures in the Nashoba terrane are best developed in several rock types, including amphibolites and foliated granitic gneisses, and in rocks near fault zones (Boutt and others, 2010). Modeling by Manda and others (2008) highlighted the importance of foliation-parallel fractures in Nashoba terrane rocks as flow conduits, as connections between fracture sets, and as sources of anisotropy. Study sites in Paxton and West Newbury, in areas surrounding the Nashoba terrane, are examples where shallow dipping, foliation-parallel fractures were the primary water-bearing fractures for high-yielding supply wells (Lyford and others, 2003); foliation-parallel fractures at lithologic boundaries also were the primary sources of water to a number of high-yielding supply wells in fractured igneous- and metamorphic-rock aquifers in Georgia (Williams and others, 2005).

Sheeting joints, the third main type of fracture in the Nashoba terrane, are subhorizontal fractures that are thought to form from stress release. Sheeting joints are found primarily in massive (unfoliated) rocks, such as granites, or steeply dipping foliated rocks (Boutt and others, 2010). Sheeting joints are expected to provide lateral connectivity between steeply dipping fracture sets and to be important components of shallow flow systems.

All three types of fractures decrease in frequency and increase in spacing with depth, based on analyses of 17 boreholes in the Nashoba terrane and nearby Avalon terrane (Boutt and others, 2010). Only about 3 percent of all fractures were hydraulically active; the number of hydraulically active fractures also decreased with depth, with most found at depths less than about 330 ft [100 meters (m)]. Findings from the borehole study suggested a decrease in aquifer permeability with depth because of the decreased density, and therefore connectivity, of fractures.

Data Sources and Methods of Analysis

A variety of methods were used to compile data on well yield in the study area and to develop datasets of hydrogeologic factors that may be related to well yield. Hydrogeologic factors include bedrock and surficial geology, hydrostructural domains, topographic setting, and distance to surface-water bodies, mapped faults, and lineaments.

Well Data

Data on well yield was compiled from three data sources: the Massachusetts database of well-completion reports (Massachusetts Department of Environmental Protection, 2012), the USGS National Water Information System (NWIS) database, and MDEP records on supply wells.

Well-Completion Report Database

Historical records and an electronic database of well-completion reports currently (2012) are maintained by the MDEP [formerly maintained by the Massachusetts Department of Conservation and Recreation (MDCR)]. Well-completion reports, with location and construction information, have been required by State law since 1962 for all wells drilled in Massachusetts. Reports filed since about 2001 have been entered into an electronic database, and since 2007, records that also provide geographic locations from global positioning systems have been filed electronically by well drillers (Laurene Poland, Massachusetts Department of Conservation and Recreation, oral commun., August 2006). The electronic database also has been populated with historical well-completion report records for some towns. This database of well-completion reports was the largest source of well-yield information for this study.

Data were obtained from the well-completion report database in several stages. Initially, all records in the electronic database for 68 towns in the study area were obtained from MDCR in November 2007 (6 towns with small areas in the buffer area around the Nashoba terrane were excluded from this initial, large data retrieval). A second, similar retrieval was requested and obtained for records entered into the database between November 2007 and August 2008 for all 74 towns in the study area. In 2007–8, the MDEP and MDCR mapped private-well locations in towns within the USGS 7.5 × 7.5-minute Westford quadrangle. As part of this project, historical well-completion report records were entered into the electronic database with verified well locations. Records for towns in the Westford quadrangle were obtained from MDEP and MDCR, along with ArcGIS data layers of verified well locations, in July 2008.

Data obtained from the well-completion report database included well location; well use; date of well construction and construction method; well depth and depth to bedrock; well casing, screen, and seal description; well yield and information about the methods used to measure well yield; and description of the aquifer materials penetrated. Wells completed in bedrock for potential inclusion in the present study were identified by using information on drilling method, well depth and depth to bedrock, description of well casing and screen, and description of aquifer materials. All data were reviewed for conflicting values or obvious errors of the data-entry type (for example, depth to bedrock greater than well depth), and questionable data were eliminated.

Well locations from the well-completion report database obtained in 2007 and 2008 were primarily described in terms of street name and street number of the property where the well was located. This location information was converted to spatial data that could be used in a geographic information system (GIS) analysis through a geocoding process, and geocoded locations were verified through comparison with digital parcel data or through site visits. This process was not applied to wells in the Westford quadrangle towns for which verified locations were obtained from MDEP. The commercially available Google Earth Pro software program was used to generate latitude and longitude locations for the street addresses in the well-completion report database after geocoded locations were tested and compared with known locations and with locations from well inventories provided by the Massachusetts Geological Survey (MGS) for parts of the study area. Misspelled street names were corrected before geocoding, where possible. Geocoded locations were verified and adjusted on screen by using ESRI's ArcMap (v. 9.3), digital orthophoto imagery (1:5,000 scale; MassGIS, April 2005), and available digital parcel data from MassGIS (accessed in August 2007 or February 2008, and available for about two-thirds of the towns in the study area). Well locations were considered verified if the geocoded location could be related to a residential, commercial, or industrial parcel with the same street address in the digital parcel data. Verified well locations were adjusted by moving the point location generated by Google Earth Pro (typically along a road) to overlie the house or other building visible in the parcel on the orthophotos. The house or building location, though not expected to represent the exact location of the well on the parcel, could be consistently located and was considered to reasonably approximate the well location, given the scale of this study. Tax assessor's maps or parcel data available directly from towns were used to verify and adjust geocoded locations for a few towns. For towns with no available digital parcel data or tax assessor's maps (about one-fourth of the towns), site visits were made to verify geocoded well locations. For towns where site visits were made, well locations were similarly adjusted during the site visit to overlie houses or other buildings visible on orthophotos. Wells for which geocoded locations could not be verified were eliminated from the dataset used in the study. Wells outside the study area also were eliminated. About 6,200 wells with verified locations and well-yield data were compiled from the well-completion report database for use in the study.

National Water Information System Database

The USGS maintains records of wells and other groundwater sites in its NWIS database. Wells used in past or current hydrologic studies or monitoring programs conducted by the USGS are inventoried in this database. Available information includes well location, well use, well depth, aquifer information, and may also include construction information, hydrologic data, and water-level data.

Well records were retrieved from the NWIS database for all well sites in the three counties in which the study area was located—Essex, Middlesex, and Worcester Counties. Latitude and longitude data were used to create a GIS datalayer of locations, and wells located outside the study area were eliminated. Wells completed in bedrock for potential inclusion in the study were identified by using information on the aquifer from which the well withdraws water, well finish type, well depth, and drilling method. Well records retrieved from the NWIS database were compared to well records and locations compiled from the MDEP/MDCR well-completion report database, specifically, by comparing the well construction date, depth, and yield by town. Records for a small number of wells (12) were removed from the NWIS dataset; such duplicates can occur because well-completion reports have been used as a source of information for past USGS hydrologic studies. Well-yield data for about 940 wells in the study area were compiled from the NWIS database for use in the study. Many of these records also were used in a previous statewide study of bedrock well yield (Hansen and Simcox, 1994).

Supply-Well Records

Wells that provide water for public water systems or for large industrial, commercial, or agricultural users are regulated by the MDEP. Public-supply systems are defined as systems that deliver water to at least 25 people at least 60 days of the year, or serve at least 15 service connections. They include large municipal-supply systems as well as smaller systems that serve apartments, condominiums, schools, businesses, and restaurants. Large industrial, commercial, or agricultural users are those that withdraw more than 100,000 gallons per day (gal/d) from water-supply sources. Permit applications to MDEP for public water sources or large withdrawals from groundwater sources contain information on well location, well depth, well yield, aquifer lithology, and aquifer responses to pumping.

Supply wells regulated by MDEP in the study area were identified through a review of MDEP records and a database of permitted water-withdrawal sources compiled for a statewide streamflow study (Archfield and others, 2009). The statewide database, which was developed from an electronic database of supply wells maintained by MDEP, contained well locations (GIS datalayer), annual withdrawal rates, and well type for some wells. The statewide database provided a preliminary list of supply wells in the study area. A review of permit-application reports and other consultants' reports in files maintained at MDEP regional offices in Worcester and Wilmington for the towns in the study area were used to identify supply wells with sufficient location, yield, and aquifer information for inclusion in the present study. Well locations in the GIS data layer from the statewide study were verified and adjusted as necessary, and wells were added on the basis of site-scale location maps in the consultants' reports. About 170 regulated supply wells were identified for use in the present study from MDEP records.

Spatial Data

Factors that potentially influence well yield were determined from spatial data that described topography, geology, and hydrology. Bedrock and surficial geology, hydrostructural domains, topographic setting, land-surface elevation and slope, and the presence or absence of wetlands were identified at well locations. Surficial geology, wetlands, and water bodies in the vicinity of wells also were characterized for 400-ft buffer areas surrounding wells. Finally, the proximity of well locations to streams, water bodies, wetlands, mapped geologic faults, and lineaments was determined by calculating the distance of the well to the nearest of each of these features. All editing and analysis of digital spatial data was done by using ESRI's ArcGIS software programs.

Bedrock Geology

Bedrock geology at the statewide scale was mapped at 1:250,000 scale by Zen and others (1983). A digital version of this statewide map was published by the USGS as part of a compilation of state geologic maps (Nicholson and others, 2006). The areal extents of bedrock geologic rock units as well as the locations of mapped regional faults that were depicted on the original paper map (Zen and others, 1983) are available in the digital version. The digital statewide geologic map was used to define the study-area boundaries and provided bedrock geologic information for well locations throughout the study area.

Maps of bedrock geology at the scale of individual 7.5 × 7.5-minute quadrangles (1:24,000) also were available for parts of the study area. New preliminary bedrock geologic maps with digital GIS data recently were compiled by the MGS for eight quadrangles in the study area. These quadrangles are the Ayer, Hudson, Lawrence, Marlborough, Reading, South Groveland, Westford (northern one-half only), and Wilmington quadrangles. Initially, all eight of these were the focus of the quadrangle-scale analysis in the study. However, the focus of the quadrangle-scale analysis was narrowed during the study to include only the Ayer, Hudson, and Marlborough quadrangles (Kopera and Hansen, 2005; Kopera, 2006; Kopera and others, 2006a; fig. 1), for which fracture data were available and hydrostructural domains had been delineated (Mabee, 2005; Kopera and others, 2006b; Mabee and Salamoff, 2006).

The bedrock geologic units shown on the state and quadrangle maps (henceforth called "geologic map units") are numerous and are based on age, rock type, and other characteristics. Geologic map unit was used as a potential factor affecting well yield, but geologic map units also were grouped into generalized rock-type categories (table 1). These five categories (amphibolites; diorite, gabbro, and other mafic intrusive rocks; granite; pelitic rocks; and schist and gneiss) were generalized from descriptions of the most abundant or dominant rock type, as described in the state map in "geologic map unit rock type" (this attribute is defined as "rocktype1" in the digital version of the state geologic map; Nicholson and others, 2006); and from the lithogeochemical classification for New England from Robinson and Kapo (2003). Bedrock geology at well locations was determined for all wells from the statewide map and, for wells that were located within the Ayer, Hudson, and Marlborough quadrangles, also from the quadrangle geologic maps.

Topography

Topographic setting was characterized by using digital elevation model data (DEMs; 1:5,000, 5 × 5-m cell size, MassGIS, 2005; fig. 3). Conceptually, topographic setting was envisioned as a continuum of hills (or ridges), slopes, flats, and valleys. Identification and mapping of these features on the landscape surface was an iterative, two-step process

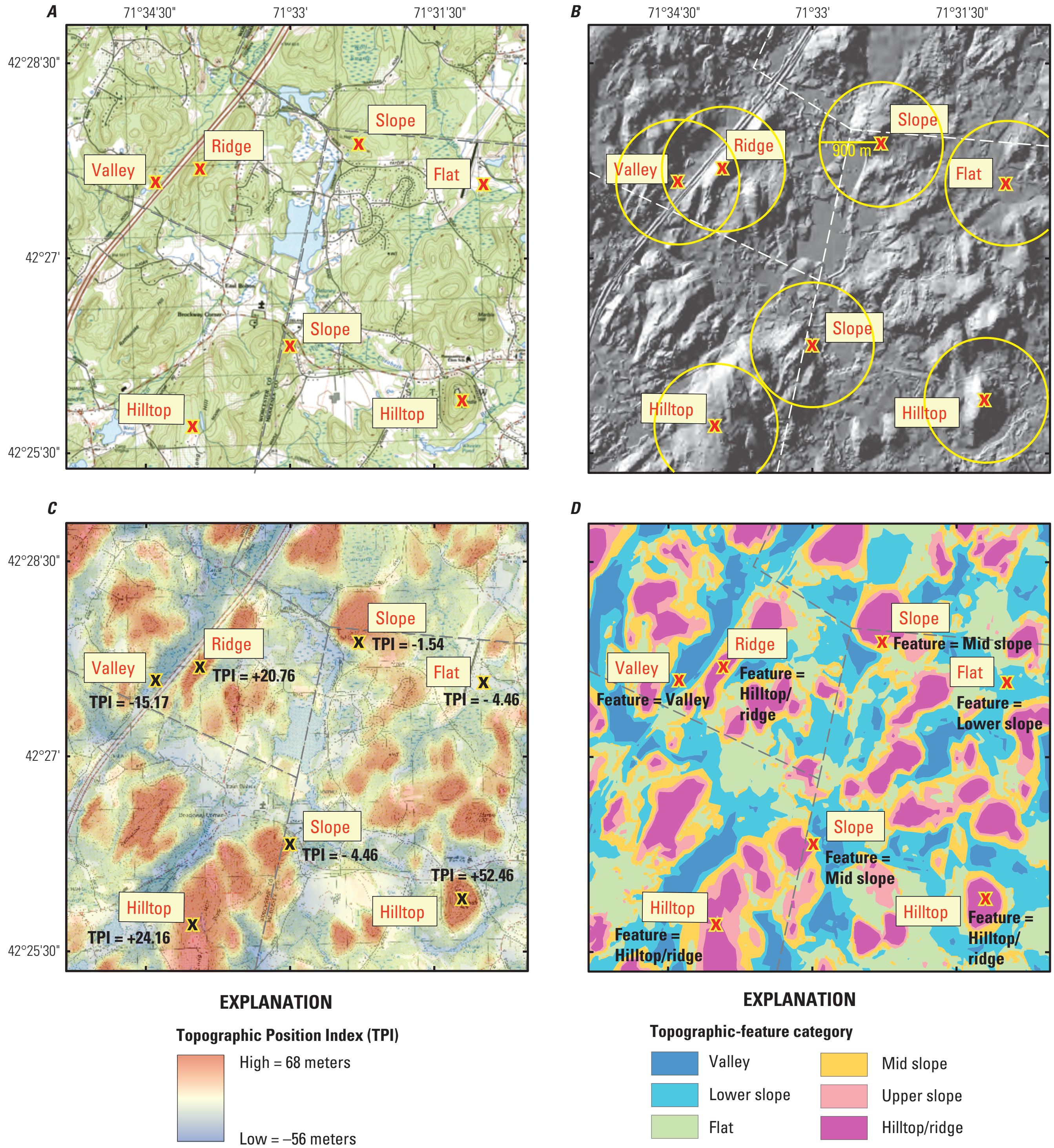


Figure 3. Example of steps used to develop topographic feature categories from digital elevation model (DEM) data. Data are for an area of about 15 square miles near the center of the Nashoba terrane. Symbols and annotation designate example locations within recognizable landscape features. *(A)* Image of topographic map showing landscape features defined by contour lines. *(B)* Shaded relief map of 1:5,000-scale DEM data (MassGIS, 2005). Circle represents "neighborhood" for comparison with elevation at the example point location. *(C)* Topographic position index (TPI), calculated by comparing the elevation at the point location of each 5-meter cell of DEM dataset to the elevation of the neighboring cells. *(D)* Topographic feature categories, determined by comparing the TPI at each point location to the TPI in the surrounding neighborhood. Methods are from Weiss (2001), T. Dilts, University of Nevada, written commun. (2009), and J. Jenness, Jenness Enterprises, written commun. (2006).

that used raster-based algorithms to analyze and classify the landscape topography as depicted by the DEM data. The algorithms were modified versions of tools developed for ESRI ArcGIS and ArcView by T. Dilts (University of Nevada, written commun., 2009) and J. Jenness (J. Jenness, Jenness Enterprises, written commun., 2006) and were obtained from the ESRI Support Center (http://support.esri.com). These tools were based on concepts described in Weiss (2001) and applied, for example, in Guisan and others (1999), Lundblad and others (2006), and Dickson and Beier (2007). Topographic features were mapped in this way by using GIS-based algorithms so that the topographic position of study wells could be identified automatically and consistently.

The process of delineating topographic features was as follows. First, the relative topographic position of each cell in the DEM raster was determined by comparing elevation at the cell to the elevation of the surrounding area. The surrounding or neighborhood area was defined by a circle centered on the cell. A topographic position index (Weiss, 2001; J. Jenness, Jenness Enterprises, written commun., 2006) was calculated as the difference between the elevation at the cell and the mean elevation in the neighborhood area. Conceptually, this difference is a positive number (cell elevation is greater than the mean elevation of the neighborhood area) for cells on hilltops and a negative number (cell elevation is less than the mean elevation of the neighborhood area) for cells in valleys (fig. 4). In cases where the topographic position index is near zero (cell elevation is similar to the mean elevation of the neighborhood area), the cell may be located in a flat area or in an area of constant slope. The land-surface slope in the vicinity of the cell, determined from the DEM raster dataset, can be used to distinguish between these two possibilities.

The topographic position index is scale dependent and also varies in magnitude with the shape of topographic features. The size of the circle used to define the neighborhood determines the scale of features that are identified—with a smaller circle, smaller hills and valleys are identified, but features that are large compared to the circle size (such as broad ridges) may not be well categorized. Larger positive or negative numbers for the topographic position index, representing larger differences between a cell and its neighborhood, are produced by topographic features that are sharply defined (for example, narrow ridges or valleys), as compared to features with more broad and gentle slopes. Consequently, the tops of hills of the same elevation may have different topographic position index values if one has a more sharply defined hilltop and the other has a flatter hilltop (for example, the topographic position index for the two hilltop examples in fig. 3C). A final step in delineating topographic features was to develop a classification scheme that normalizes the absolute values of topographic position index by comparison with the topographic position index of the cells in the surrounding neighborhood.

Several neighborhood areas and classification schemes were tested to develop an algorithm that would characterize topographic setting in the study area. Results were overlain onto images of USGS 1:24,000-scale topographic maps to evaluate how well they reproduced the landscape features shown on the topographic maps. Radii of 75, 150, 450, 675, and 900 m were tested for the size of the neighborhood areas. Initially, the 1:5,000-scale raster dataset, with elevation values for each 5 × 5-m cell, was used directly to calculate the topographic position index. However, the influence of local relief was too great in these fine-scale data, so that large hills and ridges could not be adequately defined. Also, there were computation limits on the size of the neighborhood areas that could be tested. Consequently, the 5 × 5-m -cell raster dataset was resampled to create an elevation grid of 15 × 15-m cells. Similarly, the 5 × 5-m -cell raster dataset was resampled to a larger cell size (30 × 30 m) for the calculation of slope, which is used to distinguish cells with topographic position indices near zero in flat areas from cells in areas of constant slope. Finally, topographic-feature categories were determined from the topographic position index and slope by using the mean

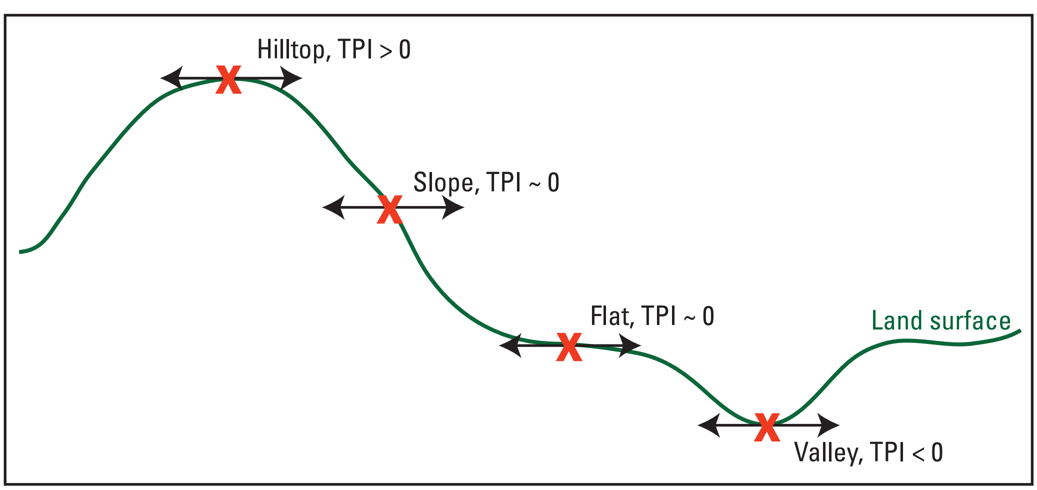


Figure 4. Relative values of topographic position index (TPI) at example locations along a typical landscape profile from hilltop to valley. >, greater than; ~, about equal to; <, less than.

and standard deviation of the topographic position index in the neighborhood rather than from any absolute value of topographic position indexes. This approach allowed hills and valleys to be defined based on local relief, which was appropriate for the irregular and dissected topography of the study area.

Several algorithms were developed that provided reasonably good representations of topographic features in the study area based on comparisons with topographic map images and with the designations of topographic settings made by field hydrologists for a subset (844) of the wells from the USGS NWIS database. The final algorithm used for the present study (fig. 3D) uses the 15 × 15-m resampled DEM data, a 2,950-ft (900-m) radius to define the neighborhood area, and a slope threshold value of 5 degrees to distinguish flat areas and areas of uniform slope. The topographic-feature categories are similar to those suggested by Weiss (2001) and are hilltop/ridge, upper slope, mid slope, flat, lower slope, and valley bottom (fig. 3D). A raster dataset (15 × 15-m cell size) of the topographic-feature category for each well was created for the study area. The topographic setting for each well was identified by determining the topographic-feature category of the raster cell at the well location. Elevation and landscape slope (30 × 30-m cell size for slope grid) also were determined for each well location.

Mapped Geologic Faults

Geologic faults depicted on the statewide map (Zen and others, 1983) were available as digital data in the USGS state geologic map compilation (Nicholson and others, 2006). These include traces of the Clinton-Newbury and Bloody Bluff fault zones, and other faults as interpreted by compilers of the statewide map (Goldsmith, 1991c). Faults depicted on MGS quadrangle geologic maps also were available as digital data and included traces of the Clinton-Newbury, Bloody Bluff, and Assabet River fault zones. The proximity of well locations to mapped geologic faults was determined as the distance to the nearest fault (1) for all wells in the study area and faults from the statewide geologic map and (2) for the wells in the Ayer, Hudson and Marlborough quadrangles and faults from the MGS quadrangle maps.

Lineaments

Lineaments are linear features identified on aerial photographs or from digital elevation data that may represent the surface expression of underlying zones of fractured bedrock. These features may include aligned topographic features, straight stream segments, aligned gaps in ridges, and tonal alignment of vegetation and soils (Clark and others, 1996). Lineaments have been used in a number of studies to investigate well yield and are used in New England in the exploration of fractured-bedrock aquifers for water supplies (Mabee and others, 1994; Hardcastle, 1995; Moore and others, 2002).

Lineaments were delineated for a part of the study area, defined by the borders of the Ayer, Hudson, Marlborough, and Westford 7.5 × 7.5-minute quadrangles. These four quadrangles are in the central part of the study area and were selected because of the availability of extensive fracture data for this area (Mabee, 2005, Kopera and others, 2006b; and Mabee and Salamoff, 2006). In the Westford quadrangle, fracture data were being collected during the study (S.B. Mabee, Massachusetts Geological Survey, oral commun., 2008). Although lineaments were delineated in the Westford quadrangle, analyses of well yield and proximity to lineaments are not included in this report for this area because quadrangle-scale bedrock and fracture data did not become available during the study period. Results for yield and proximity to lineaments for all four quadrangles, including the Westford quadrangle, were not substantially different from those for the area that included only the Ayer, Hudson, and Marlborough quadrangles.

Lineaments were delineated on the basis of three data sources: high-altitude (1:80,000) black-and-white aerial photographs, color-infrared (CIR) (1:58,000) aerial photographs, and shaded DEM (1:5,000) data (shaded DEM). These three types of images are referred to in this report as 1:80,000, CIR, and shaded DEM lineaments. Lineaments were independently delineated by two experienced observers, and coincident lineaments were identified as those delineated by both observers. Coincident lineaments are considered to be less subjectively determined than lineaments identified by only one observer (Mabee and others, 1994). Procedures for lineament delineation followed those described in Clark and others (1996).

Correlation of lineaments with fractures mapped at bedrock outcrops was used to identify lineaments that might be more likely to represent actual subsurface bedrock fractures and thus potentially transmissive bedrock aquifer zones. The fracture data were from Mabee (2005), Kopera and others (2006b), and Mabee and Salamoff (2006), who each compiled numerous measurements of fractures at outcrops in the Ayer, Hudson, and Marlborough quadrangles on MGS fracture-characterization maps. Strike, dip, and other information was compiled for the mapped fractures, which included joints, faults, and joint and fault zones. A lineament was determined to be fracture correlated if its azimuth direction fell within the range of azimuth values that defined the predominant fracture sets in the quadrangles. Lineaments were first identified as fracture correlated separately for each of the Ayer, Hudson, and Marlborough quadrangles by using the major and minor steeply dipping (dips greater than 60 degrees) fracture sets defined on the MGS fracture-characterization maps. With this approach, most (84 percent) of lineaments in these three quadrangles were determined to be fracture correlated. However, recognizing that the quadrangle limits are artificial boundaries, lineaments were subsequently identified as fracture correlated using a second approach; in the second approach, the azimuth directions of all steeply dipping fractures measured at outcrops in the three quadrangles were combined to determine principal fracture directions for the entire three-quadrangle area.

Data for 4,868 steeply dipping fractures at 195 outcrops in the Ayer, Hudson, and Marlborough quadrangles were used. This analysis, following the methods of the map authors, used the DAISY software (version 4.8.12, accessed August 24, 2009, at http://host.uniroma3.it/progetti/fralab; Salvini and Wise, 1999) to fit Gaussian curves to smoothed azimuth-frequency histograms. The two principal fracture directions identified for the three-quadrangle area with the latter approach—25 ± (plus or minus) 19 degrees and 137 ± 18 degrees—overlap at least, in part, with the azimuth ranges of fracture sets described in each of the three MGS fracture-characterization maps. These directional criteria were used to identify fracture-correlated lineaments for comparison to well yield for all wells in the three-quadrangle area. To identify fracture-correlated lineaments for comparison to well yield for wells in the Nashoba terrane only, the DAISY analysis was also performed using only fractures and outcrops within the Nashoba terrane (2,574 fractures at 122 outcrops). These principal fracture directions—27 ± 14, 113 ± 6, and 140 ± 13 degrees—are similar to those from the entire area of the three quadrangles. Both sets of fracture directions are similar to those found by Manda and others (2008) for major joint sets and foliation-parallel fractures throughout the Nashoba terrane.

Another approach, in which the directions of the mapped fractures at outcrops near individual lineaments were compared to the lineament azimuth, was investigated for identifying fracture-correlated lineaments. The approach was investigated for 1:80,000 and CIR coincident lineaments. Buffer areas of 60 m surrounding each lineament were created and outcrops within these buffer areas were identified by using the digital data supporting the quadrangle fracture-characterization maps available from the MGS. For lineaments that had outcrops within 60 m, steeply dipping fractures with strikes within 5 degrees of lineament's azimuth were mapped at the outcrops for about one-half of both types of lineaments. However, only a small percentage (less than 10 percent) of lineaments had outcrops within 60 m with fracture measurements in the MGS dataset. Consequently, this approach was not implemented.

The proximity of wells to mapped lineaments was determined as the distance of each well in the Ayer, Hudson, Marlborough, and Westford quadrangles to the closest lineament. Distance to lineaments was calculated separately for all lineaments, for coincident lineaments, for fracture-correlated lineaments, and for fracture-correlated coincident lineaments from each data source (80K, CIR, and shaded DEM).

Hydrostructural Domains

Hydrostructural domains delineated by Mabee (2005), Kopera and others (2006b), and Mabee and Salamoff (2006) for the Ayer, Hudson, and Marlborough quadrangles were obtained as Adobe Illustrator files of the map sheets from the MGS (J.P. Kopera, Massachusetts Geological Survey, written commun., 2011). Simplified versions of the files that showed only the hydrostructural domains were exported from Adobe Illustrator as image files and georeferenced in ArcMap to the quadrangle locations. A digital datalayer of the geologic maps for the quadrangles was edited in ArcMap to reproduce the hydrostructural-domain boundaries. The edited datalayer was used to identify the hydrostructural domain at well locations for wells in the three quadrangles.

Surficial Geology

Surficial geology at the 1:24,000 scale was available for most of the study area in digital form (MassGIS, 2007a). These data are based on compilations of previously published and unpublished quadrangle-map data (Stone and others, 2006, 2008; Stone and Stone, 2006, 2007) and were used to identify the surficial geologic deposits at most well locations. For small areas at the southern and east central margins of the study area, where the 1:24,000-scale data were not available, 1:250,000-scale data were used to characterize surficial geologic deposits (MassGIS, 1999a). These areas were located in the towns of Auburn, Burlington, Bedford, Charlton, Dudley, Lexington, Oxford, and Webster (appendix 1). Mapped categories of surficial geologic deposits at well locations and within 400-ft buffer areas included glacial till deposits (thin and thick till), glacial stratified deposits (coarse and fine deposits), and postglacial deposits such as flood-plain alluvium and swamp deposits (Stone and Stone, 2007).

Surface Water

Surface water in the study area—streams, ponds, and wetlands—was characterized by using networked hydrology centerline data for streams (MassGIS, 1999b) combined with 1:12,000-scale wetlands data (MassGIS, 2007b) for water bodies (stream impoundments, lakes, and ponds) and wetlands. Networked hydrology centerline data layers for major basins in the study area were appended and modified by deleting arcs that depict intermittent streams. The wetlands data layer was used in unmodified form to describe all wetlands. The wetlands data layer was modified to retain only polygons depicting open water or deep marshes and was combined with the modified centerline data layer; this data layer of perennial streams, open water bodies, and deep marshes (typically with standing water) was used to describe surface-water bodies in the study area. Hydrologic features—wetlands or water bodies—near a well were described by determining the distances to the nearest features and the percentages of the 400-ft buffer area occupied by the features.

Statistical Methods

Three types of statistical analyses were used in this study. Relations of well yield to individual hydrogeologic factors were investigated by using single-variable analysis. The relation of well yield to multiple factors considered together was investigated by using multivariate regression analysis.

The distribution of well yield throughout the study area, independent of any potential explanatory factors, was investigated by using geostatistical analysis.

Single-Variable Analysis

Well yield and individual hydrogeologic factors were compared by using rank-based methods to minimize the effects of outliers and to make assumptions about underlying data distributions unnecessary. Statistical tests comparing yield to hydrogeologic factors were performed by using the SAS software (v. 9.2; SAS for Windows). The comparisons were done for all wells, for wells in the Nashoba terrane only, and for wells grouped separately by use categories (domestic, irrigation, commercial and industrial, and public supply). Results for all wells and for wells in the Nashoba terrane only are reported in separate tables. Results for wells grouped by use categories, which were done partly to investigate whether inaccuracies or cultural effects associated with particular types of wells were obscuring relations with hydrogeologic factors, differed little from results for all wells grouped together, and so are not reported. Initially, hydrogeologic factors also were compared to specific capacity (the ratio of discharge to drawdown for a well being pumped); about two-thirds of the wells had drawdown data available. However, results of statistical analyses using specific capacity differed little from results using well yield. Consequently, well yield was selected as the preferred dependent variable, because it was available for a larger number of wells than specific capacity, and its use avoided the introduction of any additional variability associated with drawdown measurements or changes in specific capacity with time.

For comparisons of well yield and continuous factors, the Spearman correlation method was used. In this method, the Pearson product-moment correlation is performed on the ranks of the data. The resulting statistic, Spearman's r, is equivalent to the Pearson product-moment correlation coefficient (linear correlation coefficient) and measures the strength and direction of a linear relation between the ranks of the two variables. Spearman's r ranges from -1 (perfect inverse or negative relation) to +1 (perfect positive relation); values of Spearman's r near zero mean that there is a weak or no linear relation between the two variables.

For comparison of well yield and categorical variables, a one-way analysis of variance (ANOVA) test was performed on the ranks of the data. The GLM procedure of SAS was used, which is appropriate for unbalanced data (data with unequal numbers of observations in categories; SAS Institute, 2010). The multiple comparison Tukey-Kramer test was used to identify statistically significant differences between category groups (SAS Institute, 2010).

For the Spearman correlation and the ANOVA, the significance level (α) was equal to 0.05. When the attained significance level of the test (p value) was less than 0.05, the null hypothesis of hypothesis of "no correlation in ranked data" (Spearman) or "no difference in mean ranks among category groups" (ANOVA) was rejected. Note that, with large sample sizes like those used in many of the analyses in the present study, very small differences can be detected as significant with statistical tests. This means that we can be very sure about the existence of the correlation of a hydrogeologic factor with yield (for continuous factors) or difference in yield between categories of a hydrogeologic factor (for categorical factors), but the correlation or categorical difference does not explain much of the variation in the yield data.

Multivariate Regression Analysis

Multiple linear regression analysis was used to evaluate the relations between well yield and a large number of potential explanatory variables. Analysis was performed by using the Minitab 15 software (v. 15.1.30.0). Regression models were developed for (1) all wells in the Nashoba terrane and (2) wells in the Nashoba Terrane in the Ayer, Hudson, and Marlborough quadrangles. The use of wells only within the Nashoba terrane excluded any differences in yield related to differences in geology between the Nashoba terrane and adjacent Merrimack or Avalon terranes. The response variable and most of the numerical explanatory variables were log-(base-10) transformed to minimize violation of the regression assumptions of constant variance, normality, and linearity of model residuals.

Eighty-five variables were tested for inclusion in the models (table 2). Many of the variables in the regression analysis are categorical (indicator) variables and were assigned a value of 1 if a condition was met and 0 if a condition was not met. Variables describing proximity to lineaments and proximity to faults and geologic map units from quadrangle geologic maps were used in the quadrangle regression model only; variables describing proximity to faults and geologic map units shown on the statewide geologic map were used in the regional regression model only. The geologic map units included were those in which wells with yield data were located. Only one variable describing proximity to shaded DEM lineaments was included, because there was little relation between well yield and the shaded DEM lineaments in the single-variable analysis. Hydrostructural domains were not included as a variable because the data were not available at the time the multivariate regression analysis was completed. The variables describing water use were based on information from individual towns and from previous studies (for example, DeSimone, 2004), and median household income was from 2000 U.S. Census data (MassGIS, 2003). Because complete data for all variables were needed for all wells, small numbers of wells (166 for the regional dataset and 40 for the quadrangle dataset) were omitted that were missing data for some variables (well depth or construction year) or were in geologic map units with very few wells (5 or less). The total number of wells used in the regional model was 5,066, and the total number of wells used in the three-quadrangle model was 1,119.

