HYDROGEOLOGY, WATER QUALITY, AND GROUND-WATER DEVELOPMENT ALTERNATIVES IN THE LOWER WOOD RIVER GROUND-WATER RESERVOIR, RHODE ISLAND

By David C. Dickerman, Elaine C. Todd Trench,
and Joel P. Russell

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CONVERSION FACTORS

For use by those readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, conversion factors are listed below.

Multiply inch-pound unit	By	To obtain metric (SI) unit
LENGTH		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch (in.)	25.4	millimeter (mm)
AREA		
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
VOLUME		
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
FLOW		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallons per minute per foot [(gal/min)/ft]	0.2070	liters per second per meter [(L/s)/m]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
TRANSMISSIVITY		
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
HYDRAULIC CONDUCTIVITY		
foot per day (ft/d)	0.3048	meter per day (m/d)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD 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 "Mean Sea Level of 1929."

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ABSTRACT

The 36-square-mile lower Wood River study area is located within the Pawcatuck River basin in southern Rhode Island. Stratified drift is the only principal geologic unit capable of producing yields greater than 350 gallons per minute. The stratified-drift aquifer consists of interbedded lenses of sand and gravel, with lesser amounts of silt, silty sand, and clay. Transmissivity of the aquifer ranges from 8,600 to 36,400 feet squared per day. Water-table conditions prevail in the aquifer, which is in good hydraulic connection with perennial streams and ponds.

The chemical quality of ground water in the study area is generally good to excellent and suitable for most uses. The water is soft, slightly acidic, and typically contains less than 100 mg/L (milligrams per liter) dissolved solids. Locally, however, ground water has been contaminated with nitrate, pesticides, and radionuclides associated with various land-use and waste-disposal activities. Concentrations of iron and manganese locally exceed Federal drinking-water standards, but probably are derived from natural sources.

A digital finite-difference model of the ground-water flow system was used to simulate the interaction between surface water and ground water. The model was used to evaluate the effect of alternative schemes of ground-water development on ground-water levels, pond levels, and streamflow in the lower Wood River ground-water reservoir. Steady-state simulations of theoretical pumpage were made for long-term average annual hydrological conditions (1941-76) and simulated drought conditions (1963-66).

The model was used to simulate changes in stream leakage and to estimate the percentage of water withdrawn from wells that would be derived from ground-water runoff, induced recharge, and reduced evapotranspiration under long-term average annual hydrological conditions.

Differences between computed model heads and measured heads in 33 observation wells were less than 1.80 feet at 80 percent of the observation well-nodes. Total pumpage for selected development alternative simulations ranged from 6.0 to 11.0 Mgal/d (million gallons per day). Individual wells were pumped at constant rates of 1.0 Mgal/d for all simulations.

The areas most favorable for development of high-capacity wells (350 gallons per minute or more) are along the Wood River, Meadow Brook, Meadow Brook Pond, and the area around Ellis Flats. Thirty-six to 43 percent of the water withdrawn from wells will be derived from induced recharge from surface-water sources.

Development alternatives simulated in this study indicate that the ground-water reservoir can sustain withdrawals of 6 to 9 Mgal/d under long-term average annual hydrological conditions, without causing excessive streamflow depletion or decrease in aquifer saturated thickness. However, it may be necessary to reduce pumpage below 6.0 Mgal/d to maintain some flow in Meadow Brook during drought periods.

INTRODUCTION

Stratified-drift deposits, primarily in stream valleys, are Rhode Island's major aquifers. Where the transmissivity and saturated thickness of these aquifers are greatest, ground water may be present in quantities suitable for development and use; such aquifers are termed ground-water reservoirs. The lower Wood River **ground-water reservoir**[1] is located within the Pawcatuck River basin, in southern Rhode Island. It underlies an area of approximately 8 mi^2 (square miles) in the valleys drained by Canonchet Brook, Meadow Brook, and the Pawcatuck and Wood Rivers. The ground-water reservoir includes only that part of the study area underlain by the thickest and most transmissive **stratified-drift** deposits. The outline of the ground-water model shown in figure 1 approximates the area of the lower Wood River ground-water reservoir. The lower Wood River ground-water reservoir is one of nine major ground-water reservoirs in the Pawcatuck River basin (Rhode Island Statewide Planning Program, 1979), and one of five in which the Rhode Island Water Resources Board (RIWRB) has done extensive exploratory drilling and **aquifer** testing.

The RIWRB, which is responsible for implementing development of the State's major water resources, identifies sites at which high-capacity wells can be developed that yield water of suitable quality for municipal-supply use. This responsibility led to the development of a jointly funded study, between the RIWRB and the U.S. Geological Survey, which involved the collection and analysis of geohydrologic data in each of five ground-water reservoirs. In the lower Wood River ground-water reservoir, the RIWRB goal was to identify sites from which an average daily yield of 6 Mgal/d and a maximum pumping capacity of 12 Mgal/d could be obtained.

[1] Bold-face terms in text are defined in the glossary.

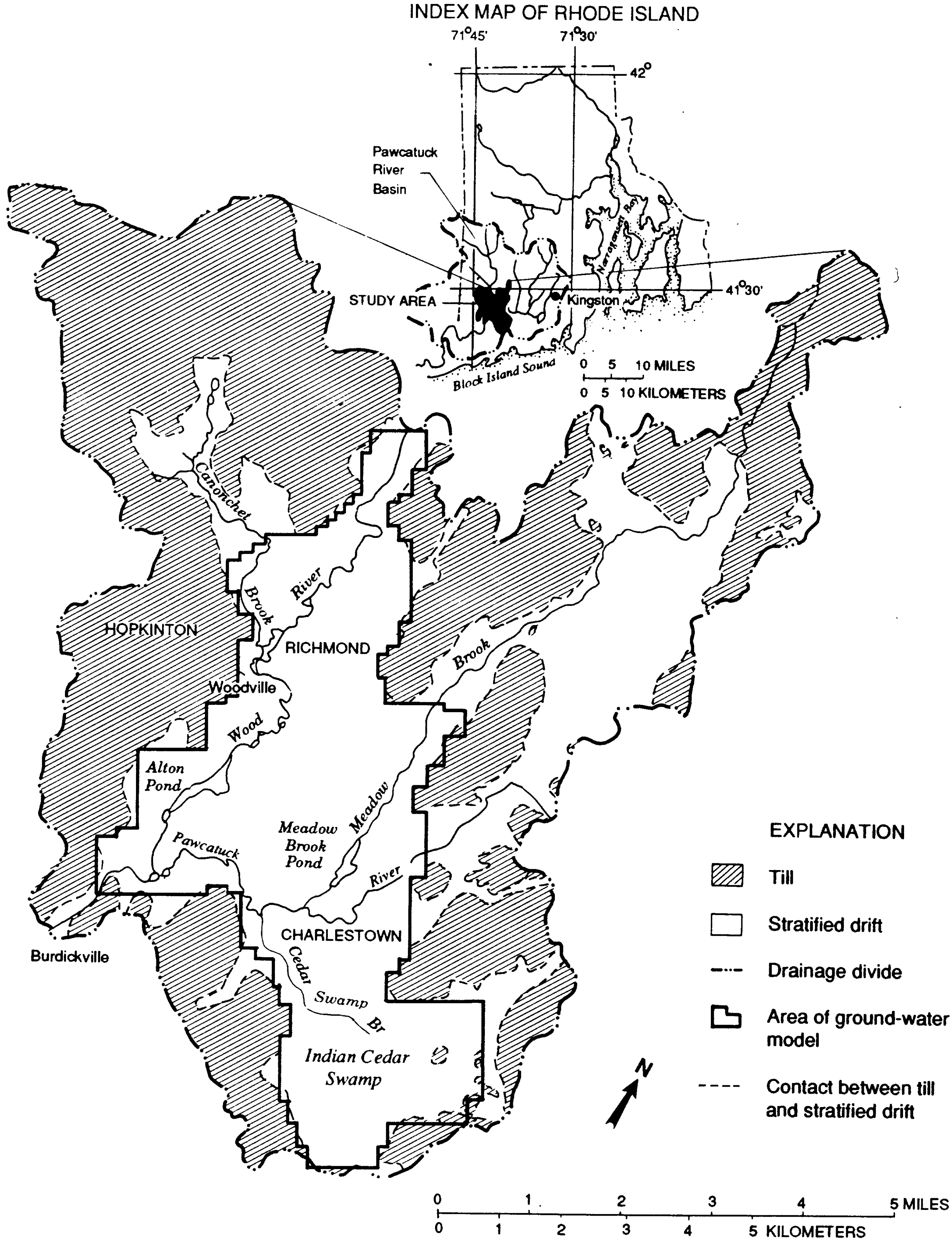

Figure 1.--Location and generalized hydrogeology of the lower Wood River study area, and the area covered by the ground-water model.

The RIWRB proposes (1) to encourage development and management of ground-water resources so as to minimize streamflow depletion during low-flow periods, and (2) to preserve selected favorable sites for future development.

Purpose and Scope

This report describes the hydrogeology, water quality, and ground-water development alternatives in the lower Wood River ground-water reservoir, Rhode Island. The report includes discussion of: (1) recharge, stream-aquifer interconnection with and hydraulic properties of the principal aquifer (the stratified-drift aquifer); (2) assessment of the chemical quality of ground water and surface water; (3) construction and calibration of a two-dimensional ground-water flow model; and (4) evaluation, on the basis of ground-water model analysis, of the effect of alternative schemes of ground-water development on ground-water levels and streamflow depletion. The stream-aquifer system, consisting of the Wood River, Pawcatuck River, Meadow Brook, Canonchet Brook, and the underlying and adjacent stratified-drift aquifer, is the principal subject of this report. The hydrogeologic interpretations in this report were based on data collected chiefly from August 1976 through September 1977; these data were supplemented by unpublished data collected in previous investigations.

Previous and Concurrent Studies

Substantial geohydrologic information is available from earlier studies that include part or all of the study area. Surficial and bedrock geology have been mapped by Feininger (1962, 1965), Moore (1958, 1959), and Schafer (1968). Reconnaissance studies on the availability of ground water were done by Bierschenk and Hahn (1959), Johnson (1961), Lang (1961), LaSala and Hahn (1960), and Randall and others (1966). A comprehensive quantitative study on the availability of ground water in the lower Pawcatuck River basin, Rhode Island, which includes the lower Wood River ground-water reservoir, was completed by Gonthier and others (1974). Data from a low-level radionuclide contamination site located within the study area have also been collected by Barlow and Ryan (1985), Ryan and Kipp (1985), and Ryan and others (1985). Most of the data on which the present report is based are contained in a geohydrologic-data report by Dickerman and Silva (1980).

Additional hydrologic data in the lower Wood River ground-water reservoir area have been collected and continue to be collected by the U.S. Geological Survey as part of the ongoing Pawcatuck River basin study. These data are presently contained in annual reports (U.S. Geological Survey, 1940 to 1950, 1951 to 1964, 1965 to 1974, and 1975 to present). Data include records of discharge (1941 to present), and temperature and specific conductance (October 1977 to present) of the Wood River at Hope

Valley, R.I.; discharge (1940 to present) of the Pawcatuck River at Wood River Junction, R.I.; discharge (1965-73) of and **precipitation** (1966-73, except during winter months) near Meadow Brook near Carolina, R.I.; measurements of low streamflow at miscellaneous sites, and records of water-level fluctuations in observation wells.

Description and Location of Study Area

The lower Wood study area (fig. 1) is in southern Rhode Island and includes parts of the towns of Charlestown, Richmond, and Hopkinton. It lies entirely within Washington County and is about 10 mi (miles) long and 5 mi across at its widest point. The study area is crossed by the boundary between the New England Upland and the Seaboard Lowland sections of the New England physiographic province (Fenneman, 1938, pl. I).

The northern half of the area is characterized by gently rolling topography with rounded hills, several depressions and kettle hole ponds (Plain, Wells, and Sandy Ponds), and the narrow, southward-trending Wood River and Canonchet Brook valleys (fig. 2). The southern half of the area also is characterized by gently rolling topography with rounded hills, but the Wood River valley becomes much broader in this area and contains a large wetland called Indian Cedar Swamp (fig. 2). An estimated 85 to 90 percent of the study area is woodland or abandoned pastureland that has become densely overgrown (Moore, 1959).

The highest point is the summit of Coon Hill (elevation 331 feet above sea level) near the northwest corner of the study area, and the lowest point is at Burdickville (elevation 40 feet) along the southwestern corner of the study area at the Pawcatuck River outlet. Maximum relief within the 36.2-mi^2 **drainage area** above Burdickville is 291 ft (feet). Based on available water level data, the **ground-water drainage divide** and surface-water **drainage divide** are identical along the boundary of the study area.

Acknowledgments

The authors express appreciation to the well drillers and private citizens who provided information and helpful discussion concerning the geohydrology of the lower Wood River ground-water reservoir. Special acknowledgment is made to Agency Realty and Mortgage Company, Frank Haberek, Norman and Janet Hale, Benjamin A. James, Robert E. James, William E. James, Normand D. Macleod, Iva Perreault, Carolina Realty, the Town of Richmond, and Charles Trumpetto, who allowed **aquifer tests** to be conducted on their property.

