Comparison of Hydraulic Conductivities for a Sand and Gravel Aquifer in Southeastern Massachusetts, Estimated by Three Methods

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CONVERSION FACTORS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
kilometer (km)	0.6214	mile
kilopascal (kPa)	0.2961	inch of mercury at 60°F
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
milliliter (mL)	0.03382	ounce, fluid
millimeter (mm)	0.03937	inch
square centimeter (cm^2)	0.1550	square inch

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation:

°C = 5/9 (°F) -32.

Comparison of Hydraulic Conductivities for a Sand and Gravel Aquifer in Southeastern Massachusetts, Estimated by Three Methods

By Linda P. Warren, Peter E.Church, *and* Michael Turtora

Abstract

Hydraulic conductivities of a sand and gravel aquifer at four sites in southeastern Massachusetts were estimated by three methods: constant-head multiport-permeameter tests, grain-size analyses (with the Hazen approximation method), and slug tests. Sediment cores from 45 boreholes were undivided or divided into two or three vertical sections to estimate hydraulic conductivity based on permeameter tests and grain-size analyses. The cores were collected from depth intervals in the screened zone of the aquifer in each observation well. Slug tests were performed in 29 observation wells installed in the boreholes.

Hydraulic conductivities of 35 sediment cores estimated by use of permeameter tests ranged from 0.9 to 86 m/d (meters per day), with a mean of 22.8 m/d. Hydraulic conductivities of 45 sediment cores estimated by use of grain-size analyses ranged from 0.5 to 206 m/d, with a mean of 40.7 m/d. Hydraulic conductivities of aquifer material at 29 observation wells estimated by use of slug tests ranged from 0.6 to 79 m/d, with a mean of 32.9 m/d. The repeatability of estimated hydraulic conductivities was estimated to be within 30 percent for the permeameter method, 12 percent for the grain-size method, and 9.5 percent for the slug-test method.

Statistical tests determined that the medians of estimates resulting from the slug tests and grain-size analyses were not significantly different but were significantly higher than the median of estimates resulting from the permeameter tests. Because the permeameter test is the only method considered which estimates vertical hydraulic conductivity, the difference in estimates may be attributed to vertical or horizontal anisotropy. The difference in the average hydraulic conductivities estimated by use of each method was less than 55 percent when compared to the estimated hydraulic conductivity determined from an aquifer test conducted near the study area.

INTRODUCTION

Salts, such as sodium chloride, are commonly applied to roadways in the United States to reduce icing during the winter months. The dissolved salt can subsequently contaminate ground water (Church and Friesz, 1993). Estimates of hydraulic conductivity are needed to quantify the movement of salt ions through the sand and gravel aquifer near State Route 25 in southeastern Massachusetts so that the effects of road-salt application on the water quality of the aquifer—a source of public water supply—can be evaluated. Hydraulic conductivity can be estimated by several available methods; however, each method may not necessarily yield the same result and may vary in applicability, depending on aquifer materials (Driscoll, 1986).

This report presents a comparison of hydraulic conductivities of a sand and gravel aquifer that were estimated by two laboratory methods (constant-head multiport-permeameter tests and grain-size analyses with the Hazen approximation) and one field method (slug tests). A detailed description of each method is provided and advantages and disadvantages of each method are discussed.

The State Route 25 research site includes four test sites, each representing a different highway-drainage design, along a 5-km section of a six-lane highway constructed in a forested area in Wareham and Plymouth, Massachusetts (fig. 1). The four test sites are designated A, B, C, and D in order of increasing highway-runoff control. The four test sites contain 52 sampling sites consisting of boreholes that penetrate the unconfined sand and gravel aquifer. After collection of sediment cores, observation wells were installed in the boreholes.

Sediment cores collected from 45 of the sampling sites were analyzed in the laboratory using multiport-permeameter tests and grain-size analyses with the Hazen (1893) approximation. Slug tests were conducted in the observation wells. These three estimation methods were selected because each had been previously used in sandy materials and were relatively inexpensive (Hazen, 1893; Freeze and Cherry, 1979; Widdowson and others, 1990).

The deposits in the area are primarily Pleistocene stratified drift. Most of the observation wells are screened in the upper unit, which consists of fine to coarse sand with gravel. The few deep wells are screened in the underlying unit of fine to coarse sand with silt. Aquifer sediments typically range from 10 to 10^{-3} mm in diameter, although boulders are present sporadically at and below land surface in the unsaturated zone. Grain-size distributions differ little within vertical sampling intervals of about 1.5 m but differ among sampling intervals from predominantly fine to coarse sand with silt to predominantly fine to coarse sand with gravel. Visual inspection of sediment cores, generally 0.45 m in length, showed no evidence of stratification within the 1.5-m sampling intervals. The water table generally is planar, fluctuates less than 1 m throughout the year, and is about 9 to 12 m below land surface (Church and Friesz, 1993). In this report, depths below the water table are referenced to the highest recorded water-table level. Average yearly aquifer water temperature is about 10°C.

The authors thank Professor Lewis Edgers at the Department of Civil and Environmental Engineering, Tufts University, Medford, Massachusetts, for his assistance and advice on permeameter tests.

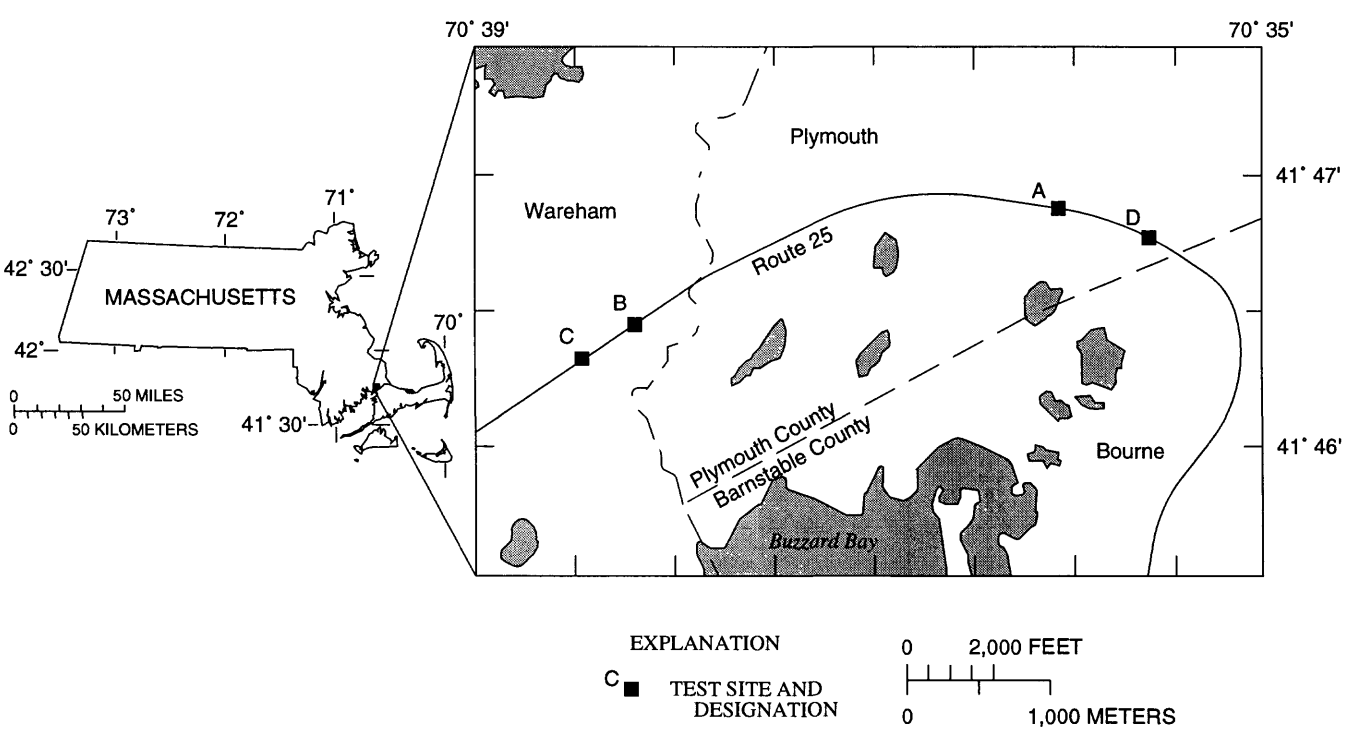

Figure 1. Locations of test sites A, B, C, and D along State Route 25, southeastern Massachusetts.