Before developing the regression models, all variables were assessed graphically for curvature, the presence of outliers, and multicollinearity among explanatory variables.

Table 2. List of variables tested for the multivariate regression models.

[NAVD 88, North American Vertical Datum of 1988; 80K, 1:80,000-scale black-and-white aerial photographs; CIR, 1:58,000-scale color infrared aerial photographs; shaded DEM, 1:5,000 shaded digital elevation model data]

Variable	Description of variable	Variable type
	Response variables	
logYield	Log of yield, in gallons per minute	Continuous
Yield	Yield, in gallons per minute	Continuous
Yield_m	Yield per length, in gallons per minute per meter of open hole	Continuous
	Predictor variables	
	Bedrock geology	
Generalized rock type		
GenRckType3_1	Schist and gneiss	Categorical
GenRckType3_2	Granite and other rock types	Categorical
GenRckType3_3	Pelitic rocks	Categorical
GenRckType3_4	Diorite, gabbro, and other mafic rocks	Categorical
GenRckType3_5	Amphibolite	Categorical
Geologic map unit from the statewide geologic map		
BedUnit_1	Granodiorite of the Indian Head pluton (igd)	Categorical
BedUnit_2	Fish Brook Gneiss (OZf)	Categorical
BedUnit_3	Marlboro Formation—amphibolite, schist, and gneiss (OZm)	Categorical
BedUnit_4	Marlboro Formation—feldspathic gneiss (OZmg)	Categorical
BedUnit_5	Nashoba Formation—sillimanite schist and gneiss (OZn)	Categorical
BedUnit_6	Nashoba Formation, Boxford Member—amphibolite (OZnb)	Categorical
BedUnit_7	Shawsheen Gneiss (OZsh)	Categorical
BedUnit_8	Unnamed granite to granodiorite (Sgr)	Categorical
BedUnit_9	Andover Granite (SOagr)	Categorical
BedUnit_10	Straw Hollow Diorite and Assabet Quartz Diorite, undifferentiated (Ssaqd)	Categorical
BedUnit_11	Sharpners Pond Diorite (Ssqd)	Categorical
BedUnit_12	Tadmuck Brook Schist (SZtb)	Categorical
BedUnit_13	Unnamed light-gray muscovite granite (mgr)	Categorical
Geologic map unit from the quadrangle geologic maps		
BedUnit_1	Unnamed amphibole and biotite schists (COas, Hudson quadrangle)	Categorical
BedUnit_2	Unnamed amphibole gneiss (COgn, Hudson quadrangle)	Categorical
BedUnit_3	Marlboro Formation, undifferentiated (COm, Marlborough quadrangle)	Categorical
BedUnit_4	Marlboro Formation, amphibolite and schist (COma, Marlborough quadrangle)	Categorical
BedUnit_5	Nashoba Formation, amphibolite schist (COna, Hudson quadrangle)	Categorical
BedUnit_6	Nashoba Formation, undifferentiated (COnu, Hudson quadrangle)	Categorical
BedUnit_7	Nashoba Formation (On, Marlborough quadrangle)	Categorical
BedUnit_8	Nashoba Formation, undifferentiated (OZnu, Ayer quadrangle)	Categorical
BedUnit_9	Tadmuck Brook Schist (COtb, Hudson quadrangle)	Categorical
BedUnit_10	Tadmuck Brook Schist (OZtb, Ayer quadrangle)	Categorical
BedUnit_11	Andover Granite (Dag, Hudson quadrangle)	Categorical
BedUnit_12	Andover Granite, pegmatitic granite (DSap, Marlborough quadrangle)	Categorical
BedUnit_13	Straw Hollow Diorite (Sshd, Hudson quadrangle)	Categorical
	Topography	
Elev_m	Land-surface elevation, in meters above NAVD 88	Continuous
SlopeDeg	Land-surface slope, in degrees	Continuous
Topographic feature category		
spi900_1	Valley	Categorical
spi900_2	Low slope	Categorical
spi900_3	Flat	Categorical
spi900_4	Mid slope	Categorical
spi900_5	Upper slope	Categorical
spi900_6	Hilltop or ridge	Categorical
	Major faults and lineaments	
Proximity to major faults		
log(ZenFaultsDist_m)	Log of distance to the nearest fault mapped on the statewide geologic map, in meters	Continuous
ZenFault_30 m	Wells within 30 meters of fault mapped on the statewide geologic map	Categorical

Table 2. List of variables tested for the multivariate regression models.—Continued

[NAVD 88, North American Vertical Datum of 1988; 80K, 1:80,000-scale black-and-white aerial photographs; CIR, 1:58,000-scale color infrared aerial photographs; shaded DEM, 1:5,000 shaded digital elevation model data]

Variable	Description of variable	Variable type
log(NDQuadFault_All)	Log of distance to the nearest major or minor fault mapped on the quadrangle geologic maps, in meters	Continuous
log(NDQuadFault_Maj)	Log of distance to the nearest major fault mapped on the quadrangle geologic maps, in meters	Continuous
Proximity to lineaments		
log(ND80Kall)	Log of distance to the nearest 80K lineament identified—all lineaments, in meters	Continuous
log(ND80Kcoinc)	Log of distance to the nearest coincident 80K lineament, in meters	Continuous
log(ND80Kall_FCNT)	Log of distance to the nearest fracture-correlated 80K lineament, in meters	Continuous
log(ND80Kcoinc_FCNT)	Log of distance to the nearest coincident, fracture-correlated 80K lineament, in meters	Continuous
log(NDCIRall)	Log of distance to the nearest CIR lineament identified—all lineaments, in meters	Continuous
log(NDCIRcoinc)	Log of distance to the nearest coincident CIR lineament, in meters	Continuous
log(NDCIRall_FCNT)	Log of distance to the nearest fracture-correlated CIR lineament, in meters	Continuous
log(NDCIRcoinc_FCNT)	Log of distance to the nearest coincident, fracture-correlated CIR lineament, in meters	Continuous
log(NDhillcoinc_FCNT)	Log of distance to the nearest coincident, fracture-correlated, shaded DEM lineament, in meters	Continuous
	Surficial geology	
%SG	Percent stratified glacial deposits in 400-foot buffer area around well	Continuous
log(BedDepth_m)	Log of depth to bedrock (overburden thickness), in meters	Continuous
Surficial geology at well location—thin and thick till combined		
SurfAtWell_1	Till or bedrock	Categorical
SurfAtWell_2	Stratified glacial deposits	Categorical
Surficial geology at well location—thin and thick till distinguished		
SurfAtWell2_1	Thin till or bedrock	Categorical
SurfAtWell2_2	Stratified glacial deposits	Categorical
SurfAtWell2_3	Thick till	Categorical
	Surface water	
log(DistStrOpW_m)	Log of distance to the nearest stream or water body, in meters	Continuous
%OPWtot	Percentage of open water in 400-foot buffer area around well	Continuous
%WCtot	Percentage of all wetland types and open water in 400-foot buffer around well	Continuous
%WCtotNW	Percentage all wetland types except wooded wetlands and open water in 400-foot buffer around well	Continuous
Wetland type at well location		
WCatWell_1	No wetlands	Categorical
WCatWell_2	Deep marsh	Categorical
WCatWell_3	Shallow marsh, meadow, or fen	Categorical
WCatWell_4	Open water	Categorical
WCatWell_5	Shrub swamp	Categorical
WCatWell_6	Wooded swamp, deciduous	Categorical
WCatWell_7	Wooded swamp, coniferous	Categorical
WCatWell_8	Wooded swamp, mixed	Categorical
	Well characteristics	
log(depth)	Log of well depth, in meters	Continuous
log(BedColLen_m)	Log of length of open hole in bedrock, in meters	Continuous
WC_Year2	Year well was constructed	Continuous
Well Use		
Use_1	Irrigation	Categorical
Use_2	Public	Categorical
Use_3	Commercial and industrial	Categorical
Use_4	Unspecified and other (monitoring, geothermal)	Categorical
Use_5	Domestic	Categorical
Duration of pumping test to determine yield		
PmpCat_1	Less than 4 hours	Categorical
PmpCat_2	4 hours or more	Categorical
PmpCat_3	Unspecified	Categorical
	Water use and income	
Public water system in town		
PubWat_1	Yes	Categorical
PubWat_2	No	Categorical
Inc_Med_HS	Median household income from 2000 Census block data	Continuous

Correlation coefficients calculated for all variable pairs indicated that, generally, there was low correlation among explanatory variables of interest. In the few cases where variables were highly correlated, one explanatory variable of the pair was selected for further analysis.

Following the exploratory data analysis, best subsets and stepwise regressions were performed using with a large number of potential explanatory variables. The best subsets regression identifies the best-fitting regression model containing one explanatory variable, two explanatory variables, and so on, up to the total number of explanatory variables under consideration. The Mallow's C_p and adjusted R^2 (coefficient of determination) statistics were used to choose the best model with the fewest explanatory variables for further analysis. The stepwise regression sequentially adds and removes variables to the regression model based on specified *p*-values to identify a reasonable subset of explanatory variables. Following preliminary model development, the selected explanatory variables were evaluated further by fitting a multiple linear regression model to the data, determining the significance of the regression coefficient, examining other statistics such as variance inflation factors (VIF) and prediction error sum of squares (PRESS), and examining residual plots to evaluate goodness-of-fit of the regression model. During this stage of model development, other potentially important variables (that is, variables not included in the best subsets regression) were tested for inclusion in the model to ensure that factors significantly related to well yield were not excluded from the model. Variables were included in the final models if they were significant at the level of α equals 0.05. Model residuals were examined for normality, constant variance, and independence to determine if model assumptions were met.

Because preliminary regression models based on the complete dataset explained only a small amount of the variance in well yield, the dataset was stratified or modified in several different ways in an attempt to provide better insight into the data and produce a model that explained more of the variance in yield. Models were developed for several stratified datasets, including domestic wells only, public and commercial wells only, wells drilled before 1970, wells with depths between about 300 and 500 ft (100 to 150 m), and wells completed in the upper 164 ft (50 m) of bedrock. In addition, several different response variables were tested, including yield divided by well depth, yield weighted by the ratio of well depth to median well depth, and the log of specific capacity for the group of wells with recorded drawdown data obtained during aquifer tests. None of these approaches produced models that were substantially better in terms of explained variance and model-fit statistics than the complete dataset, and are not discussed further.

The instrumental variable technique described by Moore and others (2002) also was applied to the well-depth data to correct the bias in well depth created by demand. This technique can correct the bias if there are variables that are correlated with yield demand but uncorrelated with the physical depth-yield relation (Moore and others, 2002). In this analysis, the year that the well was drilled and the median income of the town in which the well was located were selected as the most useful instrumental variables (that is, the variables correlated with demand). These variables were regressed on the log of well depth to produce a predicted well depth, which was then used in the main regression as an explanatory variable. By correcting the demand bias, the method is expected to provide a positive coefficient for well depth that better represents the physical relation between depth and yield. However, the year the well was drilled and median town income explained only about 25 percent of the variance in well depth in the Nashoba well-yield dataset. Consequently, the technique was not used for the final regression model.

For both models, regression diagnostics indicated that, although the models explained only a small amount of the variance of the logarithm of well yield (variable name logYield) and had large prediction errors, they could be considered appropriate for identifying site and well characteristics that influence well yield in the model areas. Visual inspection of histograms indicated that there was little skewness in the data, and residuals were nearly normally distributed. Although the Anderson-Darling statistic (p less than (<) 0.005) indicated that residuals were significantly nonnormal, the cause appeared to be outliers on the upper and lower ends of the distribution; outliers were not excluded because there was no clear evidence for erroneous yield values in the dataset. Plots of residuals versus predicted values and explanatory variables showed that, when occasional outliers were excluded, the variance of the residuals was reasonably constant with increasing yield.

Geostatistical Analysis

Variogram analysis and kriging were used to investigate the continuity and distribution of well yield in space. In variogram analysis, the empirical spatial continuity of the well-yield data is calculated; spatial continuity refers to the tendency of data values to be similar to nearby data values and dissimilar from values located at greater distances. Kriging is an estimation method in which the spatial continuity of the data is used to predict data values at unsampled locations from the sampled data and their locations in space (Isaaks and Srivastava, 1989). Variogram analysis and kriging are appropriate for data that are highly variable but also spatially dependent. Exploratory analysis was done by using the SGeMs software (v. x64-beta; http://sgems.sourceforge.net/?q=node/20; Remy and others, 2009); final analyses were done by using the Spatial Analyst and Geostatistical Analyst tools of ArcMap (v. 9.3.1).

In variogram analysis, the semivariance of the yield data is computed as a function of the distance between sampling points (wells). The semivariance is a function that describes the average squared difference between paired data values; paired data values are all possible pairs of data from wells separated by each distance value (Isaaks and Srivastava, 1989). The equation is as follows (Davis 1986):

$$\gamma_h = \sum_i^{n-h} \left(X_i - X_{i+h} \right)^2 / 2n, \quad (1)$$

where

γ_h = the semivariance, as a function of h;
h = the distance between pairs of sampling points;
n = the number of sampling points; and
X_i = the measurement of yield at location i.

The semivariance is computed for a series of incremental separation distances equal to a specified distance value (lag); an allowable distance interval around the lag distance (lag tolerance) is specified so that each incremental distance is a range rather than an exact value to accommodate data that are not uniformly spaced (Isaaks and Srivastava, 1989). Empirical variograms are plots of semivariance versus separation distance calculated by using the actual data. The empirical variograms are modeled by using one or more mathematical functions; example functions are spherical, Gaussian, and exponential models. The spherical model has the ideal properties of a variogram plot in that it starts at the origin, rises smoothly to an upper limit (sill value) at some distance (range), and then is constant at this upper limit for distances greater than the range (Davis, 1986; Isaaks and Srivastava, 1989). A variogram that does not start at the origin is said to exhibit a "nugget" effect, which is the offset in semivariance at zero distance. Omnidirectional variograms describe the spatial continuity of the data in all directions, whereas unidirectional variograms describe the spatial continuity of the data in specified directions by imposing an azimuth requirement on the direction between pairs of data points (wells) that are compared.

Experimental variograms were computed for the Nashoba terrane yield data in SGeMS with trial-and-error selection of lag distance(s) considered to best characterize the spatial structure of the data. The lag tolerance was set at one-half the lag distance. The final lag distance used to compute empirical variograms was 984 ft (300 m). For the omnidirectional variogram, used in kriging, trial-and-error also was used in SGeMS to fit a variogram model to the data by using the spherical model form. The model parameters for the fitted spherical model were then input to the ArcMap analysis tools to produce the variogram used for kriging. The log of yield was used as the variable because yield approximately followed a log-normal distribution. Directional variograms were computed at intervals of 10 azimuth degrees around the compass with a 15-degree angular tolerance around each direction.

Kriging uses the variogram model to interpolate yield values at unsampled locations from the well-yield data. The interpolated (estimated) values are weighted linear combinations of the yield data from surrounding wells; the weights are determined by using information about the spatial continuity of the well-yield data from the variogram model (Davis, 1986; Isaaks and Srivastava, 1989). The weights are optimized to provide unbiased estimates and to minimize the variance of the estimation error; the analysis can generate measures of the estimation error, which is a measure of uncertainty.

Kriging of well-yield data for the Nashoba terrane used the ordinary kriging method with a search radius of 6,890 ft (2,100 m). Yield values were estimated at central nodes of a 656 × 656-ft (200 × 200-m) grid that encompassed the study area; this grid spacing was chosen because it was less than the average minimum distance between neighboring wells and because of computational limitations.

Well-Yield Data

Data on well yield were compiled for 7,287 wells in the Nashoba terrane and within a 2.8-mi (4.5-km) buffer area around the Nashoba terrane boundary (fig. 5). Most of these data were from the MDEP well-completion report database, and most of the wells were domestic wells (private or household wells) (table 3). The MDEP well-completion report database was populated primarily with recent data at the time that the data were obtained for this study, and most of the wells for which yield data was compiled were constructed after 1980. Wells from the USGS NWIS database— about one-eighth of the wells—were mostly wells inventoried for a statewide study of bedrock well yield in the late 1980s (Hansen and Simcox, 1994); these wells were nearly all constructed in the decades before 1990 (fig. 6). The wells ranged in depth from 25 ft to 1,800 ft below land surface, with a median depth of 305 ft.

Reported yield for all wells in the Nashoba terrane and buffer area ranged from 0.04 to 625 gal/min, with a median value of 10 gal/min. Values approached a log-normal distribution, which is consistent with the expected distribution of aquifer transmissivity (fig. 7; Freeze and Cherry, 1979). Yield varied by use, and the difference was statistically significant (table 4). Public-supply wells and commercial or industrial wells had the highest yields, each with median values of 25 gal/min, followed by irrigation wells (median of 15 gal/min) and domestic wells (median of 10 gal/min) (fig. 8). The median yield for wells within the Ayer, Hudson, and Marlborough quadrangles was 12 gal/min, slightly higher than for wells throughout the entire study area. Additional information about yield values and well statistics by use is given in appendix 3.

Values for well yield were reported by the driller on well-completion reports for all wells from the MDEP database, for all wells from the MDEP supply-well files, and for most wells from the USGS NWIS database. Yields reported by drillers on the well-completion reports may be determined by one of several methods and are likely to have variable accuracy and precision. For example, nearly one-half (44 percent) of the reported yield values were determined by the air-lift or air-blow method. In this method, water is evacuated from the well with compressed air from the drill rig, and the rate at which water flows from the well is measured volumetrically

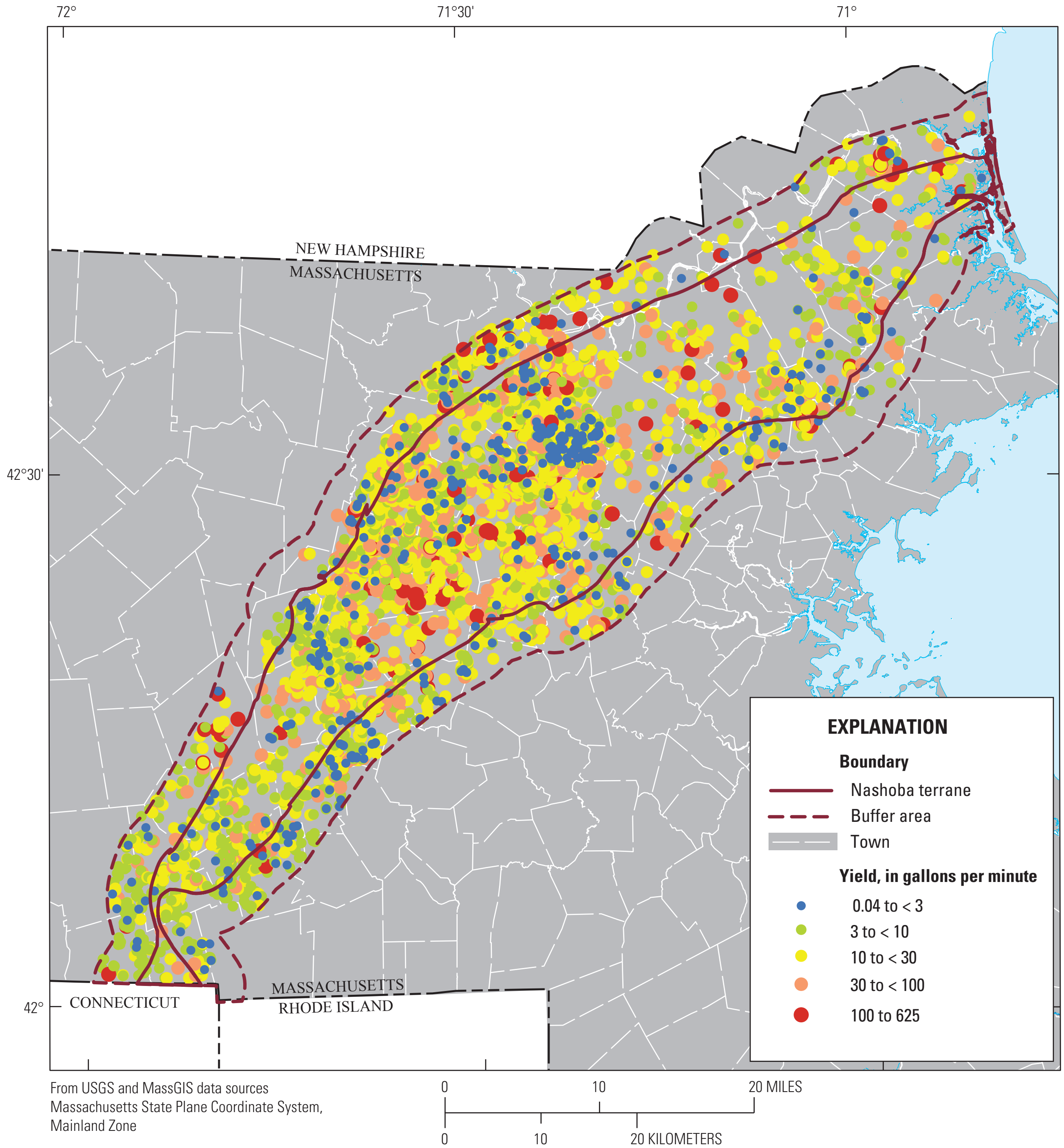


Figure 5. Well yield for 7,287 wells in the Nashoba terrane and surrounding area.

Table 3. Numbers of wells with yield data compiled for this study.

[Wells listed for Ayer, Hudson, and Marlborough quadrangles include 393 wells outside the Nashoba terrane but inside the buffer area; MDEP, Massachusetts Department of Environmental Protection; USGS, U.S. Geological Survey; NWIS, National Water Information System]

Characteristic	Number of wells		
	Nasboba terrane plus buffer area	Nashoba terrane	Ayer, Hudson, and Marlborough quadrangles only
Total number of wells	7,287	5,232	1,555
Source of data			
MDEP well completion report database	6,195	4,581	1,220
USGS NWIS database	942	560	273
MDEP supply well records	[1]150	91	62
Reported well use			
Domestic	5,813	4,247	1,321
Irrigation	1,076	770	128
Public supply	154	86	60
Commercial and industrial	78	42	12
Other	166	87	34

[1]Data for 17 additional supply wells outside the buffer area were used for the comparison of yield and aquifer transmissivity but are not included in this value.

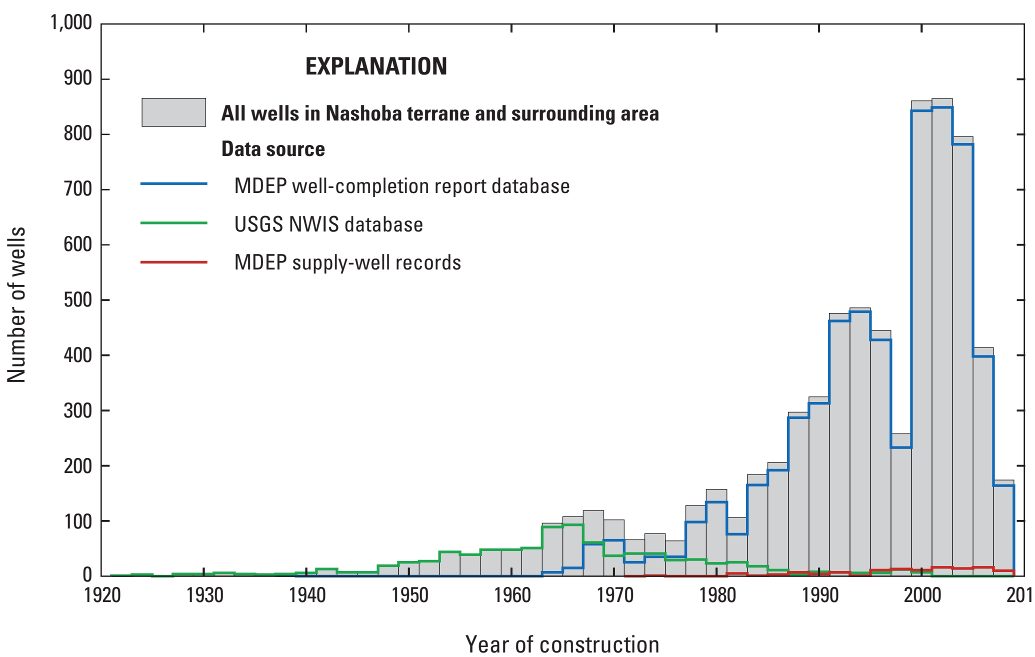


Figure 6. Number of wells by data source and year of construction for wells in the Nashoba terrane and surrounding area with yield data compiled from three data sources. A small number of wells (24) constructed before 1920 are not shown. MDEP, Massachusetts Department of Environmental Protection; USGS, U.S. Geological Survey; NWIS, National Water Information System

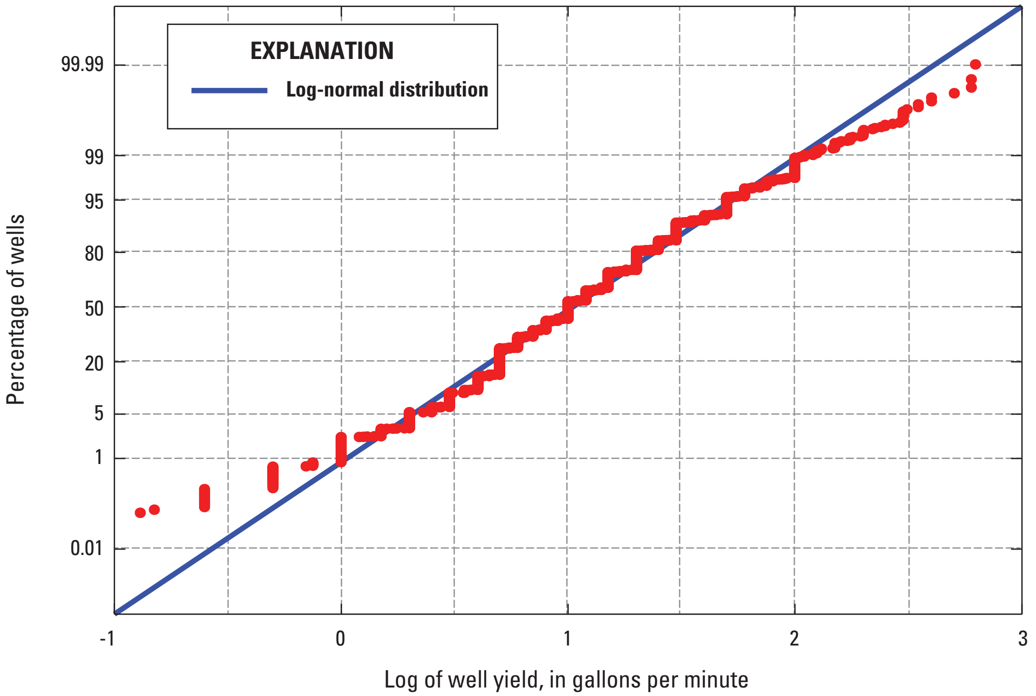


Figure 7. Probability plot of well yield and comparison to a log-normal distribution for wells in the Nashoba terrane and surrounding area.

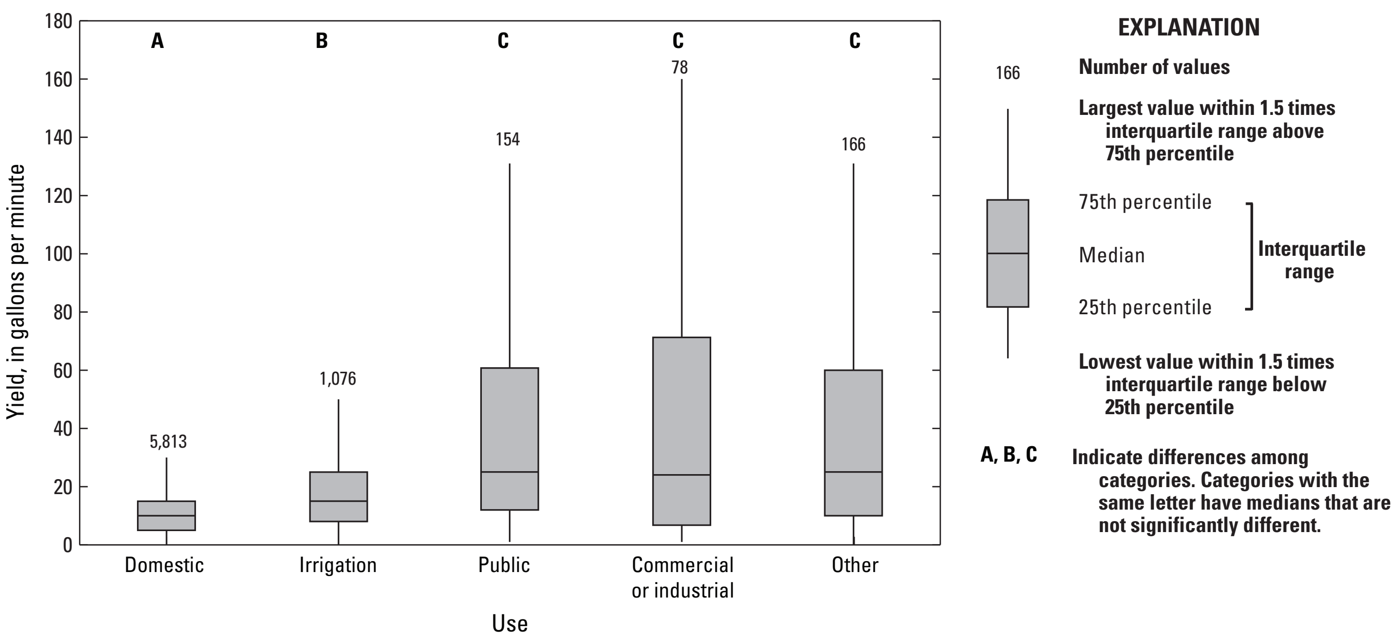


Figure 8. Well yield by use for wells in the Nashoba terrane and surrounding area. Wells in the category of "other" include geothermal wells, monitoring wells, and wells that did not have their use specified.

Table 4. Results of single-variable analyses of hydrogeological and other factors potentially affecting well yield in the Nashoba terrane and surrounding area.

[Bedrock geology and proximity to major faults based on data from the statewide geologic map; R^2, coefficient of determination; *r*, correlation coefficient; ANOVA, analysis of variance; shading indicates results of statistical significance at the alpha equal to 0.05 level; --, not applicable or analysis was not performed]

Factor	Variable type	Nasboba terrane plus buffer area			Nashoba terrane		
		R^2 of ANOVA test on ranks	Spearman's *r*	Attained significance level	R^2 of ANOVA test on ranks	Spearman's *r*	Attained significance level
Bedrock geology							
Generalized rock type	Categorical	0.035	--	<0.0001	0.011	--	<0.0001
Geologic-map unit	Categorical	--	--	--	0.035	--	<0.0001
Topography							
Land-surface elevation	Continuous	--	-0.191	<0.0001	-0.134	--	<0.0001
Land-surface slope	Continuous	--	-0.142	<0.0001	-0.107	--	<0.0001
Topographic-feature category	Categorical	0.015	--	<0.0001	0.014	--	<0.0001
Proximity to major faults							
Distance to the nearest mapped fault	Continuous	--	-0.016	0.181	--	-0.056	<0.0001
Hydrostructural domains							
Hydrostructural domain at well location	Categorical	0.009	--	<0.0001	0.03	--	<0.0001
Surficial geology							
Surficial geology at well location	Categorical	0.021	--	<0.0001	0.015	--	<0.0001
Percentage of sand and gravel in 400-foot buffer area	Continuous	--	0.157	<0.0001	--	0.134	<0.0001
Percentage of sand and gravel in 400-foot buffer area, six categories from 1 to 100 percent	Categorical	0.026	--	<0.0001	0.02	--	<0.0001
Thickness of overburden in areas of stratified glacial deposits	Continuous	--	0.108	<0.0001	--	0.138	<0.0001
Thickness of overburden in areas of till or bedrock	Continuous	--	-0.005	0.7682	--	0.021	0.2707
Proximity to surface waters							
Distance to nearest perennial stream, open-water body, or deep marsh	Continuous	--	-0.064	<0.0001	--	-0.071	<0.0001
Percentage of wetlands or open water in 400-foot buffer area	Continuous	--	0.104	<0.0001	--	0.071	<0.0001
Percentage of wetlands or open water in 400-foot buffer area, five categories from 1 to 100 percent	Categorical	0.006	--	<0.0001	--	--	<0.0001
Well characteristics							
Well use	Categorical	0.055	--	<0.0001	0.051	--	<0.0001
Method of well test to determine yield	Categorical	0.04	--	<0.0001	0.045	--	<0.0001
Duration of well test to determine yield	Categorical	0.028	--	<0.0001	0.031	--	<0.0001
Well depth	Continuous	--	-0.226	<0.0001	--	-0.201	<0.0001
Year when well was constructed	Continuous	--	0.067	<0.0001	--	0.098	<0.0001

to determine well yield. One source of inaccuracy in this method is that the entire borehole could be emptied at a rate that exceeds the rate at which water flows into the well from the aquifer (Pierce, 1998). Thus, short-term measurements by the air-lift or air-blow method may overestimate well yield by including water stored in the borehole in the flow measurement. Short-term measurements of well yield by pumping the well, similarly, may overestimate yield. In fact, yield was slightly higher when the reported measurement method was air lift or air blow than when the measurement method was reported as pumping, and yield also was slightly higher for short-term tests (less than 4 hours) than for tests of longer duration (4 hours or more) (fig. 9 and table 4). Inaccuracy and overestimation of yield values from sources such as these introduce variability in the dataset that makes it more difficult to detect actual relations of yield with hydrogeologic factors and to describe regional patterns of high and low yield. However, wells with yield values determined by both short-term and long-term tests and by both air methods and pumping are evenly distributed throughout the study area (based on visual inspection) and are unlikely to contribute any large-scale, regional bias into the dataset.

Well yield also is related to water demand in ways that affect its representativeness of aquifer characteristics. Supply wells are drilled to meet specific user needs for water, and wells are generally drilled only as deep as necessary to meet the required demand and storage capacity. As a result, the reported well yield is probably not the maximum potential yield for the well site in many cases (Cederstrom, 1972; Moore and others, 2002). Another consequence of this demand effect is that, although well yield and well depth are positively related for shallow wells, the overall relation between well yield and well depth is inverse, especially for domestic wells (fig. 10 and table 4; Loiselle and Evans, 1995). An inverse relation between well yield and well depth is contrary to expectations. Conceptually, although aquifer permeability tends to decrease with depth (Freeze and Cherry, 1979), well yield, as the cumulative total of water inflow from all depths of the aquifer penetrated by the well, would be expected to increase with well depth (Hansen and Simcox, 1994), if all other factors influencing well yield remained the same. This results because deeper wells potentially intersect more water-bearing fractures in the aquifer than shallower wells, at least until the prevalence of water-bearing fractures is diminished. At lower-yielding locations, however, wells tend to be drilled deeper than at higher-yielding locations, because the greater depth and storage capacity is needed to meet the required demand. Other cultural factors also may affect the relation between well yield and well depth. For example, well depth increased with time, so that more recently installed wells tended to be deeper than wells installed in the earlier decades (fig. 11A; Spearman's r equal to 0.393, p value less than 0.0001). This increase in well depth may reflect, in part, an increase in water demand with time by households (Moore and others, 2002); reported yield of all wells, and of domestic wells, also increased with time, although not to the same extent (fig. 11B and table 4). Changes in drilling methods with time or other changes also may have affected well depths (Drew and others, 2001). Finally, water demand affects the well-yield data through its influence on the location of high-yield public-supply and commercial or industrial wells. Such wells are sited where communities and well owners have a need for them. Thus, their distribution in the study area is affected by cultural factors and is not an unbiased sampling of the possible places in the aquifer where high-yielding wells could be located.