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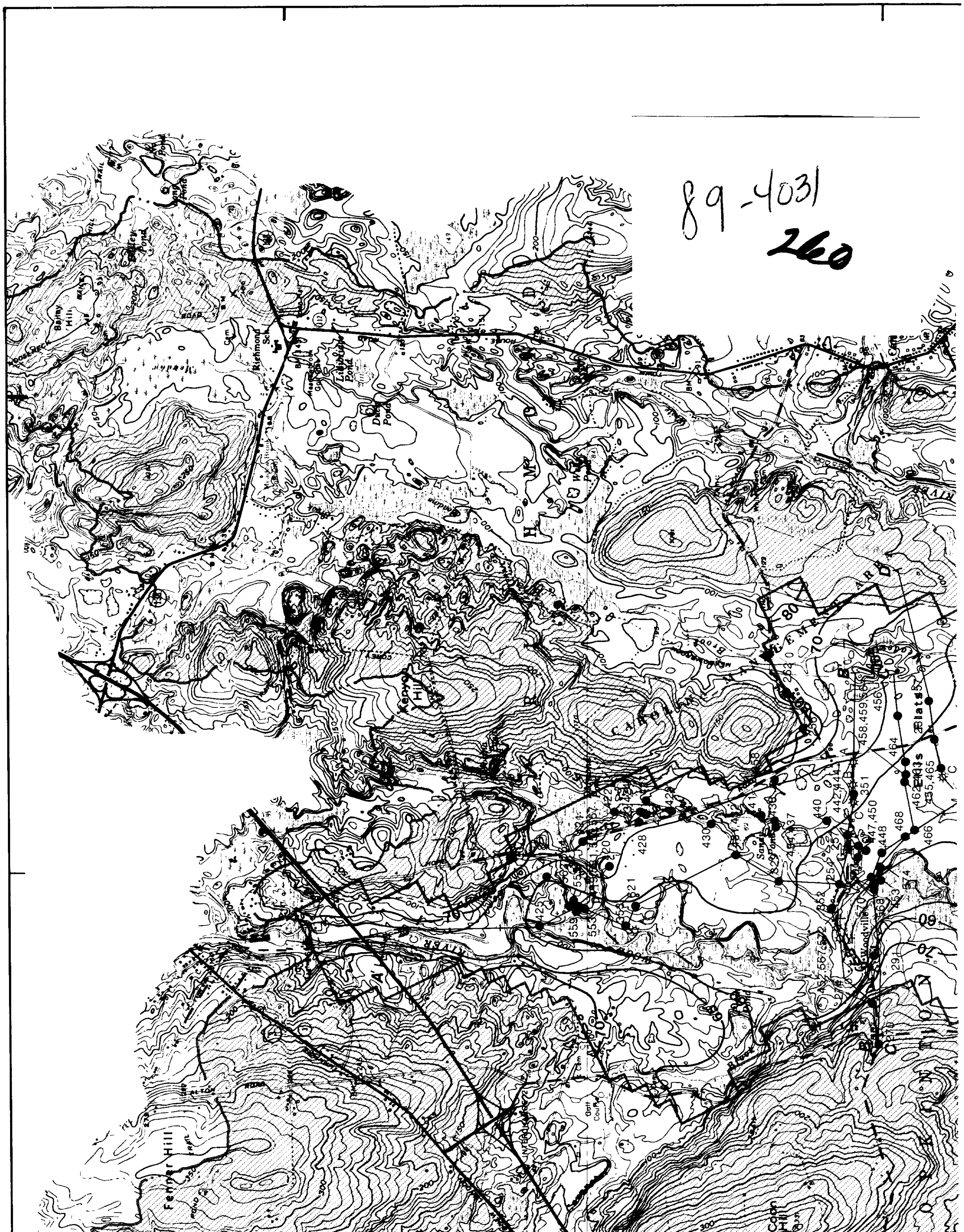
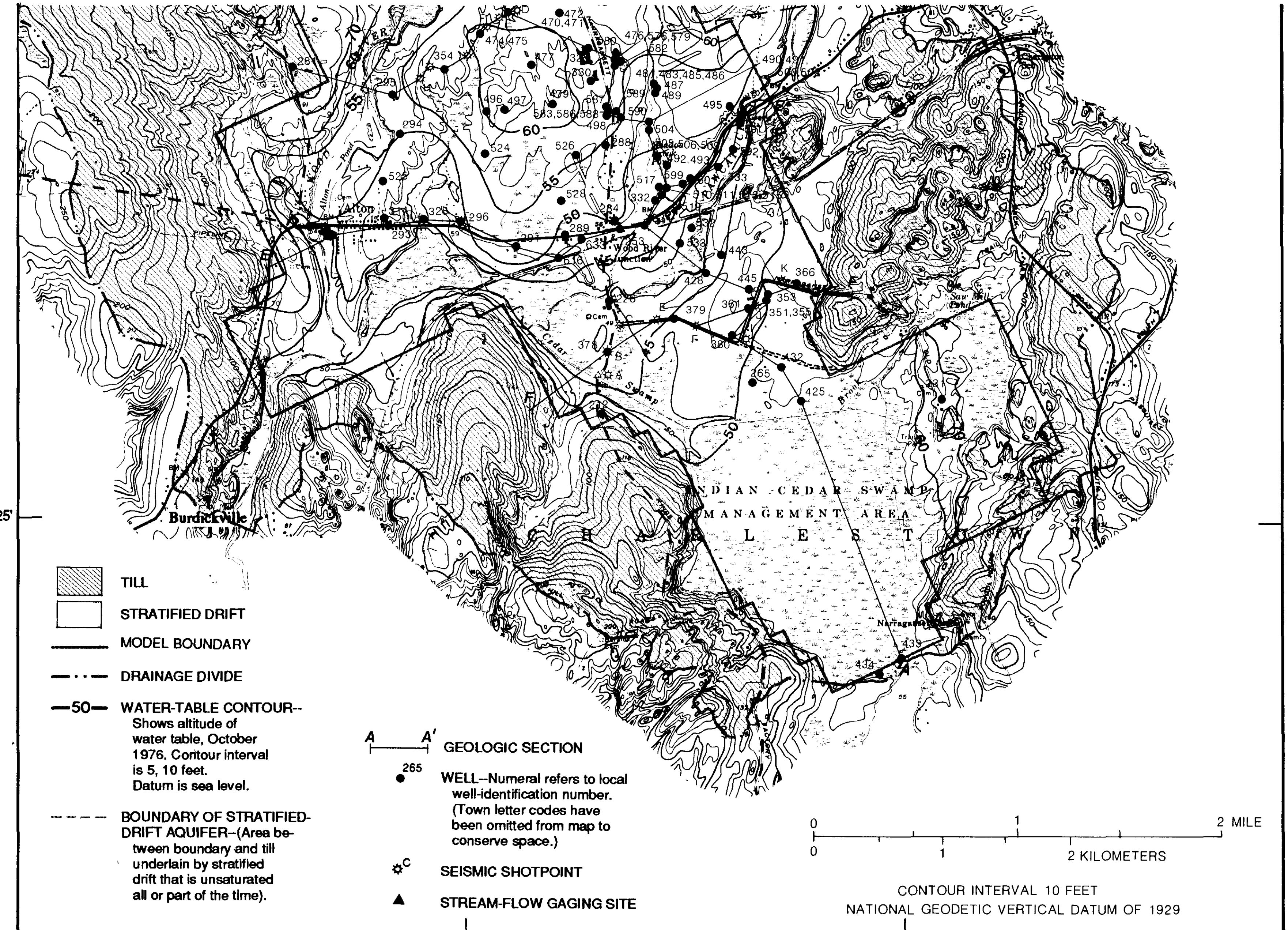


71°40'
71°42'30"
71°45'
41°30'
41°27'30"
Kenyon Hill
Fenner Hill
Woodville



Base from U.S. Geological Survey 1:24,000
Carolina, 1953 and Hope Valley, 1953 quadrangles

Figure 2.--Water table in the stratified-drift aquifer in the lower Wood River ground-water reservoir.

GEOHYDROLOGIC SETTING

General Geology

The lower Wood River study area is underlain by three principal geologic units -- bedrock, **till**, and stratified drift. These units differ significantly in geologic origin and water-yielding characteristics. The bedrock consists of crystalline rocks of igneous origin and metamorphosed **sedimentary rocks**. Crystalline or metamorphosed bedrock underlies the entire **drainage basin**. The crystalline Hope Valley Alaskite **Gneiss** and the **metasedimentary** Blackstone Group (a quartz-feldspar-biotite gneiss), all of late Precambrian age, are the predominant bedrock units in the basin. Overlying the bedrock are materials of glacial origin. The north-south trending sand and gravel deposits of the Wood River Valley and tributary valleys to the Wood River were named by Feininger (1962) as the western valley deposits.

During the Pleistocene Epoch continental glaciers advanced from the north and covered this area several times. These glacial-ice sheets deposited rock debris, called "drift", which includes till, stratified drift, and scattered rock fragments. In the lower Wood River area, most of the drift was deposited during the advance and retreat of the last ice sheet during the Wisconsin glacial age. Drift is subdivided into two kinds: nonstratified (or till) and stratified. There is no sharp dividing line between till and stratified drift; one grades into the other.

Till, locally called "hardpan", forms a generally thin discontinuous mantle over the underlying bedrock and usually reflects its topography. It is not sorted or stratified by water action and consists of a mixture of material ranging in size from boulders to clay. Till covers about 52 percent of the study area, has an average thickness of about 25 feet, and reaches a maximum known thickness of 80 feet.

The stratified drift consists of well sorted layers of sand and gravel. It is the only geologic unit with materials sufficiently permeable to yield 350 gal/min or more of water for development.

The lower Wood River ground-water reservoir is an irregularly shaped body of porous, highly permeable stratified drift extending from the **gaging station** on the Wood River near Hope Valley on the north, to the Indian Cedar Swamp Management Area on the south (fig. 2). The ground-water reservoir ranges in width from about 3,000 feet along the Wood River near the gage to about 15,000 feet near Wood River Junction (Dickerman and Silva, 1980), and has an areal extent of about 8 mi^2.

Ground Water

The stratified-drift aquifer along the Wood and Pawcatuck Rivers, and along Meadow, Canonchet, and White Brooks is **unconfined.** There are no known areally extensive layers of impervious sediment to create **confined-aquifer** conditions at any sites where lithologic data were collected. Locally, however, some parts of the stratified-drift aquifer may be semiconfined by fine grained materials (Gonthier and others, 1974).

A map showing the configuration and altitude of the **water table** in the stratified-drift aquifer was constructed from water levels measured in 33 observation wells primarily during October 1976 when streamflow and water levels were near long-term average annual conditions (fig. 2). The direction of ground-water flow in the aquifer is from the till uplands toward the Wood and Pawcatuck Rivers, and Meadow, Canonchet, and White Brooks. On the basis of water level measurements made in multilevel piezometers, ground-water flow has been shown to be predominantly horizontal.

Surface Water

The Wood and Pawcatuck Rivers and their main tributaries are the principal areas of ground-water discharge from the stratified-drift aquifer. Continuous records of streamflow have been collected since 1941 at two U.S. Geological Survey gaging stations (fig. 2), one on the Wood River at Hope Valley, and the other on the Pawcatuck River at Wood River Junction. Long-term average annual runoff was determined from the basin using a 36 year period of record. From 1941-76, long-term annual runoff averaged 150 ft^3/s (cubic feet per second) [97 Mgal/d] on the Wood River at Hope Valley, and 191 ft^3/s (123 Mgal/d) on the Pawcatuck River at Wood River Junction. Long-term average annual runoff for Canonchet Brook, the main tributary to the Wood River, and Meadow Brook, the main tributary to the Pawcatuck River, as well as the Pawcatuck River at the outlet of the study area at Burdickville, was estimated by an empirical relation between drainage area size and runoff characteristics using data from long-term surface water gaging stations. Estimated long-term average annual runoff was 12.1 ft^3/s (7.8 Mgal/d) on Canonchet Brook, 9.4 ft^3/s (6.1 Mgal/d) on Meadow Brook, and 406 ft^3/s (262 Mgal/d) on the Pawcatuck River. Records of streamflow are published in a report by Dickerman and Silva (1980) and in annual water-resources data reports of the U.S. Geological Survey.

The **duration of flow** for a stream can be shown by a cumulative frequency curve called a flow-duration curve. Flow-duration curves are shown in figure 3 for the Wood and Pawcatuck Rivers. Streamflow on the high-discharge part of the curves is largely storm water runoff and that on the low-discharge part is mainly ground-water runoff. In Rhode Island, the minimum flow for which stream water-quality standards have been developed is

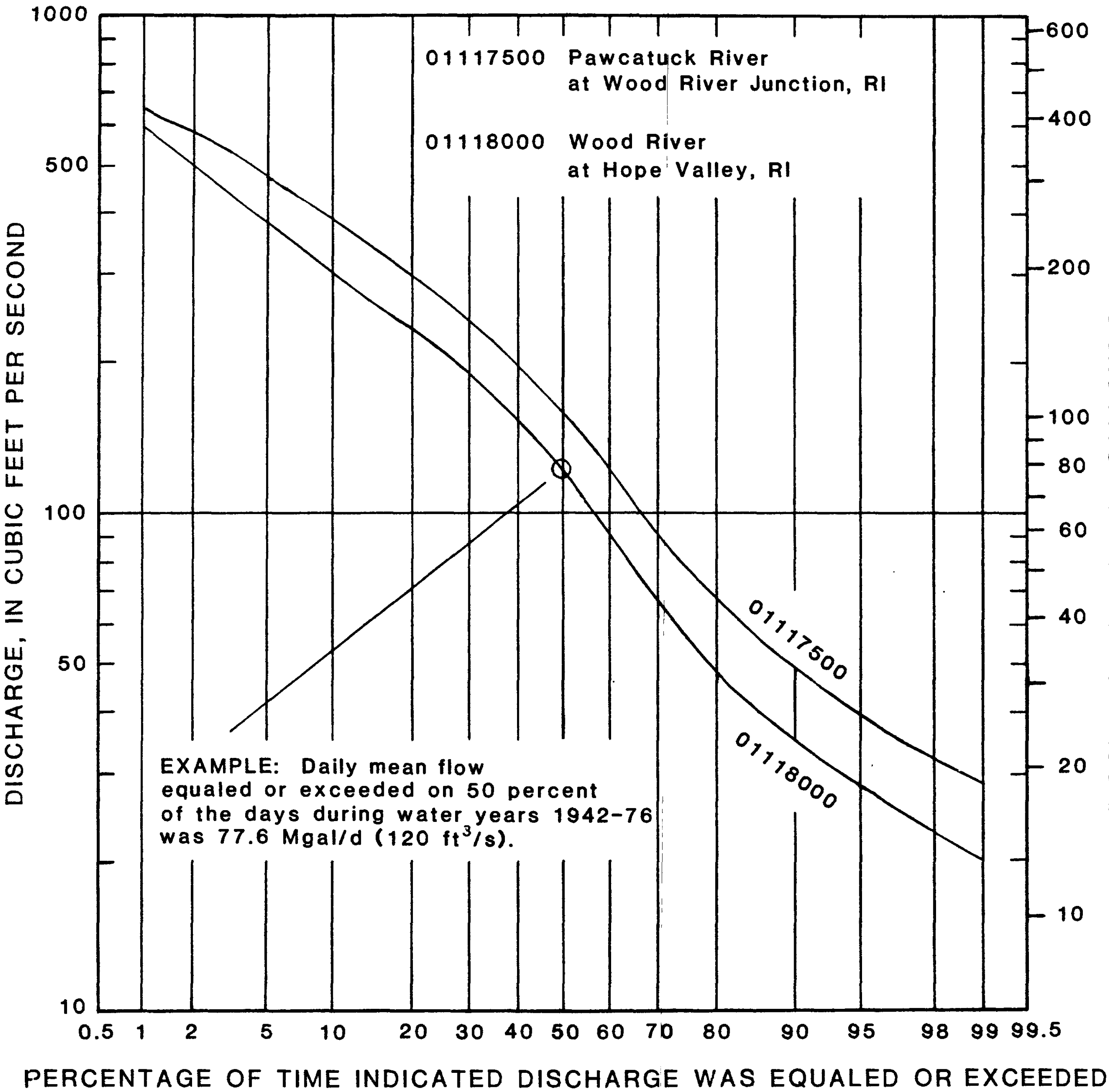


Figure 3.--Duration of daily mean stream discharge at the Pawcatuck River at Wood River Junction, R.I. and the Wood River at Hope Valley R.I., 1942-76 water years.

the minimum average daily flow for 7 consecutive days that can be expected to occur on the average once in 10 years[2] (RhodeIsland Statewide Planning Program and Rhode Island Dept. of Health, p. A-7, 1976). A relation developed by Johnston and Dickerman (table 2, 1985) for streams in the Pawcatuck River basin equates the 7-day low flow with a 10-year recurrence interval to the 99.1-percent flow duration. The combined 99.1-percent flow duration of streamflow entering the study area from the Wood River at Hope Valley and the Pawcatuck River at Wood River Junction is 31 Mgal/d.

Basin Water Budget

Water enters the lower Wood River study area through precipitation, surface runoff, and ground-water **underflow**. Underflow into the study area was considered negligible (see footnote 8, table 1). Water leaves the study area as surface outflow at Burdickville, and as evaporation and transpiration. A water budget quantitatively expresses the balance of water in the study area, and may be expressed as: inflow equals outflow plus or minus changes in storage. Over many years the net changes in storage tend to be small, and may be considered negligible. The water budget equation for the study area is expressed as:

$$\underbrace{P + Rt_{in}}_{\text{INFLOW}} = \underbrace{Rt_{out} + ET}_{\text{OUTFLOW}},$$

where P is the precipitation; Rt_{in}, the total runoff into the reservoir area; Rt_{out}, the total runoff out of the reservoir area; and ET, the evaporation and transpiration. Components of the long-term average water budget for the lower Wood River study area are summarized in table 1.