HYDRAULIC CONDUCTIVITIES ESTIMATED BY THREE METHODS

Hydraulic conductivities estimated by each of the three methods were assumed to be comparable because each method tested aquifer material from the same location in the aquifer. Samples of aquifer material were collected in transparent acrylic core liners held in a split-spoon sampler 0.6 m in length and with a 5-centimeter inside diameter. Midpoints of collected sediment cores were from depths of about 0.75, 2.25, 3.75, 5.25, 6.75, and about 20 m below the water table. Most cores retained sediment samples about 0.45 m in length (about 75 percent recovery). Core recovery was almost 100 percent for eight cores yielding sediment samples that were about 0.6 m in length. Core recovery was about 50 percent for three cores yielding sediment samples about 0.3 m in length. Sediment samples in cores were somewhat disturbed and compacted as they were forced into the core liners. Both ends of the cores were capped with plastic tops and stored upright for about 1 year before permeameter tests were conducted. During this time, pore water evaporated from most of the cores. Complete evaporation of pore water facilitated resaturation during preparation of the sediment cores for permeameter testing.

After cores were collected, a well casing with one screen 1.5 m in length was placed in each borehole. The position of the midpoint of the screened interval corresponded to the position of the midpoint of the sediment core. The wells screened at the water table contained a 3.0-m-long screen, the midpoint of which was at the estimated maximum water-table level for the site. The lower one-half of the 3.0-m-long screens was located in the interval from which the sediment cores were collected. The boreholes where wells were installed were labeled by site name (A, B, C, D), well-cluster number (1, 2, 3, 4, 5) and depth sequence, in 1.5-m intervals below the water table (01, 02, 03, 04, 05, 20, where 01 represents the well screened closest to the water table and 20 represents the well screened deepest in the aquifer). For example, site A204 is located at site A in cluster number 2 and contains a well screened with a midpoint at about 5.25 m below the water table. Each well cluster at a test site normally contained six wells, each of which was screened at a different depth.

Each method was assumed to yield estimates of horizontal hydraulic conductivity for the aquifer tested. Horizontal hydraulic conductivity is of primary interest because horizontal flow predominates in the aquifer, as demonstrated by the essentially horizontal movement of the salt plume (Church and Friesz, 1993). This report includes the use of the constant-head permeameter method that results in an estimate of vertical hydraulic conductivity. Because vertical or horizontal anisotropy may be small in the study area (Hess and others, 1992), results of tests that yield horizontal hydraulic conductivity may nonetheless be compared to results of tests that yield vertical hydraulic conductivity. Small differences in results may be attributed in part to anisotropy.

Permeameter Test

The vertical hydraulic conductivities estimated by permeameter tests are assumed to represent horizontal hydraulic conductivities for the aquifer sampled. However, small anisotropic conditions may result in hydraulic conductivities different from those expected under isotropic conditions. The commonly used constant-head permeameter consists of a supply reservoir and an overflow tube to provide constant water levels (heads). Water flows from the reservoir upward through the sediment core. Hydraulic conductivity (K) is calculated from Darcy's law (Fetter, 1988) as

$$K = 864 \times \frac{V \times \Delta l}{t \times A \times \Delta h}, \qquad (1)$$

where

- K is hydraulic conductivity at pore water temperature (about 20°C), in meters per day;
- V is volume of discharge, in milliliters;
- t is time interval during measurement of discharge, in seconds;
- A is cross-sectional area of the sediment core, in square centimeters;
- Δh is difference in hydraulic head, in centimeters; and
- Δl is length of sediment core for which Δh is measured, in centimeters.

Constant-head permeameters are useful for noncohesive, coarse-grained sediments. The constant-head permeameter was selected for this study because sediments in the aquifer generally are sandy, and the hydraulic conductivity of a nearby sand and gravel aquifer is within the suggested range for the constant-head method (Hess and others, 1992). Wolf (1988) developed the multiport constant-head permeameter used in this study (fig. 2). The placement of two to four manometer ports in a core liner filled with sediment allows for the estimation of hydraulic conductivities across small vertical sections of sediment core. If the vertical hydraulic conductivity is equal in all core sections, the relation between change in head and distance can be treated as being linear along the length of the sediment core. Conversely, differences in vertical hydraulic conductivity in core sections can be treated as indicating a nonlinear relation.

Some of the sediment cores contained pebbles that caused a decreased flow too low to measure in the permeameter. Within a core tube 4.8 cm in diameter, the presence of a pebble greater than about 2 cm in diameter significantly decreases the measured vertical hydraulic conductivity because the pebble blocks a large part of the flow channel (Wolf and others, 1991). For cores with blockages, the permeameter tests were not completed, but grain-size analyses were performed.

Sediment cores were prepared for permeameter testing on the basis of the procedure followed by Wolf (1988). Additional coarse-grained sediment from the study site was used to fill the tops of partially empty sediment cores. Manometer-port holes were drilled through the sediment core with a 1.6-millimeter-diameter drill bit. Port holes were spaced vertically at least 5 cm apart and at least 5 cm from the ends of the cores. Three manometer ports were drilled in most cores. Four manometer ports were drilled in the eight cores about 0.6 m in length, and two ports were drilled in the three cores about 0.3 m in length. Small flexible rubber stoppers, about 5 mm thick with 1.6 mm holes, were glued to the outside of the sediment core around each manometer port. Pneumatic inflation needles plugged with putty were inserted temporarily into the sediment core through the stopper holes to prevent air from entering the core during resaturation.

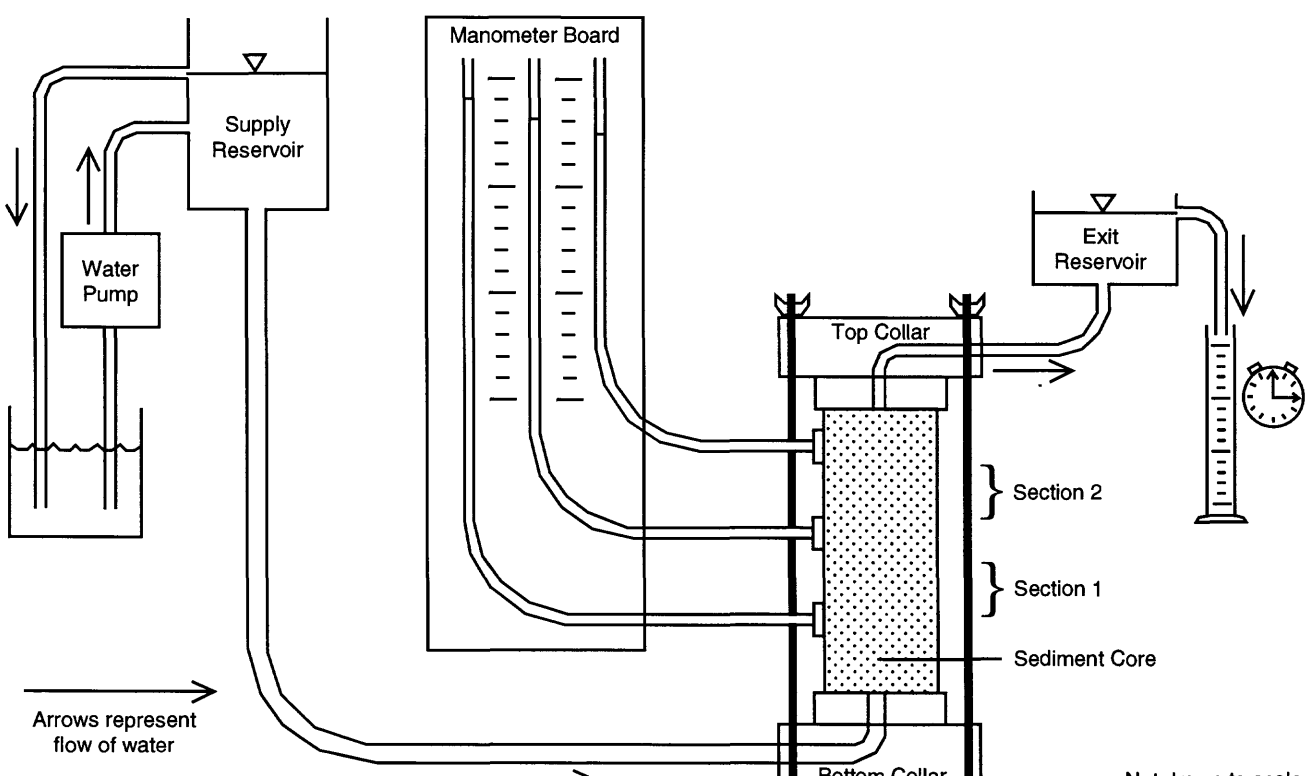

Figure 2. Multiport constant-head permeameter.