Although reported well yield from existing wells is not ideal as a measurement of aquifer yield, an assumption inherent in the present study is that it contains useful information that can describe aquifer characteristics, and that differences in reported well yield represent real differences in aquifer yield, as well as differences because of measurement method and cultural factors. This assumption was investigated with a comparison of reported driller's well yield with specific capacity at 103 public, large irrigation, and large industrial supply wells where aquifer tests were conducted. The specific capacity, as the ratio of the rate at which the well is pumped to the resulting drawdown, is theoretically related to aquifer transmissivity through basic equations of groundwater flow (Theis,1963; Huntley and others, 1992; Knopman and Hollyday, 1993) and has been empirically related to aquifer transmissivity in many studies (Huntley and others, 1992; Rotzoll and El-Kadi, 2008; Singhal and Gupta, 2010). Most of the wells for which this comparison was made were located in the Nashoba terrane and in the surrounding buffer area; 17 wells were located just outside of the buffer area in nearby towns (fig. 12). Aquifer tests, typically of 48-hour duration, were conducted by consultants at the sites in accordance with permitting regulations (Massachusetts Department of Environmental Protection, 2008; see appendix 1 for data sources). Specific capacity was calculated from the drawdown data collected during these aquifer tests after 24 hours of pumping.

Reported well yield at the public, large irrigation, and large industrial-supply wells ranged from 1 to 625 gal/min, with a median value of 50 gal/min. Reported well yield and specific capacity from aquifer tests were well correlated (fig. 13), with a rank-based Spearman correlation coefficient r of 0.74 (p value less than 0.0001). The correlation also was present for a subset of wells (57) with only low-yield values, that were typical of those in the entire yield dataset (less than or equal to 50 gal/min, the 95th percentile of yield for all wells), with a Spearman correlation coefficient of 0.68. This relation indicates that reported driller's well yield, although subject to several sources of error, does capture real information about the variability in aquifer yield.

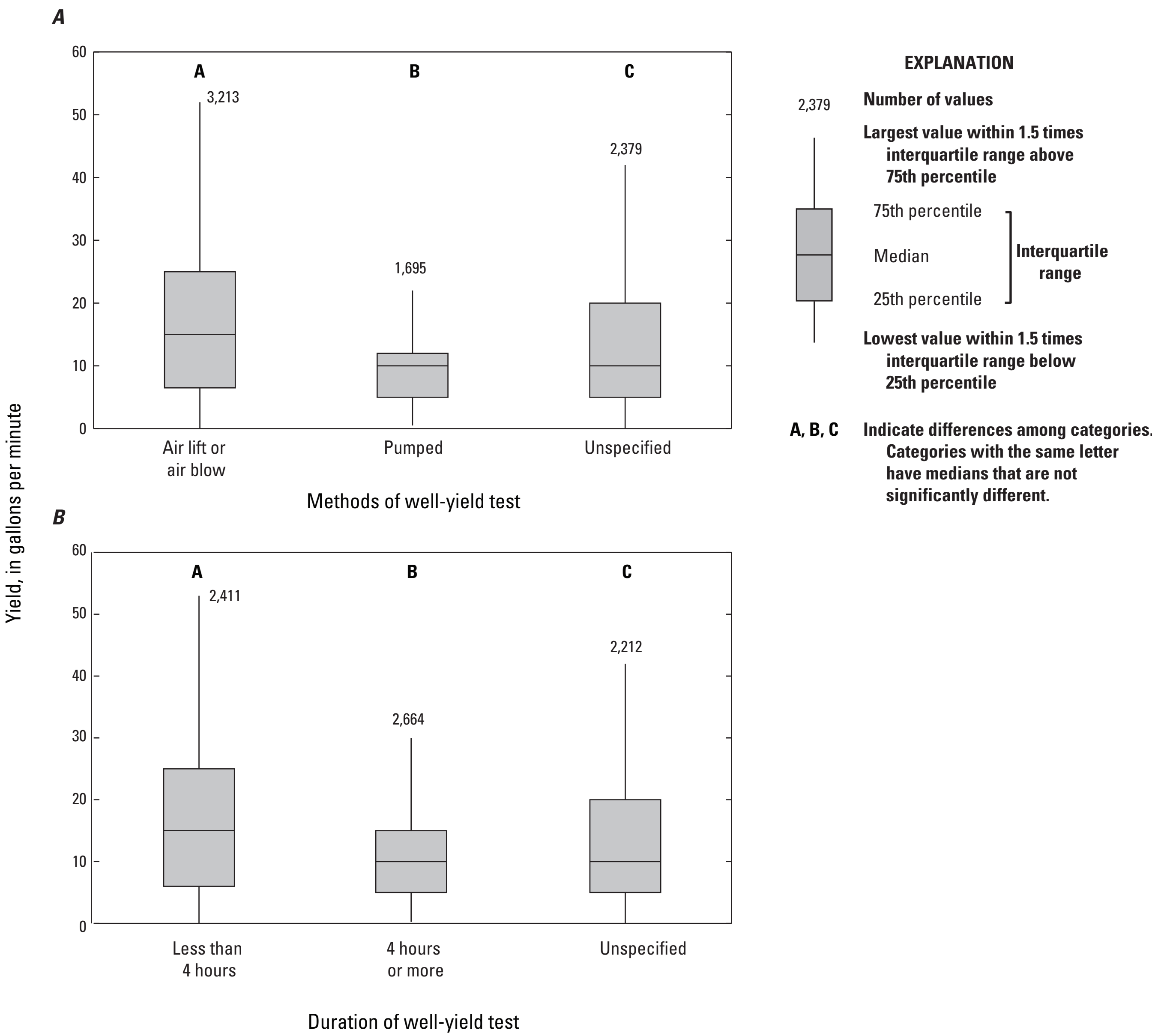


Figure 9. Well yield by *(A)* test measurement method and *(B)* test duration for wells in the Nashoba terrane and surrounding area.

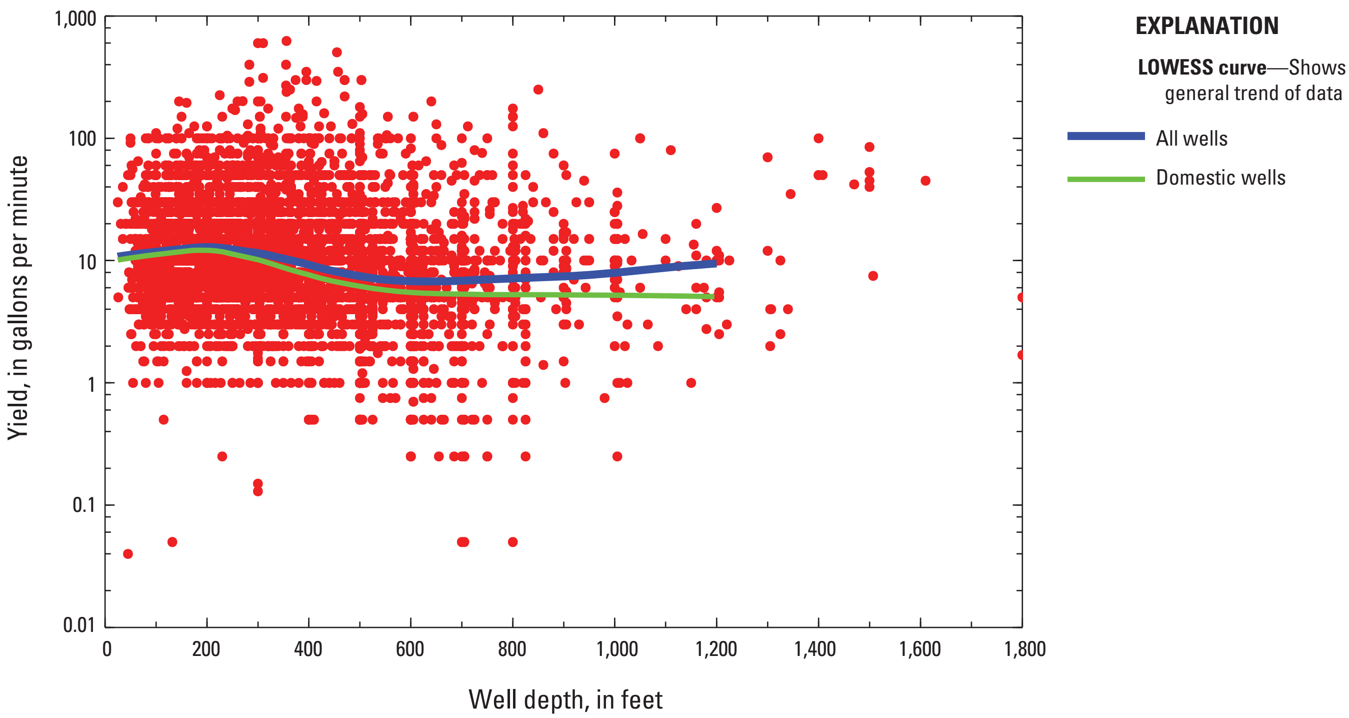


Figure 10. Comparison of well yield and well depth for wells in the Nashoba terrane and surrounding area. Data points shown are for all wells. LOWESS (locally weighted scatterplot smoothing) curves are truncated at well depth equal to 1,200 feet because of sparse data.

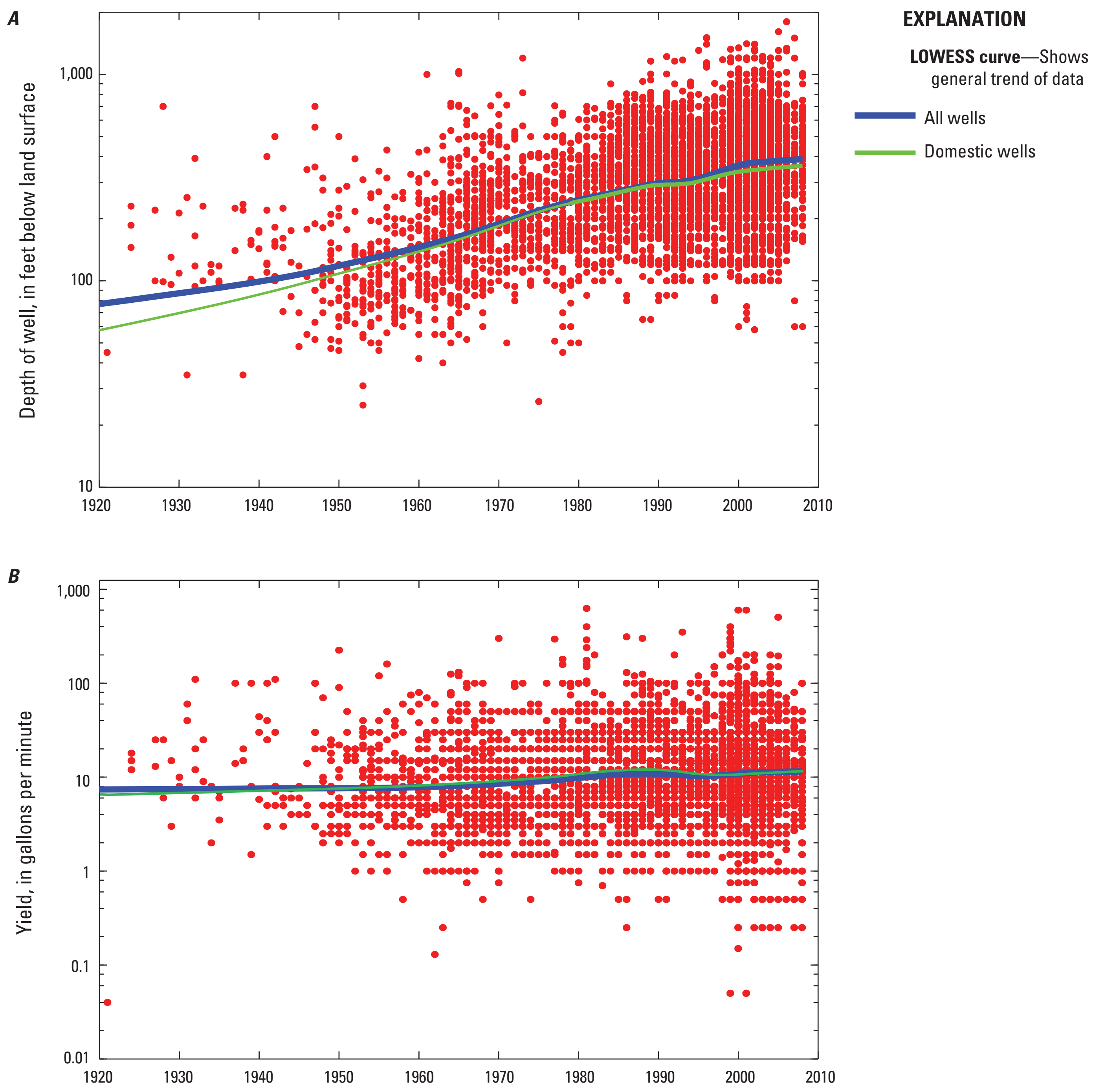


Figure 11. Comparison of *(A)* well depth and *(B)* yield with year of construction for wells in the Nashoba terrane and surrounding area. Data points shown are for all wells; data for 24 wells constructed before 1920 are not shown. LOWESS, locally weighted scatterplot smoothing.

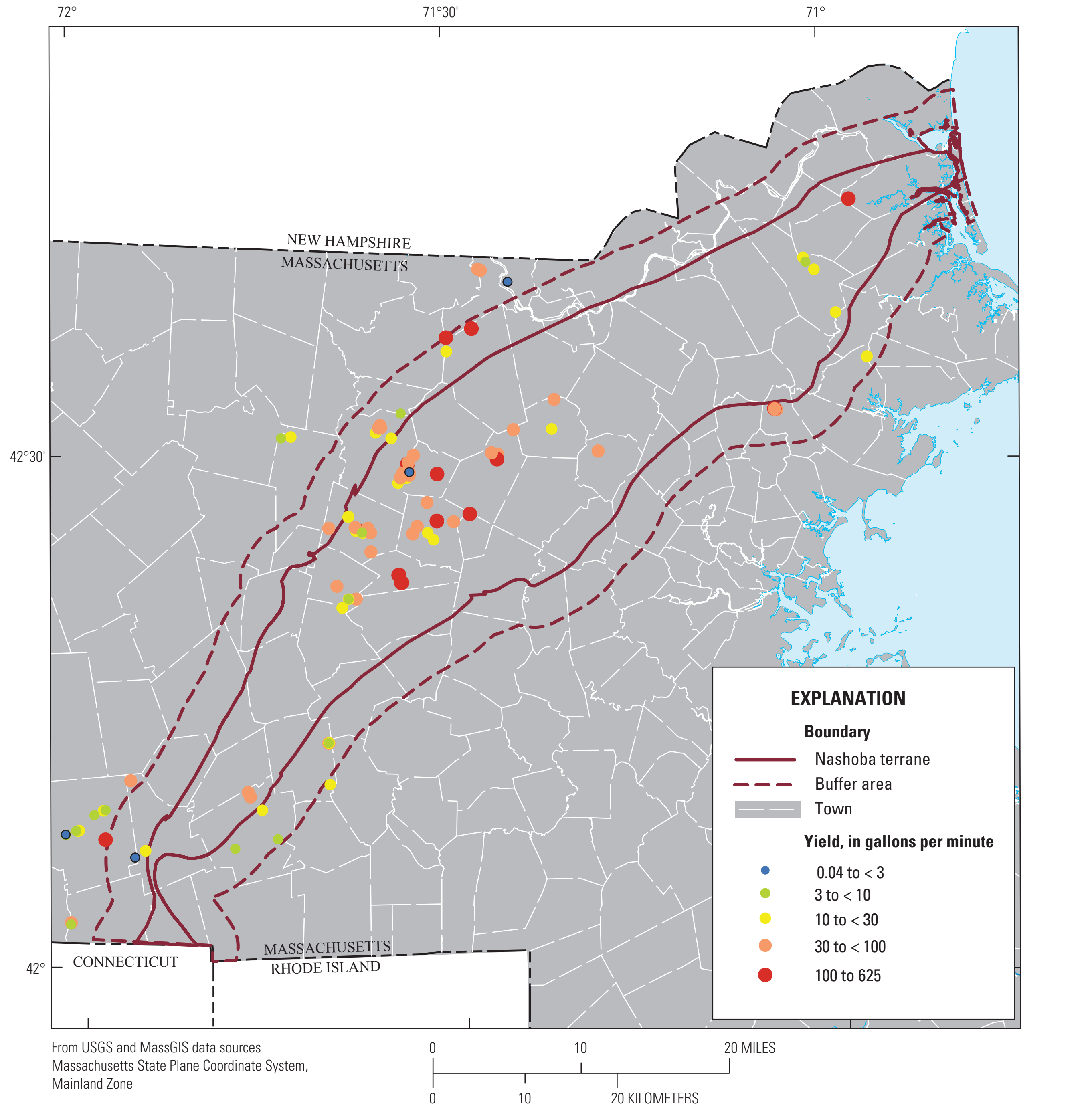


Figure 12. Well yield for 103 public, large irrigation, or large industrial supply wells in the Nashoba terrane and surrounding area used in a comparison of reported well yield and specific capacity from aquifer-test data.

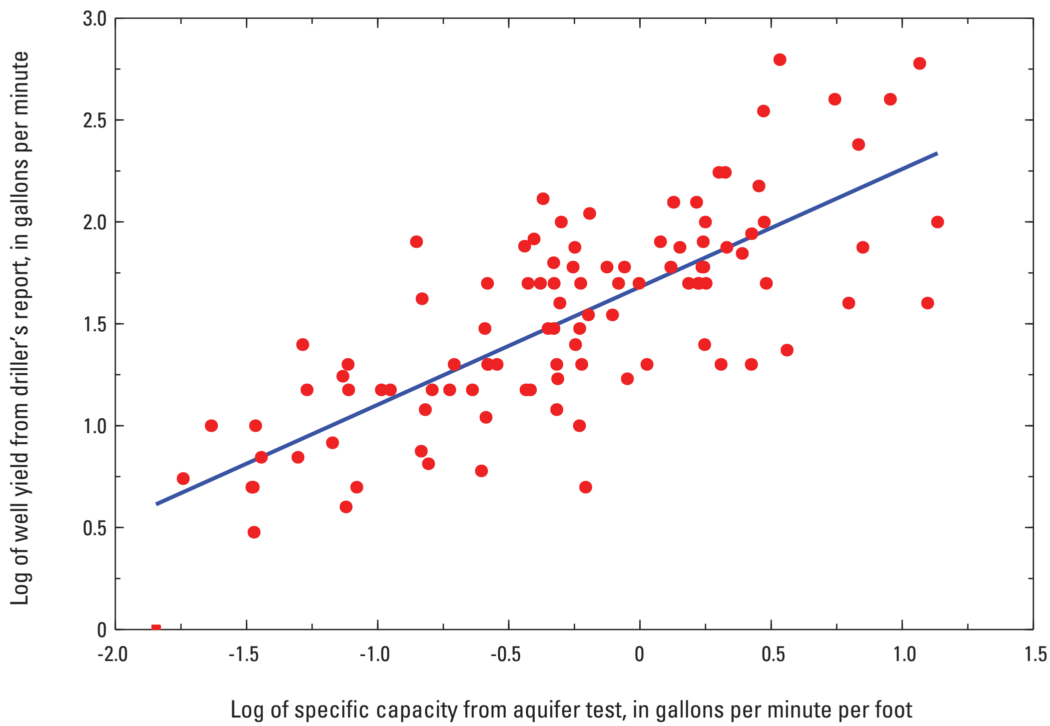


Figure 13. Specific capacity from aquifer-test data and reported driller's well yield at 103 public, large irrigation, or large industrial supply wells in the Nashoba terrane and surrounding area. Blue line is line of linear regression.

Well Yield in Relation to Hydrogeologic Factors

Conceptually, well yield is related to the hydraulic properties of the aquifer and sources of recharge. For the bedrock aquifer in the Nashoba terrane, as for most fractured-bedrock aquifers, information is lacking at the regional scale about these fundamental features. They depend on fracture-defined flow fields and their connectedness to overburden deposits and surface waters; these characteristics are difficult to measure and can vary greatly at small scales. However, there are a number of factors that can be used as descriptors of these features. Factors such as rock type, geologic structure, topographic setting, overburden character, and proximity to surface waters characterize aspects of the aquifer hydraulic properties and sources of recharge, and such factors have been related to well yield in fractured-bedrock aquifers in a number of hydrogeologic settings. Individual relations of well yield with a number of potential explanatory factors were examined by means of single-variable analysis.

Results are reported for wells within the Nashoba terrane and in the surrounding buffer area, unless otherwise indicated. In all cases, each analysis also was done for wells only within the Nashoba terrane boundaries. Differences in results for analyses based on all wells and only Nashoba terrane wells are noted. Comparisons of yield with bedrock geology, proximity to major faults, and proximity to lineaments were made separately for wells in the Ayer, Hudson, and Marlborough quadrangles in addition to analysis at the regional scale because of the additional data available for the three-quadrangle area.

Bedrock Geology

Bedrock geology may be related to well yield when geologic formations differ in terms of permeability or fracture characteristics. At the statewide scale, for example, well yields were found to be higher in the carbonate rocks of western Massachusetts than in the crystalline rocks that underlie most of the state, including the Nashoba terrane (Hansen and Simcox, 1994); carbonate rocks typically are more permeable than crystalline rocks because of solution features. Similar differences in well yield among broadly defined lithologic groups have been noted for other regions (Hollyday and others, 1996; Robinson and Rauch, 2002). The crystalline rocks themselves are similar in that they have little primary porosity and lack solution features. However, differences among the crystalline-rock types in origin (igneous compared to sedimentary), composition (mafic compared to felsic), texture (mineral grain size), and foliation (layering, schistosity) potentially lead to differences in fracture development from tectonic stresses, magmatic cooling, and unloading processes (Daniel, 1989; Drew and others, 1999; Walsh and Clark, 2000) with consequent differences in water-yielding properties among crystalline rock types (Mabee, 1999).

Small differences were observed in well yield among generalized rock types and geologic map units at the regional scale. Although small, these differences were statistically significant (generally, α less than 0.05; in many cases, p values less than 0.0001). These results are based on geologic data from the statewide geologic map (Zen and others, 1983; Nicholson and others, 2006). In the Nashoba terrane, the yield of wells located in granites, mafic intrusive rocks (including diorite and gabbro), or amphibolites was slightly higher than the yield of wells located in schists and gneisses or pelitic rocks (fig. 14A). In the parts of the surrounding areas that were included in the study area, no statistically significant differences were observed among Merrimack terrane generalized rock types, but some differences were observed among Avalon terrane generalized rock types, the largest being lower yields observed for wells in the Avalon granites than in other generalized rock types (fig. 14A). Well yields in the Avalon granites also were lower than well yields in all generalized rock types of the Nashoba terrane (results not shown in fig. 14).

Within the Nashoba terrane, small differences in yield also were observed among individual geologic map units. For example, well yields in each of the Fish Brook Gneiss (OZf), undifferentiated Straw Hollow Diorite and Assabet Quartz Diorite (Ssaqd), Granodiorite of the Indian Head Pluton (igd), Boxford Member of the Nashoba Formation (OZnb, an amphibolite), Andover Granite (SOagr), Shawsheen Gneiss (OZsh), and an unnamed granite (Sgr) were slightly higher than well yields in the each of the Tadmuck Brook Schist (SZtb), undifferentiated Nashoba Formation (OZn), Marlboro Formation (OZm), and an unnamed muscovite granite (mgr). However, as is apparent from the boxplots (fig. 14B) and results of the statistical analysis in table 4, all these differences were small and did not explain much of the variability in well yield overall.

As at the regional scale, small differences in Nashoba terrane rocks also were observed in yield among generalized rock types at the quadrangle scale (table 5). This analysis was done by using geologic data from the Ayer, Hudson, and Marlborough 1:24,000-scale quadrangle geologic maps (Kopera and Hansen, 2005; Kopera, 2006; Kopera and others, 2006a). No differences were apparent among rock types in the areas of Merrimack and Avalon terranes outside of the Nashoba terrane with the quadrangle geologic data; samples sizes for these areas were very small. In the Nashoba terrane, the yield of wells located in granites in these quadrangles was slightly higher than the yield of wells located in schists and gneisses, pelitic rocks, or amphibolites. The results at the regional scale were the same with the statewide data for the relations between granites and other rock types, but not for the relations of amphibolites and mafic intrusive rocks with other rock types. However, the differences between the results at the regional scale with the statewide data and results at the quadrangle scale with the quadrangle geologic data probably result from differences in the sample numbers, geologic map units, and characteristics of the rock types in the three-quadrangle area, as compared to the entire study area.

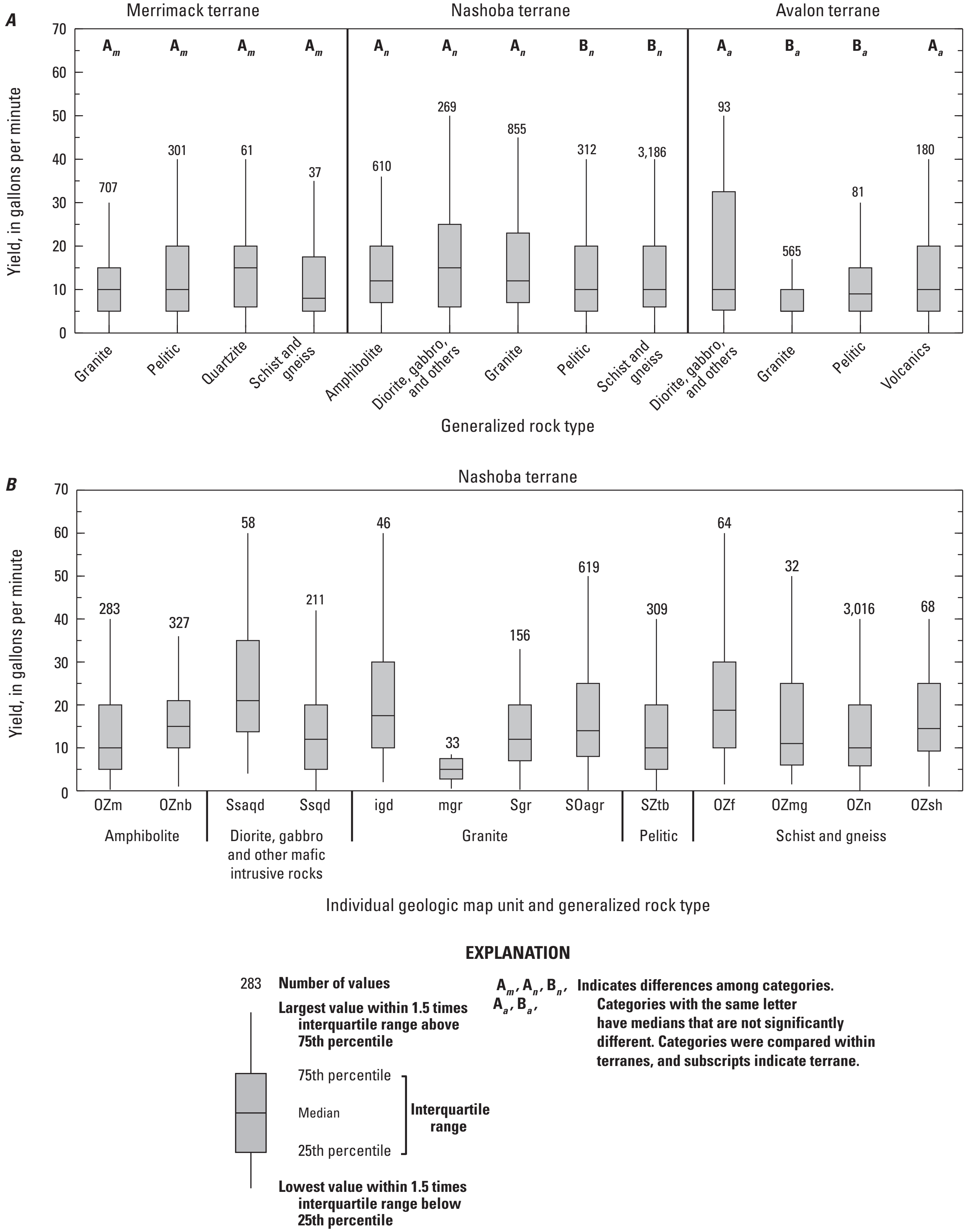


Figure 14. Well yield by bedrock geology. *(A)* Well yield by generalized rock type in the Nashoba terrane and surrounding area. *(B)* Well yield by individual geologic map unit in the Nashoba terrane. See table 1 and appendix 2 for explanation of individual geologic map unit abbreviations.

Table 5. Results of single-variable analyses of hydrogeological factors potentially affecting well yield in the Ayer, Hudson, and Marlborough quadrangles.

[Bedrock geology and proximity to major faults based on data from 1:24,000-scale quadrangle geologic maps. Lineaments delineated from 1:80,000-scale black-and-white aerial photographs (80K), 1:58,000-scale color infrared (CIR) aerial photographs, or 1:5,000-scale shaded digital elevation model data (shaded DEM). R^2, coefficient of determination; ANOVA, analysis of variance; *r*, correlation coefficient; shading indicates results of statistical significance at the alpha equal to 0.05 level; --, not applicable or analysis was not performed]

Factor	Variable type	Nasboba terraneplus buffer area			Nashoba terrane		
		R^2 of ANOVA test on ranks	Speaman's r	Attained significance level	R^2 of ANOVA test on ranks	Speaman's r	Attained significance level
Bedrock geology							
Generalized rock type	Categorical	0.046	--	<0.0001	0.039	--	<0.0001
Geologic-map unit	Categorical	--	--	--	0.042	--	<0.0001
Proximity to major faults							
Distance to the nearest mapped fault, in meters	Continuous	--	-0.096	0.0001	--	-0.111	0.0002
Proximity to lineaments							
Distance to the nearest 80K lineament (all)	Continuous	--	-0.084	0.001	--	-0.107	0.0003
Distance to the nearest CIR lineament (all)	Continuous	--	-0.059	0.021	--	-0.062	0.035
Distance to the nearest shaded DEM lineament (all)	Continuous	--	0.01	0.704	--	-0.002	0.95
Distance to the nearest coincident 80K lineament	Continuous	--	-0.003	0.895	--	-0.003	0.919
Distance to the nearest coincident CIR lineament	Continuous	--	-0.013	0.606	--	-0.049	0.092
Distance to the nearest coincident shaded DEM lineament	Continuous	--	0.062	0.014	--	0.047	0.107
Distance to the nearest fracture-correlated 80K lineament	Continuous	--	-0.049	0.055	--	-0.095	0.001
Distance to the nearest fracture-correlated CIR lineament	Continuous	--	-0.051	0.046	--	-0.064	0.029
Distance to the nearest fracture-correlated shaded DEM lineament	Continuous	--	0.022	0.372	--	0.041	0.16
Distance to the nearest fracture-correlated, coincident 80K lineament	Continuous	--	-0.051	0.043	--	-0.082	0.005
Distance to the nearest fracture-correlated, coincident CIR lineament	Continuous	--	-0.016	0.53	--	-0.002	0.942
Distance to the nearest fracture-correlated, coincident shaded DEM lineament	Continuous	--	-0.053	0.037	--	-0.069	0.019

When well yield is compared among rock types by using the statewide geologic data for wells located only in the Ayer, Hudson, and Marlborough quadrangles, results are similar to those determined by using the quadrangle geologic data. This result is not surprising because, although geologic map unit boundaries and designations differed considerably between the statewide geologic map and the quadrangle geologic maps in some areas, the identity of the geologic map unit at the well location was the same for statewide or quadrangle map data at most (80 percent) of the well locations in the three-quadrangle area.

Differences in yield among wells in individual geologic map units in the three-quadrangle area in the Nashoba terrane were few but were consistent with the differences among generalized rock types and among individual geologic map units based on the statewide geologic data. Yields of wells located in the Andover Granite (Dag; labels are from the quadrangle maps), the most extensive granite in the area, were slightly higher than yields of wells located in the undifferentiated Nashoba Formation (COnu—schist and gneiss), the Tadmuck Brook Schist (COtb—pelitic rocks), and the Marlboro Formation amphibolites and schist (COma).

Lower yields in schists, gneisses, and pelitic rocks than in the granites or amphibolites in the study area are consistent with findings for fractured-bedrock aquifers elsewhere in New England. Mabee (1999) reported lower aquifer transmissivities for wells located in schists than for wells in amphibolites in a fractured-bedrock aquifer in coastal Maine. Higher yields in granites are also consistent with conclusions of the New Hampshire statewide study (Moore and others, 2002). In the New Hampshire study, yields of wells located in granites, when statistically significant in a predictive model of well yield, were higher than average. However, the relations of yield with rock type are complicated and variable even in the study area, as indicated by the differences in results for the entire study area and for the three-quadrangle area. Moreover, differences in yield observed in the Nashoba terrane are not necessarily transferable to other areas—for example, although well yields were slightly higher in Nashoba terrane granites than in several other rock types, well yields in Avalon terrane granites were lower than in other rock types, including Nashoba terrane granites.

Topography

Well yield has been found to vary with topographic setting in many studies of fractured-bedrock aquifers. The yields of wells located in valleys and lowlands are reported as higher than the yields of wells on hilltops, ridges, or steep slopes (Siddiqui and Parizek, 1971; Snipes and others, 1984; Zewe, 1991; Yin and Brook, 1992; Hansen and Simcox, 1994; Daniel, 1989; Tiedeman and others, 1997; Moore and others, 2002). These studies were from fractured-bedrock aquifers in Appalachian physiographic provinces from New Hampshire to Georgia. The influence of topography can vary depending on physiography, geology, and the scale and criteria by which topographic features are defined (Snipes and others, 1984; Mabee, 1999). Structural and hydrologic explanations have been proposed for the effects of topography, including the greater prevalence of fractures and (for carbonates) solution features in low-lying areas than on hilltops, and (or) more groundwater flow through low-lying areas, which are typically groundwater discharge areas, than under hilltops, ridges, and high-slope areas.