From 1941-76, annual precipitation at the National Oceanic and Atmospheric Administration station at Kingston ranged from 30.69 in. (inches) (1965) to 68.48 in. (1972) and averaged 45.5 in. Total runoff from the gage on the Wood River at Hope Valley from 1941-76 ranged from 15.96 in. (1966) to 45.01 in. (1972) and averaged 28.1 in. During this same period, total runoff from the gage on the Pawcatuck River at Wood River Junction ranged from 14.70 in. (1966) to 40.80 in. (1972) and averaged 15.9 in.

Precipitation and **total runoff** data collected as part of this study show that hydrologic conditions in 1976 were near long-term average conditions. During 1976, precipitation at the Kingston station was about 42 in., and total runoff from the Wood and Pawcatuck Rivers averaged about 27 in. Comparison of 1976 data with long-term average data for 1941-76 show that precipitation and total runoff in 1976 were slightly (8 percent) less than long-term average annual hydrological conditions.

[2] This is the 7 day low flow with a 10-year recurrence interval.

Table 1.--Long-term average water budget for the lower Wood River study area, Rhode Island (1941-76).

[Mgal/d, million gallons per day; Mgal/d/mi^2, million gallons per day per square mile]

Inflow	Mgal/d	Outflow	Mgal/d
Precipitation[1]	47	**Total runoff from:** Pawcatuck River area upstream of Burdickville (206 mi^2)[2]	262
Total runoff from: Pawcatuck River area upstream of Wood River Jct. gage (100 mi^2)[3]	123	**Underflow** at Burdickville	0
Upper Wood River area upstream of Hope Valley gage (72.4 mi^2)[4]	97	**Evaporation and transpiration**[5]	19
Canonchet Brook area (5.89 mi^2)[6]	8		
Meadow Brook area (5.53 mi^2)[7]	6		
Underflow from: Pawcatuck River at Wood River Jct.; Wood River at Hope Valley; Canonchet Brook at Rockville-Alton Rd; Meadow Brk. at Pine Hill Rd	negligible[8]	**Change in storage**	negligible
Total	**281**	**Total**	**281**

1 Based on long-term average annual precipitation (45.5 inches) at Kingston, R.I., 1941-76.

2 Based on estimated long-term average annual runoff (1.27 (Mgal/d)/mi^2) of the Pawcatuck River at Burdickvile, R.I., 1941-76.

3 Based on long-term average annual runoff (1.23 (Mgal/d)/mi^2) of the Pawcatuck River at Wood River Junction, R.I., 1941-76.

4 Based on long-term average annual runoff (1.34 (Mgal/d)/mi^2) of the Wood River at Hope Valley, R.I., 1941-76.

5 Difference between total precipitation at Kingston, R.I. and long-term average annual total runoff of Pawcatuck River at Wood River Junction, R.I. and Wood River at Hope Valley R.I., 1941-76, upstream of the study area.

6 Based on estimated long-term average annual runoff (1.33 (Mgald)/mi^2) of Canonchet Brook near Woodvile, R.I., 1941-76.

7 Based on estimated long-term average annual runoff (1.09 (Mgal/d)/mi^2) of Meadow Brook near Carolina, R.I., 1941-76.

8 Total calculated underflow of 0.31 Mgal/d was considered negligible.

Water Use

An average of about 0.22 Mgal/d is estimated to have been pumped from ground water wells and surface water streams during 1976 in the lower Wood River study area. Of this amount, 0.20 Mgal/d (91 percent) was derived from ground water and 0.02 Mgal/d (9 percent) from surface water. Public water-supply systems are not available within the study area, and individual home owners rely heavily on well water. Pumpage from domestic wells accounted for about 45.5 percent (0.10 Mgal/d) of the ground-water withdrawn during 1976. Estimates of domestic pumpage were based on 400 homes with 4 persons per household times 60 gallons per day per person.

Three public schools and three industries were the largest single water users in the study area in 1976. Combined ground-water pumpage from these sources averaged 0.10 Mgal/d, and was used primarily for cooling, drinking, and sanitary needs. Public school pumpage was based on student population times 7 gallons per day per student (student usage is based on figures from metering at Tiverton High School, Tiverton, Rhode Island). Industrial pumpage is based on pumpage rates and length of pumpage period.

It is estimated that about 0.02 Mgal/d of water were pumped from the Pawcatuck and Wood Rivers for irrigation on an average annual basis. During an average year of precipitation, such as 1976, irrigation water normally is withdrawn over an 8-week period. On the basis of irrigation records from turf farmers in the adjacent Beaver-Pasquiset drainage basin, water for irrigation in the lower Wood River study area during a representative 8-week period is estimated to be about 0.32 Mgal/d. During drought years the withdrawal period for irrigation is typically extended to 20 weeks.

There were no public sewage treatment facilities in the study area in 1976. Most water withdrawn from wells was returned to the ground through individual sewage disposal systems and, therefore, most was available for reuse downgradient in the basin. The amount of water lost to evapotranspiration through sewage disposal systems was not determined, but is believed by the authors to be small (probably less than 10 percent).

HYDROGEOLOGY

Characteristics of the Stratified-Drift Aquifer

Permeable deposits of stratified drift form the major aquifer in the lower Wood River study area. The drift covers 48 percent of the study area. The drift consists of layers of material composed of sorted gravel and sand with minor amounts of silt and clay.

The stratified-drift aquifer is the only aquifer capable of producing well yields of 350 gal/min or more in the study area. Unconfined conditions prevail in the aquifer, which is hydraulically connected with perennial streams and ponds. Well yields in the stratified-drift aquifer depend on the natural recharge to the aquifer, the hydraulic properties of the aquifer, and the degree of stream-aquifer interconnection.

The water table, lithology, and thickness of the stratified-drift deposits are shown in a series of generalized geologic sections (figs. 4-8). All well and **seismic shot point** locations for the geologic sections are shown in figure 2. Seismic refraction surveys were used to help define depth to water and depth to bedrock. Geologic section A-A', a cross section parallel to the valley axis (fig. 4), shows the complex interbedding and lithologic **heterogeneity** of this aquifer system.

At the northern end of the study area, the valley is relatively narrow and the stratified drift is of moderate thickness (0-80 feet). About 2 mi downstream from the U.S. Geological Survey's gaging station on the Wood River, in the area along Woodville Road, the valley broadens and the drift deposits increase significantly in thickness (greater than 300 ft). This area, known as Ellis Flats, is the first area of glacial **overdeepening** discovered during test drilling by the U.S. Geological Survey in Rhode Island. Figure 4 (section A-A'), figure 5 (section C-C'), and figure 6 (section D-D') show the areas of glacial overdeepening. The **saturated thickness** of the stratified-drift aquifer has a maximum known thickness greater than 290 ft in this area (well RIW 470, fig. 6). The saturated thickness averages only about 70 ft throughout the study area (fig. 9). In the thickest area of stratified drift, material 100 ft or more below land surface is composed mostly of fine sand to clay and was not included in the digital model.

The highest yield from an 8-in. test well, 645 gal/min, was from well RIW (Richmond well) 510. Well RIW 510 was located on the east side of the buried preglacial valley that cuts across Ellis Flats, about 1,000 ft west of the Pawcatuck River (fig. 2).

From Ellis Flats south to Indian Cedar Swamp, the stratified drift consists mainly of coarse grained highly permeable sediments underlain by thick layers of fine grained deposits of probable lacustrine origin (figs. 6-8).

Sources of Recharge

"Water available for recharge is often a more useful concept or quantity to estimate than is recharge itself" (Lyford and Cohen, 1988). Water available for recharge is almost

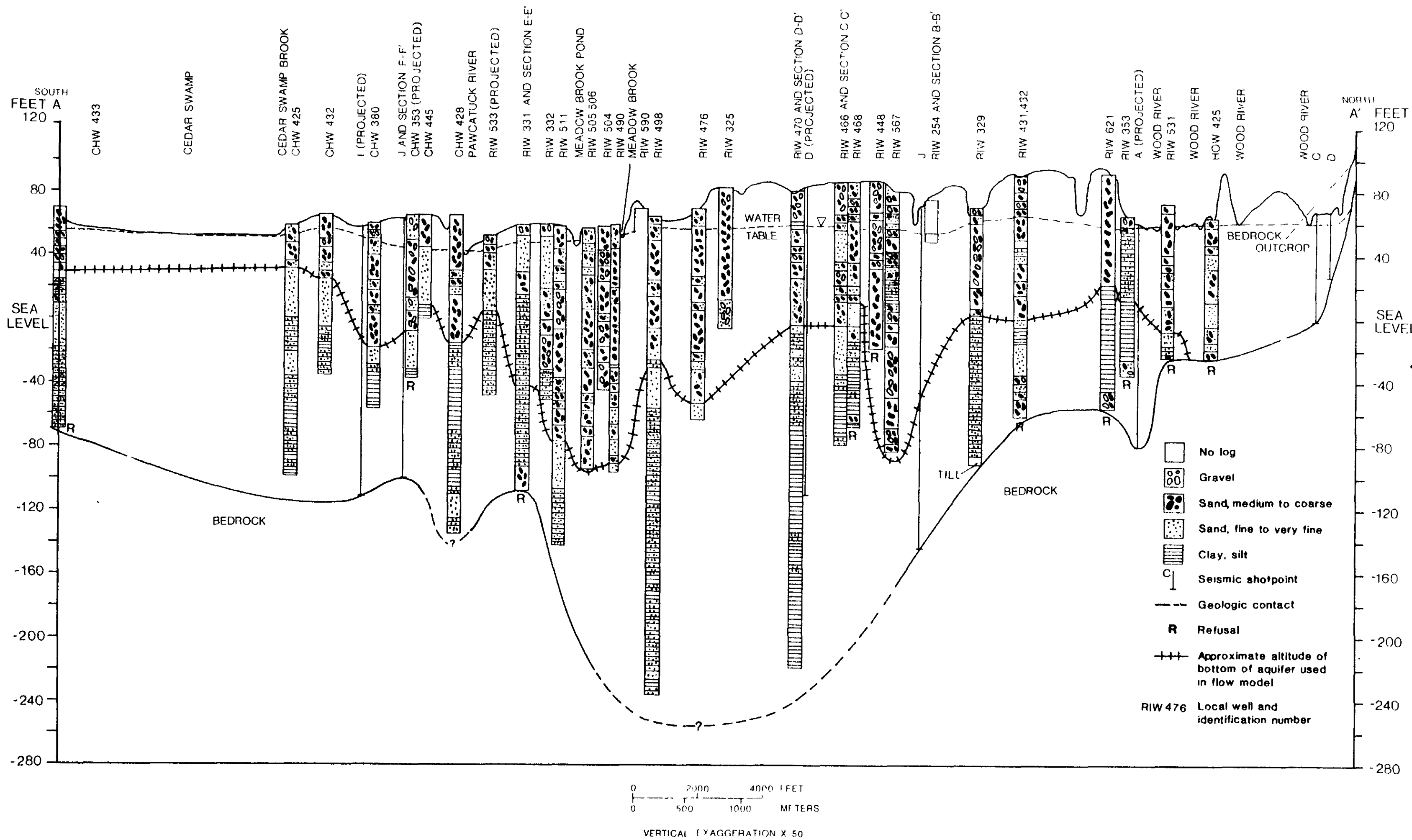


Figure 4.--Longitudinal geologic section (A-A') of the lower Wood River ground-water reservoir showing the complexly interbedded stratified-drift aquifer.

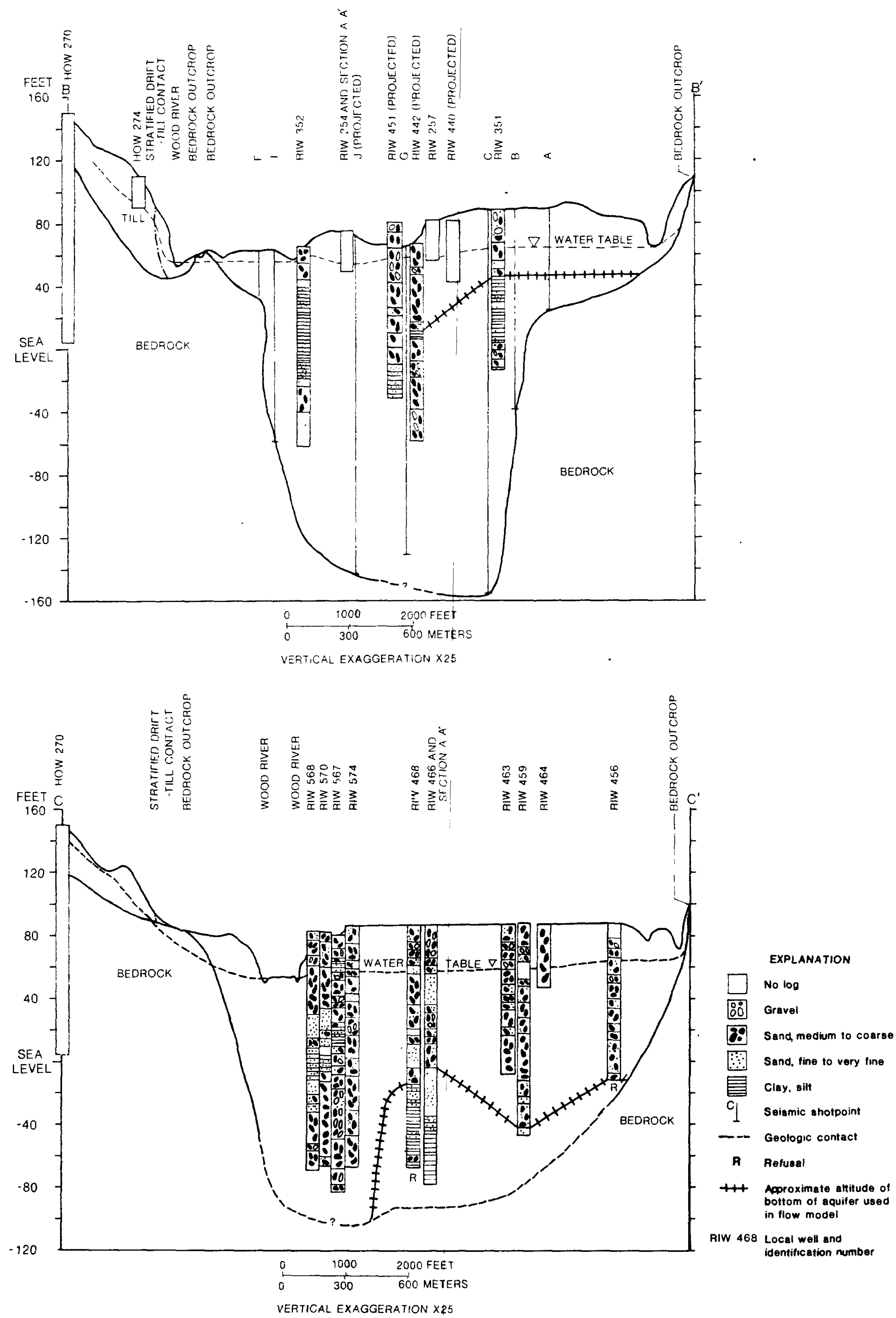


Figure 5.--Generalized geologic sections (B-B' and C-C') near Woodville Road.

