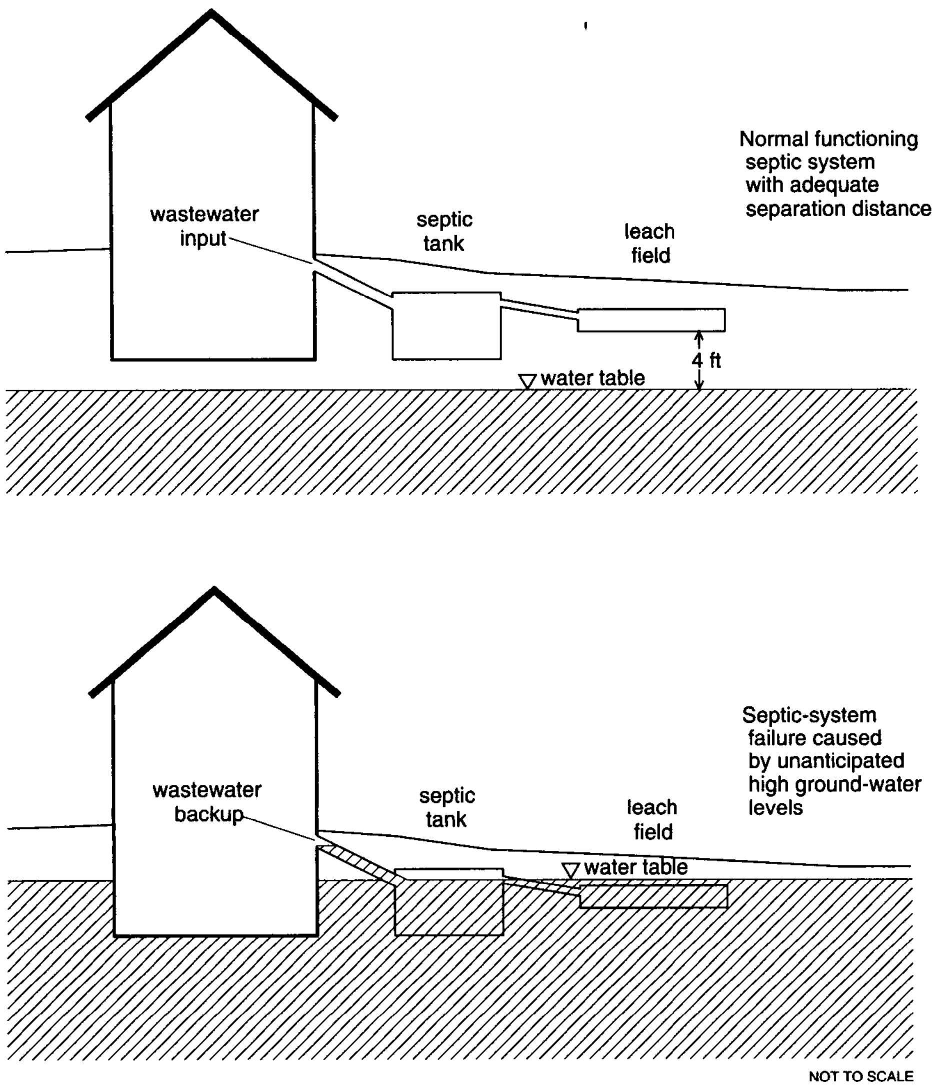
A TECHNIQUE FOR ESTIMATING GROUND-WATER LEVELS AT SITES IN RHODE ISLAND FROM OBSERVATION-WELL DATA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4138



Prepared in cooperation with the
RHODE ISLAND DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

COVER

When an individual sewage-disposal system is saturated with ground water, it will not operate properly. This report presents a technique for estimating ground-water levels that can be used to help design sewage-disposal systems.

A TECHNIQUE FOR ESTIMATING GROUND-WATER LEVELS AT SITES IN RHODE ISLAND FROM OBSERVATION-WELL DATA

By ROY S. SOCOLOW, MICHAEL H. FRIMPTER, MICHAEL TURTORA, and RICHARD W. BELL

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Providence, Rhode Island
1994

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
gallon per hour (gal/h)	3.785	liter per hour
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter

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

A Technique for Estimating Ground-Water Levels at Sites in Rhode Island From Observation-Well Data

By Roy S. Socolow, Michael H. Frimpter, Michael Turtora, *and* Richard W. Bell

Abstract

Estimates of future high, median, and low ground-water levels in Rhode Island are needed for engineering and architectural design decisions and for appropriate selection of land uses. For example, the failure of individual underground sewage-disposal systems due to high ground-water levels can be avoided if accurate water-level estimates are available. Estimates of extreme or average conditions are needed because short-duration preconstruction observations are unlikely to be representative.

The technique described in this report utilizes a single water-level measurement at a site of interest, in combination with a long-term water-level record at an observation well, to estimate the long-term high, median, and low water levels at the site of interest. The transfer of information to the site of interest depends on four fundamental assumptions: (1) Water levels will fluctuate in the future as they have in the past, (2) Water levels fluctuate seasonally, (3) Ground-water fluctuations depend on site geology, and (4) Water levels throughout Rhode Island are affected by similar precipitation and climate. The technique is based on the equivalent relation between the ratio of potential water-level change to maximum annual water-level range at the site and the ratio of potential water-level change to annual water-level range at the observation well. Equations for estimating high, median, and low water levels, and graphs of probable annual water-level range are given for selecting representative ranges of water levels for sand and gravel and till in Rhode Island.

The accuracy of the technique is evaluated by use of the equations to estimate water levels at long-term observation wells where high, median, and low water levels are known from monthly measurements over many years. As a test of the estimating procedure, 6,697 estimates each of high, median, and low water levels (depth to water level exceeded 95, 50, and 5 percent of the time, respectively) were compared with measured water levels exceeded 95, 50, and 5 percent of the time at 14 sites unaffected by pumping or other known factors. Mean squared errors (average differences squared, between estimated and measured water levels) for the estimates ranged from 0.34 to 1.53 ft^2 for high water levels, 0.30 to 1.22 ft^2 for median water levels, and 0.32 to 2.55 ft^2 for low water levels. All mean squared errors are less than the State required 3-foot separation between the bottom of the stone underlying the seepage system and the maximum altitude of the water table. This degree of accuracy is acceptable for many design purposes.

INTRODUCTION

Estimates of ground-water levels are needed to design, engineer, and regulate many structures and land uses. The upper surface of the water-saturated zone in the ground is called the water table. The position of the water table with respect to land surface is usually determined by ground-water-level measurements in wells. Ground-water levels normally fluctuate several feet through a seasonal cycle each year, but they can vary by even larger distances from year to year in response to the same variable weather conditions that cause floods and droughts. In Rhode Island, ground-water levels measured in a dry year or in a dry season of a year can be as much as 26 ft lower than the maximum water level. The maximum level to which the water table will rise must be known to avoid failure of individual underground sewage-disposal systems, referred to in this report as "septic systems." When a septic system is saturated or flooded with water because of unanticipated high ground-water levels, the septic system cannot accept wastewater at an adequate rate or may cease to function; as a result, wastewater may back up in houses, seep onto land surface, or both (fig. 1). Backup and surface seepage of wastewater can create health hazards, become unsightly and malodorous, and devalue and destroy property.

The Rhode Island Department of Environmental Management (1989, p. 9) states that "the vertical separation distance from the bottom of the stone underlying the seepage system shall be at least 3 ft above the maximum elevation of the groundwater table." Because the bottom of the leach fields and drainpipes must also be 1.5 ft below land surface, the minimum allowable depth to water would be 4.5 ft below land surface. The required 3-foot vertical separation provides a margin of safety from rejection of waste inflow by a flooded septic system, and it also provides an aerated zone in which constituents of the effluent are converted to less harmful materials, thereby partly renovating the water.

Estimates of high or low water levels also are needed to estimate infiltration rates to sewer systems, seepage into tunnels, dewatering requirements for construction, stream depletion, pond-level lowering, and wetland loss or creation. Estimates of extreme ground-water levels also can be used to (1) evaluate the suitability of home sites (to avoid wet basements), (2) evaluate landfills and other waste-disposal sites, (3) design landscaping (to avoid waterlogged land), (4) plan remediation activities at toxic-materials contamination sites, and (5) help design numerous other engineering and architectural projects. During emergency response to toxic-material spills, estimates of high, median, or low ground-water levels could be needed immediately.

Adjustment of water levels to represent average conditions commonly is needed to initialize water-level conditions for potentiometric maps and to calibrate ground-water-flow models. Hydrologists face the problems of estimating average or median hydraulic-head data needed for maps of a potentiometric surface and for input to ground-water-flow models based on water-level measurements made on different dates and representing a range of fluctuations. An approach is needed to estimate median water levels from measurements made at any time and, therefore, of any water level within the historical water-level range.

To meet these needs, the U.S. Geological Survey (USGS), in cooperation with the Rhode Island Department of Environmental Management, has developed a technique for estimating ground-water levels at sites where long-term water-level data are sparse or lacking. The water-level data used in this study were collected from the USGS observation-well network in Rhode Island.

Purpose and Scope

The purpose of this report is (1) to describe a technique for estimating high, median, and low water levels in areas where records of ground-water levels are sparse or lacking, and (2) to show how a single onsite water-level measurement can be related to long-term levels measured in Rhode Island observation wells. The report explains and justifies the fundamental assumptions needed to apply the technique. Examples of how to use the estimating technique also are provided. An evaluation of the accuracy of the technique demonstrates its utility for estimating water levels for design purposes such as septic-system permitting.

Approach

The technique described in this report utilizes a single water-level measurement at a site of interest, in combination with a long-term water-level record at an observation well, to estimate the long-term high, median, and low water levels at the site of interest. The transfer of information to the site of interest depends on four fundamental assumptions: (1) Water levels will fluctuate in the future as they have in the past, (2) Water levels fluctuate seasonally, (3) Ground-water fluctuations depend on site geology, and (4) Water levels throughout Rhode Island are affected by similar precipitation and climate. Investigation and confirmation of these assumptions for Rhode Island is based on studies of monthly and 5-day records of ground-water levels collected by the USGS. The approach used in this report further develops the approach taken by the USGS for the study and estimation of ground-water levels in Massachusetts (Frimpter, 1981).

The causes of ground-water-level fluctuations, both natural and man-induced, were identified from inspection and description of hydrographs (graphs of water level over time). Comparison of water-level

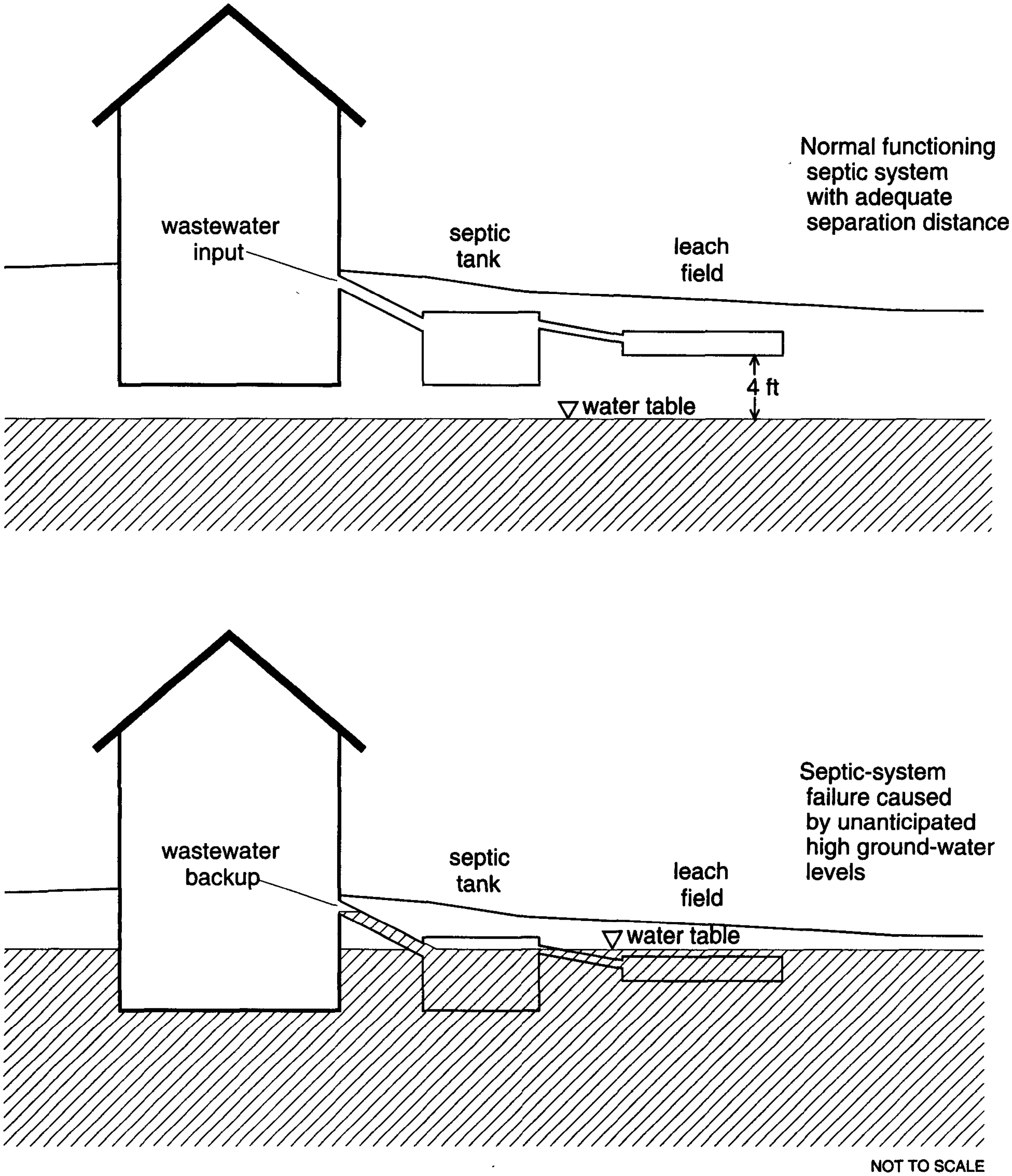

Figure 1. Normal functioning septic system and septic-system failure caused by unanticipated high ground-water levels.

fluctuations with seasonal evapotranspiration and precipitation was used to explain the regular annual rise and decline of ground-water levels in Rhode Island. Hydrogeologic characteristics were presented for selected USGS observation wells completed in coarse-grained stratified glacial drift (sand and gravel) and glacial till (till) in Rhode Island.

Probability plots were developed for water levels for 18 USGS long-term observation wells (June 1946 through December 1989) completed in sand and gravel and 19 USGS observation wells (various record lengths between July 1946 and December 1961) completed in till. These plots show exceedance probability of maximum annual water-level range (the greatest 1-year range of fluctuation of measured water levels for period of record for each well). Frequency distribution tables were developed for water levels measured monthly in 20 USGS long-term observation wells completed in sand and gravel.

Monthly water-level measurements from 20 USGS long-term observation wells completed in sand and gravel and 19 USGS observation wells completed in till were correlated by least squares regressions. Correlation results are given in matrix tables (appendix A). Variations in correlation values between selected well pairs were shown to result from wells having different hydrogeologic properties, and from wells being affected by pumping, surface water, or unknown reasons. Long-term water levels for well pairs showing both high and low correlation were used as examples in linear regression analyses to show the validity of estimating water levels at one well (and therefore one site) on the basis of water levels at another site.

Equations were developed to estimate high, median, and low ground-water levels (depth to water level exceeded 95, 50, and 5 percent of the time, respectively) at sites in Rhode Island where only a single onsite ground-water-level measurement is available. The estimation technique requires the selection and use of an index well. The term "index well" refers to a long-term observation well that is considered to be unaffected by pumping, surface-water inflow, and unknown sources of recharge or discharge, and has similar lithology and depth to water. Additionally an index well would be more representative of water-level conditions at a site for which the estimate is needed if the index well has a similar topographic setting as the site than if it has a dissimilar topographic setting (Frimpter, 1981). Currently (1994) 15 wells in Rhode Island can be used as index wells. Criteria for selecting a suitable index well are presented in this report. Use of the technique, including description and selection of variable values, is described through example estimates.

Past water-level estimates at a site are compared with subsequent measured water levels at that site to evaluate the estimation technique. Because no data were available to make such comparisons, accuracy of the estimation technique was evaluated using data from the observation-well network. Each of the 15 long-term observation wells completed in sand and gravel was used as an index well to estimate high, median, and low water levels at all other long-term observation wells completed in sand and gravel. Differences between measured and estimated values, reported as mean squared error, in feet squared, are given in matrix tables (appendix B). All mean squared errors are less than the State required 3-foot separation between the stone underlying the seepage system and the maximum altitude of the water table.

Hydrogeologic Setting

The topography of Rhode Island ranges from gently rolling—with maximum altitudes of less than 200 ft above sea level—near the ocean, to hilly—with moderate relief and maximum altitude of 812 ft above sea level—in the uplands in the northwestern part of the State. Annual precipitation is usually 42 to 48 in. On average, precipitation is fairly uniformly distributed throughout the year.

Crystalline igneous and metamorphic bedrock is overlain by glacial drift that consists of as much as 300 ft of till and stratified deposits. Most of the stratified drift is glaciofluvial sand and gravel, predominantly valley fill, which underlies about 25 percent of the State. A small part of the stratified drift is glaciolacustrine silt and clay, commonly mantled by surficial peat or silt containing abundant organic matter. Till underlies most of the remainder of the State, although bedrock is exposed at land surface in places. Estimated annual recharge rates from precipitation are 8 to 9 in. in areas underlain by till and 21 to 25 in. in areas underlain by sand and gravel (U.S. Geological Survey, 1985, p. 373). Ground water generally originates as areally distributed recharge from precipitation and discharges to local lakes and streams or to the ocean and its bays.

Observation-Well Network

The USGS has maintained a network of observation wells in Rhode Island since 1944 in cooperation with the Rhode Island Water Resources Board (formerly the Rhode Island Water Resources Coordinating Board) and the former Rhode Island Port and Industrial Development Commission. In 1991, the Rhode Island Department of Environmental Management joined in the operation of the network. The analysis described in this report was made possible by the availability of these long-term water-level records and the continued operation of the network. The observation-well network is maintained to provide the ground-water-level data needed to inventory, evaluate, plan, operate, manage, administer, and research aspects of water resources, and to provide information needed to solve water-related problems in the State. Ground-water levels measured in network wells provide indexes of water in storage in the State's major aquifers, in much the same way as reservoir stage provides indexes of water in surface-water bodies available for public supply and other uses. The network provides long-term records for aquifer-yield and drainage-basin-yield appraisals and provided records for aquifer-modeling studies completed in Rhode Island during the last three decades. The network also provides records of seasonal and long-term responses to variations in climate, which can be used as indexes of long-term recharge and discharge trends and as a means of differentiating changes in ground-water levels caused by water management, construction, land use, and waste disposal from changes caused by natural hydrologic and climatic factors.

