Analysis of Aquifer Tests to Determine Hydrologic and Water-Quality Conditions in Stratified-Drift and Riverbed Sediments near a Former Municipal Well, Milford, New Hampshire

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square foot (ft^2)	0.09294	square meter
square foot per day (ft^2/d)	0.0929	square meter per day
square mile (mi^2)	2.590	square kilometer

Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by use of the following equation:
°F = 1.8 (°C) + 32.

VERTICAL DATUM

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.

ABBREVIATED WATER-QUALITY UNITS

Chemical properties are expressed in microsiemen per centimeter at 25 degrees Celsius (µS/cm). Chemical concentrations in water are expressed in microgram per liter (µg/L). Microgram per liter is a unit expressing the concentration of chemical constituents in solution as weight (microgram) of solute per unit volume (liter) of water.

Analysis of Aquifer Tests to Determine Hydrologic and Water-Quality Conditions in Stratified-Drift and Riverbed Sediments near a Former Municipal-Supply Well, Milford, New Hampshire

By Thomas J. Mack *and* Philip T. Harte

Abstract

The hydrologic properties of a stratified-drift aquifer and riverbed at a discontinued municipal well, the Keyes well in Milford, New Hampshire, were estimated from a multiple-well aquifer test and single-well (slug) tests. The Keyes well is screened in the lower parts of a heterogeneous glacial-drift aquifer adjacent to a partially incised river and was removed from service as the result of contamination by volatile organic compounds. This study was conducted in cooperation with the U.S. Environmental Agency, Region I.

Results of a multiple-well aquifer test suggest that the stratified-drift aquifer is heterogeneous and that pumping in the Keyes well field induces inflow from the Souhegan River. Hydrologic properties of the aquifer were analyzed by a method that accounts for partial penetration of the withdrawal and observation wells under unconfined conditions. Transmissivity was estimated to be about 725 feet squared per day, with an average horizontal hydraulic conductivity of 58 feet per day in the upper part of the glacial aquifer and 10 feet per day in the lower part of the aquifer. A storage coefficient of less than 0.002 was estimated for the lower part of the aquifer. The ratio of vertical to horizontal hydraulic conductivity was estimated to be 0.1.

Single-well tests, which affect a small aquifer volume, gave comparable estimates of hydraulic conductivity as those estimated by the multiple-well aquifer test. Horizontal hydraulic conductivity estimated from single-well tests was 5.4 to 154 feet per day in the upper part of the aquifer and 1.7 to 105 feet per day in the lower part of the aquifer. The tests showed relatively high hydraulic conductivity west of the Keyes well and low hydraulic conductivity to the south.

Results of temperature trends of pumped water indicate that 25 percent of pumped water is recharged from induced inflow of water from the Souhegan River. Estimated riverbed leakage was 0.16 cubic foot per second as determined by a simple mass balance of pumped-water temperature and temperature contrast between ambient ground water and the river. Riverbed vertical hydraulic conductivity is about 2 feet per day as calculated by use of a simple one-dimensional Darcy flow equation for vertical ground-water flow and data on riverbed piezometer drawdowns and estimated riverbed leakage.

INTRODUCTION

During 1960-84, the Keyes well was a source of municipal water for the town of Milford, New Hampshire (fig. 1). In 1984, elevated concentrations of 1,2-dichloroethane, 1,1,1-trichloroethane, and tetrachloroethylene were detected in water from the Keyes well, which was subsequently removed from service. The well is at the downgradient end of a 3.3 mi^2 glacial-drift river valley aquifer, called the Milford-Souhegan aquifer in this report, and is about 40 ft from a partly incised river, the Souhegan River. The 18-inch-diameter well was formerly pumped at a rate of about 0.14 Mgal/d over a 6 to 8 hour period daily.

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), conducted a study from October 1988 to June 1990 of the Milford-Souhegan aquifer to determine the regional ground-water-flow system and provide estimates of the contributing recharge areas to the Keyes well, and to a second discontinued municipal-supply well (the Savage well), about 1.5 mi west of the Keyes well (Harte and Mack, 1992). The study included collection of geohydrologic data and water levels, and measurement of selected water-quality properties from May 1987 to June 1990, and a 7-day multiple-well aquifer test of the Keyes well in October 1988.

Some results of the Keyes well multiple-well aquifer test were examined previously by Harte and Mack (1992); however, the regional nature of the previous study prevented a more comprehensive analysis of the local ground-water-flow system around the Keyes well. As a result, in 1993, the USGS, in cooperation with the USEPA, reexamined the Keyes well multiple-well aquifer test with respect to the local heterogeneity of the aquifer and the interaction of the Souhegan River with the ground-water-flow system.

Purpose and Scope

The purpose of this report is to present the results of multiple-well aquifer test at the Keyes well and estimations of hydrologic properties of the stratified-drift aquifer and riverbed near the Keyes well. This report includes (1) geologic sections of the aquifer through the Keyes well area, (2) water-level drawdowns from the multiple-well aquifer test, (3) selected water-quality constituents of pumped water measured during the multiple-well aquifer test, and (4) estimates of aquifer and riverbed hydrologic properties. This report also includes results of single-well tests (slug tests) and grain-size analyses collected at eight observation wells and one riverbed piezometer. The hydrologic properties estimated from the multiple-well aquifer test and single-well tests are compared to improve an understanding of the heterogeneity of the aquifer.

Previous Investigations

Regional geology and hydrologic properties for glacial deposits in the Milford-Souhegan River valley are provided in Koteff (1970) and Harte and Mack (1992). These studies characterized the deposits near the Keyes well as coarse-grained sand in the upper deposits and progressively fine-grained sand and silt with depth. Sediment, water quality, and ground-water-flow information related to the Keyes well area has been collected by various investigators at a nearby former paint manufacturing site and a gasoline station (Arthur D. Little, Inc., 1994).

Geohydrologic Framework

The Milford-Souhegan stratified-drift aquifer consists of unconsolidated glacial sediments that fill a pre-glacial valley (fig. 1). These sediments were primarily deposited during the fourth stage of a glacial lake that covered the valley (Koteff, 1970). The spillway for this glacial lake, just south of the Milford town center, was at an altitude of 265 ft above sea level. The spillway outlet and the position of the glacial margin to the north controlled the depositional environment. Till discontinuously underlies stratified drift and consists of dense, poorly sorted sand, silt, and clay. Till thickness ranges from 0 to 13 ft at the Keyes well field (Harte and Mack, 1992). The total saturated thickness of the Milford-Souhegan stratified-drift aquifer ranges from 0 ft at a bedrock outcrop in the Souhegan River about 800 ft east of the Keyes well field, to about 80 ft at about 800 ft west of the Keyes well field.

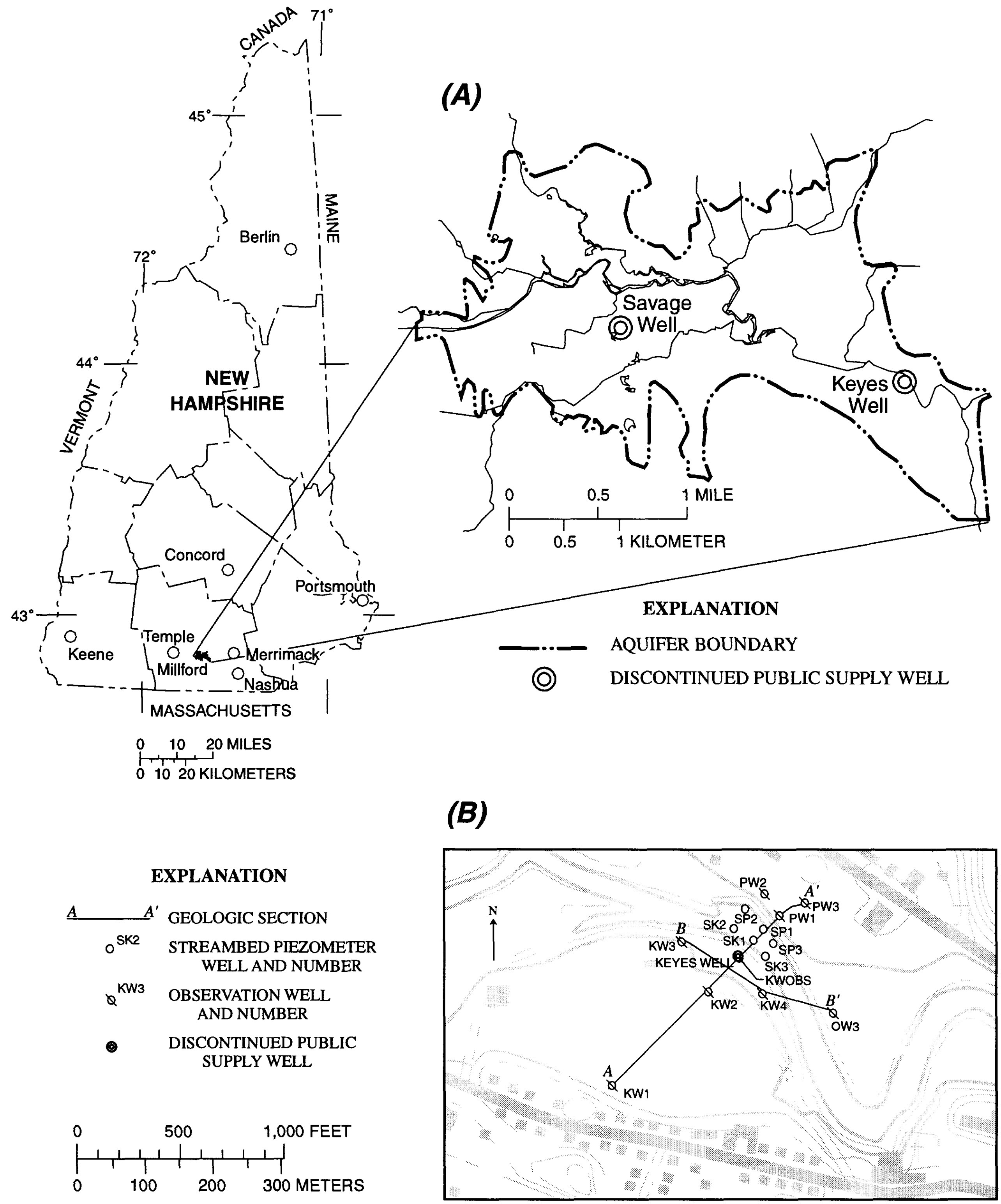


Figure 1. Location of Milford-Souhegan glacial-drift aquifer (*A*) Keyes well field and (*B*) location of wells and lines of geologic section.

The lithology of the aquifer underlying the Keyes well field area is shown in cross section in figures 2 and 3. Lines of section and locations of observation wells and riverbed piezometers are shown in figure 1. Grain-size samples were collected and analyzed during the installation of observation wells at the Keyes well field in September 1988. The distribution of lithologies from test borings indicate a heterogeneous mixture of sands, silts, and gravels. A summary of the vertical distribution of predominant material type is shown in these sections. In general, the sediments of the upper intervals of the aquifer, from land surface to a depth of about 25 ft below land surface, are coarser than sediments at greater depths. Fine-grained sediments are beneath the coarse-grained sediments throughout the area, except at the Keyes well, where coarse sands and gravels are reported in drillers' logs.

The small extent of the basal coarse sands and gravels found at the Keyes well indicate that these sediments represent an esker or ice-channel deposit. This deposit would, therefore, represent an older geologic unit than those found in the valley by Koteff (1970). Eskers and ice-channel deposits tend to be long lenticular-shaped features of limited width. During glacial retreat, a glacial lake formed and fine-grained

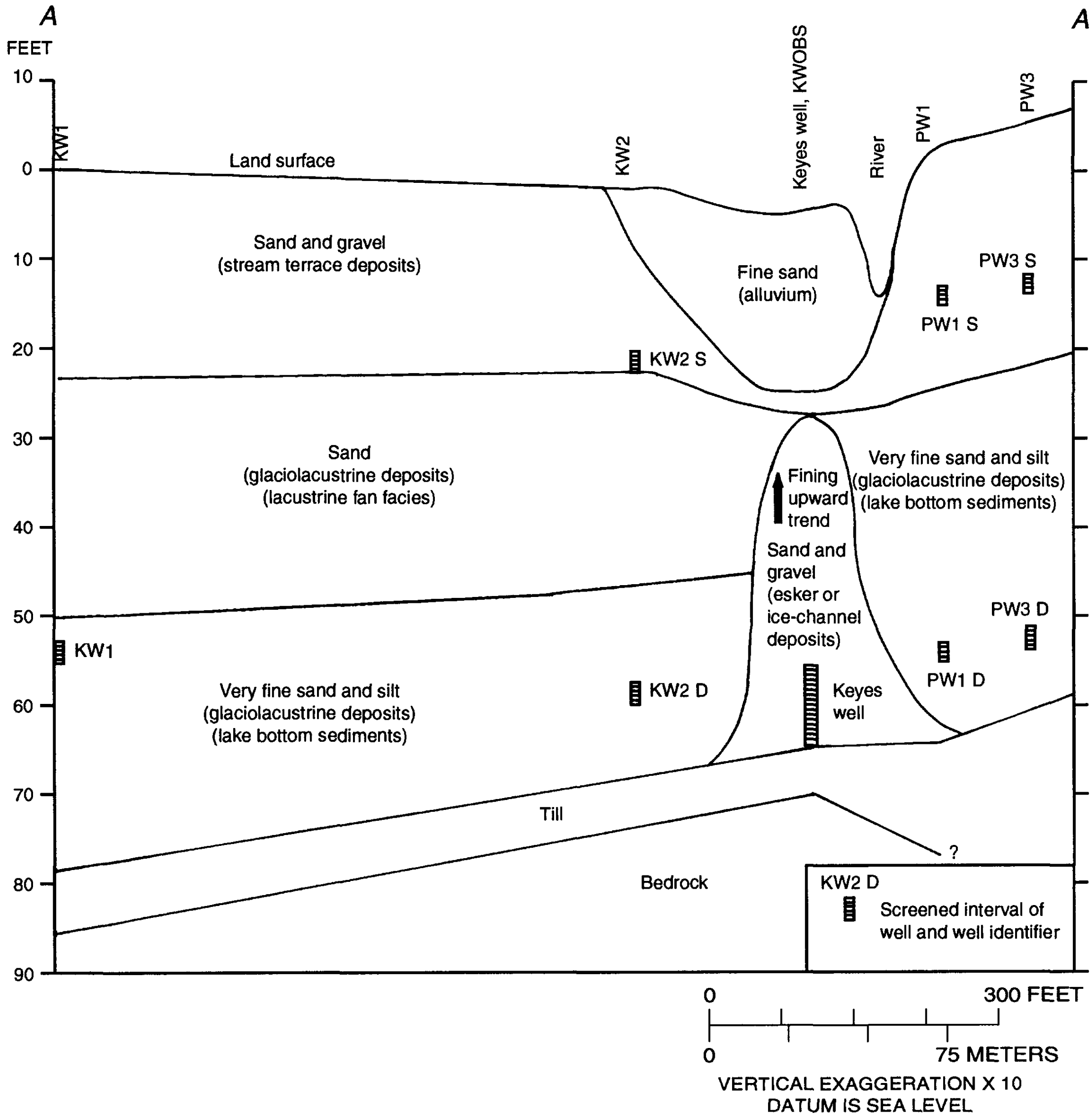


Figure 2. Geologic section *A-A′* of the Milford-Souhegan glacial-drift aquifer, Milford, New Hampshire. (Location of section shown in figure 1.)

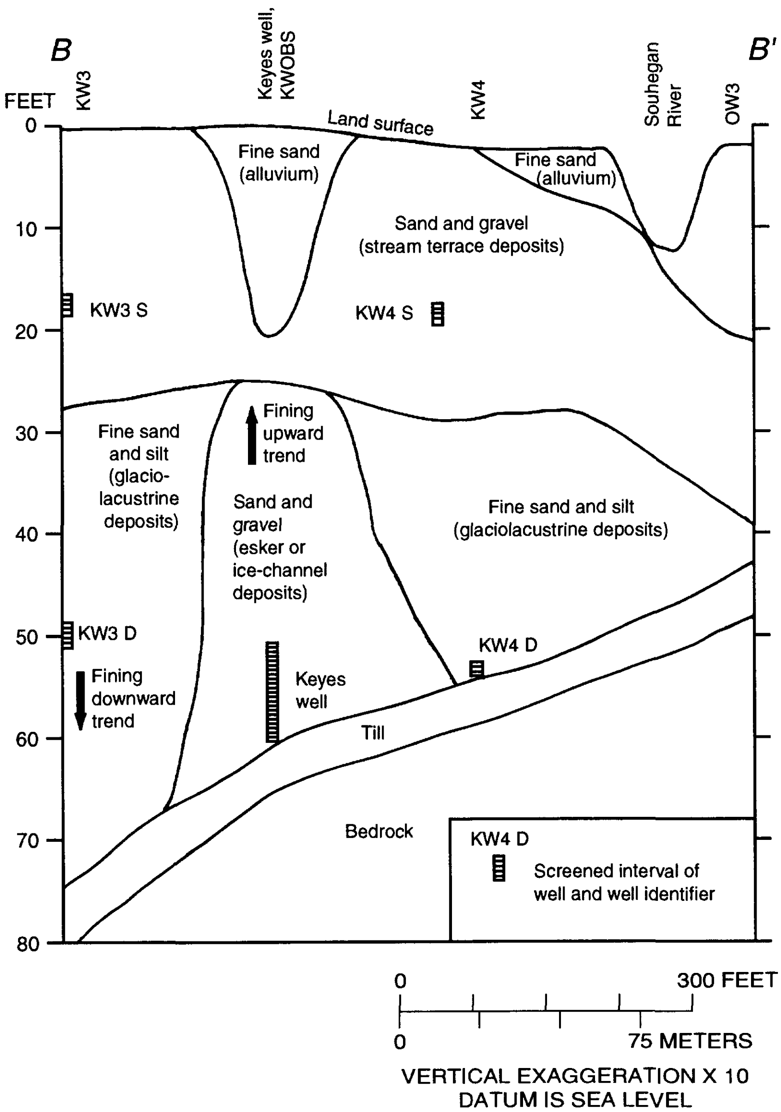


Figure 3. Geologic section *B-B′* of the Milford-Souhegan glacial-drift aquifer, Milford, New Hampshire. (Location of section shown in figure 1.)

lake bottom sediments filled in around the narrow band of sands and gravels. As sediments filled the lake, high energy meltwater caused a coarsening upward sequence to form the upper coarse-grained layer. Reworking of outwash deposits, as a result of meandering streams and deposition and erosion of sediments, left pockets of fine and coarse sands in the upper sediments.

Acknowledgments

The authors wish to acknowledge officials and employees of the Town of Milford for their cooperation and assistance.

DESCRIPTION AND RESULTS OF AQUIFER TESTS

Aquifer tests include a multiple observation-well aquifer test, and several single observation-well tests. The multiple observation-well aquifer test measured the response of several observation wells while withdrawing water at the Keyes well. The single-well tests, termed slug tests, measured the response of the aquifer to an instantaneous water-level change at a single observation well.

Multiple-Well Aquifer Test

A multiple-well aquifer test was conducted at the discontinued Keyes well beginning on October 13, 1988. The well was pumped continuously for 7 days (10,116 min) at an average rate of 300 gal/min. Prior to the test, 13 observation wells with 2-foot screens were installed near the Keyes well (fig. 1). Twelve of the wells were grouped in 6 shallow (KW2s, KW3s, KW4s, PW1s, PW2s, Pw3s) and deep (KW2d, KW3d, KW4d, PW1d, PW2d, Pw3d) well pairs. Shallow wells were screened just below the water table, at 20 to 25 ft below land surface. Deep wells were screened at the midpoint of the depth of the Keyes well screen, about 50 to 60 ft below land surface. Water levels also were measured at two pre-existing wells (OW3, KW1). Six riverbed piezometers (SK1, SK2, SK3, SP1, SP2, SP3) were installed just below the river bottom in the Souhegan River to examine water levels and hydrologic properties at the river-aquifer boundaries.