Sediment cores were resaturated under a vacuum, as suggested by Black and Lee (1973), to ensure the most complete resaturation possible. Smith and Browning (1942) found that resaturating a core under atmospheric pressure commonly incompletely saturates the sediments. Estimated vertical hydraulic conductivities decrease when air is present in the core because water is forced to flow around air pockets (Olson and Daniel, 1981). However, estimated hydraulic conductivities increase with time in partially resaturated cores as water flows through the sediment sample and air bubbles are removed by the flowing water (Christiansen, 1944). Because resaturation increased with time, the permeameter measurements made at the end of the test were used to estimate vertical hydraulic conductivity.

The core was placed in the permeameter for resaturation (fig. 3). First, the top cap of the core was removed, and the top collar of the permeameter was placed on the core liner and loosely fastened with a hose clamp. The core was inverted, the bottom cap removed, and the bottom collar attached to the core. The core and collars were righted and secured to a shelf with four threaded metal rods that penetrated the collars and the shelf. Collars were tightened against the core liner with wing nuts on the rods to prevent air from entering the core. The hose connecting the bottom collar to the supply reservoir was clamped to prevent water from entering the core. The supply reservoir was filled with ground water from a deep observation well upgradient from the highway at the study site. Aquifer water was used to avoid chemical changes that might occur if another type of water, such as distilled water, were used (Olson and Daniel, 1981). All tubing connections open to the atmosphere were clamped, and a vacuum of about 84 kPa was applied to the core and water for deaeration. Deaeration time ranged from 10 minutes for coarse-grained sediments (predominantly composed of sand and gravel) to 2 hours for fine-grained sediments (predominantly composed of silt and fine sand). When

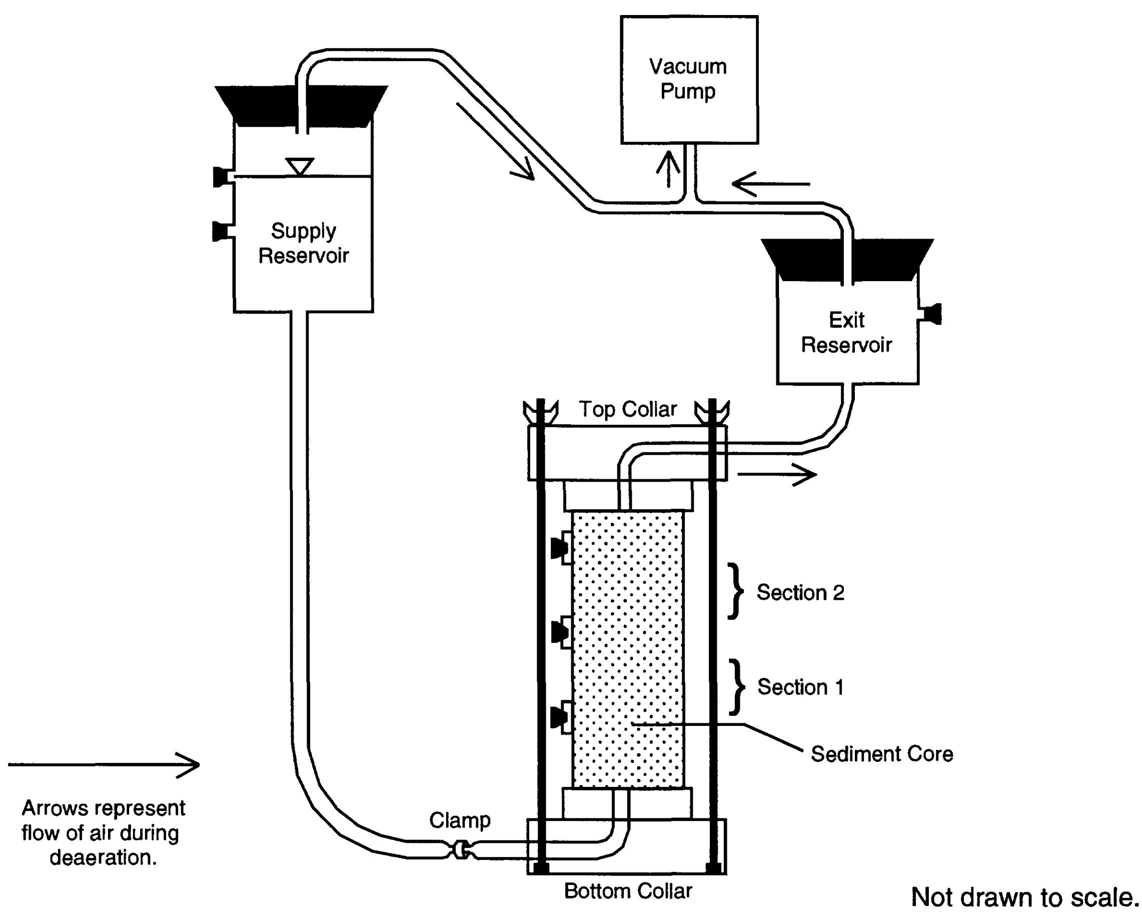

Figure 3. Deaeration of sediment core and water prior to core resaturation.

few air bubbles remained in the reservoir water, the vacuum was reduced to about 17 kPa, and the clamp on the water tube was released, allowing flow into the core through the bottom collar. Sintered brass plates inside the collars provided support for the core and evened the flow of water into and out of the core. The core was considered resaturated when the water flowed through the upper collar into the exit reservoir. At this time, the vacuum was stopped and the permeameter test began.

A constant head was maintained in the supply reservoir throughout the permeameter test. Water flowed freely from the supply reservoir through the core. The difference in elevations between the supply and exit reservoirs defined the difference in total head across the core and established the hydraulic gradient along the core. The hydraulic gradient was limited by maintaining the difference in total head between the reservoirs at less than 50 percent of the total core length. For most of the cores, the water level in the reservoirs was constant; total head difference between them was about 14 cm.

As aquifer water flowed through the core, measurements of flow rate and hydraulic head loss were made about every 30 minutes. Plugged pneumatic inflation needles were replaced with unplugged needles with tubes connected to a manometer board graduated in millimeters. These needles had six drilled 1-millimeter-diameter holes to allow water to flow easily while a hydraulic connection between the sample and the manometer tubes was maintained. Manometer levels were measured, and the difference between the levels indicated the hydraulic head loss across the length of core between manometer ports. Flow from the exit reservoir was measured with a stopwatch and graduated cylinder.

Temperature of the water from the supply and exit reservoirs was monitored throughout the permeameter test so that hydraulic conductivity could be corrected from laboratory to aquifer conditions and compared with hydraulic conductivities estimated from the other methods. Correction for aquifer temperature of about 10°C was needed because density and dynamic viscosity vary with temperature (Bowles, 1986). Estimates of vertical hydraulic conductivity were corrected by multiplying the hydraulic conductivities at laboratory pore-water temperature by the ratio of density/dynamic viscosity of water at laboratory temperature to density/dynamic viscosity of ground water at field temperature. Pore-water temperature ranged from 17 to 22°C and varied less than 2°C throughout the permeameter tests. Correction for temperature differences decreased the estimates of vertical hydraulic conductivity by about 30 percent.