In the operation of the observation-well network, water-level measurements in feet and decimal fractions of feet are made at the end of each month between and inclusive of the 20th day and the last day of the month. Measurement accuracy of 0.01 ft below a measurement point is referenced to land-surface datum. The land-surface datum is a datum plane that is approximately at land surface at each well and is established when the fixed measuring point is designated. Typically, the measurement point is marked on the top edge of the well casing. Measurements are made by the wetted-tape method, in which a chalked and weighted steel tape is suspended from the measurement point to below the water surface. The depth to water is calculated by subtracting the measurement of wetted tape from the measurement of tape suspended in the well. The depth measurement is then corrected to depth below land surface by subtracting the difference between the elevations of the measurement point and the land-surface datum.

Each observation well was assigned a unique local well number. The local well number consists of a two-letter code for the town in which the well is located, followed by W (indicating well), followed by a sequential number. Rhode Island and selected Massachusetts[1] town codes are given in table 1. The sequential numbers are unique within each town, but not between towns.

Four of the wells in Rhode Island are equipped with recorders: EXW-475 began recording March 1981, RIW-417 began recording January 1976, RIW-600 began recording September 1977, and SNW-6 began recording July 1973. Five-day water levels are read and entered with monthly data from other wells into the National Water Information System (NWIS) of the USGS; other government agencies and the public can obtain these data on paper or in electronic form (Mathey, 1989). Water levels are published monthly in "Current Water Resources Conditions in Central New England.[2]" Water levels also are published annually in water-resources data reports for Massachusetts and Rhode Island (for example, Socolow and others, 1991).

A search of the water-level records of all wells operated by the USGS in Rhode Island identified 80 wells in sand and gravel and in till with records of 4 years or longer. Wells that had median water levels greater than 30 ft below land surface, wells that flowed, and wells that were dry for more than 3 consecutive months were eliminated from this study.

During the study (1990-91), water levels in 24 wells completed in sand and gravel and located in various topographic settings were measured in Rhode

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[1]Because Rhode Island is a small State, selected wells in Massachusetts located within 25 miles of Rhode Island were used in some parts of this study.

[2]The current conditions report is available on request from the Information Officer, U.S. Geological Survey, 28 Lord Road, Suite 280, Marlborough, MA 01752.

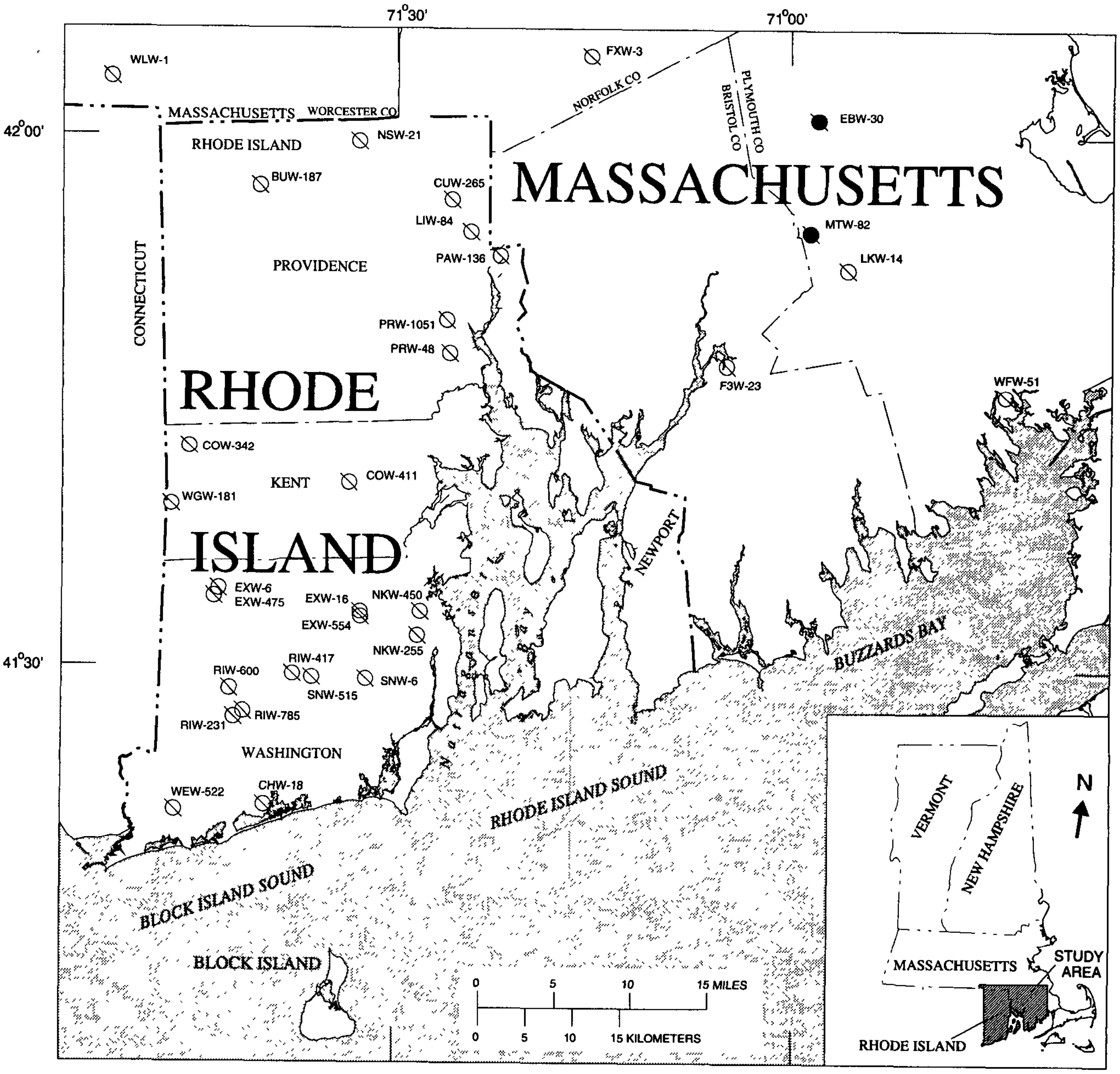
Table 1. Town codes for wells in Rhode Island and parts of Massachusetts

Code	Town name	Code	Town name
Rhode Island		Rhode Island--*Continued*	
BAW	Barrington	NSW	North Springfield
BRW	Bristol	PAW	Pawtucket City
BUW	Burrillville	POW	Portsmouth
CFW	Central Falls City	PRW	Providence City
CHW	Charlestown	RIW	Richmond City
COW	Coventry	SCW	Scituate
CRW	Cranston City	SMW	Smithfield
CUW	Cumberland	SNW	South Kingston
EGW	East Greenwich	TIW	Tiverton
EPW	East Providence City	WAW	Warren
EXW	Exeter	WCW	Warwick City
FOW	Foster	WEW	Westerly
GLW	Glocester	WGW	West Greenwich
HOW	Hopkinton	WSW	West Warwick
JAW	Jamestown	WTW	Woonsocket City
JOW	Johnston	Massachusetts	
LIW	Lincoln	EBW	East Bridgewater
LTW	Little Compton	FXW	Foxborough
MIW	Middletown	F3W	Freetown
NAW	Narragansett	LKW	Lakeville
NEW	Newport City	MTW	Middleborough
NHW	New Shoreham	WFW	Wareham
NKW	North Kingstown	WLW	Webster
NPW	North Providence		

Island (fig. 2). Three of these wells (COW-342, EXW-554, and RIW-785) had records of less than 4 years and were not included in the study. Wells in the network at the time of the study were distributed throughout most of the State, except that none were east of Narragansett Bay. Areas in southeastern Rhode Island have a mantle of till over bedrock and are largely devoid of sand deposits that are saturated throughout the year. Nearly 50 percent of the observation wells completed in sand and gravel have almost 45 years of record; however, records for some of these wells have been interrupted for a few years.

Water levels in 19 wells completed in till were measured monthly for 4 or more years in the past (July 1946 through December 1961) and were used in this study (fig. 3). Of those 19 wells, 2 were measured for 15 years (1947-61), 1 was measured for 14 years (1946-59), 1 was measured for 10 years (1946-55), 6 were measured for 7 years (1949-55 and 1953-59), and 9 were measured for 6 years (1955-60).

The observation-well network was redesigned on the basis of the analyses done in this study. Wells completed in till that were used in this study are primarily in Kent and Washington Counties; Newport, northwestern Providence, and southwestern Washington Counties were unrepresented. To improve coverage of ground-water-level data in those areas, measurements for seven wells completed in till during various periods from 1949 to 1960 were resumed in 1991. Thirteen additional wells completed in till were installed and added to the network in 1992. Water levels from some wells completed in till in southeastern Massachusetts were used to augment the water-level data base for wells in Rhode Island. Beginning October 1993, four



Base from U.S. Geological Survey.
Digital line graphs from 1:100,000 maps.

EXPLANATION

WELL AND LOCAL NUMBER

EXW-6 ● Completed in till

MTW-82 ⦰ Completed in sand and gravel

Figure 2. Locations of observation wells completed in sand and gravel in Rhode Island and observation wells completed in sand and gravel and in till in parts of Massachusetts, 1991.

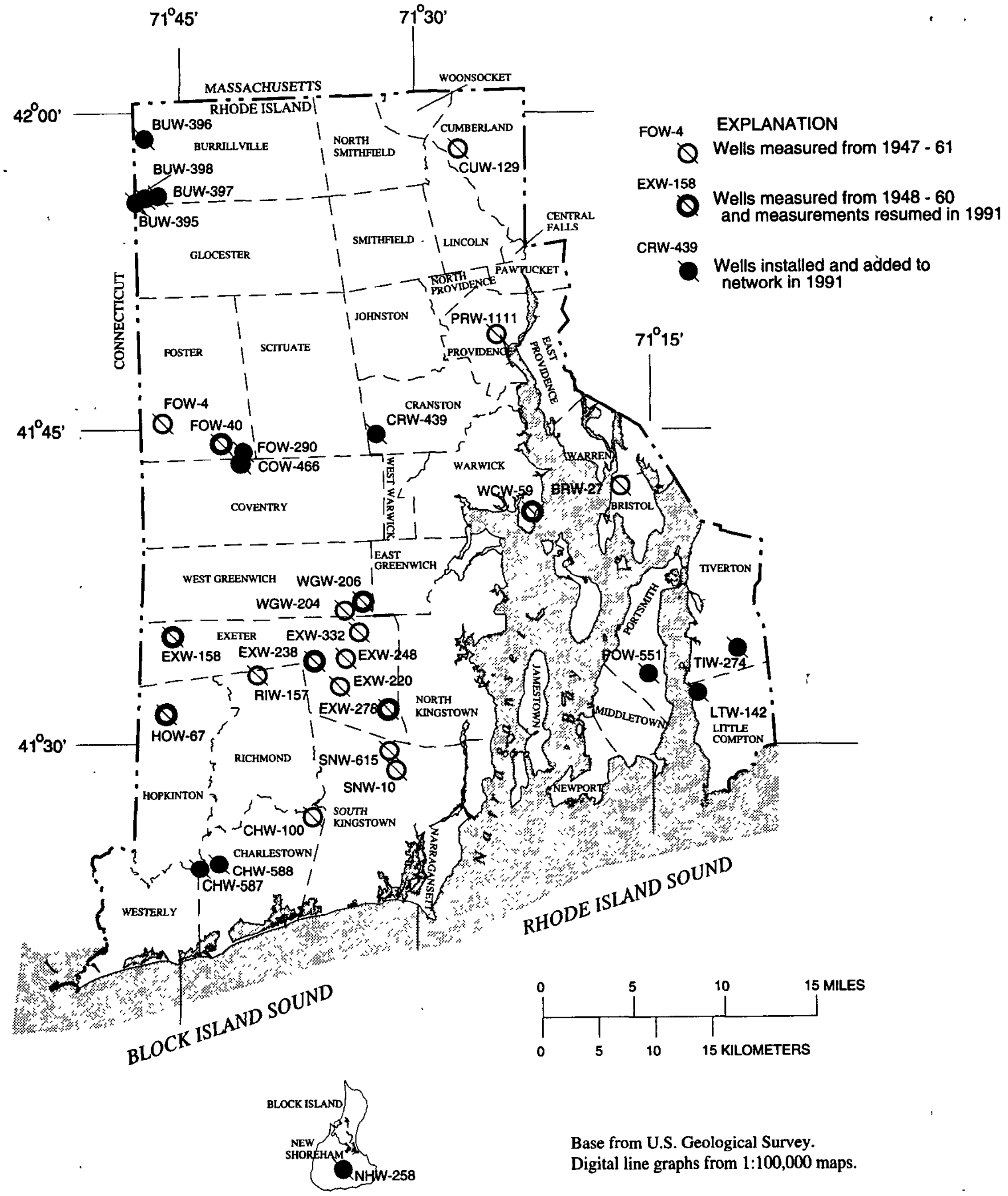


Figure 3. Locations of observation wells completed in till in Rhode Island, 1946-92.

wells completed in sand and gravel (EXW-16, NKW-450, PRW-1051, and RIW-231; fig. 2) were eliminated from the network.

FLUCTUATIONS OF GROUND-WATER LEVELS

Ground-water levels fluctuate because of ground-water recharge and discharge. Long-term average ground-water levels represent response of the ground-water system to long-term average recharge and discharge, whereas high and low ground-water levels represent the response to the magnitude, time, and duration of recharge and discharge. Water levels rise when the rate of recharge from precipitation and snow-melt exceeds the rate of discharge; water levels decline when the rate of discharge exceeds the rate of recharge. Stresses that increase either recharge or discharge are reflected as changes in the water level. Examples of natural stresses are the effects of tidal water bodies and the interaction of precipitation and evapotranspiration (ET—that portion of precipitation, water surfaces, and ground water returned to the air through direct evaporation or by transpiration of vegetation). Examples of artificial stresses are leaking sewers and pumping of ground water.

Near tidal water bodies, such as Narragansett Bay, the diurnal rise and decline in the tidal bodies is transmitted to ground water, causing a dampened cyclical fluctuation of ground-water levels (fig. 4) (Frimpter and Maevsky, 1979). This cyclical fluctuation decreases geometrically with increased distance from the shoreline. Many other factors, such as hydraulic conductivity of the earth materials and the range of fluctuation in the tidal water body, affect the magnitude of tidal-induced fluctuations in unconfined ground water.

The interaction of precipitation, recharge, and ET is the major environmental cause of ground-water-level fluctuations. The effects of precipitation and estimated potential ET on water levels are shown in figure 5. Estimated potential ET is calculated (assumes unlimited moisture supply) because actual ET decreases to less than its potential level as the soil dries out. On average, precipitation is evenly distributed throughout the year. The amount of recharge to the water table, however, is commonly small during the growing season (May through September) because most precipitation during that period either evaporates or replaces soil moisture in the top 1 or 2 ft of the ground. Considerable soil moisture is tapped by plant roots and transpired back to the atmosphere by vegetation. Only after the soil-moisture deficit is satisfied by precipitation does excess moisture pass through the soil zone to recharge the water table. As a result, from mid-spring to early autumn, the rate of ground-water discharge exceeds the rate of ground-water recharge, and ground-water levels steadily decline. Upon reduction of the ET rate in the autumn, the average rate of recharge exceeds the average rate of discharge, and ground-water levels rise in response to precipitation. The rise usually culminates in March or April, when the ground thaws, snow and ice melt, and ET rates generally are small.

Leakage to, or from sewers, is an example of an artificial stress that can affect recharge and can change water levels. Sewer lines typically are placed above the highest expected ground-water level. Leakage from sewers, in this case, could increase recharge and cause water levels to rise. Where a sewer line is submerged by high ground-water levels, leakage of ground water into the sewer could result in ground-water discharge, thereby lowering water levels. Withdrawal of ground water from wells is an example of a stress that increases discharge and results in lowered water levels. Cyclical pumping results in fluctuations of the water level (fig. 6).

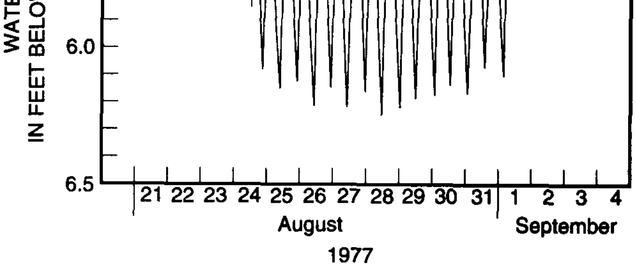


Figure 4. Water-level fluctuations in observation well BRW-23, Rhode Island, caused by tides, August 24 to September 1, 1977.

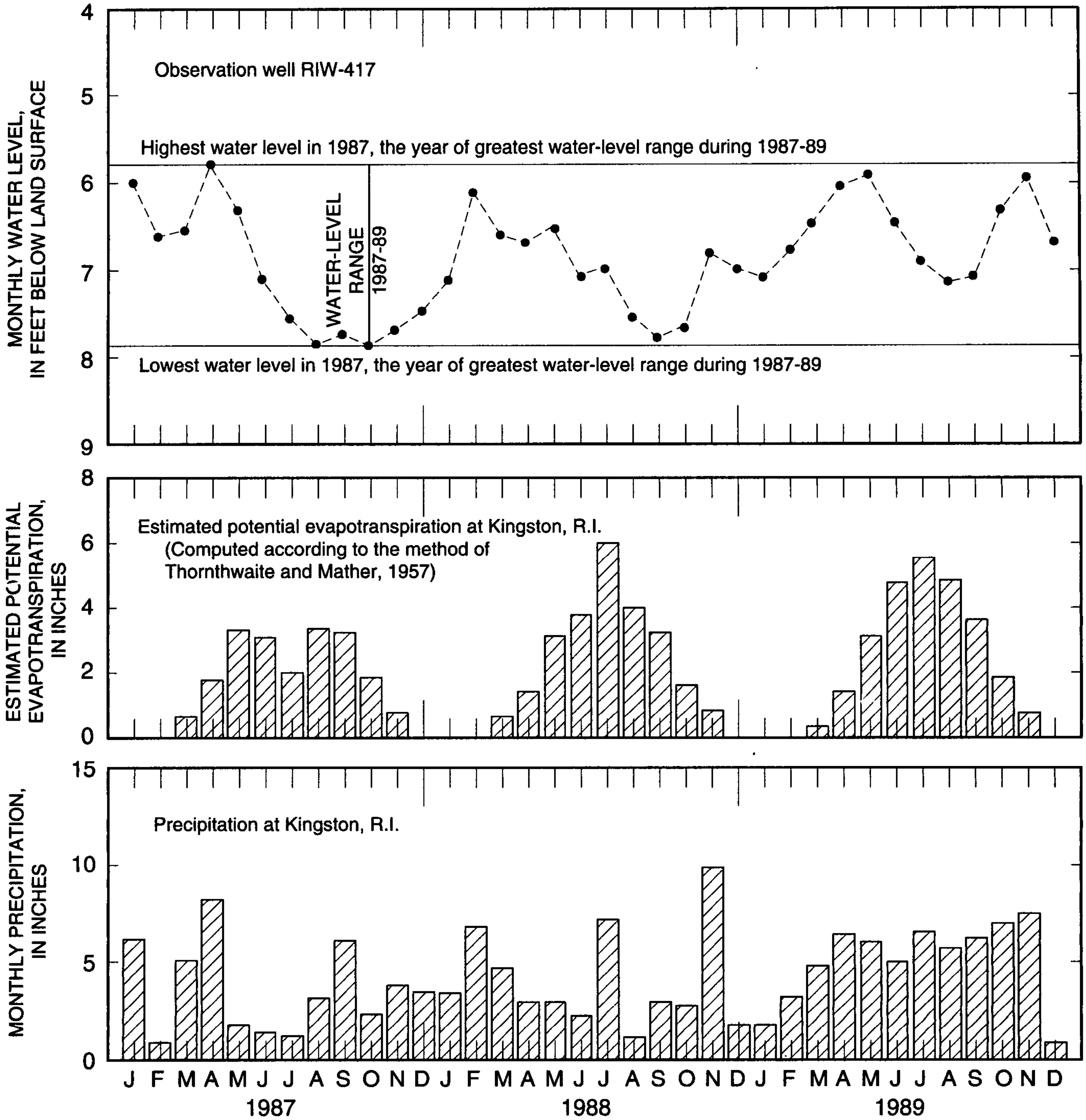


Figure 5. Seasonal water-level fluctuations in observation well RIW-417, estimated potential evapotranspiration, and monthly precipitation at Kingston, Rhode Island, 1987-89.

