YIELDS OF BEDROCK WELLS IN MASSACHUSETTS

By BRUCE P. HANSEN and ALISON C. SIMCOX

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per minute (ft^3/min)	0.02832	cubic meter per minute
foot (ft)	0.3048	meter
foot per hour (ft/hr)	0.3048	meter per hour
foot per minute (ft/min)	0.3048	meter per minute
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
gallon per minute per foot [(gal/min)/ft]	12.418	liter per minute per meter
inch (in.)	2.540	centimeter
mile (mi)	1.609	kilometer
pound per square inch ($lb/in.^2$)	6.895	kilopascal
square foot (ft^2)	0.09290	square meter

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Yields of Bedrock Wells in Massachusetts

By Bruce P. Hansen *and* Alison C. Simcox

Abstract

Six to seven percent of the population of Massachusetts obtains its water from domestic bedrock wells. Additional public, commercial, industrial, and domestic supplies from bedrock will be needed in the future. Information about the factors that are related to large well yields is needed. The factors associated with well yields were identified by use of statistical analysis of reported data from 4,218 bedrock wells.

The median reported yield of all bedrock wells was 7 gallons per minute, and the median depth was 170 feet. Wells in valleys and lowlands had the largest median yield--10 gallons per minute. The median well yield on hilltops and slopes was 6 gallons per minute. In valleys and lowlands, significant increases in well yields corresponded to increasing thickness of overburden. On hilltops and slopes, only small increases in well yield corresponded to increases in overburden thickness. Increases in well diameter corresponded to significant increases in well yields for all well locations, depths, and use categories.

The common assumptions that fractured crystalline rocks generally yield only small quantities of water to wells and that the fractures that yield water to wells pinch out or are closed because of lithostatic pressure at depths greater than 300 to 400 feet may be in error. Analysis of well data indicates that the median yield of all bedrock wells decreased as well depth increased to 400 feet and increased slightly with well depths greater than 600 feet. The median yield of bedrock wells located in valleys and lowlands reached 50 gallons per minute at depths of 600 to 700 feet. The median yield of wells located on hilltops and slopes reached 15 gallons per minute at depths of 600 to 700 feet.

Carbonate bedrock, with a median well yield of 25 gallons per minute, seemed to be the most productive bedrock type. A reported yield of 1,700 gallons per minute from an industrial well completed in carbonate bedrock is the largest reported yield from a bedrock well in Massachusetts. Yield of wells in sedimentary rocks of the Connecticut Valley increased significantly at depths greater than 400 feet, indicating that this bedrock type may have some primary permeability. Commercial or industrial wells had a median yield of 30 gallons per minute. These wells appear to be preferentially sited, large in diameter, and deeper than average to maximize potential well yields.

The median reported bedrock well yield and depth have changed over time. The median yield of about 20 gallons per minute for 1920-40 decreased to 6 gallons per minute for 1970-80. Well depth increased from 128 feet for 1950- 60 to 250 feet for 1980-90. The period during which well depths began to increase coincides with a change in bedrock-well drilling methods from cable tool to air rotary with percussion.

Four methods of testing the yield of domestic bedrock wells were evaluated: air injection, evacuation and recovery, constant-discharge, and instantaneous discharge or recharge. A constant-discharge test best satisfied the criteria established to evaluate the testing methods.

Further data collection and evaluation are needed for the systematic characterization and appraisal of the bedrock aquifers of Massachusetts. Specific elements include (1) improved and expanded collection and storage of well data, (2) detailed hydrogeologic evaluations of apparent high yield bedrock areas, (3) an evaluation of the relation between the vertical distribution of hydraulic properties measured during well drilling to actual hydraulic properties, (4) an evaluation of the effect of well diameter on well yield, and (5) areal evaluations to characterize the quality of water in bedrock.

INTRODUCTION

Nearly 400,000 people in Massachusetts, or about 7 percent of the State's population, obtain drinking water from domestic wells (private wells supplying a single residence) (Weintraub, 1988). With the exception of extreme southeastern Massachusetts, most of this water comes from wells drilled and completed in bedrock. Most public and many industrial water supplies come from lakes, ponds, rivers, and from wells developed in stratified glacial deposits. Public-water suppliers are experiencing increasing difficulty in locating additional large-capacity supplies, and some are limiting water-supply expansion. In many towns, residential, commercial, and industrial expansion will depend on the location and development of public or private water supplies, primarily from bedrock wells.

For many rural homeowners, the bedrock beneath their land is the only economically feasible source of water. Some land has remained undeveloped because the bedrock has yielded insufficient water for private use. Some land was abandoned and homes removed after water in the bedrock aquifer became contaminated. Misinformation and folklore about the source and presence of water in the bedrock underlying Massachusetts may have led to wasteful expense and contamination of bedrock wells. Information about the factors affecting the yield and methods for testing the yield of bedrock wells is needed by health officials, local government, homeowners, businesses, and well drillers.

To help meet the need for information on yields from bedrock, the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Management, Office of Water Resources, began a study to identify the factors affecting the yield from bedrock wells. This study was done under the auspices of Massachusetts Chapter 800 legislation, which provides for qualitative and quantitative assessments of ground-water resources in the State.

Purpose and Scope

The purpose of this report is to identify and discuss the major factors affecting well yields. These factors were determined from a statistical analysis of well data from 4,218 bedrock wells. The report also includes a description and evaluation of well-test methods that are, or could be, used to evaluate the yield of bedrock wells. The source and occurrence of water in bedrock and the principal methods of drilling and well construction in Massachusetts also are described.

Acknowledgments

The authors thank the many well drillers who provided information and the property owners who granted permission for their wells to be tested.

BACKGROUND INFORMATION

Information on bedrock hydrogeology and bedrock wells is presented in this section. The generalized bedrock geology of Massachusetts and the source, occurrence, and movement of water in bedrock are described. The construction and hydraulic factors affecting the yield of individual bedrock wells also are presented.

Bedrock Hydrogeology

Bedrock geology, structure, and the source of water are the primary factors that affect the occurrence and flow of water in bedrock. This section describes the generalized geology, hydrology, and source of water in bedrock aquifers.

Geology

The three principal bedrock types underlying Massachusetts are crystalline (igneous and noncarbonate metamorphic), sedimentary, and carbonate rocks (fig. 1). Crystalline bedrock of Proterozoic to Jurassic age underlies much of the State and is composed mainly of granite, gneiss, and schist. Sedimentary bedrock of Jurassic and Triassic age is present along the Connecticut River valley of west-central Massachusetts. This sedimentary bedrock includes sandstone, shale, and conglomerate, which are red in most locations, and are some the softest consolidated rocks in Massachusetts. Layers of volcanic diabase are located in these sedimentary rocks. Sedimentary bedrock of Proterozoic to Paleozoic age is present in the Boston Basin, and sedimentary bedrock of Pennsylvanian age is present in the Narragansett and Norfolk Basins. These basins contain hard, low-grade metamorphosed sedimentary rocks, which include shale, slate, sandstone, conglomerate, and, in the Narragansett Basin, coal. Carbonate

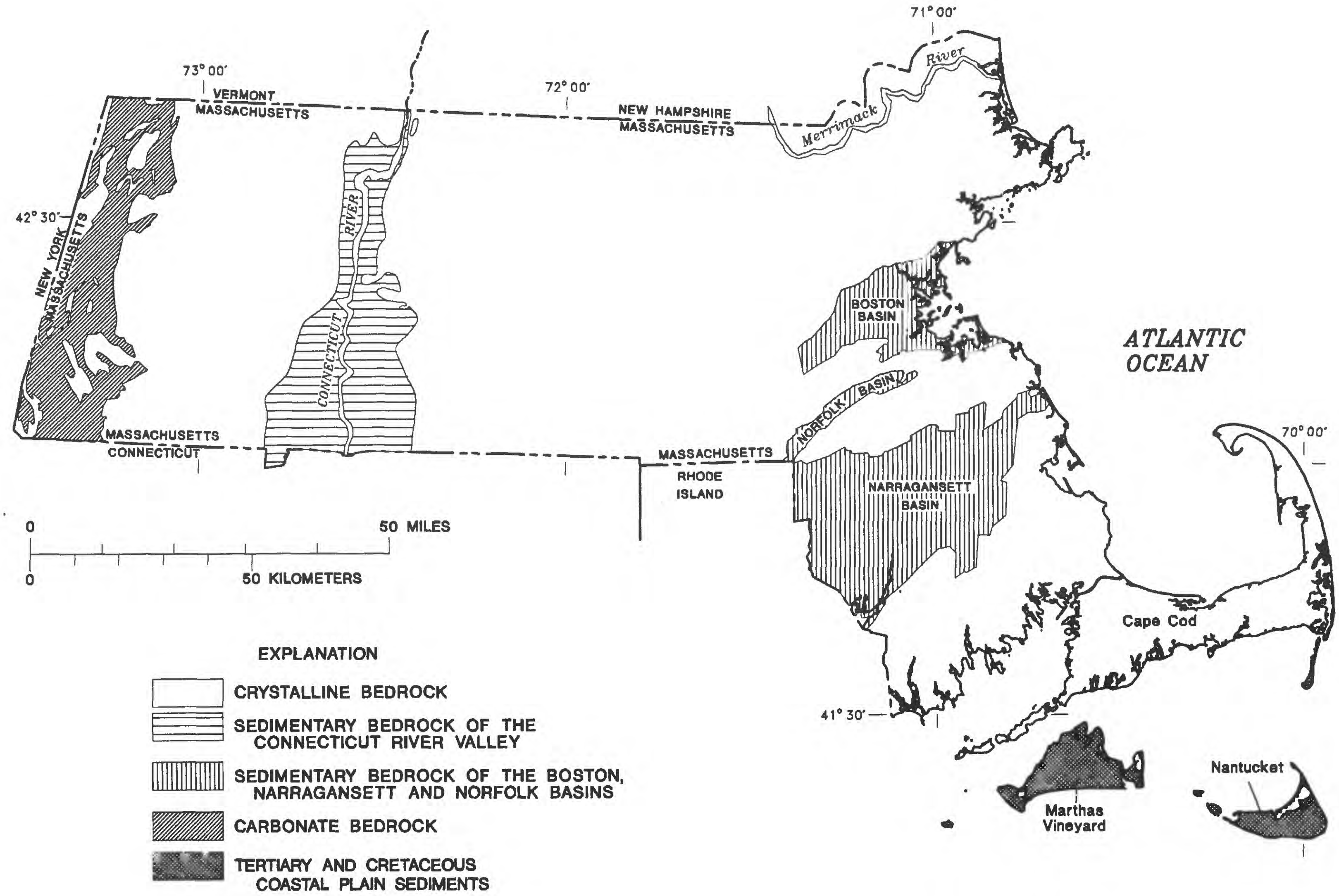


Figure 1. Generalized bedrock geology of Massachusetts.

bedrock of Proterozoic to Devonian age in Berkshire County in western Massachusetts is composed of limestone, dolomite, and marble between layers of schist and quartzite. Detailed bedrock lithology and tectonic and metamorphic zones are presented on a bedrock map of Massachusetts (Zen, 1983).

In most of the State, bedrock is overlain by a discontinuous mantle of glacial till and stratified drift. The stratified drift is thickest in valleys and consists of generally medium to coarse grained ice-contact, outwash, and deltaic deposits and fine-grained lacustrine deposits that were deposited in postglacial lakes. These lacustrine deposits are especially thick and extensive in the Connecticut River valley. In some locations, the lacustrine sediment is underlain by till and ice-contact deposits. In the southeastern corner of the State and Cape Cod, stratified drift forms a continuous layer over bedrock rather than a series of isolated valley deposits. On Martha's Vineyard and Nantucket Island, thick stratified deposits are underlain by coastal plain sediments of Cretaceous age. In this southeastern part of Massachusetts, including Cape Cod, Martha's Vineyard, and Nantucket Island, stratified drift yields sufficient amounts of water for most public and private water supplies.

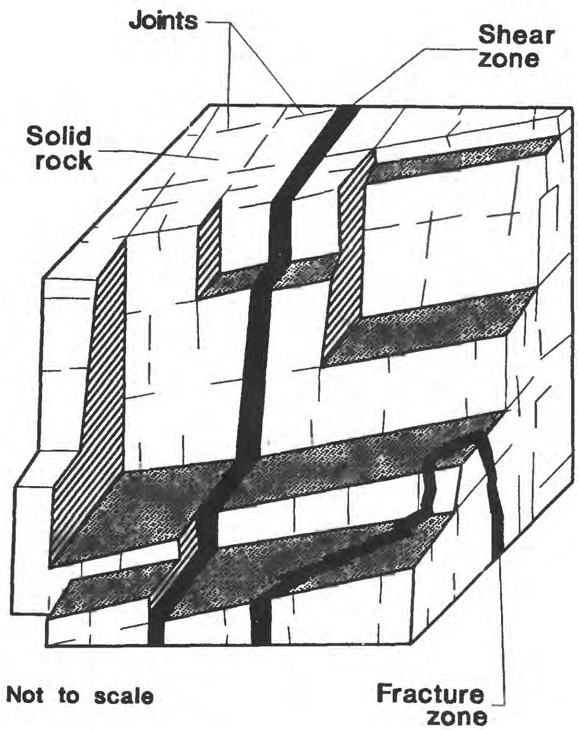


Figure 2. Structural features of fractured rock that are potential conduits of ground-water flow.

Hydrology

Bedrock can be considered simply as blocks of rock bounded by fracture planes. The porosity and permeability of the blocks differ according to the rock type. For example, sandstone, a sedimentary rock, generally has a much higher hydraulic conductivity than granite, an igneous rock. The ratio of the permeability of the rock (primary permeability) to the permeability of the fractures in the rock (secondary permeability) determines the significance of fracture flow (Gale, 1982). Large ratios indicate that a significant volume of flow occurs in the porous medium; small ratios indicate that a significant volume of flow occurs in the fracture system. The predominant form of permeability in most of the bedrock in Massachusetts is secondary permeability; however some of the sedimentary bedrock in the Connecticut Valley appears to have some primary permeability. In the carbonate rock in the western part of the State, solution channels (fractures that have been enlarged by the solution and removal of minerals) are commonly the primary conduits for ground-water flow.

The principal paths of ground-water flow in crystalline rocks are joints, fracture zones, shear zones (fig. 2), and faults (all of which are hereafter referred to as fractures). Fractures are formed mostly as a result of cooling stresses in magma, tectonic activity, reduction of overburden pressures by erosion of overlying rock, and melting of glacial ice sheets that once covered the land. The width of fractures ranges from barely visible to several inches. Fracturing of coarser grained, more brittle rocks, such as granite and basalt, can produce wider and more continuous fractures than those of finer grained rocks, such as schist and gneiss.

Flow through fractures directly affects well yield and is the subject of increasing research. The physics of fracture flow is poorly understood and is much more complex then previously believed. Results of recent research (Paillet, U.S. Geological Survey, Borehole Physics Research Project, written commun., 1987) indicate that (1) permeable fractures are intersected in most boreholes; (2) most production comes from one or two fractures in bedrock wells that do produce water; (3) most fractures do not yield water; (4) fracture frequency decreases with depth, drastically so in the 325- to 650-foot depth interval; (5) permeable fractures have been intersected as deep as 3,000 ft or more in many boreholes; (6) most fractures are discontinuous even in boreholes as little as 60 ft apart and; (7) fracture permeability may depend more on how fractures are connected to each other than on how wide they seem to be.

The effectiveness of individual fractures as conduits of ground-water flow depends on the amount of interconnection between openings along the fracture, the presence and type of fracture-filling materials (such as clay, rock fragments, calcite, and quartz) and the effects of stress on fracture permeability (fig. 3) (Gale, 1982). In some places, a few large, interconnected fractures can dominate a flow system; in others, flow can be distributed along many fractures of similar size and permeability.

Source of Water

Precipitation is the principal source of water in bedrock. Water from melting snow or rain can infiltrate the soil or unconsolidated surficial material and percolate down to the water table. Some of this water then moves into the fractures in the underlying bedrock. Recharge to bedrock also occurs in areas where bedrock is exposed at the land surface. Natural discharge from bedrock is leakage to ponds, lakes, rivers, and the ocean and by evapotranspiration in areas where ground water is near land surface. Discharge from bedrock also results from withdrawals by wells.

Two common phenomena that demonstrate that ground water originates at land surface are (1) the cause-and-effect relation between rainfall or recharge and water levels in the aquifer and (2) the susceptibility of ground-water quality to the effects of contaminant sources at or near the land surface.

Water-level rises resulting from precipitation have been measured in many wells. Water levels in wells also reflect seasonal and long-term climatic trends, as illustrated by the hydrograph of Springfield well 20 (fig. 4). This 603-foot-deep well was completed in sandstone. Water levels are usually highest in late winter and early spring when recharge from snowmelt and spring rains exceeds natural discharge. Rapid rates of evapotranspiration and slightly less precipitation during the growing season (May through September) result in slow rates of recharge and declining water levels. During late autumn and early winter, recharge is equal to or slightly greater than discharge, resulting in stable or slightly rising water levels.

An extended period of abnormally low water levels also is shown on the hydrograph. Small precipitation deficiencies during 1961-63, combined with large deficiencies during 1964-66, caused a noticeable decline in water levels from 1964 to 1967. Water levels did not fully return to normal until 1970.