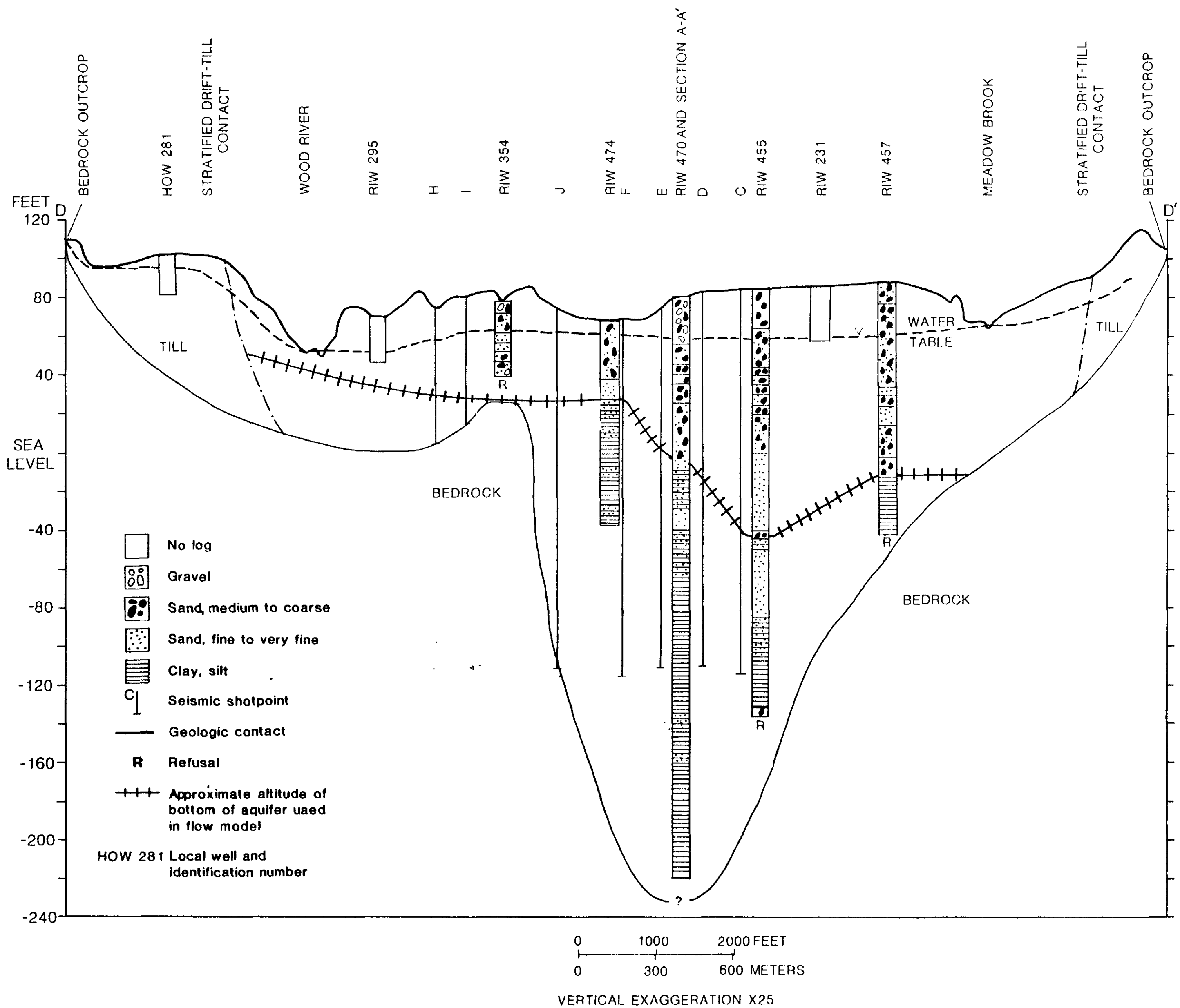


Figure 6.--Generalized geologic section (D-D') of the Ellis Flats area.

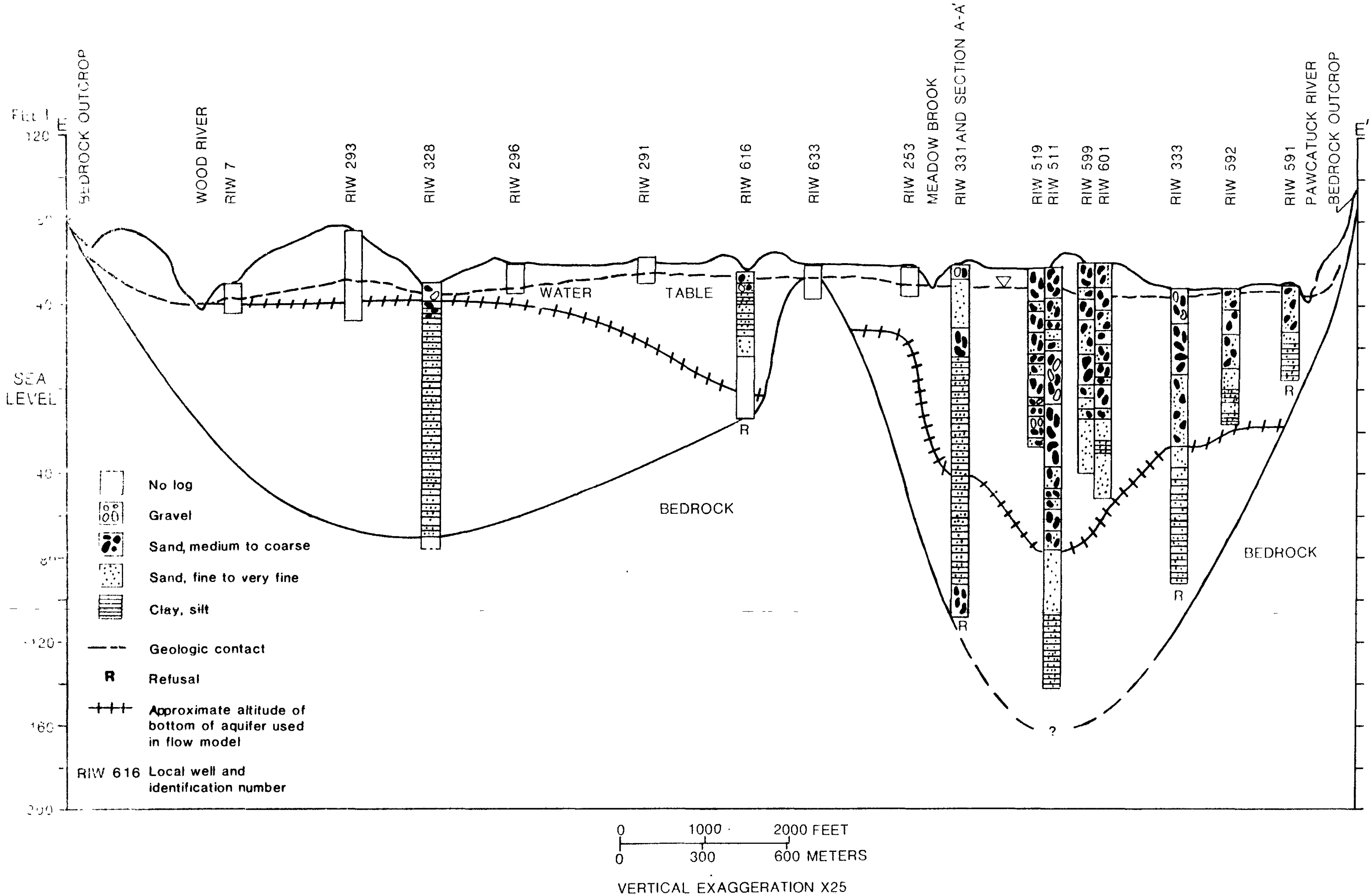


Figure 7.--Generalized geologic section (E-E') along State Highway 91.

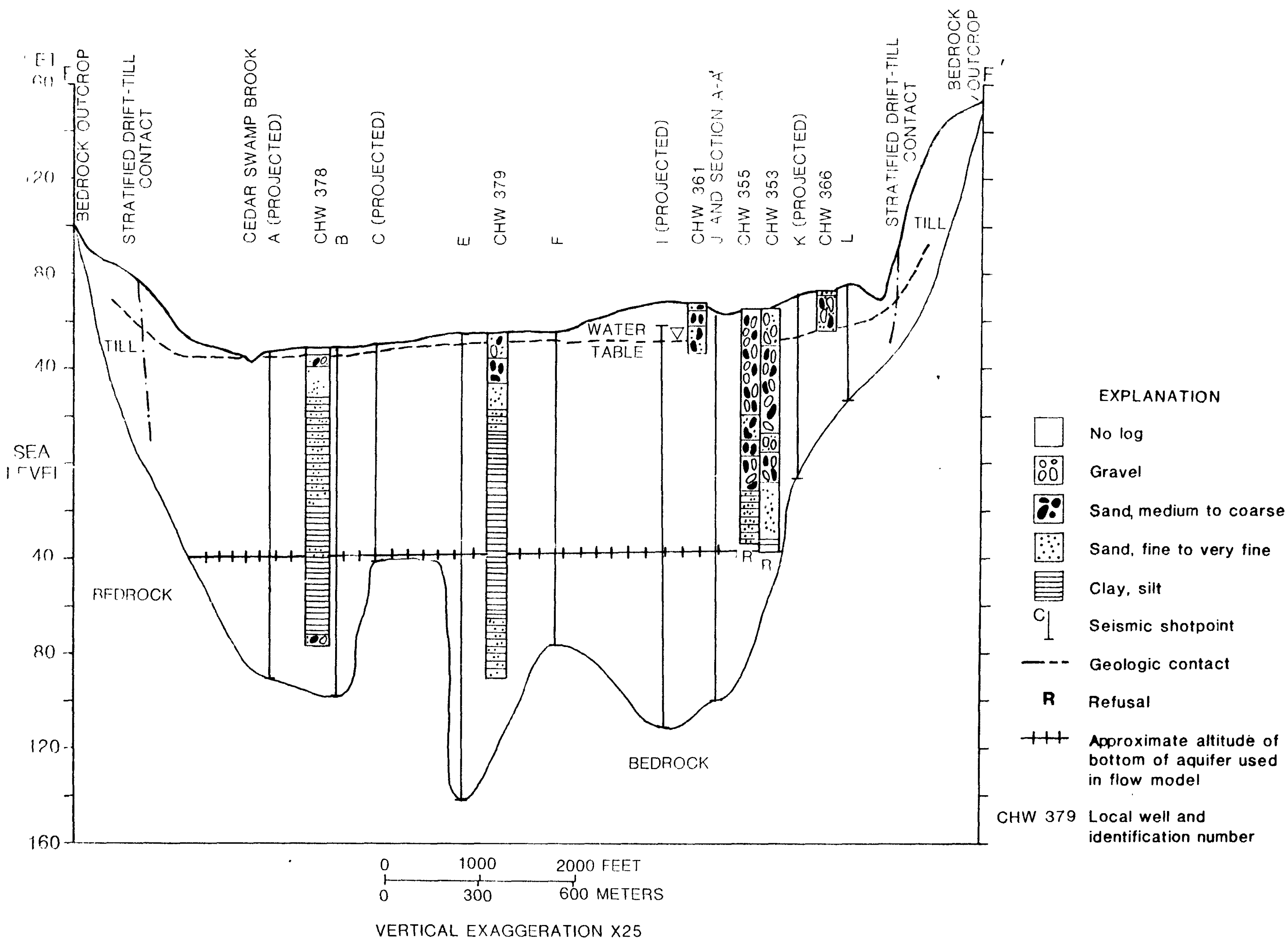
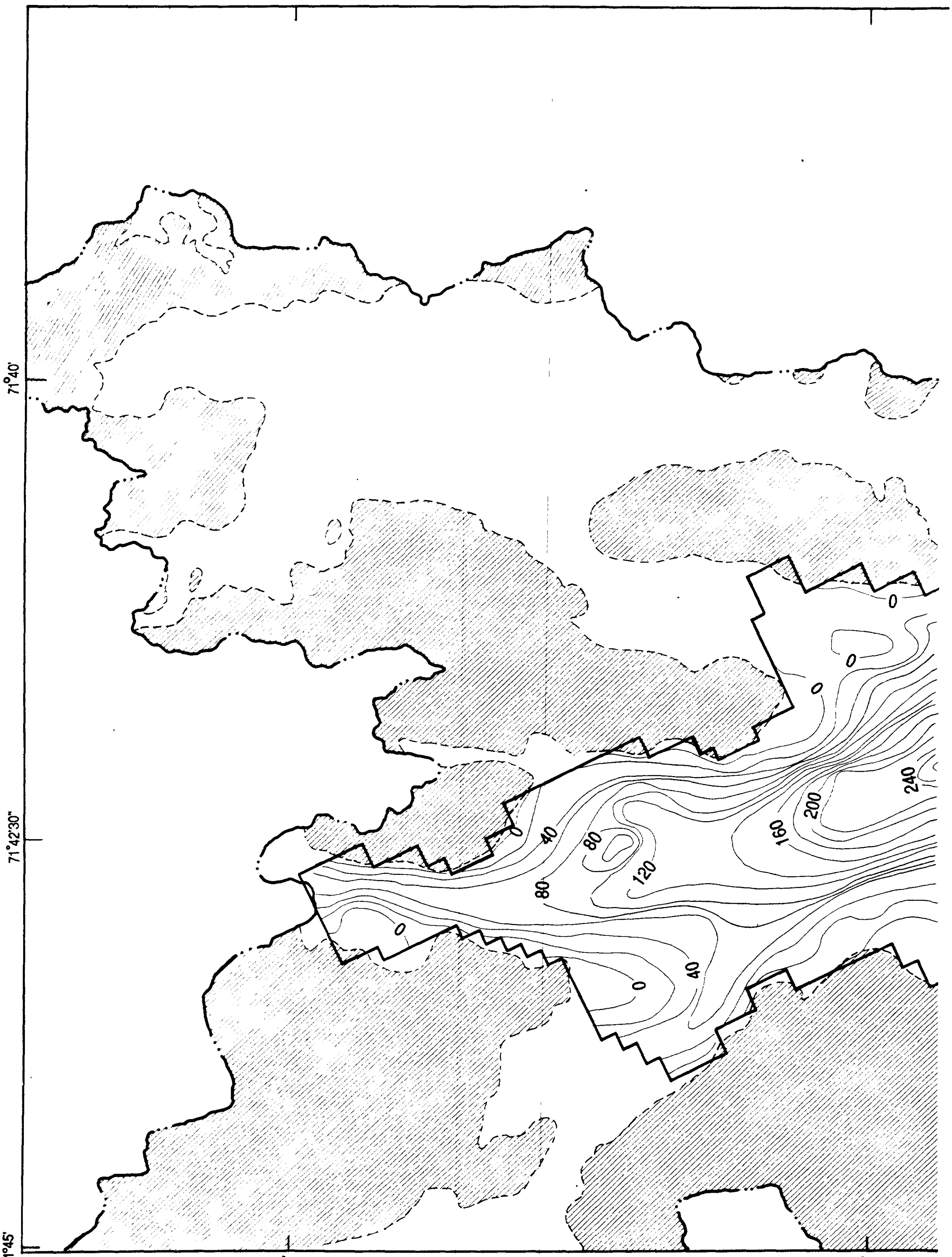


Figure 8.--Generalized geologic section (F-F') south of the Pawcatuck River.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71°42'30"
71°45'
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0
40
80
120
160
200
240