Distances from the Keyes well, screened interval below the water table, and other information for observation wells and piezometers are summarized in appendix 1. Water-level drawdowns at six observation wells during the multiple-well aquifer test are listed in appendix 2, and the water levels in six streambed piezometers and river stage are listed in appendix 3. Water-level recoveries at 10 observation wells after pumping ceased are listed in appendix 4. Specific conductance, pH, and temperature of the water pumped from the Keyes well were measured during the multiple-well aquifer test to determine sources of withdrawn water and are listed in appendix 5. Water samples collected during the multiple-well aquifer test were analyzed for volatile organic compounds (VOC's) (appendix 6), by the New Hampshire Department of Environmental Services (Patricia Hannon, written commun., 1988), and the results are listed in appendix 7.

Hydrologic conditions from natural stresses before and during the multiple-well aquifer test were relatively stable. Before the multiple-well aquifer test, on October 5–13, 1988 (Harte and Mack, 1992, appendix 3), water-table changes ranged from 0.05 to 0.21 ft in shallow wells (KW2s, KW3s, KW4s, PW1s, PW2s, and PW3s) near the Keyes well. Water-table levels measured at four wells outside the influence of pumping, before and during the multiple-well aquifer test, fluctuated by less than 0.5 ft with no pattern of rise or decline (Harte and Mack, 1992, appendix 3, well numbers 123, 150, 151, and 152). At well KW1, 870 ft from the Keyes well (fig. 1), the water level declined 0.15 ft during the multiple-well aquifer test, and at well OW3, 440 ft from the Keyes well and on the bank of the river, the water level was unchanged. Trace precipitation of 0.03 in. occurred on the sixth day of the test. On the seventh day of the test, water levels rose several tenths of a foot from a corresponding rise in the river stage. The rise in river stage was the result of precipitation in the headwaters of the Souhegan River drainage basin upstream from the Keyes well.

Water-Level Drawdowns

Water-level drawdowns from observation-well pairs are presented in figure 4. Plots of the deep-well data show smooth drawdown curves (fig. 4) with the exception of well PW2d where measurement difficulties hindered data collection. Plots of the shallow well (KW2s, KW3s, KW4s, PW1s, PW2s, and PW3s) data (fig. 4) are not as smooth as those for the deep wells (KW2d, KW3d, KW4d, PW1d, PW2d, and PW3d), because fewer data were collected at the shallow wells. The drawdown curves indicate an intermediate time, generally 50 to 2,000 min, of stabilized drawdown in the deep wells in response to the effects of either a leaky river boundary or delayed gravity drainage. Drawdowns in deep wells show a "late time" increase, but a rise in river stage at about 7,000 min effectively eliminates the remainder of the test from analysis (fig. 4). Precipitation in the headwaters of the Souhegan River drainage basin, at about 1,500 min, resulted in a rise in river stage as shown in the drawdown curve for shallow well KW3s, adjacent to the river (fig. 1). The effect of precipitation is small on other drawdown curves (fig. 4). Drawdowns in shallow wells were approaching the drawdowns in the deep wells near the end of the test. With favorable weather conditions and prolonged pumping, drawdowns in the upper part of the aquifer may have approached drawdowns in the lower part of the aquifer.

Water levels were measured in six riverbed piezometers, three on each side of the Souhegan River, during the multiple-well aquifer test (appendix 3). Water levels in the piezometers on the southwest bank of the Souhegan River adjacent to the Keyes well (SK1, SK2, SK3) and river stage are shown in figure 5A. Water levels in piezometers on the northeast bank of the Souhegan River (SP1, SP2, SP3) and river stage are shown in figure *5B*. Water-level measurements in the piezometers were from the top of each piezometer casing. River stage was measured from the top of piezometer SK1 (fig. 1). Before pumping, the water levels in the piezometers were slightly higher than the river stage. The water levels in piezometers fluctuate with changes in river stage. Early in the multiple-well aquifer test, at times less than 200 min, the river stage is constant and water-level drawdowns at the piezometers are readily apparent. Between 200 and 500 min, the river stage declined slightly, which increases drawdown in the piezometers. Later in the test, greater fluctuations in river stage of up to 0.5 ft and centered at 1,500 min, result in fluctuations in the riverbed piezometer water levels.

Water levels at SK1 and SP1 were adjusted for changes in river stage to remove river-stage changes on piezometer drawdown. Stage change was added to or subtracted from the piezometer drawdown to adjust the piezometer drawdown (fig. 6). Drawdowns at SK1 and SP1 were essentially the same early in the multiple-well aquifer test (at times less than 200 min) and were similar throughout the remainder of the multiple-well aquifer test. The maximum drawdown at piezometers SK1 and SP1 was 0.2 ft at about 6,000 min.

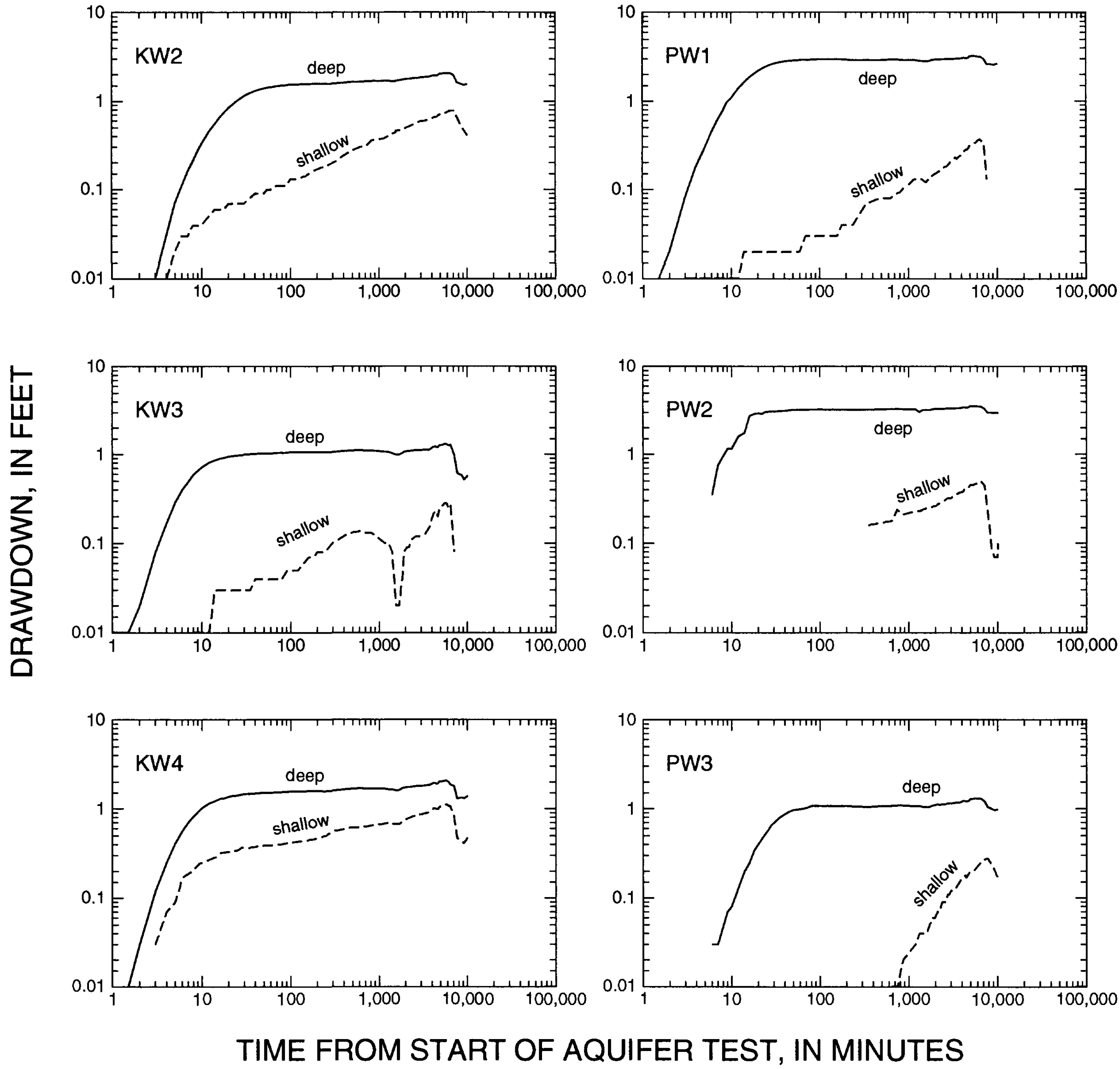


Figure 4. Water-level drawdowns in observation wells during the Keyes multiple-well aquifer test.

In general, water-level drawdowns at the shallow and deep observation wells indicate that the multiple-well aquifer test is affected by a leaky river boundary, delayed gravity drainage, and the fact that the aquifer and river leakage are heterogeneous. Delayed-gravity drainage at the water table is slight as a result of river-water leakage and the short duration of the test. Drawdowns from wells across the river from the Keyes well (PW1d, PW2d, and PW3d) show delays in initial drawdown responses that may be attributed to higher aquifer storage to the north of the Keyes well. The delayed response to the north also may be the result of river leakage. Greater drawdowns in deep wells PW1d and PW2d, than those at other deep wells, suggest low transmissivity in that area of the aquifer. Greater drawdowns in shallow wells KW4s and KW2s, than at other shallow wells, suggest low transmissivity in the upper aquifer in that area and less leakage. Induced infiltration may be greatest near well KW3s because drawdown is lower at well KW3s than at other water-table wells and this well shows a significant response to a rise in the river stage suggesting good hydraulic connection with the river.

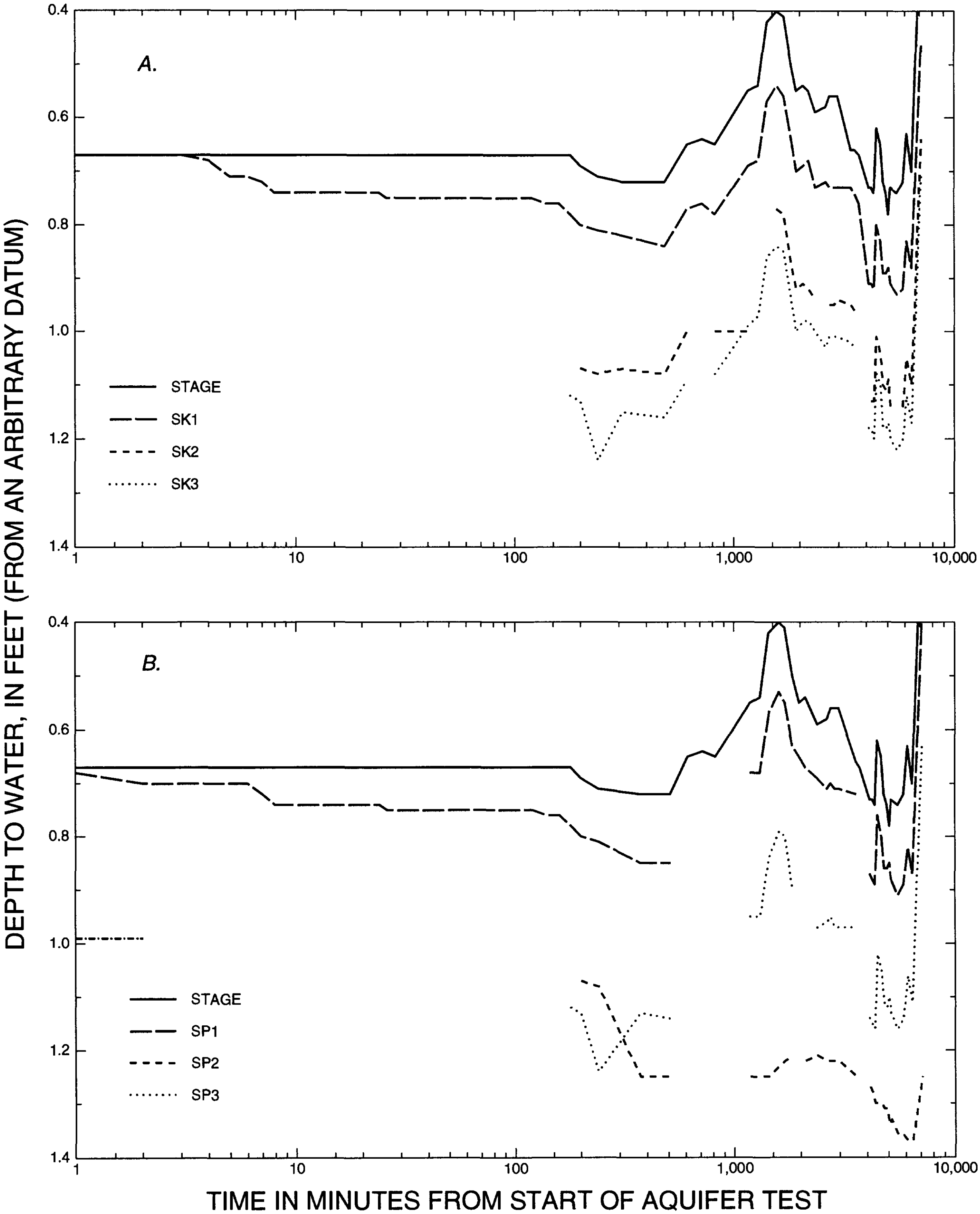


Figure 5. River stage and water levels in riverbed piezometers during the Keyes multiple-well aquifer test at (*A*) piezometers SK1, SK2, and SK3, and (*B*) piezometers SP1, SP2, and SP3.

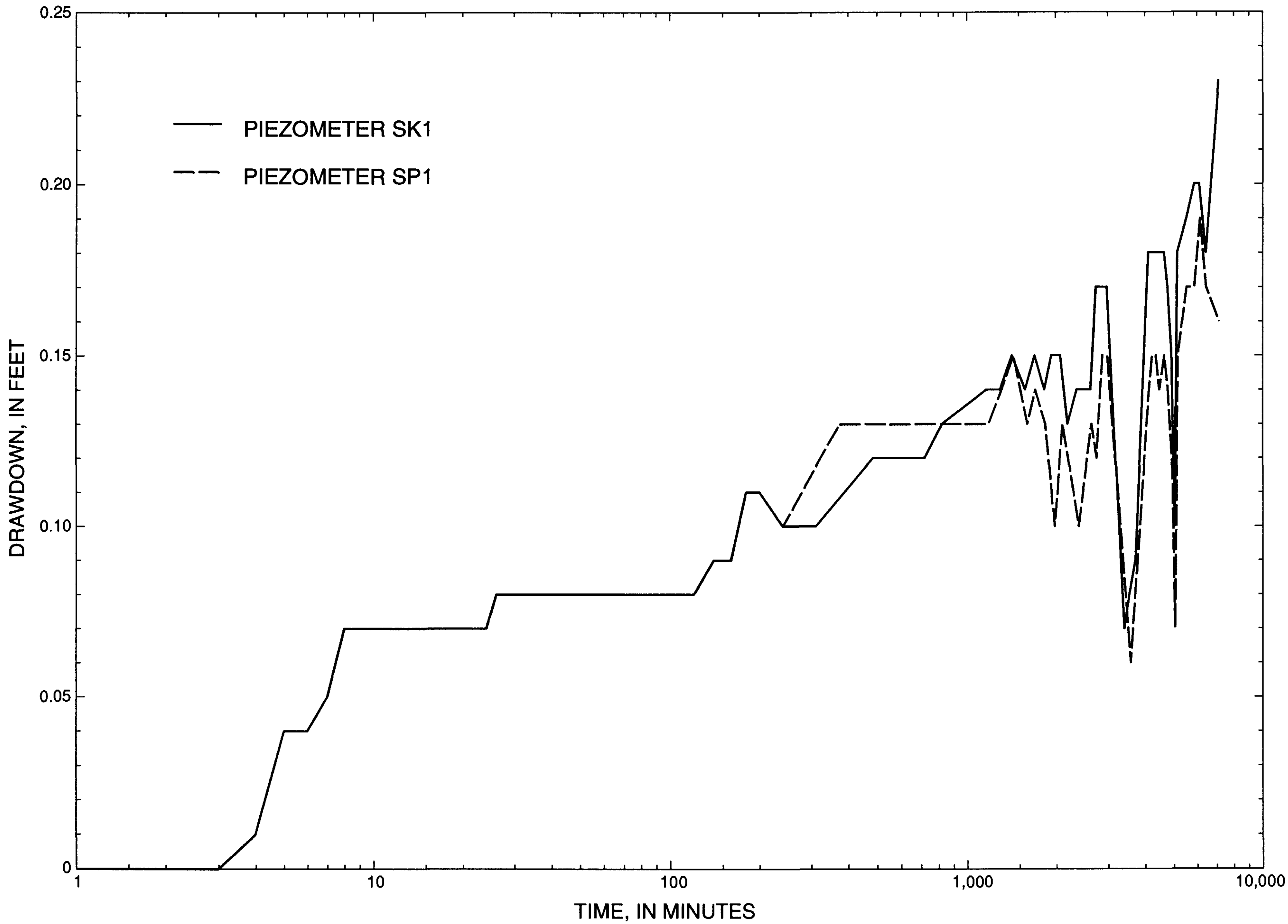


Figure 6. Normalized drawdown at riverbed piezometers SK1 and SP1 adjusted for changes in river stage.

Direction of Ground-Water Flow

The water-table surface, at the Keyes well and surrounding area, before pumping, reflects the influence of the river as the major sink in the ground-water-flow system (fig. 7*A*). A streamflow gain of 2.99 ft^3/s, measured in the Souhegan River on October 3 and 14, 1988, in the absence of pumping, at the east end of the Milford-Souhegan aquifer, indicates that this is an area where ground water discharges to the river (Harte and Mack, 1992, table 4, p. 22).

The direction of ground-water flow for the lower part of the aquifer (the part of the aquifer that corresponds to the screened zone of the Keyes well) at the Keyes well field after 720 min into the multiple-well aquifer test is shown in figure 7*B*. The ground-water-flow direction was altered by pumping so that head gradients were increased to the southwest and reversed to the southeast of Keyes well (fig. 7*B*). A head gradient is induced across the Souhegan River from the Keyes well, in the lower part of the aquifer, by pumping at the Keyes well.

Ground-water-flow directions at the water-table surface, after 720 min of pumping, were nearly unchanged from prepumping directions (fig. 7*A*). After about 7,000 min (5 days) of pumping at the Keyes well, the direction of ground-water flow at the water table changed slightly. With the exception of the pumped well, the maximum drawdown measured at the water table toward the end of the multiple-well aquifer test at the observation wells was about 1 ft. A maximum drawdown of 38 ft measured at the Keyes well was equivalent to a water-table gradient of about 0.9 ft/ft from the river to the production well. Most drawdowns at the water table were less than 0.5 ft, as compared to drawdowns in the lower aquifer of 1 to 3 ft.