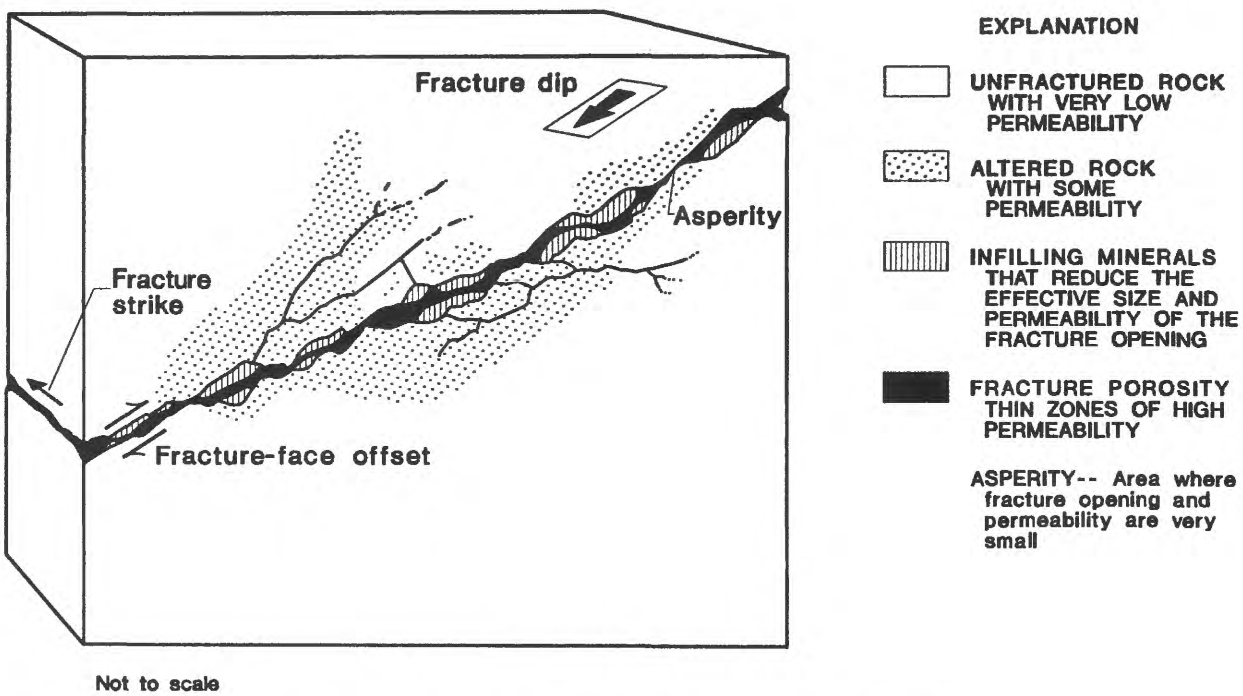


Figure 3. Factors affecting ground-water flow in individual fractures.

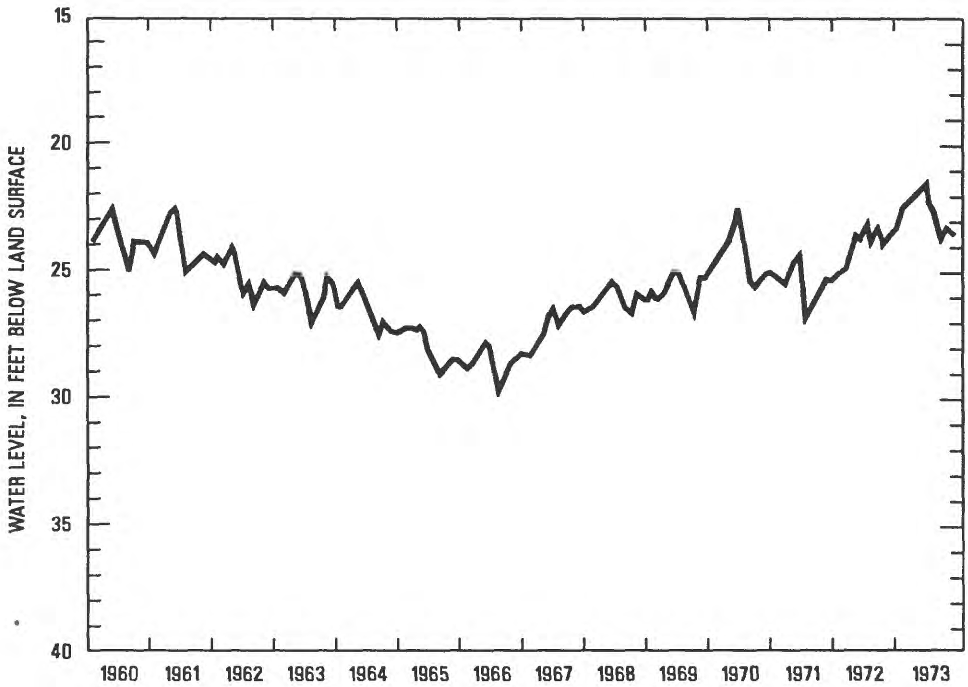


Figure 4. Water levels in Springfield Well 20, 1960-73.

The downward movement of water from land surface to an aquifer has been demonstrated by the presence of contaminants in many private wells. A recent study by the Commonwealth of Massachusetts Special Legislative Commission on Water Supply (Weintraub, 1988) found that at least 636 private wells had been abandoned as a result of contamination during the preceding 15 years. Most of the contamination resulted from chemicals, petroleum products, pesticides, road salt, bacteria, nitrates, and other constituents that were improperly stored, used, or disposed of near the wells. Many of these contaminants were carried into the ground water by infiltrating rain. These contaminated wells were identified without any comprehensive testing program; thus a large number of contaminated wells may not have not been identified.

Bedrock Wells

Bedrock wells are used extensively in the State for small domestic and commercial water supplies and, in some locations, for moderate to large municipal and industrial supplies. In certain areas, bedrock wells may offer an alternative to surface water or to wells completed in stratified-drift aquifers as a source of water.

Drilling Methods

Early wells in New England were dug by hand in unconsolidated alluvial, stratified-drift, and till deposits. Records show that a small number of these wells extended a few feet into bedrock. These "bedrock wells" were probably dug either to increase well-water storage where water levels were close to the bedrock surface or because the well digger was fortunate enough to intercept a water-filled fracture at the bedrock surface. In the latter case, the well was then continued into rock to maximize seepage from the fracture.

In the early 1800's, crude cable-tool drilling machinery was introduced into this country from Europe. Well drilling became increasingly widespread after completion of the first successful oil well near Titusville, Pennsylvania, in 1859. The cable tool, with many improvements developed primarily by the oil industry, was the primary drilling machine in New England for many years. Cable-tool drilling rigs are still used for bedrock drilling by a small number of part-time drillers and by a few full-time drillers to "finish" bedrock wells. In the early 1950's, many drillers began using air-rotary drilling, combined with a downhole hammer, to drill bedrock wells. Air-rotary drilling is now the primary method for drilling bedrock wells in Massachusetts.

In cable-tool or percussion drilling, the hole is deepened by regularly lifting and dropping a heavy string of drilling tools suspended on a steel cable in the borehole (fig. 5). The drill bit breaks or crushes hard rock into small fragments, which form a slurry with natural or added water in the borehole. When the accumulated cuttings start to lessen the impact of the bit, the drill string is removed from the hole, and cuttings are removed with a bailer (a hollow pipe with a valve on the bottom). Up-and-down movement of the bailer permits the rock cuttings to enter through the bottom valve. When loaded, the bailer is lifted to the surface and emptied. The bailer also is used to remove water to test the yield of the well.

In most locations, cable-tool drilling begins by driving an open-end steel casing (commonly 8 in. inside diameter) into the unconsolidated material overlying bedrock. Unconsolidated material forced into this casing as it is driven is cleaned out at 5- to 10-foot intervals. The casing is alternately driven and cleaned out until bedrock is reached. When bedrock is reached, the hole is normally continued 10 to 20 ft into the rock (145 ft is the maximum recorded), and casing, usually 6 in. diameter, is set (driven) or grouted into the rock. The length of casing in bedrock depends on the structural integrity of the rock--the type of rock and the amount of weathering and fracturing of the rock. After the casing is set, drilling continues with a smaller nominal 6-in. diameter bit. The rate of drilling in bedrock with this method ranges between 3 and 5 ft/hr and depends on many factors, rock hardness probably being the most important.

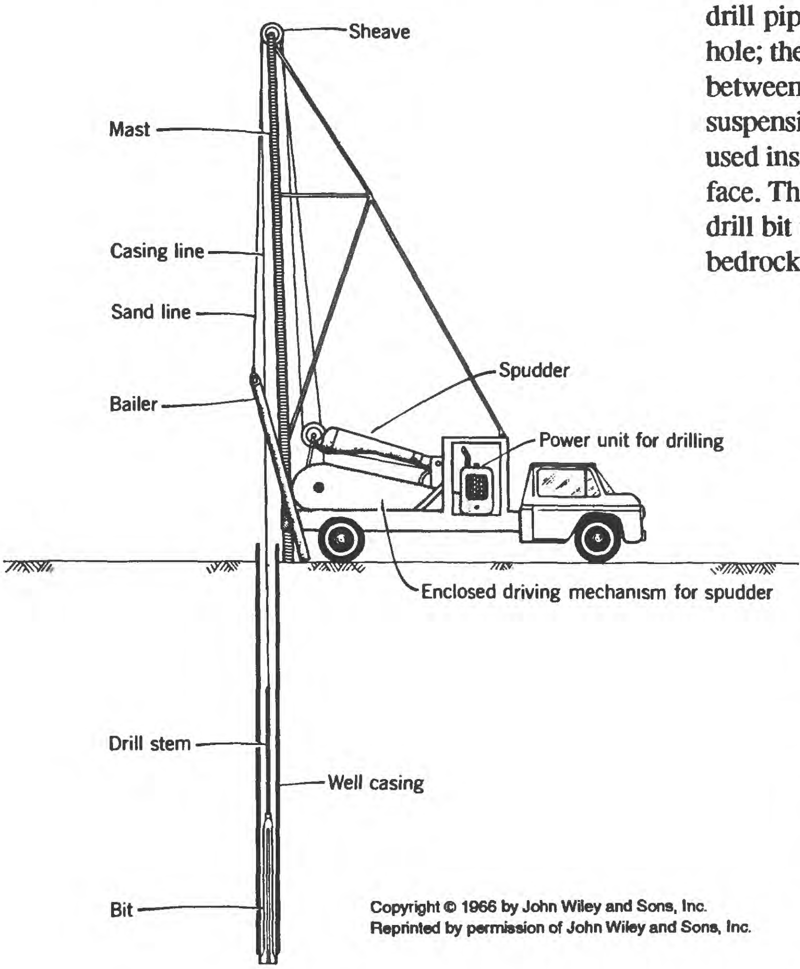


Figure 5. A cable-tool drilling rig and major components.

In the rotary method, the rock at the bottom of the borehole is crushed by a bit attached to the lower end of a string of heavy drill pipe (rod), which transmits rotating action from the drilling machine (rig) at the surface to the bit. Drilling fluid is pumped down through the drill pipe to remove drill cuttings at the bottom of the hole; the fluid returns to the surface in the annular space between the hole and drill pipe, carrying the cuttings in suspension. In the air-rotary method, compressed air is used instead of drilling fluid to force cuttings to the surface. The downhole hammer is a specialized pneumatic drill bit that is normally used after the hole has reached bedrock but also is used to drill through till deposits. The hammer rapidly strikes the rock while the drill pipe is slowly rotated. The percussion effect is similar to the blows delivered by a cable-tool bit. Cuttings are continuously removed by the air used to drive the hammer. As a result, the bit is constantly striking an unbroken (clean) rock surface. Rotation of the bit helps ensure even penetration and straight alignment of the hole. The air rotary with air-hammer method is efficient, with rates of penetration in most rock types more rapid than those by other drilling methods. Drilling rates typically range from 50 ft/hr in soft rock to 20 ft/hr in very hard granite and diabase formations.

With the air-rotary method, an upward air velocity of at least 3,000 ft/min is required to remove cuttings from the hole. Downhole hammers require an air supply at a pressure of at least 100 to 200 lb/in^2. For drilling a typical 6-inch well with a 4.5-inch drill rod, a compressor capable of supplying at least

260 ft^3/min of air at 200 lb/in^2 is required. Some air-rotary rigs are available with compressors capable of supplying 1,100 ft^3/min at 250 lb/in^2.

Many drilling rigs in operation today (fig. 6) are up-to-date examples of hydraulically operated mechanical engineering, carry 400 to 600 ft of drill rod, and are typically mounted on large 10-wheel truck bodies. These drilling machines commonly operate in conjunction with a service truck that carries water, extra drill rod, and other related equipment. These modern drill rigs range in cost from $500,000 to $700,000 (1991).

Advantages of the air-rotary method are that an estimate can be made during drilling of well yield, and in some cases, the depth and contribution of individual fractures or fracture zones can be determined. Most drillers are able to make a good estimate of increases in water discharge as each fracture zone is penetrated by the drill.

Well Construction

Typical domestic bedrock wells are constructed in several steps. A pilot hole 8 to 10 in. in diameter is drilled through the unconsolidated sediments and 10 to 20 ft into bedrock (fig. 7). A 6-inch-diameter steel casing with a drive shoe on the bottom is lowered into the pilot hole and set into bedrock at the bottom. The annular space between the casing and the pilot hole is usually allowed to refill with native formation material. Some drillers seal the casing into bedrock with a grout of bentonite cement. Drilling is continued below the casing until one or more fractures are penetrated that yield a sufficient quantity of water to meet the intended use of the well. If the water-yielding fractures are intersected at shallow depths, the well is commonly extended so that water can be stored in the well and used during short periods of increased demand. At the completion of drilling, the wells are usually pumped for 0.5 to 4 hours by use of compressed air from the drilling rig. Thus, drill cuttings are cleaned out of the wellbore and possibly out of adjacent fractures, and an estimate can be made of the maximum short-term yield. The casing then is capped 1 to 2 ft above land surface.

Local public-health regulations may require other well-construction techniques. The Massachusetts Department of Environmental Protection (DEP), formerly the Massachusetts Department of Environmental Quality Engineering, has issued model regulations for the construction of private wells (Massachusetts Department of Environmental Protection, September 1989). The DEP also has regulations controlling the construction of any well used as a source of public supply (Massachusetts Department of Environmental Protection, 1991).

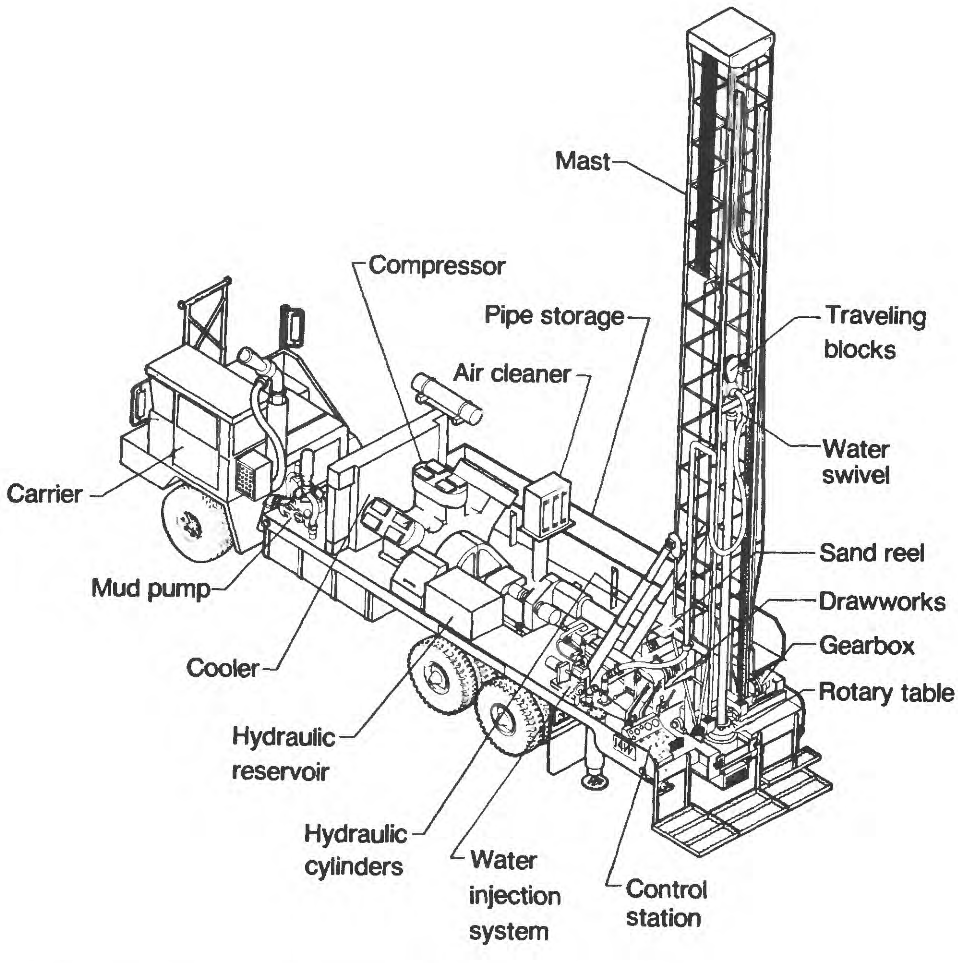


Figure 6. Major components of an air-rotary drilling rig.