The hydraulic connections between the sample and the manometer tubes were checked at least once during the test by clamping either the supply or exit tubes from the permeameter and observing the equilibration level of the water in the manometers. The height at which all the manometers stabilized while the flow to or from one reservoir was clamped should equal the elevation head of the water in the connected reservoir. Results of these tests showed that the manometers were in hydraulic connection with all the cores. When leakage or blockages were found, they were eliminated and the test was continued.

Another test was used to determine friction losses in the permeameter equipment. A core liner without sediment was placed in the permeameter and manometer levels were read. Water levels in the three manometers rose to the height of the water in the upper reservoir, signifying negligible head loss from friction in the equipment.

Each core remained in the permeameter for several hours or until water levels in the manometers stabilized. Results from the final measurements were used in Darcy's Law (eq. 1) to calculate vertical hydraulic conductivity in the sediment sections between manometer ports. Sections were numbered from the bottom to the top of the core. Sediment cores generally consisted of two sections, although some were not sectioned and others had three sections. Vertical hydraulic conductivities of these sections were averaged and weighted by section length to yield a gross vertical hydraulic conductivity for the sediment core.

The permeameter test was completed for 35 of the 45 sediment cores from boreholes where observation wells were installed (table 1). Vertical hydraulic conductivities of ten sediment cores were not estimated by the constant-head multiport permeameter test because flow in two permeameters was blocked by stones and flow in the remaining eight permeameters was too slow to measure. The vertical hydraulic conductivities of the cores ranged from 0.9 to 86 m/d, with a mean of 22.8 m/d, a standard deviation of 18.1 m/d, and a coefficient of variation of 0.794 (table 2). The coefficient of variation is large, indicating a large variability, relative to the mean in the estimated vertical hydraulic conductivities. A range in hydraulic conductivities of two to three orders of magnitude is typical for a sand and gravel aquifer (Freeze and Cherry, 1979).

Table 1. Hydraulic conductivities estimated by the three methods for each observation well location in a sand and gravel aquifer, southeastern Massachusetts

[Hydraulic conductivity is in meters per day. The following are abbreviations for test methods: **PAVG**, permeameter average of sections. Values are estimated vertical hydraulic conductivity; **GAVG**, grain-size analysis average of sections. Values are estimated bulk hydraulic conductivity (no vector); **SLUG**, slug test. Values are estimated horizontal hydraulic conductivity and 1:1 anisotropy is assumed; **PSEC1**, permeameter section 1. Values are estimated vertical hydraulic conductivity; **PSEC2**, permeameter section 2. Values are estimated vertical hydraulic conductivity; **PSEC3**, permeameter section 3. Values are estimated vertical hydraulic conductivity; **GSEC1**, grain-size analysis section 1. Values are estimated bulk hydraulic conductivity (no vector); **GSEC2**, grain-size analysis section 2. Values are estimated bulk hydraulic conductivity (no vector); **GSEC3**, grain-size analysis section 3. Values are estimated bulk hydraulic conductivity (no vector). no., number; m.d., missing data; --, test not completed]

Well and borehole No.	PAVG	GAVG	SLUG	PSEC1	PSEC2	PSEC3	GSEC1	GSEC2	GSEC3
A101	--	14	--	--	--	--	14	--	--
A102	--	33	11	--	--	--	40	26	--
A201	40	70	--	37	44	--	78	63	--
A202	42	40	60	46	38	--	40	40	--
A203	21	58	61	21	--	--	58	--	-
A204	12	40	79	12	12	--	40	40	--
A205	38	70	--	31	28	55	73	m.d.	68
A220	--	1	6	--	--	--	1	--	--
A401	20	42	--	16	23	--	36	48	--
A402	30	42	44	28	33	--	36	48	--
A403	27	59	66	37	27	16	90	53	36
A404	14	63	23	17	16	10	73	68	48
A405	--	102	.6	--	--	--	102	--	-
A420	.9	4	--	.6	1	--	5	4	--
A501	23	60	--	15	31	--	48	73	--
A502	32	53	65	25	39	--	48	58	--
A503	16	65	67	13	19	--	58	73	--
A504	30	68	31	7	52	--	68	--	--
A520	69	129	--	37	101	--	84	175	--
B101	86	206	--	68	111	80	184	249	184
B102	13	34	21	14	12	--	36	32	--
B120	12	23	--	12	--	--	23	--	--
B201	19	37	--	22	23	13	44	40	26
B202	6	16	33	10	3	--	29	4	--
B203	9	34	37	6	12	--	32	36	--
B204	8	23	25	8	9	--	26	20	--
B205	9	4	30	m.d.	9	--	4	4	--
B220	--	7	3	--	--	--	3	8	10
C101	9	23	--	8	10	--	20	26	--
C102	33	40	54	33	--	--	40	--	--
C201	50	81	--	44	56	--	84	78	--
C202	21	38	28	18	25	--	36	40	--
C203	15	30	22	10	20	--	20	40	--
C204	--	2	6	--	--	--	m.d.	2	--
C205	6	4	9	6	--	--	4	--	--
C220	--	.5	.6	--	--	--	.7	.3	.4
D101	13	32	--	21	6	--	32	32	--
D102	7	42	40	9	5	--	36	48	--
D120	22	17	--	34	10	--	29	6	--

Table 1. Hydraulic conductivities estimated by the three methods for each observation well location in a sand and gravel aquifer, southeastern Massachusetts—*Continued*

Well and borehole No.	PAVG	GAVG	SLUG	PSEC1	PSEC2	PSEC3	GSEC1	GSEC2	GSEC3
D201	--	4	--	--	--	--	4	--	--
D202	--	6	17	--	--	--	6	--	--
D203	22	48	49	8	35	--	48	48	--
D204	19	40	28	15	23	--	36	44	--
D205	7	28	36	6	8	--	28	29	--
D320	--	1	--	--	--	--	.7	2	--

Table 2. Descriptive statistics of hydraulic conductivities estimated by the three methods for a sand and gravel aquifer, southeastern Massachusetts

Method	Number of samples	Hydraulic conductivity (meters per day)			
		Range	Mean	Standard deviation	Coefficient of variation
Permeameter test[1]	35	0.9 - 86	22.8	18.1	0.794
Grain-size analysis with the Hazen approximation[2]	45	0.5 - 206	40.7	37.7	.926
Slug test[3]	29	0.6 - 79	32.9	22.4	.681

[1] Values are estimated vertical hydraulic conductivity.
[2] Values are estimated bulk hydraulic conductivity (no vector).
[3] Values are estimated horizontal hydraulic conductivity and 1:1 anisotropy is assumed.

The repeatability of hydraulic conductivity estimates from the permeameter tests was checked with results of tests on Ottawa sand, a standard uniform sand from Illinois. This sand was tested four times in the multiport permeameter with three ports, and the results were compared with a hydraulic conductivity of 23.3 m/d obtained during a separate laboratory analysis of Ottawa sand (Silas Nichols, Tufts University, Medford, Mass., laboratory report, 1991). The sand was packed to the same density for each of the four tests. Hydraulic conductivities of the Ottawa sand estimated from the permeameter tests ranged from 19.0 m/d to 30.3 m/d, or 30 percent higher to 19 percent lower than the reported 23.3 m/d.

Grain-Size Analysis with the Hazen Approximation

The Hazen approximation (Hazen, 1893) was used to estimate hydraulic conductivities from the grain-size distributions of the sediment in each permeameter section. Hazen (1893) used a permeameter to establish his approximation, although the exact derivation of the Hazen approximation is unknown. The hydraulic conductivity from the Hazen approximation is a vectorless, bulk estimate.