In the Nashoba terrane and surrounding area, relations of well yield with topography were similar to those found in fractured-bedrock aquifers elsewhere in New England and in the Appalachian provinces. Yield was slightly higher in areas categorized as valley, low slopes, and flat than in areas categorized as mid slope, upper slope, or hilltop/ridge, and these differences were statistically significant (fig. 15). These topographic features were defined in relation to neighboring land-surface elevations and slopes from digital elevation data and are shown for part of the study area in figure 16. Yield also was inversely correlated with land-surface elevation (fig. 17A) and slope values (fig. 17B) directly; higher yields were found at lower elevations and in areas of lower slope across the study area.

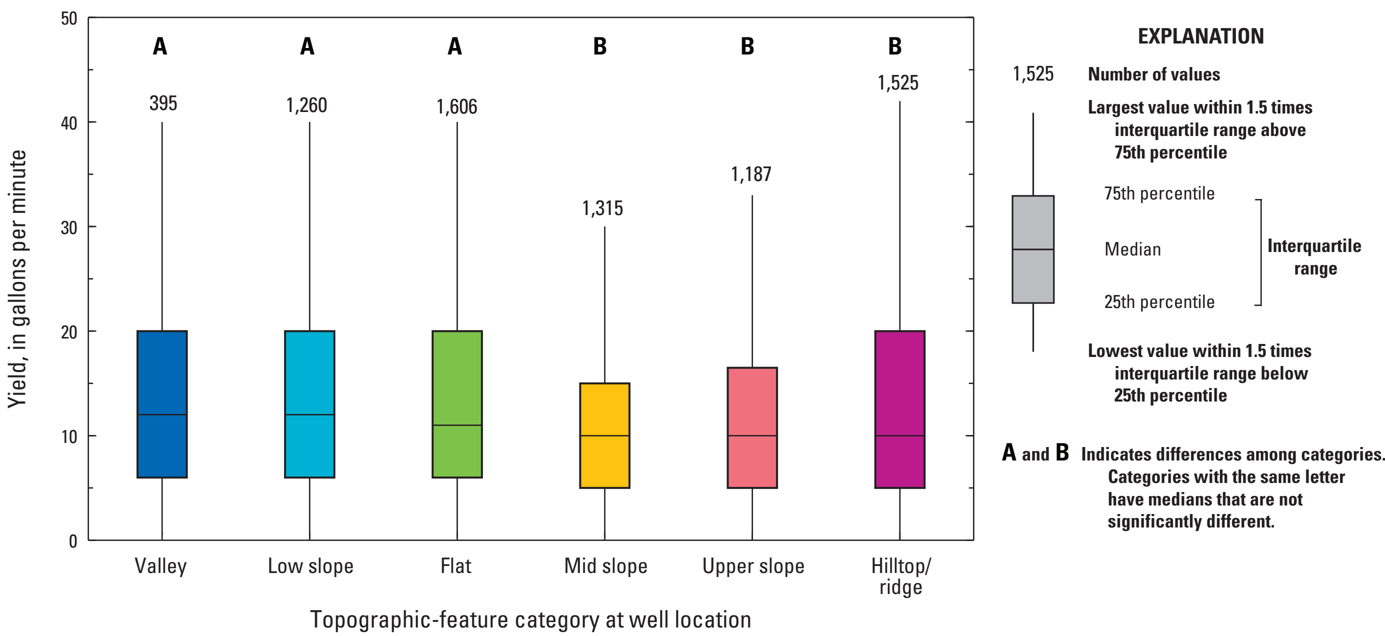


Figure 15. Well yield by topographic feature category for wells in the Nashoba terrane and surrounding area. The areal distribution of the categories is shown in figure 16.

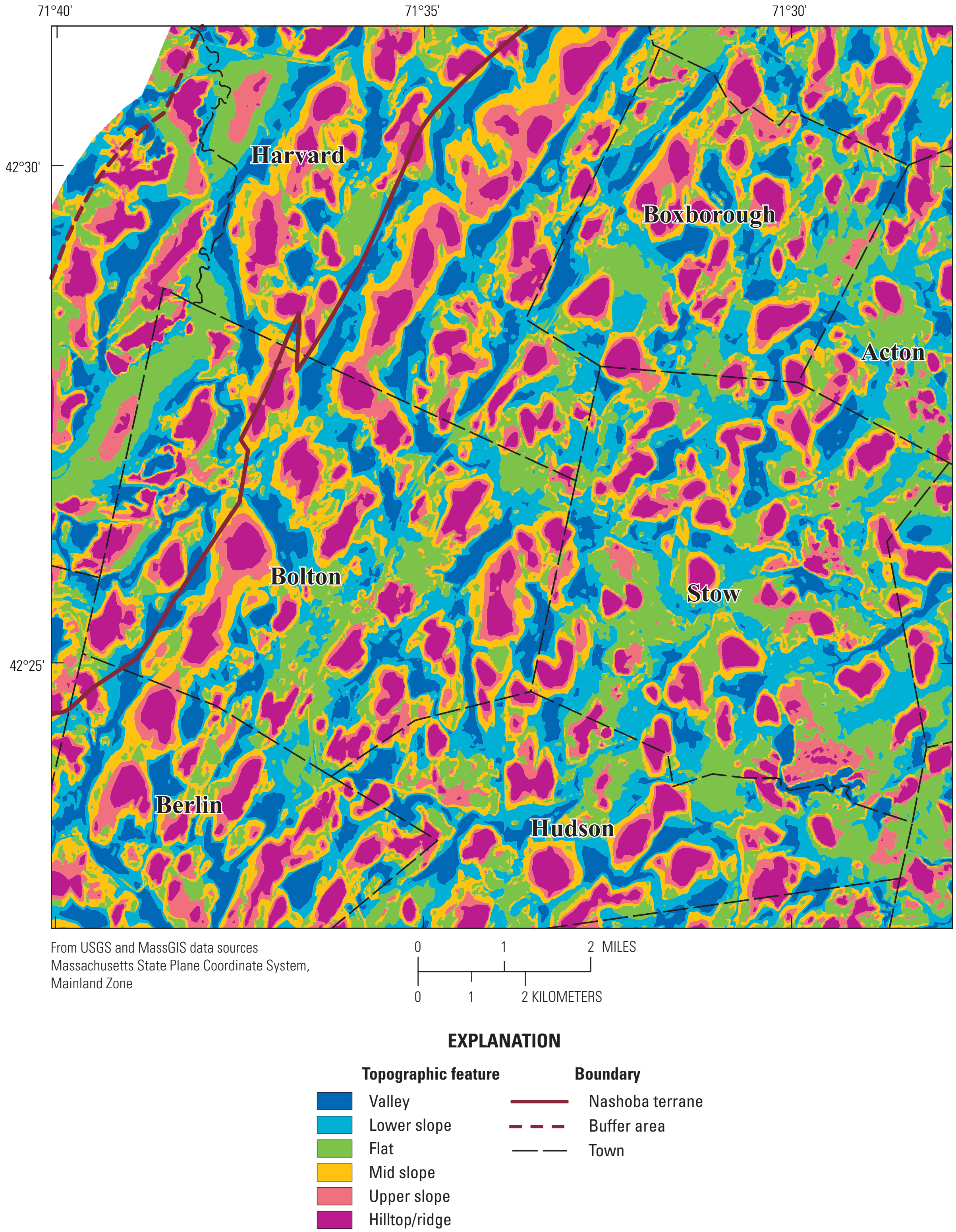


Figure 16. Topographic features in the Nashoba terrane and surrounding area. A part of the study area, about 110 square miles, is shown.

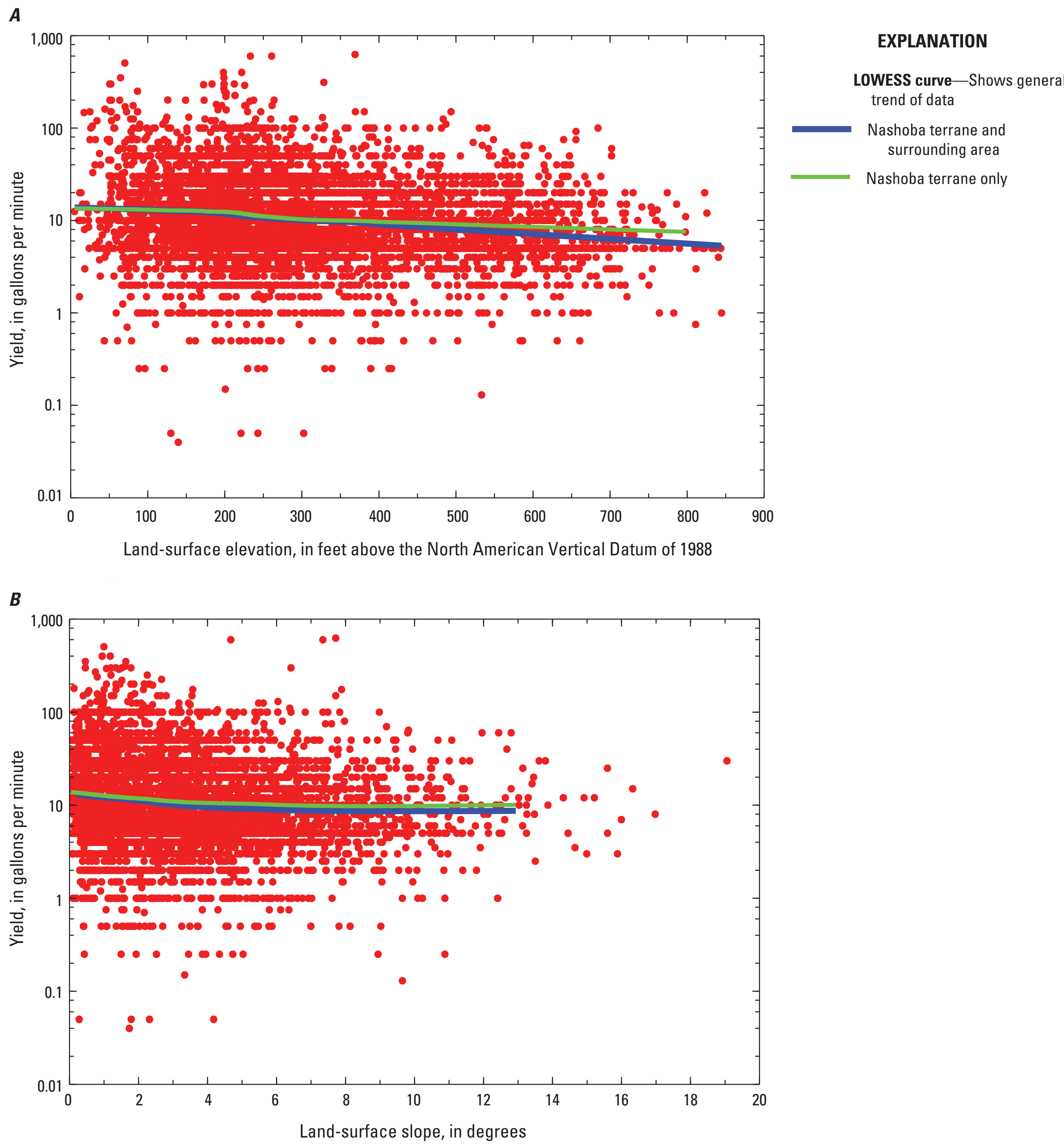


Figure 17. Well yield by *(A)* land-surface elevation and *(B)* land-surface slope for wells in the Nashoba terrane and surrounding area. LOWESS (locally weighted scatterplot smoothing) curves for land-surface slope are truncated at 13 degrees because of sparse data.

Major Faults and Lineaments

Structural features can be related to well yield where they describe or correspond to areas of more (or less) intense or abundant fracturing than other areas. Faults shown on geologic maps are major structural features that can be traced over long distances. They correspond to geologic discontinuities along which rock units have been displaced because of tectonic activity. Major faults may be areas of more abundant fractures that enhance the permeability of crystalline rocks, but they also may act as barriers to flow or have no relation to increased permeability (Caine and others, 1996; Evans and others, 1997; Caine and Tomusiak, 2003; Seaton and Burbey, 2005; Surrette and others, 2008; Boutt and others, 2010). Lineaments, also called "fracture traces," are linear features delineated from remote-sensing data, such as aligned topographic features or straight-line stream segments, that may mark areas underlain by subsurface fractures or fracture zones. Lineaments are used in bedrock aquifer exploration and have been related to well yield in a number of studies in the Appalachian provinces, although in other studies they have been of limited use (Siddiqui and Parizek, 1971; Yin and Brook, 1992; Mabee, 1992; Mabee and others, 2002; Moore and others, 2002; Robinson and Rauch, 2002; Cohen and others, 2007). The relation of well yield in the Nashoba terrane and surrounding area to proximity to major faults and lineaments is described in this section.

Major Faults

Major faults mapped on the statewide and quadrangle geologic maps include the terrane-bounding Clinton-Newbury and Bloody Bluff faults, the Assabet River fault, and a number of others (fig. 18). In its northeastern part, the Clinton-Newbury fault is shown as a single trace, whereas to the south it is shown as a zone of anastomosing faults, some of which are individually named (Goldsmith, 1991c). The Bloody Bluff fault also is shown with a number of branches. Although represented as lines on the geologic map and in the digital data, the faults are in fact zones of deformation that may be hundreds of feet wide or more in many places (Goldsmith, 1991c; Castle and others, 2005; Kopera and others, 2006b). The Assabet River and Spencer Brook faults extend northeast to southwest through the middle of the Nashoba terrane; their locations are shown as approximate in the northern and southern parts (Zen and others, 1983).

Well yield was inversely correlated with distance from the nearest major fault in the Ayer, Hudson, and Marlborough quadrangles and, in the entire study area, for wells in the Nashoba terrane only (excluding the buffer area). Three of the four correlations for faults were weak although statistically significant, with Spearman's r values ranging from -0.056 to -0.111 (tables 4 and 5 and fig. 19). The greater correlation in the three-quadrangle area than in the entire study area reflects differences in the areas, rather than differences between the statewide and quadrangle fault data. When proximity to faults is compared to well yield for the three-quadrangle area on the basis of either the quadrangle fault data (Spearman's r equal to -0.096, p = 0.0001; table 5) or the statewide fault data for that area only (Spearman's r equal to -0.117, p value less than 0.0001; not shown in table 5), correlation results were similar. Close examination of the LOWESS (locally weighted scatterplot smoothing) line fit to the data for the three-quadrangle area (fig. 19B) indicates that the inverse relation, though very weak, occurs for wells within distances of about 2 miles (11,000 ft).

Lineaments

Lineaments that were delineated from three data platforms—1:80,000-scale black-and-white aerial photographs (80K), 1:58,000-scale color-infrared aerial photographs (CIR), and illuminated 1:5,000-scale digital elevation data (shaded DEM)—were compared with well yield. Relations with well yield were investigated for (1) all lineaments (those delineated by either of two independent observers); (2) coincident lineaments (those identified by both of two observers); (3) all fracture-correlated lineaments (those trending in the same direction as major fracture sets observed at outcrops; fracture data from Mabee, 2005; Kopera and others, 2006b; and Mabee and Salamoff, 2006); and (4) fracture-correlated, coincident lineaments. All lineaments, fracture-correlated lineaments, and coincident lineaments are shown in figure 20 for the Hudson quadrangle as an example of these data. Lineaments delineated from the 80K and CIR aerial photographs were similar in number and direction. About twice as many lineaments were delineated from the shaded DEMs than from either the 80K or CIR aerial photographs, however. About 20 percent of 80K and CIR lineaments and about 12 percent of the shaded DEM lineaments were coincident; about 40 percent of all 80K, CIR, and shaded DEM lineaments were fracture correlated on the basis of the predominant directions of outcrop fractures in the area of all three quadrangles.

Well yield for wells near lineaments was slightly higher than the yield of wells that were not located near lineaments, for some categories of lineaments. These were: all 80K, all CIR, all fracture-correlated 80K, and all fracture-correlated CIR lineaments. Several distances (50, 100, 200, 300, and 400 ft) were used as criteria for proximity (fig. 21; the distance from the well to the closest lineament in each category was used to classify the wells as within each specified distance or beyond it for the lineament category). Similar differences also were apparent for coincident 80K and CIR lineaments in most distance categories, but these differences were not statistically significant (fig. 22). Relations with well yield were slightly better with 80K lineaments than with CIR lineaments, a result that is consistent with findings of Mabee and others (2002) for lineaments and water-yielding fractures in a bedrock tunnel in eastern Massachusetts. No statistically significant differences in yield were found when wells were categorized in terms of proximity to shaded DEM lineaments. An example of differences in yield for wells located closer and farther than 200 ft from 80K and CIR lineaments is shown in figure 22. Differences, although statistically significant, were small, with differences in median and 75th-percentile yields of 3 to 10 gal/min or less.

Lineament analyses are subject to a number of limitations that make identified yield-lineament relations difficult to interpret. Lineaments are delineated with subjective, qualitative criteria that vary among observers. Reproducible approaches that identify coincident lineaments, delineated by multiple observers, are one way to reduce this subjectivity (Mabee and others, 1994). Correlation of lineaments with observed fractures is another way (Mabee and others, 1994; Degnan and Clark, 2002). With the Nashoba-terrane yield data, the reproducibility approach—use of coincident lineaments—appeared to produce lineament data that were less well correlated with well yield than the unscreened data from the two observers. This may have been the result of sample sizes, however, rather than a characteristic of the lineament data. As noted previously, differences in yield values of wells close to and farther away from all lineaments and from coincident lineaments were similar in magnitude, for 80K and CIR lineaments (fig. 22). The differences were statistically significant for all lineaments, but not for coincident lineaments, probably because of the smaller sample numbers for wells close to coincident lineaments as compared to numbers of wells close to all lineaments.

Other limitations also affect the ability of lineaments to represent structural features related to well yield. Some lineaments may reflect structural features other than fractures or fracture zones (Walsh, 2000), or may represent topographic features of glacial origin that do not reflect the underlying bedrock geology (Mabee and others, 2002). Also, because they only depict features that intersect the land surface, lineaments do not indicate subhorizontal fractures, which may have a substantial influence on bedrock flow (Boutt and others, 2010). Correlation of lineament direction with the azimuth directions of observed bedrock fractures is intended to increase the likelihood that lineaments depict structural features that are related to groundwater flow. For the Nashoba-terrane yield data, boxplots suggest that wells located closer to fracture-correlated lineaments may have slightly higher yield than wells located closer to lineaments regardless of direction, but the differences are very slight. These patterns were apparent whether fracture correlation was based on the predominant directions of outcrop fractures in the areas of all three quadrangles (fig. 22) or on the major and minor fracture-set directions identified for each quadrangle (data not shown).

The relative insensitivity of the yield-lineament relations to whether lineaments were fracture correlated or coincident might also occur if the overall relations of yield and lineament proximity had more to do with some other factor with which lineaments are correlated than with the lineaments themselves. For example, lineaments were not evenly distributed across all topographic settings, but more often were present in low-lying areas than in upland areas. Lineament density (total length per unit area, using 80K lineaments as an example) was two to four times greater in valleys and low-slope areas than in areas of hilltops/ridges or upper slopes. Comparisons of well yield among topographic-feature categories indicated that yield was slightly higher in the low-lying areas than in the upper topographic settings. Overall, wells closer to lineaments may have higher yield because they are located in low-lying areas, where there also are more lineaments delineated.

Mabee and others (2002) suggested that additional screening of lineaments by topography, bedrock type, overburden type, and proximity to surface waters might improve their relation to water-bearing zones in New England fractured-bedrock aquifers. Comparison of well yield and proximity to lineaments within categories of topographic setting, surficial geology, and other factors also potentially eliminates the confounding effects of these factors on yield. These kinds of distinctions might be useful in the Nashoba terrane area. Well yield was slightly higher for wells located close to lineaments in valleys and low-slope areas than for wells not close to these lineaments, whereas no statistically significant relations between yield and lineament proximity were apparent for lineaments in hilltop/ridge or upper-slope areas (fig. 23, using the example of 80K lineaments for wells in Nashoba terrane area of Ayer, Hudson, and Marlborough quadrangles). Similarly, relations between well yield and lineament proximity were stronger for lineaments in areas overlain by glacial sand and gravel deposits (typically low-lying areas also) than for lineaments in areas underlain by glacial till. Further investigation of such patterns might be useful because differences between yields for wells close to and farther away from lineaments in low-lying areas were larger than many of the other observed differences in yield (fig. 23), but the sample sizes also were very small and unequal.

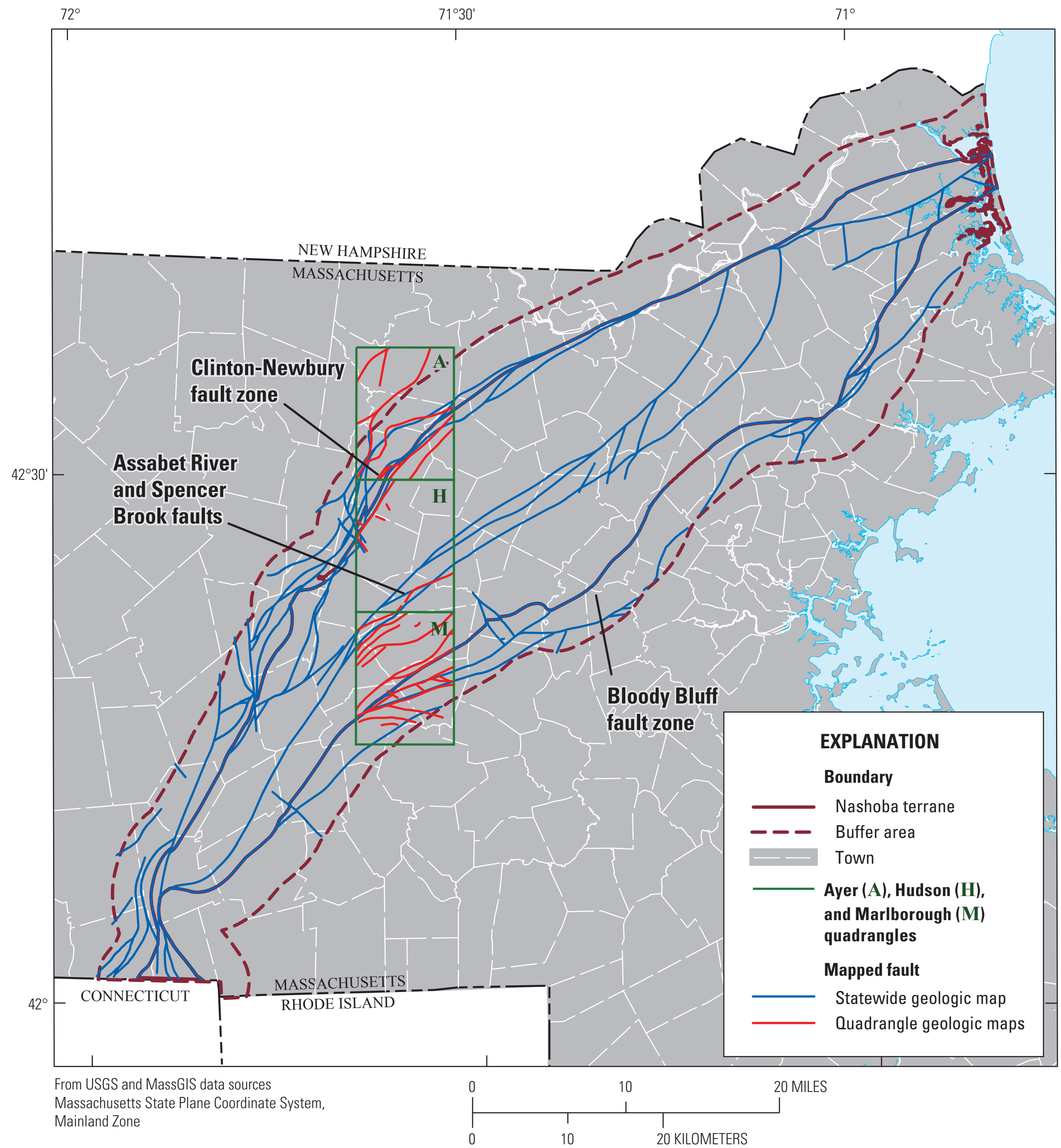


Figure 18. Major faults mapped on statewide and quadrangle geologic maps in the Nashoba terrane and surrounding area. Statewide data from Zen and others (1983) and Nicholson and others (2006). Quadrangle data are for the Ayer, Hudson, and Marlborough quadrangles and are from Kopera and Hansen (2005), Kopera (2006), and Kopera and others (2006a).

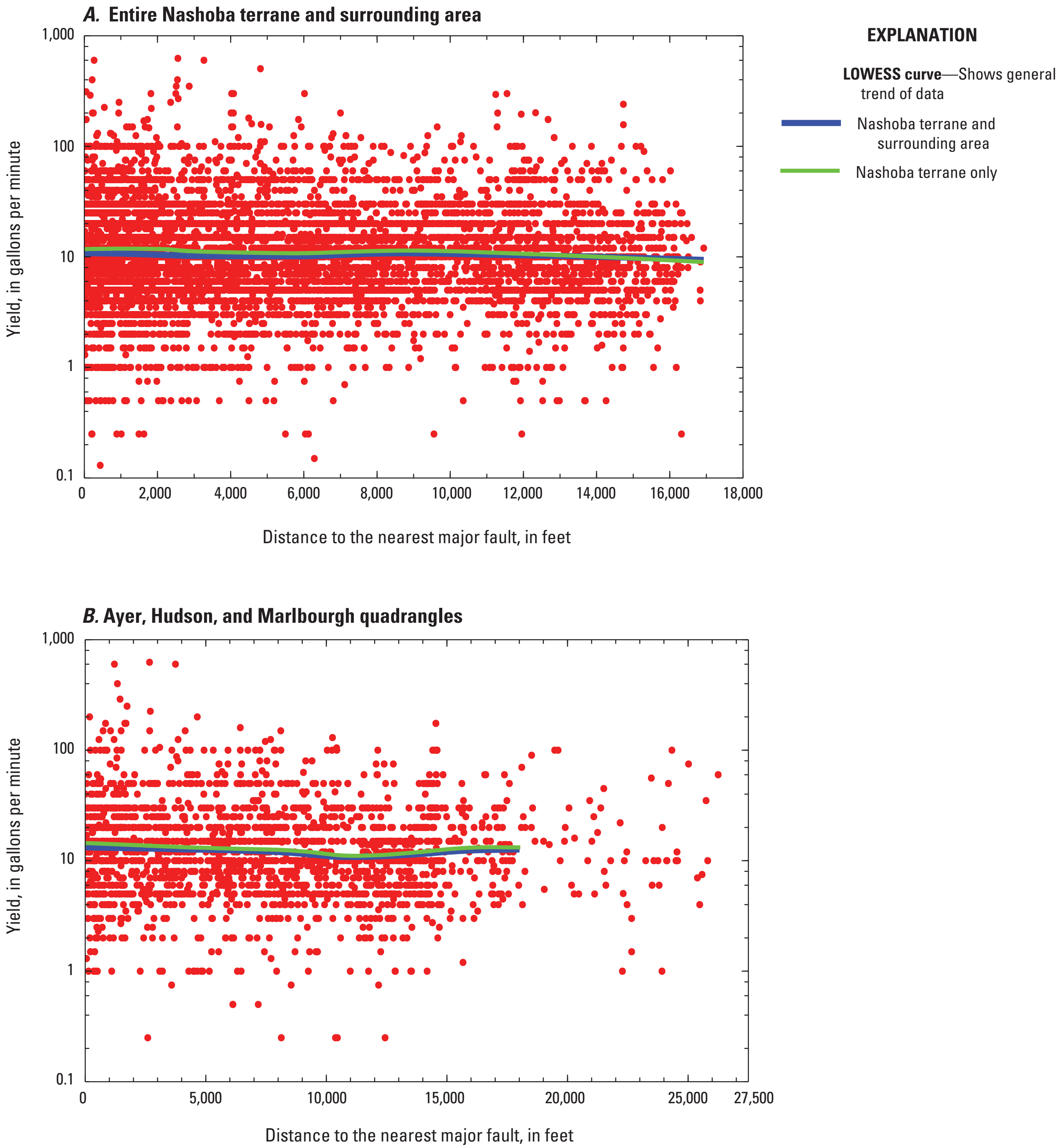


Figure 19. Comparison of well yield with distance to nearest major fault for *(A)* the Nashoba terrane and surrounding area and *(B)* the Ayer, Hudson, and Marlborough quadrangles. LOWESS (locally weighted scatterplot smoothing) curves are truncated at distance equal to 18,000 feet for quadrangle data because of sparse data.

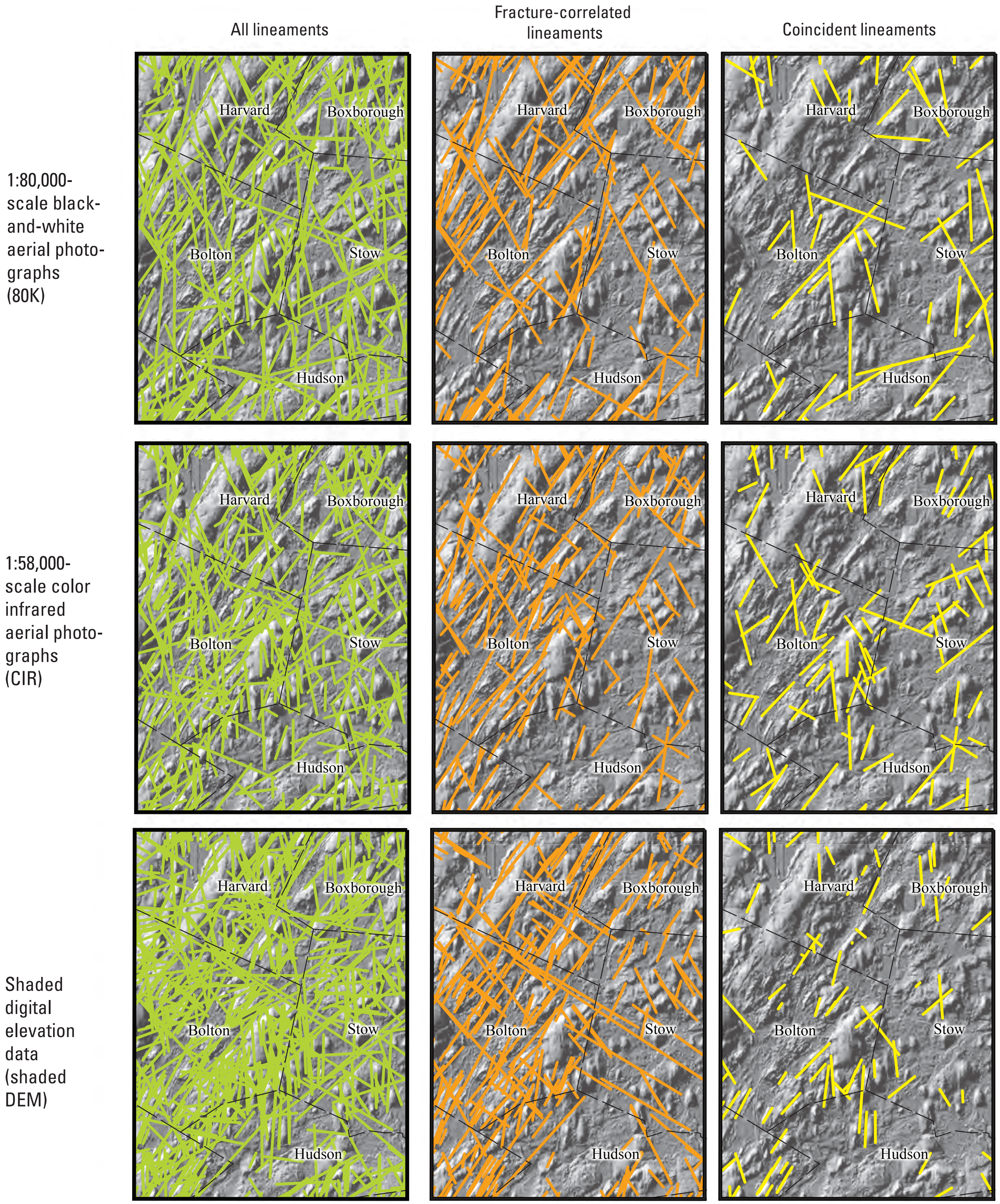


Figure 20. Lineaments delineated in the Hudson Quadrangle. All lineaments are all lineaments delineated by either of two independent observers. Coincident lineaments are those identified by both observers. Fracture-correlated lineaments are those trending in the predominant directions of fractures observed at outcrops in the Ayer, Hudson, and Marlborough quadrangles (see text for more information on fracture correlation). Coincident, fracture-correlated lineaments, not shown, also were determined.