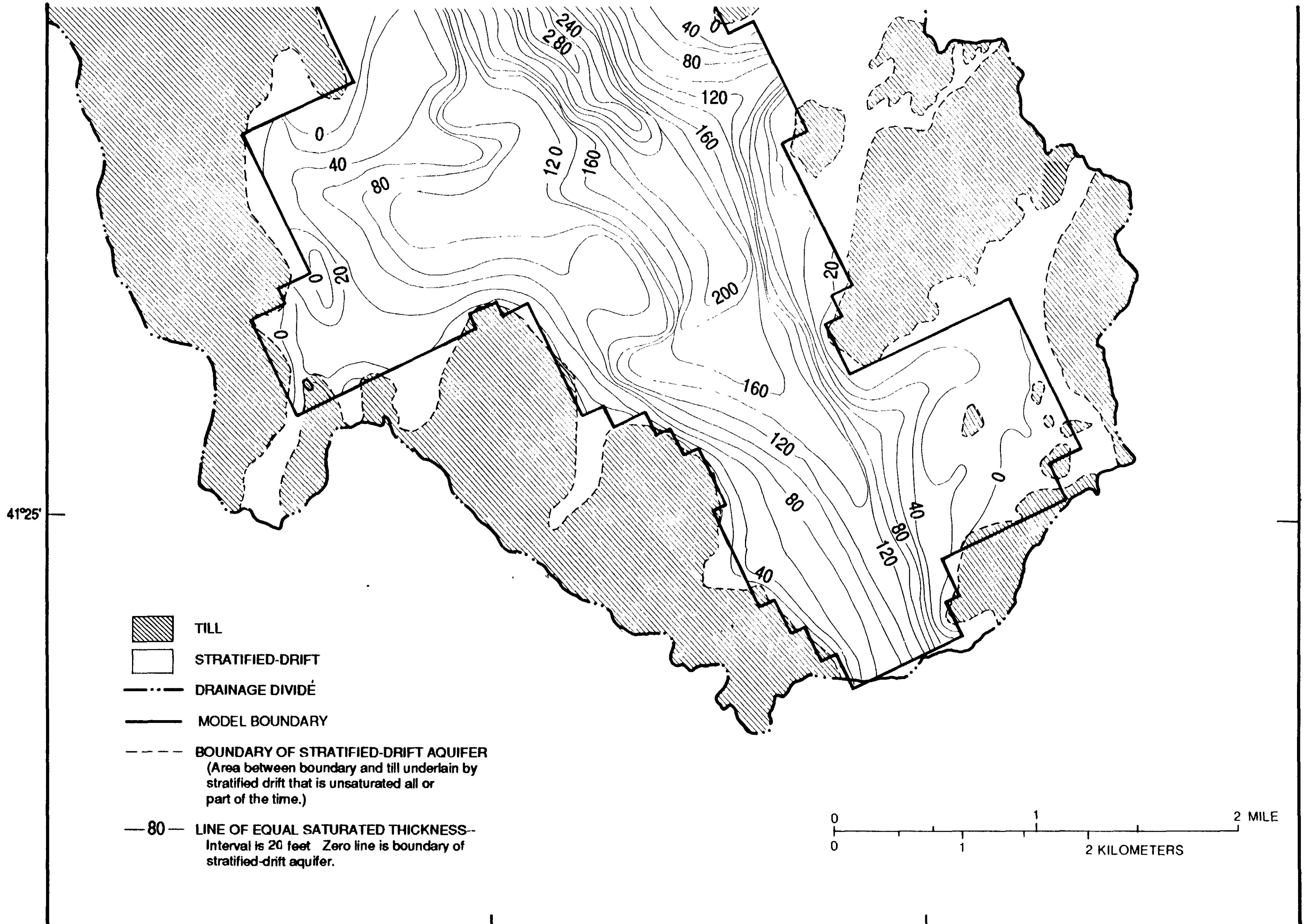


Figure 9.--Saturated thickness in the stratified-drift aquifer in the lower Wood River gound-water reservoir.

synonymous with runoff[3]; it is the water remaining on an area after **evapotranspiration** has returned to the atmosphere a substantial part of the precipitation. This surplus water is potentially available to recharge ground water in aquifers (Lyford and Cohen, 1988). Water potentially available for recharge in the lower Wood River aquifer comes principally from three sources: (1) infiltration of precipitation that falls directly on the stratified drift, (2) lateral inflow from till/bedrock uplands, and (3) leakage from streams.

Precipitation on the Stratified Drift

Under natural conditions, the primary source of water available to recharge the aquifer is precipitation directly on the stratified drift. Most of the rain and snowmelt in areas of sand and gravel, like the lower Wood River valley, infiltrates the soil and recharges the aquifer. Surface runoff is probably negligible in most areas underlain by sand and gravel (Pluhowski and Kantrowitz, 1964).

"The volume of water available annually for recharge generally is equal to annual runoff (precipitation minus evapotranspiration). Water available for recharge is almost another name for runoff; it is the water left over after evapotranspiration has returned to the atmosphere a substantial fraction of the precipitation on an area. This surplus water is potentially available to recharge ground water in earth materials (Lyford and Cohen, 1988)."

For purposes of this report, surplus water available for **ground-water recharge** was assumed equal to long-term average annual runoff. The estimate of surplus water that recharges the aquifer is based on long-term average runoff (27 inches) for the 1941-1976 period. This estimate was derived using data from **continuous-record gaging stations** on the Wood and Pawcatuck Rivers. Of the 45.5 in. of long-term average annual rainfall at Kingston, 27 in. reaches the water table as recharge, and the rest (18.5 in.) is returned to the atmosphere by evapotranspiration.

Lateral Inflow from the Till/Bedrock Uplands

The lower Wood River valley is bordered by till/bedrock uplands where surficial deposits consist largely of materials with low hydraulic conductivity (fine sand, silt, and clay). These low-permeability materials restrict the amount of rain and snowmelt that can infiltrate the soil. Water that falls as pre-

[3] Floods constitute a very small percent of annual runoff in the Wood River area.

cipitation on the uplands recharges the stratified-drift aquifer in two ways. Precipitation that does not infiltrate soils in upland areas flows overland and downslope until it reaches the valley floor, where it infiltrates the stratified drift and becomes recharge. Secondly, precipitation that does infiltrate till/bedrock uplands becomes ground water that moves downgradient laterally through the till and bedrock toward the valley floor, where it recharges the stratified drift.

Leakage from Streams

When the water level in an aquifer adjacent to a stream is lower than the water surface in the stream, water in the stream infiltrates downward into the aquifer. In the lower Wood River area, this situation occurs naturally at Meadow Brook Pond and along the lower reaches of Meadow Brook, and may also occur where small streams draining till/bedrock uplands enter the valley floor. Infiltration of stream water also can be induced along stream reaches that do not lose water naturally if water levels in the aquifer near the stream are lowered sufficiently by pumping. **Induced infiltration** of streamflow and the factors governing it are explained in more detail in the "stream-aquifer interconnection" section of this report.

Hydraulic Properties

Transmissivity and **specific yield** are the hydraulic properties that determine the capacity of an aquifer to transmit, store, and yield water. The product of the horizontal **hydraulic conductivity** and saturated thickness of the aquifer equals transmissivity. Also important to the water-yielding potential of the aquifer is the vertical hydraulic conductivity of the streambed or aquifer, whichever is smaller.

The stratified-drift aquifer is, hydraulically, anisotropic because the vertical and horizontal hydraulic conductivities differ. The **anisotropy** is due, in part, to the interbedding of coarser and finer materials and in part to the horizontal orientation of the plate-shaped fine grains. This causes the hydraulic conductivity of the aquifer to be lower in the vertical direction. The ratio of vertical to horizontal hydraulic conductivity of the stratified-drift aquifer ranges from 1:2 to 1:45, with an average of 1:6. It is the smaller vertical hydraulic conductivity of either the streambed or aquifer that affects the rate at which water moves from the stream into the aquifer and toward the well screen as induced infiltration during pumping.

Detailed **lithologic logs** of 189 wells and test holes and drawdown/recovery data for twelve aquifer tests obtained primarily between August 1976 and September 1977 were analyzed to determine aquifer hydraulic properties.

Partial penetration is accounted for when determining aquifer hydraulic properties using method 1, by choosing the proper type curve for the solution. The type curve depends on the amount of aquifer penetrated by the pumping well and the depth at which each observation well is open to the aquifer.

The hydraulic properties of the stratified-drift aquifer were determined from analyses of unadjusted **drawdown** and **recovery** data from aquifer tests by one or more of the following methods: (1) Stallman (1963, 1965) method for vertical movement in an unconfined, anisotropic aquifer, and (2) Cooper and Jacob (1946) method for graphical solution to the modified nonleaky confined formula. Method 1 is described in Lohman (1979, p. 34-38), and method 2 is described in Walton (1962, p. 9). Assumptions inherent in each analytical method are summarized in table 2.

Estimates of transmissivity also were made from lithologic logs as an additional means of checking hydraulic properties obtained by analysis of aquifer-test data. The method used to estimate transmissivities from lithologic logs in this study was also used in the Chipuxet River basin in southern Rhode Island and is explained in Dickerman (1984, p. 7-9). Table 3 summarizes well-construction and aquifer-test data, transmissivity estimates, methods of data analysis, and results of analyses.

Aquifer tests were made in the thick, permeable parts of the stratified drift. In each of the tests, large-diameter (8- to 24-in. diameter) wells were pumped at constant rates ranging from 327 to 700 gal/min for 8 to 48 hours. Depth to the water table at test sites ranged from 7.6 to 28.8 ft below land surface before the aquifer tests. Pumped wells ranged in depth from 75 to 160 ft, and 15 to 25 ft of screen were exposed near the bottom of each well. The transmissivity of the stratified-drift aquifer (fig. 10) determined from these tests ranges from 8,600 to 36,400 ft^2/d, and averages 22,300 ft^2/d. Horizontal hydraulic conductivity ranges from 125 to 545 ft/d and averages 250 ft/d; vertical hydraulic conductivity ranges from 4 to 210 ft/d, and averages 42 ft/d.

Within the lower Wood River valley, the highest transmissivity was determined from an aquifer test at 8-in.-diameter test well RIW 510. Transmissivity of the aquifer at this site, computed by different analytical methods (table 3), ranges from 25,300 to 35,500 ft^2/d, and averages 31,200 ft^2/d. Estimated horizontal hydraulic conductivity of the aquifer at this site ranges from 240 to 395 ft/d, and averages 315 ft/d. Computed vertical hydraulic conductivity ranges from 43 to 130 ft/d, and averages 65 ft/d.

The lowest transmissivity in the lower Wood River valley was determined from an aquifer test at 8-in.-diameter test well RIW 550. Transmissivity of the aquifer at this site, ranges from

Table 2.--Assumptions on which equations used to analyze aquifer-test data in the lower Wood River ground-water reservoir are based.

[x, condition treated in this report; adopted from Stallman, 1971]

Assumption	Stallman (1963, 1965)		Cooper and Jacob (1946)
A. Control-well characteristics:			
Full penetration	x		x
Partial penetration	x		
Diameter infinitesimal			x
Diameter finite	x		
B. Conductivity and flow conditions:			
Homogeneous, isotropic	x		x
Homogeneous, anisotropic	x		
Areally infinite	x		x
Dewatering negligible	x		x
Flow radial			x
Flow radial and vertical	x		
Nonsteady flow	x		x
Horizontal flow in aquifer	x		x
C. Storage relation:			
Water released from storage instantaneously	x		x
Confined (artesian)			x
Unconfined (water table)	x		

Table 3.--Summary of hydraulic properties determined from aquifer tests

[in., inches; ft, feet; hrs, hours; gal/min, gallons per minute;

Pumped well[1]	Well construction and pump test data for pumped well								Transmissivity estimated from litho-logic log (ft^2/d)
	Diameter[2] (in.)	Screened interval[3,4] (ft)	Static water level[4] (ft)	Date of aquifer test	Length of test (hrs)	Pumping rate (gal/min)	Draw-down (ft)	Specific capacity (gal/min) /ft)	
TOWN OF CHARLESTOWN									
351	24 x 18	60- 75	13.00	10-14-63	8	700	24.25	29	8,500
TOWN OF RICHMOND									
423	8	105-120	13.33	08-04-76	48	575	58.67	10	15,700
434	8	86-101	11.37	08-25-76	48	588	28.82	20	13,200
442	8	111-126	10.16	09-13-76	48	627	48.38	13	16,500
458	8	84-104	28.77	10-04-76	48	560	35.76	16	10,000
481	8	99-114	8.45	11-01-76	48	620	20.49	30	20,850
500	8	85-100	8.56	12-13-76	48	415	57.59	7	12,100

for the stratified-drift aquifer in the lower Wood ground-water reservoir.
gal/min/ft, gallons per minute per foot; ft²/d, square feet per day; ft/d, feet per day]

Method[5]	Observation well no.[1,6]	Distance from pumped well (ft)	Transmissivity (ft^2/d)	Hydraulic conductivity: Horizontal[7] (ft/d)	Hydraulic conductivity: Vertical (ft/d)	Storage coefficient[8]	Pumped well[1]
				Hydraulic properties determined by analytical methods			
			TOWN OF CHARLESTOWN				
--	--	--	--	135	--	--	351
			TOWN OF RICHMOND				
a	426	94	13,800	185	13	0.13	423
a	427	175	20,500	275	24	.34	
a	428	316	27,700	315	12	.10	
a	429	655	15,800	210	5	.05	
a	Composite plot of wells 426-429	do.	20,500	275	--	.30	
b	Composite plot of wells 424,426,427, 429	4,94,175, 655	17,000	245	--	.06	
		site average	19,200	250	14	.16	
a	437	25	16,200	180	--	--	434
a	438	175	18,900	210	27	.10	
a	441	412	16,200	180	4	.03	
b	Composite plot of wells 437,438,441, 430	25,175,412, 1858	22,100	245	--	.02	
		site average	18,350	205	16	.05	
a	444	35	18,900	180	38	.15	442
a	447	152	24,100	240	50	.06	
a	451	293	24,100	265	55	.08	
a	448	502	19,500	255	13	.04	
a	452	758	18,300	130	9	.02	
a	453	924	17,200	125	6	.02	
a	468	1151	17,200	135	4	.02	
a	Composite plot of wells 444,447,451,448, 452,453,468	do.	19,500	175	25	.05	
b	Composite plot of wells 444,447, 452	35,152, 758	20,100	180	--	--	
		site average	19,900	185	25	.06	
a	461	35	23,400	310	34	.13	458
a	462	152	32,700	435	52	.16	
a	463	157	32,200	430	210	.14	
a	464	352	32,700	435	190	.18	
b	Composite plot of wells 463,464,465	157,352,791	28,200	376	--	.14	
		site average	30,250	400	120	.15	
a	485	30	23,900	230	69	.34	481
a	487	101	23,900	230	28	.12	
a	489	200	29,800	285	20	.16	
a	Composite plot of wells 485,487, 489,490	30,101, 200,971	27,100	260	--	.12	
b	Composite plot of wells 485,487,489	30,101,200	16,800	160	--	.15	
		site average	24,300	235	40	.18	
a	502	29	27,500	305	15	.07	500
a	504	150	30,700	340	58	.19	
a	505	921	31,950	355	8	.17	
a	509	923	31,950	355	8	.16	
a	Composite plot of wells 502,504,489, 505,509	29,150,779, 921,923	31,200	345	--	.15	
b b	Composite plot of wells 504,489, 505,509, 483,492	150,779, 921,923, 971,1235	27,900	310	--	.10	
		site average	30,200	335	22	.14	

Table 3.--Summary of hydraulic properties determined from aquifer tests

[in., inches; ft, feet; hrs, hours; gal/min, gallons per minute;

Pumped well[1]	Well construction and pump test data for pumped well								Transmissivity estimated from
	Diameter[2] (in.)	Screened Interval[3,4] (ft)	Static water level[4] (ft)	Date of aquifer test	Length of test (hrs)	Pumping rate (gal/min)	Draw-down (ft)	Specific capacity (gal/min) /ft)	Litho-logic log (ft^2/d)
TOWN OF RICHMOND -- Continued									
510	8	105-120	10.66	11-17-76	48	645	65.83	10	19,000
550	8	65-85	15.45	08-09-77	48	347	27.51	13	11,500
567	8	140-160	23.16	06-27-77	48	590	29.40	20	19,700
576	8	66-91	13.96	09-06-77	48	568	29.14	19	11,450
583	8	55-80	7.57	07-13-77	48	327	28.33	12	7,500

1 Local well number based on the town in which it is located. See figure 2 for location of pumping well.

2 The smaller number or single number is the diameter of the well casing and screen, and the larger number is the diameter of the drilled hole. The space between the drilled hole and screen is filled with a highly permeable material, called the gravel pack.