The Hazen approximation is an empirical equation that relates the effective grain size of sediments to hydraulic conductivity. The effective grain size (d_{10}), as defined by Hazen (1893), is the diameter, in millimeters, at which 10 percent by mass of the sediment sample is finer and 90 percent of the sample is coarser. The Hazen approximation (Hazen, 1893) is

$$K = A \times (d_{10})^2 \times 864, \qquad (2)$$

where

- K is hydraulic conductivity, in meters per day at aquifer water temperature;
- A is a coefficient that varies with aquifer water temperature and equals 1.15 for a water temperature of 10°C; and
- d_{10} is effective grain size, in millimeters.

This simple relation has been used in many studies to estimate hydraulic conductivity (for example, Lambe and Whitman, 1969; Fetter, 1988; Wolf and others, 1991). Hazen (1893) developed his approximation on sands with a d_{10} ranging from 0.1 to 3.0 mm. Conceivably, the Hazen approximation could be used to estimate hydraulic conductivity of core samples with a d_{10} greater or less than the range used by Hazen. Although the d_{10} of core samples in this report ranged from 0.02 to 0.50 mm (fig. 4), 79 percent of the samples were within the range of d_{10} used by Hazen. Results from 21 percent of the core samples with a range of d_{10} less than that tested by Hazen provide information about the use of the Hazen approximation for sediments with a large component of fine-grained sediments. Hydraulic conductivities estimated for samples with a d_{10} as low as 0.02 mm are similar to some of the results of the permeameter and slug tests.

Sediment-core samples used in the grain-size analysis were removed from the core immediately following the permeameter test. Grain-size analysis was conducted on each section by use of a standard dry-sieving procedure (Driscoll, 1986). The sediment sample was dried in an oven, passed through a sediment splitter to yield a representative sample weighing 60 to 100 g, and dry sieved through U.S. standard half-height sieves with mesh diameters of 11.2 to 0.0625 mm. The mass of sediment collected in each sieve was weighed. Grain-size analysis was considered successful if less than 2 percent of the total mass of the sediment sample was lost during sieving (Bowles, 1986). If more than 10 percent of a sample passed through the 0.0625-mm sieve (the border between sand and silt in Tyler and U.S. standard sieves (Guy, 1969)), then the grain-size distribution of that part of the sample was determined by pipet analysis (Guy, 1969) at the USGS Sediment Laboratory in Lemoyne, Pennsylvania.

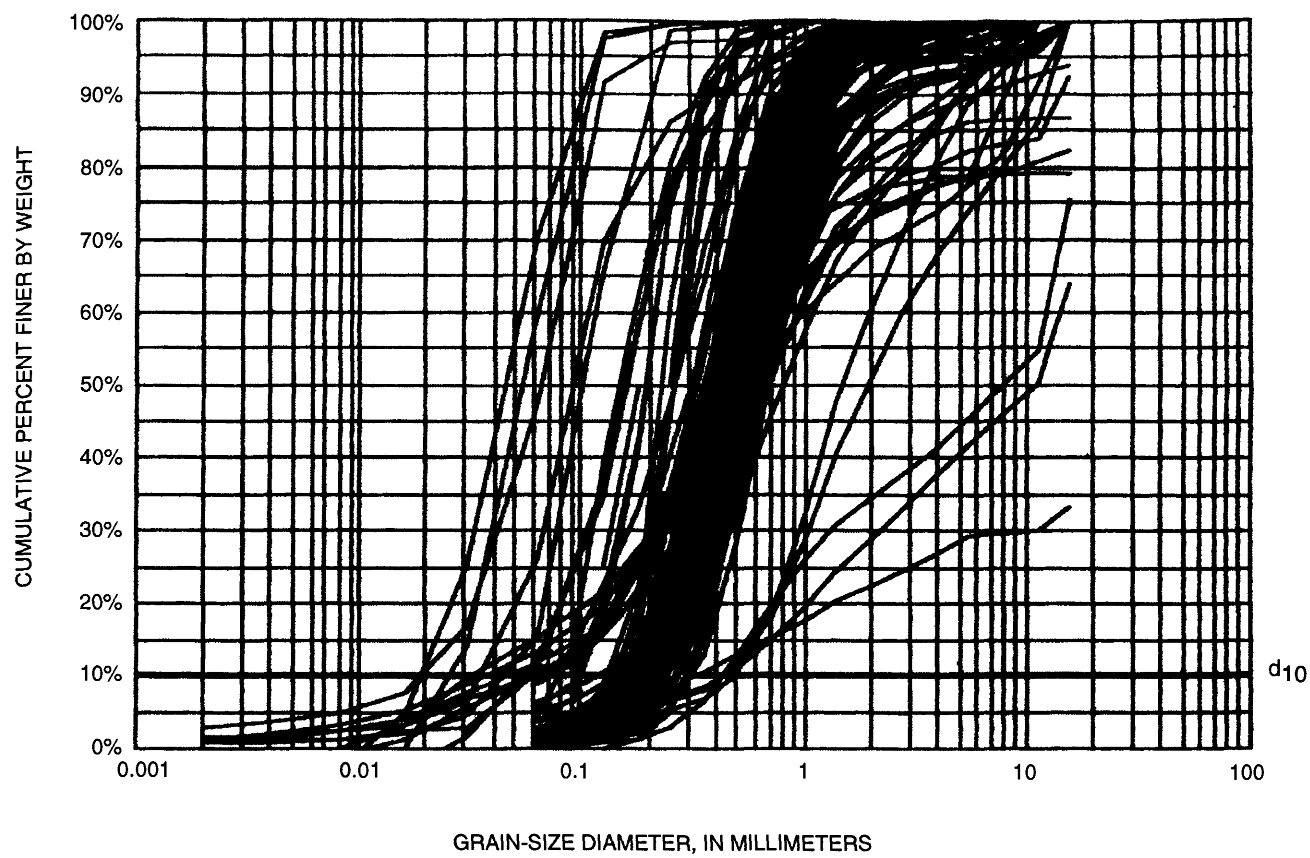

Figure 4. Range of grain sizes of 45 sediment cores at test sites A, B, C, and D, southeastern Massachusetts.

A section from each of four sediment cores dominated by sand-sized particles, or 8 percent of the total number of sediment cores, was independently reanalyzed for grain-size distribution at the USGS Sediment Laboratory in LeMoyne, Pennsylvania. These sediment samples provided a quality-control check on the repeatability of the results of the grain-size analysis. Differences in effective grain size (d_{10}) ranged from 0.0 to 0.009 mm. Corresponding hydraulic conductivities estimated from grain-size analysis from the USGS Sediment Lab ranged from 0.0 to 4.3 m/d, or 0.0 to 12 percent, lower than those estimated at the USGS Massachusetts office.

A cumulative-weight curve (fig. 4) was prepared for each sediment section. These curves indicate the cumulative percentage of the total mass of sediment less than a given grain size. The d_{10} determined from this graph was used in the Hazen approximation to estimate the bulk hydraulic conductivity of each sediment section.

An average bulk hydraulic conductivity, weighted by section length within each core, was estimated by the Hazen method for all cores. In cores where only one section was tested, the bulk hydraulic conductivity of that section represented the bulk hydraulic conductivity of the core. Bulk hydraulic conductivities were estimated for all 45 sediment cores (table 1); the hydraulic conductivities ranged from 0.5 to 206 m/d with a mean of 40.7 m/d, a standard deviation of 37.7 m/d, and a coefficient of variation of 0.926 (table 2). No equipment difficulties were encountered; thus, the estimation of bulk hydraulic conductivities was not limited to certain sediment cores as was necessary for permeameter tests.

Slug Test

During a slug test in an observation well, flow to the screened interval of the well is horizontal and vertical. The equation used to analyze the slug-test data accounts for vertical-flow effects (Widdowson and others, 1990). The equation result represents horizontal hydraulic conductivity (Bouwer, 1978). Horizontal hydraulic conductivities were estimated in the field by use of rising-head slug tests. This test is initiated by lowering a solid cylinder (slug) of known volume into a monitoring well screened within the saturated zone (fig. 5). The water table is allowed to stabilize to static conditions. Then the cylinder, which displaces a known volume of water, is removed quickly from the hole. Water levels are measured at frequent intervals with a pressure transducer to record the aquifer response—a rising water level that quickly returns to its original level. These water-level data are plotted with time to form a response curve. Slug tests are invalid for wells screened at the water table (all wells with labels ending in 01 in table 1) because the unsaturated zone temporarily retains the water displaced by the slug.