Trends in Quality of Pumped Water

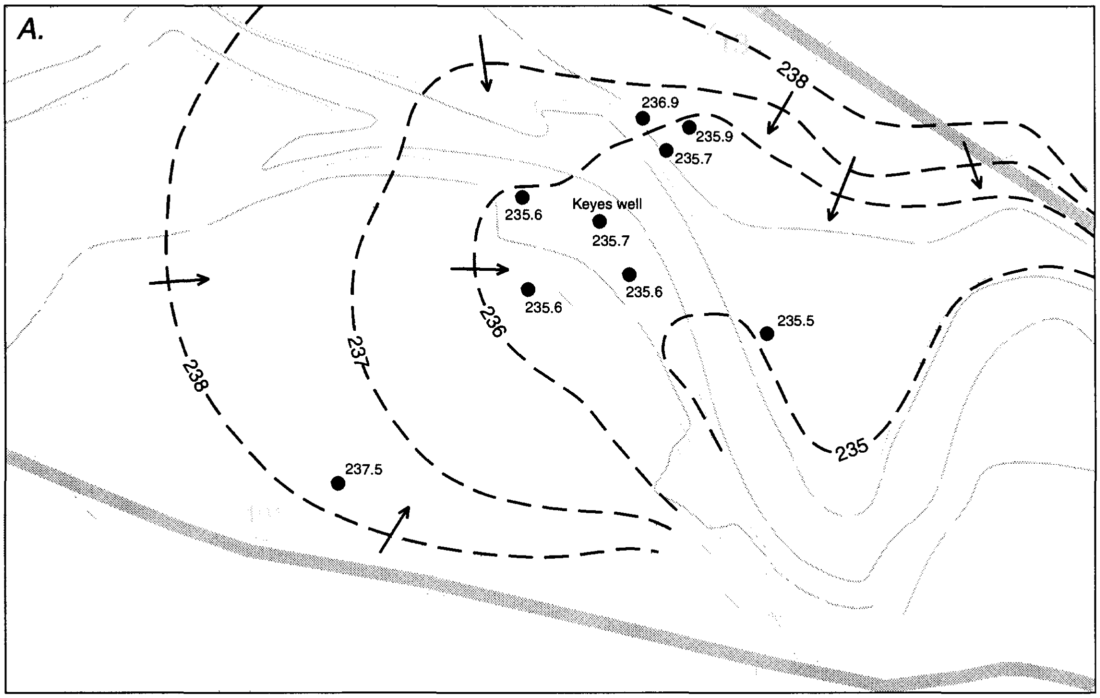
Specific conductance, pH, and temperature were collected from water pumped from the Keyes well (appendix 5) to help estimate the contribution of river water to the pumped well and the riverbed hydraulic conductivity. Specific conductance, pH, and temperature of ground water plotted against time from the start of pumping (fig. 8) the results indicate a trend in water quality of the pumped water. The change in water-quality indicates an inflow and mixing of surface water and of ground water of varying quality. Changes in water-quality characteristics are greatest early in the multiple-well aquifer test are more subtle by about 700 min, and are relatively stable towards the end of the test.

The specific conductance of the pumped water increases (fig. 8*A*) from an ambient value of 250 µS/cm and stabilizes at about 300 µS/cm after 800 min. The specific conductance of the Souhegan River water generally is about 60 to 250 µS/cm. The rise in specific conductance of pumped water during the multiple-well aquifer test may reflect an inflow of conductive contaminated ground water offsetting the effects of the influx of low-conductivity river water. Contaminants have been identified in the aquifer upgradient of the Keyes well (Arthur D. Little, Inc., 1994).

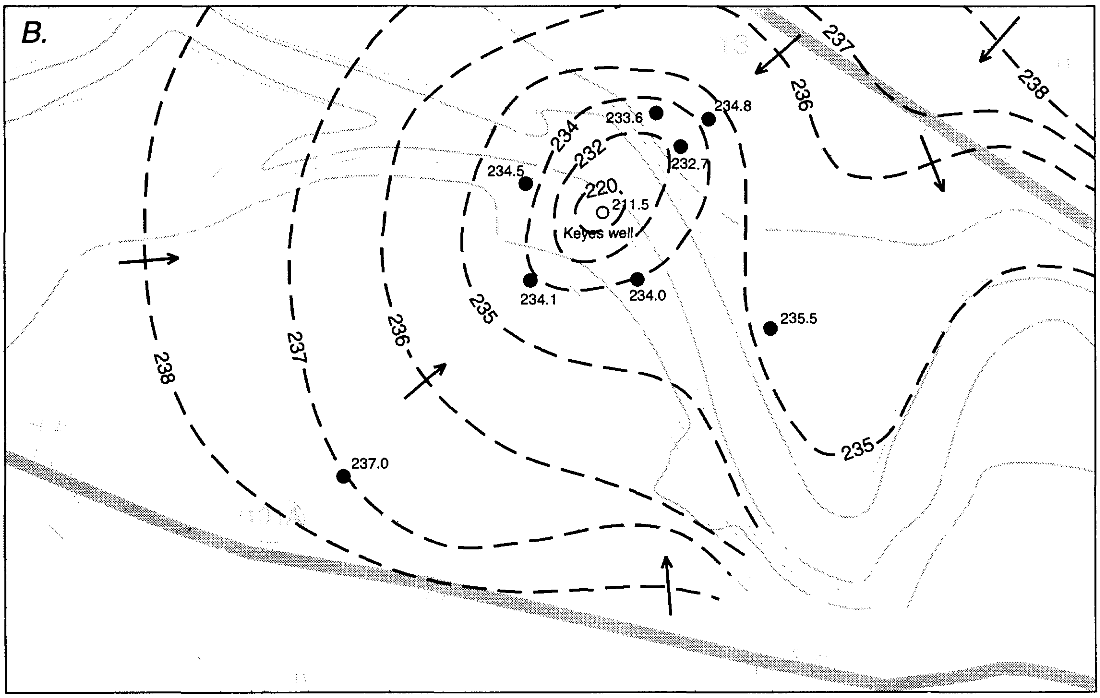
The pH of pumped water shows a similar but less well-defined trend as that for specific conductance (fig. 8). The pH of the pumped water decreases during the multiple-well aquifer test from about 7.1 to 6.5. Although the pH data (fig. 8*B*) indicate a change in the quality of water recharging the well during the multiple-well aquifer test, there is insufficient information on the pH of ambient ground water and Souhegan River water to use pH data in estimating the source, or relative amounts, of water recharging the well.

At the start of the multiple-well aquifer test, the average ambient ground water temperature at the Keyes well field was about 12.8°C and Souhegan River water temperature was 6.5°C. The temperature of the pumped water decreases from 12.8°C shortly after the start of the multiple-well aquifer test (fig. 8*C*), and stabilizes after about 600 min to a minimum of 11.2°C at 2,720 min. The decrease in the pumped-water temperature is attributed to an influx and mixing of surface water with ground water (the mixing trend is used in the section "Riverbed Leakage" to estimate riverbed leakage).

Three volatile organic contaminants (VOC's) were detected in the pumped water at 1,440 min after the start of multiple-well aquifer test—1,2-dichloroethane at 1.7 mg/L, benzene at 70 µg/L, and xylenes at 2.14 µg/L (appendix 7). Later in the multiple-well aquifer test, elevated concentrations of VOC's, including acetone (1,460 µg/L at 1,900 min) and benzene (250 µg/L at 2,325 min), were detected. From 3,360 to 11,520 min, the end of the multiple-well aquifer test, the pumped water contained a relatively constant concentration of 1,2-dichloroethane (12 to 15 µg/L) and an unknown organic compound indicated by gas chromatograph data (Patricia Hannon, New Hampshire Department of Environmental Services, written commun., 1988).



Potentiometric surface prior to pumping



Potentiometric surface after 720 minutes of pumping

EXPLANATION

— 238 — POTENTIOMETRIC-SURFACE CONTOUR--Shows inferred altitude of potentiometric surface, October 17, 1988. Contour interval varies, in feet above sea level

⟶ DIRECTION OF GROUND-WATER FLOW

● 237.5 OBSERVATION WELL--Number is altitude of potentiometric surface, in feet above sea level

○ 211.5 GROUND-WATER WITHDRAWAL WELL--Number is altitude of potentiometric surface, in feet above sea level

Figure 7. Altitude of potentiometric surface and horizontal ground-water-flow directions before and after 720 minutes of pumping at the Keyes well, Milford, New Hampshire.

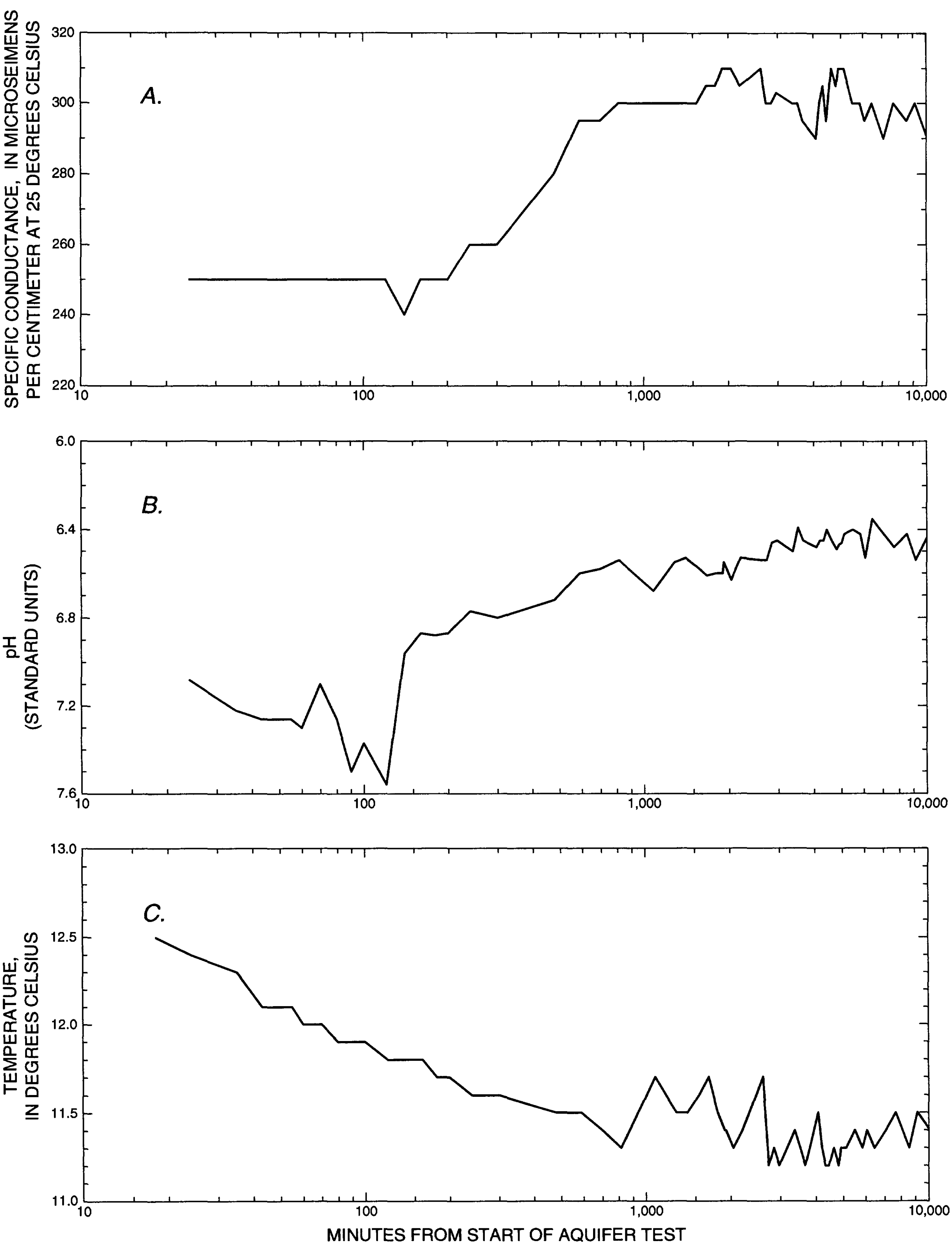


Figure 8. Specific conductance, pH, and temperature of water samples from the Keyes well during the multiple-well aquifer test.

An investigation done from 1991 to 1994 (Arthur D. Little, Inc., 1994) found elevated concentrations (hundreds to thousands of micrograms per liter) of benzene, toluene, ethylbenzene, and xylene (BETX) about 800 ft south of the Keyes well (300 ft east of KW1 fig. 1). Near a gasoline station 1,100 ft south and upgradient of the Keyes well, concentrations of these compounds of thousands of micrograms per liter were found (Arthur D. Little, Inc., 1994). BETX were not detected upgradient west of the Keyes well at observation wells KW1 or KW3s and only one detection of toluene (1.56 µg/L) was found at a site across the Souhegan River, about 400 ft east of the Keyes well, or 200 ft north of observation well OW3 (Arthur D. Little, Inc., 1994).

Single-Well Tests

Single-well tests (or slug tests) in observation wells, and grain-size distributions, sampled during observation-well installation, were analyzed to help determine the hydraulic conductivity of aquifer materials. Slug tests were performed in eight observation wells in September 1993 (appendix 8). Observation well pairs PW1, PW2, and PW3 had been destroyed by 1993; therefore, it was not possible to test all observation wells.

For these tests, a slug, with a displacement of 0.4 ft of water, in a 2-inch inside-diameter well, was lowered below the water level in a well and the change in water level from the initial positive displacement (forward test) was monitored by a pressure transducer and recorded with a data logger. After the water level equalized to the original static water level, the slug was removed and the water level rise from the negative displacement was monitored (reverse test). Comparison of forward and reverse tests allowed for verification of testing procedures.

ANALYSIS OF AQUIFER TESTS

Hydrologic properties at the Keyes well field were estimated from results of the multiple-well aquifer test and slug tests, which sample different aquifer volumes. The multiple-well aquifer test affects a relatively large volume of aquifer—several hundred to a 1,000 ft laterally and tens of feet vertically. The slug test affects a small volume of aquifer—several to tens of feet laterally and a few feet at most vertically, from the well screen. The multiple-well aquifer test provides information on transmissivity, vertical hydraulic conductivity, specific yield, and storage coefficient of the aquifer. Slug tests provide estimates of hydraulic conductivity around the individual well screens and integrate horizontal and vertical hydraulic conductivities.

Multiple-Well Aquifer Test

The multiple-well aquifer test affects an area up to several hundred feet from the pumped well that makes it possible to assess the hydrologic properties of stratified-drift aquifer, the induced riverbed leakage, and the hydrologic properties of riverbed sediments. The use of a number of analytical methods of analysis were assessed for determining hydrologic properties in this study including DeGlee (in Kruseman and deRidder, 1990, p.76), Neuman, 1974 and 1975; Theis, 1935; and Walton, 1962. The methods account for different aquifer characteristics to varying degrees but all methods assume an homogeneous, infinite aquifer.

Hydrologic Properties of Stratified Drift

In assessing the Keyes well multiple-well aquifer test, river leakage and the presence of various sediment types (figs. 2 and 3) were factors to be addressed in the analysis, both conditions result in an heterogeneous aquifer. The complex heterogeneous system examined in this study is not well suited to analysis by analytical methods. Ideally, this aquifer system would be analyzed by methods in which spatially variable geologic and hydrologic properties of the aquifer could be represented, such as by use of a three-dimensional numerical ground-water-flow model. An analytical analysis of the Keyes well multiple-well aquifer test is presented here to provide approximate estimates of hydrologic aquifer properties, and to illustrate the difficulties in assessing a complex aquifer system using an analytical approach.

Aquifer-test drawdown data were analyzed by use of the methods of Neuman (1974,1975) because the drawdown curves (fig. 4) indicate an unconfined aquifer and the pumped well is partly penetrating. This method assumes a homogeneous, vertically anisotropic, unconfined-aquifer system, and accounts for partially penetrating withdrawal and observation wells. This method can be used to estimate aquifer transmissivity, the ratio of vertical to horizontal hydraulic conductivity (k_z/k_h), storage coefficient (S), specific yield (S_y), and the ratio of storage coefficient to specific yield (S/S_y). Composite plots of drawdown and type curves for deep (fig. 9) and shallow (fig. 10) observation wells were generated according to methods described by Moench (1993, 1994). By this method, a composite set of type curves are matched to a composite set of drawdown curves simultaneously to provide a single match point for the analysis. This method provides a more realistic means of estimating bulk aquifer properties than by matching curves individually (Moench, 1994). Composite plots are separated into deep (fig. 9) and shallow (fig. 10) observation wells to illustrate the differences in the shallow-well and deep-well responses and to aid the visual curve matching process.

The type curves shown in figure 9 were generated through trial-and-error adjusting of the ratios of anisotropy—vertical to horizontal hydraulic conductivity (K_z/K_h) and of storage coefficient to specific yield (S/S_Y). For the deep and shallow observation wells, type curves generated using an anisotropy of (K_z/K_h) of 0.10 and S/S_Y of 0.001 best fit the composite drawdown curves. The composite plots for the deep observation wells (fig. 9) show the effects of aquifer heterogeneity and river leakage. Theoretically, plots of drawdown versus t/r^2 (elapsed time divided by distance from the pumped well squared) should overlay with their respective type curve if the aquifer is homogeneous and isotropic (Moench, 1994). Because this is not true, the composite plots clearly indicate a heterogeneous aquifer.

The drawdown curves for the deep observation wells can be grouped into two distinct sets, indicating that the heterogeneity at the site is not random. Wells KW3d and KW4d show an earlier response to pumping indicating a low storage coefficient. Wells KW2d, PW1d, PW2d, and PW3d show a later response to pumping indicating a high storage coefficient. A best fit of the composite type curves to early-time data yields a transmissivity and storage coefficient of about 725 ft^2/d and 0.002, respectively. The late-time deep-well drawdown data were not sufficient for detailed analysis because of precipitation late in the test period. Hydrologic properties estimated for each individual well are listed in table 1. The deep-well drawdown curves indicate nearly a 3-fold range in transmissivity values. This variation indicates that the aquifer may be sufficiently heterogeneous that the multiple-well aquifer-test results cannot be correctly analyzed by analytical methods. Additionally, the calculated storage coefficient S (0.002) and ratio S/S_Y (0.001) indicates that the analysis is affected by river leakage and does not produce realistic values. The actual storage coefficient probably is less than the calculated value. The values reported in table 1 can only be used as estimates of the actual values or to infer the variations in the relative values of the hydrologic properties of the aquifer. Type-curve match points and other information used to calculate the estimates of hydrologic properties are in appendix 9.

A composite plot of shallow observation-well drawdown curves and a plot of corresponding type curves is shown in figure 10. The shallow-well drawdown curves are not as smooth or complete as the deep-well drawdown curves, particularly the drawdown curve for PW2s. The shallow well data curves generally were adequate for estimating approximate transmissivities using early to intermediate data. Composite type curves generated using the ratios K_z/K_h of 0.10, and S/S_y of 0.001 best fit the composite data plots. The shallow-well analysis was less sensitive to the ratio of K_z/K_h than the deep well analysis. Based on early to intermediate-time data, composite transmissivity was 3,870 ft^2/d.