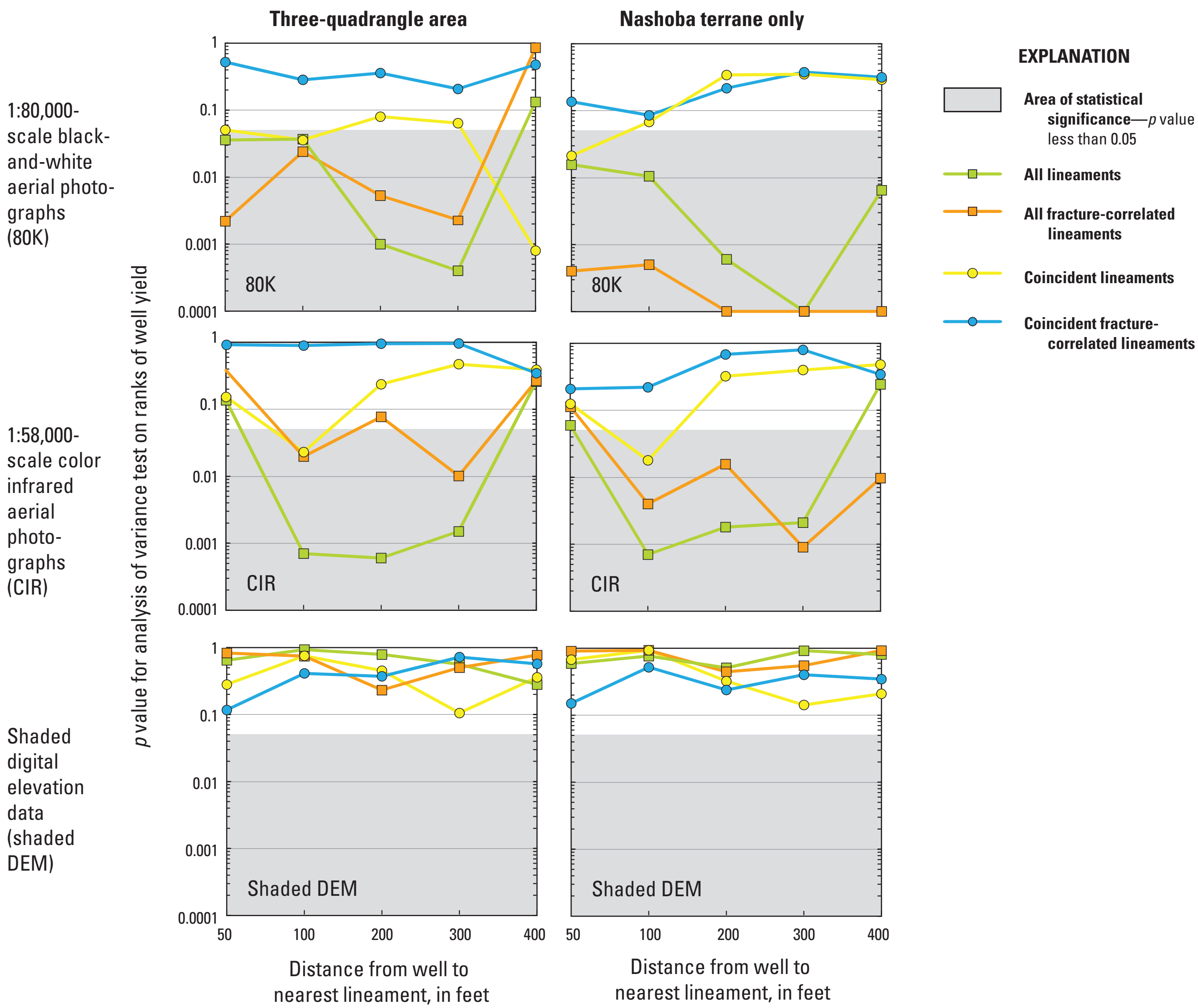


Figure 21. Comparison of well yield and distance to lineaments, represented by the *p* values of ANOVA (analysis of variance) tests on ranks of yield. *p* values less than 0.05 are considered statistically significant. 80K, 1:80,000 black-and-white aerial photographs; CIR, 1:58,000 color infrared aerial photographs; shaded DEM, 1:5,000-scale shaded digital elevation model data

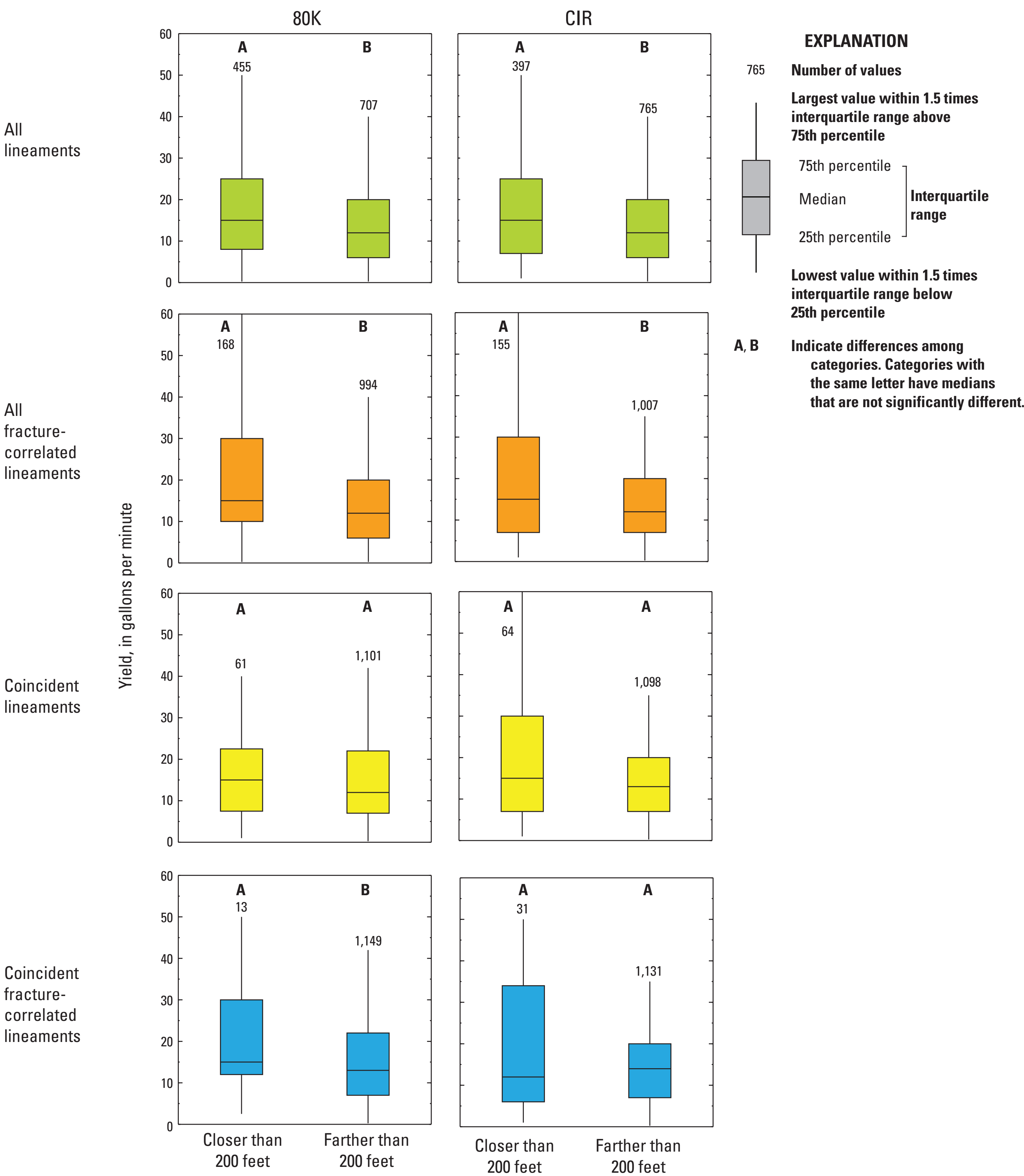


Figure 22. Well yield by proximity to lineaments, shown for the example of lineaments delineated from 1:80,000 black-and-white aerial photographs (80K) and 1:58,000 color infrared (CIR) aerial photographs, for the distance category of 200 feet, in the Nashoba terrane within the Ayer, Hudson, and Marlborough quadrangles.

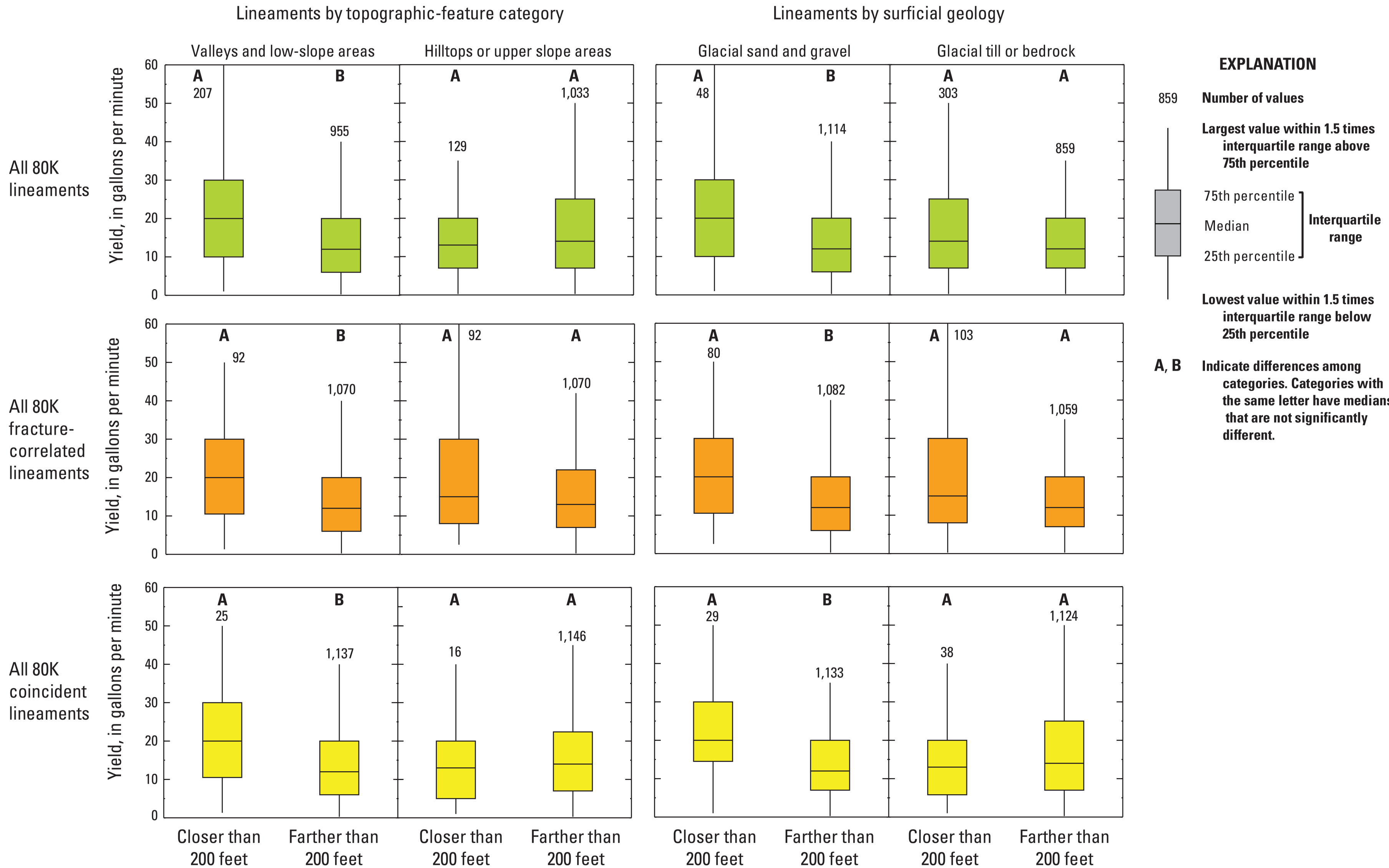


Figure 23. Well yield by proximity to lineaments delineated from 1:80,000-scale black-and-white aerial photographs (80K lineaments), where lineaments are categorized according to topographic feature categories (low-lying compared to upland areas) and surficial geology (sand and gravel overburden compared to till or no overburden). Wells are from the Nashoba terrane within the Ayer, Hudson, and Marlborough quadrangles.

Hydrostructural Domains

Both lithologic and fracture characteristics are incorporated in the hydrostructural domains that were delineated by Mabee (2005), Kopera and others (2006b), and Mabee and Salamoff (2006) for the Ayer, Hudson, and Marlborough quadrangles. These characteristics potentially influence groundwater flow in and recharge to the fractured-bedrock aquifers and were used by the authors to define areas of similar hydrogeologic characteristics for use in groundwater investigations (Mabee and Kopera, 2007; Boutt and others, 2006; Manda and others, 2006).

Four hydrostructural domains have been delineated in the Hudson and Marlborough quadrangles—massive (unfoliated or not layered) rocks, moderately dipping layered rocks (Marlborough quadrangle only), steeply dipping layered rocks, and rocks with partings (openings) parallel to layering or foliation (Mabee, 2005; Mabee and Salamoff, 2006). In the Ayer quadrangle, hydrostructural domains correspond to stratigraphic formations but are similarly defined in terms of fracture characteristics (Kopera and others, 2006b). Massive rocks include most of the granites, associated granite gneisses, and diorites. Moderately dipping rocks include the Westboro Formation, some granites, gneisses, diorites of the Avalon terrane, and small parts of the Nashoba and Marlboro Formations. Steeply dipping rocks include most of the Nashoba and Marlboro Formations, the Tadmuck Brook Schist, the Straw Hollow Diorite, and a number of unnamed metasedimentary units. The hydrostructural domain defined by the presence of partings parallel to layering includes large parts of the Marlboro and Westboro Formations and small parts of other metasedimentary and igneous formations.

Well yield was slightly higher for wells located in the massive rocks than for wells located in steeply dipping layered rocks or rocks with partings parallel to layering (fig. 24). No statistically significant differences were observed in yield (1) among wells located in moderately dipping layered rocks, steeply dipping layered rocks, or rocks with partings parallel to layering, or (2) between wells in massive rocks and wells in moderately dipping layered rocks. The difference in yield between wells in massive rocks and steeply dipping layered rocks is similar to the difference in yield observed between wells in granites and wells in schists and gneisses. The massive rocks differ from the rocks of the other hydrostructural domains in that they are characterized by well-developed subhorizontal sheeting fractures, in addition to steeply dipping fractures, which provide lateral connectivity between fractures (Mabee, 2005; Kopera and others, 2006b, Mabee and Salamoff, 2006); this could be a factor in the slightly higher yields of the massive rocks. Lateral connectivity also is provided by layering in the moderately dipping rocks (Mabee and Salamoff, 2006). Sheeting joints are poorly developed in the steeply dipping layered rocks (which are mostly part of the Nashoba Formation in terms of area and number of wells), except along the Assabet River fault and in the Straw Hollow Diorite (Mabee and Salamoff, 2006).

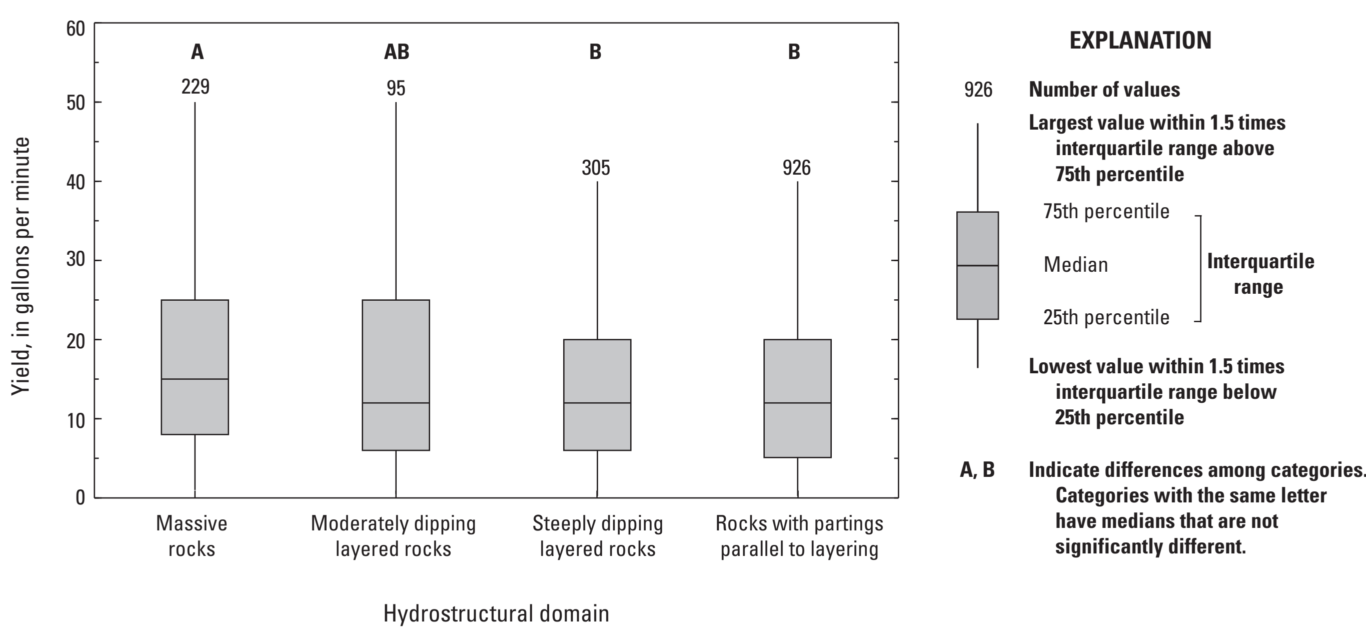


Figure 24. Well yield by hydrostructural domain in the Nashoba terrane and surrounding area, in the Ayer, Hudson, and Marlborough quadrangles. Hydrostructural domains from Mabee (2005), Kopera and others (2006), and Mabee and Salamoff (2006).

Surficial Geology and Surface Water

Surficial geologic deposits (commonly called "overburden") and surface-water bodies may influence bedrock-well yield by serving as sources of water to the underlying bedrock. Cederstrom (1972) described several studies of fractured-bedrock aquifers along the East Coast in which bedrock-well yield was higher in areas under stratified, coarse-grained glacial deposits than in areas under glacial till; he also described a number of examples in which high-yielding bedrock wells were located along rivers. Both overlying surficial geology and distance to surface-water bodies were related to well yield in the statewide New Hampshire study (Moore and others, 2002).

Surficial Geology

Surficial geology was generalized into three categories—stratified glacial deposits, thin till or bedrock, and thick till (fig. 25). Types of stratified glacial deposits included coarse-grained sand and gravel deposits as well as fine-grained glaciolacustrine deposits and overlying postglacial alluvium. The surficial geologic deposits within a 400-ft buffer area around the well were considered in addition to the surficial geologic deposits at the well location, because the surficial geologic deposits throughout the area that is contributing water to the well, rather than just the deposits at the wellhead, potentially influence well yield. The buffer-area approach greatly simplifies actual contributing areas, which vary considerably in size and shape depending on pumping rates and local hydrogeological conditions.

Both category and thickness of surficial geologic deposits (overburden) were related to well yield in the Nashoba terrane and surrounding area. Well yield was slightly higher for wells underlying stratified glacial deposits than for wells underlying thin till or bedrock, or underlying thick till (fig. 26A; table 4). There was no statistically significant difference between the yield of wells underlying thin till or bedrock and the yield of wells underlying thick till. The percentage of stratified glacial deposits in a 400-ft buffer area around the well also was positively correlated with well yield (fig. 26B; table 4), although, as with other variables, the differences were small. For wells located within areas of stratified glacial deposits, yield was positively correlated with the overburden thickness; no relation with overburden thickness was apparent for wells underlying till (table 4). These relations of yield to overburden thickness are consistent with results of the Massachusetts statewide bedrock yield study by Hansen and Simcox (1994), which reported increases in yield with increasing overburden thicknesses in valleys and lowlands, where the overburden was glacial sand and gravel.

Surface Water

Streams, open-water bodies (lakes, ponds, and reservoirs), and wetlands were included in the analysis of well yield and proximity to surface-water bodies (fig. 27). All of these categories of surface waters can be sources of water to the underlying aquifers. Streams were limited to perennial streams only and were combined with the boundaries of open-water bodies and wetlands with standing water (deep marshes) for the comparison of well yield and distance to the nearest surface-water body. Well yield also was compared to the percentage of open water and wetlands in a circular 400-ft buffer area around the well. For the buffer-area comparison, all wetland categories, including deep marshes, shallow marshes, shrub swamps, and wooded swamps, were used.

Well yield was inversely correlated with distance to the nearest surface water, with slightly higher yields of wells closer to surface-water bodies (perennial streams, open water, and deep marsh) (fig. 28, table 4). Examination of the LOWESS line fit to the data indicates that the relation occurs for wells within distances of about 1,200 ft (370 m); at greater distances, the relation between yield and distance to the nearest surface-water body is not statistically significant (p value equal to 0.206 for all wells), although it appears to be an increasing trend. Well yield also was positively correlated with the percentage of wetlands or open water in a 400-ft buffer area around the well (table 4). Figure 29 shows yield as a function of the percentage of wetlands or open water in the buffer area. The figure illustrates that, as with the other variables, the differences in yield corresponding to differences in wetland or open-water percentages are small.

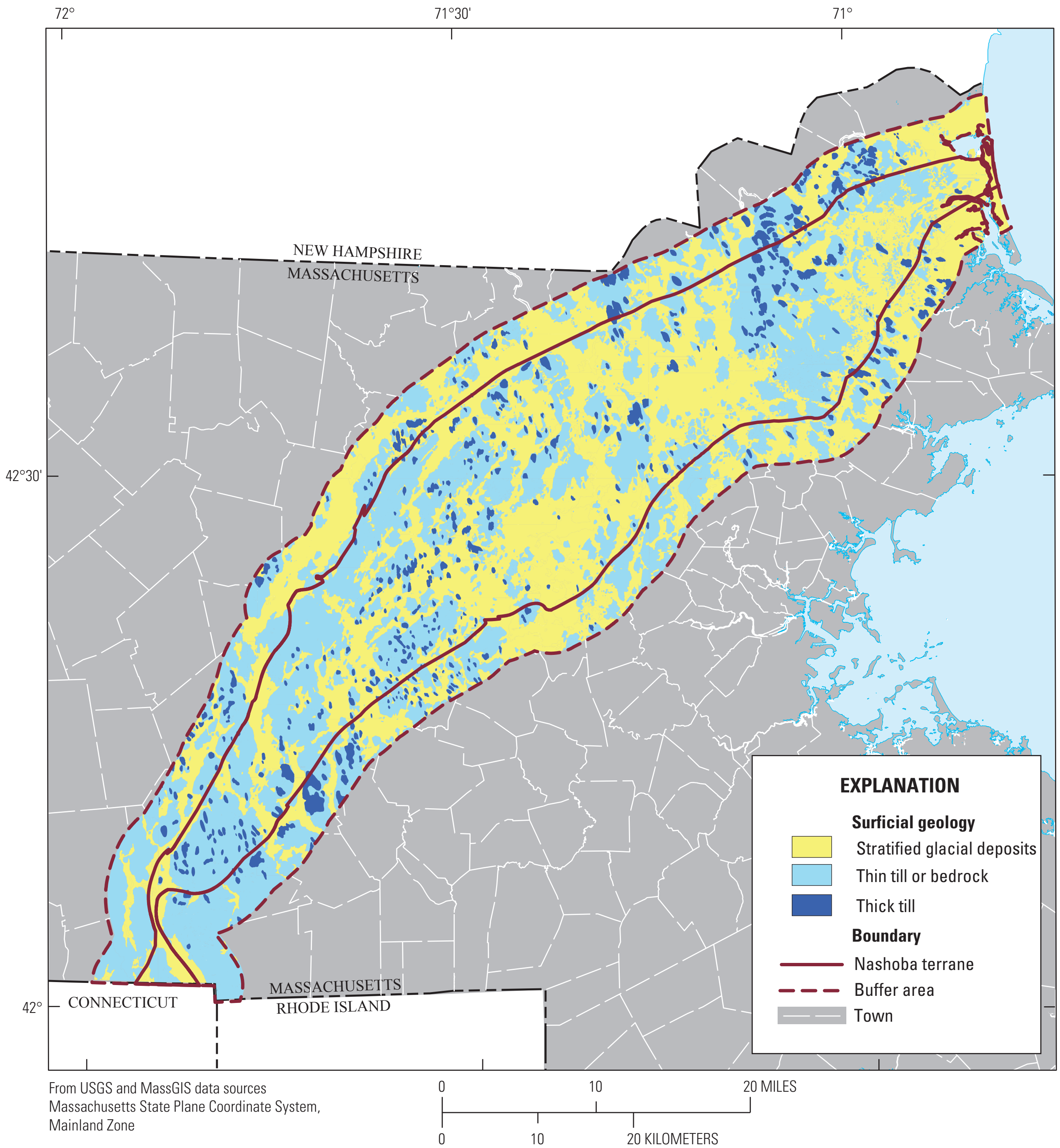


Figure 25. Generalized surficial geology in the Nashoba terrane and surrounding area. Data from MassGIS (1999a, 2007a), based on data from Stone and others (2006, 2008) and Stone and Stone (2006, 2007).

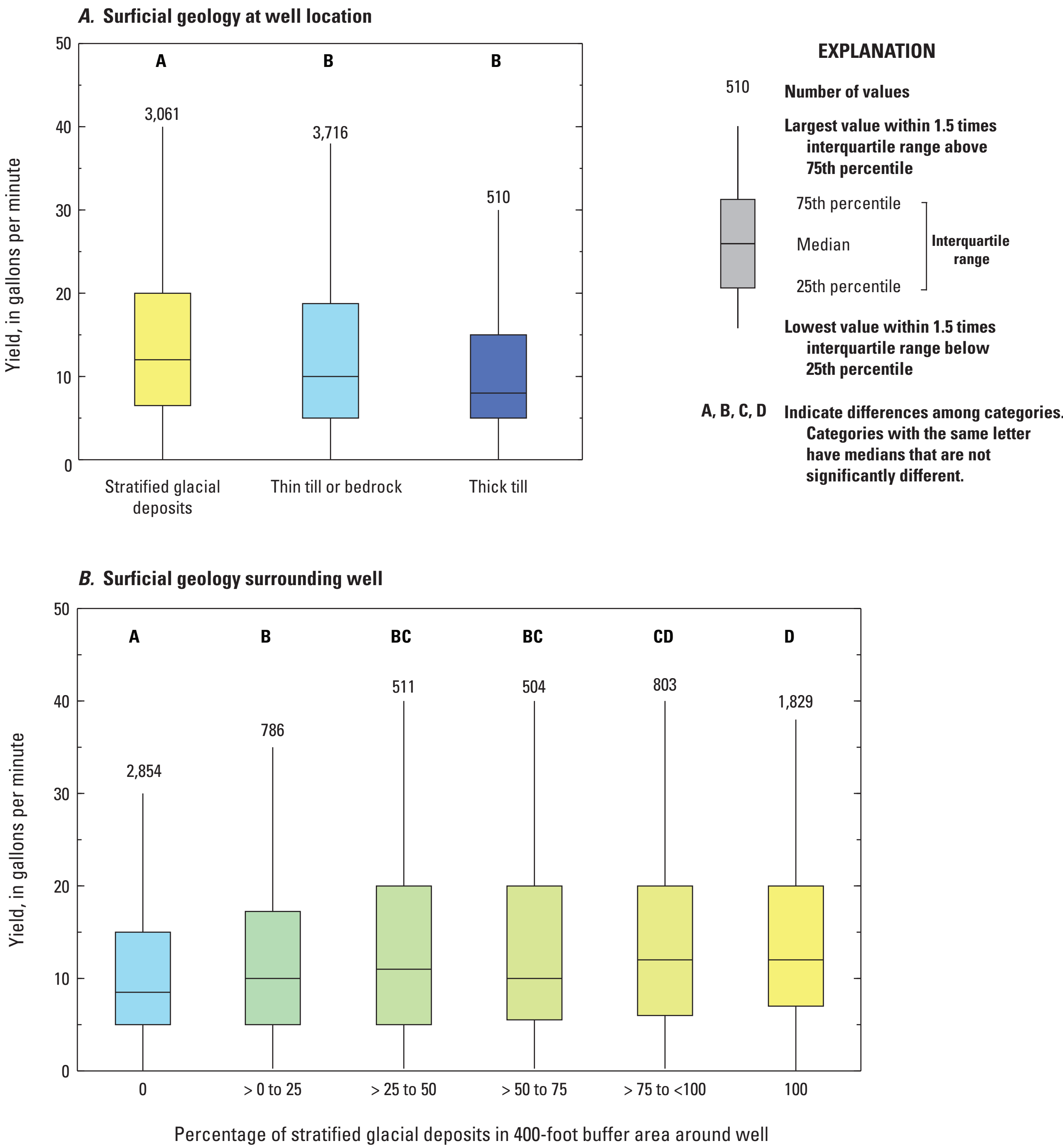


Figure 26. Well yield by overlying surficial geology for wells in Nashoba terrane and surrounding area. *(A)* Surficial geology at well location. *(B)* Surficial geology in 400-foot buffer area surrounding well. The areal distribution of surficial geology is shown in figure 25.

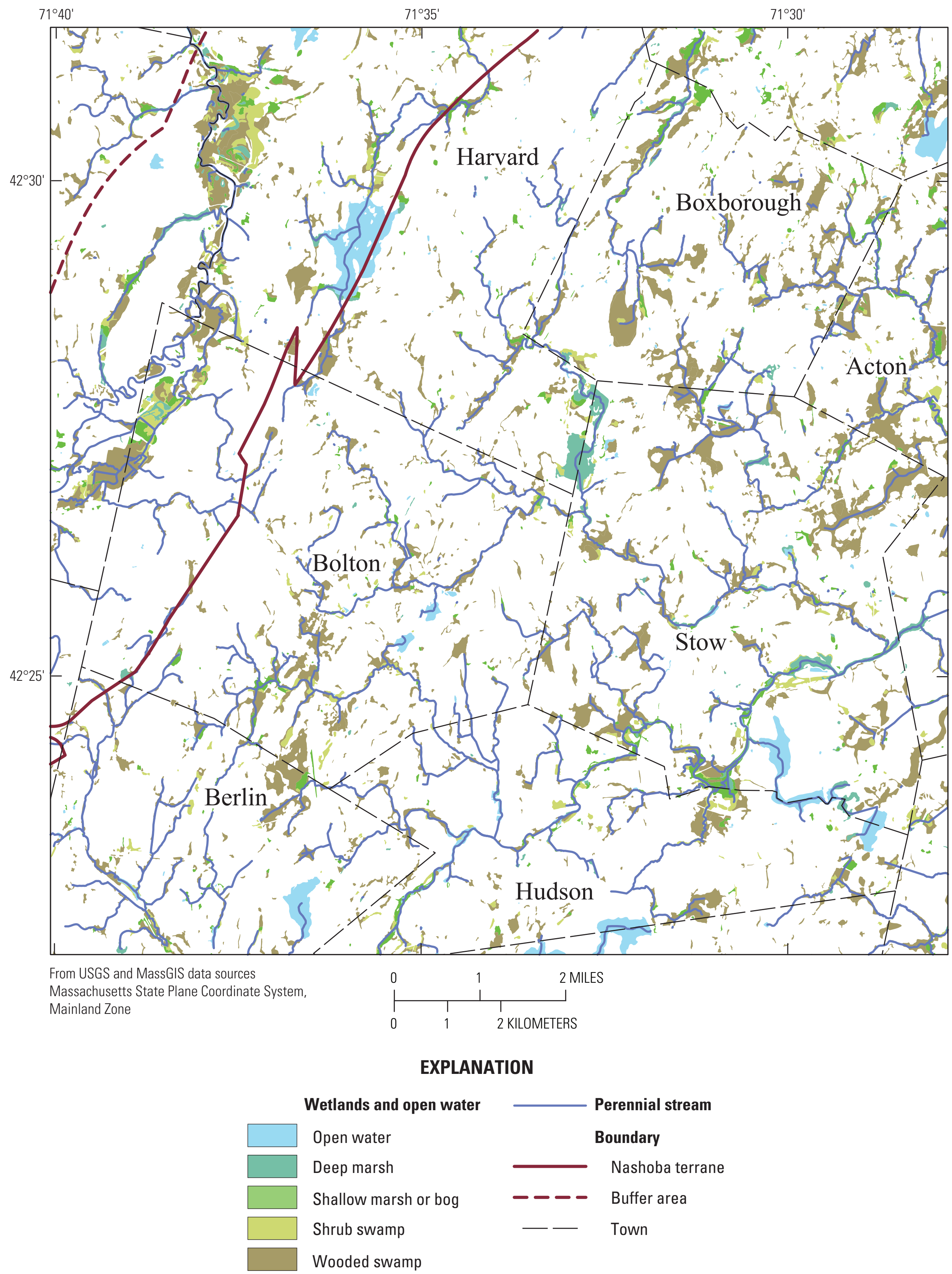


Figure 27. Streams, wetlands, and water bodies in the Nashoba terrane and surrounding area. A part of the study area, about 110 square miles, is shown.

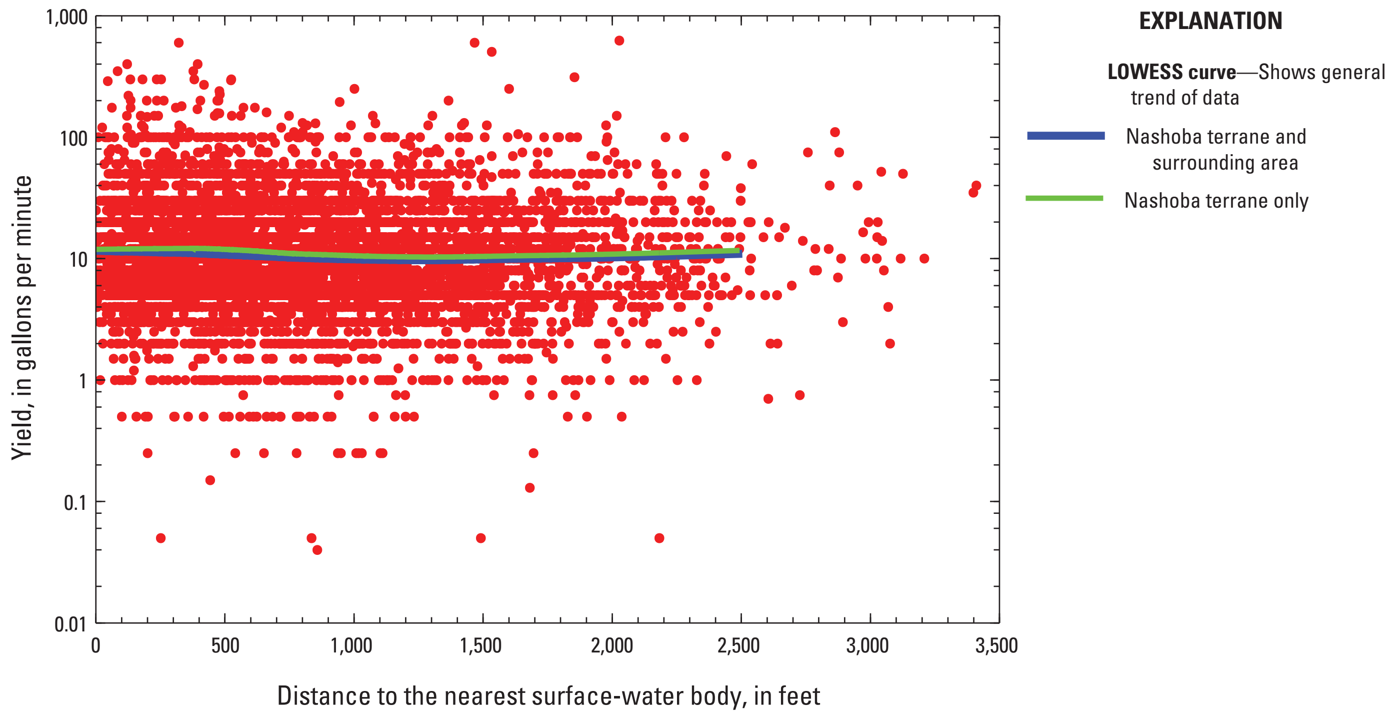


Figure 28. Comparison of well yield with distance to the nearest surface water in the Nashoba terrane and surrounding area. Surface water includes perennial streams, open water, and deep marsh. Data points shown are for all wells in the Nashoba terrane and surrounding area. One data point at a distance of 4,372 feet is not shown. LOWESS (locally weighted scatterplot smoothing) curves are truncated at distance equal to 2,500 feet because of sparse data.