3 Bottom of screened interval is well depth.

4 Feet below land-surface datum.

for the stratified-drift aquifer in the lower Wood ground-water reservoir -- Continued

gal/min/ft, gallons per minute per foot; ft^2/d, square feet per day; ft/d, feet per day; --, no data available]

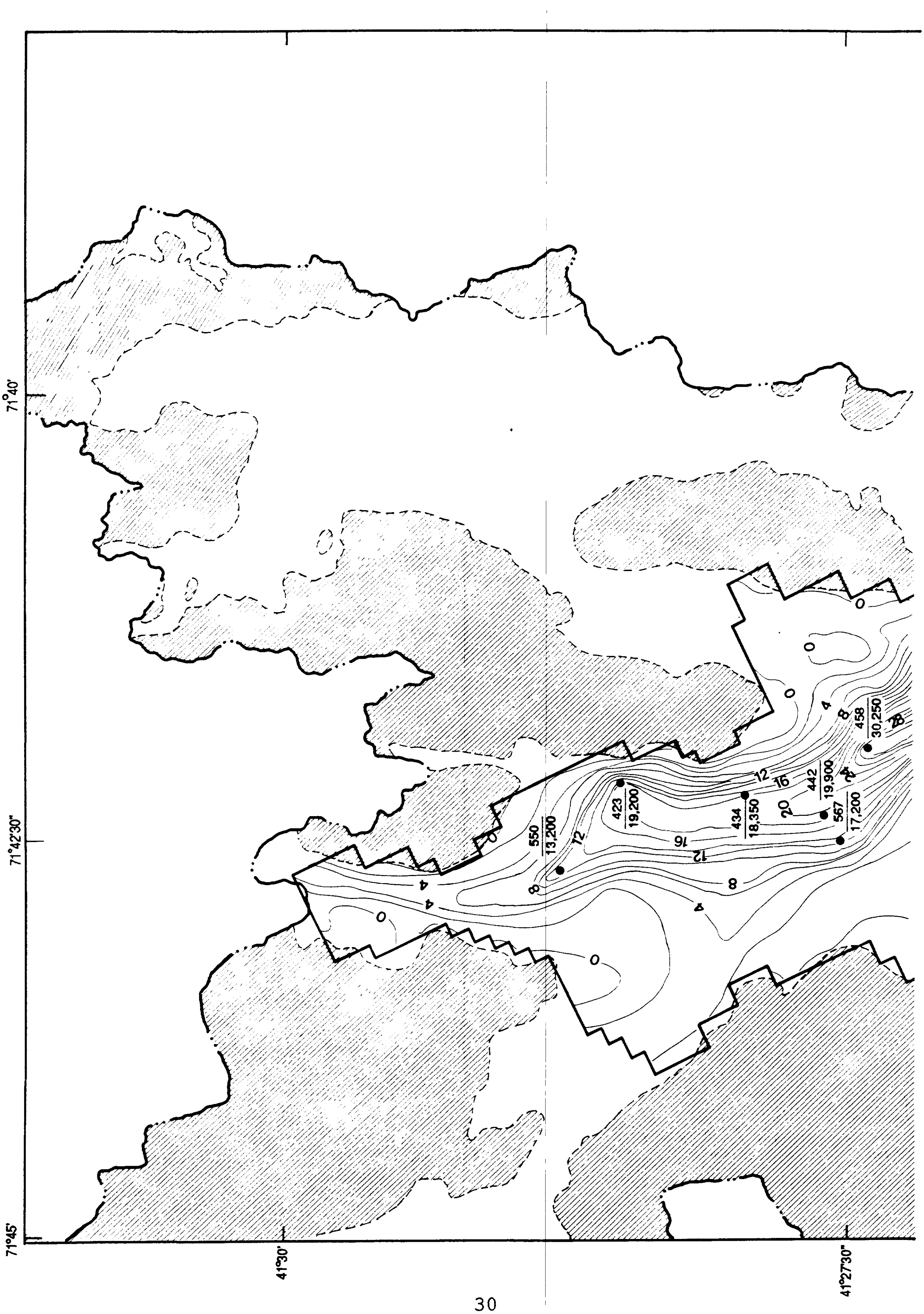
Method[5]	Observation well no.[1,6]	Distance from pumped well (ft)	Transmissivity (ft^2/d)	Hydraulic conductivity: Horizontal[7] (ft/d)	Hydraulic conductivity: Vertical (ft/d)	Storage coefficient[8]	Pumped well1
			TOWN OF RICHMOND -- Continued				
a	513	20	29,600	270	43	0.15	510
a	515	48	31,000	345	130	.19	
a	517	76	35,500	395	60	.11	
a	519	146	33,560	370	67	.28	
a	332	363	31,000	300	53	.11	
a	492	437	31,000	240	45	.18	
a	Composite plot of wells 515,517, 519,332, 492	48,76, 146,363, 437	32,700	330	--	.18	
b	do.	do.	25,300	255	--	.11	
		site average	31,200	315	65	.16	
a	557	34	12,100	175	18	.02	550
a	553	54	14,500	205	8	.04	
a	559	99	13,400	190	10	.02	
a	555	209	13,400	190	45	.03	
a	564	389	14,500	205	14	.02	
a	562	407	16,700	240	15	.02	
a	Composite plot of wells 557,553, 559,555, 564,562	34,54, 99,209, 389,407	12,400	175	--	.05	
b	do.	do.	8,600	125	--	.08	
		site average	13,200	190	18	.04	
a	572	19	14,900	115	--	.29	567
a	570	67	16,700	135	50	.10	
a	568	163	18,900	150	10	.04	
a	574	247	16,200	130	16	.04	
a	Composite plot of wells 572,570, 568,574	19,67, 163,247	16,700	130	--	.10	
b	do.	do.	19,600	155	--	.04	
		site average	17,200	135	25	.10	
a	579	20	18,200	270	70	.32	576
a	580	62	30,400	455	55	.09	
a	582	74	27,300	405	85	.12	
a	581	149	36,400	545	55	.13	
a	Composite plot of wells 579,580, 582,581, 325	20,62, 74,149, 850	27,300	405	--	.16	
b	Composite plot of wells 581,325	149,850	28,600	425	--	.10	
		site average	28,000	420	65	.15	
a	586	34	15,700	185	30	.14	583
a	588	54	15,400	225	40	.17	
a	587	102	13,700	195	45	.33	
a	589	189	13,100	195	55	.28	
a	590	357	12,800	185	70	.18	
a	Composite plot of wells 586,588,587, 589,590	34,54,102, 189,357	14,300	205	--	.27	
b	Composite plot of wells 586,588, 587,589, 590,330	34, 54, 102,189, 357,1000	12,600	180	--	.31	
		site average	13,900	195	50	.24	

5 (a) Vertical movement (Stallman, 1963, 1965) described in Lohman (1979) p. 34-38; and (b) modified nonleaky confined (Cooper and Jacob, 1946), described in Walton (1962), p. 9.

6 Well or wells used in analysis.

7 Determined by dividing transmissivity by distance from static water level to bottom of screen in pumped well.

8 Most values smaller than 0.12 are not indicative of the true storage coefficient of the aquifer. Values greater than 0.12 are believed to approach the true storage coefficient (specific yield) of the stratified-drift aquifer in the lower Wood River ground-water reservoir.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30,250

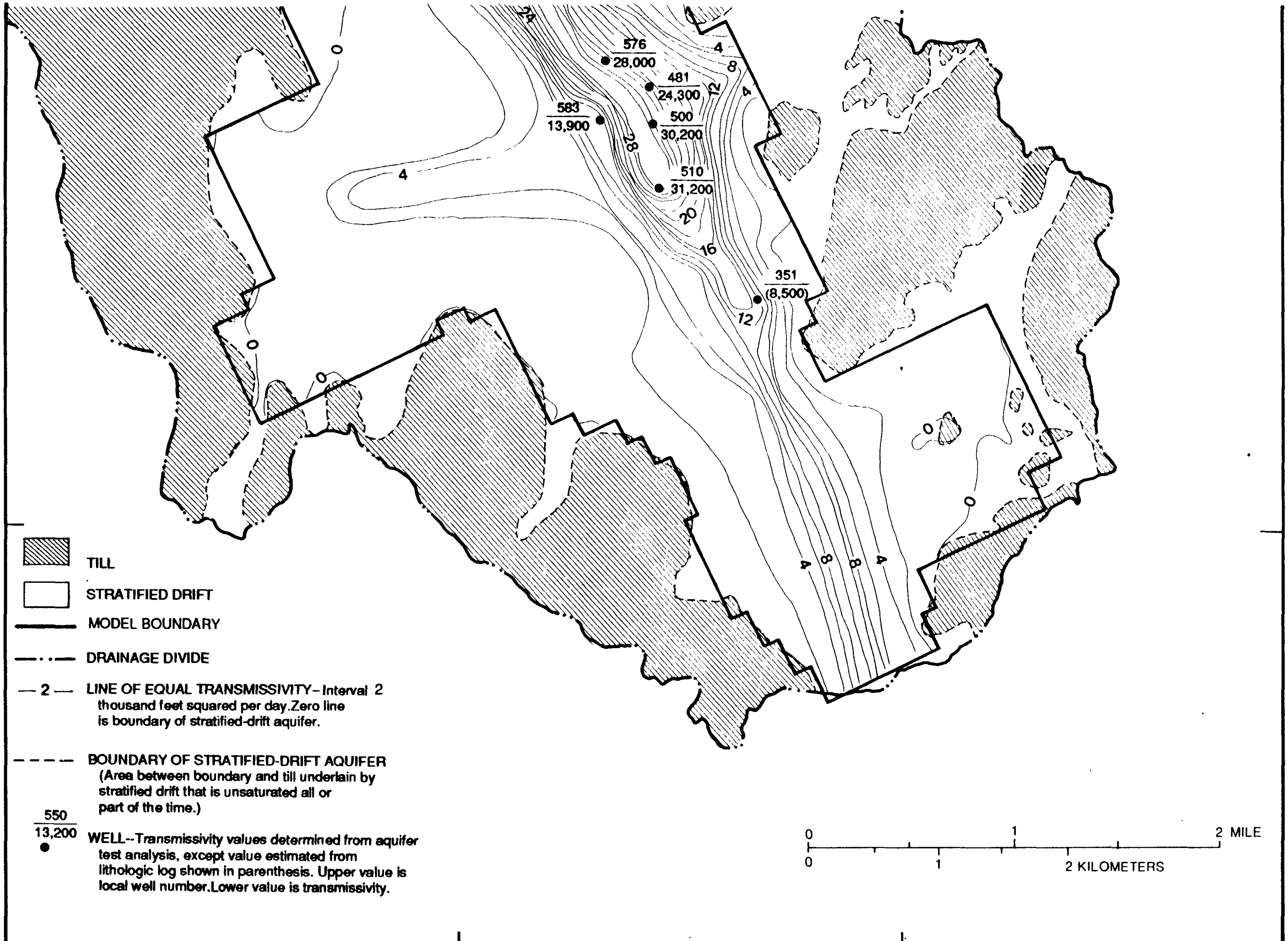


Figure 10.--Transmissivity in the stratified-drift aquifer in the lower Wood River ground-water reservoir.

8,600 to 16,700 ft^2/d, and averages 13,200 ft^2/d. Estimated horizontal hydraulic conductivity ranges from 125 to 240 ft/d,and averages 190 ft/d. Computed vertical hydraulic conductivity ranges from 8 to 45 ft/d, and averages 18 ft/d.

Storage coefficients were also determined by analysis of aquifer test data and results are shown in table 3. The **storage coefficient** in a **water-table aquifer** is virtually equal to the specific yield (Lohman and others, 1972, p. 13). In water-table aquifers, the storage coefficient or specific yield generally ranges from about 0.05 to 0.30 (Ferris and others, 1962, p. 78).

Most storage coefficient values in table 3 which are smaller than 0.12 were determined from early drawdown data and are not indicative of the true storage coefficient of the stratified-drift aquifer. Williams and Lohman (1949, p. 213, 220) state that the true value of specific yield is obtained onlyafter the saturated material has been drained for a sufficient amount of time for equilibrium in the aquifer near the well to be established. They conclude that 2 months to more than 1 year would be required for the drainage to reach equilibrium in sand-size materials.

Storage coefficients shown in table 3 range from 0.02 to 0.34, and average 0.13. These values are affected by delayed yield and reflect the duration period of the test rather than the true specific yield of the aquifer. To obtain direct measurements of the maximum specific yield would probably require a longer period of observation than the relatively short time period of most aquifer tests. Therefore, on the basis of laboratory analysis of sediment samples from the nearby upper Pawcatuck River basin (Allen and others, 1963), which are similar to the sediments of the lower Wood River study area, it was assumed that the average specific yield of the stratified-drift aquifer in the lower Wood River ground-water reservoir is about 0.20.

Site averages for hydraulic properties shown in table 3 are probably higher than those for much of the stratified drift in the lower Wood River study area. This is because aquifer-test sites were located in geologically promising areas selected after extensive 2 1/2-in. exploratory test drilling. The test results and reported well yields in the report therefore indicate what may be expected from properly constructed wells that tap the stratified drift in the more productive parts of the lower Wood River ground-water reservoir.

The sites most favorable for development of high-capacity wells (350 gal/min or more) based on aquifer testing completed to date, are located between the Wood River and Meadow Brook in the area known as Ellis Flats, or along the eastern side of Meadow Brook (fig. 10).

Stream-Aquifer Interconnection

Under natural conditions, the water-table gradient normally slopes toward the river (fig. 2), and ground water discharges from the stratified drift into the river (gaining stream). Most streams in the study area are **gaining streams** receiving ground-water discharge. However, some streams may lose water to the aquifer under natural conditions because the water level in the aquifer is below the stream level (**losing stream**). In the lower Wood River study area, Meadow Brook, south of Pine Hill Road, and Meadow Brook Pond naturally lose water to the stratified-drift aquifer. Under pumping conditions the water-table gradient to the stream decreases and **ground-water runoff** to a gaining stream is reduced. If pumping is of sufficient volume and duration, the **hydraulic gradient** may be reversed, causing water from the stream to move by induced infiltration through the streambed into the stratified-drift aquifer.

The amount of water induced to flow from streams to wells is governed by the vertical hydraulic conductivity of the streambed and underlying aquifer, streambed thickness, area of streambed through which infiltration occurs, viscosity of the water which is dependent upon the water temperature, average **head** difference between the stream and aquifer within the streambed area of infiltration, and quantity of water in the stream.

The beds of the Wood and Pawcatuck Rivers and Meadow Brook are generally composed of loosely packed sand and gravel, except in ponded and swampy areas. These loosely packed streambed materials were assumed to have a higher vertical hydraulic conductivity than that of the underlying stratified-drift aquifer, which typically contains layers of fine silt or silty sand. Based on this assumption, the average vertical hydraulic conductivity of the underlying aquifer was assumed to be the effective streambed hydraulic conductivity.