Table 1. Summary of aquifer hydrologic properties estimated from the Keyes multiple-well aquifer test, Milford, New Hampshire

[ft^2/d, square foot per day; --, data curve is inadequate to calculate the hydrologic property]

Well	Transmissivity (ft^2/d)	Storage coefficient
Shallow Wells		
KW2s	4,980	--
KW3s	8,040	--
KW4s	630	--
PW1s	1,830	--
PW2s	--	--
PW3s	--	--
Average	3,870	--
Deep Wells		
KW2d	1,020	3×10^{-3}
KW3d	1,180	2×10^{-3}
KW4d	560	1×10^{-3}
PW1d	450	2×10^{-3}
PW2d	690	2×10^{-3}
PW3d	450	1×10^{-3}
Average	725	2×10^{-3}

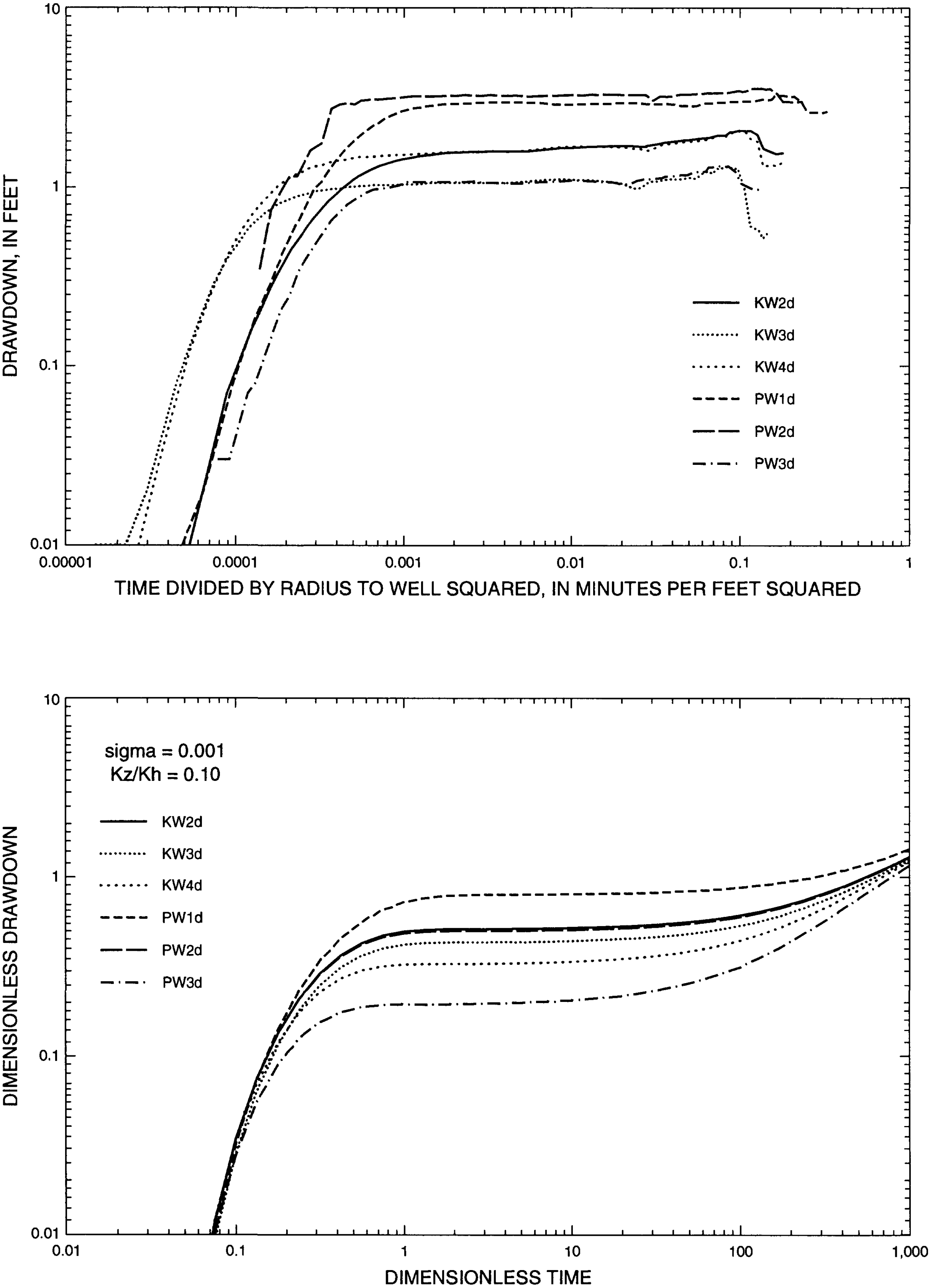
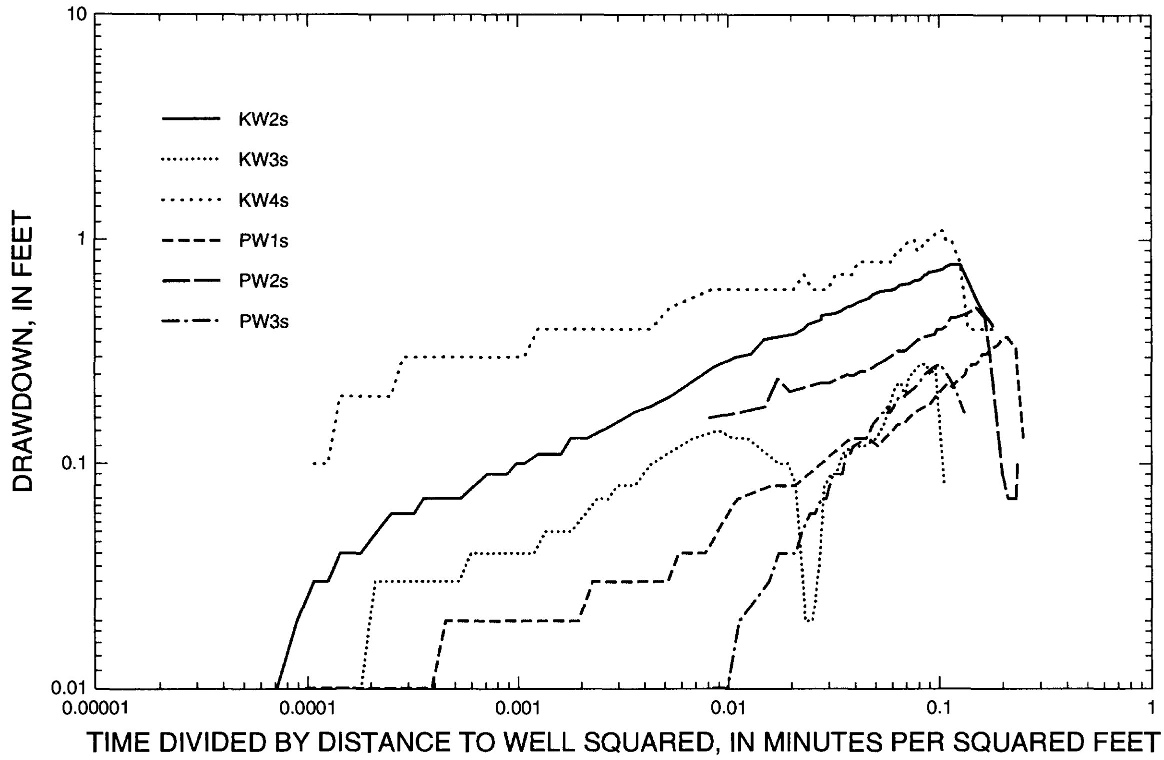


Figure 9. Composite water-level drawdowns in deep observation wells and corresponding type curves during the Keyes multiple-well aquifer test.



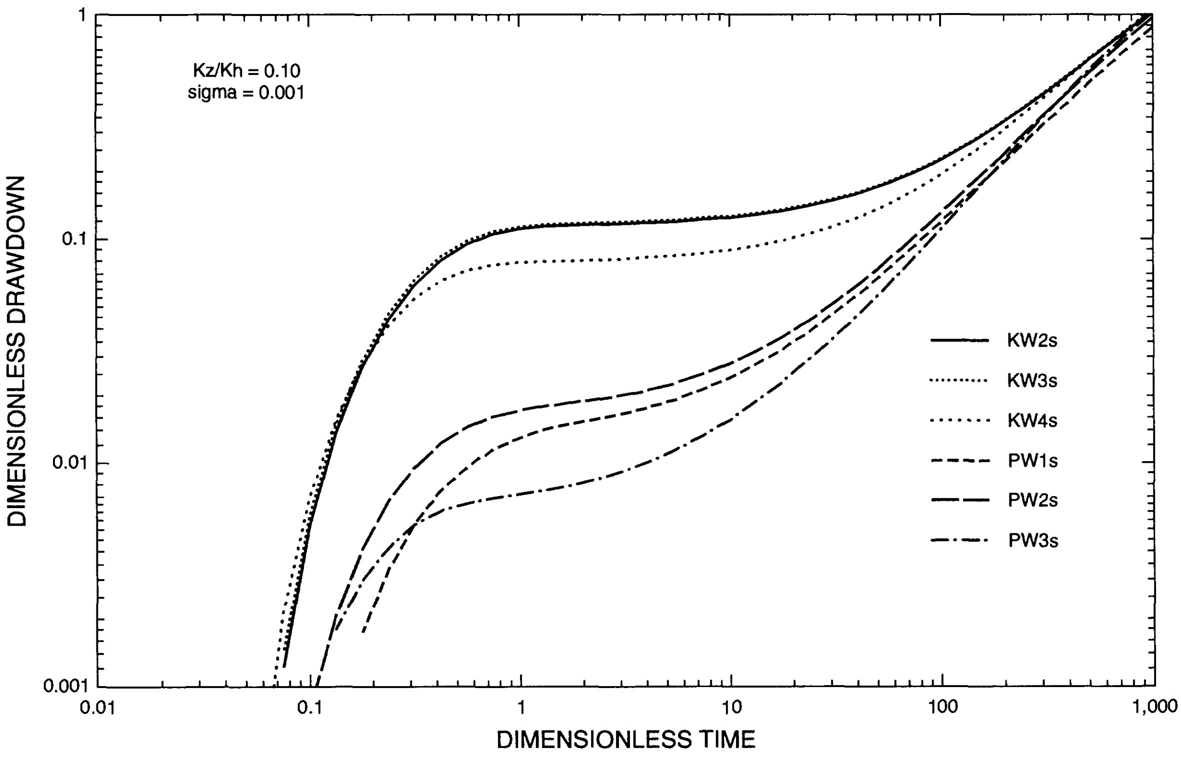


Figure 10. Composite water-level drawdowns in shallow observation wells and corresponding type curves during the Keyes multiple-well aquifer test.

In summary, although the Keyes well aquifer is not a homogeneous aquifer that can be analyzed by use of the Neuman method (or most analytical methods), some generalizations regarding aquifer properties can be made. From the response of the deep wells to pumping, the lower part of the aquifer has a transmissivity of about 725 ft^2/d, with a corresponding horizontal hydraulic conductivity of about 11 ft/d, the storage coefficient is probably less than 0.002. From the response of the shallow wells, the upper part of the aquifer has a transmissivity of about 3,870 ft^2/d. The ratio of vertical to horizontal hydraulic conductivity of the entire aquifer is about 0.10.

Riverbed Leakage

The multiple-well aquifer test indicates that ground-water withdrawals lower heads below the river stage and induce river leakage. An effective riverbed vertical hydraulic conductivity and the contribution of river water to the Keyes well were calculated from estimates of river leakage, using a mass balance mixing model, field chemical data collected during the multiple-well aquifer test, and drawdowns from riverbed piezometers.

The temperature of pumped water from the Keyes well, plotted with time from start of the multiple-well aquifer test (fig. 8*C*), indicates that the river contributes to the pumped water. River water had a lower temperature (6.5°C) than the temperature of ambient ground water (12.8°C). The ambient ground-water temperature of 12.8°C represents an average temperature of ground water near the Keyes well based on temperature data collected in early October 1988[1]. The equation for the mass-balance mixing model is

$$t_w = t_g \, p_g + t_r \, p_r \, , \qquad (1)$$

where

t_w is temperature of water pumped from the well (11.2°C at 2,720 min),

t_g is temperature of ambient aquifer ground water (12.8°C),

p_g is fraction of aquifer water contributing to the pumped water, and

t_r is temperature of river water (6.5°C),

p_r is fraction of river water contributing to the pumped water.

From the relation

$$p_g + p_r = 1, \qquad (2)$$

substitution of equation (2) into (1) provides a direct solution for p_r:

$$p_r = (t_w - t_g)/(t_r - t_g). \qquad (3)$$

Solution of equations 2 and 3 indicates that 25 percent of the water contributing to the Keyes well is from the river and 75 percent is from ground water. For the measured pumping rate of 0.65 ft^3/s, riverbed leakage was 0.16 ft^3/s of water to the well. However, the actual amount of induced infiltration may exceed 0.16 ft^3/s if the Keyes well does not capture all of the induced infiltration. This condition—termed throughflow (Newsom and Wilson, 1988)—occurs when water leaves the river as the result of induced infiltration, is not captured by the pumped well, and returns to the river downgradient of the pumped well.

The potential for throughflow during the multiple-well aquifer test appears to be minimal given the hydraulic gradients and estimated ground-water fluxes in the aquifer. Newsom and Wilson (1988) provide a method to estimate the potential for throughflow based on a two-dimensional model of ground-water flow and image-well theory. Estimates of throughflow, based on site-specific criteria, are made by computing a parameter called dimensionless pumpage (beta) and comparing figures 1 and 4 in Newsom and Wilson (1988). The dimensionless pumpage parameter also is used to determine the amount of induced infiltration from the river. The equation for determining the dimensionless pumpage parameter, and values from the Keyes well multiple-well aquifer test, are

$$\text{beta} = Q/qa \bullet pi \bullet d, \qquad (4)$$

---

[1]Although an average temperature is used, temperatures are variable in the aquifer. For example, in late October and early November 1993, shallow ground water measured in water-table wells had temperatures of about 11°C (Arthur D. Little, Inc., 1994). For that same period, ground water measured in deep wells completed in stratified drift had temperatures of about 7 to 9°C. Ground water contaminated with VOC's, measured in well KW2d, had a temperature of 14.7°C (Cheryl S. Prague, U.S. Environmental Protection Agency, written commun., 1995).

where

Q is withdrawal from the well (57,888 ft^3/d);

qa is discharge per unit width of ambient ground-water flow (27 ft^2/d);

pi is 3.14; and

d is distance of the well from river (40 ft).

For the Keyes well test, the solution of equation 4 yields a beta of 17. Ambient ground-water flow of 27 ft^2/d was determined from seepage gains near the Keyes well of 2.99 ft^3/s (Harte and Mack, 1992) divided by length of reach 9,500 ft. Newsom and Wilson (1988, fig. 2) show that beta of 17 is well above the critical value needed for a well to capture all induced inflow from the river.

A potential inflow of 65 percent of total pumpage is possible given the ambient ground-water-flow direction to the river of 52 degrees (the angle between the primary flow direction and the river) Newsom and Wilson (1988, fig. 5). This estimate exceeds the induced infiltration computed from the temperature-mixing model (25 percent). It also exceeds the induced infiltration computed from a three-dimensional ground-water-flow model (49 percent) described in Harte and Mack (1992) and Olimpio and Harte (1995). Because the analytical solutions developed by Newsom and Wilson (1988) are derived for a two-dimensional system, which assumes a fully penetrating river and well, the two-dimensional-system estimates should be higher than those estimates calculated from the multiple-well aquifer test and from a three-dimensional ground-water-flow model. Because equilibrium was not met during the Keyes well multiple-well aquifer test (water levels in shallow observation wells were still declining during test), estimates of induced infiltration from a steady-state model should be greater than estimates from the multiple-well aquifer test and the temperature-mixing model.

Hydrologic Properties of Riverbed Sediments

Riverbed vertical hydraulic conductivity was calculated by use of a one-dimensional Darcy flow equation, as follows:

$$Q = A\, i\, K_r \,, \qquad (5)$$

where

Q is riverbed leakage (0.16 ft^3/s),

A is riverbed area (300,000 ft^2),

i is hydraulic gradient across the riverbed (0.0225 ft/ft), and

K_r is riverbed vertical hydraulic conductivity.

The solution of equation 5 yields a riverbed hydraulic conductivity of approximately 2 ft/d. The parameters specified for estimating riverbed hydraulic conductivity (equation 5) are derived from the calculated river leakage (using the temperature-mixing model), estimates of riverbed leakage area, and average hydraulic gradients. The riverbed area (300,000 ft^2) is the river width times the riverbed length across which leakage is estimated to have occurred. The river width adjacent to the Keyes well is 75 ft. The length across which leakage occurred was estimated by extrapolating drawdown at the piezometers out to a 0.02 ft drawdown point for a total length of 4,000 ft. The distance-drawdown point of 0.02 ft was chosen to coincide with head difference between river and riverbed head and represents the point of zero vertical hydraulic gradient, or no flow from the river to the aquifer. A hydraulic gradient across the riverbed of 0.0225 was calculated from an average piezometer drawdown of 0.09 ft and assuming a riverbed thickness of 4 ft. Given the uncertainties involved in the understanding and measurement of river and aquifer interactions, 2 ft/d probably is within an order of magnitude of the actual mean value and is a reasonable estimate of riverbed vertical hydraulic conductivity.

A sample of riverbed material collected adjacent to the Keyes well was analyzed for grain-size distribution and a hydraulic conductivity of 10 ft/d was calculated. A riverbed-sediment sample was selected from fine-grained layers because the fine-grained layers would restrict flow and would dominate the effective hydraulic conductivity. Riverbed hydraulic conductivity estimated by the grain-size analysis is similar to the riverbed hydraulic conductivity estimated by the temperature-mixing model.

Single-Well Tests

Slug tests were analyzed by the Bouwer and Rice (1976) method, this method assumes unconfined aquifer conditions and integrates the effects of horizontal and vertical flow. Vertical flow can occur around the well screen of partially penetrating wells. Hydraulic conductivity also was estimated at eight wells by use of a grain-size distribution and hydraulic conductivity relation described by Olney (1983). This method, developed from an empirical relation between an effective grain size and hydraulic conductivity for New England glacial sands, provides a bulk estimate of hydraulic conductivity but does not account for the directional heterogeneity of the aquifer. This method has been used by Harte and Mack (1992, p. 30–38), and other studies, to provide an approximate estimate of hydraulic conductivity where no hydrologic data exists. A summary of results of slug tests (slug and grain-size analysis) are provided in table 2. Information used to calculate the estimates of hydraulic conductivity are provided in appendix 10. The analyses indicate that hydraulic conductivities from shallow wells are greater than those from deep wells. However, the slug-test results indicate greater ranges and values of hydraulic conductivities than the grain-size analysis. Hydraulic conductivities estimated from forward and reverse slug tests compare favorably. Hydraulic conductivities at shallow wells range from 5.3 to 128 ft/d (forward tests). Hydraulic conductivities at deep wells range from 1.9 to 76 ft/d (forward tests). Hydraulic conductivities estimated from grain-size analysis of sediment samples from two shallow wells were 15 and 20 ft/d and from three deep wells were about 5 ft/d.

The estimated hydraulic conductivities based on slug tests indicate that hydraulic conductivity is higher to the west of the Keyes well in the upper and lower intervals of the aquifer than in other areas near the Keyes well. This is consistent with lithologic observations which indicate that coarse-grained deposits in a narrow west to east band several hundred feet in width.

Comparison of Multiple-Well Aquifer Tests and Slug Tests

Comparison of estimates of hydraulic conductivity from aquifer and slug tests allow for a comparison of estimates of hydraulic conductivity over different scales of measurement. Other studies have indicated that measurements of hydraulic conductivity in glacial and fluvial materials are scale dependent and should be examined with respect to operational scale of measurement (Bradbury and Muldoon, 1990). Hydraulic conductivity computed from slug tests reflects small sample volumes. The data from slug tests can be correlated to hydraulic conductivities estimated from grain-size analyses of material from the well screen zone. Hydraulic conductivity computed from the Keyes well multiple-well aquifer test reflects an

Table 2. Summary of hydraulic conductivity estimates from multiple-well aquifer tests and slug tests, Keyes well, Milford, New Hampshire

[Information used to calculate the estimates of hydraulic conductivity are provided in appendix 10. ft/d, foot per day; --, no data]

Well	Aquifer tests for hydraulic conductivity			Grain-size analysis for hydraulic conductivity (ft/d)
	Multiple-well (ft/d)	Slug test: Forward analysis (ft/d)	Slug test: Reverse analysis (ft/d)	
Shallow Wells				
KW2s	58	32	--	5
KW3s	150	128	154	15
KW4s	10	5.3	5.4	20
PW1s	36	--	--	--
PW2s	--	--	--	--
PW3s	38	--	--	--
Average...	58	55	80	13
Deep Wells				
KW1	--	4.6	2.9	5
KW2d	8	1.9	1.7	5
KW3d	14	20	26	5
KW4d	8	8.6	9.4	6
PW1d	14	--	--	5
PW2d	7	--	--	--
PW3d	7	--	--	--
OW3	--	76	105	--
Average...	10	22	29	5.2

average of a large sample volume and integrates the effects of the upper and lower parts of the aquifer. The multiple-well aquifer test also incorporates the effects of local boundary conditions including the Souhegan River and variations in saturated thickness.

A comparison of hydraulic conductivity estimates from the slug, small-scale tests with the large-scale multiple-well aquifer test shows similar values of hydraulic conductivity (table 2). In areas where multiple-well aquifer test results indicate a relatively high hydraulic conductivity, slug tests also indicate a relatively high hydraulic conductivity. Aquifer and slug tests indicates a high hydraulic conductivity west of the Keyes well, and low hydraulic conductivity to the south. The slug test results indicate a slightly wider range of hydraulic conductivity values, than the multiple-well aquifer test results, because of the slug test's small sample volume and dependance on local heterogeneity. The multiple-well aquifer test samples a larger volume of the aquifer which effectively averages differences in hydraulic conductivity in that sample volume.