Although the effects of regular or periodic stresses (such as ocean tides) can be straightforward to estimate, the effects of pumping can be difficult to estimate because the pattern of pumping may vary. For example, long-term hydrographs of two wells, EXW-6 and PRW-1051, show historical ground-water-level fluctuations for 1948-90 (fig. 7). The water-level rise during 1958-78 in well PRW-1051 was caused by the cessation of pumping of nearby industrial wells. Water levels in well EXW-6, in a different hydrogeologic setting, show no such effects.

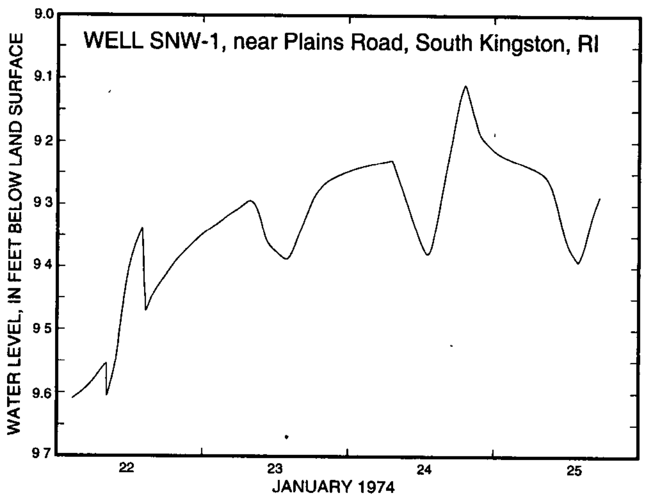


Figure 6. Water-level fluctuations in an observation well caused by pumping of nearby wells.

Measured ground-water levels reflect long-term and short-term stresses. To be valid, water levels that are used to estimate future levels caused by long-term stresses (seasonal and precipitation conditions) must be free of, or adjusted for, the effects of short-term stresses. Standard methods for computing water-level changes caused by short-term stresses, such as pumping, require complex mathematical modeling and spatially dependent or time-dependent data. Although these methods are suitable for major projects, they are expensive and generally unnecessary for small projects, such as the evaluation of septic-system sites.

In till, water-level fluctuations are not strongly related to topographic setting, whereas in sand and gravel, water-level fluctuations are strongly related to topographic setting (Frimpter, 1981, p. 12-17). In evaluating whether a site underlain by sand and gravel is suitable for septic-system installation, it is helpful to determine the topographic setting of the site so that an observation well in a similar topographic setting can be selected for use as an index well for estimating future water levels.

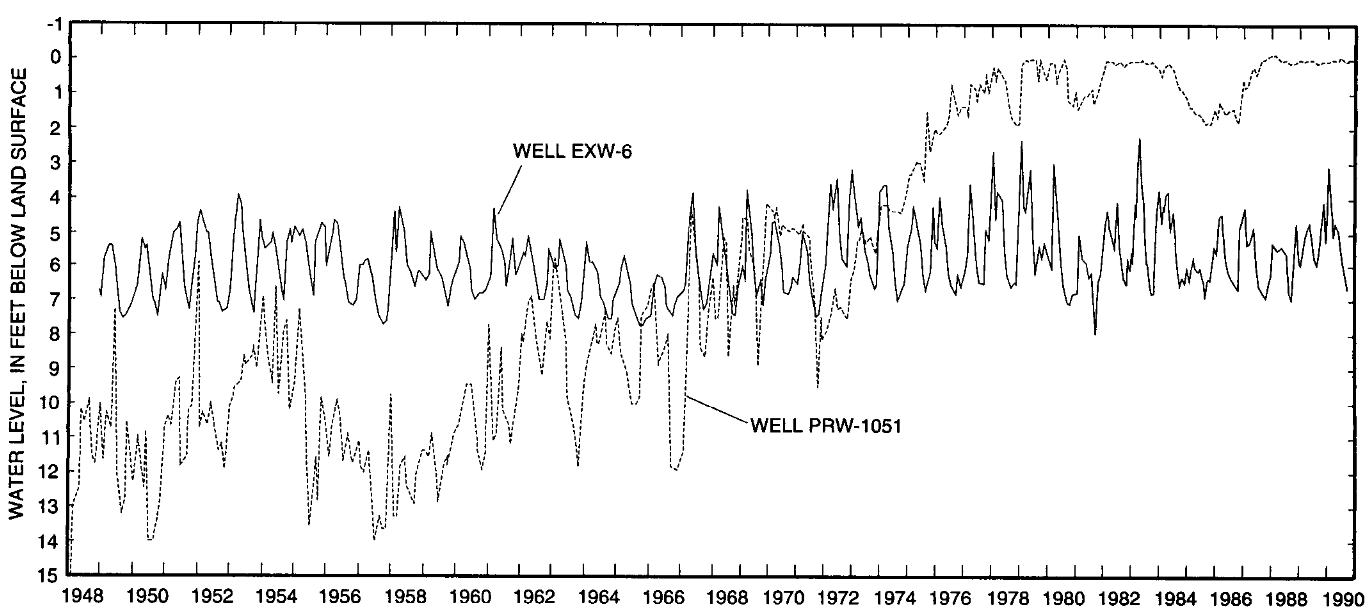


Figure 7. Water levels in observation wells EXW-6 and PRW-1051, Rhode Island, 1948-90.

Topographic settings of the 21 observation wells in Rhode Island are described as hillside, terrace, undulating, valley, or flat (table 2). The maximum annual water-level range and the highest, lowest, and median water levels were determined for each well. Characteristics of water-level fluctuations and the hydrogeology at wells completed in sand and gravel are summarized in table 2. Characteristics of water-level fluctuations and the hydrogeology at wells completed in till are summarized in table 3.

Range

The range of fluctuation can be defined as the difference between the highest and lowest water levels measured during a specific period. The range can be based on the difference between the highest and lowest water levels in a month, a year, or the period of record for the well. For this investigation, the range used is the maximum annual water-level range (the greatest difference in 1 year between the highest- and lowest-measured water levels for period of record for the well). The potential water-level change from the current water level at an observation well can be related to the maximum annual water-level range for that well. For example, if the current water level in a well is in the middle of its range, perhaps 10 ft below land surface, and the maximum historical water-level range is 6 ft, the water level in the well could potentially rise to 7 ft below land surface. The longer the period of record for the well, the less the probability that the maximum annual water-level range will be exceeded in the future.

Water-level ranges in wells completed in sand and gravel are considerably less than ranges in wells completed in till. Maximum annual water-level range at 18 wells completed in sand and gravel varied from a minimum of 3.62 ft to a maximum of 9.10 ft; the median was about 6 ft (fig. 8). These ranges are similar to those at wells completed in sand and gravel in Massachusetts (Frimpter, 1981, p. 17), an indication that hydrogeologic conditions in the two States are similar. Wells affected by pumping (EXW-16, PRW-48, and PRW-1051) were not included in figure 8.

Maximum annual water-level range for 19 wells completed in till varied from a minimum of 3.2 ft to a maximum of 26.1 ft; the median was about 11 ft. Most of the maximum annual ranges were in water year 1958 (October 1957 through September 1958) because water levels were very low in November 1957 and very high in April 1958. The probability of exceedance for the maximum annual water-level fluctuations in till for various periods during 1946-61 is shown in figure 9. Maximum annual ranges in wells completed in till in Rhode Island are larger than those in 15 wells completed in till in Massachusetts, where the minimum range is about 7 ft, the maximum range is 16.8 ft, and the median range is about 12 ft (Frimpter, 1981, p. 12). This difference might be attributed to the generally greater topographic relief in Massachusetts than in Rhode Island.

The relation between water-level ranges and the probability scale in figures 8 and 9 is generally linear. For figures 8 and 9, linear regression between maximum annual range and standard normalized probability of exceedance was calculated by use of a least-squares algorithm. The result of the regressions was the development of a linear equation, the coefficient of determination (R^2), and the standard error of the mean response estimate (SE), all shown in figures 8 and 9. (Complete descriptions of R^2 and SE are given in the "Regression Analysis of Ground-Water Levels" section in appendix A.)

Water-level range at a site *Sr* for a given probability of exceedance can be selected from figures 8 and 9. *Sr* can be determined by two different methods: it can be read directly from the line of best fit or it can be calculated by use of the regression equation and the quantiles (*Q*) of the standard normal distribution on the upper scale of figures 8 and 9.

Frequency Distribution

An analysis of the records of the Rhode Island observation wells completed in sand and gravel and in till indicates that annual water levels are highest during March and April and lowest during September and October (figs. 10 and 11). In some years, however, highest or lowest levels of the year occur in other months. Some recent years when March and April were not the months of highest water level were 1978 (when levels in 15 of 19 wells were highest in January), 1985 (when levels in 16 of 21 wells were highest in November or December), and 1988 (when levels in 14 of 21 wells were highest in February). These differences were caused largely by variations in precipitation.

Table 2. Hydrogeologic characteristics of observation wells completed in sand and gravel in Rhode Island

[Water levels are in feet below land surface (a smaller numerical value corresponds to a higher level, negative values are above land surface). Range is the greatest difference in one year between the highest and the lowest water levels for the period of record for that well; Wr, variable indicating maximum annual water-level range used in estimation equations; >, actual value is greater than value shown; --, no data available]

Local well No. (fig. 2)	Period of record	Topo-graphic setting	Maximum annual range		Measured water level			Remarks
			Water level (Wr)	Year	Highest	Lowest	Median	
BUW-187	Jan 1968 to Dec 1989	Terrace	7.10	1983	10.74	18.83	15.10	--
CHW-18	Oct 1946 to Dec 1989	Flat	9.10	1983	10.09	21.63	17.87	--
COW-411	Oct 1961 to Dec 1989	Hillside	6.43	1983	16.43	23.73	21.57	--
CUW-265	Aug 1946 to Dec 1989	Hillside	6.33	1969	9.20	17.20	12.71	--
EXW-6	June 1946 to Dec 1989	Valley	4.53	1983	2.25	7.97	5.96	--
EXW-16	July 1946 to Dec 1989	Hillside	7.46	1958	5.98	15.40	10.94	Affected by surface runoff; water-level measurement discontinued in 1991.
EXW-475	March 1981 to Dec 1989	Valley	6.16	1983	9.58	16.73	14.65	--
LIW-84	June 1946 to Dec 1989	Valley	7.21	1969	-.97	7.30	5.39	Affected by flooding.
NKW-255	Aug 1954 to Dec 1989	Valley	6.46	1982	3.81	13.03	8.49	--
NKW-450	Oct 1961 to Dec 1989	Flat	6.30	1983	8.32	[1]>17	13.32	Dry at times; well destroyed in 1992; water-level measurement discontinued.
NSW-21	June 1947 to Dec 1989	Terrace	6.97	1979	3.67	11.71	7.99	--
PAW-136	Jan 1962 to Dec 1989	Terrace	3.62	1984	1.98	7.28	4.84	--
PRW-48	Dec 1944 to Dec 1989	Terrace	2.23	1979	2.78	10.06	6.89	Affected by pumping.
PRW-1051	Jan 1948 to Dec 1989	Valley	6.02	1983	-.17	15.53	6.67	Flowing at times, affected by pumping; water-level measurement discontinued in 1992.
RIW-231	June 1955 to Dec 1989	Flat	7.50	1958	19.38	28.99	25.03	Water-level measurement discontinued in 1991.
RIW-417	Jan 1976 to Dec 1989	Valley	3.72	1983	4.08	8.01	6.92	--
RIW-600	Sept 1977 to Dec 1989	Terrace	4.35	1982	31.45	35.91	33.87	--
SNW-6	Feb 1955 to Dec 1989	Valley	6.48	1983	6.91	15.06	12.20	--
SNW-515	March 1955 to Dec 1989	Undulating	7.45	1966	22.44	[1]>34	27.32	Dry at times.
WEW-522	Jan 1969 to Dec 1989	Flat	4.66	1976	9.23	14.61	12.23	--
WGW-181	Jan 1969 to Dec 1989	Undulating	4.88	1980	12.15	17.78	15.94	--

[1]Depth of well.

Table 3. Hydrogeologic characteristics of observation wells completed in till in Rhode Island

[Water levels are in feet below land surface (a smaller numerical value corresponds to a higher level). Range is the greatest difference in one year between the highest and the lowest water levels for the period of record for that well; *Wr*, variable used in water-level estimating equations indicating maximum annual water-level range]

Local well No. (fig. 3)	Period of record	Topographic setting	Maximum annual range		Measured water level		
			Water level (*Wr*)	Year	Highest	Lowest	Median
BRW-27	July 1949 to Dec 1955	Hilltop	9.06	1953	8.82	18.51	13.66
CHW-100	Nov 1955 to May 1960	Hillside	16.66	1958	12.58	27.44	20.01
CUW-129	July 1946 to Feb 1959	Hilltop	14.15	1958	4.05	18.28	11.16
EXW-158[1]	Sept 1953 to Feb 1959	Hillside	11.09	1956	4.43	18.30	11.36
EXW-220	Nov 1955 to June 1960	Hillside	9.60	1956	13.40	20.70	17.05
EXW-238[1]	Nov 1955 to June 1960	Flat	3.53	1956	10.54	13.43	11.98
EXW-248	Nov 1955 to June 1960	Hillside	12.43	1958	3.27	16.10	9.68
EXW-278[1]	Nov 1955 to June 1960	Hilltop	20.11	1958	3.69	23.80	13.74
EXW-332	Nov 1955 to June 1960	Hillside	13.96	1958	8.76	22.08	15.42
FOW-4	Oct 1947 to Dec 1961	Hillside	9.62	1958	6.48	16.71	11.60
FOW-40[1]	July 1953 to Feb 1959	Hilltop	12.02	1958	1.29	13.97	7.63
HOW-67[1]	Aug 1953 to Feb 1959	Hillside	12.20	1958	10.70	22.90	16.80
PRW-1111	Nov 1946 to Dec 1955	Undulating	9.16	1950	9.22	18.37	13.80
RIW-157	Oct 1953 to Feb 1959	Hilltop	26.07	1958	2.63	28.73	15.68
SNW-10	Nov 1947 to Dec 1961	Hilltop	12.36	1958	2.44	14.70	8.57
SNW-615	Nov 1955 to June 1960	Hillside	8.20	1958	5.23	13.47	9.35
WCW-59[1]	April 1949 to Dec 1955	Hillside	13.66	1950	4.26	24.77	14.52
WGW-204	Nov 1955 to June 1960	Hillside	3.29	1958	2.41	5.75	4.08
WGW-206[1]	Nov 1955 to June 1960	Hillside	6.30	1958	3.33	9.34	6.34

[1]Water-level measurement resumed October 1991.

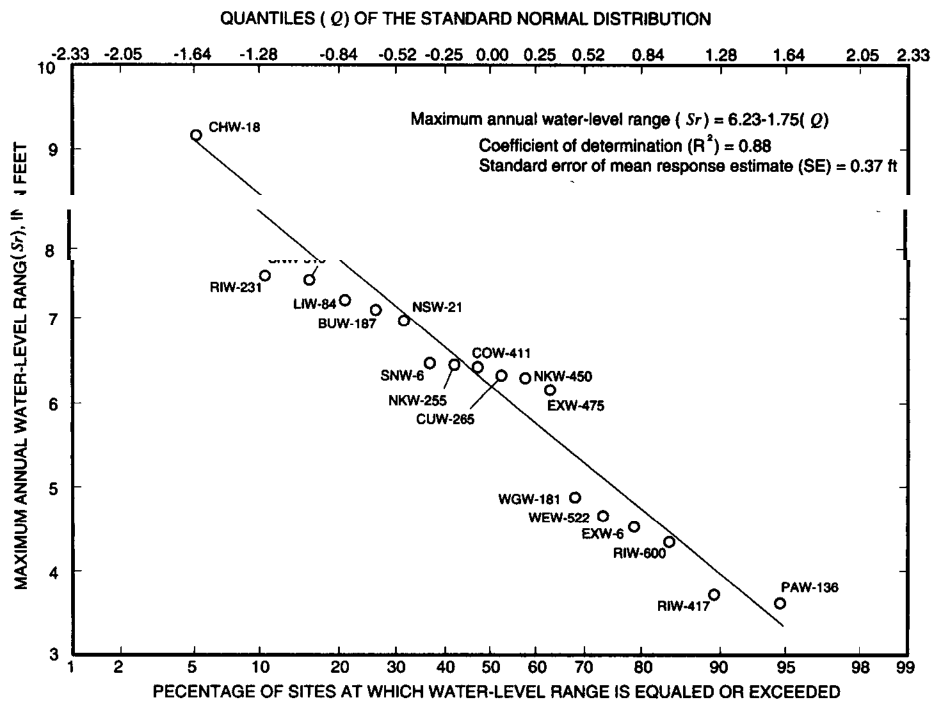


Figure 8. Probability of water-level ranges for wells completed in sand and gravel in Rhode Island, 1946-90.