Many methods have been developed to estimate horizontal hydraulic conductivity from the response curve. The method used in this report is described in Widdowson and others (1990) and is applicable to a partially penetrating well screen in an unconfined aquifer. This method was selected because it accounts for radial and vertical flow during the slug test. The equation is

$$K = \frac{r^2}{2 \times P \times L} \times 2.30 \times B , \qquad (3)$$

where

- K is hydraulic conductivity, in meters per day, at aquifer water temperature;
- r is the radius of the well casing and well screen, in meters;
- P is a dimensionless parameter of flow based on screen length, radius, and depth below water table;
- L is the well-screen length, in meters; and
- B is the slope of the response curve.

Slug tests were done in 29 of the 45 observation wells from which sediment cores were collected. Two slug tests were done in rapid succession in 28 of these wells. A typical response curve for the wells is shown in figure 6. The slopes of both response curves for each well were used in equation 3 to estimate horizontal hydraulic conductivity. The average estimate from the two tests is an estimate of the horizontal hydraulic conductivity of the aquifer near the screen in each well. Differences in estimated hydraulic conductivities from the 28 wells in which two tests were done—a measure of their repeatability—ranged from 0.03 to 3.2 m/d, or 0.08 to 9.5 percent of their respective means.

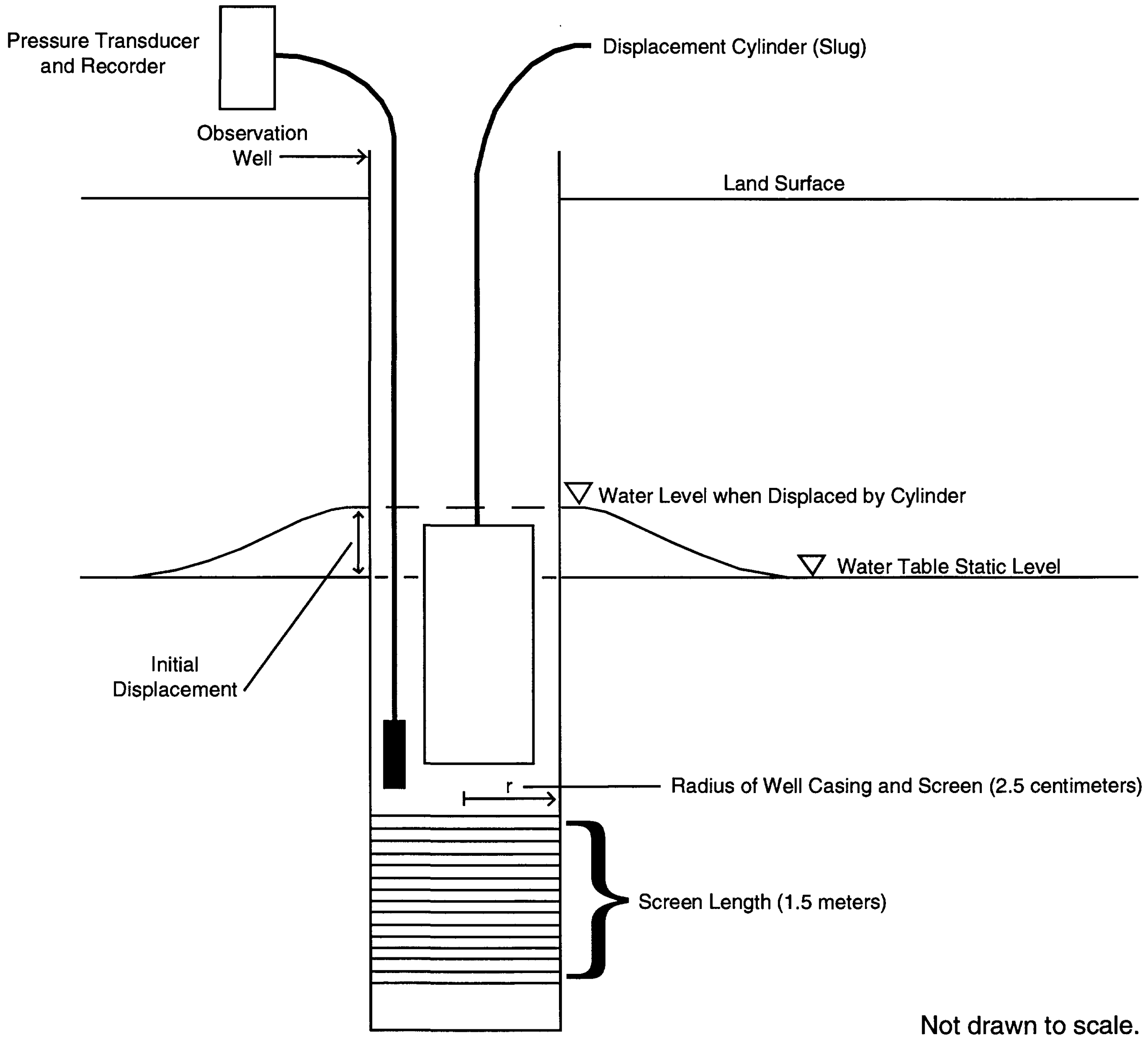

Figure 5. Slug-test variables.

For the aquifer tested, the horizontal hydraulic conductivities estimated in slug-test analyses did not depend on the anisotropy ratio of the sediments used in the calculation. The slug test was analyzed using horizontal-to-vertical anisotropy ratios of 1:1 (isotropic conditions), 2:1, and 5:1. Differences in estimated hydraulic conductivity ranged from 0 to 25 percent in calculations based on the 1:1 and 5:1 ratios. These differences are minor for hydraulic conductivity tests because estimates vary so widely that even hydraulic conductivities within one order of magnitude are considered useful (Freeze and Cherry, 1979). In this report, hydraulic conductivities calculated with the isotropic 1:1 ratio are considered to be the hydraulic conductivities at the observation wells (table 1). Accordingly, the hydraulic conductivities estimated by the use of slug tests can be considered a bulk hydraulic conductivity, comparable to the bulk hydraulic conductivity estimated by use of grain-size analysis with the Hazen approximation. Estimated hydraulic conductivities of the aquifer at the 29 wells used in the