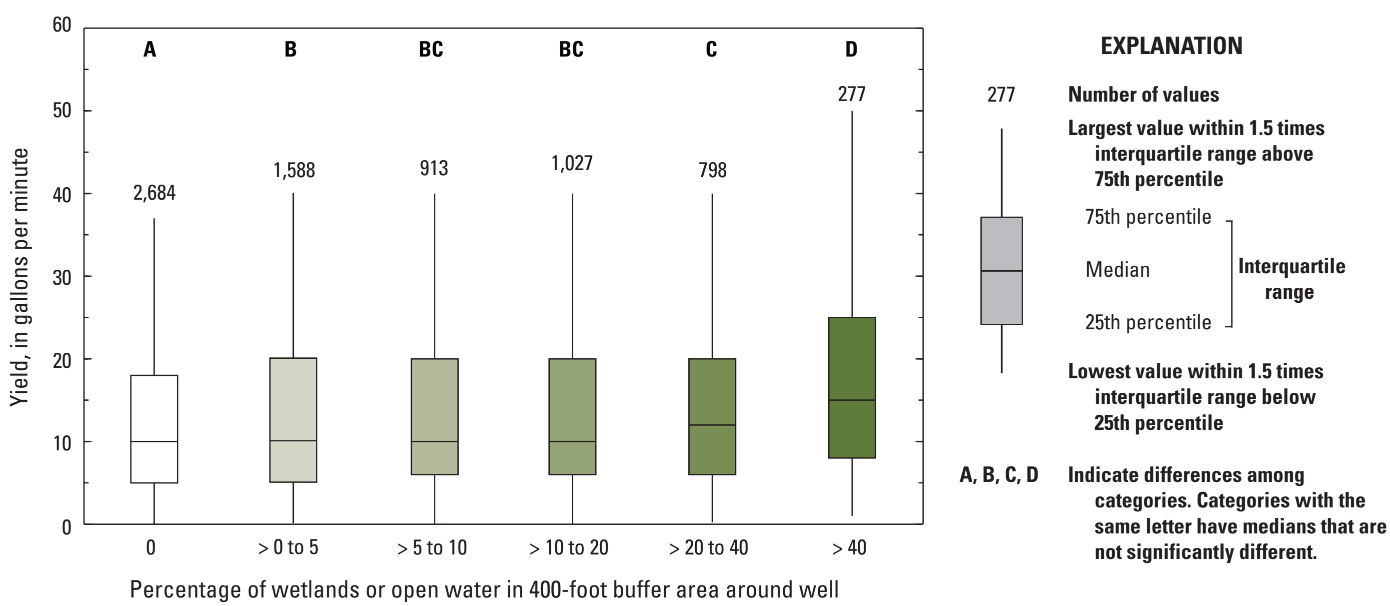


Figure 29. Well yield and percentage of wetlands or open water near well locations in the Nashoba terrane and surrounding area. The areal distribution of wetland types is shown in figure 27; all wetland types and open water are included in each percentage category here.

Multivariate Regression Analysis of Well Yield

Well yield is potentially influenced by many hydrogeologic and cultural factors, some of which are related to one another, and there is more than one way to measure many of them. Multiple linear regression was used to examine the relations of well yield and a large number of hydrogeologic and cultural variables together. The regression model that is developed by including multiple explanatory variables explains more of the variance in the response variable (well yield) than would be explained by any one factor individually (Helsel and Hirsch, 1992). Multivariate regression models were developed in this study to improve understanding of the hydrogeologic factors affecting well yield by identifying the variables that have the largest effects, rather than to predict yield throughout the study area. Cultural factors (for example, intended use of the well) were included because, although they are unrelated to characteristics of the bedrock aquifer, they potentially explain relatively large amounts of the total variation in well-yield data (Knopman and Hollyday, 1993).

Models were developed for the Nashoba terrane area and for the Ayer, Hudson, and Marlborough quadrangles; the quadrangle-scale model incorporated variables that describe the proximity to lineaments and the 1:24,000-scale geologic map data. The models were limited to the areas within the Nashoba terrane to avoid including any differences in yield arising from differences in geology between the Nashoba and adjacent terranes. The response variable in the models was the base-10 logarithm (log) of well yield, and numerical (continuous) variables also were log transformed.

A large number of variables (85, table 2) were evaluated for inclusion in the regression models. These variables included multiple measures of bedrock and surficial geology, topography, and proximity to major faults, lineaments (for quadrangle models), surface water, and wetlands as described in the previous section entitled “Well Yield in Relation to Hydrogeologic Factors” in terms of their individual relations with well yield (table 4) and additional variables. Some of the additional variables were related to the town in which wells are located and characteristics of the wells themselves: whether or not the town provides a public-water supply; the median household income in the town from 2000 Census block data; the logs of the depth of the well and the length of the uncased, open hole in bedrock; the year when the well was constructed; the use of the well (irrigation, public, commercial or industrial, domestic, and unspecified and other uses, such as monitoring and geothermal); and the duration of the aquifer test used to determine well yield. As described in the section entitled “Well-Yield Data,” several of these factors were related to well yield; in some cases, their individual relations with well yield were stronger than those of hydrogeologic factors. Relations of well yield to well use and well depth, in particular, were important to evaluate in the model, because of their relatively strong relations with well yield (figs. 8 and 10).

The overall results of the multivariate regression model analysis indicate that well yield in the Nashoba terrane is related to a number of the tested factors, but the amount of variance in the yield explained by these factors was low (measured as the variance in the response variable, logYield). The regression model for the entire Nashoba terrane dataset explained 21 percent of the variance in logYield, and the model for the Ayer, Hudson, and Marlborough quadrangles explained 30 percent of the variance in logYield. The model variables, which described well characteristics, bedrock geology, topography, and, for the quadrangle model, proximity to lineaments and hydrography, are listed in tables 6 and 7. Positive influences on well yield are indicated by a coefficient with a positive sign, and negative (inverse) influences on well yield are indicated by a coefficient with a negative sign. The magnitudes of the influence of individual variables cannot be compared by comparing coefficient values, however, except for categorical variables within the same group (for example, for different values of well use). Most of the explained variance in logYield was attributed to variables describing well characteristics. Alternative models for the entire Nashoba terrane that excluded well characteristics explained only about 5 percent of the variance in logYield.

Well depth was one of the well characteristics found to be statistically significant in the regional regression model for the Nashoba terrane. The coefficient for the log of well depth is negative (-0.61), indicating that yield decreases with well depth (table 6). This relation likely reflects the effect of drilling to meet a specified demand rather than the true physical relation between yield and depth, as discussed previously in the section on well-yield data. Wells tend to be drilled deeper at lower-yielding locations, because they are drilled as deep as necessary to meet the needed demand. Also, most of the wells in the dataset were domestic wells. The typical flow rate needed for a domestic well is in the range of 2 to 5 gal/min (B.R. Bouck, Massachusetts Department of Environmental Protection, written commun., 2012), which is low compared to the yield needed for public or industrial water supplies. Thus, the dataset spans a smaller range of yields than if well depths were random or if all wells were drilled to a uniform depth (Moore and others, 2002). Also, low-yielding shallow wells and high-yielding deep wells are underrepresented in the dataset. As a result, the expected physical relation of increasing well yield with total well depth at any given location is not represented in the dataset, and yield decreases with well depth in the well-yield dataset. This is one way that the yield requirements of supply wells introduce bias into the dataset that is not geologic in nature.

Other well characteristics found to be statistically significant in the regional model were three well-use categories, the year when the well was constructed, and the duration of the test used to determine well yield. Coefficients indicate that public-supply wells and commercial or industrial wells were associated with higher than average yields (positive coefficient), and domestic wells were associated with lower than average yields (negative coefficient). The coefficient for

Table 6. Multivariate regression model for well yield in the Nashoba terrane.

[Variables with attained significance levels (*p* values) of less than 0.05 were retained in the model. =, equal to; NA, not applicable; R^2, coefficient of determination]

Model variable or other information	Variable coefficent and *p* value		Variable type
	Coefficient	*p* value	
Well characteristics			
Log of well depth	-0.61	<0.001	Continuous
Well use = public supply	+0.36	<0.001	Categorical
Well use = commercial or industrial	+0.47	<0.001	Categorical
Well use = domestic	-0.15	<0.001	Categorical
Year when well was constructed	+0.0096	<0.001	Continuous
Duration of well test to determine yield = more than 4 hours	-0.14	<0.001	Categorical
Bedrock geology			
Generalized rock type = granite	+0.053	0.002	Categorical
Geologic-map unit = Fish Brook Gneiss (OZf)	+0.12	0.010	Categorical
Geologic-map unit = Nashoba Formation, Boxford member - amphibolite (OZnb)	+0.10	<0.001	Categorical
Geologic-map unit = unnamed granite to granodiorite (Sgr)	-0.13	<0.001	Categorical
Geologic-map unit = Straw Hollow Diorite and Assabet Quartz Diorite, undifferentiated (Ssaqd)	+0.18	<0.001	Categorical
Geologic-map unit = Sharpners Pond Diorite (Ssqd)	-0.10	0.001	Categorical
Geologic-map unit = unnamed muscovite granite (mgr)	-0.33	<0.001	Categorical
Topography			
Log of land-surface elevation	-0.17	<0.001	Continuous
Topographic-feature category = low slope	+0.060	<0.001	Categorical
Topographic-feature category = upper slope	-0.042	0.003	Categorical
Surficial geology			
Log of depth to bedrock, in meters	+0.035	0.003	Continuous
Response variable = log of well yield, in gallons per minute	NA	NA	Continuous
Constant	-16.5	<0.001	NA
Adjusted R^2	0.21	NA	NA
Mean square error	0.14	NA	NA
Number of wells	5,066	NA	NA

the year the well was drilled also is positive, indicating that older wells tend to have lower yields. This may be a result of increases in demand with time or changes in drilling methods, as discussed previously. Finally, logYield tends to be lower for wells pumped more than 4 hours to measure yield.

The generalized rock type representing granitic rocks had a positive coefficient of +0.053, indicating that wells in areas with these rocks tended to have higher than average yields. None of the other generalized rock types in this group of categorical variables had a significant effect on well yield. Six of the 13 individual geologic-map units were statistically significant at the α equals 0.05 level. Three units—the Fish Brook Gneiss (OZf); the Boxford member of the Nashoba Formation (amphibolite, OZnb); and the Straw Hollow Diorite and Assabet Quartz Diorite, undifferentiated (Ssaqd)—had positive coefficients and were associated with higher than average yields. The other three units—the Sharpners Pond Diorite (Ssqd), an unnamed granite to granodiorite (Sgr), and an unnamed muscovite granite (mgr)—had negative coefficients and were associated with lower than average yields (table 6). These results are consistent with the single-variable analysis of bedrock geology at the statewide scale: higher yield in granites than in several other generalized rock types and higher yields in the Straw Hollow Diorite, Fish Brook Gneiss, and

Table 7. Multivariate regression model for well yield in the Nashoba Terrane in the Ayer, Hudson, and Marlborough quadrangles.

[Variables with attained significance levels (p values) of less than 0.05 were retained in the model. R^2, coefficient of determination; =, equal to; CIR, color infrared; NA, not applicable]

Model variable or other information	Variable coefficent and *p* value		Variable type
	Coefficient	*p* value	
Well characteristics			
Log of well depth	-0.65	<0.001	Continuous
Well use = commercial or industrial	+0.40	0.045	Categorical
Well use = domestic	-0.38	<0.001	Categorical
Year when well was constructed	+0.012	<0.001	Continuous
Duration of well test to determine yield = more than 4 hours	-0.18	<0.001	Categorical
Bedrock geology			
Generalized rock type = granite	+0.25	<0.001	Categorical
Geologic-map unit = Marlboro Formation, amphibolite and schist (COma, Marlborough quadrangle)	-0.26	<0.001	Categorical
Topography			
Topographic-feature category = low slope	+0.12	<0.001	Categorical
Proximity to lineaments			
Log of distance to nearest fracture-correlated CIR lineament	-0.060	0.009	Continuous
Surface water			
Percentage of open water and deep marsh in 400-foot buffer area around well	-0.0045	0.012	Continuous
Response variable = log of well yield, in gallons per minute	NA	NA	Continuous
Constant	-21	<0.001	NA
Adjusted R^2	0.30	NA	NA
Mean square error	0.11	NA	NA
Number of wells	1,119	NA	NA

Boxford Member of the Nashoba Formation. (If a given well is in an area represented by the granitic generalized rock type and also represented by one of the geologic map units that is included in the generalized rock type, the coefficient for the geologic map unit either adds or subtracts from the positive coefficient of the generalized rock type to achieve its net effect on yield. This effect applies to wells in areas of the unnamed granite to granodiorite, Sgr, explaining what might appear to be inconsistent results for Sgr for the multivariate and single-variable analysis.)

Topographic variables found to be significant in the regional model were land-surface elevation and two of the topographic-feature categories. The coefficient for the log of land-surface elevation at the well was negative (-0.17), indicating that wells at higher elevations tend to have lower than average well yields (table 6). Similarly, topographic feature categories indicate that wells on upper slopes are associated with lower than average yields, and wells in low-slope areas are associated with higher than average yields. The coefficient for the log of depth to bedrock, which also represents overburden thickness, is positive (+0.035), indicating that well yields are higher in areas with thicker unconsolidated overburden deposits overlying the bedrock surface. In the Nashoba terrane, thick unconsolidated deposits typically represent stratified glacial deposits, which tend to be located in flat, low-elevation stream valleys; although till drumlins also are areas of thick overburden, few wells (7 percent) in the model dataset were located in drumlins. Thus, the topographic and overburden-depth variables indicate that wells in flat, low-elevation areas tend to have higher than average yields. Similar relations also were found with the single-variable analysis.

The regression model developed for the subset of wells in the Ayer, Marlborough, and Hudson quadrangles is similar, for the most part, to the regional model for the entire Nashoba terrane, but differed in terms of some of the variables included (table 7). The regression model for this quadrangle dataset also explained a little more (30 percent) of the variance in logYield than did the regional model. Well depth, well use (commercial or industrial and domestic), the year the well was constructed, the duration of the test to determine well yield, and the generalized granitic rock type were significant variables, with coefficients and *p* values similar to those in the regional model. Only one geologic map-unit variable, the Marlboro Formation amphibolites and schist in the Marlborough quadrangle (COma), was significant; yields of wells in this geologic map unit were lower than average, which is consistent with the single-variable results at the quadrangle scale. The quadrangle model also included a surface-water variable—the percentage of open water and deep marsh in a 400-ft buffer area around the well: the negative coefficient for this variable (-0.0045) indicates that yields tended to decrease with distance from open-water bodies. Of the additional variables describing proximity to lineaments, only one—log of distance to nearest fracture-correlated CIR lineament—was statistically significant at the α equals 0.05 level. Several variables that were significant in the regional model, including land-surface elevation, depth to bedrock, the upper slope topographic feature category, and public-supply well use, were not statistically significant in the quadrangle scale model.

For regional and quadrangle models, some variables that were significant individually were removed from the regression equation as new variables were added. These variables included the log of distance to the nearest major fault; the log of distance to the nearest perennial stream; the percentage of stratified glacial deposits in the 400-ft buffer areas around wells; the percentage of wetlands in the 400-ft buffer areas around wells; and the generalized rock type consisting of diorite, gabbro, and other mafic intrusive rocks. For the quadrangle dataset, the log of distance to the nearest fracture-correlated 80K lineament was significant in the absence of other lineament variables. These variables were removed because of correlation with other variables in the model, leading to unacceptably high *p* values; the retained variables in the final models had the greatest statistical significance. The excluded variables may have important physical significance, but were not included in the final regression models because they were correlated with other variables that had greater statistical significance in the model.

Results of the multivariate regression analysis were consistent with the single-variable analyses of yield with respect to well characteristics and hydrogeologic factors. Relations of yield with topography (higher yields in low-lying areas) and bedrock geology (higher yields in granitic rocks) were similar. The inclusion of overburden thickness and percentage of open water in buffer areas around wells suggests that the thickness of the overlying unconsolidated deposits (not just overburden type) and proximity to surface water also may be important influences to consider on well yield. Other descriptors of surficial geology and hydrography, which were found to be statistically significant when considered individually, may have dropped out of the multivariate regression models because they were better represented by other variables—for instance, by the topographic variables. Proximity to lineaments did not add much to the ability of regression models to describe well yield at the quadrangle scale; this result was consistent with the single-variable analysis of proximity to lineaments. Finally, most of the variation in the dataset that could be explained was due to well characteristics rather than hydrogeologic factors that could be quantified at the regional scale. This result is consistent with results of single-variable statistical tests as well as with visual inspection of the scattergrams and boxplots that illustrated the relations of yields to these factors individually. The hydrogeologic factors such as topography and geology are important, and explain some of the variability in well yield in ways that are consistent with conceptual understanding of their influence. However, the well-yield data are highly variable, partly because of limitations of the dataset, but also because of the high variability in the hydraulic properties of the fractured-bedrock aquifers. This high variability makes it difficult to detect the influence of hydrogeologic factors and would make it difficult to use hydrogeologic factors to predict well yield in the study area.

Geostatistical Analysis

The high variability in well yield makes it well-suited for geostatistical analysis. In geostatistical analysis, variables are characterized by means of their geographic distribution and otherwise are treated as random variables (Isaak and Srivastava, 1989). They are considered regionalized variables, which are spatially continuous but very complex (Davis, 1986)—too complex to be described, for example, by deterministic functions or in terms of simple hydrogeologic factors. Spatial continuity means that values near each other are more similar than values at greater distances, but they appear random in the sense that values are highly variable, even locally. To characterize the distribution of such a variable, its spatial continuity can be described with variogram analysis, and then the modeled variogram can be used to interpolate values at unsampled locations between geographically located data points. In other words, the distribution of yield is predicted from the yield data themselves, rather than from mathematical descriptions of how yield is related to explanatory variables or from equations describing groundwater flow.

Variograms were computed for the Nashoba terrane and surrounding area by using the log of yield as the modeled variable. The variogram is a plot of the semivariance of the yield data (a measure of the average squared difference between paired data values) versus the separation distance (lag distance) between data pairs. Omnidirectional variograms describe the spatial continuity of the data regardless of direction. The empirical omnidirectional variogram (fig. 30), computed at lag distances that increment at 984-ft (300-m) intervals, shows a gradual increase in semivariance for separation distances as large as about 5,000 ft, and a nugget effect, which refers to the vertical offset in semivariance at zero distance. The spherical model that is fit to the empirical variogram (fig. 30) has a nugget value of 0.12 (log yield)^2, range of 4,530 ft (1,380 m), and a sill (the value at which the modeled semivariance stops increasing) of 0.158 (log yield)^2. The empirical omnidirectional variogram indicates that there is spatial continuity in the yield data, over distances as much as a mile; this spatial continuity can be used to estimate or predict yield values at unsampled locations at the regional scale. The relatively large nugget effect, about 75 percent of the total variability in the variogram, also indicates high variability at small distances. This characteristic is commonly observed in the yield data: wells located near one another can have very different yields. Because of the presence of so much small-scale variability, however, the predictive power of any analysis method, including kriging, will be limited.

Variograms computed for specified directions can show patterns of anisotropy in the spatial continuity of well yield. Because semivariance is a measure of the difference between data pairs, directions with lower semivariance are directions with greater spatial continuity of yield data; semivariance may be considered lower in variograms that plateau at a lower sill value or in variograms that reach the sill value more gradually with increasing separation distance between pairs.

For the Nashoba terrane yield data, directional variograms were computed at directional intervals of 10 azimuth degrees, from 0 to 180 degrees, to investigate anisotropy in the spatial continuity of well yield (directions from 180 to 360 degrees are equivalent to directions from 0 to 180 degrees). All directional variograms approached sill values of about 0.16 (log yield)^2, similar to the omnidirectional variogram. The directional variograms also were generally more erratic, reflecting the smaller sample sizes that result when data pairs are limited to those in specific directions. Small differences were apparent, however, suggesting that there might be some directional quality to the spatial continuity of the yield data. Empirical variograms at azimuth directions of 40 and 130 degrees are compared to the omnidirectional variogram in figure 31. The directions are roughly parallel and perpendicular to the directions of regional structural features. Along the 40-degree direction (northeast-southwest), semivariance increased more gradually with increasing separation distance than in the omnidirectional variogram or in most other directions, suggesting that there might be more spatial continuity in the yield data in this direction than in other directions. The 40-degree direction indicated the greatest difference from the omnidirectional variogram in this regard, compared to all other azimuths in the northeast (or southwest) quadrant. Along the 130-degree direction, semivariance also increased more gradually than in the omnidirectional variogram, but the sill value for the 130-degree variogram was higher than that of the omnidirectional or 40-degree variograms, and the variogram showed less relation (was flatter) with distance overall. This indicates that there may be more small-scale variability and less overall continuity in the yield data in this direction than in other directions. The variogram at 130 degrees was similar to other variograms in the southeast (or northwest) quadrant, and, along with the variogram at 120 degrees, had the highest sill value of all directional variograms. Although small, the differences among the directional variograms suggest that the yield data may be more spatially correlated in the northeast-southwest direction than average, and less spatially correlated in the southeast-northwest direction than average. The northeast-southwest direction is similar to the overall trend of the Nashoba terrane and the direction of regional geologic structures.

The omnidirectional variogram and fitted spherical model was used with ordinary kriging to estimate log yield throughout the study area from the well-yield data. Estimated log yield ranged from 0.18 (1.5 gal/min) to 2.24 (174 gal/min), which is less than the range in yield in the actual data because of the smoothing effects of the kriging interpolation (fig. 32A). The standard error in the prediction, in units of the log of yield, ranged from 0.13 to 0.20 and was higher in areas with less yield data (fig. 32B). The standard error values can be used as confidence intervals around the yield estimate, with a probability of 68 percent that the true value is within

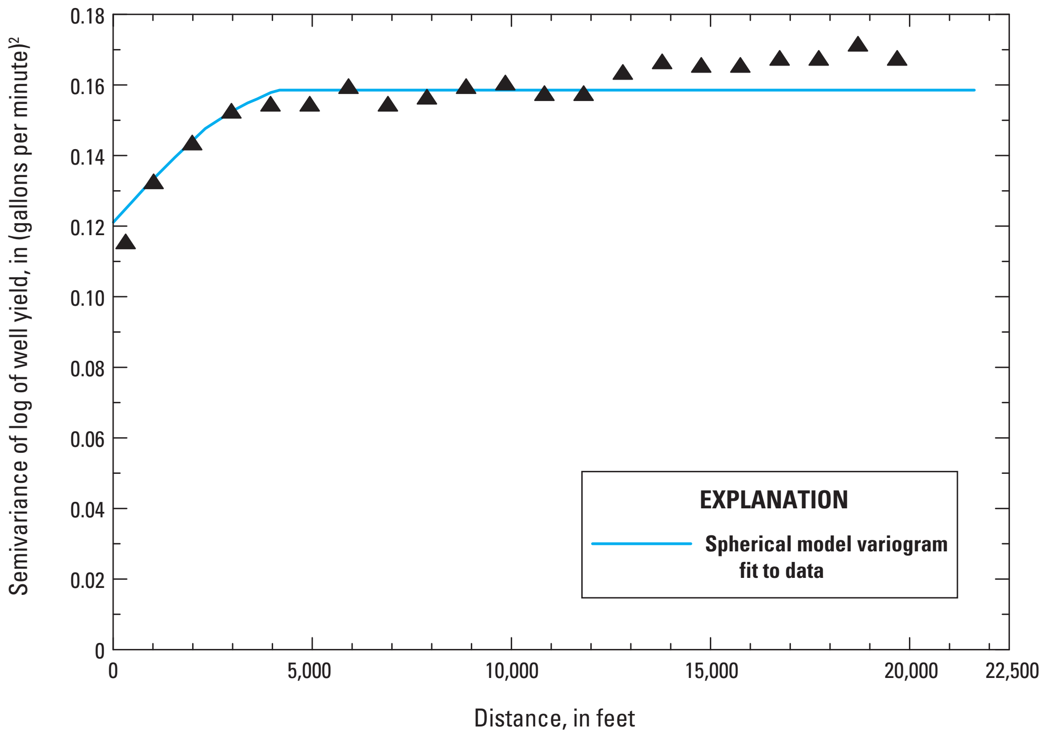


Figure 30. Empirical omnidirectional variogram of log of yield for wells in the Nashoba terrane and surrounding area, with fitted spherical model.

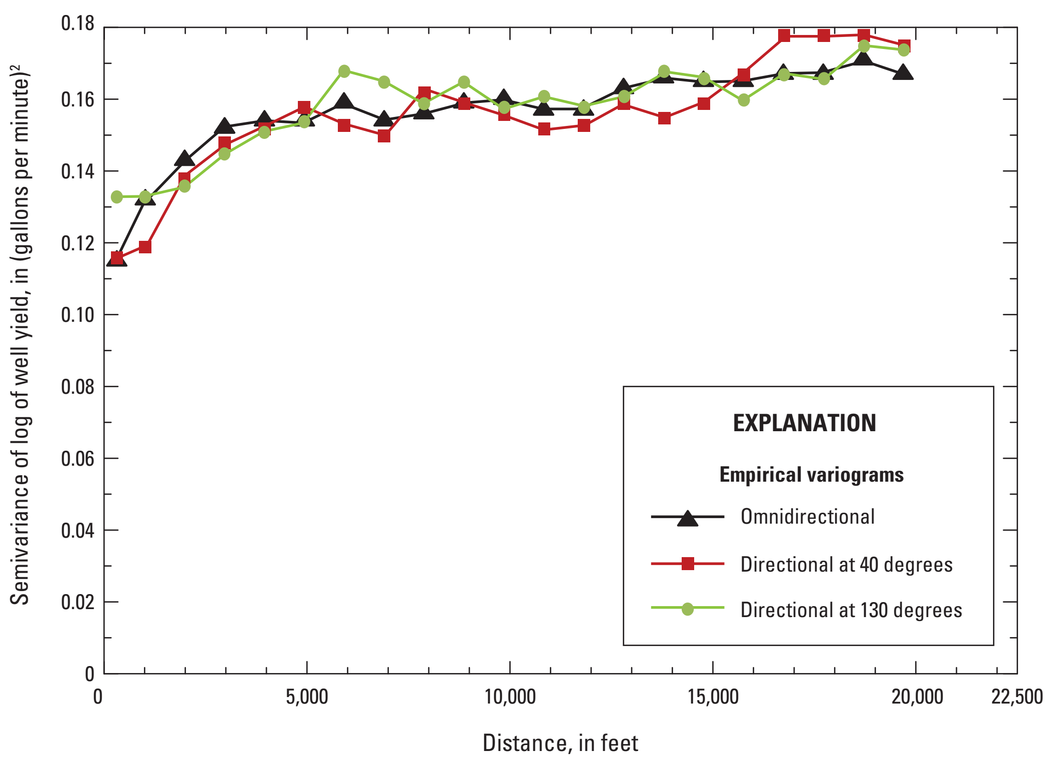


Figure 31. Comparison of empirical omnidirectional variogram of log of well yield with empirical directional variograms, at azimuth directions of 40 and 130 degrees, for wells in the Nashoba terrane and surrounding area.

one standard error above or below the estimated value, and a probability of 95 percent that the true value is within two standard errors of the estimate (Davis, 1986). As an example, an estimated log yield of 1 (10 gal/min) and a standard error of 0.17 would have an associated 95-percent confidence interval of 0.66 to 1.34 in log yield units or 4.6 to 22 gal/min. The wide confidence intervals reflect the high variability in the yield data, even at small scales.

Cross-validation was used to investigate the performance of the kriging estimation model by using the technique named "leave-one-out.". This approach generates a set of predicted values at well locations for comparison with measured values by iteratively omitting each data value and then predicting yield at the location of that data value on the basis of the remaining data (Isaaks and Srivastava, 1989); leave-one-out is a commonly used technique to evaluate kriging models (U.S. Environmental Protection Agency, 2004). Comparison of predicted and measured values generated by cross-validation (fig. 33) illustrates that the kriging estimates substantially overestimate low values and underestimate high values. Overestimates and underestimates are evenly distributed throughout the study area (fig. 34), however, indicating that there is no apparent spatial bias, at least at the regional scale.

Spatial trends are apparent in the estimated log yield and may be related to regional structural features within the Nashoba terrane (fig. 32A). An area of relatively high yield extends through the middle of the study area in the northeast-southwest direction. Other areas of relatively high yield occur at the northern end of the study area and along the northwest Nashoba terrane boundary near the Massachusetts-New Hampshire border. The central, northeast-southwest trending area of relatively high yield is roughly coincident and subparallel to the traces of the Assabet River and Spencer Brook faults, as mapped on the statewide geologic map; the area of relatively high yield at the northern end of the study area also roughly coincides with an area of mapped faults. Relatively high yield in the area of the Assabet River and Spencer faults is consistent with a site-specific study of the bedrock aquifer in this area for water supply, which describes the area as one of abundant faults (Walsh, 2001; Lyford and others, 2003). A fracture-trace study in part of the northern area of relatively high yield also suggested that this area was highly fractured (D.L. Mahar Company, 1990). Areas of relatively low yield, in the northern and southern ends of the study area and in the middle of the study area between the Assabet River fault and the Nashoba terrane boundary, occur mostly outside of areas of mapped faults. Similar spatial trends were apparent when ordinary kriging was applied to yield data from domestic wells only by using a spherical variogram model developed for the domestic-well data (data not shown). This analysis was done to investigate whether the spatial trends apparent in the entire dataset could have resulted from the preferential siting of high-yielding wells in areas where there were needs for those water supplies. The similar results obtained when these high-yielding wells were excluded indicate that the spatial trends are not the result of this kind of bias in the dataset.

The geostatistical analysis indicates that, although well yield is highly variable in the Nashoba terrane and surrounding area, spatial patterns exist that in the yield values may be useful in understanding the regional hydraulic characteristics of the fractured-bedrock aquifers. The apparent coincidence of several areas of relatively high yield with the locations of mapped faults also points to the importance of geologic structure as an influence on yield at the regional scale. Some areas of relatively high yield that are not associated with mapped faults may indicate the presence of geologic structures that have not previously been documented at the regional scale, for example, in the area between the Assabet and Spencer Brook faults and the Clinton-Newbury fault zone along Interstate 495 in Boxborough and Harvard (Beals and Thomas, 1998; D.L. Mahar, 2002). The high variability in the yield data, however, means that even in areas shown as being associated with relatively high yield, there also are many low-yielding wells. Conversely, overall low well yields, particularly in areas where data are sparse, do not preclude the occurrence of high-yielding well sites. Thus, while the geostatistical analysis helps explain and describe the spatial characteristics of well yield at the regional scale, it does not generate precise predictions of yield at specific locations. The regional-scale analyses, both with hydrogeologic variables and geostatistics, provide a context for understanding the variability in well yield, within which smaller scale, site-specific information would be needed to understand local conditions.

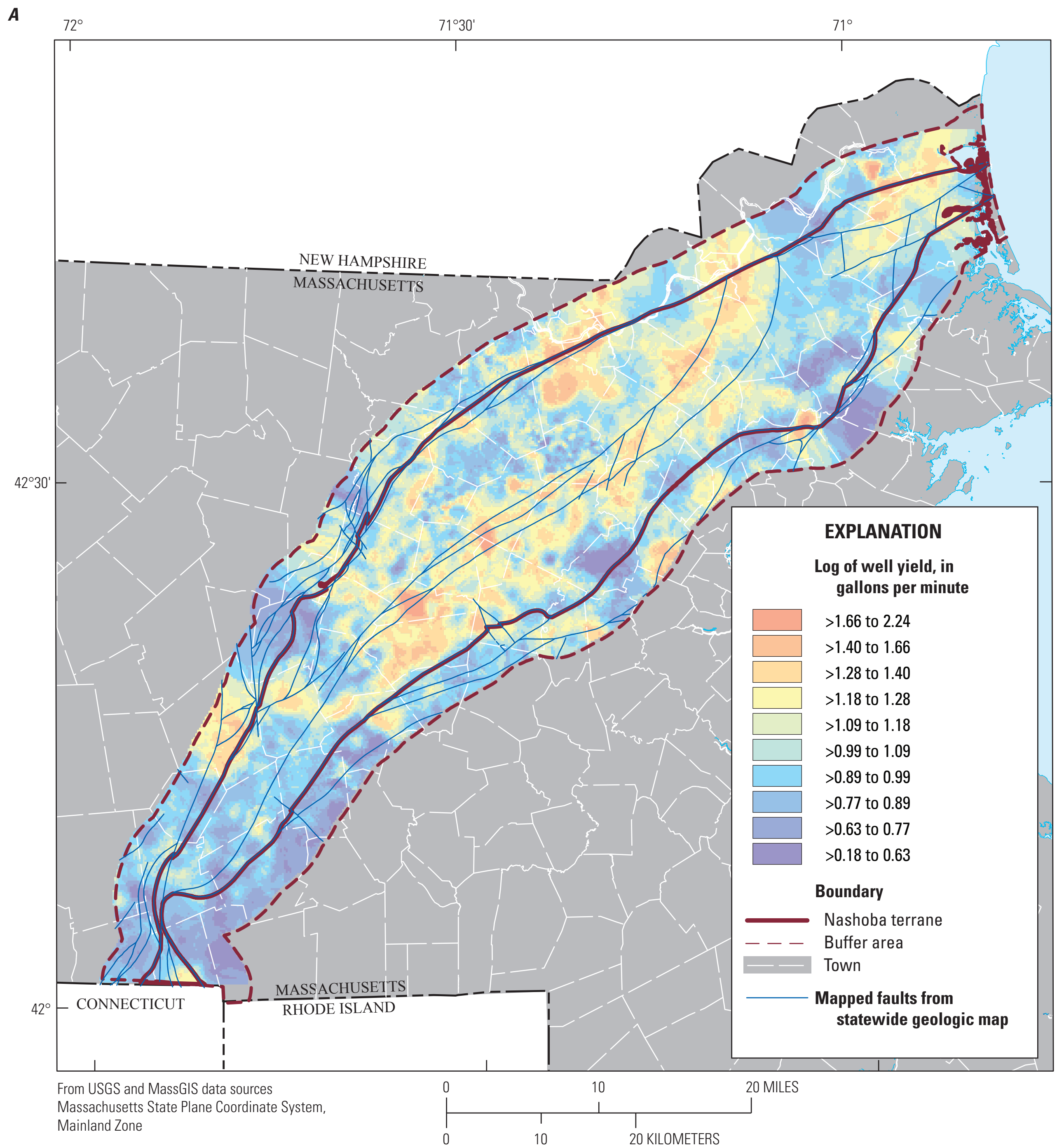


Figure 32. Distribution of estimated log yield determined by ordinary kriging from well yield data in the Nashoba terrane and surrounding area. *(A)* Estimated log of well yield. *(B)* Predicted standard error of estimated log of well yield. Mapped faults are from the statewide geologic map (Zen and others, 1983; Nicholson and others, 2006).