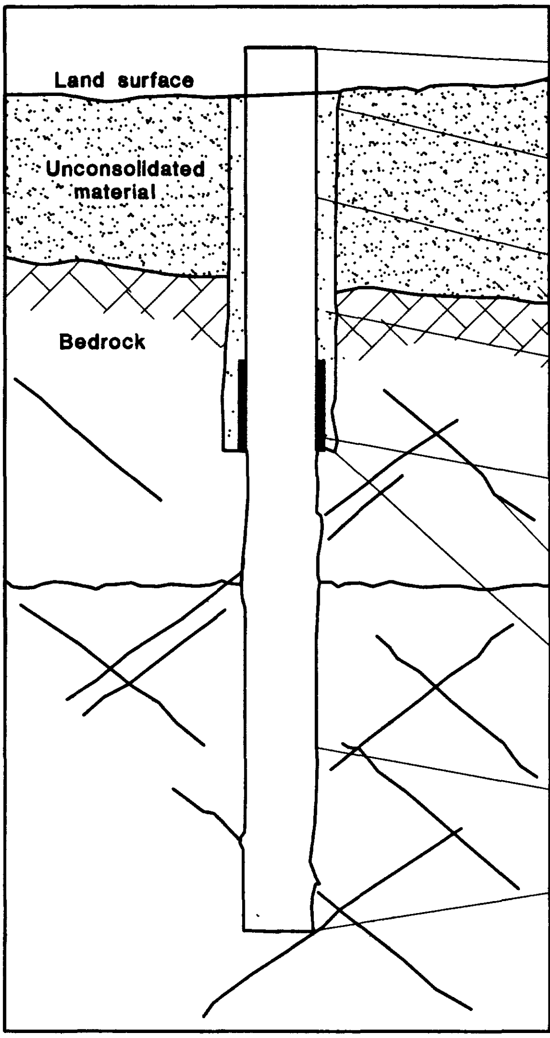


Figure 7. Typical domestic bedrock-well construction.

Well Yield

The yield of a bedrock well depends primarily on the fracture thickness (aperture), number of water-yielding fractures, and depth of water-yielding fractures penetrated by the well. In the long-term, yield also depends on the availability of recharge to the water-yielding fractures.

In general, the flow of water through individual fractures is related to the pressure gradient in the fracture and the fracture thickness, according to the equation (Witherspoon and others, 1981)

$$Q = \frac{P'b^3}{12n}$$

where Q is measured discharge per unit width of fracture (L^2/T),
P' is pressure gradient (F/L),
b is fracture thickness (L), and
n is viscosity of water ((F/L) T).

In bedrock wells the pressure gradient in the intersected water-yielding fractures is created when the water level in the well is lowered by pumping. The amount by which the water level is lowered during pumping is called drawdown (fig. 8).

Other conditions being equal, a doubling of fracture thickness results in about an eight-fold increase in well yield (fig. 9). For a given fracture thickness, a doubling of drawdown results in a doubling of discharge (fig. 10). Yield from a fracture is at the maximum when the water level in a well is drawn down to the depth of the fracture. When the water level is lowered below a water-yielding fracture, flow from the fracture into the well is

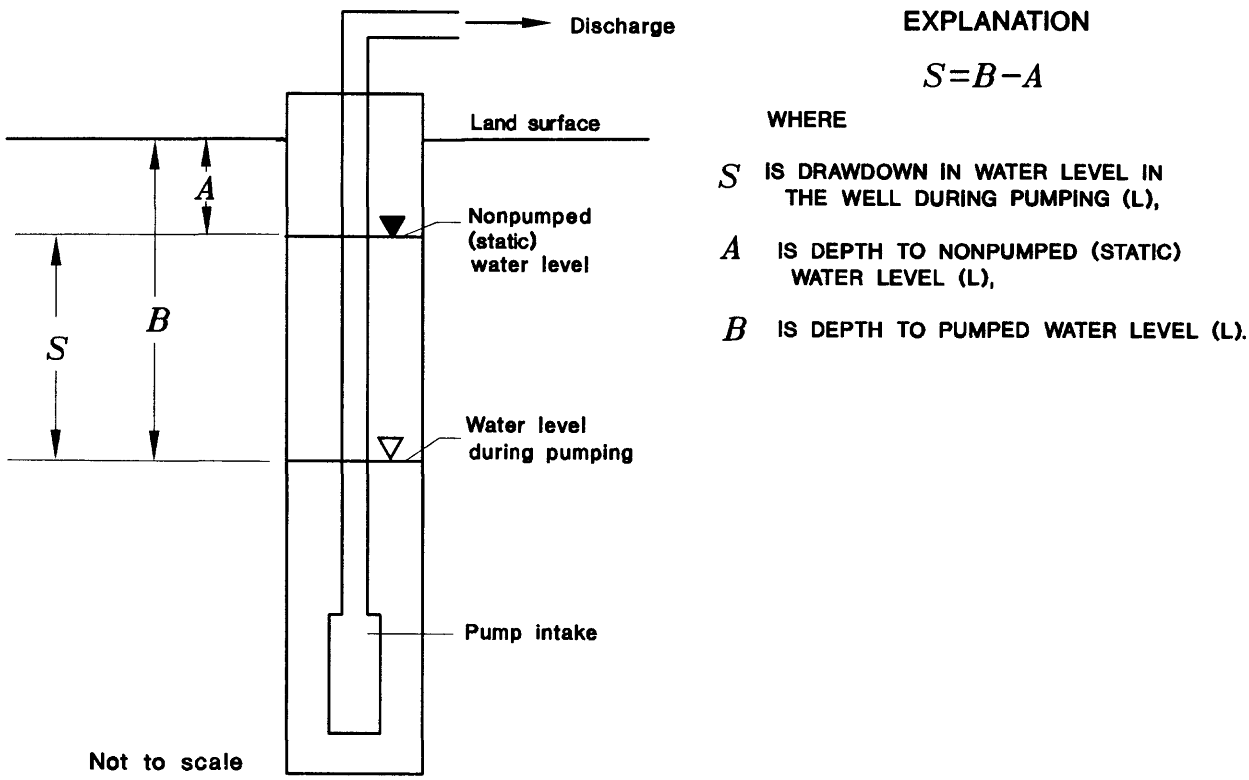


Figure 8. Pumped well and equation for determining drawdown.

unrestricted by hydrostatic pressure in the well. Under these conditions, the fracture is referred to as "free flowing." For fractures of equal thickness but different depth, it is possible to obtain more water from the deeper fracture because of the increased drawdown that is available (fig. 11).

Most wells intersect from a few to scores of water-yielding fractures at diverse depths and with varying fracture thicknesses. As a well is drilled deeper and more water-yielding fractures are penetrated, the yield of the well increases.

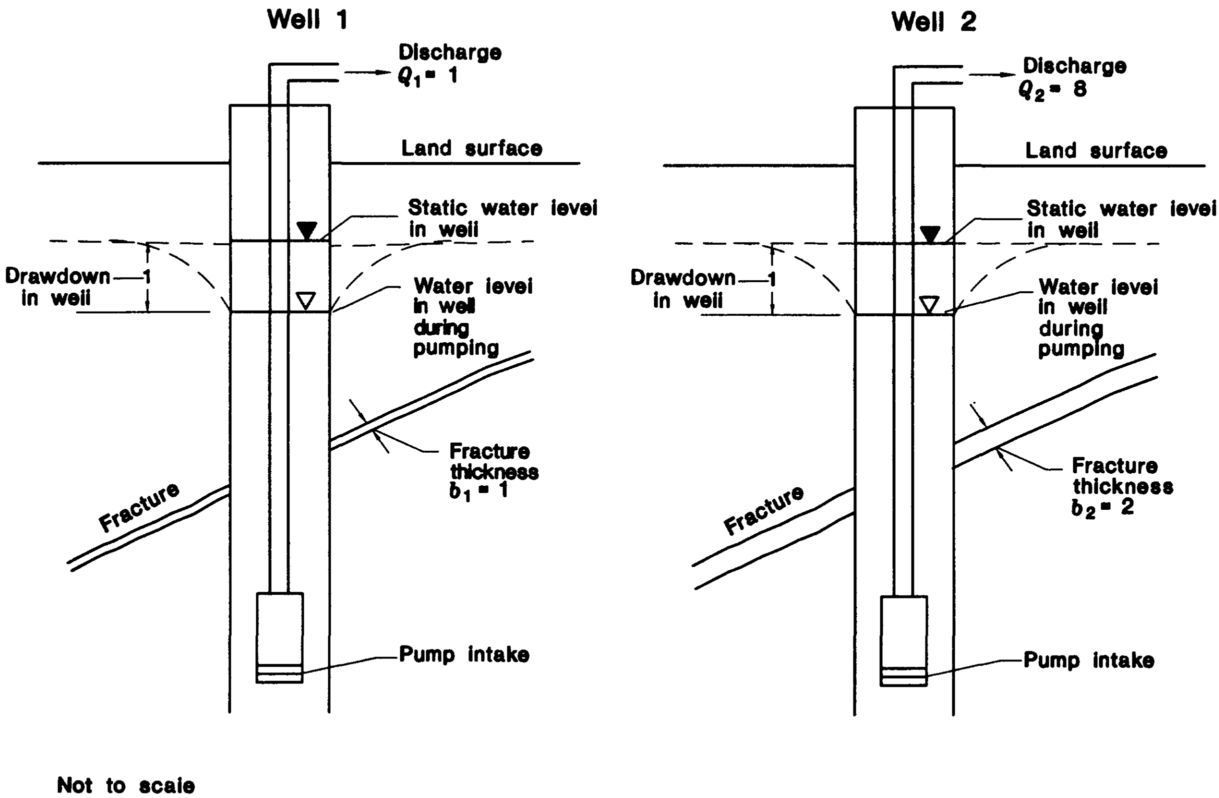
YIELDS OF BEDROCK WELLS

The yield of a bedrock well depends on many factors, the most important of which are the number of water-yielding fractures intersected and their hydraulic characteristics. These two factors are related to the type and structure of the bedrock. Bedrock structure, in turn, may be related to topographic setting. Other factors that appear to affect well yield are the depth and diameter of the well and the type and thickness of overlying sediments. Statistical analysis of well records was used to determine the relative importance of many of these factors on the yields of bedrock wells in Massachusetts.

The well yields reported by drillers (dependent variable) and used in the following analysis of factors affecting yield were determined by several methods that have a wide range of accuracy. Most yields reported before 1950 were determined by bailer tests. Since then, most reported-yield data are probably the result of short-term compressed air pumping tests. Other data that may have been used by drillers to estimate well yield include results of constant-rate pumping tests, capacity of the pump installed in the well, minimum yield required for bank loan or municipal requirements, and rough estimates.

Statistical Analysis Relating Well Yield to Other Factors

Information on 4,218 bedrock wells in Massachusetts was compiled from the USGS Ground-Water Site Inventory (GWSI) data base. This well information was collected by the USGS during many water-resources investigations from 1955 through 1990. Before a well



EXPLANATION

$$Q_2 = Q_1 \cdot \frac{b_2^3}{b_1^3}$$

$$Q_2 = 1 \cdot \frac{(2)^3}{(1)^3}$$

$$Q_2 = 8$$

Where

Q_1 is discharge from well 1 ;

Q_2 is discharge from well 2 ;

b_1 is fracture thickness in well 1 ; and

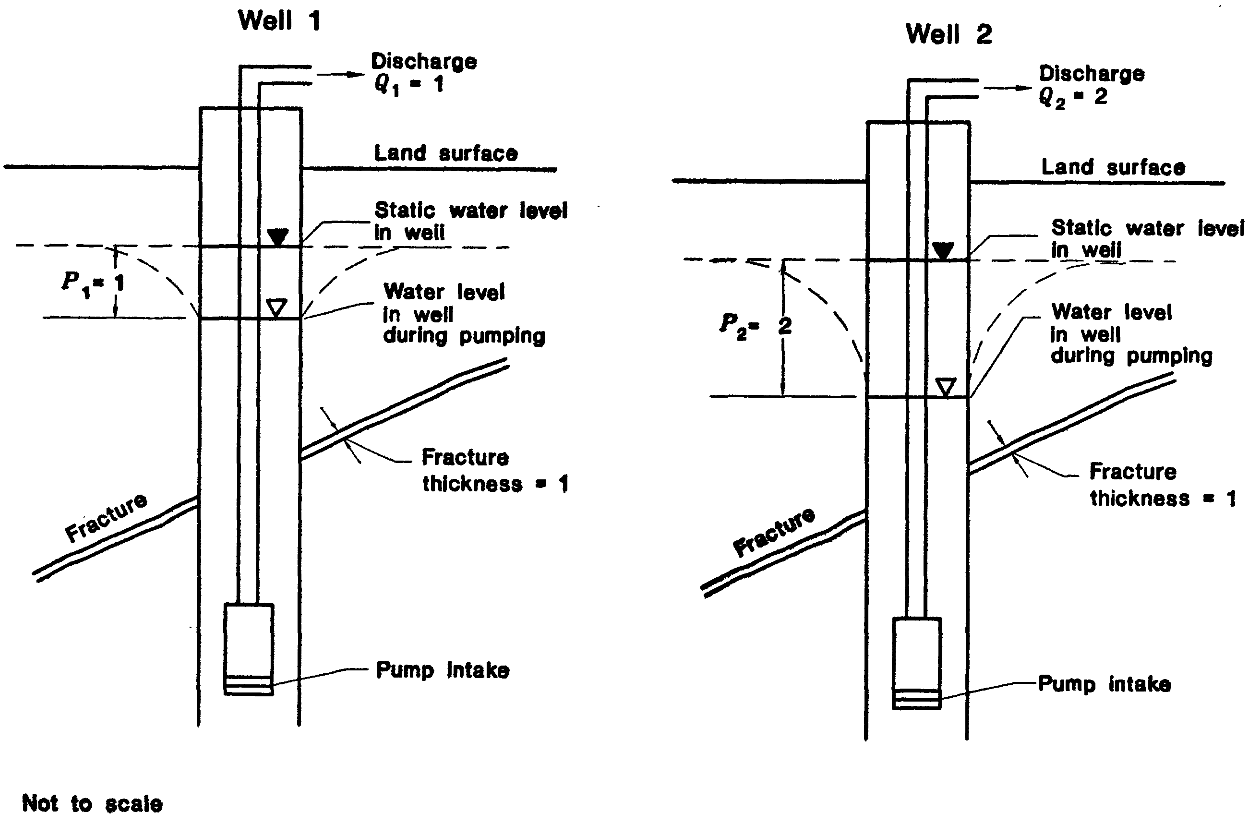
b_2 is fracture thickness in well 2.

Figure 9. Relation between well yield and fracture thickness.

was included in the study's bedrock-well data base for analysis, the location and yield of the well had to be known, and the yield had to be derived mostly from open holes drilled into bedrock. This data set may not represent a random sample of bedrock wells in Massachusetts.

Information categories (variables) selected from the GWSI data base include (1) USGS well number, (2) latitude of the well, (3) longitude of the well, (4) county where well is located, (5) date of well construction, (6) name of drilling contractor, (7) method of construction, (8) altitude of land surface at the well, (9) topographic setting of the well, (10) total depth of the well, (11) well diameter, (12) casing depth, (13) casing diameter, (14) depth to top of open interval, (15) depth to bottom of open interval, (16) primary use of water, (17) yield of well, (18) static water level, (19) specific capacity, (20) depth to top of rock, (21) aquifer code, and (22) lithology. All variables were not available for all wells in the data base. The variables used for analysis and the total number of entries for each are listed in table 1.

Yield per foot of saturated open hole was a variable derived to eliminate the effect of unequal well depths. Yield per foot was computed by dividing yield by (a) the



EXPLANATION

$$Q_2 = Q_1 \cdot \frac{P_2}{P_1}$$

$$Q_2 = 1 \cdot \frac{2}{1}$$

$$Q_2 = 2$$

Where

Q_1 is discharge from well 1 ;

Q_2 is discharge from well 2 ;

P_1 is drawdown in well 1, and

P_2 is drawdown in well 2.

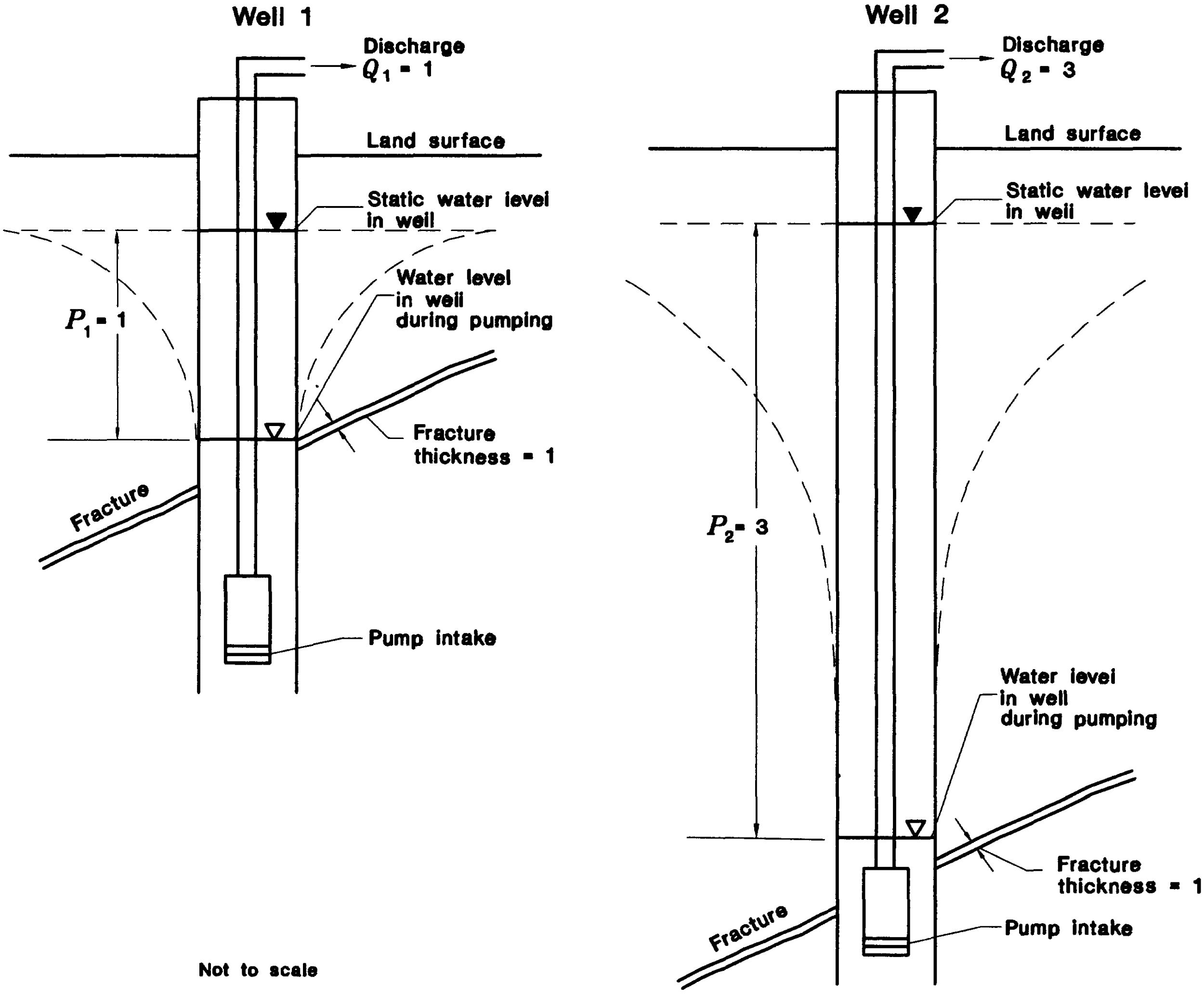
Figure 10. Relation between well yield and drawdown.

total depth of the well minus depth to bottom of the casing if the reported water level was at or above the casing depth, or (b) total depth of well minus depth to water if the reported water level was below the bottom of casing.