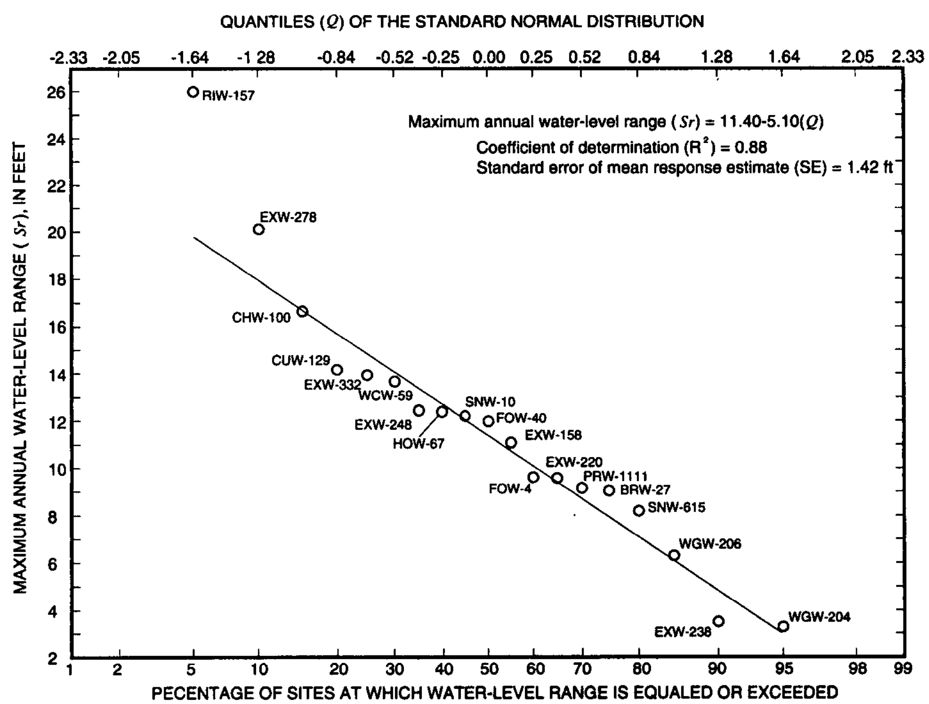


Figure 9. Probability of water-level ranges for wells completed in till in Rhode Island, 1946-61.

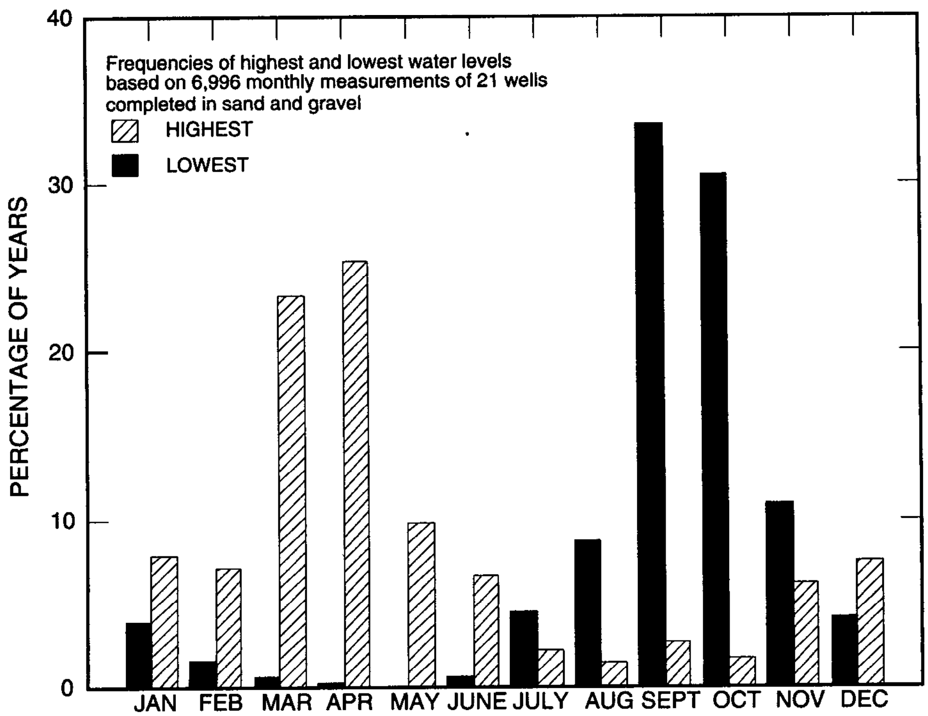


Figure 10. Frequency of the highest and lowest measured annual water levels, by month, in 21 observation wells completed in sand and gravel in Rhode Island.

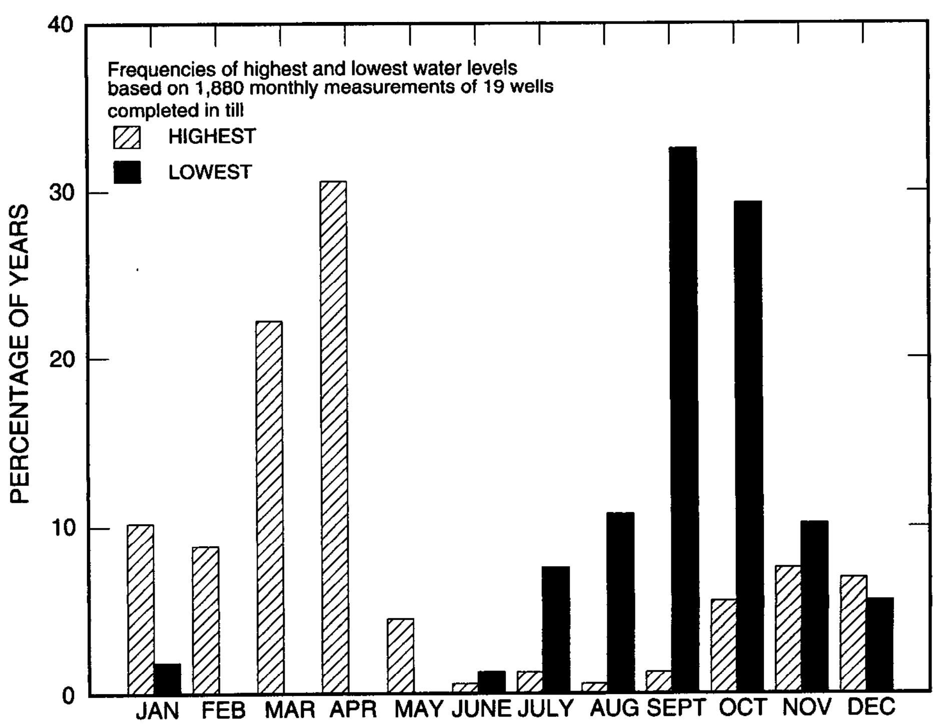


Figure 11. Frequency of the highest and lowest measured annual water levels, by month, in 19 observation wells completed in till in Rhode Island.

Lower than average precipitation (based on records for a National Oceanic and Atmospheric Administration [NOAA] precipitation site at Kingston, R.I., reference period 1948-90) during winter and spring in some years (1957, 1965, 1966, 1971, 1975, 1981, 1985, and 1988) resulted in lower than average ground-water recharge and abnormally low water levels in March and April. If onsite measurements of March and April ground-water levels in those years had been used as a measure of high ground-water levels for the design and permitting of septic systems, then those systems in marginally acceptable locations would have greater than normal chance of failure, backups, and breakouts because of high water levels. Similarly, the use of abnormally low seasonal high water levels would result in other design failures for construction or landscaping, such as wet basements and waterlogged lawns, during normal years. Comparison of current water levels with historical levels is a way of determining whether or not current water levels are high.

Frequency distribution of monthly water levels in 20 wells completed in sand and gravel and used in this study was calculated (table 4). (Data from well PRW-1051 was excluded because water levels were severely affected by nearby pumping.) The table shows 95, 90, 85, 75, 50, 25, 15, 10, and 5 percent of months within the period of record that monthly depths to water exceeded (was greater than) the measured water level. If the frequency distribution of historic water levels is assumed to be representative of the future distribution of water levels, table 4 can be used to estimate the

Table 4. Frequency distribution of monthly ground-water levels for wells completed in sand and gravel in Rhode Island

[Water levels are in feet below land surface (a smaller numerical value corresponds to a higher level); negative value (-) indicates water level above land surface]

Local well No. (fig. 2)	Period of record	Measured water level		Percentage of time monthly depth to water level was equaled or exceeded								
		High	Low	95	90	85	75	50	25	15	10	5
BUW-187	Jan 1968-Dec 1989	10.74	18.83	12.88	13.39	13.66	13.98	15.10	16.66	17.20	17.54	18.04
CHW-18	Oct 1946-Dec 1989	10.09	21.63	14.27	15.02	15.58	16.34	17.87	19.37	20.06	20.40	20.80
COW-411	Oct 1961-Dec 1989	16.43	23.73	19.22	19.63	19.93	20.60	21.57	22.28	22.60	22.83	23.23
CUW-265	Aug 1946-Dec 1989	9.20	17.20	10.67	11.10	11.44	11.84	12.71	14.34	15.13	15.54	15.93
EXW-6	June 1946-Dec 1989	2.25	7.97	3.91	4.30	4.71	5.15	5.96	6.57	6.89	7.07	7.38
EXW-16[1]	July 1946-Dec 1989	5.98	15.40	7.79	8.60	8.90	9.43	10.94	12.50	13.26	13.62	14.16
EXW-475	Mar 1981-Dec 1989	9.58	16.73	11.75	12.03	12.38	13.12	14.65	15.44	15.64	15.81	16.40
LIW-84	June 1946-Dec 1989	-.97	7.30	2.74	3.48	4.00	4.62	5.39	6.01	6.31	6.50	6.84
NKW- 255	Aug 1954-Dec 1989	3.81	13.03	6.19	6.69	7.03	7.45	8.49	9.56	9.99	10.36	11.02
NKW-450[2]	Oct 1961-Dec 1989	8.32	DRY	10.47	11.21	11.48	12.03	13.32	14.54	14.94	15.18	15.59
NSW-21	June 1947-Dec 1989	3.67	11.71	5.62	6.15	6.43	6.92	7.99	9.30	9.97	10.23	10.57
PAW-136	Jan 1962-Dec 1989	1.98	7.28	2.91	3.26	3.49	3.98	4.84	5.57	5.95	6.18	6.40
PRW-48	Dec 1944-Dec 1989	2.78	10.06	4.09	4.46	4.73	6.01	6.89	7.64	8.28	8.57	9.37
RIW-231[1]	June 1955-Dec 1989	19.38	28.99	21.75	22.46	23.01	23.65	25.03	26.43	26.98	27.31	27.73
RIW-417	Jan 1976-Dec 1989	4.08	8.01	5.54	5.76	5.93	6.18	6.92	7.40	7.58	7.67	7.77
RIW-600	Sept 1977-Dec 1989	31.45	35.91	32.52	32.74	32.93	33.17	33.87	34.42	34.66	34.79	35.55
SNW-6	Feb 1955-Dec 1989	6.91	15.06	9.85	10.24	10.58	11.12	12.20	13.38	13.72	14.00	14.44
SNW-515	Mar 1955-Dec 1989	22.44	DRY	25.18	25.59	25.87	26.27	27.32	28.27	28.76	29.05	29.43
WEW-522	Jan 1969-Dec 1989	9.23	14.61	10.46	10.82	11.08	11.37	12.23	13.09	13.48	13.67	13.86
WGW-181	Jan 1969-Dec 1989	12.15	17.78	13.86	14.31	14.64	15.24	15.94	16.59	16.78	16.87	17.08

[1] Water-level measurement discontinued in 1991.

[2] Well destroyed in 1992, water-level measurement discontinued.

probability that future water levels will be higher than those given. For example, the water level in well NKW-255 has been deeper than 6.19 ft 95 percent of the time (19 out of 20 months in the past) and equal or shallower than 6.19 ft 5 percent of the time (1 out of 20 months). Therefore, future water levels in the well can be expected to be as high or higher (shallower) than 6.19 ft 5 percent of the time. Estimation of low water levels is similar; because a water level of 17.54 ft or deeper has occurred in well BUW-187 10 percent of the time (table 4), a level deeper than 17.54 ft would be expected 10 percent of the time in the future. Monthly water-level measurements in well NKW-255 for 1986-89 and the historical (1954-89) water-level frequency distribution are shown in figure 12. During 1986-89, depth to water was greater than the 95-percent depth and less than the 10-percent depth, and was at least 2 ft lower than the historical maximum water levels. Water levels were higher than the historical median (50-percent depth) for much of 1989, a pattern that indicates wetter than normal conditions at the well (fig. 12).

The difference between mean and median water levels in 18 observation wells completed in sand and gravel was calculated and ranged from +0.06 to -0.32 ft and averaged -0.13 ft. Therefore, the median is a close approximation of mean, or average, and is suitable for use in ground-water-flow simulations and other analyses where average levels are required. Estimates based on the records of the Rhode Island observation-well network should be representative of the average period of record for the wells, about 33 years.

In addition to the frequency at which a water level is expected to be higher than a given water level, the amount by which a given water level would be exceeded is of concern. This amount is calculated as the difference between the smallest measured depth to water on record, and the depth to water that is exceeded 95 percent of the time (fig. 13). These maximum differences ranged from 0.17 to 4.18 ft and averaged 2.02 ft. For the period of record, maximum differences in 2 of 21 wells (about 10 percent) were greater than 3 ft.

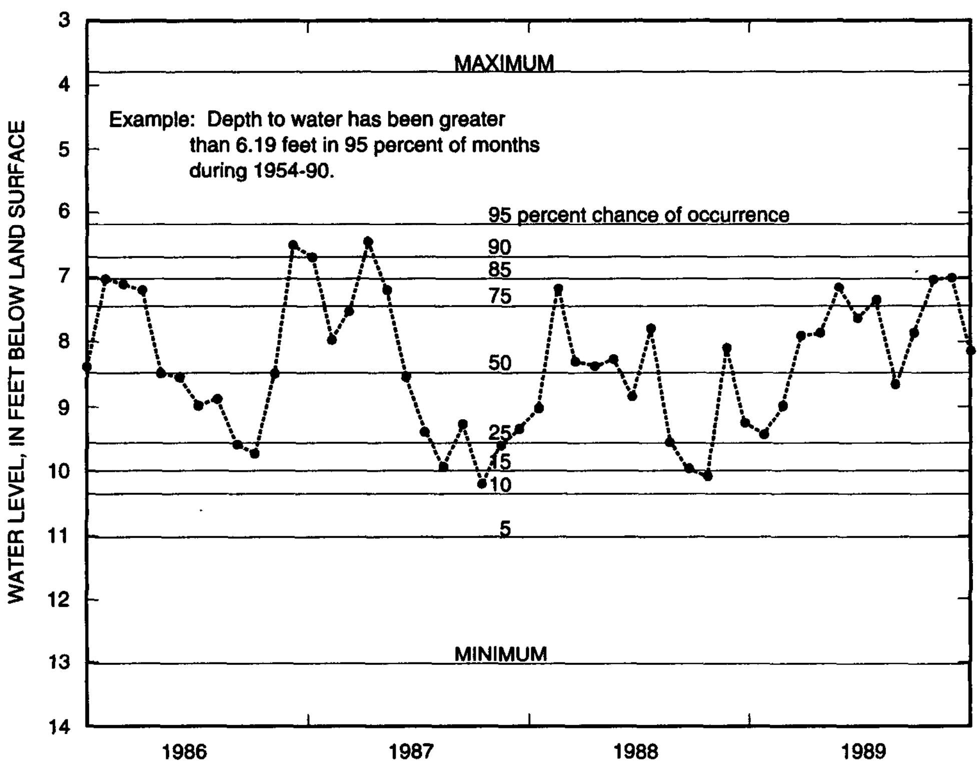


Figure 12. Monthly water-level fluctuations during 1986-89 and historical (1954-90) water-level frequency in well NKW-255, Rhode Island.

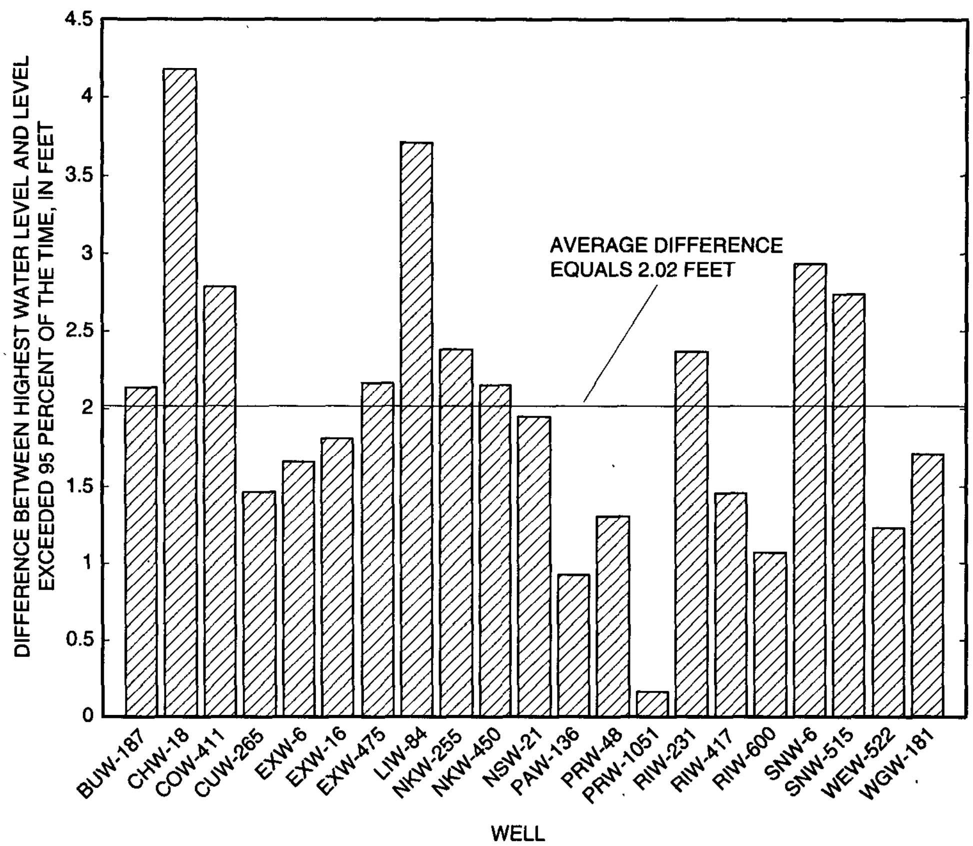


Figure 13. Difference between smallest measured depth to water on record and depth to water exceeded 95 percent of the time in wells completed in sand and gravel in Rhode Island.

Four wells for which 6.5 to 11 years of water-level measurements were available were used to test the hypothesis that monthly water-level measurements are sufficient to describe the frequency of occurrence of water levels. The frequency of water levels exceeded in 95, 90, 85, 75, 50, 25, 15, 10, and 5 percent of the measurements was computed from measurements made every 5 days and then compared to similar data computed from the monthly measurements. Comparison of the two data sets indicates a close match between the water levels (table 5). The greatest difference among all exceedance percentages was 0.39 ft, and the greatest difference in water levels exceeded in 95 percent of the measurements was 0.11 ft. This close match, particularly for high water levels, shows that the frequency data based on monthly measurements are virtually as accurate as frequency data based on 5-day increments. This finding is expected, because ground-water levels generally respond slowly to stresses. Measurement frequency greater than monthly would not appreciably change or improve the accuracy of ground-water-level frequency data to be used in estimating water levels by the technique described in this report.