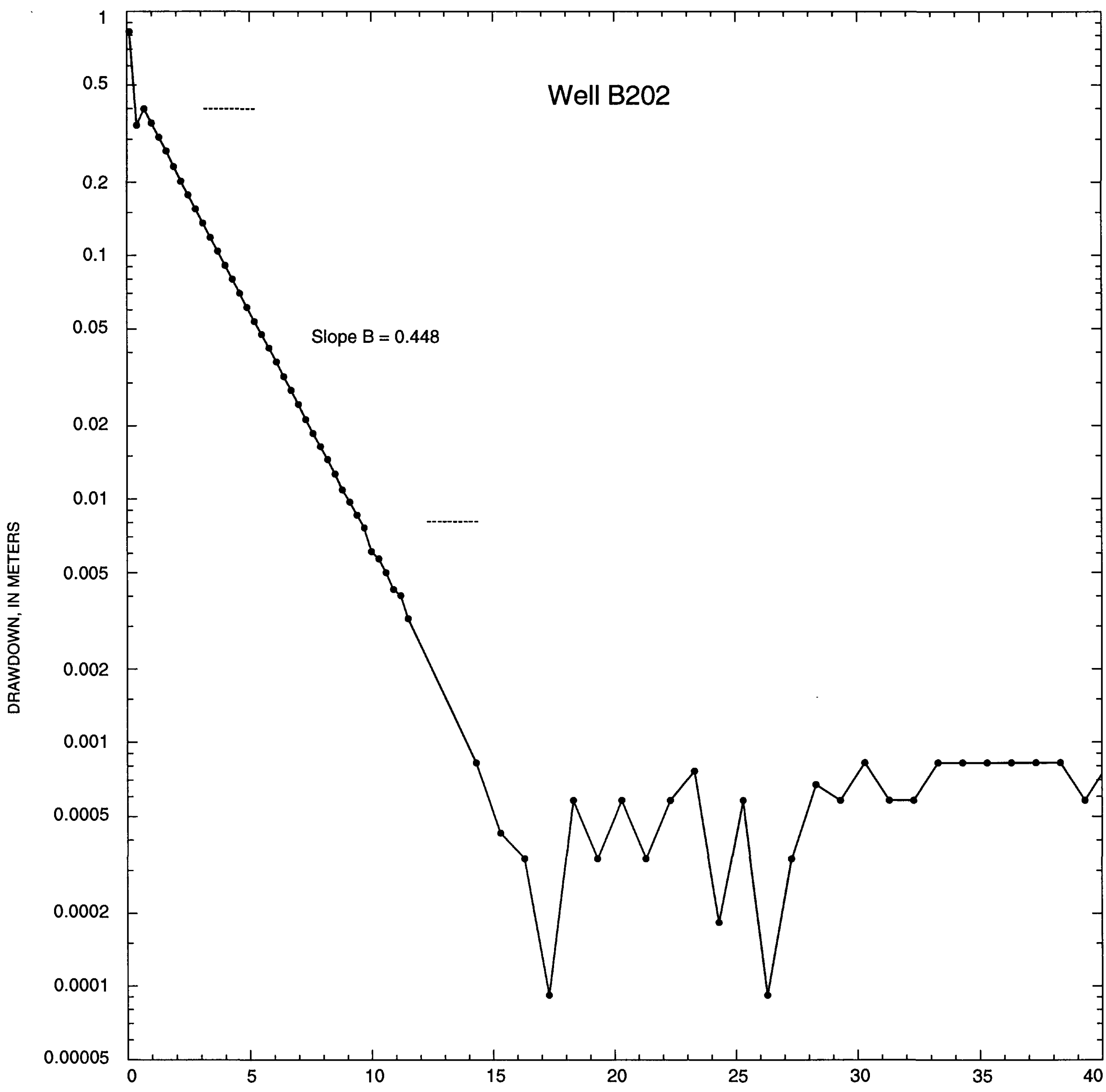

Figure 6. Typical response curve for slug test in a sand and gravel aquifer (site B202), southeastern Massachusetts.

slug tests ranged from 0.6 to 79 m/d, with a mean of 32.9 m/d, a standard deviation of 22.4 m/d, and a coefficient of variation of 0.681 (table 2).

The slug test is best conducted in large-diameter wells so that a large amount of water can be displaced; in this way, a large part of the aquifer is tested and error is reduced. Levy and Pannel (1991) reported that problems with a slug test include insufficient initial water displacement, little control over the amount of initial displacement, disturbance of pressure-transducer cables, and loss of initial data because of the oscillating water table from slug emplacement. In this study, these problems were not apparent during the slug tests.

COMPARISON OF HYDRAULIC CONDUCTIVITIES ESTIMATED BY THREE METHODS

Comparisons were made of hydraulic conductivities estimated by the permeameter test, grain-size analysis, and slug test for each sampling site. The data set for this intermethod analysis consisted of estimated hydraulic conductivities at the 22 sampling sites for which all three methods were completed. The normality of the data distribution of hydraulic conductivities was first determined so that proper statistical analysis methods could be selected. A boxplot (fig. 7) was used to check normality. The skewness of the data are evidence of a nonnormal distribution. Therefore, nonparametric tests were selected for the data analysis. The significance level to reject the null hypotheses of all statistical tests in this study was α less than 0.05, where α is the test statistic.

The data for each sampling site were assigned a rank from 1 to 4 according to the magnitude of the hydraulic conductivity estimated by each of the three methods. An Analysis of Variance (ANOVA) on the ranks, blocking on sampling site so as to remove any effect of location, was used to compare the estimated hydraulic conductivities (Helsel and Hirsch, 1992). This ANOVA is an approximation to the nonparametric Friedman test and determines whether or not the hydraulic conductivities estimated by at least one method are different from those estimated by the other methods. Once a difference was established, a multiple comparison test known as the Ryan-Winot-Gabriel-Welsch multiple range test (SAS Institute, 1990) was used to delineate hydraulic conductivities estimated by one method from those estimated from another method; the multiple-comparison test also was used to indicate the method or methods that yielded consistently high or low hydraulic conductivities.

The comparison of estimates from all methods with the multiple comparison test showed that the median hydraulic conductivities estimated from results of the slug test and grain-size analysis with the Hazen approximation were not significantly different (table 3). However, median hydraulic conductivities estimated from the slug tests and grain-size analyses were significantly greater than the median hydraulic conductivity estimated from the permeameter tests. The

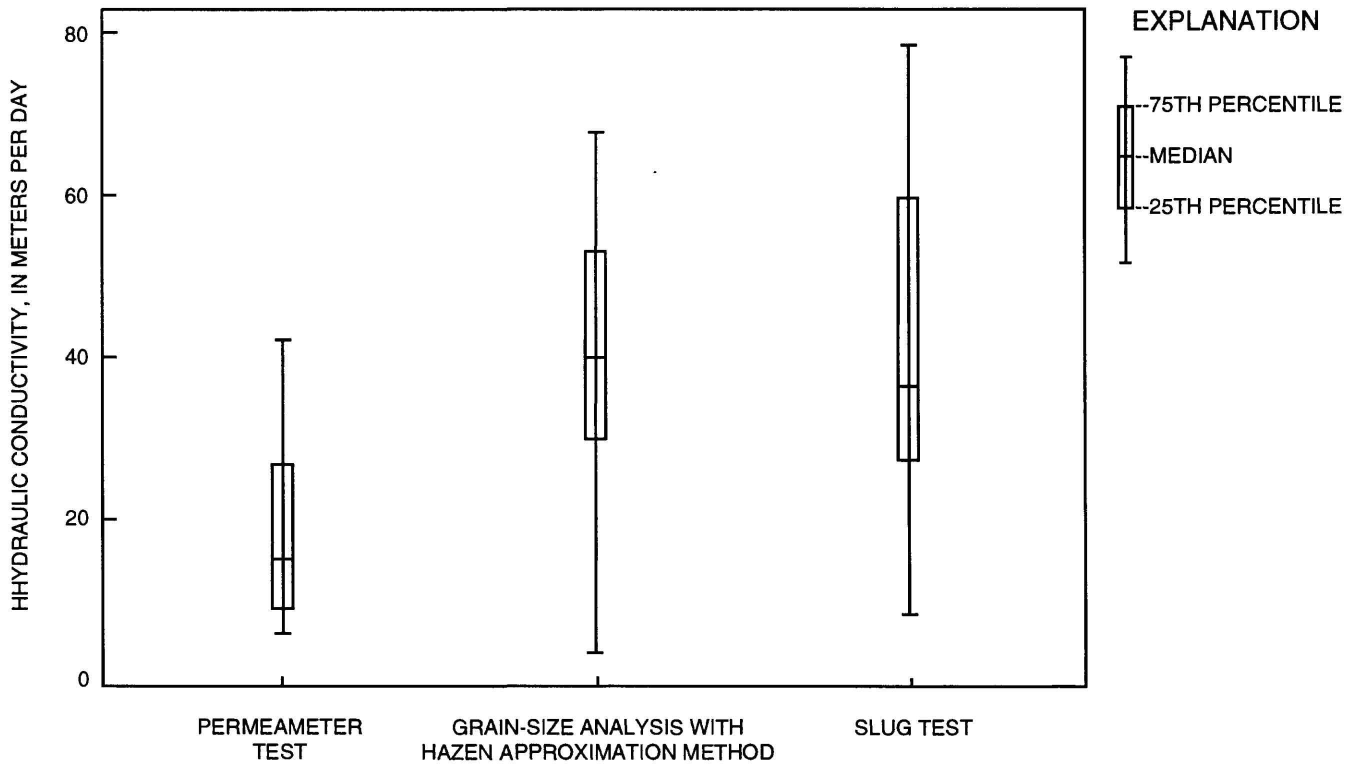

Figure 7. Estimated hydraulic conductivities for a sand and gravel aquifer at 22 sampling sites in southeastern Massachusetts, using three methods.