Estimates from the multiple-well aquifer test could not be compared at observation well OW3, to the east of the Keyes well (fig. 1), because drawdown was not measurable at this well during the multiple-well aquifer test. Because well OW3 was screened in coarse-grained deposits that are in hydraulic connection with the Souhegan River, it was not possible to produce a drawdown at this well by pumping at the Keyes well. Therefore, the location of the observation wells for the multiple-well aquifer test were not adequate to estimate the high transmissivity east of the Keyes well. Results of the slug tests at this well indicate a high hydraulic conductivity (76 and 105 ft/d, table 2), which is consistent with the interpreted geologic section (fig. 3).

SUMMARY AND CONCLUSIONS

An multiple-well aquifer test of the Keyes well was done on October 13, 1988, and continued for 7 days at a pumping rate of 300 gal/min. During the test water levels at 13 observation wells and 6 piezometers in the Keyes well field, and the water quality of the pumped well were monitored. Seven wells were screened at the same depth as the Keyes well, six wells were screened at the water-table surface, and six piezometers were set in the riverbed of the Souhegan River. The aquifer in the Keyes well area consists of from 0 to 80 ft of unconsolidated glacial sediments that fill a buried pre-Pleistocene valley. The glacial sediments at the well field are generally fine-grained sands and silts with the exception of a narrow area of coarse-gained sands and gravels within which the Keyes well is screened. The coarse-grained glacial sediments most likely represent a buried esker or ice-channel deposit and account for the high yield of this well (0.14 Mgal/d).

The ground-water-flow direction at the Keyes well field under unstressed conditions is towards the Souhegan River, which is gaining near the well field. During the Keyes well multiple-well aquifer test, ground-water-flow directions in the Keyes well field were altered so that flow was towards the Keyes well in the lower part of the aquifer. A downward head gradient was induced, in the lower part of the aquifer across the Souhegan River from the Keyes well, during pumping. Ground-water flow at the water table is nearly unchanged during the multiple-well aquifer test with the exception of the area near the Keyes well where the water table was drawn down.

Trends in specific conductance, pH, and temperature of water pumped from the Keyes well indicated that induced infiltration and capture of river water occurred during the multiple-well aquifer test. The temperature of the pumped water showed a clear trend of the influence of induced infiltration of river water at the well. Ground-water temperature at the Keyes well before the aquifer-test withdrawals was 12.8°C. After 600 min of pumping, the temperature of pumped water stabilized at about 11.2°C. Stream-water temperature was 6.5°C at the time of the multiple-well aquifer test. After 1,440 min of pumping, 1,2-dichloroethane was detected at 1.7 µg/L and from 3,360 min to the end of the test the concentration remained constant at 12 to 15 µg/L.

A transmissivity of about 725 ft^2/d was estimated for the lower part of the aquifer where the Keyes well is screened. The horizontal hydraulic conductivity of the lower part of the aquifer, with the exception of the immediate vicinity of the Keyes well, is about 10 ft/d. The horizontal hydraulic conductivity of the upper part of the aquifer, from analysis of individual observation well data, is about 58 ft/d and ranges from about 10 to 150 ft/d. The ratio of vertical to horizontal hydraulic conductivity was estimated to be about 0.10. The storage coefficient was estimated to be less than 0.002. Although the aquifer was unconfined, delayed gravity drainage effects were limited during the 7 day test, because of river leakage and because a multiple-well aquifer test greater than 7 days is needed.

Riverbed leakage was estimated to be 0.16 ft^3/s, or about 25 percent of the water pumped from the Keyes well. Riverbed hydraulic conductivity, based on riverbed leakage, drawdown at the piezometers, and Darcian flow, was estimated to be 2 ft/d.

Hydraulic conductivities of the aquifer estimated by slug tests (1.7 to 154 ft/d) were comparable to those estimated from the multiple-well aquifer test (10 to 150 ft/d). The slug tests gave a slightly wider range of hydraulic conductivity values than the multiple-well aquifer test because of their small sample volume and dependence on local heterogeneity. The multiple-well aquifer test affects a larger volume of the aquifer, than the slug test, which effectively averages hydraulic conductivity for a large aquifer volume. For hydraulic conductivities estimated at individual wells by the both slug tests and the multiple-well aquifer test, the range and distribution of the estimates are similar. Both tests indicate an increase in hydraulic conductivity west of Keyes well, and a decrease in hydraulic conductivity to the south. Results of the small (slug) and large scale (multiple-well) tests indicate the scale dependency of hydraulic-conductivity measurements.

Drawdown responses at observation wells during the Keyes well test show the effect of aquifer heterogeneity and river leakage. The proximity of the Keyes well to significant hydrologic boundaries (that is, the Souhegan River and the limited areal extent of the aquifer) complicates the analysis of the Keyes well multiple-well aquifer test. Estimates of hydrologic properties of such a complex hydrogeologic system with significant surface- and ground-water-flow interactions are approximate. An analysis of such a multiple-well aquifer test would best be evaluated using a numerical three-dimensional ground-water-flow model. This model would accommodate the varied and complex aquifer boundaries conditions found at the Keyes well.

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APPENDIX 1. Well and piezometer construction data, Milford, New Hampshire

Appendix 1. Well and piezometer construction data, Milford, New Hampshire

[**Other identifier:** From Harte and Mack (1992). ft, foot; in., inch; --, no data]

Well or piezometer	Other identifier	Distance from Keyes well (ft)	Altitude of measurement point (ft above sea level)	Altitude of land surface (ft above sea level)	Diameter (in.)	Screened interval below land surface (ft)	Altitude of water-level (ft above sea level)
KEYES	126	0	250	240.1	18	50-60	235.58
KWOBS	--	2	248.47	--	2	?-60	--
KW1	1	870	250.71	248.7	2	53-55	237.26
KW2s	142	236	248.45	246.1	2	22-24	235.90
KW2d	2	237	248.61	246.6	2	59-61	235.79
KW3s	143	259	247.67	246.0	2	18.6-20.6	235.52
KW3d	3	251	246.84	244.8	2	50.7-52.7	235.59
KW4s	144	237	245.28	244.3	1.25	19.2-21.2	235.58
KW4d	4	237	245.31	243.3	2	54.7-56.7	235.61
PW1s	145	176	253.76	252.0	2	18.0-20.0	235.69
PW1d	132	176	253.75	251.8	2	62.0-64.0	235.65
PW2s	146	208	255.79	253.7	2	21.0-23.0	235.69
PW2d	133	208	255.77	253.8	2	62.0-64.0	235.72
PW3s	147	276	255.66	253.7	2	22.0-24.0	236.01
PW3d	134	276	255.67	253.7	2	62.0-64.0	235.97
SK1	--	41	235.60	--	1.25	5-7	234.93
SK2	--	81	235.79	--	1.25	5-7	234.8
SK3	--	103	235.78	--	1.25	5-7	234.79
SP1	--	115	237.60	--	1.25	5-7	236.92
SP2	--	167	236.25	--	1.25	5-7	235.26
SP3	--	146	235.92	--	1.25	5-7	234.93
OW3	135	440	241.4	241.4	2.25	40-50	--

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APPENDIX 2. Water-level drawdowns at observation wells during the Keyes multiple-well aquifer test, Milford, New Hampshire

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Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-well aquifer test, Milford, New Hampshire

[min, minute; ft, feet; --, no data]

t (min)	Well KW2d (ft)	Well KW2s (ft)	*t* (min)	Well KW3d (ft)	Well KW3s (ft)	*t* (min)	Well KW4d (ft)	Well KW4s (ft)
0.5	0.00	0.00	0.5	0.00	0.00	0.5	0.00	0.00
1.0	.00	.00	1.0	.01	.00	1.0	.00	.00
1.5	.00	.00	1.5	.01	.00	1.5	.01	.00
2.0	.00	.00	2.0	.02	.00	2.0	.03	.00
3.0	.01	.00	3.0	.08	.00	3.0	.12	.03
4.0	.03	.01	4.0	.17	.00	4.0	.25	.07
5.0	.07	.02	5.0	.29	.00	5.0	.41	.09
6.0	.11	.03	6.0	.40	.00	6.0	.56	.17
7.0	.16	.03	7.0	.49	.00	7.0	.70	.19
8.0	.21	.04	8.0	.59	.01	8.0	.82	.21
9.0	.27	.04	9.0	.66	.01	9.0	.92	.24
10.0	.33	.04	10.0	.72	.01	10.0	1.02	.25
12.0	.45	.05	12.0	.81	.01	12.0	1.15	.27
14.0	.55	.06	14.0	.86	.03	14.0	1.22	.29
16.0	.66	.06	16.0	.90	.03	16.0	1.30	.32
18.0	.75	.06	18.0	.92	.03	18.0	1.32	.33
20.0	.84	.07	20.0	.95	.03	20.0	1.37	.33
22.0	.91	.07	22.0	.96	.03	22.0	1.40	.34
24.0	.98	.07	24.0	.97	.03	24.0	1.41	.34
26.0	1.04	.07	26.0	.98	.03	26.0	1.43	.35
28.0	1.10	.07	28.0	.98	.03	28.0	1.45	.37
30.0	1.15	.07	30.0	1.00	.03	30.0	1.47	.37
35.0	1.24	.08	35.0	1.01	.03	35.0	1.47	.37
40.0	1.31	.09	40.0	1.02	.04	40.0	1.49	.38
45.0	1.36	.09	45.0	1.03	.04	45.0	1.50	.38
50.0	1.40	.09	50.0	1.03	.04	50.0	1.51	.39
55.0	1.43	.10	55.0	1.03	.04	55.0	1.51	.39
60.0	1.45	.10	60.0	1.03	.04	60.0	1.52	.39
70.0	1.49	.11	70.0	1.04	.04	70.0	1.53	.40

Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-wellaquifer test, Milford, New Hampshire—*Continued*

t (min)	Well KW2d (ft)	Well KW2s (ft)	*t* (min)	Well KW3d (ft)	Well KW3s (ft)	*t* (min)	Well KW4d (ft)	Well KW4s (ft)
80.0	1.51	0.11	80.0	1.04	0.04	80.0	1.54	0.40
90.0	1.53	.11	90.0	1.05	.05	90.0	1.55	.41
100	1.55	.13	100	1.06	.05	100	1.56	.42
120	1.56	.13	120	1.06	.05	120	1.57	.43
140	1.57	.14	140	1.06	.06	140	1.57	.44
160	1.57	.15	160	1.06	.07	160	1.58	.45
180	1.58	.16	180	1.06	.07	180	1.58	.46
200	1.58	.17	200	1.06	.08	200	1.59	.47
240	1.58	.18	240	1.06	.08	240	1.57	.49
300	1.58	.20	290	1.06	.10	300	1.60	.56
480	1.65	.27	460	1.10	.13	474	1.67	.61
610	1.66	.30	603	1.11	.14	612	1.69	.62
720	1.68	.31	708	1.10	.13	716	1.68	.63
832	1.69	.36	827	1.10	.13	836	1.68	.65
1,160	1.70	.38	1,160	1.07	.10	115	1.67	.68
1,285	1.70	.40	1,285	1.06	.10	1,291	1.64	.70
1,350	1.69	.42	1,407	1.03	.08	1,413	1.64	.69
1,560	1.68	.44	1,560	.99	.02	1,555	1.60	.67
1,684	1.70	.46	1,684	.99	.02	1,675	1.61	.68
1,818	1.74	.47	1,832	1.03	.04	1,825	1.69	.72
1,918	1.76	.48	1,922	1.07	.08	1,915	1.72	.76
2,054	1.78	.50	2,064	1.08	.09	2,081	1.74	.77
2,176	1.79	.51	2,182	1.08	.09	2,171	1.74	.78
2,335	1.80	.53	2,340	1.10	.11	2,331	1.76	.81
2,618	1.83	.55	2,615	1.11	.12	2,620	1.79	.84
2,726	1.83	.57	2,723	1.11	.12	2,728	1.79	.85
2,847	1.84	.58	2,843	1.11	.12	2,847	1.80	.86
2,967	1.85	.59	2,963	1.11	.12	2,969	1.80	.86
3,400	1.88	.60	3,390	1.13	.13	3,404	1.83	.89
3,535	1.88	.61	3,531	1.12	.14	3,539	1.84	.90

Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-wellaquifer test, Milford, New Hampshire—*Continued*

t (min)	Well KW2d (ft)	Well KW2s (ft)	*t* (min)	Well KW3d (ft)	Well KW3s (ft)	*t* (min)	Well KW4d (ft)	Well KW4s (ft)
3,680	1.89	0.63	3,681	1.12	0.15	3,689	1.84	0.91
4,094	1.94	.64	4,090	1.21	.21	4,097	1.94	1.00
4,200	1.95	.65	4,198	1.21	.22	4,203	1.94	1.00
4,320	1.95	.66	4,327	1.23	.23	4,322	1.95	1.01
4,440	1.95	.66	4,438	1.21	.23	4,442	1.91	.99
4,620	1.95	.67	4,628	1.19	.20	4,620	1.92	.99
4,820	2.01	.70	4,823	1.26	.24	4,816	2.02	1.04
4,912	2.04	.70	4,915	1.27	.25	4,909	2.03	1.05
5,030	2.03	.72	5,032	1.26	.25	5,024	2.01	1.05
5,140	2.04	.72	5,143	1.27	.26	5,134	2.03	1.07
5,508	2.07	.73	5,502	1.30	.28	5,511	2.06	1.10
5,847	2.07	.74	5,845	1.30	.28	5,851	2.06	1.11
6,086	2.06	.76	6,084	1.26	.25	6,088	2.02	1.08
6,461	2.07	.78	6,455	1.28	.27	6,465	1.86	1.05
7,093	1.96	.78	7,089	.99	.08	7,090	1.80	.81
7,690	1.64	.66	7,695	.61	--	7,686	1.30	.47
8,560	1.57	.53	8,656	.58	--	8,563	1.34	.44
9,173	1.53	.47	9,177	.52	--	9,169	1.31	.41
10,014	1.55	.42	10,011	.57	--	10,016	1.38	.47
10,116	1.54	.41	10,116	.57	--	10,116	1.39	.47

Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

t (min)	PW1d (ft)	PW1s (ft)	*t* (min)	PW2d (ft)	PW2s (ft)	*t* (min)	PW3d (ft)	PW3s (ft)
0	0.00	0.00	0	0.00	0.00	0	0.00	0.00
.5	.00	.00	6.0	.35	--	.5	.00	.00
1.0	.00	.00	7.0	.75	--	1.0	.00	.00
1.5	.01	.00	8.0	.95	--	1.5	.00	.00
2.0	.02	.00	9.0	1.15	--	2.0	.00	.00
3.0	.08	.01	10.0	1.15	--	6.0	.03	.00
4.0	0.18	.01	12.0	1.60	--	7.0	.03	.00
5.0	.29	.01	14.0	1.75	--	9.0	.07	.00
6.0	.45	.01	16.0	2.75	--	10.0	.08	.00
7.0	.61	.01	18.0	2.90	--	14.0	.20	.00
8.0	.77	.01	20.0	2.95	--	16.0	.25	.00
9.0	.97	.01	22.0	2.90	--	18.0	.34	.00
10.0	1.08	.01	24.0	3.05	--	19.0	.37	.00
12.0	1.38	.01	26.0	3.07	--	20.0	.40	.00
14.0	1.64	.02	28.0	3.11	--	22.0	.46	.00
16.0	1.85	.02	30.0	3.09	--	24.0	.52	.00
18.0	2.03	.02	35.0	3.13	--	26.0	.58	.00
20.0	2.19	.02	40.0	3.16	--	28.0	.65	.00
22.0	2.31	.02	45.0	3.20	--	35.0	.80	.00
24.0	2.43	.02	50.0	3.23	--	40.0	.87	.00
26.0	2.52	.02	55.0	3.23	--	45.0	.93	.00
28.0	2.59	.02	60.0	3.22	--	50.0	.97	.00
30.0	2.66	.02	70.0	3.23	--	55.0	.98	.00
35.0	2.76	.02	80.0	3.25	--	60.0	.99	.00
40.0	2.82	.02	90.0	3.25	--	70.0	1.02	.00
45.0	2.87	.02	100	3.28	--	80.0	1.07	.00
50.0	2.89	.02	120	3.24	--	90.0	1.07	.00
55.0	2.92	.02	140	3.27	--	96.0	1.07	.00
60.0	2.93	.02	160	3.25	--	100	1.07	.00
70.0	2.93	.03	180	3.25	--	120	1.07	.00
80.0	2.96	.03	200	3.26	--	125	1.07	.00

Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

t (min)	PW1d (ft)	PW1s (ft)	*t* (min)	PW2d (ft)	PW2s (ft)	*t* (min)	PW3d (ft)	PW3s (ft)
90.0	2.97	0.03	240	3.22	--	140	1.07	0.00
100	2.99	.03	300	3.25	--	160	1.07	.00
120	2.99	.03	349	3.25	0.16	180	1.07	.00
140	2.99	.03	496	3.28	.17	200	1.08	.00
160	2.99	.03	649	3.30	.18	205	1.07	.00
180	2.98	.04	744	3.31	.24	240	1.06	.00
200	2.97	.04	850	3.29	--	365	1.05	.01
240	2.91	.04	1,195	3.28	.23	507	1.07	.00
340	2.91	.07	1,318	3.06	.23	645	1.08	.01
501	2.94	.08	1,440	3.22	.24	751	1.09	.01
642	2.97	.08	1,595	3.21	.25	858	1.09	.02
747	2.97	.09	1,710	3.22	.25	1,188	1.07	.03
854	2.93	.10	1,853	3.28	.26	1,320	1.07	.04
1,182	2.92	.13	1,971	3.31	.26	1,443	1.05	.04
1,315	2.88	.13	2,101	3.31	.27	1,590	1.04	.04
1,438	2.85	.13	2,224	3.31	.28	1,711	1.05	.05
1,592	2.84	.12	2,375	3.32	.29	1,865	1.09	.06
1,709	2.85	.13	2,647	3.34	.31	1,967	1.10	.06
1,860	2.93	.14	2,751	3.36	.32	2,115	1.12	.07
1,975	2.96	.15	2,865	3.36	.32	2,231	1.11	.07
2,095	2.96	.15	2,985	3.36	.32	2,390	1.12	.09
2,227	2.96	.16	3,437	3.37	.36	2,649	1.13	.09
2,373	2.98	.17	3,575	3.37	.36	2,754	1.15	.11
2,645	3.00	.18	3,702	3.38	.37	2,872	1.15	.11
2,748	3.01	.18	4,125.	3.45	.38	2,991	1.15	.12
2,868	3.02	.19	4,225	3.46	.40	3,439	1.17	.13
2,987	3.00	.20	4,343	3.45	.40	3,585	1.17	.14
3,429	3.03	.23	4,465	3.42	.40	3,700	1.17	.15
3,580	3.03	.22	4,652	3.44	.41	4,124	1.22	.17
3,699	3.03	.23	4,789	3.47	.43	4,228	1.22	.17
4,122	3.09	.25	4,938	3.56	.45	4,345	1.22	.18

Appendix 2. Water-level drawdowns at observation wells during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

t (min)	PW1d (ft)	PW1s (ft)	*t* (min)	PW2d (ft)	PW2s (ft)	*t* (min)	PW3d (ft)	PW3s (ft)
4,223	3.10	0.27	5,059	3.55	0.45	4,467	1.21	0.17
4,341	3.10	.27	5,175	3.56	.45	4,654	1.22	.18
4,463	3.07	.28	5,532	3.57	.46	4,790	1.23	.19
4,650	3.09	.28	5,871	3.56	.47	4,945	1.29	.20
4,786	3.11	.29	6,123	3.53	.48	5,064	1.29	.20
4,942	3.24	.31	6,487	3.55	.50	5,176	1.29	.20
5,062	3.23	.31	7,134	3.34	.45	5,535	1.31	.21
5,173	3.24	.31	7,724	3.02	.25	5,872	1.31	.22
5,531	3.26	.33	8,591	3.00	.09	6,132	1.30	.23
5,869	3.23	.34	9,192	2.98	.07	6,478	1.31	.25
6,127	3.20	.36	10,025	3.02	.07	7,141	1.22	.27
6,481	3.22	.37	10,116	2.93	.10	7,726	1.05	.28
7,139	3.01	.33	--	--	--	8,597	1.00	.24
7,724	2.64	.13	--	--	--	9,204	.97	.21
8,591	2.62	--	--	--	--	10,030	.98	.17
9,192	2.59	--	--	--	--	--	--	--
10,025	2.64	--	--	--	--	--	--	--
10,116	2.66	--	--	--	--	--	--	--