For analysis, several subsets of the GWSI data were created by grouping or segregating the data into categories of well use, topographic setting, well depth, casing diameter, and depth to bedrock (tables 2 and 3).

A digitized bedrock-geology map of the State was overlain by a map of the location of each well in the data base. The wells were assigned to one of the four generalized bedrock units: crystalline (includes igneous and noncarbonate metamorphic rocks), carbonate, Connecticut Valley (includes sedimentary and volcanic rocks), and sedimentary (includes sedimentary rocks of eastern Massachusetts; table 2). The areal extent of each bedrock unit is shown in figure 1.

Maximum, mean, median, and percentile statistics were computed for the sorted data. The median (50 percent of the wells have smaller values and 50 percent have larger values) was used to represent the average in this report because it tended to give values that were in accord with field experience with bedrock wells and it did not give excessive importance to extreme values (outliers).



EXPLANATION

$$Q_2 = Q_1 \cdot \frac{P_2}{P_1}$$

$$Q_2 = 1 \cdot \frac{3}{1}$$

$$Q_2 = 3$$

Where

Q_1 is discharge from well 1 ;

Q_2 is discharge from well 2 ;

P_1 is drawdown in well 1, and

P_2 is drawdown in well 2.

Figure 11. Relation between fracture depth and potential well yield.

Table 1. Total number of data entries for each variable in bedrock-well data base for Massachusetts

[USGS, U.S. Geological Survey]

Variable	All wells	Domestic wells	Commercial or industrial wells
		Well-use category	
USGS well number	4,218	3,759	345
Latitude	4,218	3,759	345
Longitude	4,218	3,759	345
County	4,218	3,759	345
Date of construction	4,009	3,603	308
Drilling contractor	4,104	3,759	345
Method of construction	4,218	3,759	345
Altitude of land surface	4,211	3,755	344
Topographic setting	4,218	3,052	247
Well depth	4,198	3,741	343
Well diameter	1,849	1,726	82
Casing depth	1,640	1,553	66
Casing diameter	3,969	3,553	317
Top of open hole	3,732	2,506	176
Bottom of open hole	1,318	1,251	49
Use of water	4,169	3,759	345
Well yield	4,216	3,758	344
Static water level	3,148	2,846	225
Specific capacity	213	171	35
Depth to top of rock	3,552	3,239	229
Aquifer code	4,218	3,759	345
Lithology	4,218	3,759	345
Yield per foot of saturated open hole	1,624	1,537	66
Geology code	4,218	2,132	590
Well use (grouping)[1]	4,173	3,759	345
Topographic setting (grouping)[1]	2,798	2,529	195
Geologic unit (grouping)[1]	4,218	2,132	590
Well depth (grouping)[2]	4,198	3,741	343
Diameter of well (grouping)[2]	3,967	3,553	317
Depth to bedrock (grouping)[2]	3,552	3,239	229

[1]See table 2.
[2]See table 3.

Table 2. Subsets of Ground-Water Site Inventory (GWSI) data for Massachusetts used in analysis

Data category (variable name)	Name	GWSI coding or range of values
Well use (use-group)	Domestic	Domestic, stock
	Commercial or industrial	Commercial, industrial, public supply, irrigation, recreation, institutional
Topographic setting (Topo-group)	Hilltops or slopes	Hilltop, hillside, upland draw, pediment
	Valley or lowlands	Valley flat, flood-plain terrace, depression
Geologic unit (Geo-group)	Crystalline	Igneous and metamorphic rocks of Massachusetts and rock units not included in groups 2-4
	Carbonate	Carbonate rocks of western Massachusetts
	Connecticut Valley	Jurassic and Triassic sedimentary and volcanic rocks of the Connecticut Valley area
	Sedimentary	Sedimentary rocks of the Boston, Narragansett, and Norfolk Basins

Table 3. Range of values used for data analysis

[ft, feet; in., inch]

Data category (variable name)	Range
Well depth (ft) (Wd-group)	0 to 100
	101 to 200
	201 to 300
	301 to 400
	401 to 500
	501 to 600
	601 to 700
	Deeper than 700
Diameter of well casing (in.) (Diam-group)	0 to 5.4
	5.5 to 6.4
	6.5 to 8.4
	Larger than 8.4
Depth to bedrock (ft) (Drock-group)	0 to 9
	10 to 19
	20 to 39
	40 to 79
	80 to 159
	Deeper than 159

Changes With Time

Reported well yields and depths have changed with time (fig. 12). Reported well yields increased from a median of 10 gal/min for 1910-20 to a median of 20 gal/min for 1930-40, but then generally declined through 1980-90. Well depths however, increased substantially since the 1950's, from 128 ft for 1950-60 to 250 ft for 1980-90. The period when depths began to increase coincides with the period when the method used to drill wells changed from cable tool to air rotary with percussion (fig. 13).

General Well Characteristics

Some of the hydraulic and physical characteristics of the bedrock wells are listed in table 4. The median yield and depth of all wells used in the analysis were 7 gal/min and 170 ft. Reported yields and depths ranged from 0 to 760 gal/min and 6 to 1,120 ft, respectively. Domestic and commercial or industrial wells were notably different in their characteristics, with yields and depths being substantially larger for commercial or industrial wells. The altitude of land surface for commercial or industrial wells also was substantially lower than for domestic wells. The differences in characteristics between well-use categories will be discussed later in this section.

Well Depth and Diameter

Characteristics for bedrock wells with various depths are shown in table 5 and of different diameter in table 6. Yield and yield per foot for different well depths and well use are shown in table 7. Yield and yield per foot decreased as well depth increased to 400 ft but increased slightly at depths greater than 600 ft. Well yields and depths increased substantially with increases in well diameter.

The relations among well yields and well depth, diameter, and use are summarized in table 8. Well yield increased with increasing diameter for all well depths and was larger for wells in the industrial or commercial use category. The factors associated with the larger increases in well yields for commercial or industrial wells are discussed in the well-use section of this report. The apparent increase in yield at depths greater than 600 ft is difficult to assess. At present (1992), little information is available about the depths and yields of individual water-yielding zones in bedrock wells. Detailed studies of wells in crystalline rock have noted an irregularly decreasing number of water-yielding fractures with increasing depth, especially below the 350- to 650-foot depth interval, but water-yielding fractures have been intersected near or at depths greater than 3,000 ft (Paillet, U.S. Geological Survey Borehole Geophysics Research Project, written commun., 1987).

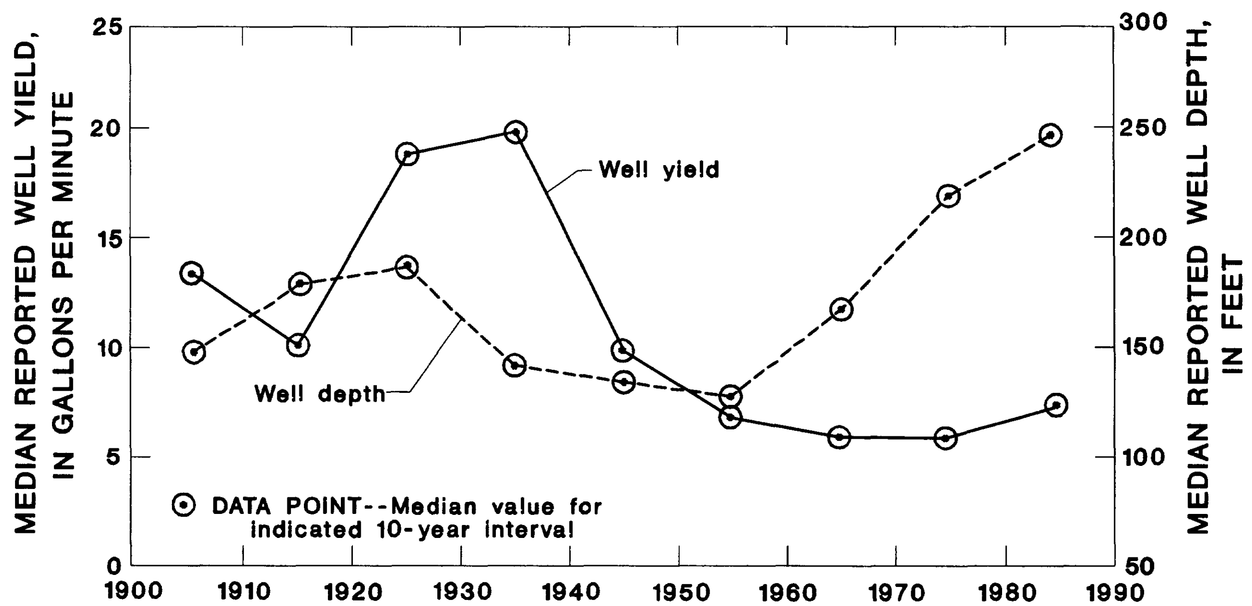


Figure 12. Median reported yields and depths of bedrock wells in Massachusetts by decade, 1900-90.

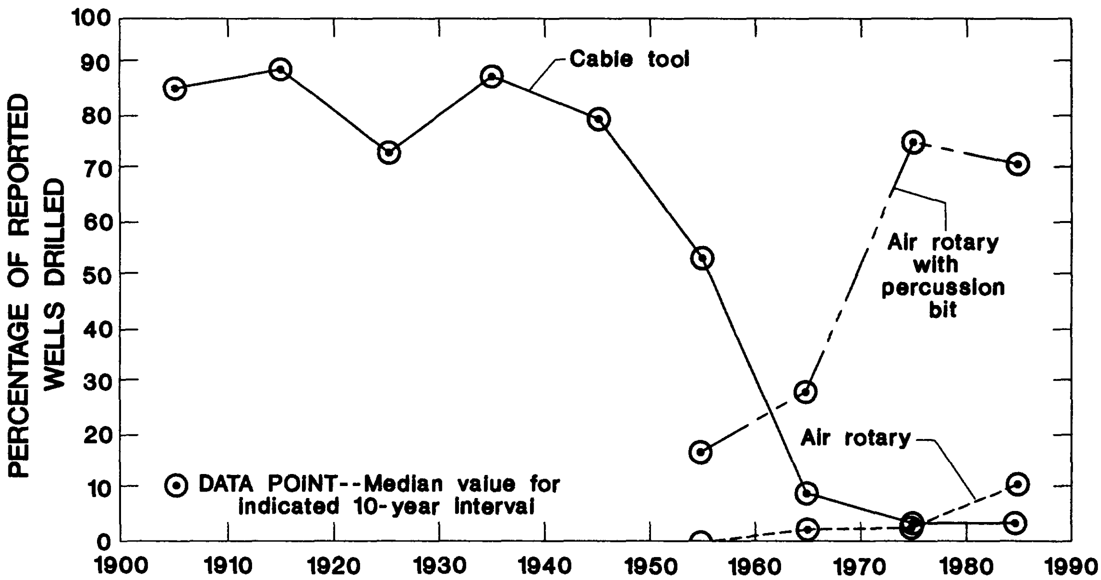


Figure 13. Reported drilling methods for bedrock wells in Massachusetts by decade, 1900-90.

Topographic Setting

Characteristics of bedrock wells in various topographic settings are given in table 9. Median yields, casing depths, and depths to bedrock were larger for wells located in valleys and lowlands. In addition, the effect of topography is reflected by the greater depths to the water table on hilltops and slopes.

The larger yields in valleys may be related to several factors. Valleys commonly have developed along zones of intense fracturing or along zones where rock is less resistant to erosion than the surrounding rocks. As valleys erode, removal of overlying rock can reduce compressional stress on the underlying rock and can cause horizontal stress-relief fracturing beneath the valleys; thus, secondary permeability can be increased further. Valley bottoms are natural discharge areas for ground water, and more water passes through these discharge areas than through the adjacent upland areas. In carbonate bedrock, large solution channels can be developed by the large volumes of water that pass through the bedrock underlying the valley before discharging. Valleys also can contain thick overburden deposits that provide recharge to the underlying bedrock. Because yields in valleys commonly are affected by combinations of these factors, the likelihood of obtaining large yields from bedrock wells is greater in valleys than on hilltops and slopes.

Overburden Thickness

Characteristics of bedrock wells with various depths of overburden are listed in tables 10 and 11. The median altitude of land surface and depth to water increased with depths of overburden. This was because more wells in each overburden-thickness range were on hilltops and slopes where the altitude of land surface and depth to water are greater than in valleys and lowlands. The apparent effect of overburden thickness on the yields of wells is particularly significant in valleys and lowlands as compared to hilltops and slopes. On hilltops and slopes, only small increases in yield corresponded to large increases in overburden thickness. In valleys and lowlands, substantial increases in yield corresponded to a large increase in the thickness of overburden. This difference indicates the effect of a hydrogeologic factor(s) other than overburden thickness, which coincides with the deepest parts of the valleys and results in large well yields in those locations. These areas of large yield probably correspond to zones of more intense fracturing. The type of overburden material also may affect these results. The bedrock in valley areas generally is overlain by saturated, permeable stratified deposits, or poorly permeable lakebed deposits. Upland areas commonly are overlain by unsaturated poorly permeable till deposits.

Table 4. Median values for hydraulic and physical characteristics of all bedrock wells in data base for Massachusetts

[Well characteristic: Not all characteristics were available for all wells; number in parentheses is number of data values analyzed. ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot]

Well characteristic	All wells	Well-use category: Domestic wells	Well-use category: Commercial or industrial wells
Yield (gal/min)	7 (4,218)	6 (3,758)	30 (344)
Yield per foot[1] (gal/min)/ft	.06 (1,626)	.05 (1,537)	.15 (66)
Specific capacity[2] (gal/min)/ft	.10 (213)	.10 (171)	.80 (35)
Well depth (ft)	170 (4,202)	160 (3,741)	258 (343)
Depth to bedrock (ft)	27 (3,555)	26 (3,239)	35 (229)
Depth to bottom of casing (ft)	34 (1,642)	33 (1,553)	40 (66)
Depth to water in feet below land surface	19 (3,149)	20 (2,846)	16 (225)
Altitude of land surface in feet above sea level	300 (4,211)	315 (3,755)	170 (344)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping.

Table 5. Median values for hydraulic and physical characteristics of bedrock wells in Massachusetts in various depth intervals

[Well characteristic: Not all characteristics were available for all wells; number in parentheses is number of data values analyzed. ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot; >, actual value is greater than value shown]

Well characteristic	Well depth intervals, in feet							
	1-100	101-200	201-300	301-400	401-500	501-600	601-700	>700
Yield (gal/min)	9.5	7.0	6.0	5.0	6.0	8.5	20	32
	(784)	(1,843)	(899)	(362)	(159)	(76)	(33)	(40)
Yield per foot[1] (gal/min)/ft	.18	.08	.03	.01	.01	.01	.03	.02
	(263)	(678)	(413)	(150)	(71)	(32)	(10)	(7)
Specific capacity[2] (gal/min)/ft	.20	.10	.04	.30	.25	.80	2.1	.20
	(43)	(85)	(47)	(23)	(4)	(5)	(1)	(4)
Well depth (ft)	82	147	246	350	460	545	675	804
	(784)	(1,844)	(899)	(362)	(160)	(76)	(33)	(40)
Depth to bedrock (ft)	20	30	32	27	27	22	25	45
	(657)	(1,543)	(786)	(305)	(137)	(60)	(24)	(27)
Depth to bottom of casing (ft)	26	35	40	36	39	32	33	52
	(265)	(681)	(413)	(150)	(71)	(32)	(10)	(7)
Depth to water in feet below land surface	15	19	20	20	20	24	20	17
	(587)	(1,392)	(679)	(267)	(113)	(53)	(21)	(22)
Altitude of land surface in feet above sea level	279	285	380	315	250	260	300	270
	(783)	(1,842)	(899)	(360)	(160)	(75)	(33)	(39)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping.