Table 3. Comparative statistics of hydraulic conductivities for a sand and gravel aquifer in southeastern Massachusetts, estimated by the three methods

[Methods compared by the Ryan-Winot-Gabriel-Welsch multiple comparison test (SAS Institute, 1990). Means range from 1 to 3 (smallest to largest results) because three methods were compared]

Method	Number of data points	Means of the ranks of data for each method	Significant correlation between this estimation method and another method
Permeameter test	22	1.1	No
Grain-size analysis with the Hazen approximation	22	2.4	Yes
Slug test	22	2.7	Yes

distribution of hydraulic conductivities at the 22 sampling sites that were estimated by all three methods is shown in the plots in figure 8. Pertinent statistics are shown in the plots; the hydraulic conductivities estimated by the Hazen approximation generally were close to the hydraulic conductivities estimated by the slug tests, and the hydraulic conductivities estimated for both of these methods were higher than the hydraulic conductivities estimated by the permeameter test. Small anisotropy may partially cause these differences.

As a check that the hydraulic conductivities estimated by each method used were reasonable, the estimated hydraulic conductivities were compared with the horizontal hydraulic conductivity of 45 m/d from an aquifer test conducted near Site B by SEA Consultants[1] in 1991 (Warren, 1992). When averaged over the aquifer area, vertical hydraulic conductivities estimated by the permeameter tests, bulk hydraulic conductivities estimated by grain-size analyses with the Hazen approximation, and horizontal (or bulk) hydraulic conductivities estimated by the slug tests are expected to be within one order of magnitude of a horizontal hydraulic conductivity calculated from an aquifer test (Todd, 1959; Freeze and Cherry, 1979). Each of the average hydraulic conductivities at site B estimated by the three methods tested differed from hydraulic

[1]The use of firm names in this report is for identification purposes only and does not constitute an endorsement by the U.S. Geological Survey.

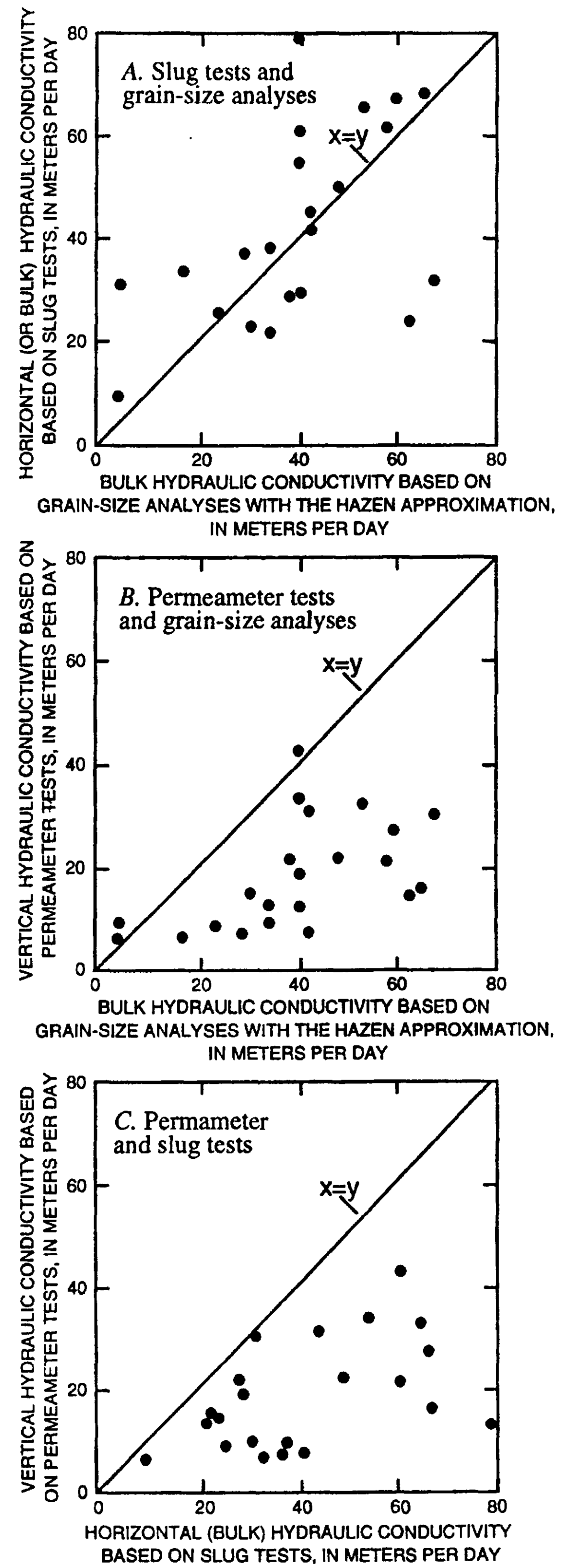

Figure 8. Hydraulic conductivities estimated by three methods for a sand and gravel aquifer at 22 sampling sites, southeastern Massachusetts.

conductivity calculated from the aquifer-test analysis by less than 55 percent. These results indicate that hydraulic conductivities estimated by each method are within an acceptable range (less than an order of magnitude of difference from aquifer-test results) for the aquifer.

SUMMARY AND CONCLUSIONS

Comparisons were made between hydraulic conductivities of a sand and gravel aquifer in southeastern Massachusetts that were estimated by constant-head multiport permeameter tests, grain-size analysis with the Hazen approximation, and slug tests. The median hydraulic conductivities estimated from results of the slug tests and the grain-size analysis with the Hazen approximation were not significantly different. However, median hydraulic conductivities estimated from the slug tests and grain-size analyses were significantly greater than the median hydraulic conductivity estimated from the permeameter tests. This difference may be partially attributed to potential anisotropic conditions of the aquifer and direction in which hydraulic conductivity is estimated by each method—the permeameter test yields estimates of vertical hydraulic conductivity, the grain-size method yields vectorless estimates, and the slug test yields estimates of horizontal hydraulic conductivity.

The repeatability of each method in estimating hydraulic conductivity was tested. The repeatability of the permeameter was tested by estimating the hydraulic conductivity of four samples of Ottawa sand, a standard, uniform sand. Results show a range of estimated hydraulic conductivities from 19 percent lower to 30 percent higher than the standard hydraulic conductivity. Replicate analyses of grain-size distributions of four sediment samples were used to estimate the repeatability of hydraulic conductivity estimated by grain-size analyses with the Hazen approximation. Estimated hydraulic conductivities from the replicate analyses ranged from 0.0 to 12 percent lower than from the original sediment analyses. Repeatability of estimated hydraulic conductivities from the slug test were tested by conducting two slug tests, one after the other, in each of 28 wells. Estimated hydraulic conductivities ranged from 0.8 to 9.5 percent of their respective means.

Estimation of hydraulic conductivity provides information on the advantages and disadvantages of the methods used to derive the estimates. The multiport-permeameter test and grain-size analysis are methods suited for estimating hydraulic conductivities within thin layers of the aquifer. However, leaks in the permeameter equipment can cause measurement problems and require frequent attention. The permeameter test could require hours or days of testing for each core until saturation of the sediments was reached and measurements were consistent. The permeameter test is optimal for minimally disturbed samples; however, the samples in this study were disturbed as they were collected. Unlike the permeameter test and grain-size analysis, the slug test cannot be applied to layers of sediment a few centimeters thick. Instead, each individual slug test yields the estimated hydraulic conductivity of a vertical thickness of the aquifer that is defined by the length of the well screen. An advantage of the slug test over the permeameter test and grain-size analysis is that the slug test yields horizontal hydraulic conductivity estimates rather than the vertical or vectorless estimates that the permeameter test and grain-size analyses yield, respectively. Grain-size analysis is a simple procedure, can be completed within a few hours, and equipment problems are uncommon.

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