TECHNIQUE FOR ESTIMATING GROUND-WATER LEVELS FROM OBSERVATION-WELL DATA

Future high, median, and low ground-water levels can be estimated at any site from (1) a single measurement made at any time at the site and (2) concurrent measurements in a long-term observation well. Through hydrographic and statistical analyses of water-level fluctuations in Rhode Island observation wells, a relation between observation wells and, by inference, a relation between observation wells and nearby sites was developed to calculate estimated ground-water levels.

Table 5. Frequency distribution of ground-water levels computed from 5-day and monthly measurements for four wells in Rhode Island

Local well No. (fig. 3)	Period of comparison	Frequency of measurements	Number of measurements	Percentage of time depth to water level was equaled or exceeded								
				95	90	85	75	50	25	15	10	5
EXW-475	Mar 1981-	5-day	467	11.43	11.95	12.33	13.09	14.66	15.42	15.64	15.76	16.04
	Sept 1987	Monthly	80	11.40	12.10	12.34	13.09	14.47	15.47	15.66	15.84	16.43
RIW-417	Jan 1976-	5-day	788	5.55	5.75	5.92	6.17	6.92	7.40	7.58	7.67	7.79
	Sept 1987	Monthly	168	5.56	5.77	5.89	6.19	6.90	7.45	7.58	7.69	7.78
RIW-600	Sept 1977-	5-day	664	32.54	32.74	32.93	33.18	33.87	34.43	34.65	34.77	35.41
	Sept 1987	Monthly	148	32.43	32.74	32.94	33.19	33.89	34.44	34.69	34.89	35.39
SNW-6	Oct 1976-	5-day	721	9.72	10.12	10.51	11.07	12.17	13.34	13.63	13.92	14.54
	Sept 1987	Monthly	132	9.70	10.00	10.57	11.03	12.23	13.38	13.67	14.07	14.56

Estimation Equations

Results of correlation and regression analyses (discussed in the appendixes) indicate a relation between water-level fluctuations in an index well and water levels at a nearby site. (An index well is a long-term observation well that is unaffected by pumping, discharges, surface-water diversions, and other water management activities. An index well should have similar lithology and depth to water as the site for which the estimate is needed. Also, in the case of sand and gravel aquifers, the index well should have the same topographic setting as the site of interest.) This relation can be expressed as a proportion in which the ratio between potential water-level change and the annual water-level range at the site is equal to the ratio between potential water-level change and the maximum annual water-level range at the index well. The proportion to estimate high water level is expressed as

$$\frac{\text{Potential water-level change at site}}{\text{Annual water-level range at site}} = \frac{\text{Potential water-level change at index well}}{\text{Maximum annual water-level range at index well}} \qquad (1)$$

which can be written as

$$\frac{Sc - Sh}{Sr} = \frac{Wc - Wh}{Wr} . \qquad (2)$$

Through rearrangement of equation 2, the following equations were developed for estimating high, median, and low ground-water levels, where water levels are in depth below a reference plane:

$$Sh = Sc + [(Sr/Wr)\,(Wh - Wc)]. \qquad (3)$$

Similar equations were developed for estimating median and low water levels:

$$Sm = Sc + [(Sr/Wr)\,(Wm - Wc)] \qquad (4)$$

$$Sl = Sc + [(Sr/Wr)\,(Wl - Wc)], \qquad (5)$$

where

- Sh is estimated depth to high water level at the site, in feet;
- Sm is estimated depth to median water level at the site, in feet;
- Sl is estimated depth to low water level at the site, in feet;
- Sc is measured depth to water level at the site, in feet;
- Sr is range of water level at the site, in feet (figs. 8 and 9);
- Wr is maximum annual water-level range recorded for the observation well being used as an index well, in feet (from table 2; wells affected by pumping should not be used as index wells);
- Wc is measured depth to water level at the observation well, in feet, measured within 15 days of measurement of Sc (Wc is available from "Current Water Resources Conditions in Central New England");

Wh is depth to high water level (95th percentile) in the observation well, in feet (from table 4);

Wm is depth to median water level (50th percentile) in the observation well, in feet (from table 4); and

Wl is depth to low water level (5th percentile) in the observation well, in feet (from table 4).

If the estimated levels are to be in altitude above some reference plane, such as sea level, the same equations should be used, except that all depths must be converted to altitudes.

Selection of Index Well

Use of the estimating technique requires a water-level measurement at the estimation site (herein referred to as site) and a concurrent water-level measurement (within about 15 days) at an index well. Selecting suitable index wells is essential for making accurate water-level estimates at sites. Some observation wells included in this study are of limited use as index wells. Those wells, and the reasons for their limitations, are described in the following paragraphs.

The index well must be unaffected by pumping, discharges, surface-water diversions, or other water-management activities. Most wells listed in table 2 can be used as index wells. Several wells (EXW-16, LIW-84, NKW-450, PRW-48, PRW-1051, RIW-231, and SNW-515) should not be used at all or should only be used selectively as index wells to represent local conditions. Wells EXW-16, PRW-48, and PRW-1051 are affected by nearby pumping and are not recommended for use as index wells to estimate water levels at distant sites.

Well NSW-21 was pumped for domestic supply from about 1947 through about 1980; however, information from the landowner and hydrographic analysis of water levels before and after pumping indicate that pumping did not adversely affect historical water-level data. Because the water-level record of well NSW-21 does not vary in response to pumping, the well can be use as an index well for estimating water levels.

Well LIW-84 is affected by lower-bank flooding of the Blackstone River (highest water level is 0.97 ft above land surface). Although the well casing was extended, it should not be used for estimating high water levels when the Blackstone River is at extreme flood stage.

Water-level measurements in well RIW-231 were discontinued in 1991 at the request of the property owner. Water-level measurements in well NKW-450 were discontinued in 1992 when the well was destroyed. Water levels in wells RIW-231 and NKW-450 are used for demonstration purposes only and are no longer available.

Well SNW-515 has a median water level of 27.32 ft and is reported to be dry at times; the water levels have declined an unknown distance below the bottom of the well. Although well SNW-515 is not appropriate for estimating low water levels, it can be used for estimating high and median water levels at sites where depth to water is similar (median water level depth greater than approximately 20 ft).

The index well should have approximately the same measured depth to water (in "Current Water Resources Conditions in Central New England") as the site. For example, well RIW-600 has a median water level of 33.87 ft and can be used as an index well to estimate high, median, and low water levels at sites where depth to water is similar (median water level greater than approximately 30 ft).

The index well should be completed in the same or similar lithologic material as the site. For sites in sand and gravel, 15 potential index wells are currently (1994) available. Because of insufficient length of record (less than 5 years), and lack of recent and simultaneous record (data for wells completed in till span various time periods from 1946-61), no wells completed in till are currently (1994) available for use as index wells to estimate water levels at sites in till. As a result of this study, monthly measurements for seven wells used in this report and completed in till (EXW-158, EXW-238, EXW-278, FOW-40, HOW-67, WCW-59, and WGW-206) were resumed in October 1991. These wells will be available for use as index wells as of September 1996. Thirteen additional wells completed in till (BUW-395, BUW-396, BUW-397, BUW-398, CHW-586, CHW-587, COW-466, CRW-439, FOW-290, LTW-142, NHW-258, POW-551, and TIW-274) were added to the Rhode Island observation-well network in October 1992, and will be available for use as index wells as of September 1997. Use of selected wells completed in sand and gravel as index wells to estimate water levels at sites in till is possible as described in the section "Guidelines for Selecting Index Wells to Estimate Water Levels at Sites in Till."

Guidelines for Selecting Index Wells to Estimate Water Levels at Sites in Sand and Gravel

The following guidelines, which incorporate assumptions, analyses, and criteria described in this report, can be used to select index wells for estimating water levels at sites in sand and gravel in Rhode Island. Three ways to select index wells for estimating water levels at sites in sand and gravel are presented.

Use of table 2

Factors that should be considered when selecting index wells include their proximity to the site, topographic setting, and measured depth to water. Correlation and regression analysis (appendixes A and B) of water-level fluctuations based on these factors indicate a relation among such factors. The following steps for selecting index wells for sites in sand and gravel are based on these analyses:

1. Use table 2 to select an index well (excluding wells EXW-16, NKW-450, PRW-48, PRW-1051, and RIW-231) that is nearest the site, has similar topographic setting, and has similar measured depth to water[3] as that at the site.
2. If the site is farther than approximately 10 mi from the potential index well, use topographic setting and depth to water as primary guides.
3. If the site is farther than approximately 10 mi from the potential index well and has a unique topographic setting, use depth to water as the primary guide.

Use of tables 2 and 6

Water-level measurements for 20 long-term USGS observation wells completed in sand and gravel were correlated to show that water levels at different sites can be mathematically related and the strength of relation quantified. Correlation coefficients, *r* (calculated according to the method of Ott, 1988, p. 321-322) are presented in table 6 (appendix A). Correlation analysis showed that certain well pairs, separated by distances greater than 10 mi, were strongly correlated (correlation coefficients approximately 0.85 or greater). This is an important finding because it shows that, in certain cases, wells distant from a site can be used as index wells. Table 6 can be used, in conjunction with table 2 and criteria discussed earlier, to select index wells for use in the estimating equations. The objective is to select an index well from table 6 that correlates the best with wells in the area for which a water-level estimate is needed. Tables 2 and 6 and the following steps can be used to select an index well:

1. Use table 2 to select a well with similar topographic setting and median depth to water as the site.
2. Find that well in the left column of table 6.
3. Read across to the greatest correlation coefficient.
4. Select the index well from the top row that corresponds to the greatest correlation coefficient.

For example, an index well is needed to estimate water levels at a site in sand and gravel in Exeter. The site is in a valley topographic setting, and the measured depth to water at the site is 13 ft. From table 2, possible wells are EXW-475 (valley topographic setting, 14.65 ft, median depth to water) and SNW-6 (valley topographic setting, 12.20 ft, median depth to water). In table 6, well EXW-475 in the left column shows the greatest correlation with well CHW-18 (.933). Well SNW-6, in the left column in table 6, shows the greatest correlation with well EXW-475 (.936). In this case, select EXW-475 as the index well, because the site is in Exeter. Because correlation coefficients for CHW-18 and EXW-475 are virtually identical, both wells could be used as index wells. This example represents a best-case scenario (more than one possible index well). In a worst-case scenario (no comparable wells in table 2), option 3 in "Use of table 2" is recommended.

Use of tables 10 through 12

Water-level data for 15 long-term USGS observation wells completed in sand and gravel and unaffected by pumping and unknown factors were analyzed as a test for potential index wells. The test involved monthly measurements from each well and the estimation equations to estimate high, median, and

[3]This water level can be found in monthly publication, "Current Water Resources Conditions in Central New England."

low water levels at all other wells completed in sand and gravel. The estimated water levels were compared to measured water levels and differences, in terms of mean squared error (MSE), were determined (tables 10, 11, and 12, appendix B). The underlying assumption is, that if well A provides the best water-level estimate (lowest MSE) for well B, then well A would be the most appropriate one to use as an index well to estimate water levels at sites nearest well B. On the basis of this assumption, tables 10, 11, and 12 and the following steps can be used to select potential index wells:

1. Choose the appropriate table to select index well (table 10 for estimating high water level, table 11 for estimating median water level, or table 12 for estimating low water level).
2. From the left column of the table, locate the well nearest the site. Read across to lowest MSE, then select index well from top row.

For example, an index well is needed to estimate high water levels at a site in sand and gravel near West Greenwich. Find well WGW-181 in the left column of table 10 and read across to lowest MSE. In this example, the lowest MSE corresponds to index well RIW-417.

In tables 10 through 12, several towns have more than one well. When selecting index wells in or near these towns, table 2 should be used to select the well with characteristics (median depth to water, topographic setting) that best represent conditions at the site.

Guidelines for Selecting Index Wells to Estimate Water Levels at Sites in Till

Currently (1994), selecting suitable index wells completed in till to estimate water levels at sites in till in Rhode Island is not possible because recent and simultaneous monthly measurements for wells completed in till have less than the recommended 5 years of record. An alternative is to use wells completed in sand and gravel to estimate water levels at sites in till. Two ways to select index wells for estimating water levels at sites in till are presented.

Use of Table 8

Water-level measurements for selected wells completed in sand and gravel were correlated with selected wells completed in till (table 8, appendix A) to determine the utility of estimating water levels in till from water levels in wells completed in sand and gravel. From table 8, one well pair with a correlation value of 0.852 (NKW-255 completed in sand and gravel and EXW-332 completed in till) was selected to illustrate estimation of water levels in the till well based on water levels in the sand and gravel well (figure 17, appendix A). Table 8 and the following steps can be used to select index wells completed in sand and gravel to estimate water levels at sites in till:

1. Locate the well nearest the estimate site in left column of table 8.
2. Read across to greatest correlation coefficient and select index well from top row.

Use of table 2 and proximity

Water-level estimates made at sites in till from index wells selected by this approach can vary greatly, depending on the strength of correlation, depth to measured water level at the site, and the maximum annual water-level range for the selected index well completed in sand and gravel. Table 2 and proximity to select index wells completed in sand and gravel can be used to estimate water levels at sites in till:

1. Select the well nearest the site.
2. Select the nearest well with the largest maximum annual water-level range.
3. Select the well (not necessarily nearest the site) with the largest maximum annual water-level range (CHW-18).

Selecting suitable index wells to estimate water levels at sites in till will be somewhat limited until the new network of observation wells completed in till has sufficient measurements to define local water-level fluctuations and conditions.

Procedure for Use of the Technique

1. Choose an appropriate index well for the site of interest. (See section on "Selection of Index Well.")

2. Measure the water level at the site *Sc*. Measurement technique is shown in figure 14. The Rhode Island Department of Environmental Management recommends installing a perforated pipe in a test pit and then backfilling the excavation to the original land surface (R.C. Chateauneuf, Rhode Island Department of Environmental Management, oral commun., 1991).

3. Select a water-level range *Sr* (from figure 8 for a site in sand and gravel, figure 9 for a site in till). When estimating median water level for a site underlain by sand and gravel, use 6 ft; for a site underlain by till, use 11 ft. These ranges, which are median water-level ranges for the two types of material, are based on relations shown in figures 8 and 9 and are considered representative for sites in Rhode Island. When estimating high or low water levels for sites underlain by either sand and gravel or till, select a percentage of probability value less than 50 (figs. 8 and 9). The smaller the percentage of probability (larger the range) selected, the smaller the probability of exceedance of either the estimated high or low water level.

4. Find the maximum annual water-level range of fluctuation for the selected index well *Wr* in table 2.

5. From table 4, find the high water level (*Wh*; 95-percent column), median water level (*Wm*; 50-percent column), or low water level (*Wl*; 5-percent column), as needed for the equation being used.

6. Obtain current water level at index well *Wc* from "Current Water Resources Conditions in Central New England." For proper use of the estimation equations, water-level measurements at the selected index well and at the test site must be made within about 15 days of each other. Occasionally, a water-level measurement at an index well made during the previous month is closer in time to a water-level measurement made at a test site.

7. Calculate the estimated depth to high, median, or low water-level at the site (*Sh*, *Sm*, or *Sl* using equations 3, 4, or 5, respectively).

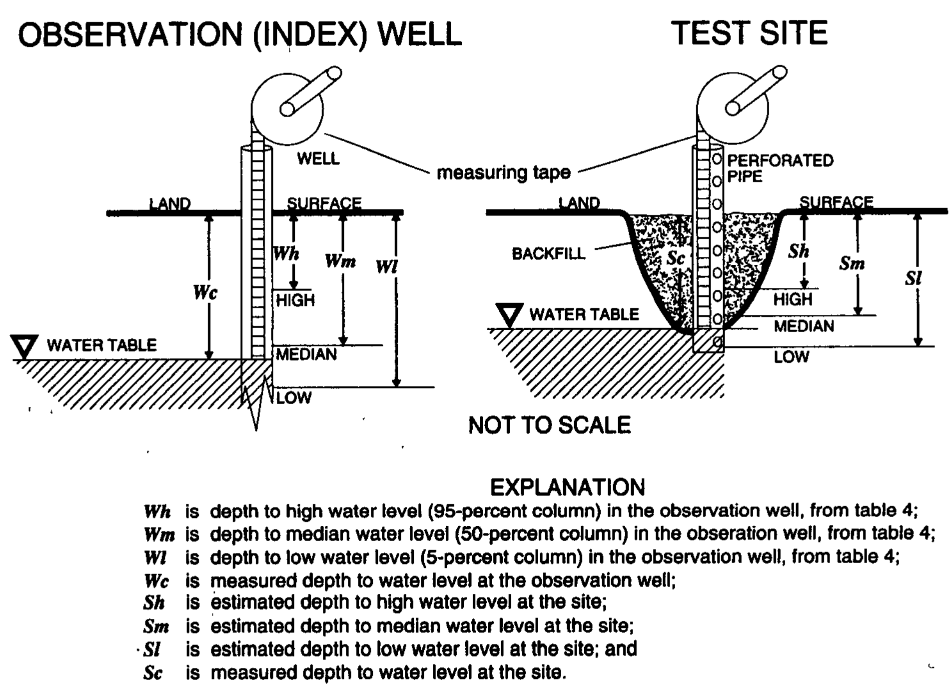


Figure 14. Water-level measurements at observation well and test site as related to estimation equations, Rhode Island.

Example Use of the Technique For Estimating Depth to High Ground-Water Level

As an example use of the estimating technique, well EXW-475 was used as the index well, in conjunction with equation 3, to estimate depth to high (95-percent column in table 4) ground-water level in well SNW-6 (assumed test site for example). The correlation coefficient for the well pair EXW-475 and SNW-6 was 0.936 (table 6). Water levels in EXW-475 and SNW-6 during August 1990 were at a level exceeded about 50 percent of the time. The range for the site Sr was selected to be 6 ft, the median range for wells in sand and gravel (fig. 8); the depth to high water level *Wh* in EXW-475 was selected to be the 95th percentile, 11.75 ft (table 4). The maximum annual range *Wr* in EXW-475 is 6.16 ft (table 2), and the August depth to water level *Wc* in EXW-475 was 15.44 ft (Current Water Resources Conditions in Central New England, August 1990, p. 6). When computing a water-level estimate, use a *Wc* value (water-level measurement from index well) that is within about 15 days of the *Sc* (water-level measurement at test site). Ordinarily, *Sc* would be determined by measuring from land surface to the ground-water level. For the purpose of this example, *Sc* is the measured depth to water level in well SNW-6 for August 1990. These values were substituted in equation 3, and the equation was solved for the depth to high ground-water level in well SNW-6. The proper sequence of operations for solution of the equations is as follows: first, substitute the values of *Sc, Sr, Wc, Wr,* and either *Wh, Wm* or *Wl* in the equation; second, complete all operations within the parentheses; third, complete all operations within the brackets; and fourth, complete all operations on the right side of the equation.

The solution to the example given above is

$$Sh = Sc + [(Sr/Wr)\,(Wh\text{-}Wc)],$$

where

Sc = 12.72,
Sr = 6,
Wh = 11.75,
Wr = 6.16, and
Wc = 15.44.