Table 6. Median values for hydraulic and physical characteristics of all wells, domestic wells, and commercial or industrial bedrock wells in Massachusetts with various diameters

[Well characteristic: Not all charcteristics were available for all wells; number in parentheses is number of data values analyzed; ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot, -- no data available; <, actual value is less than value shown, >, actual value is greater than value shown]

Well characteristic	Well diameters, in inches			
	< 6	6	8	> 8
ALL WELLS				
Yield (gal/min)	16 (18)	7.0 (3,795)	36 (143)	50 (15)
Yield per foot [(gal/min)/ft][1]	.17 (4)	.05 (1,573)	.20 (35)	.09 (5)
Specific capacity [(gal/min)ft][2]	-- (0)	.90 (177)	8.6 (9)	.10 (4)
Well depth (ft)	143 (18)	164 (3,780)	299 (142)	275 (15)
Depth to bedrock (ft)	12 (10)	28 (3,245)	37 (103)	18 (10)
Depth to bottom of casing (ft)	54 (4)	33 (1,588)	42 (36)	27 (5)
Depth to water in feet below land surface	18 (9)	20 (2850)	15 (108)	14 (12)
Altitude of land surface in feet above sea level	347 (18)	291 (3,789)	180 (142)	170 (15)
DOMESTIC WELLS				
Yield (gal/min)	15 (13)	6.0 (3,487)	12 (47)	26 (6)
Yield per foot [(gal/min)/ft][1]	.17 (4)	.05 (1,513)	.10 (13)	.08 (1)
Specific capacity [(gal/min)ft][2]	-- (0)	.10 (150)	.20 (1)	60 (1)
Well depth (ft)	142 (13)	160 (3,473)	173 (46)	145 (6)
Depth to bedrock (ft)	10 (9)	27 (3,029)	18 (34)	12 (4)

Table 6. Median values for hydraulic and physical characteristics of all wells, domestic wells, and commercial or industrial bedrock wells in Massachusetts with various diameters

Well characteristic	Well diameter, in inches			
	< 6	6	8	> 8
DOMESTIC WELLS--Continued				
Depth to bottom of casing (ft)	54 (4)	33 (1,528)	44 (14)	15 (1)
Depth to water in feet below land surface	17 (8)	20 (2,644)	18 (39)	7.0 (5)
Altitude of land surface in feet above sea level	540 (13)	305 (3,483)	255 (47)	220 (6)
COMMERCIAL OR INDUSTRIAL WELLS				
Yield (gal/min)	18 (4)	22 (230)	65 (76)	50 (7)
Yield per foot [(gal/min)/ft][1]	-- (0)	.09 (41)	.20 (18)	.47 (4)
Specific capacity [(gal/min)ft][2]	-- (0)	.70 (23)	.85 (6)	3.6 (3)
Well depth (ft)	245 (4)	210 (229)	337 (76)	463 (7)
Depth to bedrock (ft)	25 (1)	34 (157)	37 (53)	26 (4)
Depth to bottom of casing (ft)	-- (0)	40 (41)	40 (18)	36 (4)
Depth to water in feet below land surface	25 (1)	16 (153)	13 (54)	25 (5)
Altitude of land surface in feet above sea level	210 (4)	170 (230)	150 (75)	130 (7)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping.

Table 7. Median values for yield and yield per foot of all wells, domestic wells, and commercial or industrial bedrock wells in Massachusetts in various depth intervals

[Number in parentheses is number of data values analyzed. ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot]

Well depth interval (ft)	Well yield (gal/min)			Yield per foot (gal/min)/ft		
	All wells	Domestic wells	Commercial or industrial wells	All wells	Domestic wells	Commercial or industrial wells
0-100	9.5 (784)	9.0 (743)	20 (34)	0.18 (263)	0.18 (257)	0.19 (5)
101-200	7.0 (1,843)	7.0 (1,718)	20 (98)	.08 (678)	.07 (666)	.23 (7)
201-300	6.0 (899)	5.0 (793)	25 (77)	.03 (413)	.03 (385)	.10 (19)
301-400	5.0 (362)	4.0 (298)	32 (48)	.01 (150)	.01 (140)	.08 (8)
401-500	6.0 (159)	3.0 (110)	35 (33)	.01 (71)	.01 (55)	.09 (13)
501-600	8.5 (76)	2.0 (47)	60 (22)	.01 (32)	0 (22)	.26 (8)
601-700	20 (33)	15 (13)	50 (16)	.03 (10)	.03 (8)	.12 (2)
Greater than 700	32 (40)	6.5 (15)	49 (13)	.02 (7)	.02 (3)	.16 (3)

Table 8. Median values for yield for all wells, domestic wells, and commercial or industrial bedrock wells in Massachusetts with various depths and diameters

[Well yield, in gallon per minute. Number in parentheses is number of data values analyzed. ft, foot; in., inch. --, no data available]

Well depth intervals (ft)	All wells			Domestic wells			Commercial or industrial wells		
		Well diameter			Well diameter			Well diameter	
	All	6 in.	8 in.	All	6 in.	8 in.	All	6 in.	8 in.
0-100	9.5 (784)	9.0 (724)	18 (14)	9.0 (743)	9.0 (692)	12 (9)	20 (34)	20 (28)	20 (4)
101-200	7.0 (1,843)	7.0 (1,703)	12 (30)	7.0 (1,718)	7.0 (1,603)	8.5 (18)	20 (98)	20 (79)	20 (11)
201-300	6.0 (899)	5.0 (798)	33 (32)	5.0 (793)	5.0 (728)	15 (9)	25 (77)	15 (49)	40 (17)
301-400	5.0 (362)	5.0 (309)	72 (22)	4.0 (298)	4.0 (270)	17 (7)	32 (48)	25 (29)	90 (14)
401-500	6.0 (159)	4.0 (134)	95 (18)	3.0 (110)	3.0 (108)	-- (0)	35 (33)	25 (18)	100 (11)
501-600	8.5 (76)	6.0 (61)	90 (11)	2.0 (47)	2.0 (45)	12 (1)	60 (22)	40 (13)	120 (7)
601-700	20 (33)	16 (22)	70 (7)	15 (13)	15 (13)	-- (0)	50 (16)	35 (7)	70 (7)
Greater than 700	32 (40)	20 (25)	48 (8)	6.5 (15)	4.0 (11)	26 (2)	49 (13)	33 (5)	49 (5)

Table 9. Median values for hydraulic and physical characteristics of all wells, domestic wells, and commercial or industrial bedrock wells in Massachusetts with various topographic settings

[Well characteristic: Not all characteristics were available for all wells; number in parentheses is number of data values analyzed; ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot]

Well characteristics	Topographic setting, by type of well					
	All wells		Domestic wells		Commercial or industrial wells	
	Hilltops and slopes	Valleys and lowlands	Hilltops and slopes	Valleys and lowlands	Hilltops and slopes	Valleys and lowlands
Yield (gal/min)	6.0 (2,188)	10 (609)	6.0 (2,049)	8.0 (479)	20 (82)	40 (111)
Yield per foot[1] [(gal/min)/ft]	.05 (1,149)	.10 (307)	.05 (1,108)	.09 (273)	.09 (24)	.21 (31)
Specific capacity[2] [(gal/min)/ft]	.10 (94)	.20 (43)	.10 (85)	.10 (29)	1.0 (8)	.80 (13)
Well depth (ft)	174 (2,179)	165 (608)	171 (2,040)	149 (478)	250 (82)	286 (111)
Depth to bedrock (ft)	22 (2,044)	35 (559)	22 (1,921)	33 (455)	23 (72)	45 (92)
Depth to bottom of casing (ft)	30 (1,159)	42 (309)	30 (1,118)	42 (275)	32 (24)	40 (31)
Depth to water in feet below land surface	20 (1,724)	16 (471)	20 (1,631)	16 (384)	23 (50)	16 (76)
Altitude of land surface in feet above sea level	500 (2,187)	340 (609)	500 (2,047)	330 (479)	410 (83)	350 (111)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping.

Table 10. Median values for hydraulic and physical characteristics of bedrock wells in Massachusetts with various overburden thicknesses

[Well characteristic: Not all characteristics were available for all wells; number in parentheses is number of data values analyzed; ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot]

Well characteristics	Overburden thickness, in feet					
	0-9	10-19	20-39	40-79	80-159	Greater than 159
Yield (gal/min)	6.0 (587)	6.0 (859)	7.0 (934)	7.0 (785)	9.0 (351)	9.5 (36)
Yield per foot[1] [(gal/min)/ft]	.04 (323)	.05 (410)	.05 (375)	.08 (340)	.08 (141)	.10 (22)
Specific capacity[2] [(gal/min)/ft]	.10 (34)	.10 (49)	.10 (42)	.20 (43)	.20 (15)	.04 (1)
Well depth (ft)	173 (584)	150 (857)	152 (931)	172 (782)	212 (349)	311 (36)
Depth to bedrock (ft)	7 (587)	15 (859)	30 (934)	56 (785)	100 (351)	180 (36)
Depth to bottom of casing (ft)	17 (325)	22 (415)	38 (378)	66 (343)	114 (143)	183 (22)
Depth to water in feet below land surface	18 (456)	16 (695)	18 (728)	20 (601)	30 (254)	40 (27)
Altitude of land surface in feet above sea level	470 (586)	383 (858)	285 (933)	290 (785)	360 (351)	475 (36)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping

Table 11. Median yields of bedrock wells in Massachusetts with various overburden thicknesses and topographic settings

[Values are in gallons per minute. Number in parentheses is number of data values analyzed]

Overburden thickness (feet)	Topographic setting	
	Hilltops and slopes	Valleys and lowlands
0-9	6.0 (431)	6.0 (66)
10-19	6.0 (552)	8.0 (104)
20-39	6.0 (476)	10 (152)
40-79	6.0 (381)	10 (159)
79-159	7.0 (183)	11 (66)
Greater than 160	8.0 (21)	30 (12)

Bedrock Type

Characteristics of wells in different types of bedrock are listed in table 12. Wells in carbonate rock had the largest median yield. The largest yield from a bedrock well in Massachusetts (1,700 gal/min) was reported to be from an industrial well drilled in carbonate rock (Norvitch and Lamb, 1966). Data for many additional high-yield wells in carbonate rock were not included in the data base used for this study because the data for these wells is not in the GWSI data base used for analysis.

Within the individual rock units, topographic setting (table 13), well depth, and thickness of overburden (table 14) had similar apparent effects, as discussed previously. Well yields in crystalline rock decreased with depth to about 500 ft and then increased slightly with further increases in depth. Well yields in sedimentary rocks of the Connecticut Valley appeared to increase substantially at depths greater than 400 ft; it is possible, therefore, that this rock unit may have some primary

Table 12. Median values for hydraulic and physical characteristics of all wells, domestic wells, and commercial or industrial wells in Massachusetts completed in generalized bedrock units

[Well characteristic: Not all charcteristics were available for all wells. Number in parentheses is number of data values analyzed; --, no data available; ft, foot; gal/min, gallon per minute; (gal/min)/ft, gallon per minute per foot]

Well characteristic	Crystalline rock	Carbonate rock	Sedimentary rock of Connecticut Valley	Sedimentary rock of Boston, Narragansett, and Norfolk Basins
ALL WELLS				
Yield (gal/min)	6.0 (3,351)	25 (32)	8.0 (157)	12.0 (676)
Yield per foot [(gal/min)/ft][1]	.05 (1,482)	-- (0)	.08 (141)	.03 (1)
Specific capacity [(gal/min)ft][2]	.1 (183)	-- (0)	.5 (4)	.3 (26)
Well depth (ft)	173 (3,336)	152 (31)	190 (156)	145 (675)
Depth to bedrock (ft)	26 (2,969)	30 (29)	34 (148)	30 (406)
Depth to bottom of casing (ft)	33 (1,496)	-- (0)	40 (143)	73 (1)
Depth to water in feet below land surface	20 (2,620)	18 (18)	20 (142)	15 (368)
Altitude of land surface in feet above sea level	410 (3,347)	995 (32)	261 (157)	80 (675)
DOMESTIC WELLS				
Yield (gal/min)	6.0 (3,029)	4.5 (14)	7.0 (131)	10 (581)
Yield per foot [(gal/min)/ft][1]	.05 (1,410)	-- (0)	.06 (125)	.03 (1)
Specific capacity [(gal/min)ft][2]	.1 (152)	-- (0)	-- (0)	.2 (19)
Well depth (ft)	165 (3,014)	90 (13)	171 (130)	140 (581)
Depth to bedrock (ft)	25 (2,718)	23 (14)	30 (129)	30 (376)

Table 12. Median values for hydraulic and physical characteristics of all wells, domestic wells, and commercial or industrial wells in Massachusetts completed in generalized bedrock units--*Continued*

Well characteristic	Crystalline rock	Carbonate rock	Sedimentary rock of Connecticut Valley	Sedimentary rock of Boston, Narragansett, and Norfolk Basins
DOMESTIC WELLS--Continued				
Depth to bottom of casing (ft)	33 (1,424)	-- (0)	37 (127)	73 (1)
Depth to water in feet below land surface	20 (2,405)	10 (9)	20 (123)	16 (309)
Altitude of land surface in feet above sea level	415 (3,026)	1,130 (14)	267 (131)	90 (581)
COMMERCIAL OR INDUSTRIAL WELLS				
Yield (gal/min)	25 (226)	50 (16)	60 (25)	30 (76)
Yield per foot [(gal/min)/ft][1]	.09 (50)	-- (0)	.28 (15)	-- (0)
Specific capacity [(gal/min)ft][2]	.7 (27)	-- (0)	.5 (4)	3.1 (4)
Well depth (ft)	275 (226)	300 (16)	342 (25)	181 (75)
Depth to bedrock (ft)	30 (174)	52 (13)	62 (18)	45 (23)
Depth to bottom of casing (ft)	32 (50)	-- (0)	70 (15)	-- (0)
Depth to water in feet below land surface	16 (151)	36 (8)	20 (19)	11 (46)
Altitude of land surface in feet above sea level	250 (227)	870 (16)	200 (25)	40 (75)

[1]Reported yield divided by the length of saturated open hole.

[2]Reported yield divided by the drawdown (pumped water level minus static water level) in the well during pumping.

Table 13. Median yields of bedrock wells in Massachusetts with different rock types, topographic settings, and well depths

[Values are in gallons per minute. Number in parentheses is number of data values analyzed. ft, foot. --, no data available]

Well depth intervals (ft)	Crystalline rock		Carbonate rock		Sedimentary rock of Connecticut Valley		Sedimentary rock of Boston, Narragansett, and Norfolk Basins	
	Hilltops and slopes	Valleys and lowlands	Hilltops and slopes	Valley and lowlands	Hilltops and slopes	Valley and lowlands	Hilltops and slopes	Valley and lowlands
0-100	8.0 (315)	12 (110)	3.5 (4)	28 (8)	9.5 (12)	8.0 (5)	15 (47)	34 (5)
101-200	6.0 (812)	10 (208)	4.5 (4)	40 (3)	7.0 (37)	10 (20)	12 (104)	50 (10)
201-300	5.0 (464)	6.0 (100)	24 (4)	12 (1)	4.3 (24)	25 (15)	10 (21)	10 (3)
301-400	4.0 (177)	8.0 (43)	-- (0)	345 (2)	3.0 (11)	14 (6)	6.0 (10)	30 (1)
401-500	4.0 (68)	6.0 (25)	-- (0)	80 (1)	28 (1)	66 (6)	4.0 (3)	25 (1)
501-600	6.0 (33)	33 (8)	-- (0)	-- (0)	56 (2)	110 (2)	2.0 (1)	40 (1)
601-700	15 (9)	50 (10)	200 (1)	278 (2)	1.0 (1)	200 (1)	-- (0)	-- (0)
Greater than 700	11 (14)	20 (9)	215 (1)	-- (0)	-- (0)	430 (2)	-- (0)	-- (0)

Table 14. Median yields of bedrock wells in Massachusetts with different rock types, topographic settings, and overburden thicknesses

[Values are in gallons per minute. Number in parentheses is number of data values analyzed. ft, foot; --, no data available]

Thickness of overburden (ft)	Crystalline rock		Carbonate rock		Sedimentary rock in Connecticut Valley		Sedimentary rock in Boston, Narragansett, and Norfolk Basins	
	Hilltops and slopes	Valleys and lowlands	Hilltops and slopes	Valley and lowlands	Hilltops and slopes	Valley and lowlands	Hilltops and slopes	Valley and lowlands
0 - 9	6.0 (405)	6.0 (60)	7.0 (2)	10 (4)	3.5 (8)	15 (1)	11 (16)	4.0 (1)
10 - 19	6.0 (469)	9.0 (94)	102 (4)	55 (2)	7.0 (32)	4.0 (5)	14 (47)	7.0 (3)
20 - 39	5.5 (402)	8.0 (129)	5.0 (1)	40 (4)	7.0 (18)	8.0 (15)	10 (55)	30 (4)
40 - 79	6.0 (332)	10.0 (134)	-- (0)	50 (2)	4.8 (16)	12 (16)	6.0 (33)	50 (7)
80 - 159	7.0 (155)	10 (55)	4.0 (16)	278 (2)	3.0 (9)	25 (8)	10 (13)	100 (1)
Greater than 160	8.0 (20)	16 (4)	-- (0)	660 (1)	15 (1)	30 (7)	-- (0)	-- (0)

permeability. The effect of depth on well yields in the carbonate rocks and the sedimentary rocks of the Boston, Narragansett, and Norfolk Basins is unknown because of sparse data for these rock types. For each bedrock type, well yields generally were larger in valleys than on hilltops and slopes, and increasing well yields corresponded to increasing overburden thickness.