APPENDIX 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire

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Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire

[Measurements relative to an arbitrary datum. **Riverbed piezometers:** Depth to water from top of piezometer casing. **Stage:** Depth to river stage from top of piezometer SK1 casing. ft, foot; min, minute; --, no data]

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SK1 (ft)	SK2 (ft)	SK3 (ft)	
1.0	0.67	0.99	0.99	0.67
2.0	.67	--	--	.67
3.0	.67	--	--	.67
4.0	.68	--	--	.67
5.0	.71	--	--	.67
6.0	.71	1.00	--	.67
7.0	.72	--	--	.67
8.0	.74	--	--	.67
9.0	.74	--	--	.67
10.0	.74	--	--	.67
12.0	.74	--	--	.67
14.0	.74	--	--	.67
16.0	.74	--	--	.67
18.0	.74	1.02	--	.67
20.0	.74	--	--	.67
22.0	.74	--	--	.67
24.0	.74	--	--	.67
26.0	.75	--	1.08	.67
28.0	.75	--	--	.67
30.0	.75	1.02	--	.67
35.0	.75	--	--	.67
40.0	.75	1.05	1.08	.67
45.0	.75	--	--	.67
50.0	.75	--	--	.67
55.0	.75	--	--	.67
60.0	.75	--	--	.67
70.0	.75	--	--	.67
80.0	.75	1.01	1.08	.67

Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SK1 (ft)	SK2 (ft)	SK3 (ft)	
90.0	0.75	--	--	0.67
100	.75	--	--	.67
120	.75	--	--	.67
140	.76	1.05	--	.67
160	.76	--	--	.67
180	.78	--	1.12	.67
200	.80	1.07	1.13	.69
240	.81	1.08	1.24	.71
311	.82	1.07	1.15	.72
485	.84	1.08	1.16	.72
615	.77	1.00	1.09	.65
720	.76	--	--	.64
823	.78	1.00	1.08	.65
1,165	.69	1.00	.99	.55
1,295	.68	--	.97	.54
1,420	.57	--	.86	.42
1,575	.54	.77	.84	.40
1,695	.56	.78	.85	.41
1,830	.64	.87	.94	.50
1,930	.70	.92	1.00	.55
2,070	.69	.91	.98	.54
2,190	.68	.92	.98	.55
2,354	.73	.94	1.00	.59
2,625	.72	--	1.03	.58
2,735	.73	.95	1.01	.56
2,855	.73	.95	1.01	.56
2,975	.73	.94	1.01	.56
3,405	.73	.95	1.02	.66
3,540	.74	.96	1.03	.66
3,715	.76	--	--	.67

Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SK1 (ft)	SK2 (ft)	SK3 (ft)	
4,103	0.91	--	1.18	0.73
4,213	.91	1.13	1.18	.73
4,333	.92	1.13	1.20	.74
4,453	.80	1.01	1.08	.62
4,635	.83	1.04	1.10	.65
4,765	.89	1.10	1.18	.72
4,915	.89	1.11	1.18	.74
5,035	.88	1.09	1.17	.78
5,145	.91	1.14	1.20	.73
5,518	.93	--	1.22	.74
5,864	.92	1.14	1.20	.72
6,102	.83	1.05	1.12	.63
6,419	.88	1.10	1.17	.70
7,120	.46	.64	.70	.23

Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SP1	SP2 (ft)	SP3 (ft)	
1.0	0.68	0.99	0.99	0.67
2.0	.57	.99	.99	.67
3.0	.53	--	--	.67
4.0	.55	--	--	.67
5.0	.63	--	--	.67
6.0	.65	1.00	--	.67
7.0	.72	--	--	.67
8.0	.74	--	--	.67
9.0	.74	--	--	.67
10.0	.74	--	--	.67
12.0	.74	--	--	.67
14.0	.74	--	--	.67
16.0	.74	--	--	0.67
18.0	.74	1.02	--	.67
20.0	.74	--	--	.67
22.0	.74	--	--	.67
24.0	.74	--	--	.67
26.0	.75	--	1.08	.67
28.0	.75	--	--	.67
30.0	.75	1.02	--	.67
35.0	.75	--	--	.67
40.0	.75	1.05	1.08	.67
45.0	.75	--	--	.67
50.0	.75	--	--	.67
55.0	.75	--	--	.67
60.0	.75	--	--	.67
70.0	.75	--	--	.67
80.0	.75	1.01	1.08	.67
90.0	.75	--	--	.67
100	.75	--	--	.67

Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SP1	SP2 (ft)	SP3 (ft)	
120	0.75	--	--	0.67
140	.76	1.05	--	.67
160	.76	--	--	.67
180	.78	--	1.12	.67
200	.80	1.07	1.13	.69
240	.81	1.08	1.24	.71
374	.85	1.25	1.13	.72
512	.85	1.25	1.14	.72
1,182	.68	1.25	.95	.55
1,310	.68	1.25	.95	.54
1,435	.57	1.25	.84	.42
1,600	.53	1.23	.79	.40
1,702	.55	1.22	.80	.41
1,840	.63	1.21	.90	.50
1,977	.65	--	--	.55
2,107	.67	1.22	--	.54
2,384	.69	1.21	.97	.59
2,640	.71	1.22	.96	.58
2,745	.70	1.22	.95	.58
2,865	.71	1.22	.97	.56
2,983	.71	1.22	.97	.56
3,577	.72	1.25	.97	.66
4,120	.87	1.27	1.14	.73
4,223	.88	1.28	1.15	.73
4,342	.89	1.30	1.16	.74
4,462	.76	1.30	1.02	.62
4,641	.80	1.30	1.05	.65
4,770	.86	1.31	1.11	.72
4,920	.86	1.31	1.12	.74
5,045	.85	1.34	1.10	.78

Appendix 3. Water levels in riverbed piezometers and river stage during the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

Time from start of test (min)	Riverbed piezometers			River stage (ft)
	SP1	SP2 (ft)	SP3 (ft)	
5,156	0.88	1.33	1.13	0.73
5,524	.91	1.36	1.16	.74
5,867	.89	1.36	1.14	.72
6,130	.82	1.37	1.06	.63
6,425	.87	1.37	1.11	.70
7,132	.39	1.25	.63	.23

APPENDIX 4. Water-level recovery at observation wells after the Keyes multiple-well aquifer test, Milford, New Hampshire

Appendix 4. Water-level recovery at observation wells after the Keyes multiple-well aquifer test, Milford, New Hampshire

[min, minute; ft, foot]

t (min)	KWOBS (ft)	*t* (min)	KW2d (ft)	KW2s (ft)	*t* (min)	KW3d (ft)	KW3s (ft)	*t* (min)	KW4d (ft)	KW4s (ft)
0.0	21.10	0.0	14.38	12.97	0.0	11.83	11.67	0.0	11.07	10.13
.5	21.10	.5	14.38	12.97	.5	11.83	11.67	.5	11.07	10.13
1.5	20.90	1.0	14.38	12.97	1.0	11.83	11.67	1.0	11.07	10.13
3.0	20.90	1.5	14.38	12.97	1.5	11.83	11.67	1.5	11.07	10.13
3.8	20.75	2.0	14.38	12.96	2.0	11.83	11.66	2.0	11.07	10.13
5.2	20.62	3.0	14.38	12.96	3.0	11.83	11.66	3.0	11.07	10.13
6.1	20.62	4.0	14.37	12.96	4.0	11.80	11.66	4.0	11.02	10.12
7.3	20.47	5.0	14.36	12.95	5.0	11.74	11.66	5.0	10.93	10.09
8.3	20.41	6.0	14.34	12.95	6.0	11.63	11.65	6.0	10.80	10.07
9.2	20.35	7.0	14.31	12.94	7.0	11.54	11.65	7.0	10.67	10.04
10.6	20.30	8.0	14.27	12.94	8.0	11.45	11.65	8.0	10.54	10.02
11.5	20.17	9.0	14.22	12.93	9.0	11.36	11.65	9.0	10.43	9.98
12.3	20.05	10.0	14.17	12.93	10.0	11.29	11.64	10.0	10.29	9.97
13.7	19.93	11.0	14.12	12.93	12.0	11.18	11.64	12.0	10.15	9.93
15.2	19.90	12.0	14.07	12.93	14.0	11.10	11.64	14.0	10.03	9.91
17.0	19.80	14.0	13.97	12.92	16.0	11.05	11.63	16.0	9.94	9.89
18.6	19.58	15.0	13.92	12.92	18.0	11.00	11.63	18.0	9.88	9.88
19.7	19.50	16.0	13.87	12.92	20.0	10.97	11.63	20.0	9.82	9.86
21.5	19.42	17.0	13.82	12.92	22.0	10.95	11.63	22.0	9.79	9.86
23.3	19.20	18.0	13.77	12.92	24.0	10.94	11.63	24.0	9.76	9.85
26.0	19.00	19.0	13.73	12.91	25.0	10.94	11.63	26.0	9.75	9.85
28.0	18.86	20.0	13.68	12.91	26.0	10.94	11.63	28.0	9.72	9.84
29.6	18.80	21.0	13.64	12.91	27.0	10.93	11.62	30.0	9.71	9.83
32.5	18.57	22.0	13.61	12.91	28.0	10.93	11.62	35.0	9.68	9.81
35.0	18.48	23.0	13.57	12.90	30.0	10.92	11.62	40.0	9.65	9.80
40.7	18.07	24.0	13.54	12.90	31.0	10.91	11.62	45.0	9.64	9.79
45.7	17.75	25.0	13.50	12.90	32.0	10.91	11.62	50.0	9.62	9.78
50.0	17.51	26.0	13.48	12.90	33.0	10.90	11.62	55.0	9.60	9.78
55.2	17.28	27.0	13.44	12.90	34.0	10.90	11.62	60.0	9.60	9.77

Appendix 4. Water-level recovery at observation wells after the Keyes multiple-well aquifer test, Milford, New Hampshire—*Continued*

t (min)	KWOBS (ft)	*t* (min)	KW2d (ft)	KW2s (ft)	*t* (min)	KW3d (ft)	KW3s (ft)	*t* (min)	KW4d (ft)	KW4s (ft)
60.0	17.08	28.0	13.42	12.90	35.0	10.90	11.62	65.0	9.60	9.76
65.0	16.80	29.0	13.38	12.90	36.0	10.90	11.62	70.0	9.60	9.76
70.0	16.62	30.0	13.37	12.89	37.0	10.90	11.62	80.0	9.59	9.75
79.0	16.20	32.0	13.32	12.89	38.0	10.89	11.62	90.0	9.58	9.74
90.0	15.58	35.0	13.27	12.89	39.0	10.89	11.62	100	9.57	9.73
100	15.50	37.0	13.23	12.89	40.0	10.88	11.61	120	9.56	9.72
120	14.95	39.0	13.20	12.89	45.0	10.88	11.61	140	9.54	9.70
140	14.55	40.0	13.18	12.89	50.0	10.88	11.61	160	9.54	9.70
160	14.26	45.0	13.13	12.89	55.0	10.87	11.61	180	9.53	9.69
180	13.90	50.0	13.08	12.88	60.0	10.87	11.61	220	9.53	9.68
220	13.54	55.0	13.05	12.88	65.0	10.87	11.61	1,491	9.34	9.41
1,415	12.56	60.0	13.03	12.88	70.0	10.86	11.61			
		65.0	13.00	12.87	80.0	10.86	11.61			
		70.0	12.99	12.87	90.0	10.85	11.61			
		80.0	12.96	12.86	100	10.85	11.61			
		90.0	12.94	12.85	120	10.84	11.61			
		100	12.93	12.84	140	10.85	11.61			
		121	12.90	12.83	160	10.85	11.61			
		140	12.88	12.82	180	10.85	11.61			
		160	12.87	12.81	220	10.85	11.61			
		180	12.87	12.79	1,400	10.80	11.63			
		220	12.84	12.77						
		1,394	12.61	12.47						

Appendix 4. Water-level recovery at observation wells after the Keyes multiple-well aquifer test—*Continued*

t (min)	PW1d (ft)	*t* (min)	PW2d (ft)	*t* (min)	PW3d (ft)
0.0	20.76	0.0	21.80	0.0	20.68
.5	20.75	.5	21.85	.5	20.68
1.0	20.75	1.0	21.80	1.0	20.68
1.5	20.75	1.5	21.80	1.5	20.69
2.0	20.75	2.0	21.80	2.0	20.69
3.0	20.75	3.0	21.80	3.0	20.69
4.0	20.72	4.0	21.80	4.0	20.68
5.0	20.65	5.0	21.75	5.0	20.67
6.0	20.56	6.0	21.65	6.0	20.67
7.0	20.45	7.0	21.50	7.0	20.67
8.0	20.31	8.0	21.35	8.0	20.66
9.0	20.17	9.0	21.22	9.0	20.65
10.0	20.02	10.0	20.98	10.0	20.64
12.0	19.74	12.0	20.82	12.0	20.56
14.0	19.47	14.0	20.58	14.0	20.52
16.0	19.25	16.0	20.48	16.0	20.47
18.0	19.06	18.0	20.37	18.0	20.41
20.0	18.88	20.0	20.17	20.0	20.35
21.0	18.80	22.0	20.19	22.0	20.31
22.0	18.72	24.0	20.19	24.0	20.23
23.0	18.66	26.0	20.17	26.0	20.20
24.0	18.61	28.0	20.13	28.0	20.14
25.0	18.55	31.0	20.07	31.0	20.06
26.0	18.50	33.0	20.06	33.0	20.01
27.0	18.45	35.0	20.04	35.0	19.99
28.0	18.42	37.0	20.01	38.0	19.95
29.0	18.38	39.0	20.02	40.0	19.91
31.0	18.32	43.0	20.00	45.0	19.84
33.0	18.27	45.0	20.00	50.0	19.80
35.0	18.23	50.0	19.99	55.0	19.78
37.0	18.19	55.0	19.96	60.0	19.75

Appendix 4. Water-level recovery at observation wells after the Keyes multiple-well aquifer test—*Continued*

t (min)	PW1d (ft)	*t* (min)	PW2d (ft)	*t* (min)	PW3d (ft)
39.0	18.16	60.0	19.96	65.0	19.72
45.0	18.10	65.0	19.95	70.0	19.70
50.0	18.07	70.0	19.94	80.0	19.67
55.0	18.03	80.0	19.94	90.0	19.67
60.0	18.02	90.0	19.92	100	19.66
65.0	18.02	100	19.92	120	19.66
70.0	18.01	120	19.92	140	19.67
80.0	18.00	140	19.90	160	19.67
90.0	17.98	160	19.89	180	19.66
100	17.97	180	19.90	220	19.72
120	17.96	220	19.95	1,382	19.61
140	17.95	1,380	19.82		
160	17.95				
180	17.94				
220	17.94				
1,378	17.78				

APPENDIX 5. Water-quality constituents measured at the Keyes well during the multiple-well aquifer test, Milford, New Hampshire

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Appendix 5. Water-quality constituents measured at the Keyes well during the multiple-well aquifer test, Milford, New Hampshire

[µS/cm, microsiemen per centimeter at 25 degrees Celsius; --, no data]

Minutes from start of aquifer test	Specific conductance (µS/cm)	pH (units)	Temperature (degrees Celsius)
16	220	--	--
18	--	--	12.5
24	250	7.08	12.4
35	250	7.22	12.3
43	250	7.26	12.1
55	250	7.26	12.1
60	250	7.30	12.0
70	250	7.10	12.0
80	250	7.26	11.9
90	250	7.50	11.9
100	250	7.37	11.9
120	250	7.56	11.8
140	240	6.96	11.8
160	250	6.87	11.8
180	250	6.88	11.7
200	250	6.87	11.7
240	260	6.77	11.6
300	260	6.80	11.6
480	280	6.72	11.5
590	295	6.60	11.5
700	295	6.58	11.4
815	300	6.54	11.3
1,080	300	6.68	11.7
1,285	300	6.55	11.5
1,405	300	6.53	11.5
1,545	300	6.57	11.6
1,672	305	6.61	11.7
1,799	305	6.60	11.5
1,902	310	6.60	11.4

Appendix 5. Water-quality constituents measured at the Keyes well during the multiple-well aquifer test, Milford, New Hampshire

Minutes from start of aquifer test	Specific conductance (μS/cm)	pH (units)	Temperature (degrees Celsius)
1,920	310	6.55	11.4
2,040	310	6.63	11.3
2,200	305	6.53	11.4
2,605	310	6.54	11.7
2,720	300	6.54	11.2
2,840	300	6.46	11.3
2,965	303	6.45	11.2
3,370	300	6.50	11.4
3,520	300	6.39	11.3
3,665	295	6.45	11.2
4,080	290	6.48	11.5
4,200	300	6.45	11.3
4,320	305	6.45	11.2
4,440	295	6.40	11.2
4,620	310	6.45	11.3
4,805	305	6.49	11.2
4,895	310	6.47	11.3
5,010	310	6.46	11.3
5,115	310	6.42	11.3
5,495	300	6.40	11.4
5,840	300	6.42	11.3
6,070	295	6.53	11.4
6,440	300	6.35	11.3
7,075	290	6.42	11.4
7,675	300	6.48	11.5
8,535	295	6.42	11.3
9,160	300	6.54	11.5
10,116	290	6.43	11.4

APPENDIX 6. Volatile organic chemicals sampled for and detection limits of analysis

Appendix 6. Volatile organic chemicals sampled for at the Keyes well and detection limits of analysis

[µg/L, microgram per liter]

Constituent	Detection limit (µg/L)	Constituent	Detection limit (µg/L)
Acetone	50	Tetrahydrofuran	36
Dichloromethane	4	Trichlorofluoromethane	5
Tetrachloromethane	5	Styrene	.9
1,1-Dichloroethane	.5	Methyl t-butyl ether	1.7
1,2-Dichloroethane	.8	Diethyl ether	3.3
1,1,1-Trichloroethane	.4	Methyl ethyl ketone	28
1,1,2-Trichloroethane	5	Methyl isobutyl ketone	4.4
Tetrachloroethane	1.2	Propene 1,3 dimethyl t	5
1,1-Dichloroethylene	.4	Trichlorotrifluoroethane	1.4
cis & trans 1,2-Dichloroethylene	.7	Cyclohexane	5
Trichloroethylene	.6	Chlorofluoromethane	5
1,2-Dichloropropane	5	Dichlorodifluoromethane	5
1,3-Dichloropropane	5	Dichlorotrifluoroethane	5
Benzene	.5	Trihalomethanes:	
Chlorobenzene	1	Tribromomethane	5
Dichlorobenzenes	9.6	Trichloromethane	.5
Ethylbenzene	1.1	Dichlorobromomethane	5
Toluene	1.7	Chlorodibromomethane	5
Xylene, meta isomer	1.3	Chloroethylene (Vinyl chloride)	2.4
Xylenes, ortho and para	1.2	1,1,2,2 Tetrachloroethene	5
Camphor	66	Chloroethylene	5

APPENDIX 7. Volatile organic chemical analysis of water from the Keyes well during the multiple-well aquifer test, Milford, New Hampshire

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Appendix 7. Volatile organic chemical analysis of water from the Keyes well during the multiple-well aquifer test, Milford, New Hampshire