First, $Sh = 12.72 + [(6/6.16)\,(11.75 - 15.44)]$
second, $Sh = 12.72 + [(0.974)\,(-3.69)]$
third, $Sh = 12.72 - 3.59$
fourth, $Sh = 9.13$ ft.

Compared to the actual high (95-percent column) ground-water level for SNW-6 (9.85 ft), the estimated depth is 0.72 ft higher. A higher estimate may be conservative in that it would be less likely to be exceeded.

Limitations and Special Conditions of Estimation Technique

Reliability of this technique for estimating ground-water levels is limited by the basic assumptions and by the physical features of the sites for which estimations are made. The seasonal hydrologic stresses at the site are assumed to be similar to those at an observation well. Stresses caused by pumping, such as drawdown and recovery of water levels, can change the measured level at the site. Similarly, near tidal water bodies, tidal stresses can cause 1/2-day changes in the water levels at the site. These effects can be identified by measuring the water level at the site over the range of water levels caused by the stress. The measurements can then be used to apply corrections to the water-level estimates.

Because Rhode Island, the Ocean State, has more than 500 mi of shoreline, tides affect ground-water levels in many locations. Tidal effects are transmitted from tidal water bodies to adjacent ground water, but they are smaller in magnitude and delayed with respect to time. Tidal efficiency for a site can be computed by dividing the measured tide-cycle range in the ground by the tide-cycle range in the tidal water body (measured or derived from tables) and multiplying by 100. This tidal efficiency can then be applied to estimate ground-water tide fluctuations during greatest tidal ranges, such as new- or full-moon tides. Tidal efficiency decreases geometrically with increased distance from the shoreline, so that the effect in unconfined sand and gravel approaches zero at about 500 ft from the shoreline. Many other factors, such as hydraulic conductivity of the earth materials and the range of fluctuation in the tidal water body, affect the magnitude of tidal-induced fluctuations in unconfined ground water. Because these factors differ considerably from site to site, measuring ground-water levels over 24 hours, or

12 hours during a new or full moon, provides the most reliable information for estimating the effect of tides on ground-water levels. Because the tidal effects also are delayed in the ground, a single ground-water-level measurement made at the same time as high tide in the sea may not suffice for an accurate estimate of tidal effects. Tidal magnitudes are different at different phases of the moon and in different seasons; therefore, the period of measurement can have an effect on the measured range in ground-water levels. Information on tides can be found in "Tide Tables (Current Year) High and Low Water Estimations, East Coast of North America.[4]"

Changes in weather and climate will most likely cause changes in ground-water-level fluctuations at all sites and observation wells in Rhode Island and therefore will be taken into account in use of an observation well as an index to estimate water levels. Changes in coastal areas that might be caused by possible sea-level changes, however, are not taken into account.

Regional changes, such as drainage rearrangement (channeling drainage into culverts at construction sites or altering drainage and runoff patterns from landscaping changes) or long-term changes in pumping patterns (as reflected in the water levels in well PRW-1051, figure 6) might not be accounted for by an index well. Estimates under these conditions are likely to be inaccurate.

Other physical conditions that interfere with accurate water-level estimates include proximity of the site to surface-water bodies with regulated stage, such as those used for water supply and power generation (large fluctuations) or for recreation (stable water levels). Other situations that can cause problems are those that alter the rate of recharge or discharge, such as irrigation, infiltration from lagoons, leakage from or to storm sewers, and drainage rearrangement.

Lithologic conditions also can limit the applicability of the technique described in this report. Water levels affected by underlying clay layers or other materials of low permeability that cause perched ground water cannot be accounted for in this technique. Moreover, the method cannot be used to estimate water levels in clay or silty soils or in sandy soils with silt or clay layers that could interfere with uniform ground-water flow.

[4]Tide tables can be purchased from National Ocean Service, Distribution, 6501 Lafayette Ave., Riverdale, MD 20840.

Applicability of Estimation Technique to Areas Outside Rhode Island

Equations 1-5 could be applied to other regions where weather and climatic patterns produce regular annual cycles of water-table rise and decline. Equation 3 has been applied to make water-level estimates in Massachusetts (Frimpter, 1981). Application in other regions would depend on the availability of wells with sufficiently long water-level records. Analyses would be needed to determine values of *Wr, Sr, Wh, Wm*, and *Wl*, and tests would be needed to describe the accuracy of the estimates. The USGS maintains long-term observation-well networks in cooperation with States, territories, counties, municipalities, and water districts, and these water-level records could be analyzed for application of equations 1-5 in other parts of the Nation.

SUMMARY

Measurements or estimates of high, median, and low ground-water levels are needed for many design and regulatory purposes. One of these is the design of individual underground sewage-disposal systems (septic systems), where an unsaturated zone needs to be maintained between the bottom of a leach field and the highest ground-water level.

The historical records of water-level fluctuations in wells operated for the Rhode Island observation-well network were analyzed to provide a basis from which to estimate future water levels. The maximum annual water-level ranges were calculated for 18 wells completed in sand and gravel and 19 wells completed in till. The medians of these ranges (the ranges expected to be exceeded at 50 percent of the sites) in Rhode Island, are about 6 ft in sand and gravel and 11 ft in till. The analysis is based on the assumption that water-level fluctuations in the past will be similar in the future. Frequency analysis of the water-level records from the 20 wells completed in sand and gravel provides a reference for evaluating current water levels with respect to the historical record. The approximate probability that the current level will be exceeded in

the future can be estimated by comparison of current water levels in the wells with statistical summaries of historical water levels in observation wells.

Water levels from 21 wells completed in sand and gravel and 19 wells completed in till were used in this study to demonstrate that fluctuations caused by seasonal and long-term weather and climate changes are similar in nearly all wells. Only those fluctuations caused by short-term stresses, such as tides and pumping, differ from site to site. Fluctuations measured in all the wells were attributed to variations in recharge rate caused by variations in precipitation and seasonal variations of evapotranspiration rates. Water levels generally decline during the summer growing season and rise during the nongrowing season.

Equations developed by linear regression of water levels from two sites can be used to estimate water levels at one of the sites from water levels at the other site. This approach also can be used to estimate missing records and to identify anomalous data. Applications of this type of relational analysis can assist in the differentiation between manmade and natural causes of water-level fluctuations and in evaluation of water levels in individual wells in a network. Analysis of the records of water levels from the Rhode Island observation-well network indicates that water levels from 15 wells completed in sand and gravel can be used to estimate water levels at other sites. Except for wells and sites where water levels are affected by pumping, correlation of water levels is significant at the 0.05 level (using a one-sided T-test).

An estimation technique was developed on the basis of correlation between water levels at geographically different sites and on the assumption that the past is representative of the future. In the principal equation used in this technique, the ratio of potential water-level change and the annual water-level range at the estimation site is equal to the ratio of potential water-level change and the maximum annual water-level range at the index well. A series of transformations of this equation was developed to estimate high, median, and low water levels at a site from one measurement made at any time at a site. The transformed equations can be used to estimate high, median, and low water levels at a site by substitution of known water-level range; the high, low, and median levels and a concurrent water level from the observation well used as an index; the single measurement at a site; and an estimated range of water level at the site (6 ft in sand and gravel, or 11 ft in till).

The equations for estimating high, median, and low water levels were initially tested by use of 15 wells completed in sand and gravel and unaffected by pumping and other factors as index wells to estimate water levels in all other wells completed in sand and gravel. A total of 102,899 estimated high, median, and low water levels were then compared to measured high, median, and low water levels (depth to water level exceeded 95, 50, and 5 percent of the time), and mean squared errors were determined. Of all the estimates, those for well CHW-18 had the lowest overall mean squared error, 0.90 ft^2 for high water levels, 0.81 ft^2 for median water levels, and 1.07 ft^2 for low water levels.

Because well CHW-18 had the lowest overall average mean squared error, it was used as an index well in equations 3, 4, and 5 to calculate 6,697 estimates of high, median, and low water levels for 14 wells unaffected by pumping and other factors: mean squared error of high estimates ranged from 0.34 to 1.53 ft^2, mean squared error of median estimates ranged from 0.30 to 1.27 ft^2, and mean squared error of low estimates ranged from 0.32 to 2.55 ft^2. All mean squared errors are less than the State required 3-foot separation between the bottom of the stone underlying the seepage system and the maximum altitude of the water table.

This technique can be applied to regions outside of Rhode Island where similar weather and climate patterns cause water-table fluctuations. The technique is applicable in areas of uniform geology where layering does not cause locally perched water. Generally, the technique does not account for short-term stresses; but if the stresses are known, corrections can be made to the estimates. The extremes of water level caused by tides can be subtracted from estimates of high water level and added to estimates of low water level.

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APPENDIX A

CORRELATION AND REGRESSION ANALYSIS OF GROUND-WATER LEVELS

The technique described in this report estimates the quantiles of the distribution of water levels at a test site. Inputs to the estimating technique are paired water-level measurements (measurements made within 15 days of each other) at the test site and observation well (termed "index well"), and historical water-level data for the observation well. The technique depends on a linear relation between water levels in observation wells and at test sites. This relation cannot be tested explicitly because, by definition, data are not available at test sites; however, relations between pairs of observation wells can serve as indicators of the relation between test sites and observation wells.

Correlation is a statistical method by which a value, *x*, is related to a corresponding value, *y*. Regarding water levels in a pair of observation wells, the water level in well *y* can be related to the water level in well *x*, and a measure of the linearity of the relation can be determined. Regression is a more powerful statistical method than correlation in that it determines the linear relation of *x* and *y*, calculates the amount of variation of *y* that can be explained by *x*, and develops a regression equation enabling one to relate and thereby to estimate *y* from *x*. Several methods (probability of significance, variance, residuals analysis) can be used to test the accuracy of the regression equation.

Correlation analysis was done to examine the strength of the linear relation between all possible pairs of observation wells in the Rhode Island network. Correlation analysis was also done between wells in Rhode Island and wells in Massachusetts to identify possible index wells outside of Rhode Island. Linear regression analysis was used to examine the relation of selected wells in more detail than correlation analysis allows. Results of the linear regression analysis are provided in the section "Regression Analysis of Ground-Water Levels."

Correlation of Ground-Water Levels

Standard correlation techniques were used to quantify the strength of linear relations of water levels between wells in Rhode Island and between selected wells in Massachusetts and wells in Rhode Island. The result of any correlation is a correlation coefficient, or *r* value, that is greater than 0 and less than 1. The closer to 1, the greater the strength of linear relation between well pairs and the greater the likelihood that water-level estimates of one well based on the other will be accurate. In this report, values of *r* greater than 0.85 are considered indicative of a reasonably strong linear relation, whereas values of *r* from 0.70 to 0.85 indicate moderate linear relation and values of *r* less than 0.70 indicate weak linear relation.

Correlation of Water-Level Data from Wells Completed in Sand and Gravel

To quantify the relation of water levels in wells completed in sand and gravel, correlation coefficients for all possible pairs of wells were determined (table 6). Most of the correlations were based on 230 to 480 pairs of monthly measurements, but those involving water levels from wells RIW-417, RIW-600, and EXW-475 were based on approximately 160, 140, and 100 pairs of monthly measurements, respectively. Correlations involving levels in well PRW-1051 were not calculated because of the known effects that cessation of pumping has on monthly water levels (fig. 6).

Values of *r* ranged from 0.125 (CUW-265 with RIW-231) to 0.940 (EXW-475 with NKW-450). The well having the highest overall correlation of water levels with levels from all other wells was EXW-475 (average *r* of 0.824). Correlations of water levels in wells affected by pumping with levels in all other wells is weak. For example, water levels from well PRW-48 have the lowest average correlation with water levels from all other wells (0.386). Water levels from well EXW-16, which are affected by pumping and surface runoff, also have a lower than average correlation with levels from most other wells (*r* equals 0.464 to 0.836). Additionally, these analyses indicated generally low correlations for water levels from wells CUW-265 (0.125 to 0.877) and RIW-231 (0.125 to 0.742) with levels from most of the wells, as shown in table 6. Therefore, these wells were eliminated from further analyses. Further investigation of these wells indicated that water levels in well CUW-265 may be affected by pumping and wastewater discharge, but no explanation for the low correlation of water levels in well RIW-231 was identified.

Table 6. Correlation of water levels in wells completed in sand and gravel in Rhode Island, 1946-90

[Correlation coefficient, *r*, calculated according to the method of Ott, 1988, p. 321-322]

Local well No. (fig. 2)	Local well number																		
	BUW-187	CHW-18	COW-411	CUW-265	EXW-6	EXW-16	EXW-475	LIW-84	NKW-255	NKW-450	NSW-21	PAW-136	PRW-48	RIW-231	RIW-417	RIW-600	SNW-6	SNW-515	WEW-522
CHW-18	0.807	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
COW-411	.711	0.874	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
CUW-265	.603	.591	0.592	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
EXW-6	.766	.831	.814	0.781	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
EXW-16[1]	.737	.834	.718	.464	0.731	—	—	—	—	—	—	—	—	—	—	—	—	—	—
EXW-475	.821	.933	.858	.582	.891	0.755	—	—	—	—	—	—	—	—	—	—	—	—	—
LIW-84	.625	.662	.683	.709	.846	.631	0.705	—	—	—	—	—	—	—	—	—	—	—	—
NKW-255	.719	.735	.799	.599	.702	.583	.822	0.672	—	—	—	—	—	—	—	—	—	—	—
NKW-450[2]	.796	.932	.874	.615	.859	.836	.940	.706	0.836	—	—	—	—	—	—	—	—	—	—
NSW-21	.728	.738	.739	.877	.852	.543	.771	.778	.695	0.765	—	—	—	—	—	—	—	—	—
PAW-136	.741	.802	.839	.525	.779	.724	.852	.675	.730	.829	0.657	—	—	—	—	—	—	—	—
PRW-48	.331	.446	.264	.269	.469	.617	.602	.421	.303	.444	.163	0.368	—	—	—	—	—	—	—
RIW-231[1]	.560	.680	.628	.125	.495	.655	.726	.253	.594	.713	.321	.742	0.262	—	—	—	—	—	—
RIW-417	.730	.863	.795	.747	.907	.675	.865	.752	.817	.839	.853	.653	.405	0.460	—	—	—	—	—
RIW-600	.777	.935	.837	.586	.830	.812	.895	.675	.872	.912	.762	.760	.549	.637	0.854	—	—	—	—
SNW-6	.793	.924	.842	.573	.792	.797	.936	.666	.747	.935	.695	.772	.460	.700	.854	0.926	—	—	—
SNW-515	.801	.900	.786	.669	.828	.777	.914	.657	.677	.898	.788	.713	.368	.576	.902	.895	0.853	—	—
WEW-522	.742	.891	.808	.793	.897	.724	.869	.726	.864	.849	.829	.688	.336	.474	.878	.863	.873	0.879	—
WGW-181	.608	.679	.663	.826	.864	.486	.703	.809	.723	.657	.850	.523	.256	.195	.821	.675	.655	.699	0.810

[1]Water-level measurement discontinued in 1991.

[2]Well destroyed in 1992; water-level measurement discontinued.

Correlation of Water-level Data from Wells Completed in Till

Rhode Island lithology includes many areas of till in which observation wells were measured for various periods from 1946 through 1961. Water levels for 16 wells completed in till were correlated to determine the strength of linear relation between selected well pairs. Correlation coefficients for water levels from wells with at least 2 years of monthly measurements (24 pairs) are shown in table 7. Most of the correlations are based on 36 to 120 pairs of measurements. Correlation was not attempted for well pairs with fewer than 24 paired water-level measurements. The matrix table contains several well pairs without entries because these wells did not have 2 years of overlapping record. Three wells (EXW-238, EXW-248, and EXW-278) were excluded from correlations in table 7. Water-level measurements in well EXW-158 (which had the longest period of record of all the wells in Exeter), well EXW-220, and well EXW-332 adequately represented areas of till in Exeter.

Values of *r* ranged from 0.422 (CHW-100 with FOW-40) to 0.966 (EXW-332 with HOW-67). Water levels from well SNW-615 had the highest overall correlation with levels from all other wells (average *r* equal to 0.875), and water levels from well CHW-100 had the lowest overall correlation with levels from all other wells (average *r* equal to 0.602). Individual and average *r* values (tables 6 and 7) indicate that water levels from wells completed in till correlated better with one another than with water levels from wells completed in sand and gravel. These results are consistent with results from a previous study by Frimpter (1981, p. 12), in which topographic setting was found to have less effect on water-level fluctuations in wells completed in till than in wells completed in sand. Generally, the use of water levels from a well completed in till nearest the site of interest would result in an accurate estimate of ground-water level.

Correlation of Water-Level Data from Wells Completed in Sand and Gravel with Water-Level Data from Wells Completed in Till

To determine whether water-level fluctuations in wells completed in sand and gravel are comparable to those in wells completed in till, records from 4 wells completed in sand and gravel in the Rhode Island observation-well network (CHW-18, EXW-6, NKW-255, and SNW-6) were correlated with records of 19 Rhode Island wells completed in till that were measured for various periods between 1946 and 1961 (table 8). Four wells completed in sand and gravel were selected because they were measured during the time most wells completed in till were measured. In addition, the four wells are apparently unaffected by pumping and unknown factors. Only those wells with more than 50 pairs of data are shown in table 8. Although the wells completed in till are not geographically representative of all of Rhode Island, the correlation of water levels from them with water levels from wells completed in sand and gravel is close enough to warrant estimation of water levels at sites in till on the basis of water levels in wells completed in sand and gravel.