The effective streambed hydraulic conductivity controls the rate at which water will move from a stream to a well in the aquifer. It is equal to the minimum of either the streambed vertical hydraulic conductivity or the aquifer vertical hydraulic conductivity. The vertical hydraulic conductivity of the stratified-drift aquifer was determined from data collected during controlled aquifer tests at two sites along the Wood River and three sites along Meadow Brook. Values of vertical hydraulic conductivity at these sites ranged from 8 to 130 ft/d, with a median of 24 ft/d.

If stream reaches are to maintain some flow at all times, then the quantity of streamflow during low-flow periods limits the amount of water available for **induced recharge** to the stratified-drift aquifer. For this study, the flow equaled or exceeded 99 percent of the time was considered the index of streamflow available for induced recharge to the aquifer. The combined 99-percent flow duration entering the study area by way of the Wood and Pawcatuck Rivers is 31 Mgal/d.

Water-Bearing Characteristics of Bedrock and Till

Bedrock and till are capable of yielding usable quantities of water to wells and, therefore, constitute aquifers. The bedrock aquifer should yield at least a small quantity of water to a well almost anywhere. Water-bearing fractures in the bedrock decrease in size and frequency with depth and become sparse below 300 ft. Reported yields of wells in these bedrock units range from 1 to 10 gal/min, with a median yield of 4 gal/min (Dickerman and Silva, 1980, table 1). Data from bedrock wells reported by Dickerman and Silva (1980) show that well depths ranged from 15 to 665 ft, with a median depth of 98 ft.

Although till is usually a poor water-bearing material, it does constitute an aquifer capable of yielding small but sometimes unreliable supplies for domestic and agricultural use. Generally, till does not yield more than 5 gal/min to large-diameter wells (Bierschenk and Hahn, 1959; LaSala and Hahn, 1960). Wells in till typically go dry during drought periods and may go dry annually during late summer or early fall.

WATER QUALITY

Water in the lower Wood River study area is soft and slightly acidic, and typically has a concentration of less than 100 mg/L (**milligrams per liter**) of **dissolved solids.** Table 4 summarizes chemical and physical properties of ground water and surface water in the study area, based on data published by Dickerman and Silva (1980). Some additional data are available in annual data reports of the U.S. Geological Survey. Median values for most common chemical constituents and physical properties are below the Maximum Contaminant Levels (MCL's) for drinking water (table 4). There are some areas where water quality has been degraded.

Surface Water

The drainage areas of stream reaches in the study area are relatively undeveloped. There is some industrial development along the Wood and Pawcatuck Rivers. Agricultural and forested land predominates within the study area.

Table 4.--Summary of chemical and physical properties of ground water and surface water in the lower Wood River study area.

[Values for ground water at the low-level radionuclide site are not included in this table; they are shown separately in table 8. Analyses are in milligrams per liter, except as indicated; --, no data available; uS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius]

Constituent or property	Maximum contaminant level for drinking water	Ground water				Surface water			
		Samples	Low	Median	High	Samples	Low	Median	High
Silica (SiO_2)	--	17	5.1	8.8	12	13	4.5	7.9	11
Iron (Fe)	[1] 0.3	115	.00	.12	17	13	.04	.20	.82
Manganese (Mn)	[1] .05	108	.00	.02	5.5	13	.00	.03	.09
Calcium (Ca)	--	37	2.2	4.8	25	13	2.1	2.8	4.6
Magnesium (Mg)	--	37	0.0	1.5	5.8	13	.4	.8	1.3
Sodium (Na)	--	33	3.6	5.7	25	13	2.4	3.5	9.9
Bicarbonate (HCO_3)	--	17	3	10	32	13	3	6	14
Sulfate (SO_4)	[1] 250	37	.8	14	58	13	1.4	6.3	12
Chloride (Cl)	[1] 250	108	3.0	10	69	13	3.1	5.6	11
Fluoride (F)	[2] 2.0	43	.0	.1	1.4	13	.0	.2	.4
Nitrate (NO_3) as N	[2,3] 10	108	.00	.02	16	13	.09	.16	.38
Nitrite (NO_2) as N	--	20	.00	.00	.04	--	--	--	--
Ammonia Nitrogen as N	--	22	.00	.04	.40	--	--	--	--
Total solids (residue at 105°C)	[1] 500	22	32	76	250	--	--	--	--
Dissolved solids (residue at 180°C)	[1] 500	5	36	54	100	13	31	38	74
Dissolved oxygen	--	40	.0	4.0	11.4	--	--	--	--
Hardness as ($CaCO_3$)	--	31	8	22	84	13	8	10	17
Alkalinity as ($CaCO_3$)	--	40	2	10	65	8	2	4	7
Specific conductance (uS/cm at 25°C)	--	191	26	68	500	37	33	94	145
pH (Units)	[1] 6.5-8.5	39	5.1	5.8	7.2	13	5.5	5.7	6.5
Color (Platinum cobalt units)	[1] 15	35	0	0	30	13	8	28	140
Temperature (°C)	--	175	5.0	10	28	36	.5	12	24
MBAS[4]	[1] .5	14	.00	.01	.08	--	--	--	--

1 Secondary maximum contaminant level established for public water systems by the U.S. Environmental Protection Agency (1979).

2 Maximum contaminant level for inorganic chemicals established for public water systems by the Rhode Island Department of Health, Division of Water Supply (1977).

3 Maximum contaminant level for inorganic chemicals established for public water-supply systems by the U.S. Environmental Protection Agency (1975).

4 Detergents as methylene-blue-active substance (MBAS).

The chemical and physical properties of surface water sampled between 1953 and 1977 are summarized in table 4 (Dickerman and Silva, 1980). Nineteen sites were sampled from one to three times each. An additional site, the Wood River at Hope Valley, was sampled 12 times. Sampling sites are shown in figure 11.

Continuous records of specific conductance and water temperature were collected at the U.S. Geological Survey gaging station on the Wood River at Hope Valley during water years 1978-85 (U.S. Geological Survey). Water temperature during this period ranged from 0.0 °C (degrees Celsius) to 28.0 °C and averaged 11.6 °C. Specific conductance, a measure of the electrical conductivity of a solution, provides a general indication of the concentration of dissolved ions in water. From October 1977 through September 1985, specific conductance ranged from 21 to 244 uS/cm (microsiemens per centimeter at 25 degrees Celsius), and averaged 66 uS/cm. These values indicate generally low concentrations of dissolved constituents.

Maximum values shown in table 4 for color and concentrations of fluoride, silica, dissolved solids, nitrate, iron, and manganese were all obtained for samples collected from Cedar Swamp Brook in October 1967. Cedar Swamp Brook drains Indian Cedar Swamp, a large wetland at the southern end of the study area (fig. 11). Decaying vegetation in contact with surface water may be partly responsible for the high values of color and concentrations of nitrate, iron, and manganese.

Ground Water

The natural quality of ground water is influenced by the composition of the soils and rocks through which it moves. In the lower Wood River study area, the bedrock and overlying glacial deposits and soils are composed chiefly of relatively insoluble silicate minerals. As a result, uncontaminated ground water contains low concentrations of dissolved minerals. The low to median concentrations of naturally occurring constituents shown in table 4 are believed to be representative of relatively uncontaminated ground water in the study area. The high concentrations are generally associated with contaminated ground water.

Water-quality data summarized in table 4 are based on samplings of 171 wells in the town of Richmond and 2 wells in the town of Hopkinton (Dickerman and Silva, 1980). Of these, 158 wells were sampled once; 10 wells, 2 to 3 times; and 5 wells, 8 to 9 times. Sampling dates range from 1953-77; most samples were collected from 1974-77. All of the wells sampled are located in the stratified-drift aquifer.

Major ground-water-quality problems in the study area are discussed in the following sections.

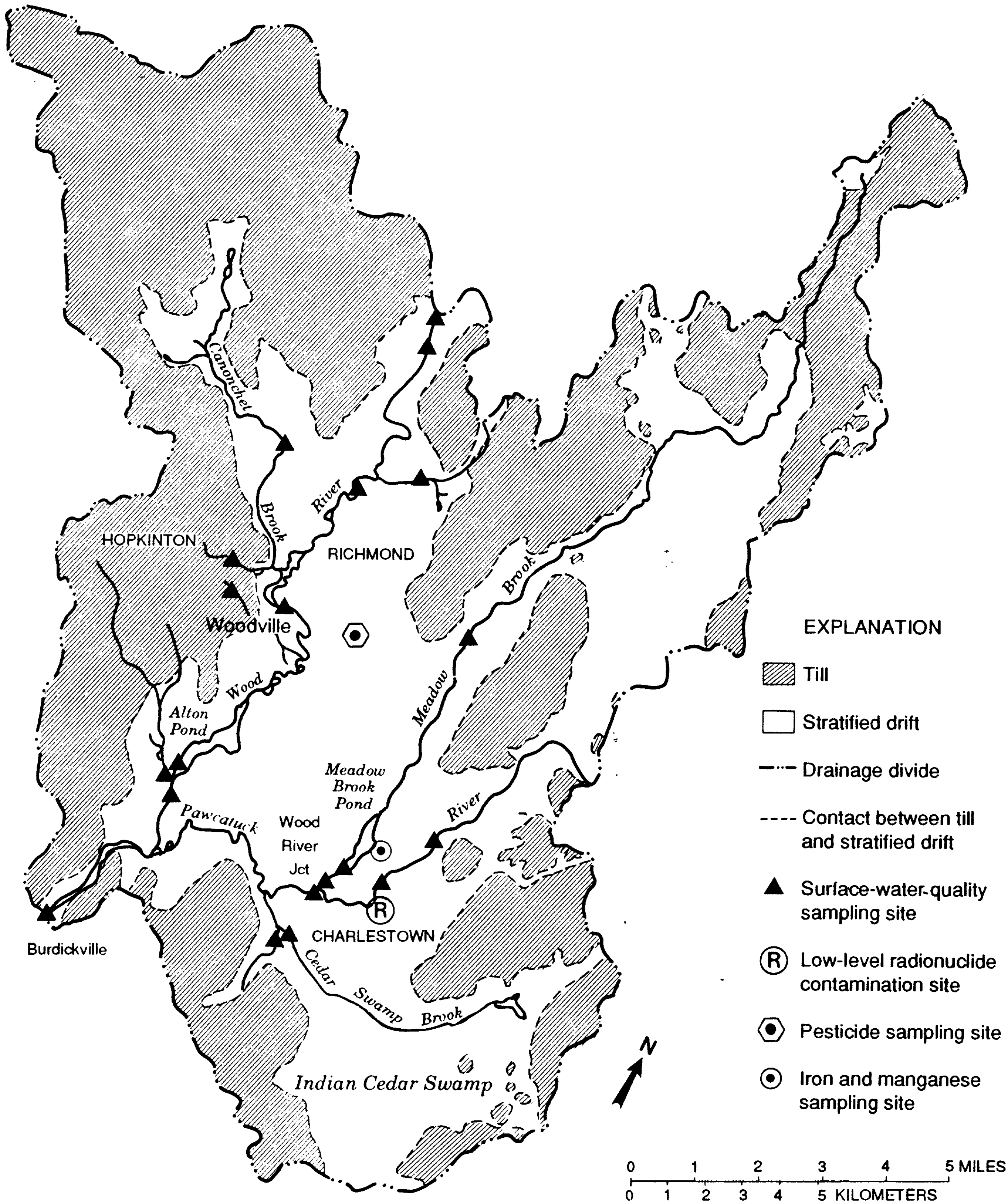


Figure 11.--Map of Lower Wood River study area showing major water quality sampling sites.

Iron and Manganese

Concentrations of iron and manganese in the study area are generally below the MCL's established for drinking water by the U.S. Environmental Protection Agency (USEPA) (table 4). However, both metals are present locally in concentrations above these levels. Excessive levels of these constituents may be derived from natural sources, human activities, or both. Although iron and manganese are essential elements for plant and animal life, at high concentrations they are undesirable impurities in domestic and industrial water supplies because of the red and black stains that they deposit on laundry and plumbing fixtures.

High concentrations of iron and manganese have been measured in ground water at an aquifer test site east of Meadow Brook Pond (fig. 11). A manganese concentration of 1.47 mg/L was measured in water withdrawn from test well RIW 510 during an aquifer test in November 1976 (Dickerman and Silva, 1980, p. 181-182). This finding prompted additional water-quality sampling at the site. Following completion of the aquifer test, two shallow and two deep observation wells were installed. Aquifer-test wells RIW 515, 516, 517, and 518 were rescreened with PVC (polyvinyl chloride) casing and renumbered as RIW 535, 536, 537, and 538, respectively (fig. 2), for water-quality monitoring purposes. Well locations are shown in Dickerman and Silva (1980). These four wells were monitored intermittently during 1976 and 1977 for selected constituents and physical properties (Dickerman and Silva, 1980, p. 181-184). A summary of values obtained for specific conductance and concentrations of dissolved oxygen, iron, and manganese is shown in table 5. Four to eight samples from each well were analyzed for each constituent.

Median values of manganese in water from the two shallow wells (RIW 536 and 538) are approximately double the median values for manganese in ground water for the whole study area (tables 4 and 5). The median values for iron in water from the shallow wells are below the maximum limit for drinking water. The median values for manganese equal or slightly exceed the drinking water limit (tables 4 and 5).

Concentrations of iron and manganese in water from the two deep wells (RIW 535 and 537) are significantly higher than in water from the two shallow wells at this site and from the study area as a whole (tables 4 and 5). Median values of iron and manganese for the two deep wells exceed median values for the study area by one to two orders of magnitude, and substantially exceed the MCL's for drinking water for these two constituents.

Table 5.--Ranges of dissolved oxygen, specific conductance, iron, and manganese in ground water at aquifer test site RIW 510 near Wood River Junction, R. I., 1976-77.

[ft, feet; mg/L, milligrams per liter; uS/cm at 25° C, microsiemens per centimeter at 25 degrees Celsius; <, less than]

Local well number	**RIW 536**	**RIW 538**	**RIW 535**	**RIW 537**
Depth to top of screen (ft)	18.0	18.0	86.0	70.0
Dissolved oxygen (mg/L)				
Samples	4	5	4	5
Low	.1	.2	.0	.0
Median	.4	.8	.0	.0
High	3.8	3.3	.0	4.1
Specific conductance (uS/cm at 25°C)				
Samples	5	6	5	6
Low	48	44	68	70
Median	<50	<50	78	82
High	64	68	105	99
Iron (mg/L)				
Samples	7	8	7	8
Low	.03	.13	14	.00
Median	.06	.22	15	12.9
High	.40	.45	17	15
Manganese (mg/L)				
Samples	6	7	6	7
Low	.04	.05	.42	.35
Median	.06	.05	.46	.39
High	.13	.11	.48	2.11

Specific conductance values for water from the two shallow wells are generally lower than the median value for the whole study area. The specific conductance of water from the two deep wells generally exceeds the median value for the study area (tables 4 and 5). The higher specific conductance values for the two deep wells reflect the higher concentration of dissolved minerals in this zone of the aquifer (table 5).

Residence time of water in the ground may affect iron and manganese concentrations. Water from the deeper wells may have been in contact with aquifer materials longer than water from shallower wells. The relatively slow weathering reactions of silicates may have proceeded further, thereby increasing dissolved ion concentrations.

The presence of high iron and manganese concentrations in water from the two deep wells is related to the absence of dissolved oxygen in this zone of the aquifer. No dissolved oxygen was measured in eight out of nine samples analyzed from these two wells (table 5). Iron and manganese compounds are soluble in water without dissolved oxygen (low redox potential); conversely, they tend to precipitate out of oxygenated water (high redox potential) (Silvey and Johnston, 1977).