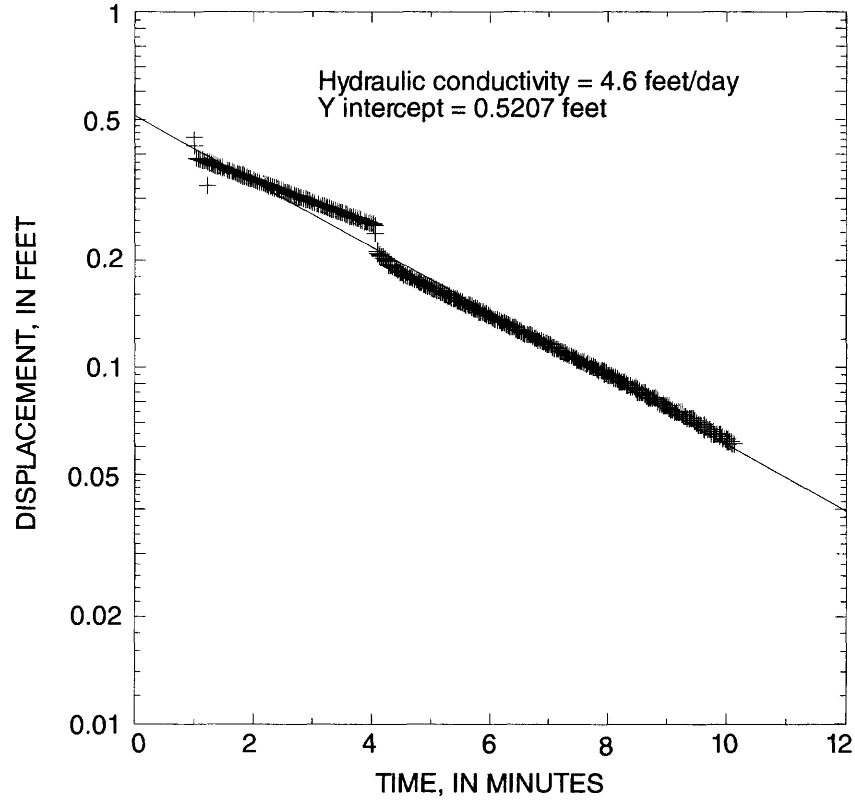
[**Time:** number shown is minutes from start of aquifer test. min, minute; mg/L, milligram per liter; NA, not applicable; --, indicates no detection]

Time (min)	Concentration and organic compound (mg/L)		Notes
28	--	--	NA
39	--	--	NA
60	--	--	NA
120	--	--	NA
180	--	--	NA
240	--	--	NA
450	--	--	NA
720	--	--	NA
1,440	1.7	1,2-Dichloroethane	NA
	70	Benzene	
	2.14	Xylenes (ortho & para)	
1,900	9.34	1,2-Dichloroethane	([a])
	4.0	Toluene	
	51.8	Xylenes (ortho & para)	
	1,460	Acetone	
	596	Tetrahydrofuran	
2,325	5.79	1,2-Dichloroethane	([a])
	250	Benzene	
	15.8	Xylenes (ortho & para)	
	701	Acetone	
2,850	8.50	1,2-Dichloroethane	([a, b])
	152	Benzene	
	19.5	Xylenes (ortho & para)	
3,360	12.5	1,2-Dichloroethane	([b])
4,320	13.8	1,2-Dichloroethane	([a, b])
4,800	14.8	1,2-Dichloroethane	([b])
5,118	14.8	1,2-Dichloroethane	([b])
5,850	15.4	1,2-Dichloroethane	([b])
6,450	14.9	1,2-Dichloroethane	([b])
8,550	13.1	1,2-Dichloroethane	([b])
11,520	12.0	1,2-Dichloroethane	([b])

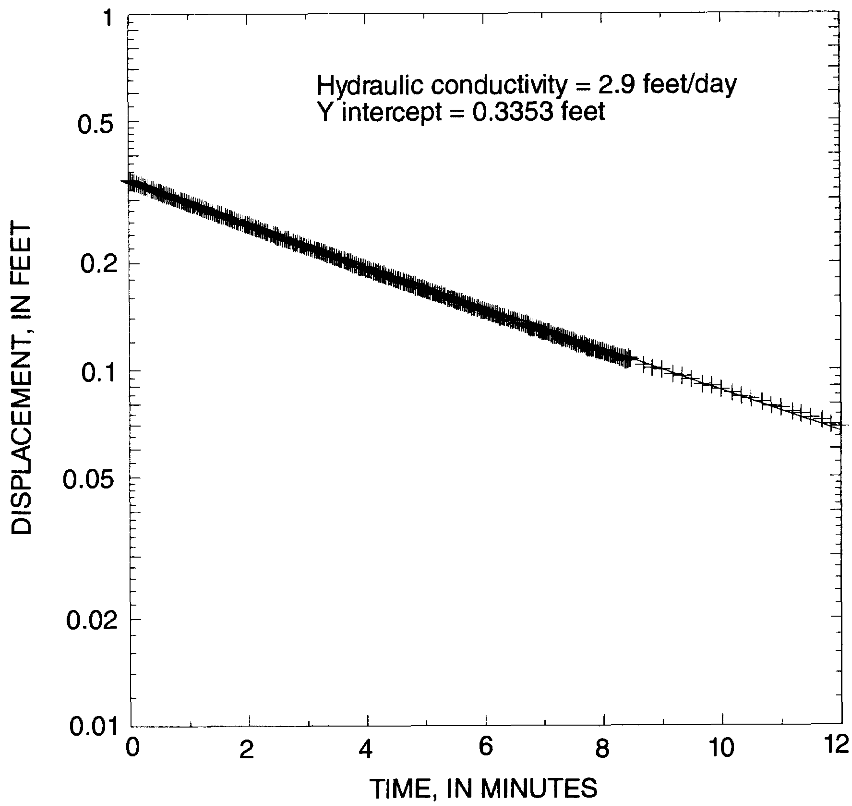
[a]Indicates hydrocarbons present indicative of gasoline.
[b]Indicates unknown gaschromatograph peak present.

APPENDIX 8. Plots of slug test data response at observation wells, Milford, New Hampshire

(A)

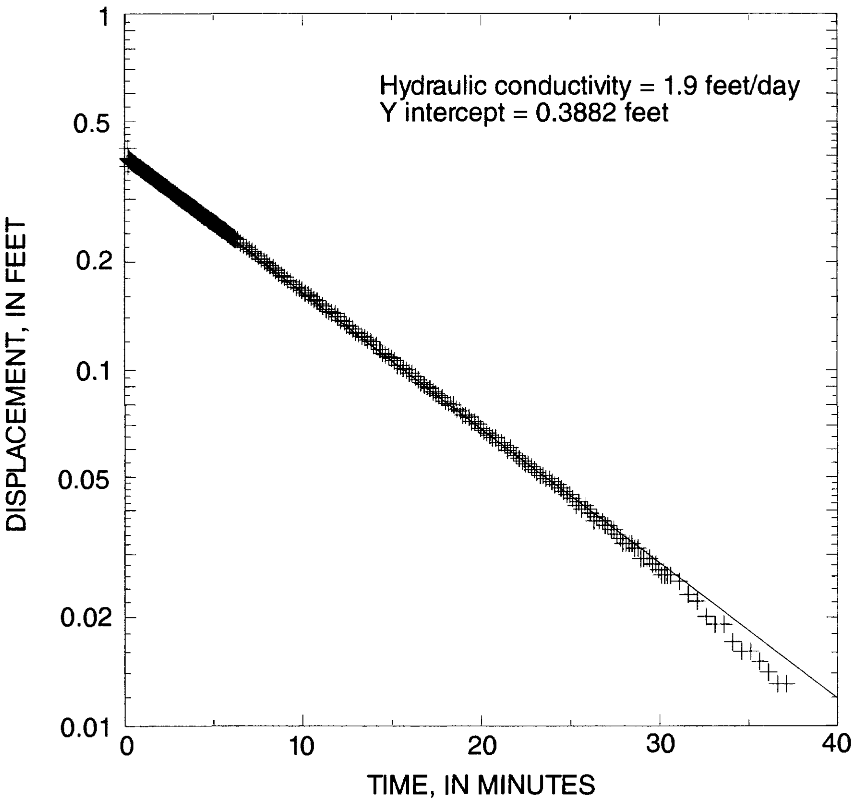


(B)

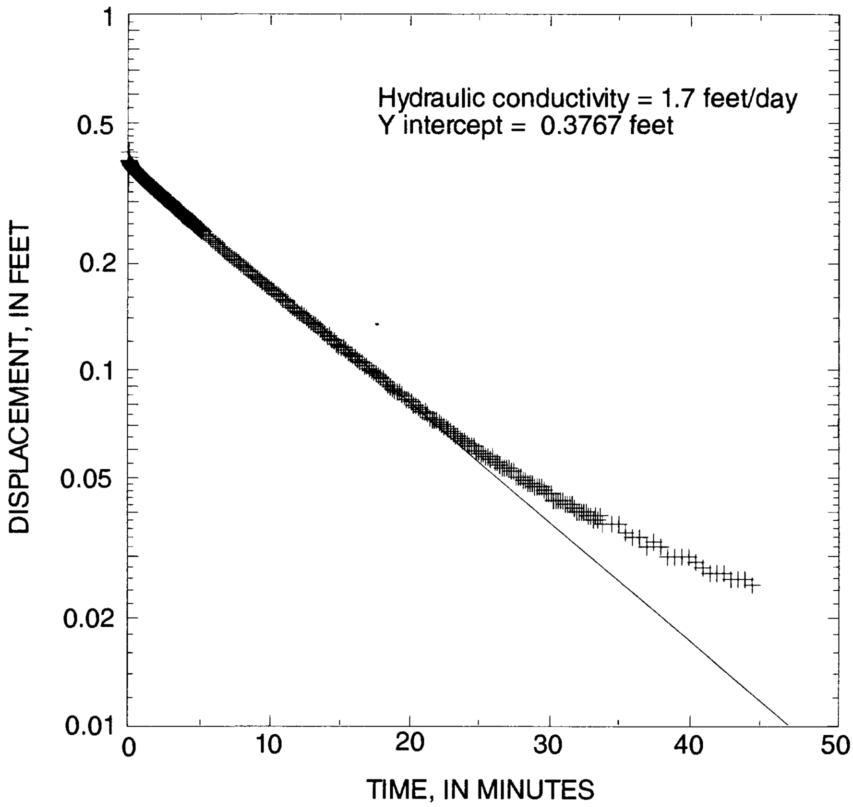


Appendix 8. Plots of slug test data response at KW1 (*A*) forward, and (*B*) reverse, Milford, New Hampshire.

(A)

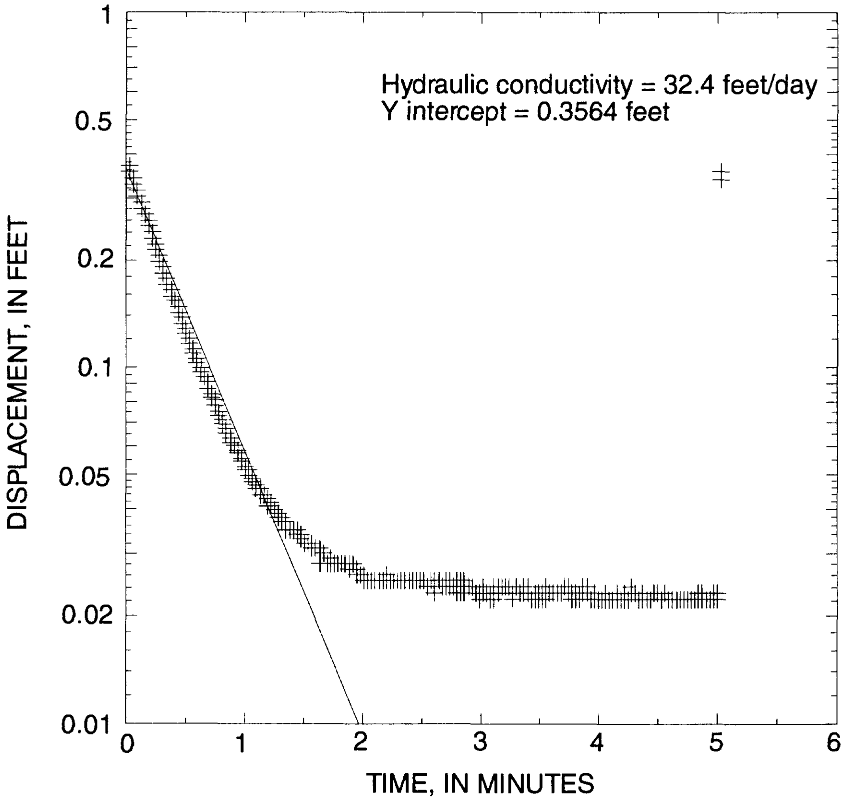


(B)

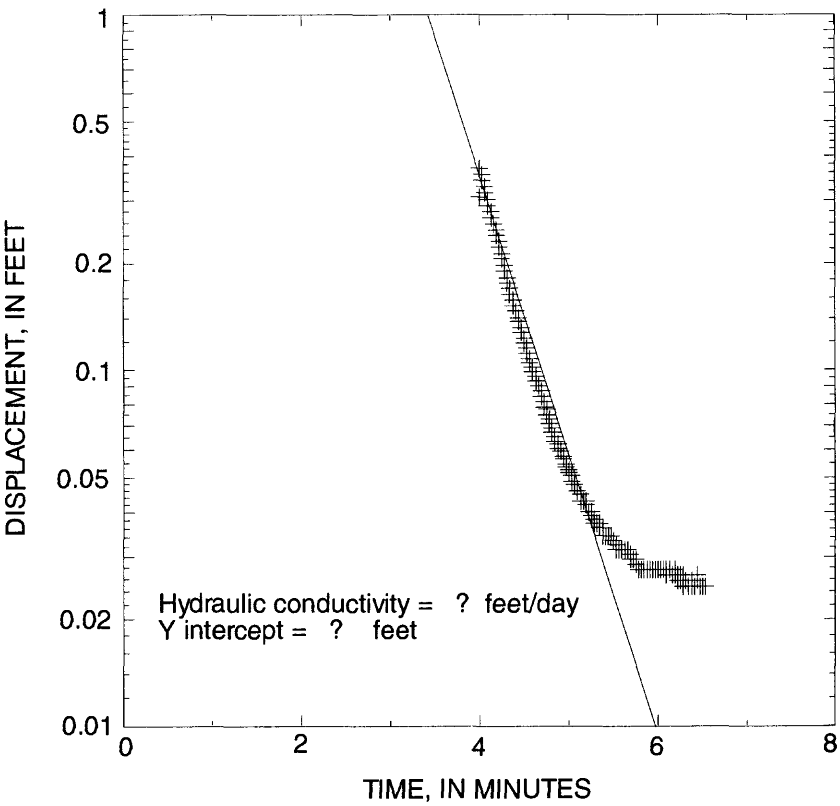


Appendix 8. Plots of slug test data response at KW2D (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*

(A)

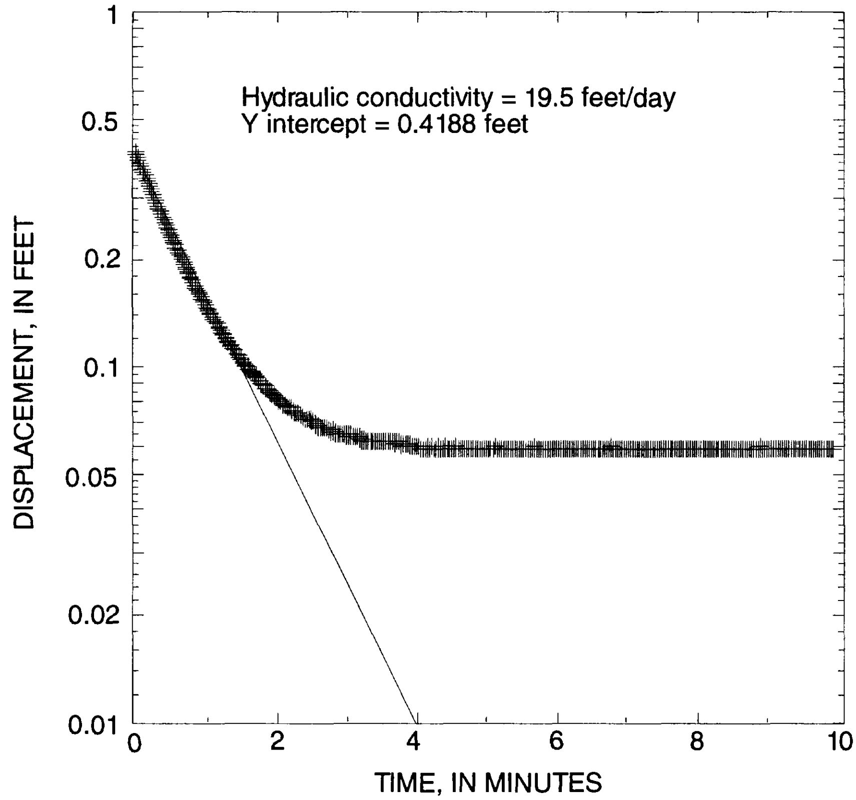


(B)

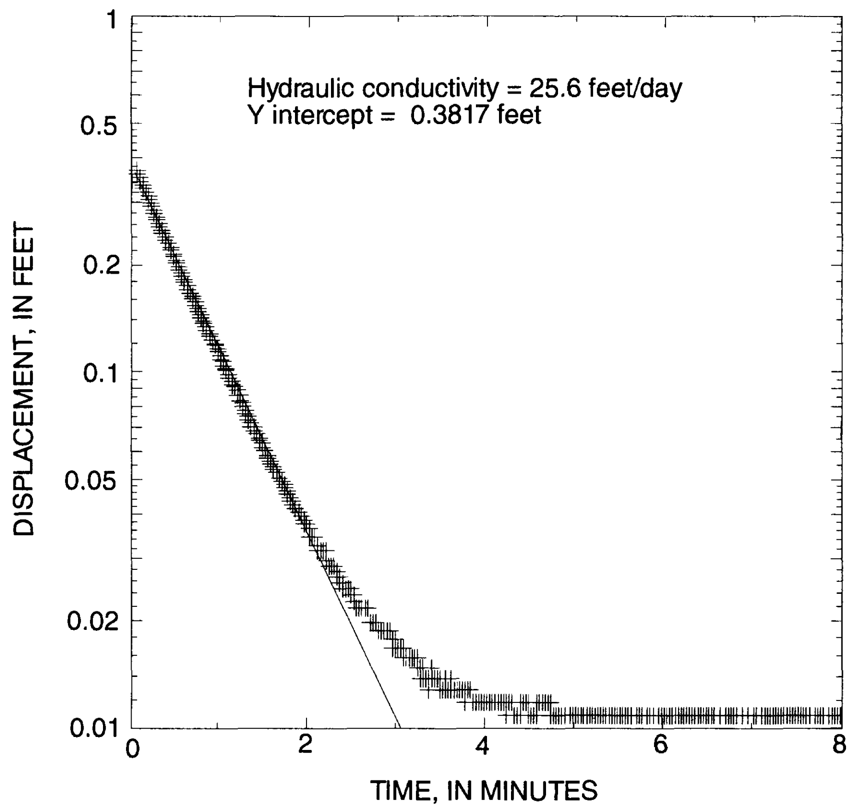


Appendix 8. Plots of slug test data response at KW2S (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*

(A)