Well Use

Commercial or industrial bedrock wells had median reported yields about five times larger than those of domestic wells (table 4). The large well yields in this category are not directly related to well use but to several indirectly related factors. More than one-half of the commercial or industrial wells were in valleys or lowlands (table 9), the topographic setting that had the largest well yields. Commercial or industrial wells were deeper than domestic wells; 25 percent were deeper than 400 ft, as opposed to only 5 percent of the domestic wells (table 6). Twenty-six percent of commercial or industrial wells had diameters larger than 6 in., whereas only 1.5 percent of domestic wells had diameters larger than 6 in. The reported yields of domestic wells probably were underestimated because these wells generally were not tested to determine yields exceeding those considered adequate for household use. In contrast, commercial or industrial wells generally seem to have been located, developed, and tested in an effort to obtain as much water as possible. Domestic wells were commonly located on hilltops and slopes with good views and along roads that tended to follow ridgelines and drainage divides. As a consequence, the reported well-yield data for the domestic well-use category are biased toward the smaller yields, whereas the well-yield data for commercial or industrial wells are biased toward the larger yields.

Interaction Among Factors

For wells completed in crystalline bedrock, the relation between median yield and well depth for two topographic settings is shown in figure 14. Yields from wells in crystalline rock generally decreased with depth to 500 ft and increased substantially at greater depths. Wells in valleys and lowlands had consistently higher yields than wells on hilltops and slopes. The data for wells in crystalline rock (fig. 14) were sorted further to show the effect of well use in two topographic settings (figs. 15 and 16). Increasing yield of commercial or industrial wells with increasing well depth as much as 500 ft is significant in both topographic settings. The yields of domestic wells, however, consistently decreased through this depth interval. As discussed previously, this trend may be due to the underdevelopment, testing, and reporting of domestic well yields.

The yields of wells drilled in the sedimentary rocks of the Connecticut Valley seem to increase substantially with depth when well depths exceeded 400 ft (fig. 17). This increased yield indicates some hydrologic change with depth. Sediments may be coarser, (or) better sorted, and (or) more loosely cemented at depth, resulting in an increase in primary permeability with depth.

Data for the sedimentary rock of the Boston, Narragansett, and Norfolk Basins (fig. 18) indicate that well yield decreases consistently with increasing well depth. Because of a lack of data, this relation was not well established, especially for depths greater than 300 ft. Insufficient data for wells in carbonate bedrock prevented the display of any multiple relations other than those already shown in this report.

Other factors that affect well yields, such as well diameter and overburden thickness, also may affect the median yields shown in figures 14 through 18. For example, for a given well depth and topographic setting in figure 14, a 6-inch well may have a median yield less than that shown, and an 8-inch or larger diameter well may have a median yield larger than that shown.

Well-Yield Testing

Adequate and useful analysis and quantification of the significant factors affecting bedrock well yields requires well-yield data that are meaningful and comparable. Ideally, such data should be obtained by use of standardized well-testing methods. Areal evaluation and management of water resources requires well-test data from which the horizontal and vertical distribution of hydraulic properties of bedrock aquifers can be determined. Test data can be used by local health officials, lending institutions, and homeowners to verify that a well will yield water at a rate that is adequate for its intended use and, combined with information from a complete and accurate driller's log, can be valuable in the diagnosis of the cause of quality or yield problems that may develop in a well.

Testing Methods

At present, the reported yields of bedrock wells drilled for private supplies are determined by various methods, some of which do not provide the data needed to determine aquifer hydraulic properties. This problem is most prevalent for wells drilled for domestic supplies. Reported yields determined by different methods are only relatively comparable. Bedrock wells drilled for public supply (Massachusetts Department of Environmental Protection, Division of Water Supply, 1991) and most industrial supplies are tested by use of methods that generate data from which the horizontal hydraulic properties of the bedrock aquifer at the well site can be determined. In this section, some methods that are or could be used to test private bedrock wells are described and compared. A meaningful evaluation of the results from any of the testing methods requires information about the well-construction geometry and the depth and relative yield of water-producing zones in a well. Detailed description of the analytical methods used to determine hydraulic properties is beyond the scope of this report; additional information about these methods is provided in the references listed at the end of this report.

Air Injection

Air injection is used by most well drillers in the Massachusetts to determine potential well yields and is sometimes referred to as "blow testing" or a "blow test." This test is usually done shortly after the completion of drilling and is used to determine the short-term maximum yield of the well. Yield measured during this test is used by drillers to specify the pump capacity to be installed in the well and is usually reported as the well yield on State and local well-completion reports.

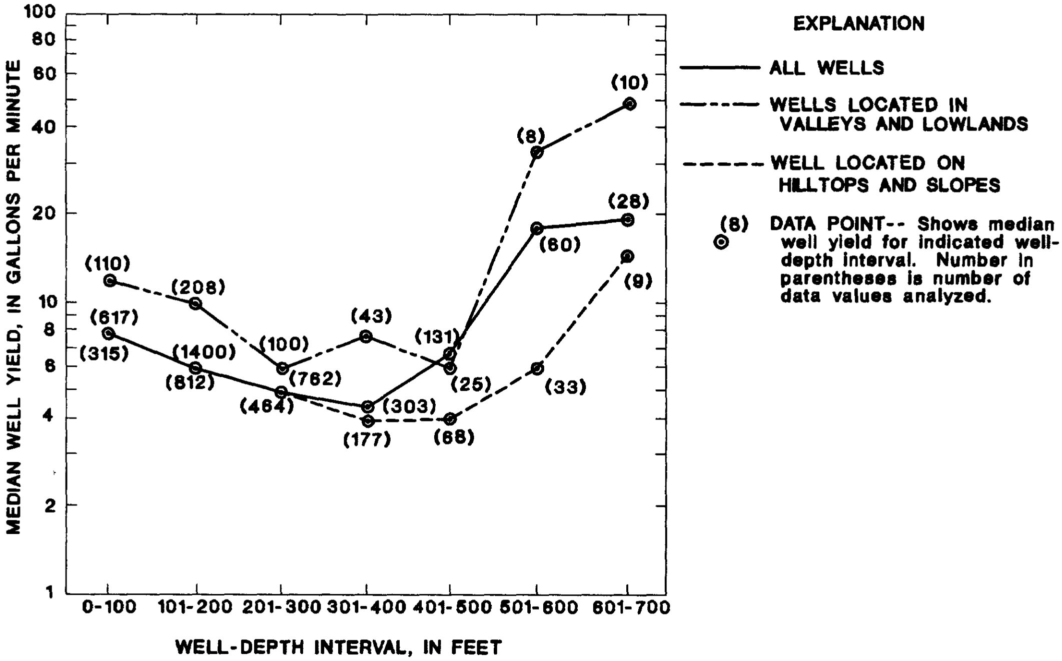


Figure 14. Relation between median yields and depths for wells in Massachusetts completed in crystalline bedrock, by topographic setting.

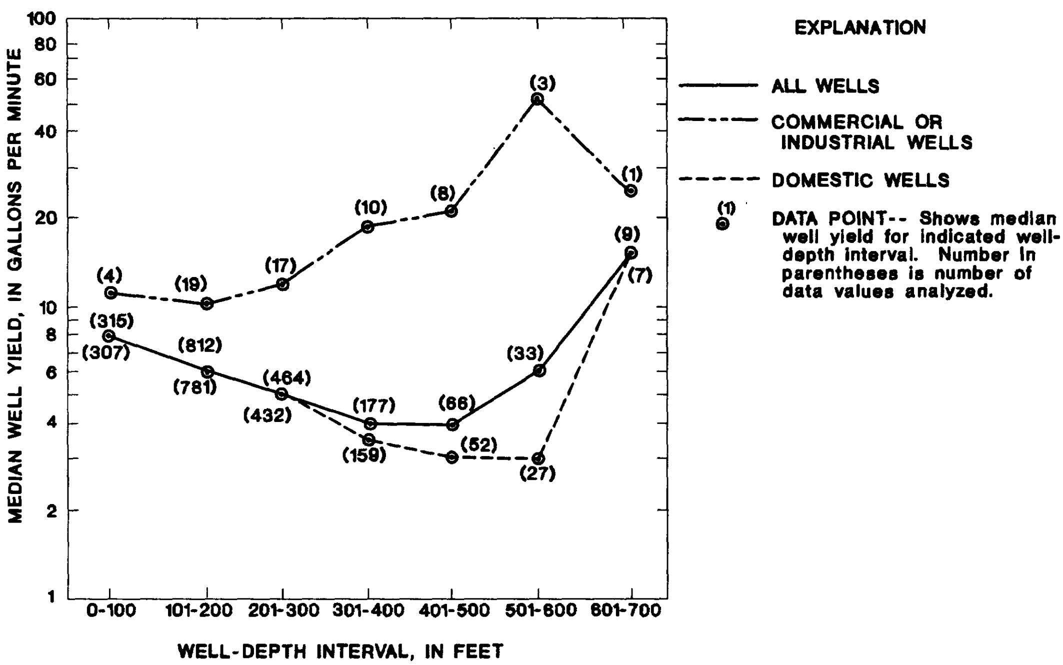


Figure 15. Relation between median yields and depths for wells in Massachusetts completed in crystalline bedrock on hilltops and slopes, by well use category.

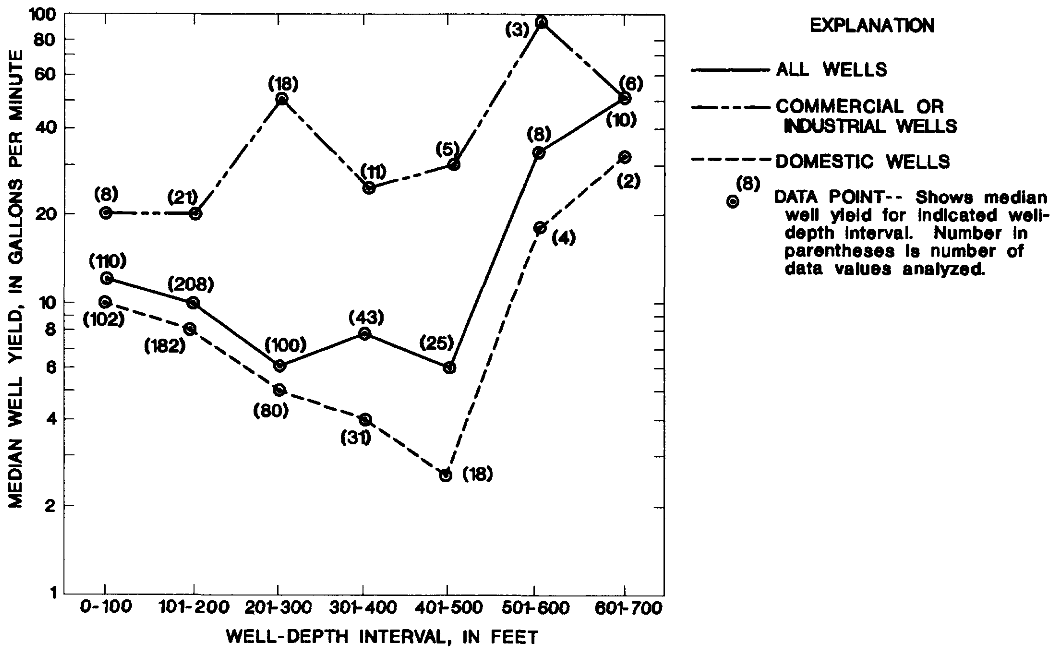


Figure 16. Relation between median yields and depths for wells in Massachusetts completed in crystalline bedrock in valleys and lowlands, by well use category.

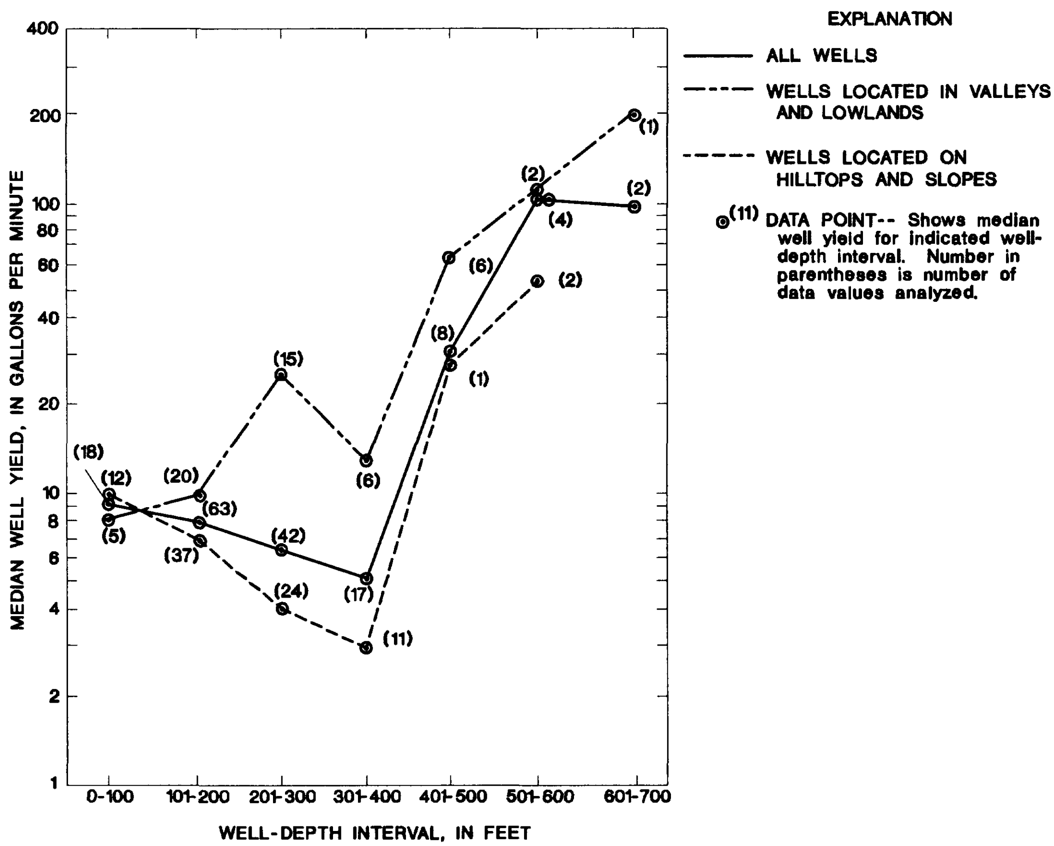


Figure 17. Relation between median yields and depths for wells in Massachusetts completed in sedimentary rock of the Connecticut Valley, by topographic setting.

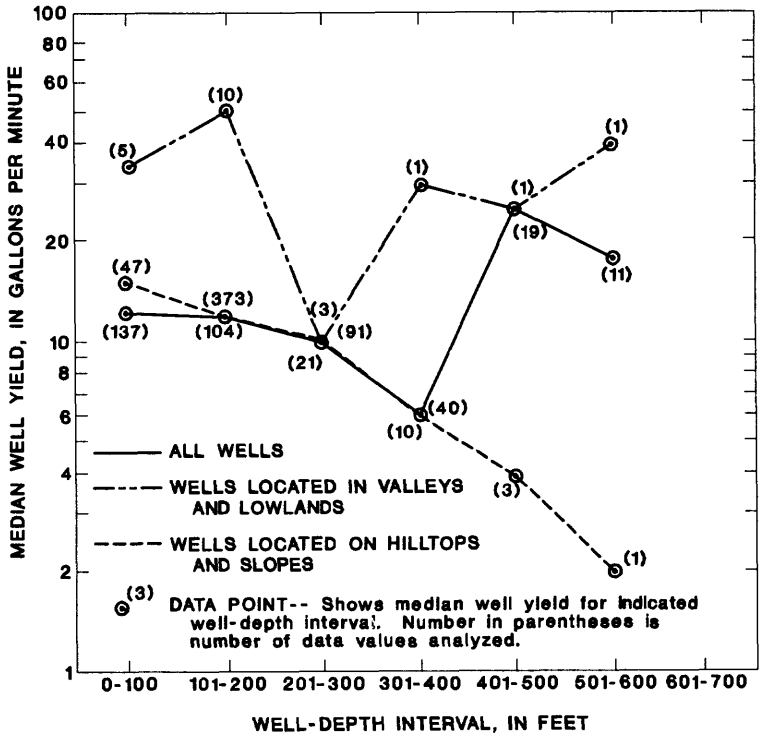


Figure 18. Relation between median yields and depths for wells in Massachusetts completed in sedimentary rock of the Boston, Narragansett, and Norfolk Basins, by topographic setting.

the well are unknown, and (3) water-yielding fractures may be free-flowing because the pumped water level in the borehole is below the depth of some or all of the water-yielding fractures.

Evacuation and Recovery

As with air injection, an evacuation and recovery test of a well is done after drilling, cleaning, and development are completed but before the drill pipe is removed from the well. Usually, the water level in the well is allowed to return to a static level before the test is started. Compressed air is injected through the drill pipe into the bottom of the well (fig. 19) in sufficient pressure and quantity to blow all the water out of the well. Infrequently, a pump is used to evacuate the well. As soon as all the water has been evacuated, the flow of compressed air or the pump is stopped, and removal of the drill pipe or pump from the well begins.

At the start of the test, the bottom of the drill pipe (drill stem or drill rod) is positioned at or near the bottom of the well (fig. 19), and compressed air is injected through the drill pipe into the bottom of the well at a rate that blows out all the water stored in the well bore. After the initial well-bore storage is removed, the rate of air injection is adjusted to produce maximum water discharge from the well. The duration of this test varies considerably, but usually lasts 1 to 4 hours.