B

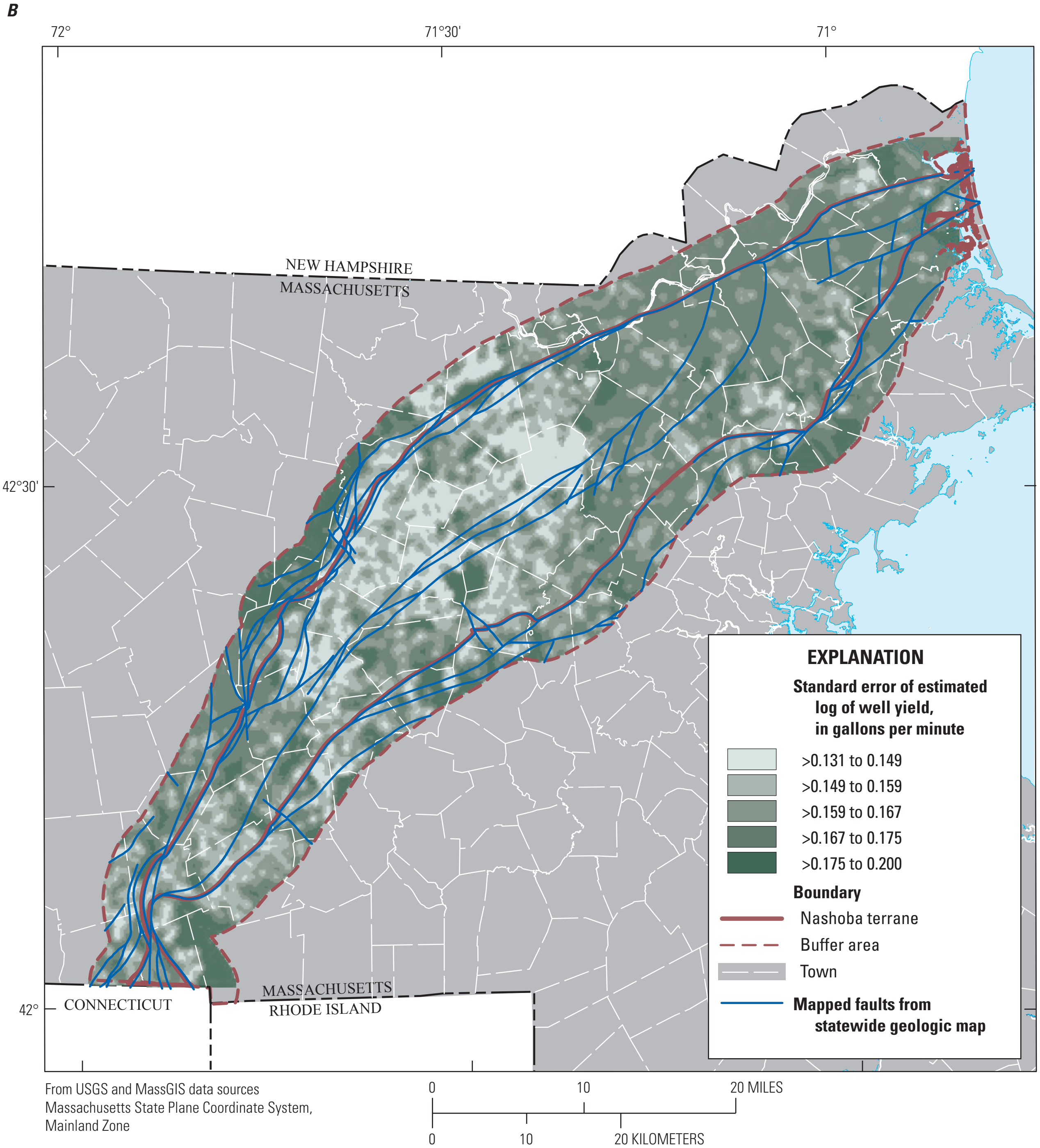


Figure 32. Distribution of estimated log yield determined by ordinary kriging from well yield data in the Nashoba terrane and surrounding area. *(A)* Estimated log of well yield. *(B)* Predicted standard error of estimated log of well yield. Mapped faults are from the statewide geologic map (Zen and others, 1983; Nicholson and others, 2006).—Continued

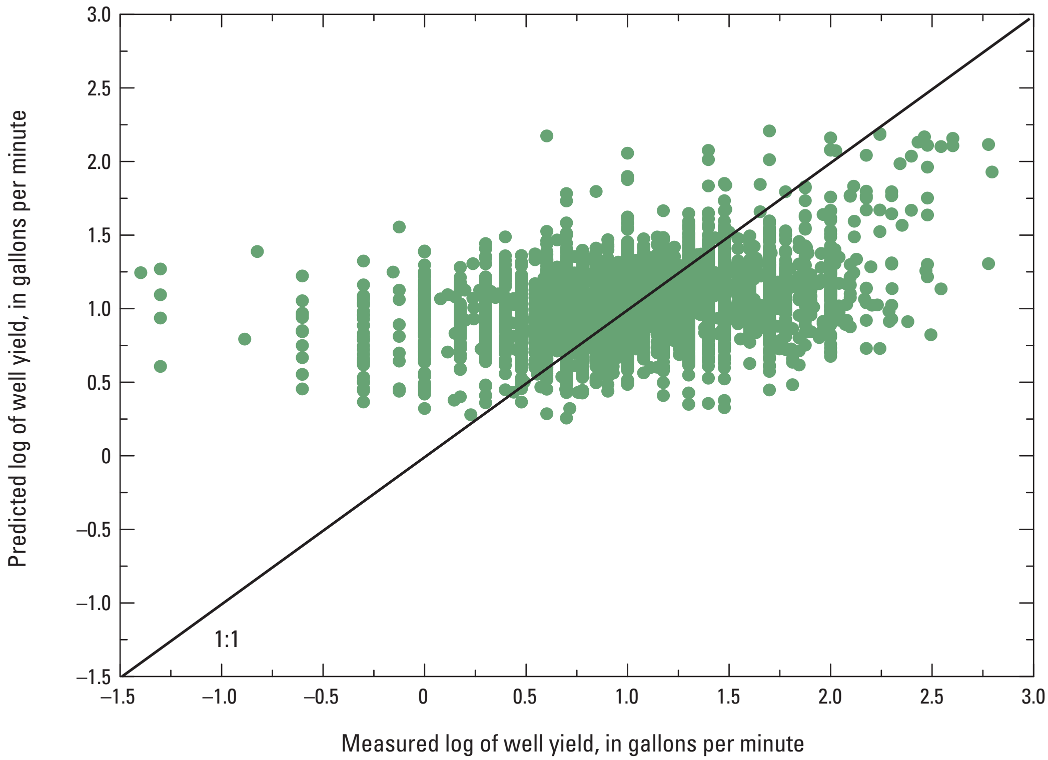


Figure 33. Results of cross-validation of kriging estimates of log of well yield, comparing reported well yield at each well location (measured) and well yield predicted at the well location by kriging of the remaining data, when each well yield data value is iteratively removed.

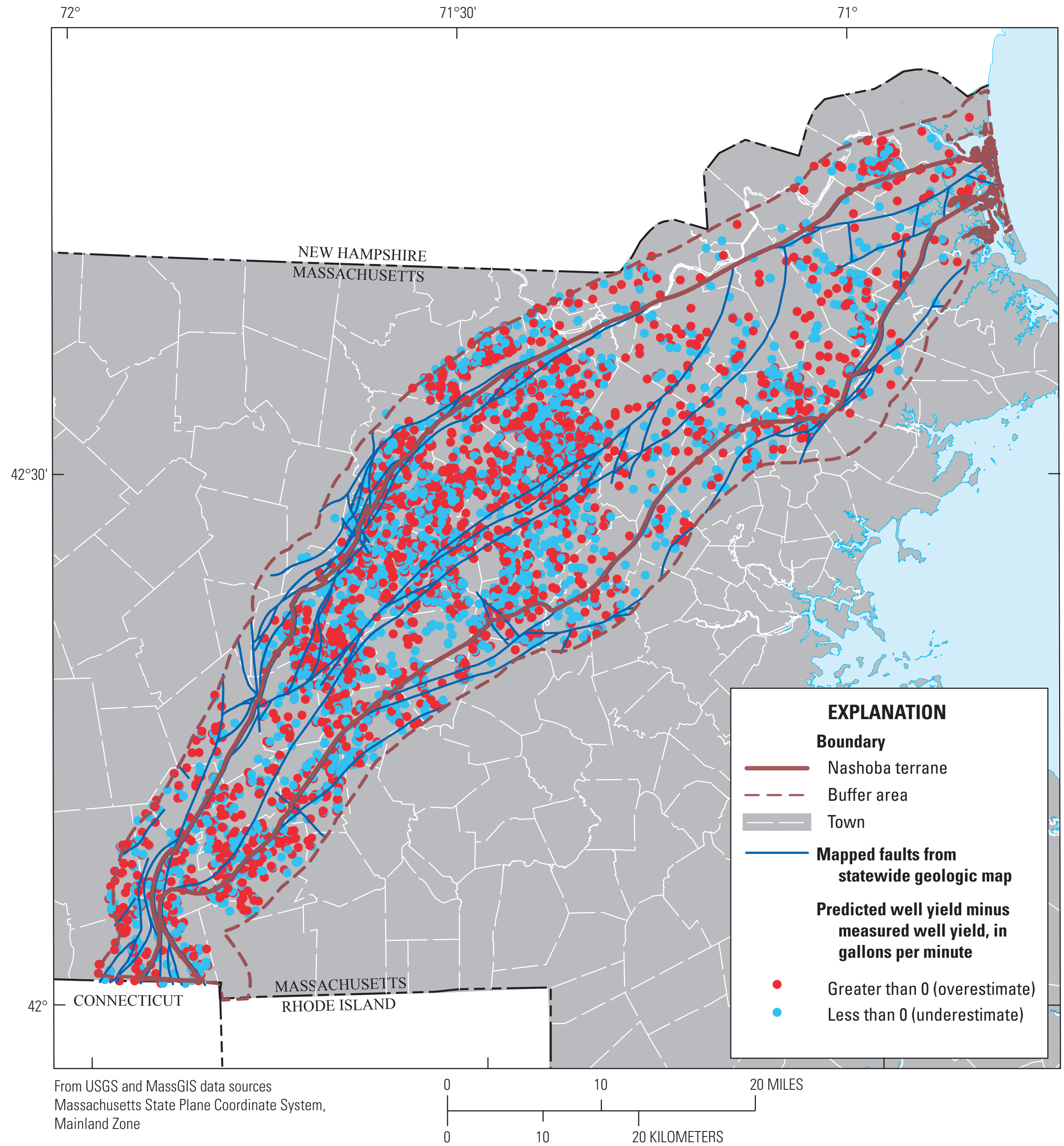


Figure 34. Distribution of cross-validation results for kriging estimates of log of well yield, showing over- and underestimated values, in the Nashoba terrane and surrounding area.

Summary

The yield of bedrock wells in the fractured-bedrock aquifers of the Nashoba terrane and surrounding area was investigated with analyses of existing data. The Nashoba terrane is a fault-bounded lithotectonic unit of metasedimentary and igneous crystalline rocks in central and eastern Massachusetts. Reported well yield and ancillary data for 7,287 domestic, irrigation, commercial, industrial, and public-supply wells were compiled from Massachusetts Department of Environmental Protection and U.S. Geological Survey databases. Yields of these wells ranged from 0.04 to 625 gallons per minute (gal/min). A comparison of yield with specific capacity determined from aquifer tests at 103 supply wells indicated that yield and specific capacity were well correlated (Spearman's *r* correlation coefficient equal to 0.74) and that reported well yield was a reasonable measure of aquifer characteristics in the study area.

Statistically significant relations were found between well yield and a number of cultural and hydrogeologic factors, although little of the overall variability in the yield data was explained by these relations. Yield varied by intended water use, well depth, year of construction, and method of yield measurement. Bedrock geology and topography at well locations were statistically significant hydrogeologic factors. Yield was slightly higher for wells in areas of granites, mafic intrusive rocks, and amphibolites than for wells in areas of schists and gneisses or pelitic rocks. Well yield also was slightly higher for wells in valleys and low-slope areas than for wells on hilltops, ridges, or high-slope areas. Surficial geology and prevalence of surface-water bodies near wells were statistically significant; slightly higher yields were associated with stratified glacial deposits overlying wells and with proximity to wetlands and other surface waters. Proximity to major faults shown on geologic maps and to lineaments from aerial photographs were statistically significant by some measures in the part of the study area for which lineaments were delineated (the Ayer, Hudson, and Marlborough quadrangles). Although many of these relations were highly significant statistically (p values less than 0.0001), the variability in yield explained by these factors was low, with Spearman's *r* correlation coefficients of less than 0.2 for continuous variables and R^2 values of one-way analysis of variance tests on ranked data of less than 0.05 for categorical values.

In a multivariate regression analysis that tested 85 variables, a number of cultural and hydrogeologic factures were significant in a regional model that was developed for the entire Nashoba terrane. These included well depth, well use, well-construction year, the duration of the test to determine yield, granitic rock type, several individual geologic map units, land-surface elevation, two categories of topography, and the thickness of overlying unconsolidated deposits. A similar multivariate regression model for the Ayer, Hudson, and Marlborough quadrangles included several variables describing proximity to surface waters and lineaments. These results are consistent with the comparisons of well yield individually with cultural and hydrogeologic factors. As expected from the individual comparisons, the amount of the overall variance in the yield data that was explained by the models was low, as indicated by model R^2 values of 0.21 for the regional model and 0.30 for the quadrangle model. Moreover, most of the explained variance was due to well characteristics rather than to hydrogeologic factors. Although hydrogeologic factors such as topography and geology are likely important, the overall high variability in the well-yield data, which resulted partly from limitations of the dataset but also from the high variability in hydraulic properties of the fractured-bedrock aquifers, would make them difficult to use to predict well yield in the study area.

Geostatistical analysis (variograms and kriging) indicated that, although highly variable, the well-yield data are spatially correlated, and regional-scale areas of higher and lower yield can be identified. Some of these areas may be related to regional structural features within the Nashoba terrane. Specifically, a northeast-southwest trending area of relatively high yield through the center of the study area roughly follows the traces of the Assabet River and Spencer Brook faults. An area of relatively high yield at the northern end of the study area also coincides with an area of mapped faults within the Nashoba terrane. Directional variograms suggest that the yield data may be more spatially continuous in the northeast-southwest direction and less spatially continuous in the southeast-northwest direction. The results from geostatistical analyses in this study demonstrate the importance of geologic mapping and basic understanding of geologic structure at the regional scale for hydrogeologic investigation. Although the geostatistical analysis helps explain and describe the spatial characteristics of well yield at the regional scale, like the other analysis methods, it does not generate precise predictions of yield at specific locations. The regional analysis provides a context for understanding the large-scale variability in well yield, within which smaller scale, site-specific information would be needed to understand local conditions.

References Cited

Acaster, Martin, and Bickford, M.E., 1999, Geochronology and geochemistry of Putman-Nashoba terrane metavolcanic and plutonic rocks, eastern Massachusetts—Constraints on the early Paleozoic evolution of eastern North America: Geological Society of America Bulletin, v. 111, no. 2, p. 240–253.

Archfield, S.A., Vogel, R.M., Steeves, P.A., Brandt, S.L., Weiskel, P.K., and Garabedian, S.P., 2009, The Massachusetts sustainable-yield estimator—A decision-support tool to assess water availability at ungaged stream locations in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2009–5227, 41 p., plus CD–ROM.

Barosh, P.A., 1984, The Bloody Bluff fault system, *in* Hansen, L.S., ed., Geology of the coastal Lowlands, Boston, MA to Kennebunk, ME: Salem, MA, Salem State College, 76th Annual Meeting, New England Intercollegiate Geological Conference, October 12–14, 1984, p. 310–324.

Beals and Thomas, Inc., 1998, Pump test report, Bedrock water supply wells—Water Management Act Application (BRP WM 03) for Towermarc Business Park and proposed championship golf course, Boxborough and Harvard, Massachusetts: Westborough, Mass., Beals and Thomas, Inc., January 20, 1998, variously paginated.

Boutt, D.F., Diggins, Patrick, and Mabee, Stephen, 2010, A field study (Massachusetts, USA) of the factors controlling the depth of groundwater flow systems in crystalline fractured-rock terrain: Hydrogeology Journal, v. 18, p. 1839–1854.

Boutt, D.F., Mabee, S.B., Manda, A.K., and Diggins, J.P, 2006, Characterizing fractured crystalline bedrock aquifers using discrete fracture networks in the Nashoba terrane, eastern Massachusetts: American Geophysical Union, Fall Meeting 2006, abstract KH13D–1429, accessed November 21, 2011, at http://adsabs.harvard.edu/abs/2006AGUFM.H13D1429B.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025–1028.

Caine, J.S., and Tomusiak, S.R.A., 2003, Brittle structures and their role in controlling porosity and permeability in a complex Precambrian crystalline-rock aquifer system in the Colorado Rocky Mountain Front Range: Geological Society of America Bulletin, v. 115, p. 1410–1424.

Castle, R.O., Hepburn, J.D., and Kopera, J.P., 2005, Bedrock geologic map of the Lawrence quadrangle, Massachusetts, v. 1.0, Massachusetts Geologic Survey (4th), April 2005 (in review), accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Caswell, W.B., 1979, Ground water handbook for the State of Maine: Augusta, Maine, Maine Geological Survey, 145 p.

Cederstrom, D.J., 1972, Evaluation of yields of wells in consolidated rocks, Virginia to Maine: U.S. Geological Survey Water-Supply Paper 2021, 38 p.

Clark, S.F., Jr., Moore, R.B., Ferguson, E.W., and Picard, M.Z., 1996, Criteria and methods for fracture-trace analysis of the New Hampshire bedrock aquifer: U.S. Geological Survey Open-File Report 96–479, 12 p.

Cohen, R.M., Fause, C.R., and Skipp, D.C., 2007, Evaluating ground water supplies in fractured metamorphic rock of the Blue Ridge Province in northern Virginia, *in* Proceedings of the 2007 USEPA/NGWA Fractured Rock Conference: Portland, Maine, Sept. 24–26, 2007, p. 450–464.

Daniel, C.D., III, 1989, Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge Provinces of North Carolina: U.S. Geological Survey Water-Supply Paper 2341–A, 27 p.

Davis, J.C., 1986, Statistics and data analysis in geology (2d ed): New York, John Wiley & Sons, 646 p.

Day-Lewis, F.D., Hsieh, P.A., and Gorelick, S.M., 2000, Identifying fracture-zone geometry using simulated annealing and hydraulic-connection data: Water Resources Research, v. 36, no. 7, p. 1707–1721.

Degnan, J.R., and Clark, S.F., Jr., 2002, Fracture-correlated lineaments at Great Bay, southeastern New Hampshire: U.S. Geological Survey Open-File Report 02–13, 14 p.

Degnan, J.R., Moore, R.B., and Mack, J.J., 2001, Geophysical investigations of well fields to characterize fractured-bedrock aquifers in southern New Hampshire: U.S. Geological Survey Water-Resources Investigations Report 01–4183, 54 p.

DeSimone, L.A., 2004, Simulation of ground-water flow and evaluation of water-management alternatives in the Assabet River Basin, eastern Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004–5114, 133 p.

Dickson, B.G., and Beier, P., 2007, Quantifying the influence of topographic position on cougar (*Puma concolor*) movement in southern California, USA: Journal of Zoology, v. 271, p. 270–277.

D.L. Mahar Company, 2002, An assessment of ground water favorability for the Town of Boxborough, MA within the unconsolidated overburden and by a fracture trace study of the underlying bedrock, *in* CDM, 2002, Town of Boxborough, Massachusetts, Final Report, Water resources analysis study, Final—December 2002: Cambridge, Mass., CDM, December 27, 2002, variously paginated.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Science Publishers, Studies in Environmental Science 49, 522 p.

Hepburn, J.C., Hon, Rudolph, Dunning, G.R., Bailey, R.H., and Galli, Kenneth, 1993, The Avalon and Nashoba Terranes (Eastern margin of the Appalachian Orogen in southeastern New England), *in* Cheney, J.T., and Hepburn, J.C., eds., Field Trip Guidebook for the Northeastern United States, 1993 Boston GSA, 1993 Geological Society of America Annual Meeting and 85th New England Intercollegiate Geologic Conference, Boston, Massachusetts: Amherst, Massachusetts, Department of Geology and Geography, University of Massachusetts, Contribution No. 67, v. 1, p. X–1 to X–31.

Hill, M.D., Hepburn, J.C., Collins, R.D., and Hon, Rudolph, 1984, Igneous rocks of the Nashoba Block, Eastern Massachusetts, *in* Hanson, L.S., ed., Geology of the Coastal Lowlands, Boston, MA to Kennebunk, ME: 76th New England Intercollegiate Geologic Conference, Salem State College, Salem, Mass., p. 61–80.

Hollyday, E.F., Hileman, G.E., Smith, M.A., and Pavlicek, D.J., 1996, Hydrogeologic terranes and potential yield of water to wells in the Valley and Ridge physiographic province in Maryland, New Jersey, and Pennsylvania: U.S. Geological Survey Hydrologic Investigations Atlas HA–732A, 2 sheets.

Huntley, David, Nommensen, Roger, and Steffey, Duane, 1992, The use of specific capacity to assess transmissivity in fractured-rock aquifers: Ground Water, v. 30, p. 396–402.

Isaaks, E.H., and Srivastava, R.M., 1989, An introduction to applied geostatistics: Oxford, United Kingdom, Oxford University Press, 561 p.

Johnson, C.D., 1999, Effects of lithology and fracture characteristics on hydraulic properties in crystalline rock, Mirror Lake Research Site, Grafton County, New Hampshire, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program, Proceedings of the Technical Meeting, Charleston, South Carolina, March 8–12, 1999: U.S. Geological Survey Water-Investigations Report 99–4018C, p. 795–802.

Knopman, D.S., 1990, Factors related to the water-yielding potential of rocks in the Piedmont and Valley and Ridge Provinces of Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 90–4174, 52 p.

Knopman, D.S., and Hollyday, E.F., 1993, Variation in specific capacity in fractured rocks, Pennsylvania: Ground Water, v. 31, p. 135–145.

Kopera, J.P., 2006, Preliminary bedrock geologic map of the Ayer quadrangle, Massachusetts: Office of the Massachusetts State Geologist, Open-File Report 06–02, 1 sheet, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Kopera, J.P. and Hansen, W.R., 2005, Preliminary bedrock geologic map of the Hudson quadrangle, Massachusetts: Massachusetts Geologic Survey (4th), 1 sheet, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Kopera, J.P., Hepburn, J.C., and DiNitto, R.G., 2006a, Bedrock geologic map of the Marlborough quadrangle, Massachusetts: Office of the Massachusetts State Geologist Map 06–01, scale 1:24:000, 1 sheet, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Kopera, J.P., Mabee, S.B., and Powers, D.C., 2006b, Preliminary fracture characterization map of the Ayer quadrangle, Massachusetts: Office of the Massachusetts State Geologist, Open-File Report 06–03, scale 1:24,000, 4 sheets, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

LeGrand, H.E., 1967, Ground water of the Piedmont and Blue Ridge Provinces in the southeastern states: U.S. Geological Survey Circular 538, 11 p.

Lipfert, Gail, Tolman, A.L., and Loiselle, M.C., 2004, Methodology of delineating wellhead protection zones in crystalline bedrock in Maine: Journal of the American Water Resources Association: v. 40, p. 999–1010.

Loiselle, Marc, and Evans, David, 1995, Fracture density and well yields in coastal Maine: Ground Water, v. 33, p. 190–196.

Lundblad, E.R., Wright, D.J., Miller, Joyce, Larkin, E.M., Rinehart, Ronald, Naar, D.F., Donahue, B.T., Anderson, S.M., and Battista, Tim, 2006, A benthic terrain classification scheme for American Samoa: Marine Geodesy, v. 29, no. 2, p. 89–111.

Lyford, F.P., Carlson, C.S., and Hansen, B.P., 2003, Delineation of water sources for public-supply wells in three fractured-bedrock aquifer systems in Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 02–4290, 113 p.

Lyford, F.P., Garabedian, S.P., and Hansen, B.P., 1999, Estimated hydraulic properties for the surficial-and bedrock-aquifer system, Meddybemps, Maine: U.S. Geological Survey Open-File Report 99–199, 27 p.

Mabee, S.B., 1992, Lineaments—Their value in assessing groundwater availability and quality in bedrock aquifers of glaciated metamorphic terrains—A case study: Amherst, Mass., University of Massachusetts, Department of Geology and Geography, Ph.D. dissertation, May 1992, 567 p.

Mabee, S.B., 1999, Factors influencing well productivity in glaciated metamorphic rocks: Ground Water, v. 32, p. 88–97.

Mabee, S.B., 2005, Preliminary fracture characterization map of the Hudson quadrangle, Massachusetts: Office of the Massachusetts State Geologist, scale 1:24,000, 5 sheets, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Mabee, S.B., Curry, P.J., and Hardcastle, K.C., 2002, Correlation of lineaments to ground water inflows in a bedrock tunnel: Ground Water, v. 40, p. 37–43.

Mabee, S.B., Hardcastle, K.C., and Wise, D.C., 1994, A method of collecting and analyzing lineaments for regional-scale fractured-bedrock aquifer studies: Ground Water, v. 32, p. 884–894.

Mabee, S.B., and Kopera, J.P., 2007, Fracture characterization mapping for regional geologic studies—The hydrostructural domain approach, Ayer Quadrangle, Massachusetts, *in* Proceedings, 2007 U.S. EPA /NGWA Fractured Rock Conference, September 24–26, 2007, Portland, Maine, p. 169–186.

Mabee, S.B., and Salamoff, S., 2006, Preliminary fracture characterization map of the Marlborough quadrangle, Massachusetts: Office of the Massachusetts State Geologist, Open-File Report 06–02, scale 1:24,000, 5 sheets, accessed January 30, 2008, at http://www.geo.umass.edu/stategeologist/frame_maps.htm.

Mack, T.J., 2009, Assessment of ground-water resources in the Seacoast Region of New Hampshire: U.S. Geological Survey Scientific Investigations Report 2008–5222, 188 p.

Manda, A.K., Mabee, S.B., and Boutt, D.F., 2006, Characterizing fractured crystalline bedrock aquifers using hydrostructural domains in the Nashoba Terrane, eastern Massachusetts, *in* Abstracts with Programs: Geological Society of America, v. 38, no. 7, p. 25.

Manda, A.K., Mabee, S.B., and Wise, D.U., 2008, Influence of rock fabric on fracture attribute distribution and implications for groundwater flow in the Nashoba Terrane, eastern Massachusetts: Journal of Structural Geology, v. 30, p. 464–477.

MassGIS, 1999a, Surficial geology, October 1999: accessed January 6, 2009, at http://www.mass.gov/mgis/sg.htm.

MassGIS, 1999b, Watershed analyst data, July 1999: accessed December 16, 2009, at http://www.mass.gov/mgis/watrshed.htm.

MassGIS, 2003, Datalayers from the 2000 U.S. Census, block groups, January 2003: accessed November 23, 2011, at http://www.mass.gov/mgis/cen2000_blockgroups.htm.

MassGIS, 2005, Digital elevation model (1:5,000), February 2005: accessed December 10, 2009, at http://www.mass.gov/mgis/img_elev5k.htm.

MassGIS, 2007a, Surficial geology (1:24,000), December 2007: accessed September 16, 2009, at http://www.mass.gov/mgis/sg24k.htm.

MassGIS, 2007b, DEP wetlands (1:12,000), April 2007: accessed December 16, 2009, at http://www.mass.gov/mgis/wetdep.htm.

Massachusetts Department of Environmental Protection, 2008, Guidance for public water systems, Chapter 4—Groundwater supply development and source approval process, *in* Water, Wastewater, and Wetlands: Boston, Mass., Massachusetts Department of Environmental Protection, March 2008, accessed October 4, 2011, at http://www.mass.gov/dep/water/laws/policies.htm#dwguid.

Massachusetts Department of Environmental Protection, 2010, Environmental progress report FY2011—Drinking water: Boston, Mass., Department of Environmental Protection, Bureau of Resource Protection, accessed November 27, 2010, at http://www.mass.gov/dep/water/dwhome.htm.

Massachusetts Department of Environmental Protection, 2012, Search well data status: Boston, Mass., Department of Environmental Protection, Water, Wastewater, and Wetlands, accessed April 17, 2012, at http://www.mass.gov/dep/water/drinking/statussw.htm.

Massachusetts Executive Office of Environmental Affairs, 2006, Water assets study—Regional summary report—Drinking water: Boston, Mass., Commonwealth of Massachusetts, Executive Office of Environmental Affairs, November 28, 2006, variously paginated, accessed November 29, 2010, at http://www.mass.gov/mgis/water_assets_budgets.htm.

Moore, R.B., Schwarz, G.E., Clark, Jr., S.F., Walsh, G.J., and Degnan, J.R., 2002, Factors related to well yield in the fractured-bedrock aquifer of New Hampshire: U.S. Geological Survey Professional Paper 1660, 51 p.

Nicholson, S.W., Dicken, C.L., Horton, J.D., Foose, M.P., Mueller, J.A.L., and Hon, Rudi, 2006, Preliminary integrated geologic map databases for the United States—Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, Rhode Island and Vermont: U.S. Geological Survey Open-File Report 2006 –1272, accessed September 15, 2006, at http://pubs.usgs.gov/of/2006/1272.

Pierce, J., 1998, Estimating private well yields using DEM's well completion report and pumping test information: Boston, Mass., Massachusetts Department of Environmental Protection, Drinking Water Program, accessed September 27, 2011, at http://www.mass.gov/dep/water/drinking/privatew.htm.

Rast, Nicholas, and Skehan, J.W., 1983, The evolution of the Avalonian plate: Tectonophysics, v. 100, p. 257–286.

Remy, Nicholas, Boucher, Alexandre, and Wu, Jianbing, 2009, Applied geostatistics with SGeMS: Cambridge, United Kingdom, Cambridge University Press, 264 p.

Robinson, G.R., and Kapo, K.E., 2003, Generalized lithology and lithogeochemical character of near-surface bedrock in the New England region: U.S. Geological Survey Open-File Report 03–225, v. 1.0, accessed December 7, 2011, at http://pubs.usgs.gov/of/2003/of03-225.

Robinson, J.S., and Rauch, H.W., 2002, Influence of hydrogeologic setting, including lineaments, on water well yield in Lebanon and Dauphin Counties, Pennsylvania: Geological Society of America 2002 Denver Annual Meeting, Paper No. 155–11, accessed October 23, 2007, at http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_46080.htm.

Robinson, Peter, and Goldsmith, Richard, 1991, Stratigraphy of the Merrimack Belt, central Massachusetts, *in* Hatch, N.L., Jr., ed., 1991, The bedrock geology of Massachusetts: U.S. Geological Survey Professional Paper 1366–G, 37 p.

Robinson, Peter, Ratcliffe, N.M., and Hepburn, J.C., 1993, A tectonic-stratigraphic transect across the New England Caledonides of Massachusetts, *in* Cheney, J.T., and Hepburn, J.C., eds., Field trip guidebook for the northeastern United States, 1993 Boston GSA: Amherst, Mass., University of Massachusetts, Department of Geology and Geography, contribution no. 67, p. C–1 to C–47.

Rotzoll, Kolja, and El-Kadi, A.I., 2008, Estimating hydraulic conductivity from specific capacity for Hawaii aquifers, USA: Hydrogeology Journal, v. 16, p. 969–979.

Salvini, F., Billi, A., and Wise, D.U., 1999, Strike-slip fault-propagation cleavage in carbonate rocks—the Mattinata fault zone, Southern Apennines, Italy: Journal of Structural Geology, v. 21, p. 1731–1749.

SAS Institute, 2010, SAS/STAT 9.22 User's Guide: Cary, N.C., SAS Institute, Inc., 8,444 p.

Seaton, W.J., and Burbey, T.J., 2005, Influence of ancient thrust faults on the hydrogeology of the Blue Ridge Province: Ground Water, v. 43, p. 301–313.

Shapiro, A.M., 2003, Characterizing fractured rock—Hydrogeologic conceptual models of ground-water flow and the influence of the problem scale, *in* U.S. Environmental Protection Agency Technical Support Project, Meetings, Fractured Bedrock Sessions, Niagara Falls, N.Y., October 20–23, 2003, accessed April 19, 2012, at http://www.epa.gov/tio/tsp/download/2003_meeting_fall/shapiro_abstract.pdf.

Shapiro, A.M., and Hsieh, P.A., 1998, How good are estimates of transmissivity from slug tests in fractured rock?: Ground Water, v. 36, p. 37–48.

Shapiro, A.M., and Hsieh, P.A., 2001, Aquifer testing in fractured rock—Conceptual similarities in aquifer heterogeneity from varied geologic settings: EOS Transactions, American Geophysical Union, v. 82, no. 47, Fall meeting supplement, Abstract H11E–04, p. F360.

Siddiqui, S.H., and Parizek, R.R., 1971, Hydrogeologic factors influencing well yields in folded and faulted carbonate rocks in central Pennsylvania: Water Resources Research, v. 7, p. 1295–1312.

Singhal, B.B.S., and Gupta, R.P., 2010, Applied hydrogeology of fractured rocks(2d ed.): New York, Springer Science + Business Media, 408 p.

Skehan, J.W., 2001, Roadside geology of Massachusetts: Missoula, Montana, Mountain Press Publishing Company, 378 p.

Snipes, D.S., Burnett, L.L., Wylie, J.A., Sacks, L.A., Heaton, S.B., Dalton, G.A., Israel, B.A., and Padgett, G.G., 1984, Indicators of ground water quality and yield for a public water supply in rock fracture zones of the Piedmont—Clemson, South Carolina: Water Resources Research Institute, Technical Completion Report G–868–02, 80 p.

Starn, J.J., and Stone, J.R., 2005, Simulation of ground-water flow to assess geohydrologic factors and their effect on source-water areas for bedrock wells in Connecticut: U.S. Geological Survey Scientific Investigations Report 2004–5132.

Stone, J.R., and Stone, B.D., 2006, Surficial geologic map of the Clinton-Concord-Grafton-Medfield 12-quadrangle area in east central Massachusetts: U.S. Geological Survey Open-File Report 2006–1260A, 12 p.

Stone, J.R., Stone, B.D., and DiGiacomo-Cohen, M.L., 2006, Surficial geologic map of the Salem Depot-Newburyport East-Wilmington-Rockport 16-quadrangle area in northeast Massachusetts: U.S. Geological Survey Open-File Report 2006–1260B, 15 p.

Stone, J.R., and Stone, B.D., 2007, Surficial geologic map of the Ashby-Lowell-Sterling-Billerica 11-quadrangle area in northeast-central Massachusetts: U.S. Geological Survey Open-File Report 2006–1260C, 13 p.

Stone, J.R., Stone, B.D., and DiGiacomo-Cohen, M.L., 2008, Surficial geologic map of the Worcester North-Oxford-Wrentham-Attleboro nine-quadrangle area in south-central Massachusetts: U.S. Geological Survey Open-File Report 2006–1260D, 13 p.

Surrette, M., Allen, D.M., and Journeay, M., 2008, Regional evaluation of hydraulic properties in variably fractured rock using a hydrostructural domain approach: Hydrogeology Journal, v. 16, p. 11–30.

Theis, C.V., 1963, Estimating the transmissivity of a water-table aquifer from the specific capacity of a well, *in* Bentall, Ray, comp., Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water Supply Paper 1536–I, p. 332–336.

Tiedeman, C.R., Goode, D.J., and Hsieh, P.A., 1997, Numerical simulation of ground-water flow through glacial deposits and crystalline bedrock in the Mirror Lake area, Grafton County, New Hampshire: U.S. Geological Survey Professional Paper 1572, 50 p.

U.S. Environmental Protection Agency, 2004, Developing spatially interpolated surfaces and estimating uncertainty: Research Triangle Park, N.C., U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, EPA–454/R–04–004, November 2004, 159 p., accessed May 24, 2012 at http://www.epa.gov/airtrends/specialstudies/dsisurfaces.pdf.