Correlation of Water-Level Data from Wells Completed in Sand and Gravel in Massachusetts with Water-Level Data from Wells Completed in Sand and Gravel in Rhode Island

The relation is weak between water levels in wells in northern Rhode Island, indicated by low correlation coefficients for wells BUW-187, CUW-265, LIW-84, NSW-21, PAW-136, and PRW-48. Records from selected wells in Rhode Island were, therefore, compared with records from nearby wells in Massachusetts to identify the reason for the weak relation. Records from five wells completed in sand and gravel in Massachusetts were correlated with records from six geographically distributed wells in Rhode Island (table 9). Correlation coefficients ranged from 0.588 (EXW-6 with WLW-1) to 0.882 (NKW-450 with FXW-3). The well with the highest overall correlation of water levels with levels from all other wells is FXW-3 (average *r* equal to 0.832) and the well with the lowest overall correlation of water levels with levels from all other wells is WLW-1 (average *r* equal to 0.660). Of the six Rhode Island wells, PAW-136 in northeastern Rhode Island had the highest overall *r* value when paired with five wells in Massachusetts; of the five Massachusetts wells, FXW-3 had the highest overall *r* value when paired with six wells in Rhode Island. Well WLW-1 in Webster, Mass., had consistently low *r* values when paired with all Rhode Island wells, indicating that it is not subjected to the same climatological or hydrogeologic conditions. Although Rhode Island well PAW-136 seems to be representative of northern Rhode

Table 7. Correlation of water levels in selected wells completed in till in Rhode Island, 1946-61

[--, not computed, fewer than 24 data pairs available; correlation coefficient, *r*, calculated according to the method of Ott, 1988, p. 321-322]

Local well No. (fig. 3)	Local well number														
	BRW-27	CHW-100	CUW-129	EXW-158	EXW-220	EXW-332	FOW-4	FOW-40	HOW-67	PRW-1111	RIW-157	SNW-10	SNW-615	WCW-59	WGW-204
CHW-100[1]	--														
CUW-129[1]	0.790	0.446													
EXW-158[2]	.831	.533	0.852												
EXW-220[1]	--	.645	.746	0.882											
EXW-332[1]	--	.687	.771	.846	0.900										
FOW-4[1]	.733	.455	.887	.855	.726	0.842									
FOW-40[2]	.705	.422	.922	.839	.733	.790	0.924								
HOW-67[2]	.673	.793	.772	.831	.921	.966	.770	0.768							
PRW-1111[1]	.865	--	.832	.893	--	--	.841	.778	0.685						
RIW-157[1]	.558	.769	.694	.788	.889	.940	.775	.746	.928	0.792					
SNW-10[1]	.778	.643	.699	.778	.823	.891	.735	.775	.882	.778	0.933				
SNW-615[1]	--	.633	.868	.941	.930	.927	.864	.852	.943	--	.893	0.892			
WCW-59[2]	--	--	.819	.869	--	--	.868	.862	.682	.887	.895	.916	--		
WGW-204[1]	--	.699	.746	.855	.876	.900	.759	.747	.944	--	.894	.814	0.902	--	
WGW-206[2]	--	.493	.894	.915	.801	--	.863	.903	.865	--	.834	.798	.857	--	0.835

[1]Water-level measurement discontinued; well use has been used for demonstration purposes only.
[2]Water-level measurement resumed October 1991.

Table 8. Correlation of water levels in selected wells completed in sand and gravel with water levels in selected wells completed in till in Rhode Island, 1946-61

[Correlation coefficient, *r*, calculated according to the method of Ott, 1988, p. 321-322]

Wells completed in till (fig. 3)	Wells completed in sand and gravel (fig. 2)			
	CHW-18	EXW-6	NKW-255	SNW-6
BRW-27[1]	0.694	0.829	--	--
CHW-100[1]	.755	.568	0.719	0.854
CUW-129[1]	.605	.824	.603	.618
EXW-158[2]	.728	.897	.642	.760
EXW-220[1]	.840	.785	.805	.853
EXW-238[2]	.772	.860	.757	.724
EXW-248[1]	.879	.803	.886	.915
EXW-278[2]	.868	.720	.811	.932
EXW-332[1]	.839	.789	.852	.876
FOW-4[1]	.611	.811	.643	.600
FOW-40[2]	.662	.827	.665	.658
HOW-67[2]	.889	.915	.839	.946
PRW-1111[1]	.758	.715	--	--
RIW-157[1]	.925	.877	.886	.936
SNW-10[1]	.826	.809	.798	.855
SNW-615[1]	.865	.842	.856	.867
WCW-59[2]	.784	.890	--	--
WGW-204[1]	.867	.865	.872	.871
WGW-206[2]	.769	.816	.815	.697

[1]Measurement of well has been discontinued; well has been used for demonstration purposes only.

[2]Measurement of well resumed October 1991.

Table 9. Correlation of water levels in selected wells completed in sand and gravel in Massachusetts with those in selected wells completed in sand and gravel in Rhode Island, 1946-90

[Value shown is correlation coefficient, *r* (from Ott, 1988, p. 321-322)]

Rhode Island wells, local well No. (fig. 2)	Massachusetts wells, local well No.				
	WLW-1	WFW-51	LKW-14	FXW-3	F3W-23
BUW-187	0.637	0.632	0.632	0.807	0.621
CHW-18	.684	.786	.703	.860	.781
EXW-6	.588	.706	.615	.835	.674
NKW-450[1]	.699	.820	.751	.882	.777
PAW-136	.731	.837	.832	.839	.834
SNW-6	.618	.734	.759	.772	.763

[1]Well destroyed June 1992.

Island, the other wells in northern Rhode Island do not correlate strongly with any other wells in either State or with each other.

Comparison of Water Levels from Wells Completed in Till in Massachusetts with Water Levels from Wells Completed in Till in Rhode Island

Water levels in one well completed in till in Winchester, Mass. (XOW-14), were being measured when water levels in the wells completed in till in Rhode Island were measured. This well is about 60 mi from Providence and is outside the area shown in fig. 3. Correlation of the overlapping records from the Winchester well with the three Rhode Island wells with the longest records (SNW-10, CUW-129, and FOW-4) yielded correlation coefficients of 0.69, 0.91, and 0.82, respectively. Water levels in well XOW-14 showed a significant linear relation with those in wells CUW-129 and FOW-4 despite large intervening distances. Although significant linear relations exist between well XOW-14 and wells CUW-129 and FOW-4, estimates of water levels at Rhode Island sites in till based on water levels from well XOW-14 as an index well are not expected to be as accurate as those made from records from index wells in sand and gravel in Rhode Island. One well, EBW-30, in East Bridgewater, Mass., is about 25 mi from Providence (fig. 2) and about 45 mi from FOW-4. Correlation of the 40 months of overlapping record with wells SNW-10 and FOW-4 yielded correlation coefficients of 0.79 and 0.40, respectively.

Regression Analysis of Ground-Water Levels

Correlation is used only to determine the strength of linear relation between water levels in two different wells; linear regression analysis can be used to develop a linear equation that relates sets of water levels, thereby allowing estimation of water levels in one well based on water levels in the other well. Within the context of Rhode Island observation wells completed in sand and gravel, linear regression analysis based on a least-squares algorithm (Ott, 1988, p. 304) was used to evaluate whether hydrogeologic conditions at test sites and observation wells were similar by analyzing water levels in pairs of wells for similarity. Because test sites are not available, observation wells are used as test sites.

Linear regression analysis is used to relate two variables, x and y, commonly called the explanatory and response variables. A primary result of linear regression is the development of the linear equation, $y = mx + b + e$, where y is the water level in one well (the test site), x is the water level in the other well (the index site), m is the slope of the line, b is the intercept of the line with the y-axis, and e is random error, which is assumed to be zero for a given value of x (Ott, 1988, p. 301).

When the linear equation is developed, the coefficient of determination (R^2), a proportion of the variability in the response variable (y) that can be accounted for by the explanatory variable (x) (Ott, 1988, p. 490), and the standard error of the mean response estimate (SE), an estimate of the variability of correlations, are calculated. When multiplied by 100, R^2 can be defined as the percentage of total variability in the response variable that can be explained by the explanatory variable.

Scatter Plots

Scatter plots are graphs commonly used to show the manner in which two variables relate to each other. The position of the data points with respect to a straight line illustrates the degree to which the data fit the linear model. For example, the fairly tight grouping of data points about the regression line in figure 15 shows a good fit based on the linear model, whereas the fairly wide scatter of data points with respect to the regression line in figure 16 shows a poor fit. The linear regression equation for the line of relation in figure 15 is CHW = 1.76 (WEW) - 4.15, R^2 is 0.79, and SE is 0.98 ft. This regression was significant at the 0.05 level (using a one-sided T-test). The linear regression equation for the line of relation in figure 16 is WGW = 0.11 (RIW) + 13.10, R^2 is 0.03, and SE is 1.83 ft. This regression also was significant at the 0.05 level. The weak correlation between water levels in well WGW-181 and RIW-231, shown in figure 16, is not likely to yield accurate water-level estimates for one well based on water-level data from the other.

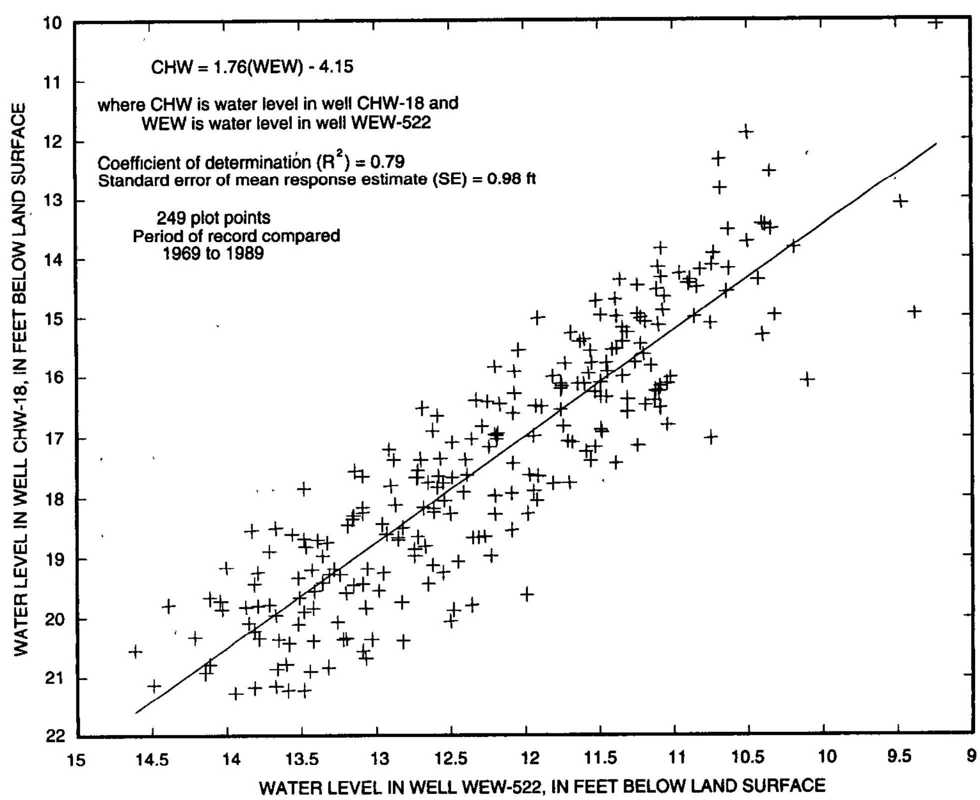

Figure 15. Relation of water levels in two wells (WEW-522 and CHW-18) completed in sand and gravel in Rhode Island.

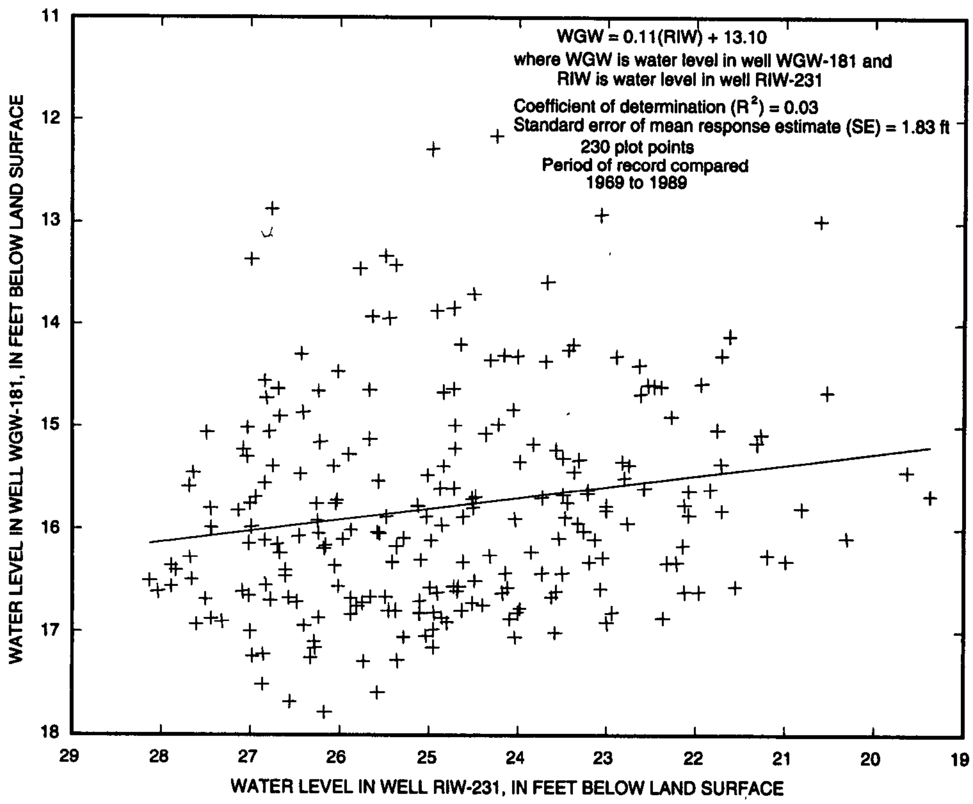

Figure 16. Relation of water levels in two wells (RIW-231 and WGW-181) completed in sand and gravel in Rhode Island.

Estimation of Ground-Water Levels Based on Regression Equations

When the correlation between water levels in well pairs is strong, a linear regression equation can be developed that estimates water levels in one well based on water levels in the other. As an example, water levels in a well completed in sand and gravel (NKW-255, the explanatory variable) were regressed with water levels in a well completed in till (EXW-332, the response variable) to obtain the equation EXW = 1.57 (NKW) + 0.80; R^2 is 0.72, and SE is 1.43 ft. The equation and monthly water levels for 1956 through 1959 in NKW-255 were used to estimate water levels in EXW-332. Hydrographs of measured water levels in well NKW-255 completed in sand and gravel, well EXW-332 completed in till, and estimated water levels in EXW-332 based on measured water levels in NKW-255, are shown in figure17. Although the water level for the well completed in till has a greater range than the water level for the well completed in sand and gravel, the water levels in both wells rise and decline at nearly the same time and in proportion to one another. The estimated water level closely matches the measured water level, especially at the annual maximums.

Analysis of residuals is one way to test the accuracy of a regression equation. Residuals are the measured water levels of the response variable, EXW-332, minus the estimated water levels of the response variable (estimated from the regression equation and water levels for the explanatory variable, NKW-255. Under ideal circumstances, all residuals, when plotted against all corresponding water levels of the explanatory variable, are randomly distributed about a mean of 0 ft (Ott, 1988, p. 365). Residuals based on the regression equation used to estimate water levels in well EXW-332 from those in well NKW-255 indicate that variance depends slightly on the mean water level in the explanatory variable. Transformations of the water-level data were not attempted because the variance was not extreme. Estimated water levels closely match measured water levels except at depths greater than

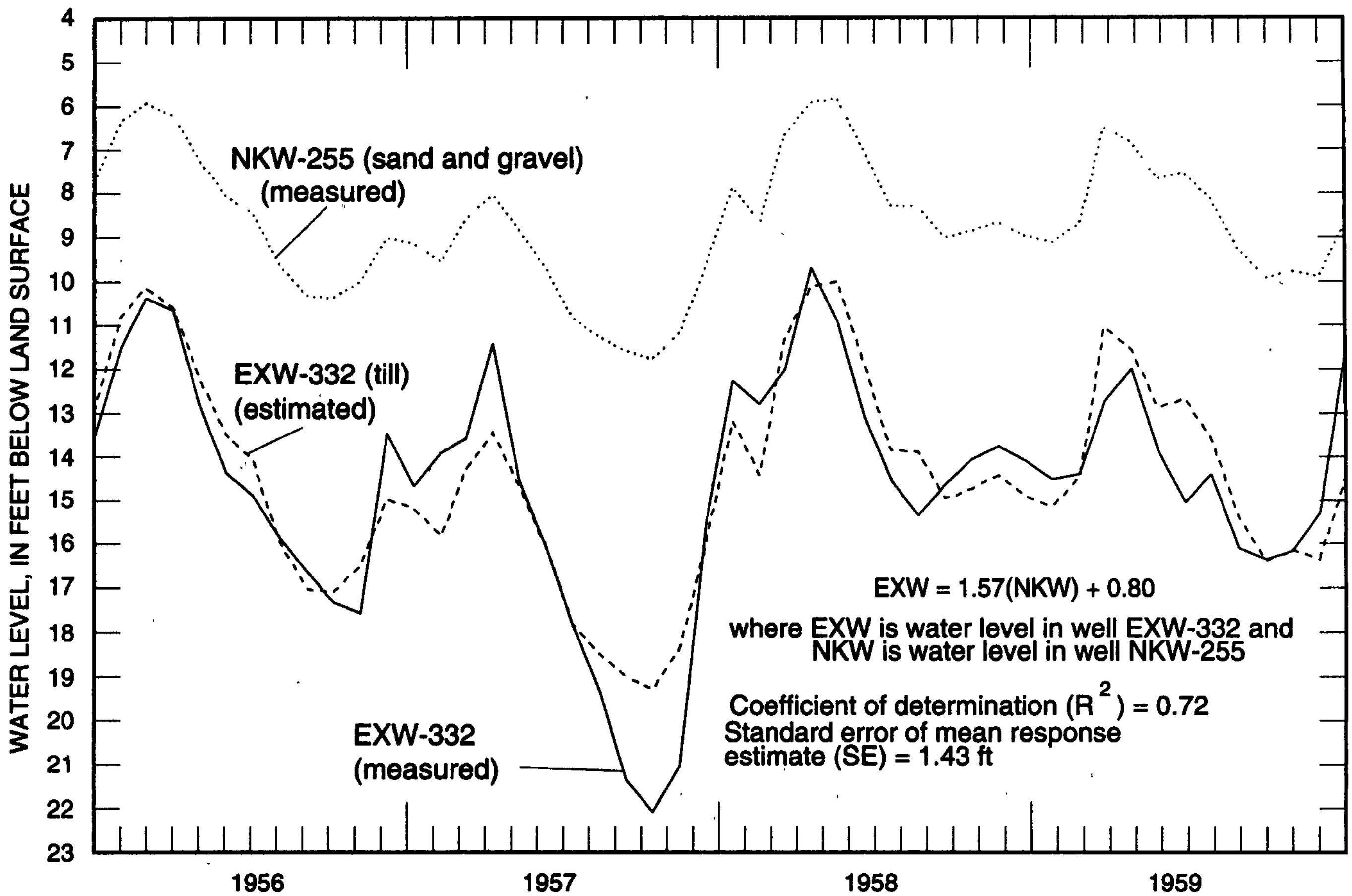

Figure 17. Measured and estimated water levels in a well completed in till (EXW-332) and measured water levels in a well completed in sand and gravel (NKW-255), Rhode Island, 1956-59.

about 19 ft. Thus, estimates of low water levels (19 ft or deeper) for EXW-332 based on NKW-255 would be less reliable than those for median or high levels.

Another practical use of a regression equation is estimation of water levels for periods of missing record. For example, gaps in the record for well SNW-515 during 1980 through 1983 were estimated from water levels in RIW-417 with the regression equation SNW = 1.62 (RIW) + 16.12; R^2 is 0.84, and SE is 0.54 ft) (fig. 18). Analysis of residuals indicates that variance is randomly distributed throughout the range of measured and estimated water levels. This regression technique can also be used to (1) identify measurement errors, transcription errors, and mathematical errors, (2) identify abnormal changes to expected water levels, (3) identify unrepresentative wells, and (4) help differentiate between manmade and natural causes of water-level fluctuation, which can help establish cause and effect when water-level conditions cause harm and need to be corrected.