The reported yield based on this type of well-yield test is an estimate of the short-term maximum yield, which may not be accurate. Depending on the location of the water-yielding zones in the well, water may be forced back into the aquifer rather than discharged at the surface. The reported yield may not be accurate depending on the methods used to measure or estimate the flow rate. If the test immediately follows a period of blowing to drill, clean, or develop the well and the water level has not returned to a static level, then the short-term well yield may be underestimated. Hydraulic properties cannot be determined by this type of test because (1) the static water level in the well and adjacent formation are unknown, (2) the depths of water-yielding fractures in

The water level in the well is measured at some time after evacuation or at increments of time until the water level has partly or fully returned to the static level. Using the well-bore volume and the depth of the column of water recovered, the driller calculates the rate of water entering the well over some time interval after evacuation. The driller also might report the amount of water entering the well at some percentage of total recovery or the total time required for recovery. Recovery rates are affected by well depth and depth and hydraulic characteristics of the water-yielding fractures. Recovery rates will be most rapid initially and will decrease as the water level recovers to the static level. Recovery rates will be relatively constant until the water-yielding fracture(s) become submerged by the ascending column of water in the well bore. As the water level rises above the water-yielding fracture, increasing hydrostatic pressure causes the yield of the fracture(s) to decrease. The analysis of evacuation and recovery tests can be complicated if several fractures are at times above and below the water level in the well during recovery. In some wells, the rate of water-level recovery is faster than the rate at which the drill pipe can

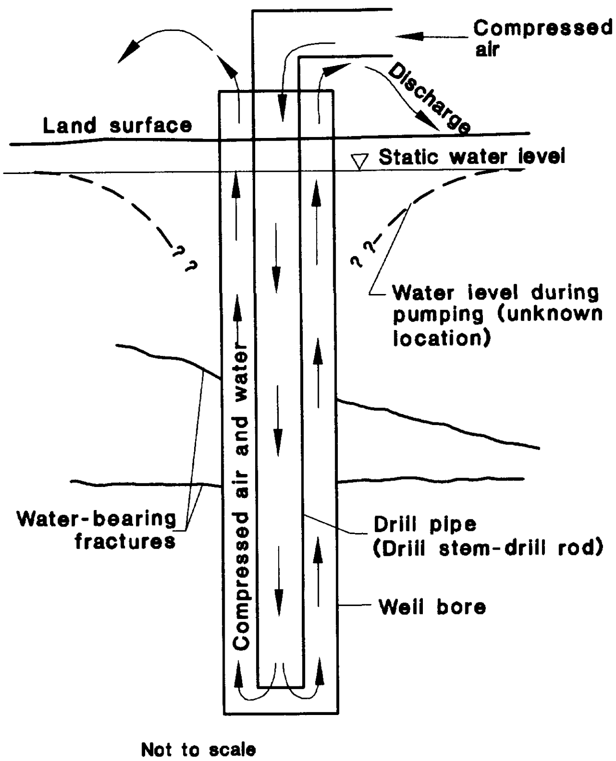


Figure 19. Basic features of pumping a well by use of air injection.

be removed from the well, and displacement of water by the drill stem will affect the measured rate of recovery.

Recovery measurements are sometimes made after a period of blowing with compressed air to clean and develop the well. Under these conditions, the water-level-recovery rate will be affected by the preceding withdrawal. Hydraulic characteristics cannot be determined from this type of test for the same reasons as listed for pumping with compressed air in the preceding section. At best, this method will only determine a well's short-term water- yielding potential relative to other wells tested with the same procedure and duration.

Constant Discharge and Recovery

A constant-discharge test of a bedrock well usually is done by use of a submersible or jet pump to withdraw water from the well at a constant rate (fig. 8). The pumping period usually is 2 to 5 hours. Some local boards of health require a 3-hour test for domestic wells. The water level in the well being tested is measured and recorded before pumping begins (static level) and at increments of time after pumping begins. A log showing the water level and time since pumping began during a constant-discharge test of a domestic bedrock well is shown in figure 20. The pumping rate should be consistent with the water-yielding characteristics of the well and should stress the well without exceeding its capacity to yield water. If possible, the pumping rate should be set to minimize the possibility of dewatering any of the water-yielding fractures in the well. If the pumping rate is too high, a large percentage of the pumped water will come from wellbore storage, and the resulting water levels in the well will not be indicative of the water-yielding characteristics of the bedrock aquifer adjacent to the well. Data collected during a properly done constant-discharge test can be used to determine the average hydraulic properties of the section of the aquifer penetrated by the well. Figure 21 shows an analysis of the test data in figure 20. Data from a constant-discharge test, combined with information from a drilling log indicating depth and relative yield of water-yielding fractures in a well, can be used to compute an approximation of the vertical distribution of hydraulic properties in the section of the aquifer penetrated by the well and to estimate the potential yield of the well. Often, the pumping rate during these tests is equal to the capacity of the permanently installed pump. The results of such tests are reliable indications of well performance during actual operating conditions.

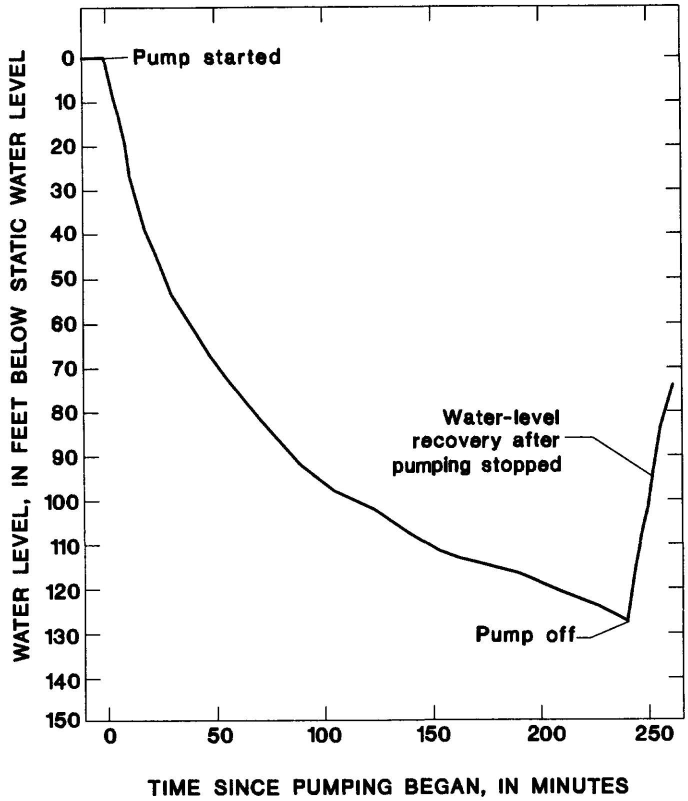
Measurements of water levels in a well after pumping has ended (recovery) also can be used to determine the average hydraulic properties of the section of bedrock aquifer adjacent to the well, and are valuable in verifying the aquifer properties determined from drawdown data. Recovery water-level data are not affected by changes in pump discharge that may have occurred during pumping, and thus, can be more reliable then drawdown data. Recovery water-level data also can indicate the presence of water-yielding fractures that were dewatered during pumping.

Instantaneous Discharge or Recharge

In the instantaneous discharge or recharge method, referred to in this report as, a "slug test," the static water level in a well is changed instantaneously either by the sudden introduction or removal of a known volume of water or by the introduction or removal of a solid cylinder of known volume. Recovery of the water level is then measured at very small time increments until

CONSTANT-DISCHARGE TEST DATA
Haverhill Well No. 103

Date -------------------------------- 8/23/89
Length of open hole ------------- 645 feet
Rate of Discharge ---------------- 5 gallons per minute
Radius of well --------------------- 0.25 foot



Response of water level in well to a discharge rate of 5 gallons per minute for 4 hours

Entry	Time since start of pumping (minutes)	Drawdown in well (feet)
0	0	0.0
1	5	8.4
2	10	20.14
3	15	30.54
4	20	38.34
5	25	45.04
6	30	50.84
7	35	55.74
8	40	59.94
9	45	64.34
10	50	67.34
11	55	70.98
12	60	74.20
13	70	81.05
14	80	86.71
15	90	91.20

Entry	Time since start of pumping (minutes)	Drawdown in well (feet)
16	100	96.29
17	110	98.48
18	120	101.98
19	130	104.32
20	140	107.29
21	150	110.68
22	160	113.34
23	170	115.41
24	180	117.32
25	190	118.22
26	200	119.69
27	210	121.81
28	220	124.14
29	230	124.86
30	240	127.63

Figure 20. Constant-discharge test data and graph showing response of water level in well to withdrawal of water.

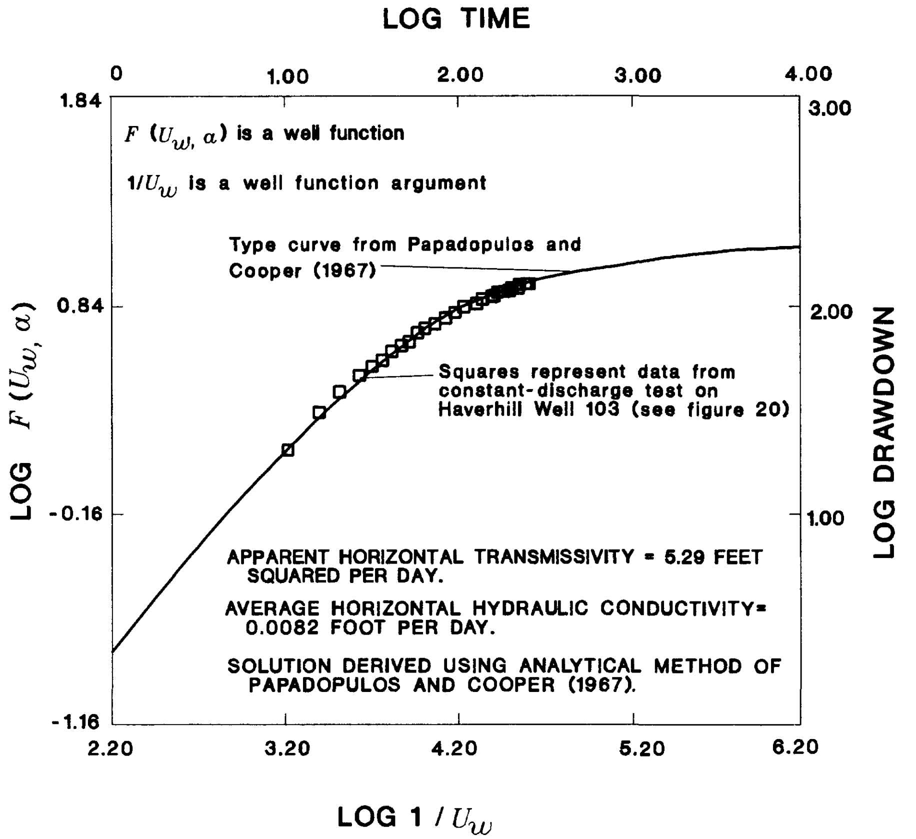


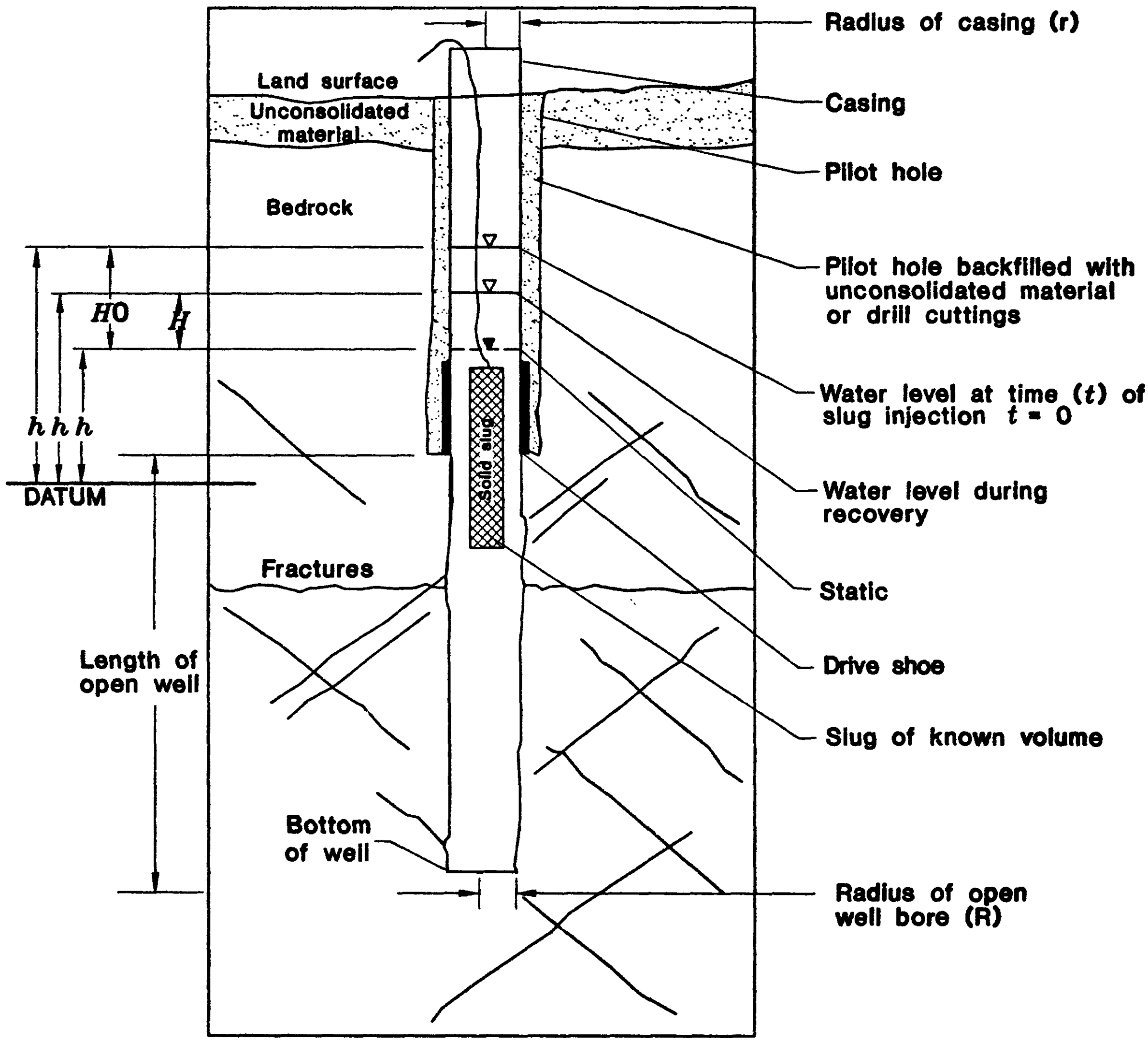
Figure 21. Water-level data recorded during a constant-discharge test superposed on a type curve used for analysis of hydraulic properties.

water-level recovery is complete. The basic features of a slug test are shown in figure 22. The recovery of the water level to its previous level is a function of the hydraulic properties of the water-yielding fractures intersected by the well and the geometry of the well. Data from a slug test can be used to determine the average hydraulic properties of the section of the aquifer intersected by a well. Data from a slug test and a match with a type curve (Cooper and others, 1967; Papadopulos and others, 1973) to determine hydraulic properties are shown in figures 23 and 24. Hydraulic properties derived from slug tests are considered accurate to about one order of magnitude, as is the case with the slug test on Haverhill Well No. 103, and should be considered only as estimates (Lohman, 1972). If any fractures are clogged, measured values could be inaccurate (Freeze and Cherry, 1979). Slug tests on some bedrock wells in Massachusetts in which slug volume was 0.4 ft^3 had recovery times that ranged from less than 1 minute to several hours. The use of a water-level measuring device that can record water levels at small time increments (0.5 second) is usually required for this type of test.

No indication of well performance during actual pumping is obtained from this testing method. The results from slug tests in bedrock wells, however, can be used to estimate the rate at which the well could be pumped if the vertical distribution of hydraulic properties in the section of the aquifer penetrated by the well is known. The vertical distribution of hydraulic properties can be estimated if the driller records the depth and relative increase in discharge from each water-yielding zone penetrated during drilling.

Comparison of Testing Methods

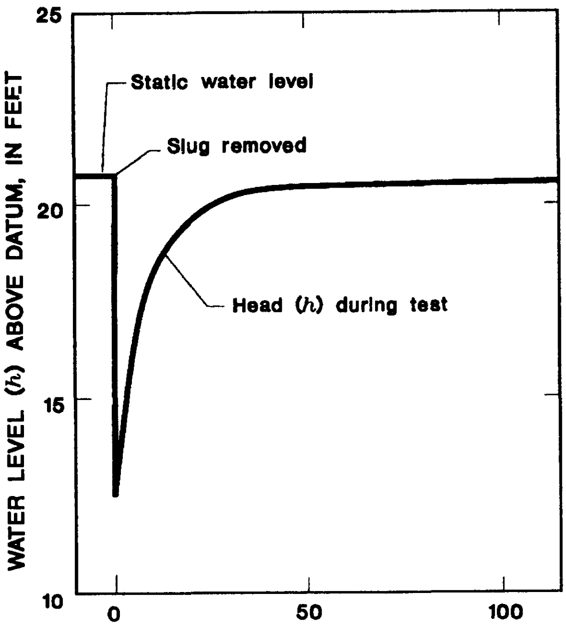
Testing methods used for domestic and other private bedrock wells should ideally produce results that are meaningful and useful to drillers, plumbers, owners,



EXPLANATION

t	TIME SINCE START OF TEST, IN MINUTES
h	WATER LEVELS IN WELL ABOVE OR BELOW DATUM, IN FEET
Static	WATER LEVEL IN WELL ABOVE OR BELOW DATUM JUST BEFORE START OF TEST (*t* LESS THAN 0), IN FEET
H	DIFFERENCE BETWEEN STATIC AND *h* IN WELL DURING TEST (*t* EQUAL TO OR GREATER THAN 0), IN FEET
*H*O	DIFFERENCE BETWEEN STATIC AND *h* IN WELL AT START OF TEST (*t* EQUAL TO 0), IN FEET

Figure 22. Basic features of a slub test in a bedrock well.