Walsh, G.J., 2000, Geologic controls on remotely sensed lineaments in southeastern New Hampshire, *in* Annual meeting, 2000 Northeastern Section of the Geological Society of America, Abstracts with Programs: v. 32, no. 1, p. A81.

Walsh, G.J., 2001, Bedrock geology in the vicinity of the Rockland Avenue well site, Maynard, Massachusetts: U.S. Geological Survey Open-File Report 01–354, 15 p.

Walsh, G.J., and Clark, S.F., Jr., 2000, Contrasting methods of fracture trend characterization in crystalline metamorphic and igneous rocks of the Windham Quadrangle, New Hampshire: Northeastern Geology and Environmental Sciences, v. 22, p. 109–120.

Watts, B.C., Dorais, M.J., and Wintsch, R.P., 2000, Geochemistry of Early Devonian calc-alkaline plutons in the Merrimack Belt–Implications for mid-Paleozoic terrane relationships in the New England Appalachians: Atlantic Geology, v. 36, p. 79–102.

Weiss, A.D., 2001, Topographic position and landforms analysis (Conference poster): ESRI International User Conference, San Diego, Calif., July 9–13, 2001.

Williams, L.J., Kath, R.L., Crawford, T.J., and Chapman, M.J., 2005, Influence of geologic setting on ground-water availability in the Lawrenceville Area, Gwinnett County, Georgia: U.S. Geological Survey Scientific Investigations Report 2005–5136, 50 p.

Wintsch, R.P., Sutter, J.F., Kunk, M.J., Aleinikoff, J.N., and Dorais, M.J., 1992, Contrasting P-T-t paths—thermochronologic evidence for a Late Paleozoic final assembly of the Avalon composite terrane in the New England Appalachians: Tectonics, v. 11, no. 3, p. 672–689.

Wones, D.R., and Goldsmith, Richard, 1991, Intrusive rocks of eastern Massachusetts, *in* Hatch, N.L., Jr., ed., 1991, The bedrock geology of Massachusetts: U.S. Geological Survey Professional Paper 1366–I, 61 p.

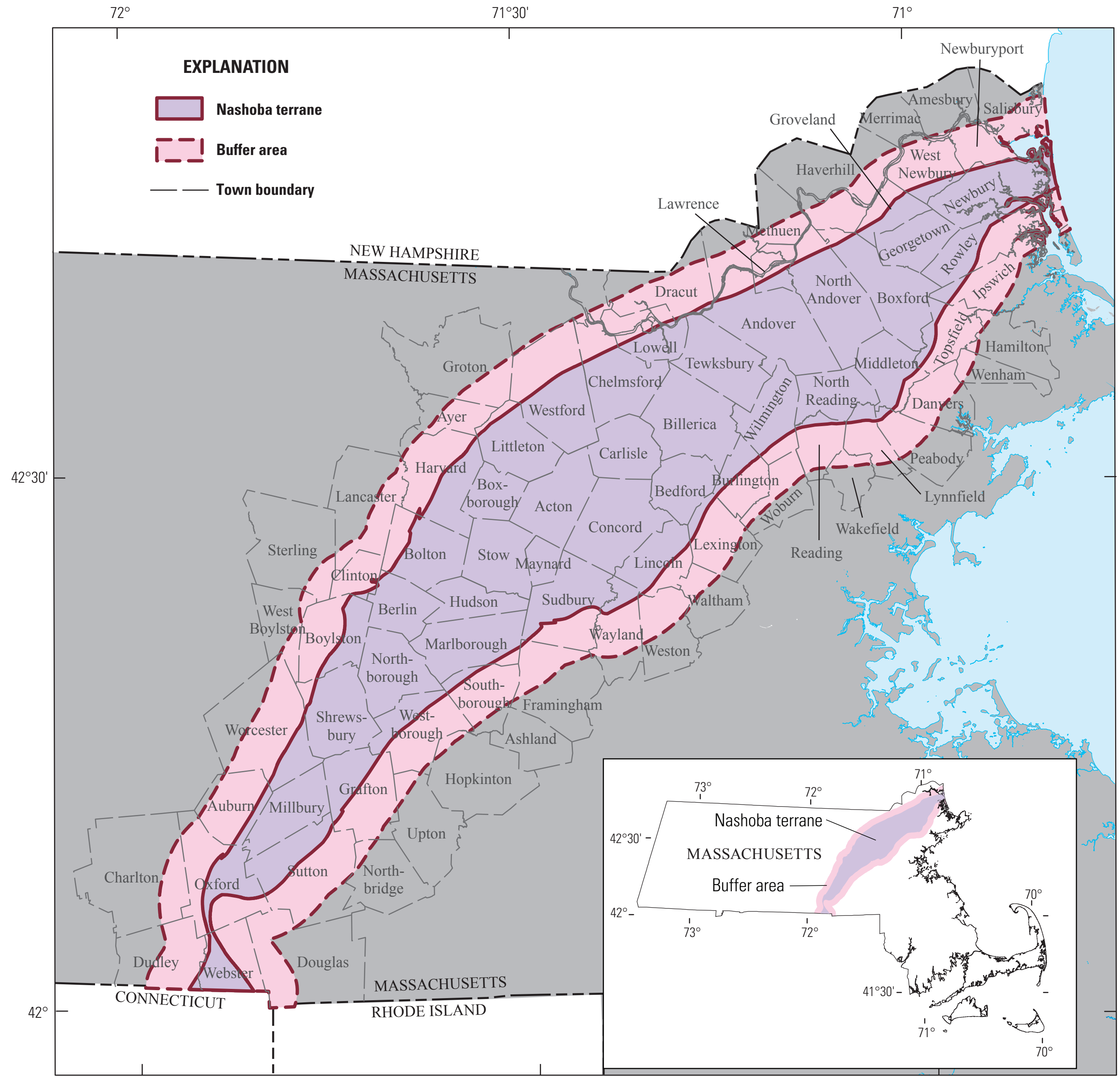
Yin, Z-Y., and Brook, G.A., 1992, The topographic approach to locating high-yield wells in crystalline rocks—Does it work?: Ground Water, v. 30, p. 96–102.

Zen, E-an, Goldsmith, G.R., Ratcliffe, N.L., Robinson, Peter, and Stanley, R.S., 1983, Bedrock geologic map of Massachusetts: U.S. Geological Survey, Monograph series, 3 map sheets, 1:250,000.

Zewe, B.T., 1991, The influence of lineaments and hydrogeologic setting on well yield in the Berkely and Jefferson counties, West Virginia: Morgantown, West Virginia, West Virginia University, M.S. Thesis, 232 p.

This page is intentionally left blank

Appendix 1. Towns in the Nashoba Terrane and Surrounding Area



From USGS and MassGIS data sources
Massachusetts State Plane Coordinate System,
Mainland Zone

0 10 20 MILES
0 10 20 KILOMETERS

Appendix 2. Geologic-map units in the Nashoba terrane and surrounding area.

[Description from the statewide geologic map for Massachusetts, Zen and others (1983). Units included are those shown on figure 2. NA, rock type not classified]

Map symbol	Bedrock formation	Generalized rock type	Description
		Nashoba terrane	
igd	Granodiorite of the Indian Head pluton	granite	Gray, fine- to medium-grained biotite granodiorite, and gray fine-grained hornblende-biotite tonalite
mgr	unnamed	granite	Light-gray muscovite granite
OZf	Fish Brook Gneiss	schist and gneiss	Light grey, biotite-plagioclase quartz gneiss, with a distinctive swirl-form foliation
OZm	Marlboro Formation	amphibolite	Thinly layered amphibolite, biotite schist and gneiss, minor calc-silicate granofels, and felsic granofels
OZmg	Marlboro Formation	schist and gneiss	Light-gray feldspathic gneiss
OZn	Nashoba Formation	schist and gneiss	Sillimanite schist and gneiss, partly sulfidic; amphibolite, biotite gneiss, calc-silicate gneiss, and marble
OZnb	Nashoba Formation—Boxford Member	amphibolite	Amphibolite, with minor biotite gneiss
OZsh	Shawsheen Gneiss	schist and gneiss	Sillimanite gneiss, sulfidic at base, with minor amphibolite
OZt	Tatnic Hill Formation	schist and gneiss	Sillimanite schist and gneiss and biotite gneiss, with minor amphibolite; calc-silicate gneiss; and marble
OZtf	Tatnic Hill Formation—Fly Pond Member	schist and gneiss	Calc-silicate schist and marble
OZty	Tatnic Hill Formation—Yantic Member	pelitic rocks	Gray mica schist
Sgr	unnamed	granite	Orange-pink, rusty weathering, medium-to coarse-grained biotite granite to granodiorite
SOagr	Andover Granite	granite	Light to medium grey, foliated, medium to coarse-grained muscovite-biotite granite, with pegmatite common. Includes the Acton Granite.
Ssaqd	Straw Hollow Diorite and Assabet Quartz Diorite undifferentiated	diorite, gabbro, and other mafic intrusive rocks	Gray, medium-grained, slightly foliated biotite-hornblende diorite and quartz diorite
Ssqd	Sharpners Pond Diorite	diorite, gabbro, and other mafic intrusive rocks	Non-foliated, medium-grained equigranular biotite-hornblende tonalite and diorite
SZtb	Tadmuck Brook Schist	pelitic rocks	Andalusite phyllite and sillimanite schist, partly sulfidic, with local quartzite in upper part
		Merrimack terrane	
Dcgr	Chelmsford Granite	granite	Light gray, even and medium-grained, muscovite-biotite granite; locally foliated
Dl	Littleton Formation	pelitic rocks	Black to grey mica schist, quartzose schist, and phyllite
Dmgr	unnamed	granite	Muscovite-biotite granite
DSdi	unnamed	diorite, gabbro, and other mafic intrusive rocks	Diorite and tonalite
DSw	Worcester Formation	pelitic rocks	Carbonaceous slate and phyllite and minor metagraywacke
Pcm	Coal Mine Brook Formation	pelitic rocks	Carbonaceous slate and phyllite with a lens of meta-anthracite; conglomerate and arkose
Ph	Harvard Conglomerate	pelitic rocks	Conglomerate and phyllite
Sacgr	Ayer Granite—Clinton facies	granite	Porphyritic biotite granite with a non-porphyritic border phase

Appendix 2. Geologic-map units in the Nashoba terrane and surrounding area.—Continued

[Description from the statewide geologic map for Massachusetts, Zen and others (1983). Units included are those shown on figure 2. NA, rock type not classified]

Map symbol	Bedrock formation	Generalized rock type	Description
Sagr	Ayer Granite	granite	Granite to tonalite, partly porphyritic; locally gneissic; locally muscovitic
Sb	Berwick Formation	pelitic rocks	Thin- to thick-bedded metamorphosed calcareous sandstone, siltstone, and minor muscovite schist
Se	Eliot Formation	pelitic rocks	Phyllite and calcareous phyllite
So	Oakdale Formation	pelitic rocks	Metamorphosed thin-bedded pelitic and calcareous siltstone and muscovite schist
SOad	Ayer Granite - Devens-Long Pond facies	granite	Equigranular to porphyritic gneissic biotite granite and granodiorite
SObo	Boylston Schist	pelitic rocks	Carbonaceous phyllite and schist; locally sulfidic; quartzite; calc-silicate beds
SOngd	Newburyport Complex	granite	Gray, tonalite and granodiorite
Sngr	Newburyport Complex	granite	Gray, porphyritic granite
SOvh	Vaughn Hills Quartzite	quartzite	quartzite, phyllite, conglomerate, and chlorite schist
Sp	Paxton Formation	schist and gneiss	Biotite granofels, calc-silicate granofels, and sulfidic schist
St	Tower Hill Quartzite	quartzite	Quartzite and phyllite
Sts	Tower Hill Quartzite	pelitic rocks	Gray phyllite associated with the Tower Hill Quartzite
		Avalon (Milford-Dedham) terrane	
Dcygr	Cherry Hill Granite	granite	Alaskite granite
Dpgr	Peabody Granite	granite	Alkalic granite
DSn	Newbury Volcanic Complex	volcanics	Sedimentary and volcanic rocks, including rhyolite, porphyritic andesite, basalt, tuff, mudstone, and siltstone
DSna	Newbury Volcanic Complex	volcanics	Porphyritic andesite, including tuffaceous mudstone
DSnl	Newbury Volcanic Complex	volcanics	Lower members; basalt, andesite, rhyolite, and tuff
DSnr	Newbury Volcanic Complex	volcanics	Rhyolite
DSnu	Newbury Volcanic Complex	volcanics	Upper members; mudstone and siltstone
Dwm	Wenham Monzonite	NA	Monzonite
Jd	unnamed	diorite, gabbro, and other mafic intrusive rocks	Diabase dikes and sills
SOcgr	Cape Ann Complex	granite	Alkalic granite to quartz syenite
Tre	unnamed	basin sedimentary	Red arkosic conglomerate, sandstone, and siltstone
u	unnamed	NA	Serpentinite
Zdgr	Dedham Granite	granite	Light grayish-pink to greenish-gray, equigranular to slightly porphyritic granite
Zdigb	unnamed	diorite, gabbro, and other mafic intrusive rocks	Diorite and gabbro
Zgr	unnamed	granite	Biotite granite
Zhg	Hope Valley Alaskite Gneiss	granite	Mafic-poor gneissic granite, locally muscovitic
Zpg	Ponaganset Gneiss	granite	Gneissic biotite granite
Zrdi	unnamed	diorite, gabbro, and other mafic intrusive rocks	Diorite at Rowley
Zsg	Scituate Granite Gneiss	granite	Gneissic granite containing biotite in small clots
Ztgd	Topsfield Granodiorite	granite	Gray to gray-green, porphyritic granodiorite containing blue quartz; usually cataclastically foliated and altered
Zv	unnamed	volcanics	Metamorphosed mafic to felsic flow, and volcaniclastic and hypabyssal intrusive rocks
Zvf	unnamed	volcanics	Metamorphosed feslic metavolcanic rocks
Zw	Westboro Formation	pelitic rocks	Quartzite, schist, calc-silicate quatrzite, and amphibolite

Appendix 3. Yield and well depth by use category for wells in the Nashoba terrane and surrounding area.

[Use category of "other" includes geothermal wells, monitoring wells, and wells with no use specified]

Use category	Yield, in gallons per minute						
	Number of Wells	Miniumum	25th percentile	Median	75th percentile	Maximum	Mean
Domestic	5,813	0.04	5	10	15	504	14
Irrigation	1,076	0.05	8	15	25	600	21
Public	154	1	12	25	61	400	54
Commercial or industrial	78	1	7	24	71	625	58
Other	166	0.05	10	25	60	400	52
All wells	7,287	0.04	5	10	20	625	18

Use category	Well depth, in feet below land surface						
	Number of Wells	Miniumum	25th percentile	Median	75th percentile	Maximum	Mean
Domestic	5,728	25	200	285	405	1,800	320
Irrigation	1,076	35	300	425	600	1,610	461
Commercial or industrial	78	35	215	356	505	1,200	382
Public	154	65	300	400	601	1,470	480
Other	162	74	259	382	600	1,507	484
All wells	7,198	25	205	305	460	1,800	349

Appendix 4. Data Sources for Aquifer Tests for 103 Public, Large Irrigation, or Large Industrial Wells in the Nashoba Terrane and Surrounding Area

Beals and Thomas, Inc., 1986, Codman Hill Partnership, Codman Hill Road, Boxborough, Massachusetts, Water well supply: Southborough, Mass., Beals and Thomas, Inc., June 13, 1986, variously paginated.

Beals and Thomas, Inc., 1988, Water well report, Touchstone Community School, Route 140, Grafton, Massachusetts: Westborough, Mass., Beals and Thomas, Inc., April 1988, variously paginated.

Beals and Thomas, Inc., 1998, Pump test report, Bedrock water supply wells, Water Management Act Application (BRP WM 03) for Towermarc Business Park and proposed championship golf course, Boxborough and Harvard, Massachusetts: Westborough, Mass., Beals and Thomas, Inc., January 20, 1998, variously paginated.

Beals and Thomas, Inc., 1989, Water well report, Lot 1, Tyngsborough Business Park, Kendall Road, Tyngsborough, Massachusetts: Westborough, Mass., Beals and Thomas, Inc., May 1989, variously paginated.

Beals and Thomas, Inc., 2000, Source final report, New source approval of pumping test report and construction of a source less than 70 gpm (DEP permit BRP WS 15) for 6-inch potable bedrock water supply well, Codman Hill Tech Center, Boxborough, Massachusetts: Southborough, Mass., Beals and Thomas, Inc., October 24, 2000, variously paginated.

Camp, Dresser and McKee, Inc., 1988, MIT/Lincoln Laboratories, Final report on groundwater testing and bedrock well installation program at the Millstone Facilities: Boston, Mass., Camp, Dresser and McKee, Inc., November 2008, variously paginated.

Camp, Dresser and McKee, Inc., 2008, Lynnfield Center Water District, Bedrock wellfield source final report: Cambridge, Mass., Camp, Dresser and McKee, Inc., May 2008, variously paginated.

D'Amore Associates, Inc., 1997a, Jill Realty Trust pumping test report for Harvard Green: Lancaster, Mass., D'Amore Associates, Inc., February 1997, variously paginated.

D'Amore Associates, Inc., 1997b, Pumping test report for Harvard Green, Lancaster County Road, Harvard: Lancaster, Mass., D'Amore Associates, Inc., May 1997, variously paginated.

D'Amore Associates, Inc., 1999, 48-hour pumping test report, 340 Codman Hill Road, Boxborough: Lancaster, Mass., D'Amore Associates, Inc., September 1999, variously paginated.

D.L. Mahar Company, 1989, Final report on 48 hour pump test, Andrews Farm Affordable Housing Project, Boxford, Massachusetts: North Reading, Mass., D.L. Mahar Company, October 1989, variously paginated.

D.L. Mahar Company, 1991, Final report on 48 hour pump test, Clubhouse well, Shaker Hills Golf Course, Ayer/Harvard, Massachusetts: North Reading, Mass., D.L. Mahar Company, June 1991, variously paginated.

D.L. Mahar Company, 1993, Request for a D.E.P. site exam and proposed pump test submittal for a 10 inch diameter bedrock production well, Forest Street site, Byfield Water District: North Reading, Mass., D.L. Mahar Company, May 1993, variously paginated.

D.L. Mahar Company, 1994, The final report on the well construction, pump testing, and Zone II and III delineations for the Forrest Street well site, well no. 3, Byfield Water District, Massachusetts: North Reading, Mass., D.L. Mahar Company, May 1994, variously paginated.

D.L. Mahar Company, 1995, Final report on 48 hour pump test, MCI Telecommunications Inc., 82B Northside Road, Charlton, Massachusetts: North Reading, Mass., D.L. Mahar Company, December 1995, variously paginated.

D.L. Mahar Company, 2003, A request for a site examination and a proposed pumping test on a multiple rock well configuration, Sugar Road, in Bolton, Massachusetts: North Reading, Mass., D.L. Mahar Company, May 29, 2003, variously paginated.

D.L. Mahar Company, 2004, The results of a 48 hour pumping test on a 6 inch diameter drilled rock well at the proposed Lancaster Condominium Complex, Lunenburg Road, Lancaster, Massachusetts: North Reading, Mass., D.L. Mahar Company, February 2004, variously paginated.

Ducharme and Wheeler, Inc., and D.L. Mahar Company 2002a, Supplemental data on a proposed water supply system for the Bolton Senior Housing Corporation, Bolton, Massachusetts: Bolton, Mass., Ducharme and Wheeler, Inc., January 23, 2002, variously paginated.

Ducharme and Wheeler, Inc., and D.L. Mahar Company 2002b, Water source final report for Bolton Senior Housing Corporation, Bolton, Massachusetts: Bolton, Mass., Ducharme and Wheeler, Inc., September 30, 2002, variously paginated.

Dufresne-Henry, Inc., 1996, Request for site exam, pumping test proposal, Carlisle Town Building: Westford, Mass., Dufresne-Henry, Inc., October 1996, variously paginated.

Dufresne-Henry, Inc., 1997, Report on pumping test, Carlisle Town Hall well: Westford, Mass., Dufresne-Henry, Inc., May 1997, variously paginated.

Dufresne-Henry, Inc., 1999, Request for site exam, Rockland Avenue wellfield, Maynard Department of Public Works, Maynard, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., September 17, 1999, variously paginated.

Dufresne-Henry, Inc., 2000a, Source final report, Blanchard School well, Boxborough, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., July 2000, variously paginated.

Dufresne-Henry, Inc., 2000b, Source final report, Rockland Avenue bedrock wellfield, Town of Maynard, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., April 2000, variously paginated.

Dufresne-Henry, Inc., 2000c, Source final report, Meadowbrook Village, well no. 1, Berlin, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., July 2000, variously paginated.

Dufresne-Henry, Inc., 2001, Report on prolonged pumping test, Hager site bedrock well, Blanchard School, Boxborough, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., November 2011, variously paginated.

Dufresne-Henry, Inc., 2005, Final report on prolonged pumping test, community water supply, High Point Acres, Grafton, Massachusetts: Westford, Mass., Dufresne-Henry, Inc., December 2005, variously paginated.

EarthTech, 2005, New source final report, Bedrock well TW 1, Sutton, Massachusetts: Concord, Mass., EarthTech, August 2005, variously paginated.

Epsilon Associates, Inc., 2000a, Preliminary draft report, Intel Corporation, Pump test of production well D-1: Maynard, Mass., Epsilon Associates, Inc., July 14, 2000, variously paginated.

Epsilon Associates, Inc., 2000b, Pump test report, Production well D-1, Intel Corporation, Hudson, Massachusetts, *in* Fab 17 Expansion Project, Mod 4, Water management application: Maynard, Mass., Epsilon Associates, Inc., November 15, 2000, variously paginated.

Epsilon Associates, Inc., 2002a, Water Management Act amendments to existing withdrawal permit 9P4-2-14-141.03: Maynard, Mass., Epsilon Associates, Inc., June 14, 2002, variously paginated.

Epsilon Associates, Inc., 2002b, Quail Ridge Country Club Water Management Act application: Maynard, Mass., Epsilon Associates, Inc., December 20, 2002, variously paginated.

Fay, Spoffard, and Thorndike, Inc., 1996, Pump test report for police station/municipal building bedrock well: Burlington, Mass., Fay, Spoffard, and Thorndike, Inc., June 1996, variously paginated.

GEI Consultants, Inc., 1990, Final pumping test report, New source approval, 60-unit Suites Hotel, Bolton, Massachusetts: Winchester, Mass., GEI Consultants, Inc, April 19, 1990, variously paginated.

Geologic Services Corporation, 1988a, Report on the installation and testing of a bedrock water supply well, Transition School, Harvard, Massachusetts: Hudson, Mass., Geologic Services Corporation, March 1988, variously paginated.

Geologic Services Corporation, 1988b, Report on the installation and testing of a bedrock water supply well, The International Golf Club, Bolton, Massachusetts: Hudson, Mass., Geologic Services Corporation, April 1988, variously paginated.

Geologic Services Corporation, 1989, Report on the installation and testing of a bedrock water supply well, Pilot Grove Hill, Stow, Massachusetts: Hudson, Mass., Geologic Services Corporation, January 27, 1989, variously paginated.

Geologic Services Corporation, 1995, Pumping test for a replacement well at the Emerson Elementary School in Bolton, Massachusetts: Hudson, Mass., Geologic Services Corporation, December 1995, variously paginated.

Geologic Services Corporation, 1996, Report on the installation and testing of a satellite well adjacent to well no. 1, Holiday Inn at Boxborough Woods, Boxborough, MA: Hudson, Mass., Geologic Services Corporation, October, 1996, variously paginated.

Geologic Services Corporation, 2002, Report on the installation and testing of a bedrock well water supply well PW-1, Early Learning Center of Sutton, Sutton, Massachusetts: Hudson, Mass., Geologic Services Corporation, March 2002, variously paginated.

Geoscience, 2008a, Source final report, Century Mill Estates, Bolton, Massachusetts: Norwell, Mass., Geoscience, March 2008, variously paginated.

Geoscience, 2008b, Source final report (back-up water supply) for a community public water supply, Century Mill Estates, Bolton, Massachusetts: Norwell, Mass., Geoscience, December 2008, variously paginated.

Geosphere Environmental Management, Inc., 2000, Source water assessment program conceptual zone II delineation, Four Mile Village well #3 (PWS-3038001-03G), Boxford, MA: Hampton, N.H., Geosphere Environmental Management, Inc., September 2000, variously paginated.

Geosphere Environmental Management, Inc., 2003, BRP WS 15 Application for approval of a pumping test report and to construct a source less than 70 gallons per minute, Blackstone National Golf Club, 227 Putman Hill Road, Sutton, Massachusetts: Hampton, N.H., Geosphere Environmental Management, Inc., August 13, 2003, variously paginated.

GeoTrans, Inc., 1995, Pumping test report and approval to construct a public water supply source, Emerson School, Bolton, Massachusetts: Harvard, Mass., GeoTrans, Inc., November 20, 1995, variously paginated.

GeoTrans, Inc., 1996, Pumping test report and approval to construct a public water supply source (BRP WS-15), Village Nursery School, Harvard, Massachusetts: Harvard, Mass., GeoTrans, Inc., April 17, 1996, variously paginated.

GS Environmental and Groundwater Associates, Inc., 2008, Development of a new public water supply well, Bolton Public Safety Facility, Bolton, Massachusetts: Portsmouth, N.H., GS Environmental and Groundwater Associates, Inc., December 2008, variously paginated.

Goldberg-Zoino and Associates, 1988, On-site drinking water summary report, Main Street Site, Acton, Massachusetts: Newton Upper Falls, Mass., Goldberg-Zoino and Associates, September 1988, variously paginated.

Goodkind and O'Dea, Inc., 2001, BRP WS 15, Pumping test report approval and approval to construct a source under 70 gallons per minute for a new source bedrock well at the Boxborough Executive Center, Boxborough, MA: Boston, Mass., Goodkind and O'Dea, Inc., August 2001, variously paginated.

Graves Engineering, Inc., 1988, Report on prolonged pump test, Windswept Meadows, Carpenter Hill Road, Charlton, Massachusetts: Worcester, Mass., Graves Engineering, Inc., September 1988, variously paginated.

Graves Engineering, Inc., 2003, Source final report, D'Ambrosia Eye Care, 479 Old Union Turnpike, Lancaster, Massachusetts: Worcester, Mass., Graves Engineering, Inc., June 2, 2003, variously paginated.

Haley and Aldrich, Inc., 1987, Report on preliminary aquifer evaluation, Huckins Farm, Bedford, Massachusetts: Cambridge, Mass., Haley and Aldrich, Inc., variously paginated.

Hamer D. Clarke, P.E., 1992, Source final report, Butternut Farm Golf Course, Stow, Massachusetts: Southbridge, Mass., Hamer D. Clarke, P.E., variously paginated.

IEP, Inc., 1984, Report on siting of bedrock wells at the Flatley site, Bolton, Massachusetts: Northborough, Mass., IEP, Inc., October 1984, variously paginated.

IEP, Inc., 1995, Pump test report, Flatley Field, Bolton, Massachusetts: Northborough, Mass., IEP, Inc., June 1985, variously paginated.

Jawarski Geotech, Inc., 2004, Source final report TW-4, The Overlook (CCRC) at the Masonic Home, Charlton, Massachusetts: Manchester, N.H., Jaworski Geotech, Inc., v.1, March 31, 2004, variously paginated.

Judith Nitsch Engineering, Inc., 1997, Request for pumping test report approval and approval to construct source (BRP-WS15), proposed Berlin Elementary School, Berlin, Massachusetts: Cambridge, Mass., Judith Nitsch Engineering, Inc., December 18, 1997, variously paginated.

Lenard Engineering, Inc., 1992, Source final report, Toria Heights Condominiums: Storrs, Conn., Lenard Engineering, Inc., September 1992, variously paginated.

Lewis Companies, 1996, Boxford Friendship Foundation, Four Mile Village, Boxford—PWS-3038001, BRP WS 15—Well construction pumping test approval, Transmittal #104161: Litchfield, N.H., Lewis Companies, January 11, 1996, variously paginated.

Lewis Companies, 2000, BRP WS-15 Application, Juniper Hill Water Company, Juniper Hill—Stow, Massachusetts, PWS #2286000: Litchfield, N.H., Lewis Companies, July 2000, variously paginated.

Lycott Environmental Research, Inc., 1988, Bedrock well installation, F & R Realty Trust Property, Carroll Hill Road, Charlton, Massachusetts: Southbridge, Mass., Lycott Environmental Research, Inc., July 28, 1988, variously paginated.

Lycott Environmental Research, Inc., 1989, Buffumville Heights Condominiums, Oxford, Massachusetts: Southbridge, Mass., Lycott Environmental Research, Inc., October 27, 1989, variously paginated.

McClure Engineering, LLC, 2007, 48-hour pumping test report (BRP WS 15 for new source <70 gpm), PWS ID #2290027, Sutton Medical Center, 188 Worcester-Providence Turnpike, Sutton, Massachusetts, 01590: McClure Engineering, Charlton, Massachusetts, December 12, 2007, variously paginated.

Northeast Geoscience, Inc., 2003, Source final report, Bedrock water supply well BR-1 at the Minuteman Airfield, Stow, Massachusetts: Clinton, Mass., Northeast Geoscience, Inc., October 2003, variously paginated.

Northeast Geoscience, Inc., 2005a, Source final report, Bedrock water supply wells BR-1 and BR-2, Arbor Glen, Hudson Road, Stow, Massachusetts: Clinton, Mass., Northeast Geoscience, Inc., May 2005, variously paginated.

Northeast Geoscience, Inc., 2005b, Source final report, Bedrock water supply wells BR-2 and BR-3, Summer Village, Formerly Wyman's Beach, Westford, Massachusetts: Clinton, Mass., Northeast Geoscience, Inc., June 2005, variously paginated.

P.B. Hatch Consulting Engineers, 1998, Well pump test report, BRP WS 15, Transmittal W002817, New Middle School, Dudley-Charlton Regional School district, Mugget Hill, Oxford Road, Charlton, Massachusetts: Monson, Mass., P.B. Hatch Consulting Engineers, September 1998, variously paginated.

P.B. Hatch Consulting Engineers, 2005, Well pump test report, BRP WS 15, Transmittal W066608, Karl Storz Endovision, Inc., 91 Carpenter Hill Road, Charlton, Massachusetts: Monson, Mass., P.B. Hatch Consulting Engineers, August 2005, variously paginated.

Pine and Swallow Associates, Inc., 1992, BRP WS 15 pump test resubmittal, Haystack Development, DEP project no. 089-0620-034, Westford, Massachusetts: Groton, Mass., Pine and Swallow Associates, Inc., March 4, 1992, variously paginated.

Professional Engineering and Management Services, 1996, Report on prolonged pumping test—Phase 1, Pumping test report and approval to construct a source less than 70 gallons per minute for a new source bedrock well at Pinewood on the Green, Oxford, Massachusetts: Milford, Mass., Professional Engineering and Management Services, October 1996, variously paginated.

Provencher Engineering, 2003, Source final report, New source approval—Pumping test and construction approval less than 70 gpm (DEP Permit BRP WS 15; Transmittal #W046801) for Dunkin Donuts/convenience store/gasoline station, 626 Great Road (Route 117), Stow, Massachusetts: Merrimack, N.H., Provencher Engineering, December 19, 2003, variously paginated.

Provencher Engineering, 2005, Source final report, Pump test report and construction application < 70 gpm (DEP Permit BRP WS 15; Transmittal #W063422) at Bright Horizons Daycare Center, 20 Codman Hill Road, Boxborough, Massachusetts: Merrimack, N.H., Provencher Engineering, April 25, 2005, variously paginated.

Provencher Engineering, 2006, New source construction and pumping test approval < 70 gpm (DEP Permit Application BRP WS 15; Transmittal #W107973) at Exxon Tiger Mart/Dunkin Donuts, 1425 Massachusetts Avenue, Boxborough, Massachusetts: Merrimack, N.H., Provencher Engineering, November 22, 2006, variously paginated.

Rizzo Associates, Inc., 2005, Pump test and source construction report, 1 Pleasant Street, Berlin, Massachusetts: Framingham, Mass., Rizzo Associates, Inc., January 5, 2005, variously paginated.

Stantec Consulting Services, Inc., 2007, Source final report, Replacement well no. 1, Kids-A-Lot Country Day School, Stow, Massachusetts: Westford, Mass., Stantec Consulting Services, Inc., May 2007, variously paginated.

Tata and Howard, 2006, 48-hour pump test report for bedrock wells no. 1 and 2, The Residence at River Run: Westborough, Mass., Tata and Howard, August 2006, variously paginated.

Trifone Design Associates, Inc., 2007a, 48-hour pumping test report for G & B Realty Trust "Dawning Place School," 185 Southbridge Road, Dudley, Massachusetts: Southbridge, Mass., Trifone Design Associates, Inc., January 11, 2007, variously paginated.

Trifone Design Associates, Inc., 2007b, 48-hour pumping test report for Southbridge Tool & Manufacturing, Inc., 181 Southbridge Road, Dudley, Massachusetts: Southbridge, Mass., Trifone Design Associates, Inc., January 30, 2007, variously paginated.

W. Bradford Caswell, Hydrogeologic Consulting, 2001, Letter to Mr. James J. Dillon, Massachusetts Department of Environmental Protection: West Topsham, Vt., W. Bradford Caswell Hydrogeologic Consulting, June 2, 2001, variously paginated.

Weston and Sampson Engineers, Inc., 2002, Source final report and request for approval to construct source, well no. 2, Tyngsborough Business Park: Portsmouth, N.H., Weston and Sampson Engineers, Inc., June 4, 2002, variously paginated.

Whitman and Bingham Associates, Inc., 1996, BRPWS15 permit application for pumping test report approval to construct a source under 70 gallons per minute, Purgatory Chasm State Park, Sutton, Massachusetts: Leominster, Mass., Whitman and Bingham Associates, Inc., April 14, 1996, variously paginated.

Whitman and Bingham Associates, Inc., 2003, BRPWS15 permit application for pumping test report approval to construct a source under 70 gallons per minute, Great Brook Farm State Park, Carlisle, Massachusetts: Leominster, Mass., Whitman and Bingham Associates, Inc., June 2, 2003, variously paginated.

Whitman and Howard, Inc., 1981, Report on groundwater exploration for Digital Equipment Corporation: Wellesley, Mass., Whitman and Howard, Inc., September 1981, variously paginated.

Prepared by the Pembroke and the Rolla Publishing Service Centers.

For more information concerning this report, contact:

Office Chief
U.S. Geological Survey
New England Water Science Center
Massachusetts-Rhode Island Office
10 Bearfoot Road
Northborough, MA 01532
dc_ma@usgs.gov

or visit our Web site at:
http://ma.water.usgs.gov

DeSimone and Barbaro—**Yield of Bedrock Wells in the Nashoba Terrane, Central and Eastern Massachusetts**—Scientific-Investigations Report 2012–5155

ISBN 978-1-4113-3518-9

9 781411 335189

Printed on recycled paper