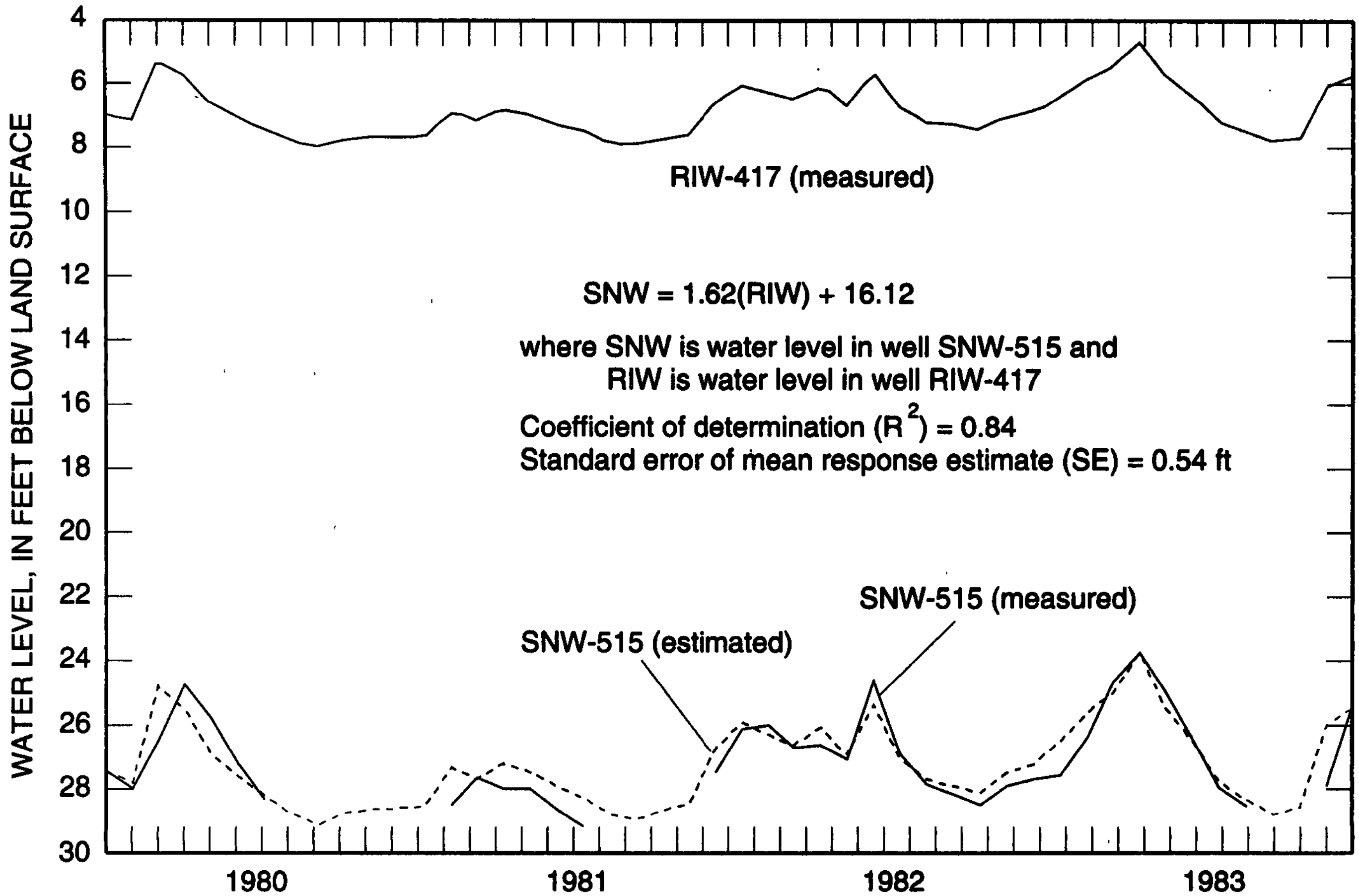

Figure 18. Measured water levels in well RIW-417 and measured and estimated water levels for periods of missing record in well SNW-515, Rhode Island, 1980-83.

APPENDIX B

ANALYSIS OF OBSERVATION WELLS USED AS INDEX WELLS

In Rhode Island, water-level data for 15 observation wells completed in sand and gravel and unaffected by pumping and unknown factors were analyzed to determine their suitability for use as index wells in estimation equations 3, 4, and 5. Data from each index well completed in sand and gravel in equations 3, 4, and 5 were used to estimate high (95th percentile), median (50th percentile), and low (5th percentile) water levels in all other wells completed in sand and gravel. Results of the estimates are shown in tables 10, 11, and 12, respectively. Differences (residuals) between measured and estimated high, median, and low water levels were calculated. For each index-test pair, the summation of squared differences was divided by the number of estimates, which yielded the mean squared error (MSE). The equations that describe average mean squared error ($\overline{MSE}$) are as follows:

$$\overline{MSE} = \frac{MSE_j}{14} \qquad (6)$$

and

$$MSE_j = \frac{(Sh - Sh_i)^2}{n_j} \qquad (7)$$

where

j indexes a test well,

n_j is the number of common measurements between the index and test wells, and

$$Sh_i = Sc_i + [(Sr/Wr)\,(Wh - Wc_i)]$$

derived from equation 3, where each i indexes a single monthly measurement.

Averaging the individual MSE_js avoids bias of the total error estimate that may occur due to the difference in sample sizes.

Mean squared error is analogous to variance, with potential bias included, and is an indication of potential error of the estimating technique, it is expressed in feet squared. A high MSE indicates greater potential error and a low MSE indicates lesser potential error. The process was done 15 times for a total of 102,899 estimates, and the average MSE's for high, median, and low water-level estimates were calculated (table 13).

Average MSE for high water-level estimates ranged from 0.90 to 1.44 ft^2 and averaged 1.13 ft^2; for median water-level estimates, average MSE ranged from 0.72 to 1.24 ft^2 and averaged 0.92 ft^2; and for low water-level estimates, average MSE ranged from 1.07 to 1.83 ft^2 and averaged 1.34 ft^2 (table 10). Well CHW-18 yielded the lowest overall average MSE (average of high, median, and low average mean squared error values), 0.93 ft^2, and well LIW-84 had the highest overall average MSE, 1.47 ft^2. (Some of the water levels from well LIW-84 had been affected by flooding, but the well casing has been extended so that this is unlikely to occur in the future.)

Accuracy of Equations

As a test of the accuracy of the high, median, and low water-level estimates for wells completed in sand and gravel, the well with the lowest overall average MSE (CHW-18) (table 13) was selected for use as an example index well in estimation equations 3, 4, and 5. A total of 6,697 estimates of high, median, and low water levels were calculated (table 14). For wells considered to be unaffected by pumping or other factors, MSE of high estimates ranged from 0.34 to 1.53 ft^2; MSE of median estimates ranged from 0.30 to 1.27 ft^2; and MSE of low estimates ranged from 0.32 to 2.55 ft^2. Estimates of water levels for well PAW-136 yielded generally low MSE's, which could indicate that water levels in well PAW-136 are weakly affected by pumping or other factors. The above analysis illustrates that the degree of accuracy can vary when estimating water levels at other sites in Rhode Island with the equations in this report; the use of other Rhode Island observation wells as index wells would yield somewhat different estimates and accuracy.

Table 10. Mean squared error for estimates of high water levels (depth to water level exceeded 95 percent of the time) for wells in Rhode Island completed in sand and gravel, based on water levels in index well

[Value shown is mean squared error, in feet squared. To select index well, read across from local well number nearest the site to lowest value of mean squared error]

Local well No. (fig. 2)	INDEX WELLS														
	BUW-187	CHW-18	COW-411	EXW-6	EXW-475	LIW-84	NKW-255	NKW-450	NSW-21	RIW-417	RIW-600	SNW-6	SNW-515	WEW-522	WGW-181
BUW-187	----	1.03	1.54	1.15	0.92	2.31	1.37	0.96	1.46	1.21	1.20	0.99	1.37	1.22	1.68
CHW-18	2.92	----	3.28	2.18	1.45	4.67	2.44	1.15	3.85	3.14	3.06	2.32	3.66	1.91	3.03
COW-411	1.03	.46	----	.78	.61	1.05	.61	.82	.94	.80	.82	.56	.77	.76	1.24
EXW-6	.92	.68	.53	----	1.26	.41	.81	1.33	.54	.41	.49	.77	.41	.86	.98
EXW-475	1.23	.63	.74	.61	----	1.85	.88	.26	1.08	.89	1.05	.54	.93	.71	1.15
LIW-84	1.55	1.20	1.12	.68	1.22	----	1.20	1.46	.91	.79	.97	1.43	1.38	1.24	.87
NKW-255	1.17	.63	.87	.82	.84	1.46	----	.55	1.29	.91	.88	.58	1.07	.55	1.02
NKW-450[1]	1.22	.72	1.27	.80	.33	2.18	.81	----	1.67	1.09	1.18	.60	1.70	.78	1.45
NSW-21	1.35	1.27	1.28	.68	1.02	1.28	1.29	1.21	----	.96	1.61	1.41	1.26	.85	.77
RIW-417	1.38	1.53	1.40	1.38	2.39	.63	1.79	2.33	1.48	----	.78	1.44	.38	1.69	1.68
RIW-600	1.12	1.06	1.23	1.29	2.04	.70	1.40	1.99	1.58	.85	----	.92	.34	1.34	1.71
SNW-6	.93	.34	.84	.84	.35	1.62	.52	.32	1.36	.65	.47	----	.93	.51	1.23
SNW-515	.67	.35	.70	.75	.39	1.11	.66	.71	.82	.29	.38	.51	----	.45	1.11
WEW-522	.90	.52	.57	.55	1.21	.76	.61	1.14	.67	.40	.38	.58	.26	----	.91
WGW-181	1.19	1.08	.91	.58	1.44	.56	.90	1.48	.58	.46	.79	1.06	.74	.81	----

[1]Well destroyed in 1992, water-level measurement discontinued.

Table 11. Mean squared error for estimates of high water levels (depth to water level exceeded 50 percent of the time) for wells in Rhode Island completed in sand and gravel, based on water levels in index well

[Value shown is mean squared error, in feet squared. To select index well, read across from local well number nearest the site to lowest value of mean squared error]

Local well No. (fig. 2)	INDEX WELLS														
	BUW-187	CHW-18	COW-411	EXW-6	EXW-475	LIW-84	NKW-255	NKW-450	NSW-21	RIW-417	RIW-600	SNW-6	SNW-515	WEW-522	WGW-181
BUW-187	----	1.16	1.52	1.63	0.89	2.29	1.33	1.12	1.33	1.22	0.96	0.97	0.93	1.24	1.81
CHW-18	2.13	----	1.48	1.39	1.26	2.46	1.36	.81	2.04	2.05	1.93	1.06	1.47	1.45	2.59
COW-411	1.27	.46	----	.72	.62	.98	.71	.57	.97	.76	.68	.66	.65	.79	1.15
EXW-6	1.08	.57	.50	----	.49	.42	.75	.68	.55	.30	.62	.70	.43	.60	.47
EXW-475	.78	.30	.61	.48	----	1.11	.93	.28	1.08	.55	.51	.29	.56	.56	1.05
LIW-84	2.22	1.22	1.15	.67	1.08	----	1.41	1.40	.94	1.06	1.35	1.57	1.19	1.62	.95
NKW-255	1.15	.67	.79	.93	1.00	1.37	----	.53	1.17	.86	.61	.54	.71	.54	1.07
NKW-450[1]	1.07	.36	.65	.72	.31	1.37	.58	----	1.07	.82	.68	.40	.61	.73	1.43
NSW-21	1.33	1.27	1.18	.72	1.21	1.15	1.28	1.11	----	.87	1.22	1.39	.96	.85	.77
RIW-417	.89	.95	.78	.83	.79	.76	.88	1.07	.82	----	.45	.67	.23	.74	.59
RIW-600	.71	.74	.69	1.06	.66	.89	.66	.89	.96	.43	----	.40	.21	.64	.90
SNW-6	.81	.35	.70	.91	.29	1.50	.51	.33	1.24	.59	.32	----	.56	.50	1.27
SNW-515	.73	.40	.72	.71	.42	1.14	.66	.44	.80	.31	.30	.51	----	.41	.97
WEW-522	.86	.54	.62	.75	.55	1.07	.45	.72	.64	.34	.36	.41	.26	----	.58
WGW-181	1.27	1.10	.92	.72	.99	.66	.87	1.25	.58	.43	.83	1.02	.64	.71	----

[1]Well destroyed in 1992; water-level measurement discontinued.

Table 12. Mean squared error for estimates of high water levels (depth to water level exceeded 5 percent of the time) for wells in Rhode Island completed in sand and gravel, based on water levels in index well

[Value shown is mean squared error, in feet squared. To select index well, read across from local well number nearest site to lowest value of mean squared error]

Local well No. (fig. 2)	INDEX WELLS														
	BUW-187	CHW-18	COW-411	EXW-6	EXW-475	LIW-84	NKW255	NKW-450	NSW-21	RIW-417	RIW-600	SNW-6	SNW-515	WEW-522	WGW-181
BUW-187	----	1.17	2.08	1.21	1.73	2.73	1.43	1.09	1.48	2.58	1.17	1.49	1.98	1.63	3.07
CHW-18	2.90	----	3.57	2.49	3.43	5.10	2.11	1.79	2.83	5.40	2.97	2.26	3.85	2.94	5.87
COW-411	1.15	.52	----	.80	.65	1.03	.71	.65	1.07	.82	.98	.54	.64	.74	1.27
EXW-6	1.01	.81	.51	----	.51	.42	1.11	.99	.89	.32	.64	.84	.40	.48	.48
EXW-475	.89	.35	.76	.57	----	1.20	.79	.33	.90	.75	.54	.27	.61	.55	1.18
LIW-84	1.60	1.28	1.10	.76	.99	----	1.39	1.35	1.02	1.15	1.00	1.48	1.07	1.15	1.00
NKW-255	1.17	.71	1.08	.90	1.00	2.06	----	.53	1.21	1.49	.62	.67	1.36	.69	1.84
[1]NKW-450	.94	.39	.97	.69	.49	1.83	.55	----	1.07	1.79	.66	.52	1.03	.84	2.37
NSW-21	1.39	1.48	1.88	.88	1.22	2.22	1.37	1.27	----	1.73	1.22	1.67	1.90	1.16	1.92
RIW-417	2.75	2.55	1.31	2.84	1.81	1.24	2.47	3.29	2.25	----	2.3	1.95	.88	2.11	1.03
RIW-600	1.17	.99	.68	1.34	.68	.61	1.01	1.39	1.14	.40	----	.63	.21	.89	.83
SNW-6	.81	.32	.69	.84	.39	1.88	.50	.31	1.23	1.07	.31	----	.87	.52	1.63
SNW-515	.69	.36	.83	.65	.29	1.43	.70	.45	.82	.63	.34	.51	----	.42	1.41
WEW-522	1.32	.83	.58	1.10	.59	.76	.91	1.26	1.07	.32	.75	.59	.27	----	.55
WGW-181	2.27	2.01	1.19	1.91	1.39	.72	1.89	2.58	1.59	.48	1.73	1.57	.91	1.34	----

[1]Well destroyed in 1992; water-level measurement discontinued.

Table 13. Average mean squared error for wells in Rhode Island completed in sand and gravel used as index wells in equations 3, 4, and 5 to estimate depth to water level exceeded 95, 50, and 5 percent of the time in all other Rhode Island wells completed in sand and gravel

Well used as index well (fig. 2)	Average mean squared error, in feet squared, for estimated depth to water level exceeded: Number of estimates	95 percent of time	50 percent of time	5 percent of time	Well used as index well (fig. 2)	Average mean squared error, in feet squared, for estimated depth to water level exceeded: Number of estimates	95 percent of time	50 percent of time	5 percent of time
BUW-187	6,941	1.28	1.20	1.48	NSW-21	6,707	1.25	1.00	1.33
CHW-18	6,697	.90	.81	1.07	RIW-417	7,033	.93	.78	1.47
COW-411	6,875	1.16	.92	1.33	RIW-600	7,053	1.03	.83	1.17
EXW-6	6,721	.96	.90	1.25	SNW-6	6,792	1.04	.84	1.17
EXW-475	7,003	1.16	.83	1.20	SNW-515	6,810	1.10	.72	1.25
LIW-84	6,682	1.44	1.24	1.73	WEW-522	6,952	1.01	.84	1.18
NKW-255	6,805	1.13	.94	1.27	WGW-181	6,952	1.35	1.11	1.83
NKW-450[1]	6,876	1.20	.87	1.31					

[1]Well destroyed in 1992; water-level measurement discontinued.

Table 14. Mean squared error and mean of 6,697 estimates of high, median, and low water levels (depth to water levels exceeded 95, 50, and 5 percent of the time, respectively) in wells in Rhode Island based on water levels in well CHW-18 (1946-90) and equations 3, 4, and 5

[Water levels are in feet, mean squared errors are in feet squared; *Wh*, *Wm*, and *Wl* are variables used in water-level estimation equations]

Local well No. (fig. 2)	Number of estimates	Depth to water level exceeded: 95 percent of time (*Wh*)	50 percent of time (*Wm*)	5 percent of time (*Wl*)	Mean of estimate of water levels: High (eq. 3)	Median (eq. 4)	Low (eq. 5)	Mean squared error of estimates: High	Median	Low
BUW-187	260	12.88	15.10	18.04	13.23	15.60	17.53	1.03	1.16	1.17
COW-411	326	19.22	21.57	23.23	19.17	21.54	23.47	.46	.46	.52
EXW-6	480	3.91	5.96	7.38	3.60	5.94	7.88	.68	.57	.81
EXW-475	198	11.75	14.65	16.40	12.34	14.71	16.64	.64	.30	.35
LIW-84	519	2.74	5.39	6.84	2.84	5.22	7.15	1.20	1.22	1.28
NKW-255	396	6.19	8.49	11.02	6.38	8.76	10.69	.63	.67	.71
NKW-450[1]	325	10.47	13.32	15.59	11.08	13.46	15.39	.72	.36	.39
NSW-21	494	5.62	7.99	10.57	5.78	8.16	10.09	1.27	1.27	1.48
RIW-417	168	5.54	6.92	7.77	4.75	7.12	9.05	1.53	.95	2.55
RIW-600	148	32.52	33.87	36.32	31.85	34.23	36.16	1.06	.74	.99
SNW-6	409	9.85	12.20	14.44	10.03	12.41	14.34	.34	.35	.32
SNW-515	391	25.18	27.32	29.43	25.17	27.55	29.48	.35	.40	.36
WEW-522	249	10.46	12.23	13.86	10.18	12.55	14.48	.52	.54	.83
WGW-181	249	12.15	15.94	17.08	13.74	16.12	18.05	1.08	1.10	2.01

[1]Well destroyed in 1992; water-level measurement discontinued.

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