Response of water level in well to sudden withdrawal of a solid slug

EXPLANATION

t	TIME SINCE START OF TEST, IN MINUTES
h	WATER LEVELS IN WELL ABOVE OR BELOW DATUM, IN FEET
Static	WATER LEVEL IN WELL ABOVE OR BELOW DATUM JUST BEFORE START OF TEST (t LESS THAN 0), IN FEET
H	DIFFERENCE BETWEEN STATIC AND h IN WELL DURING TEST (t EQUAL TO OR GREATER THAN 0), IN FEET
H0	DIFFERENCE BETWEEN STATIC AND h IN WELL AT START OF TEST (t EQUAL TO 0), IN FEET
H/H0	H DIVIDED BY H0

Entry	t (minutes)	Head (feet)	H (feet)	H/H0
1	0.250	20.78 (Static)		
2	.000	12.50	8.28 (H0)	1.000
3	.083	12.75	8.03	.970
4	.183	12.83	7.95	.960
5	.250	12.84	7.94	.959
6	.417	12.94	7.84	.947
7	.583	13.09	7.69	.929
8	.750	13.21	7.57	.914
9	.917	13.32	7.46	.901
10	1.000	13.38	7.40	.894
11	2.000	14.04	6.74	.814
12	5.000	15.93	4.85	.586
13	10.000	18.25	2.53	.306
14	15.000	19.04	1.74	.210
15	25.000	20.20	.58	.070
16	30.000	20.34	.44	.053
17	53.000	20.54	.24	.029
18	67.000	20.58	.20	.024
19	85.000	20.61	.17	.021
20	102.000	20.63	.15	.018
21	115.000	20.64	.14	.017

SLUG-TEST DATA
Haverhill Well 103

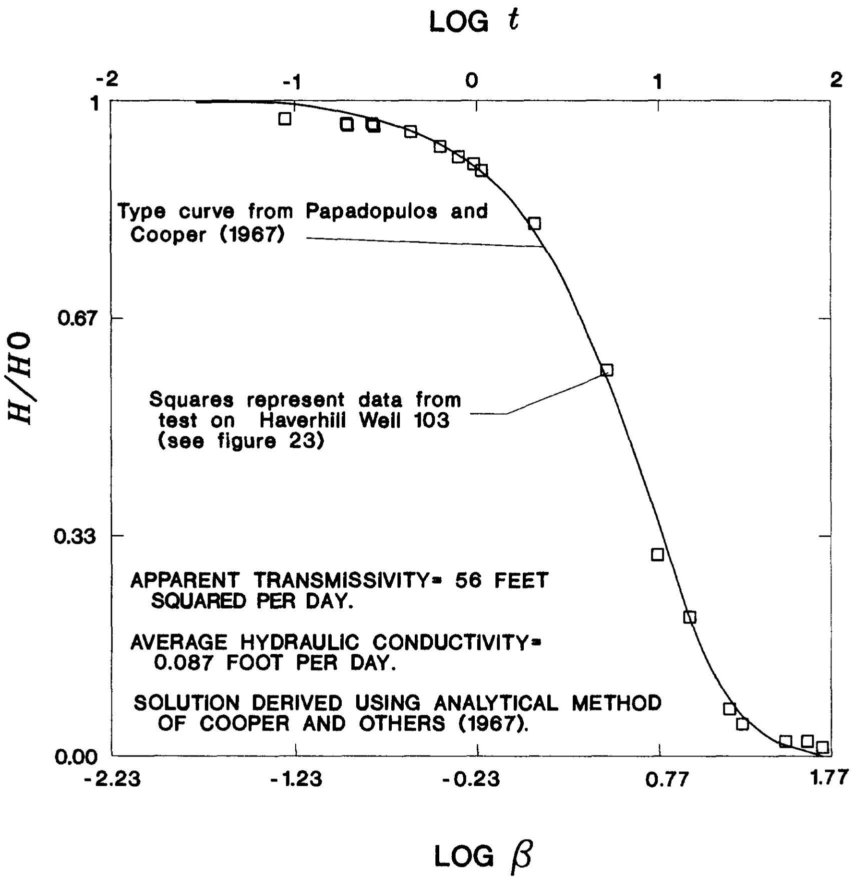
Date of test 07/18/89

Length of open well .... 645 feet

Change in water volume
(volume of slug) .... 3.447 cubic feet

Radius of well in
which water levels
are measured .... 0.257 feet

Figure 23. Slug-test data and graph of water levels in bedrock well showing response to sudden withdrawal of a solid slug.



EXPLANATION

t	TIME SINCE START OF TEST, IN MINUTES
h	WATER LEVELS IN WELL ABOVE OR BELOW DATUM, IN FEET
Static	WATER LEVEL IN WELL ABOVE OR BELOW DATUM JUST BEFORE START OF TEST (t LESS THAN 0), IN FEET
H	DIFFERENCE BETWEEN STATIC AND h IN WELL DURING TEST (t EQUAL TO OR GREATER THAN 0), IN FEET
HO	DIFFERENCE BETWEEN STATIC AND h IN WELL AT START OF TEST (t EQUAL TO 0), IN FEET
H/HO	H DIVIDED BY HO
β	TYPE CURVE VALUE FROM COOPER AND OTHERS (1967)

Figure 24. Water-level data recorded during slug test superposed on type curve used for analysis of hydraulic properties.

health and water-resources officials, and hydrologists. The results of a well test should (1) allow the determination of the discharge rate of the pump to be installed in the well, (2) document well performance at a pumping rate similar to actual operating conditions, (3) indicate de-watering of major water-yielding fractures as a result of pumping, and (4) allow the determination of the average hydraulic properties of the section of the formation penetrated by the well. In addition, the testing procedure should be easy to understand and require minimal and easily operated equipment and instrumentation. On the basis of these criteria, the relative merits of the four testing methods described in this report are summarized in table 15.

Of the four testing methods, a short-duration blow test followed by a constant-discharge test best satisfied the above criteria. The results of the blow test can be used to determine the optimum size pump to be installed in the well. During the constant-discharge test, the performance of a well at a pumping rate similar to actual operating conditions is documented. Water levels measured at increments of time during the constant-discharge test can be used to determine the average hydraulic properties of that section of the bedrock aquifer tapped by the well and can indicate the presence of significant fracture dewatering. An indication of fracture dewatering and hydraulic properties also can be obtained from water-level recovery measurements made at the conclusion of the pumping period.

The air-injection method gives a good indication of the maximum short-term yield of a well when all of the water-yielding fractures have been

Table 15. Relative rating and summary of well-testing methods for domestic bedrock wells

[Hydraulic conductivity of aquifer adjacent to well bore. Relative cost of doing the test and recording the data; no data analysis costs included]

Test method	Relative effective rating			Summary		
	Well performance characteristics	Hydraulic conductivity	Cost	Equipment needed	Advantages	Disadvantages
Air injection (blow test)	Medium	Very low	Medium[1] to low	Drilling rig	No additional equipment needed; good for estimating pump size; estimate of maximum short-term well yield.	May not maximize yield; water-yielding zones dewatered; reported discharge may not be accurate. No indication of water level during pumping.
Evacuation and recovery	Medium[2] to high	Low to medium	Medium	Drilling rig or pump and water-level measuring device	Easy to do; usually no additional equipment needed; water-level recovery usually complete before driller leaves well site. Can determine approximate maximum short-term well yields.	Well yield may actually be larger than yield determined; water-yielding zones dewatered; water-level recovery may take several days; no standard procedure for conducting test.
Constant-discharge	High	High	Medium[3] to high	Pump and water-level measuring device	Reliable record of well performance at selected pumping rate; hydraulic properties of aquifer can be determined.	Pump may have to be installed and removed; well-storage effects and yielding zones dewatered if pumping rate is too high.
Instantaneous discharge or recharge (slug test)	Low	High	Low	Displacement device (slug), and water-level recorder	Fast and easy; hydraulic properties of aquifer can be determined.	No indication of well performance during pumping without additional data and analysis.

[1]Assumes that the test is conducted for 1 hour. If the duration of the test is shorter, the relative cost is lower.
[2]Relative evaluation of well performance is high if the depth and relative capacity of water-yielding zones in the well are known.
[3]Medium cost if permanently installed pump is used for test; high cost if pump has to be installed and removed.

dewatered; however, yield may be underestimated if water is forced back into the formation by the compressed air. The well yield measured during this test can give an indication of the capacity of the pump necessary for the well. Well performance during actual pumping and hydraulic properties of the section of the aquifer penetrated cannot be determined by this method.

The evacuation and recovery test can provide a reliable indication of well yield under certain conditions. However, at present there is no standard procedure for collection of data or reporting of results from this test. As a result, the reported results from different drillers may or may not be comparable. Even if the collection and reporting of results were uniform, the diversity of hydraulic conditions and well-construction geometry among bedrock wells could result in divergent test results.

Slug tests are being used by some hydrologists and engineers to estimate the average hydraulic properties of the section of a bedrock aquifer intersected by a well. With the information collected during a slug test, it is necessary to know the depth and relative hydraulic properties of the water-yielding fractures intercepted by the well in order to determine or estimate well performance during pumping. Water levels collected during slug tests must be measured and recorded by electronic and other fairly complex instrumentation.

The analysis and interpretation of the results from any of the testing methods discussed requires information about well-construction geometry and the depth of water-yielding zones in the well. Additional information about the depth and relative water-yielding capacity of each water-yielding zone is necessary in order to ensure a more complete interpretation of the results of any of the test methods.

SUGGESTIONS FOR ADDITIONAL DATA COLLECTION AND EVALUATION

Important to any detailed investigation and evaluation of the hydrogeology of bedrock aquifers is accurate and standardized reporting of well data, and storage of these data so that they are easily retrieved, manipulated, and displayed. Ideally these well data would include the following:

1. location of the bedrock well to within 100 ft of its actual site,
2. well-construction geometry,
3. lithologic and driller's logs that include the depth and relative increase in yield of water-yielding zones, and
4. data from standardized well-yield tests.

These data needs are consistent with recommendations made by a study of private well contamination in Massachusetts prepared for the Commonwealth of Massachusetts Special Legislative Commission on Water Supply (Weintraub, 1988) and in a U.S. Geological Survey planning document for the regional study of the hydrology of bedrock of New England (Lapham, 1990). Detailed hydrogeologic evaluations to determine the hydrologic properties, delineate high-yield zones, and determine the quality of the water of these bedrock areas will be crucial for future use and management.

As previously noted, the identification and characterization of the vertical distribution of water-yielding fractures or fracture zones is important to the hydrogeologic understanding of a bedrock aquifer. Sparse and mostly unverifiable information about the vertical distribution of water-yielding fractures is all that is currently (1992) available. Many drillers record the location of water-yielding zones observed during drilling, and some also record the change in the quantity of water being discharged from the well when these water-yielding zones are encountered. These changes in discharge may be related to the water-yielding properties of the corresponding fracture or fracture zone. Much information on the distribution and properties of water-bearing fractures can be obtained from drillers' well records if the observed locations and corresponding change in discharge of water-yielding zones are related to actual hydraulic conditions in the bedrock penetrated by the well. However, these records are seldom available for use. A determination of the relation between the observed information from driller's well logs and the actual hydraulic conditions in the bedrock adjacent to the well would be useful.

Statistical analysis of bedrock-well data indicates that increased well diameter is related to large increases in well yield. The increase in yield is much larger than would be expected on the basis of theoretical calculations. The relation between well yield and well diameter is important for the development of meaningful guidelines for constructing bedrock wells. An evaluation of the effect of increasing well diameter on well yield and a characterization and description of the physical and hydraulic changes in the well when the well diameter increases is needed.

The problem of ground-water contamination in bedrock is of increasing concern. One of the first steps that is required at any site to address this concern is a determination of the uncontaminated, background water quality in bedrock and its relation to rock chemistry, depth of occurrence, and land use. Only limited appraisals of these characteristics and relations are available. Areal appraisals are needed to characterize the quality of water in bedrock and its relation to bedrock chemistry, depth of occurrence, and land use.

SUMMARY

With the exception of extreme southeastern Massachusetts, including Cape Cod and the islands of Martha's Vineyard and Nantucket, most domestic, and many other private water supplies are obtained from bedrock. Crystalline, sedimentary, and carbonate bedrock underlies the State. With the possible exception of the sedimentary rocks of the Connecticut Valley, most of the usable water in bedrock is found in and flows through fractures. The principal source of water in bedrock is recharge from precipitation.

The factors that affect the yield of bedrock wells were determined by the statistical analysis of reported data from 4,218 wells. The well data were classified according to bedrock type, depth, diameter, topographic setting, thickness of overburden, well use, and year of construction.

The median reported yield of all bedrock wells was 7 gal/min, and the median depth was 170 ft. The median reported yield of about 20 gal/min for 1920-40 decreased to 6 gal/min for 1970-80. Well depths increased from 128 ft for 1950-60 to 250 ft for 1980-90. The period 1950-60, during which well depths began to increase, coincides with a change in well-drilling methods from cable tool to air rotary with percussion, which is the predominant drilling method currently (1992) used.

Bedrock well yields decreased as well depth increased to 400 ft and increased slightly at well depths greater than 600 ft. Median well yields increased from 6 gal/min in the 400- to 500-foot depth interval to 20 gal/min in the 600- to 700-foot depth interval. The increase in well yields for wells deeper than 600 ft is difficult to assess because little reported information exists about the depth of water-yielding zones in the wells. Well yields and well depths increased substantially with increasing well diameter. Median well yield and depth for 6-inch-diameter wells was 7.0 gal/min and 164 ft, respectively; these median values increased to 36 gal/min and 299 ft for 8-inch-diameter wells.

Median yields, casing depths, and depths to bedrock were largest for wells located in valleys and lowlands. The median well yield was 10 gal/min in valleys and lowlands, and 6.0 gal/min on hilltops and slopes. In valleys and lowlands, substantial increases in well yields corresponded to increasing thickness of overburden, but on hilltops and slopes only small increases in yield corresponded to increases in overburden thickness. This difference indicates that some hydrogeologic factor(s) other than overburden thickness, which coincides with the deepest parts of the valleys, cause large well yields in those locations.

Carbonate bedrock (with a median well yield of 25 gal/min) seemed to be the most productive bedrock type, followed by sedimentary rocks of the Boston, Narragansett, and Norfolk Basins (12.0 gal/min), sedimentary rocks of the Connecticut Valley (8.0 gal/min), and crystalline rock (6.0 gal/min). A reported yield of 1,700 gal/min from an industrial well completed in carbonate rock is the largest reported bedrock-well yield in Massachusetts. Yields from wells in sedimentary rocks of the Connecticut Valley seemed to increase substantially at depths greater than 400 ft, indicating that this bedrock type may have some primary permeability. Primary permeability may increase at depth because the sediment in the bedrock is coarser, (or) better sorted, and (or) less cemented at greater depths. The scarcity of data for wells in carbonate bedrock and for deep wells in the sedimentary bedrock of the Boston, Narragansett, and Norfolk Basins hinder the analysis of the factors affecting well yield in these rock types.

Commercial or industrial wells had a median yield of 30 gal/min--a yield five times larger than that of domestic wells. More than 50 percent of commercial or industrial wells are in valleys or lowlands, 25 percent are deeper than 400 ft, and 26 percent have a median diameter larger than 6 in. Commercial or industrial wells tend to be sited, constructed, and tested in an effort to obtain as much water as possible; domestic wells are sited mainly on the basis of cultural and aesthetic considerations.

The common assumption that fractured crystalline rocks generally yield only small quantities of water to wells may be in error. Statistical analysis shows that wells in valley and lowlands, deeper than average, and with large diameters, yield quantities of water considerably larger than the median yield.

Another long-held concept that may be in error is that bedrock wells in crystalline rock obtain water from fractures and joints that pinch out or are closed at depths greater than 300 to 400 ft because of lithostatic pressure. Because of this belief, many people working in the water industry have suggested that wells should not be drilled deeper than 400 ft; indeed, 94 percent of all bedrock wells in Massachusetts are less than 400 ft deep. It appears, however, that the full potential of most sites has not been tested. Analysis of well data demonstrates that the median yield of wells in valleys and lowlands reached 50 gal/min at depths of 600 to 700 ft. The median yield of wells on hilltops and slopes reached 15 gal/min at depths of 600 to 700 ft. This observation is based on the assumption that the presence or lack of fractures that yield water at or near the bottom of the wells significantly affects the total well yield. However, a deep well can obtain most of its yield from fractures at shallow depths. Data that describe the location of yielding zones in bedrock wells are sparse.

Four methods of testing the yield of domestic bedrock wells were evaluated. A constant-discharge pump test best satisfied the criteria established to evaluate the testing methods. These criteria were:

1. the testing procedure had to be easy to perform and require minimal and easily operated equipment, and
2. the results had to document well performance at a pumping rate similar to that under actual operating conditions, indicate the presence of fractures that are free-flowing during pumping, and allow determination of the average hydraulic properties of the section of the bedrock tapped by the well.

The following five areas of additional data collection and evaluation are suggested to improve the systematic characterization and appraisal of the bedrock aquifers of Massachusetts:

1. Well data and storage of these data should be standardized and accurately reported so that they can be easily retrieved, manipulated, and displayed.
2. Detailed hydrogeologic evaluations are needed of the apparent high-yield fracture zones within and bordering the sedimentary rocks of the Narragansett Basin, the crystalline bedrock formations underlying valley areas, the sedimentary and diabase bedrock formations of the Connecticut Valley, and the carbonate bedrock formations of western Massachusetts.
3. The relation between the location and yield of fracture observed during well drilling and actual location and hydraulic properties of water-yielding fractures needs to be evaluated.
4. The relation of well yield to well diameter needs to be evaluated.
5. Characterization of the quality of water in bedrock and relation of the observed quality to bedrock chemistry, depth of occurrence, and land use are needed.

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