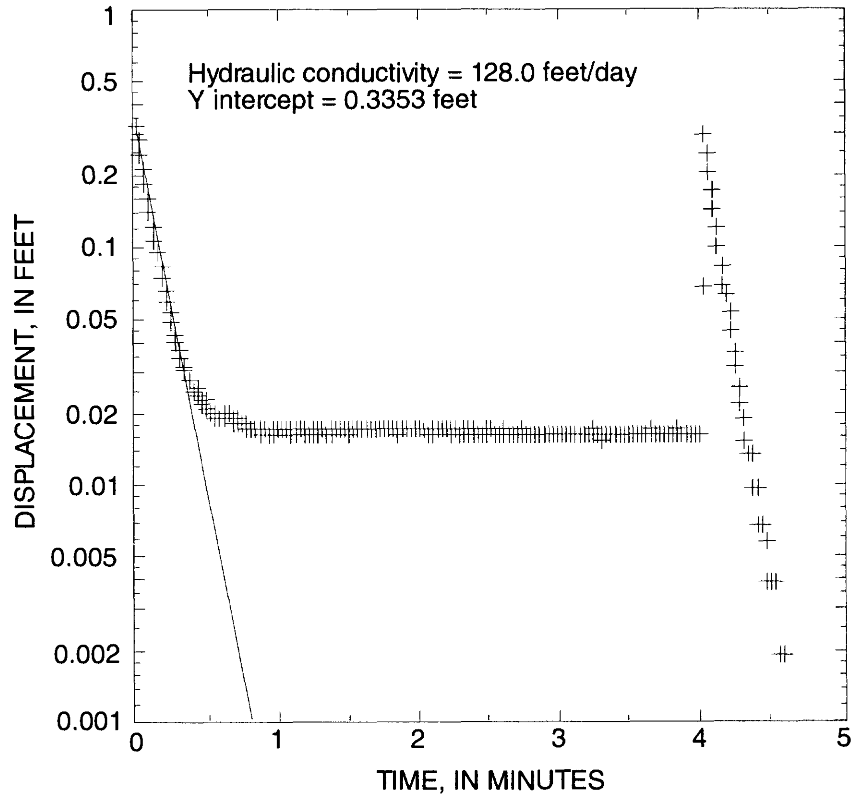


(B)

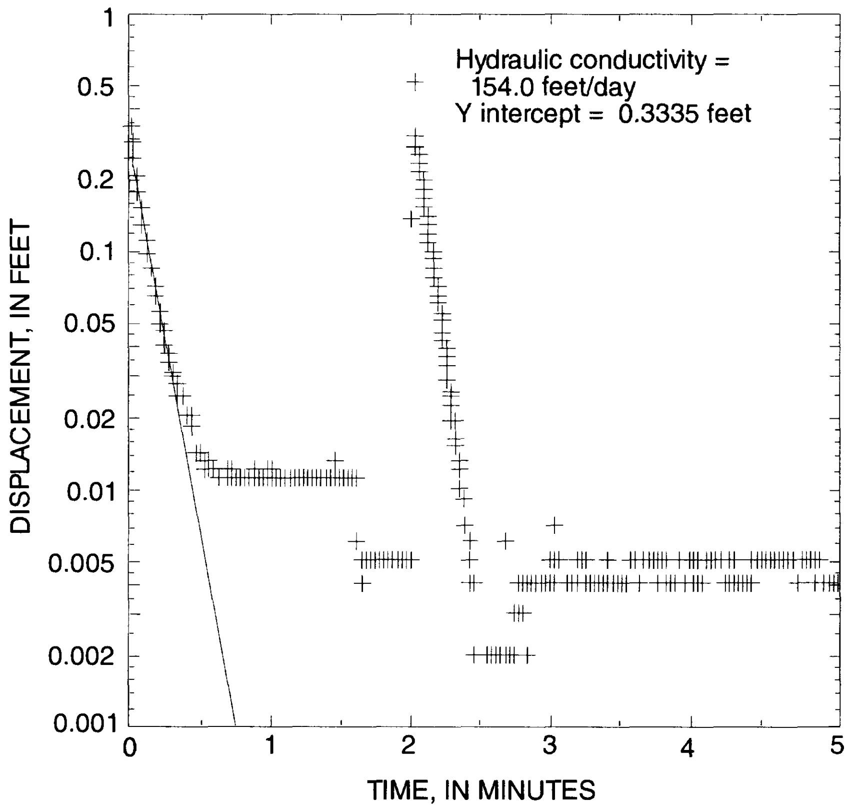


Appendix 8. Plots of slug test data response at KW3D (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*

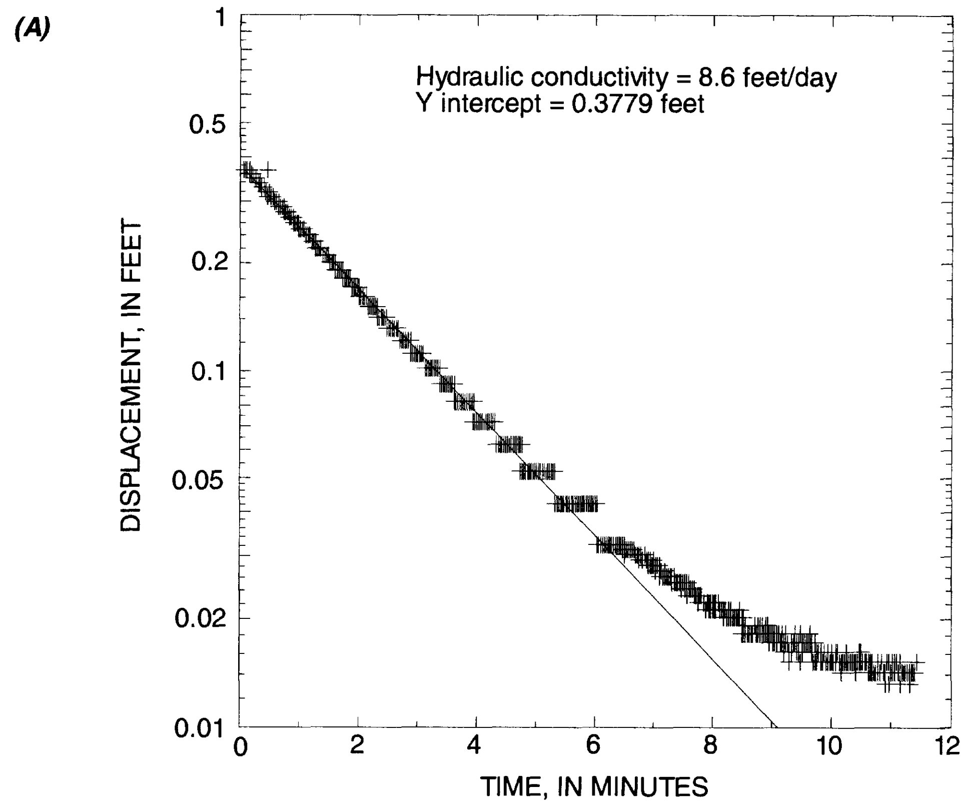
(A)

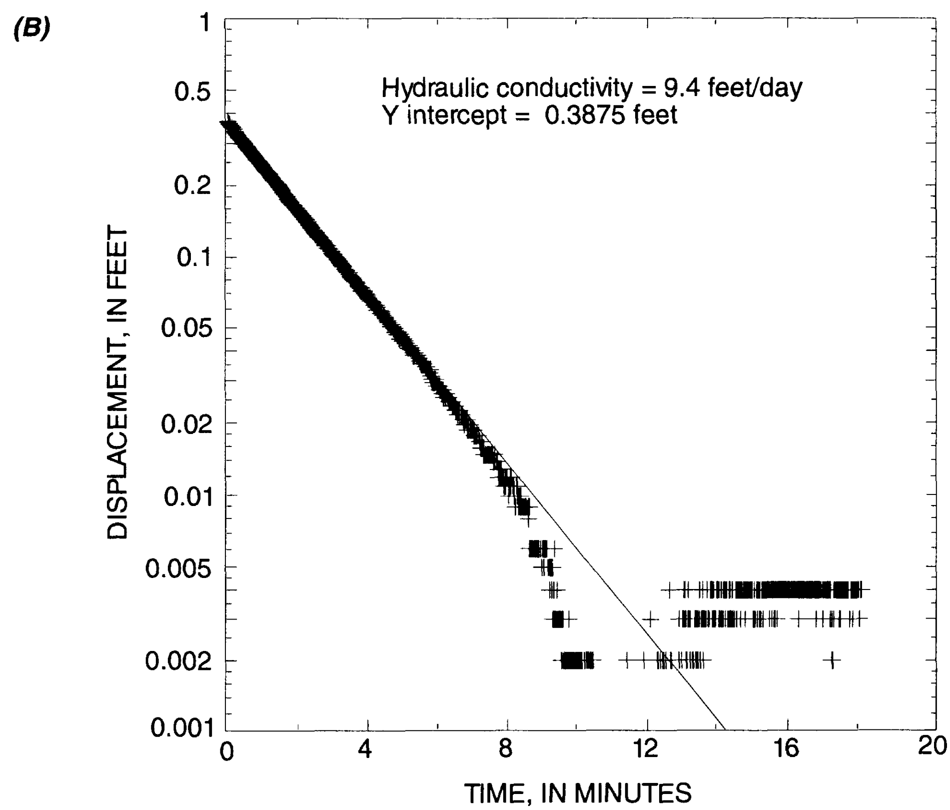


(B)



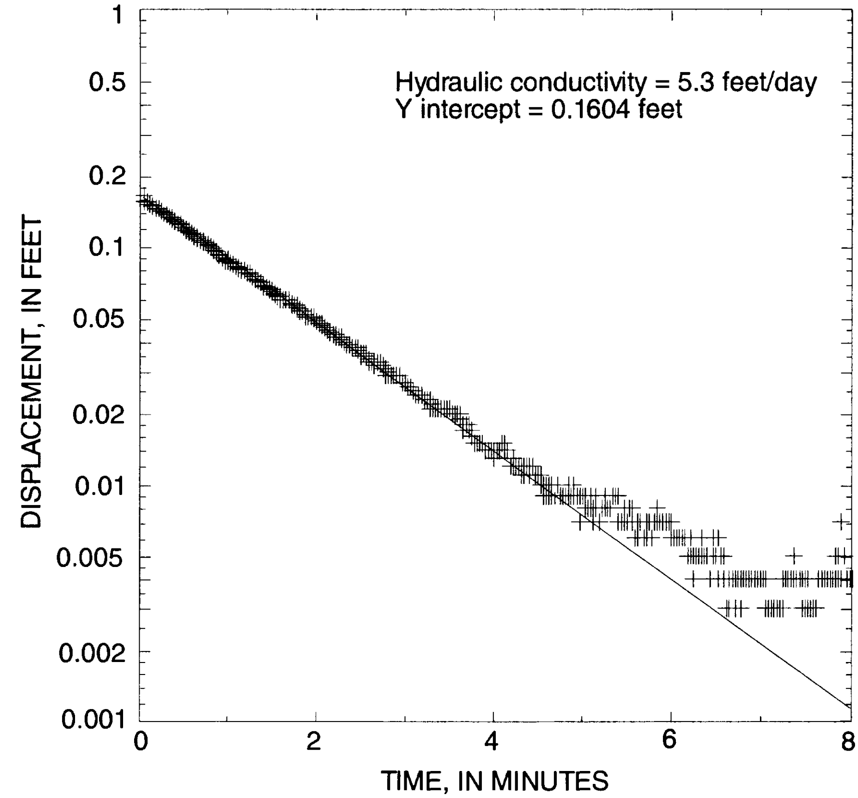
Appendix 8. Plots of slug test data response at KW3S (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*



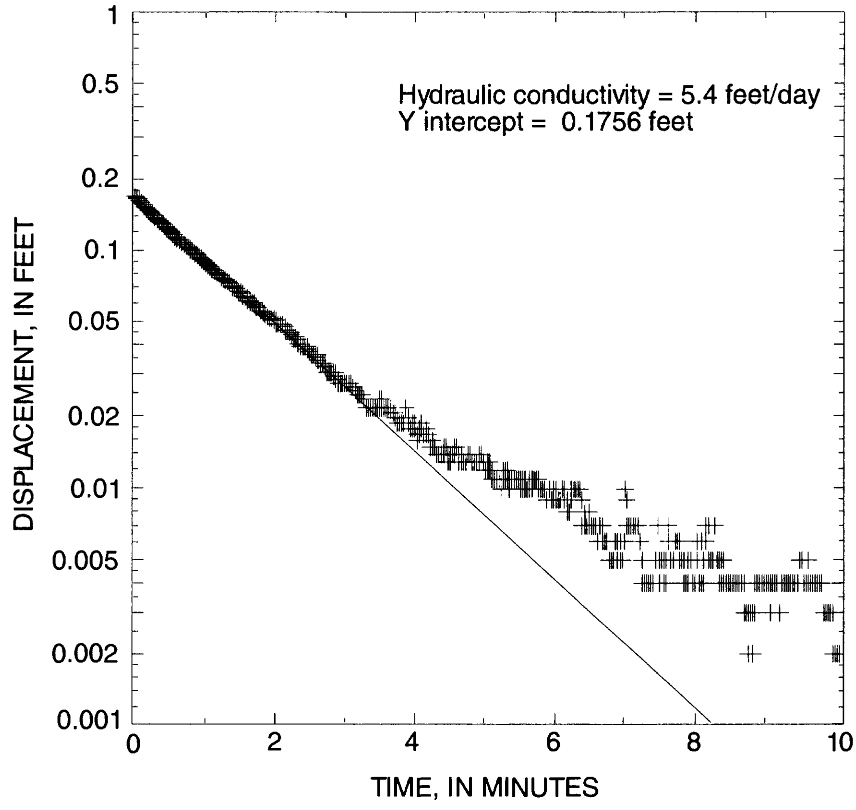


Appendix 8. Plots of slug test data response at KW4D (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*

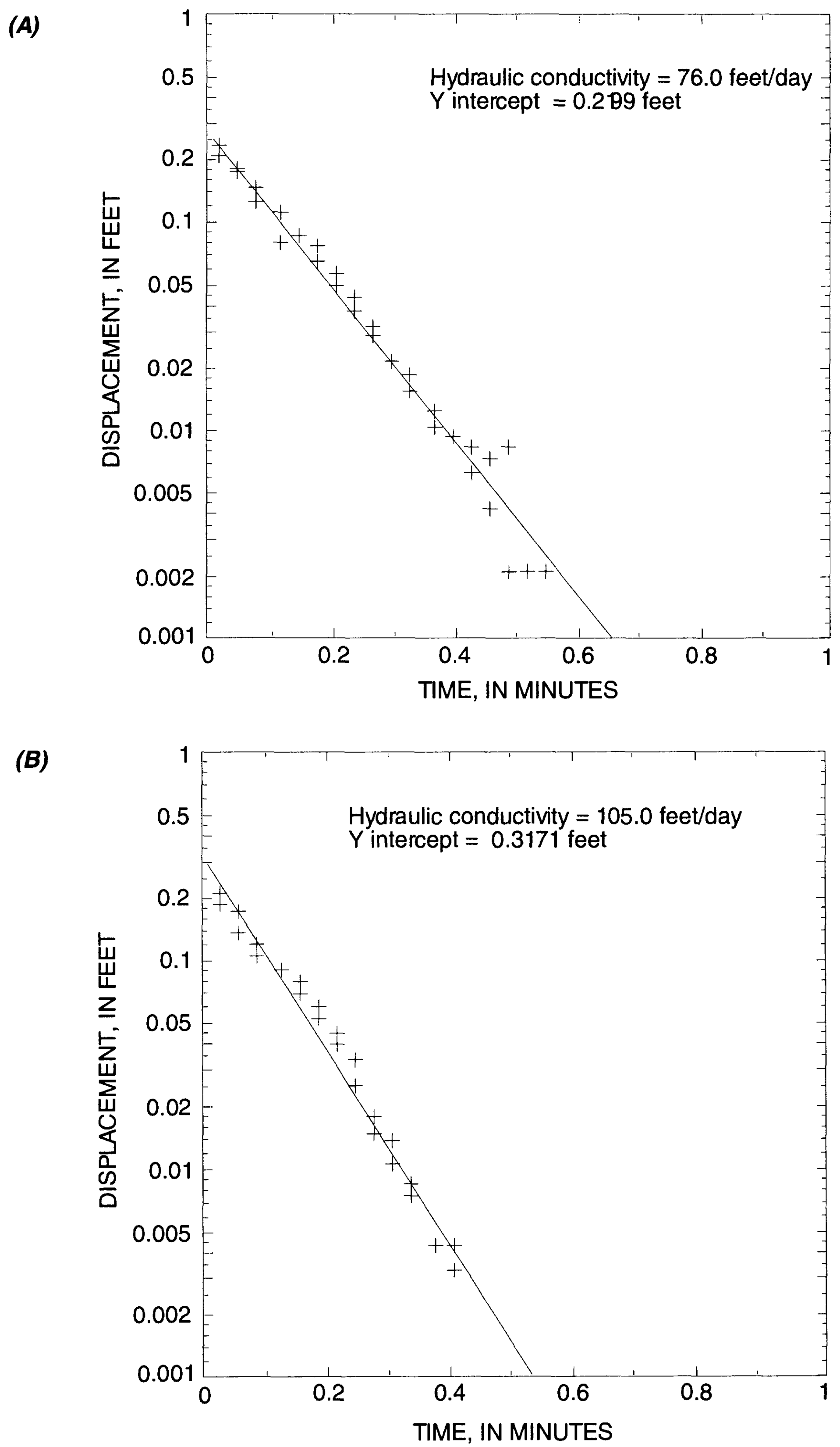
(A)



(B)



Appendix 8. Plots of slug test data response at KW4S (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*



Appendix 8. Plots of slug test data response at OW3 (*A*) forward, and (*B*) reverse, Milford, New Hampshire—*Continued.*

APPENDIX 9. Information used for analysis of multiple-well aquifer test, Milford, New Hampshire

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Appendix 9. Information used for analysis of multiple-well aquifer test, Milford, New Hampshire

[**Type curve match points:** *u* and W(*u*) both equal to 1, ratio of storage to specific yield of 0.001, and a ratio of vertical to horizontal hydraulic conductivity of 0.1. Withdrawal rate was 40.2 ft^3/d; ~, indicates approximation; --, indicates poor data not shown]

Observation well	Radial distance from Keyes well (*r*) (ft)	Saturated thickness (*b*) (ft)	Height above base of the aquifer to middle of well screen divided by *b*	Type curve match points			
				Early time (*t*)		Late time	
				t/r^2 (min/ft)	Draw-down (ft)	t/r^2 (min/ft)	Draw-down (ft)
KW2s	236	66	0.87	0.0005	0.9	0.0006	1.2
KW2d	237	66	.32	.001	4.5	.002	8.8
KW3s	259	68	.86	.0006	.6	.00004	.45
KW3d	251	68	.42	.0006	3.9	.001	4.8
KW4s	237	~56	.85	.0007	7.2	.0002	7.0
KW4d	237	~56	.19	.0007	8.1	.002	8.5
PW1s	176	64	.99	.0008	2.5	.0008	2.0
PW1d	176	64	.38	.0016	6.6	.001	5.1
PW2s	208	61	.98	--	--	.006	1.5
PW2d	208	61	.31	.001	10.1	.002	10.0
PW3s	276	64	.98	--	--	.0005	1.8
PW3d	276	64	.23	.002	10.2	.002	9.6

APPENDIX 10. Information used for analysis of slug tests, Milford, New Hampshire

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Appendix 10. Information used for analysis of slug tests, Milford, New Hampshire

[Well and casing radius are 0.083 foot, except for OW3 which is 0.18 foot.; ~, indicates approximation]

Well	Test	Displacement (feet)	Length of open interval (feet)	Height of static column (feet)	Saturated thickness (feet)	Displacement at specified time (feet)	Time at specified displacement (minutes)	Computed hydraulic-conductivity (feet per day)
KW1	Forward	0.52	2.0	46	73	0.2	4.4	4.6
	Reverse	.34	2.0	46	73	.2	3.8	2.9
KW2s	Forward	.36	2.0	9	66	.2	.6	32.4
KW2d	Forward	.39	2.0	46	66	.2	7.4	1.9
	Reverse	.38	2.0	46	66	.2	9	1.7
KW3s	Forward	.34	2.0	8.6	68	.1	.38	128
	Reverse	.42	2.0	8.6	68	.1	.35	154
KW3d	Forward	.42	2.0	41	68	.2	.8	19.5
	Reverse	.38	2.0	41	68	.2	.75	25.6
KW4s	Forward	.16	2.0	10.7	~56	.05	2.0	5.3
	Reverse	.18	2.0	10.7	~56	.04	2.35	5.4
KW4d	Forward	.38	2.0	46	~56	.1	3.05	8.6
	Reverse	.39	2.0	46	~56	.03	6.45	9.4
OW3	Forward	.22	3.0	36.5	~40	.01	.36	76
	Reverse	.32	3.0	36.5	~40	.1	.1	105