Dissolved oxygen in ground water comes from recharge water and from air that moves through the **unsaturated zone** (Hem, 1985, p. 155). As ground water moves along a flow path, dissolved oxygen is depleted as it reacts with buried organic matter and oxidizable minerals; conversely, dissolved-oxygen concentrations may remain high if oxidizable materials are not encountered (Hem, 1985, p. 155-156).

In a study of manganese enrichment in ground water near Thirty Acre Pond in the Chipuxet River basin, Silvey and Johnston (1977) conclude that induced infiltration of highly oxygenated surface water through organic-rich sediments on the bottom of the pond and river is responsible for the high concentrations of manganese. As the surface water passes through the organic sediments, oxygen is consumed in reactions with the organic material. The reduced infiltrate that results is then able to dissolve iron and manganese from organic matter or from iron and manganese coatings on the aquifer materials.

The physical process responsible for high iron and manganese concentrations in ground water at the Thirty Acre Pond site probably prevails at other locations in Rhode Island where a significant percentage of well water is derived from surface water that infiltrates through organic-rich sediments. Meadow Brook Pond and the lower reaches of Meadow Brook in the lower Wood River study area are losing surface-water bodies. This hydrogeologic condition may lead to oxygen depletion and result in iron and manganese enrichment in ground water at the site of test well RIW 510. No land-use or waste-disposal activities are known to contribute iron or manganese to the ground-water system in this area. The sources of these constituents appear to be naturally occurring organic sediments on the pond bottom and iron and manganese coatings on aquifer materials.

At most locations in Rhode Island where iron and manganese have reached objectionable concentrations in ground water, the concentrations of these two constituents were initially low and have risen after a period of months or years of ground-water withdrawal (Johnston, H. E., U.S. Geological Survey, oral commun., 1987). It appears likely that the water derived from stream infiltration undergoes a change in **redox potential** from oxidizing to reducing conditions. Over time, this increases the ability of the ground water to dissolve iron and manganese from aquifer materials. In the case of the Meadow Brook Pond site, however, iron and manganese concentrations were initially high. This may be because water from the stream and pond naturally infiltrates downward into the aquifer, creating conditions favorable for high concentrations of dissolved iron and manganese, independent of well pumpage.

Nitrate

Nitrogen is present in ground water chiefly in the oxidized form as nitrate (NO_3). Natural concentrations of nitrate in ground water are derived from precipitation and from decomposition of organic matter in soils. Minerals that constitute the bedrock and overlying glacial deposits in the study area do not contain nitrogen. Concentrations of nitrate (as N) in uncontaminated ground water in the Pawcatuck River basin are generally less than 0.1 mg/L (Johnston and Dickerman, 1985, p. 65). Nitrate concentrations in excess of 0.1 mg/L may be derived from artificial sources, which include industrial wastes, synthetic agricultural and lawn fertilizers, septic-tank effluent, and animal wastes. In 51 of 108 water samples analyzed for nitrate (as N), no nitrate was detected (Dickerman and Silva, 1980). The median concentration for all samples was 0.02 mg/L (Table 4).

The highest concentrations of nitrate in the study area have been measured at a low-level **radionuclide** contamination site near Wood River Junction (fig. 11). Liquid wastes including nitric acid and aluminum nitrate were discharged to artificial ponds and trenches at the site from 1966-80 (Ryan and Kipp, 1985, p. 22). While wastes were being discharged at the site, measured concentrations in the contaminant **plume** ranged from 20 to 2,200 mg/L of nitrate (as N) (Dickerman and Silva, 1980, p. 177-178). During a study conducted from 1981 to 1983, after plant processing ended and some contaminated sediments were excavated and removed, concentrations ranged from 5 to 600 mg/L (Ryan and Kipp, 1985, p. 29). Other constituents in the contaminant plume are discussed below in the section "Low-Level Radionuclides and Other Contaminants."

With the exception of the area of industrial contamination near Wood River Junction, nitrate concentrations that exceed the State and Federal MCL of 10 mg/L were measured in samples from only two other wells in the lower Wood River study area. Both of these wells are located in agricultural areas. Concentrations in 106 of 108 samples analyzed for this study were below the MCL for drinking water (Dickerman and Silva, 1980, p. 177-186).

Nitrate is transported readily by ground water and is not filtered by aquifer materials. Where ground water has been contaminated by nitrate at shallow depths, large-capacity supply wells may cause downward movement of the shallow, nitrate-degraded ground water, resulting in contamination of deeper zones within the aquifer (Johnston and Dickerman, 1985, p. 66).

Excessive concentrations of nitrate in drinking water are associated with a serious and occasionally fatal blood disorder in infants called methemoglobinemia (U.S. Environmental Protection Agency, 1977, p. 81). Nitrate processing by the immature digestive system results in an inability of the blood to transport oxygen, which may cause suffocation. The Federal MCL for drinking water has been set at 10 mg/L of nitrate (as N) (U.S. Environmental Protection Agency, 1977, p. 81-82).

Pesticides

The flat or gently rolling land surface and well-drained soil of areas underlain by stratified drift are well suited to agricultural use. There are a number of agricultural operations in the study area. A limited amount of sampling for pesticides was conducted during the present study, as a first step in evaluating the potential threat that pesticide contamination poses to large-scale ground-water development.

Aldicarb

Aldicarb is a highly toxic pesticide used to control nematodes, Colorado potato beetles, and other agricultural pests (Zaki and others, 1982). Potato farms are numerous in southern Rhode Island, and aldicarb has been used extensively. Aldicarb belongs to a group of pesticides called carbamates, which affect the nervous system.

The U.S. Environmental Protection Agency (1985, p. 46986) has proposed a Recommended Maximum Contaminant Level (RMCL) of 0.009 mg/L (9 micrograms per liter) for total aldicarb residues in drinking water. Total aldicarb residues include aldicarb (the parent compound), and its degradation products aldicarb sulfoxide and aldicarb sulfone.

The following factors are conducive to ground-water contamination by aldicarb residues: high aldicarb usage, highly permeable and acidic soils, high recharge rates, low soil and water temperatures, low content of organic matter in soil, low soil microbial activity, and a shallow water table (Jones and Back, 1984, p. 9). These combined factors create conditions favorable for rapid transport through the unsaturated zone, which reduces the time available for aldicarb decomposition.

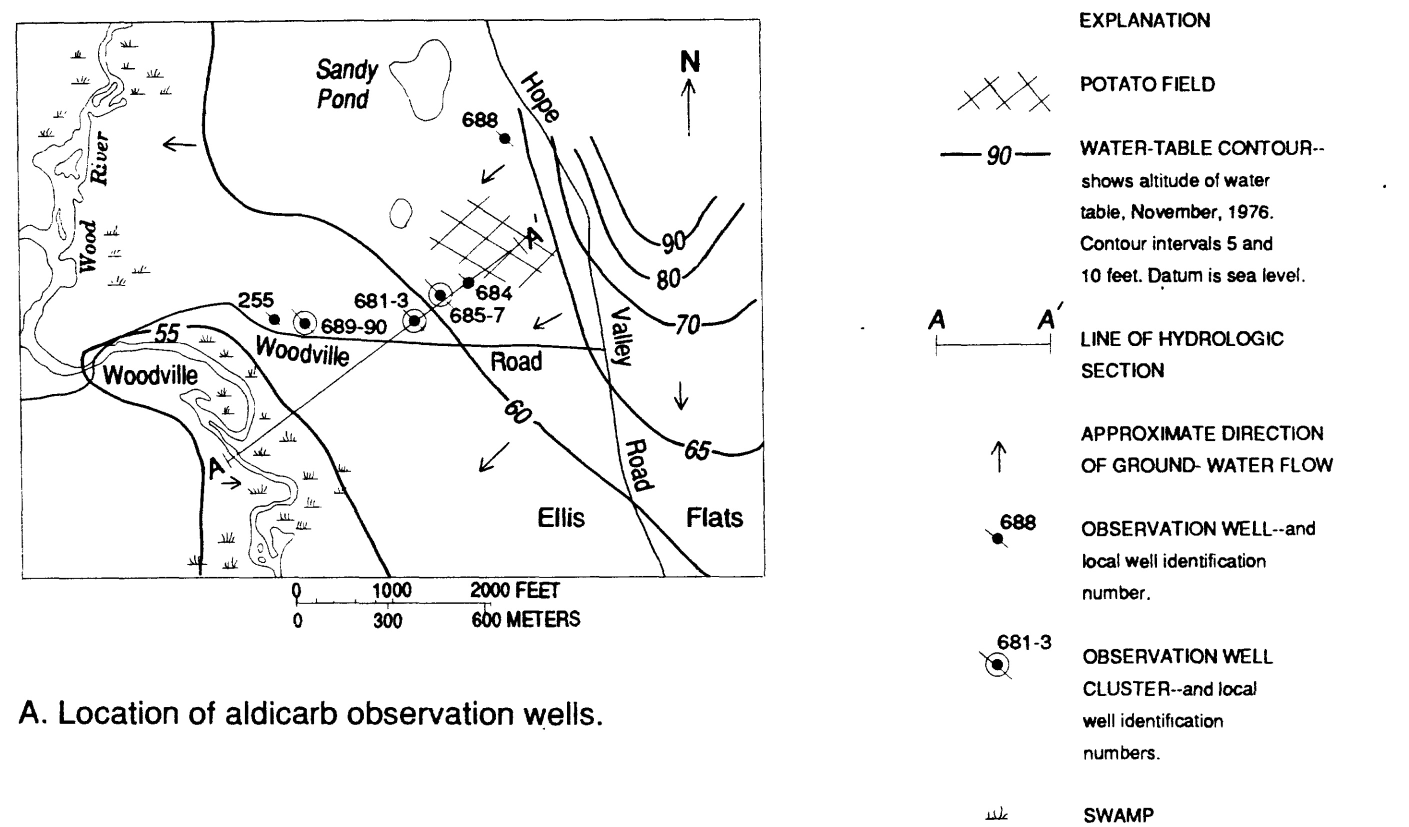
During its investigation of the lower Wood River ground-water reservoir, the U.S. Geological Survey installed a network of monitoring wells in the vicinity of a potato field near Woodville, Rhode Island (fig. 11) to determine whether aldicarb was present in the ground water. Recharge rates, soil characteristics, and ground-water occurrence in Rhode Island's stratified-drift aquifers are similar to conditions found on Long Island, New York, where widespread ground-water contamination by aldicarb had been discovered in 1979.

Aldicarb was applied annually on the potato field at the time of planting (April 15-25), from 1977-81 and in 1983. No aldicarb was applied in 1982 or 1984 (Johnston, H. E., U.S. Geological Survey, written commun., 1984). The RIDEM prohibited the reregistration of aldicarb use in Rhode Island as of January 1985. In the Northeast, aldicarb applied at the time of planting has been found to be more likely to infiltrate permeable soils and contaminate ground water than aldicarb applied at the time of plant emergence (Jackson and Webendorfer, 1983).

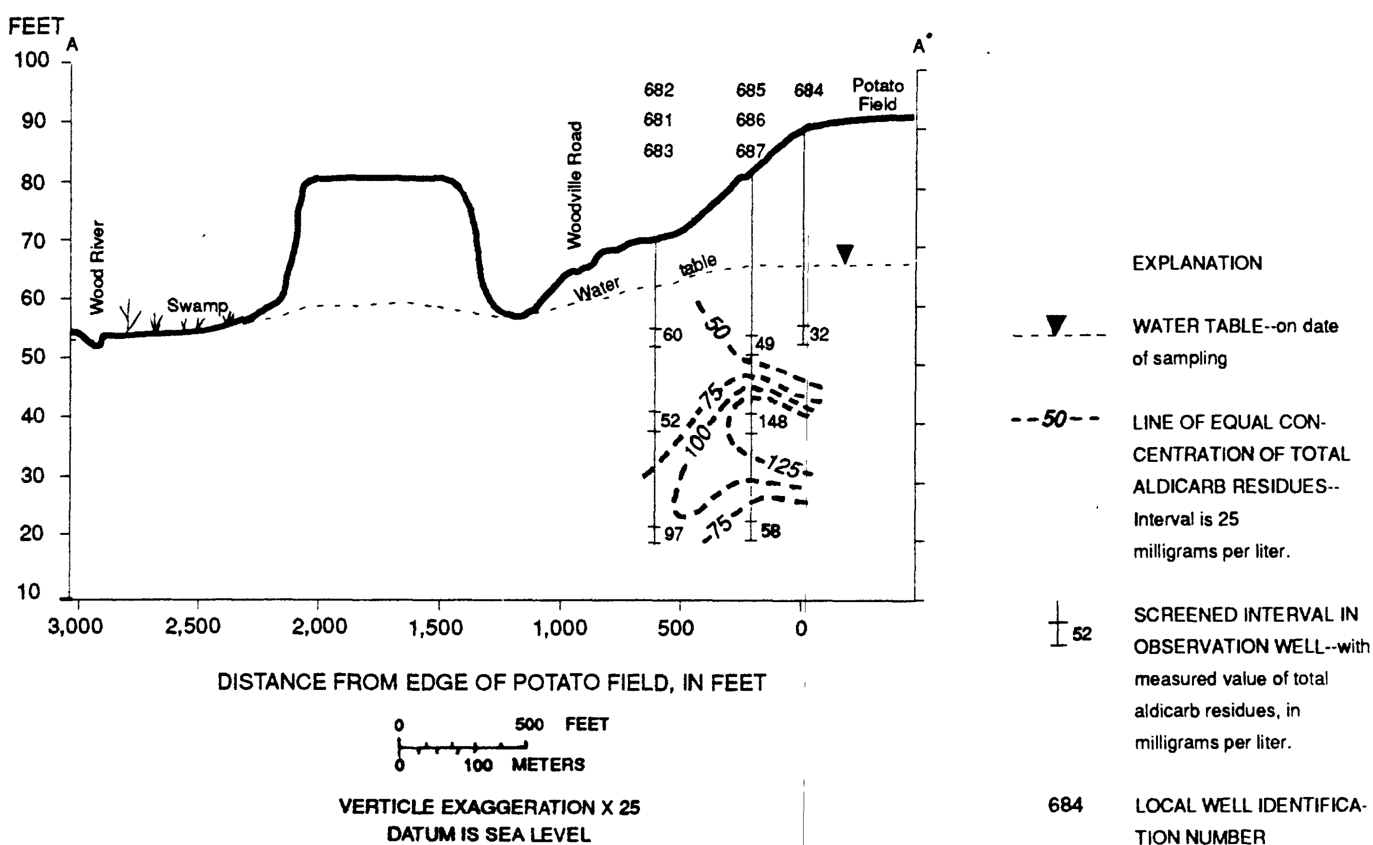
Ten observation wells were installed in 1983 at five sites: one well at a site upgradient from the potato field and nine wells at four sites downgradient from the potato field (fig. 12). At three of the downgradient sites, cluster wells were installed at various depths within the aquifer (table 6). Figure 12a shows the potato field, observation-well locations, approximate water-table configuration, and approximate direction of ground-water flow.

These ten observation wells and one domestic supply well downgradient from the field were sampled on April 23 and July 16, 1984. An additional sampling of the ten observation wells was conducted on December 17, 1985. The results of these analyses are shown in table 7. Replicate samples for two wells were analyzed for quality-control purposes.

The total aldicarb residue for a particular sample is equal to the aldicarb sulfoxide concentration plus the aldicarb sulfone concentration. No parent compound aldicarb was detected in any of the samples. The detection limit fcr each of the pesticides shown in table 7 is 1 ug/L (microgram per litter). Thus, a value of less than 1 ug/L indicates that the pesticide was not detected, within the limits of the analytical method.

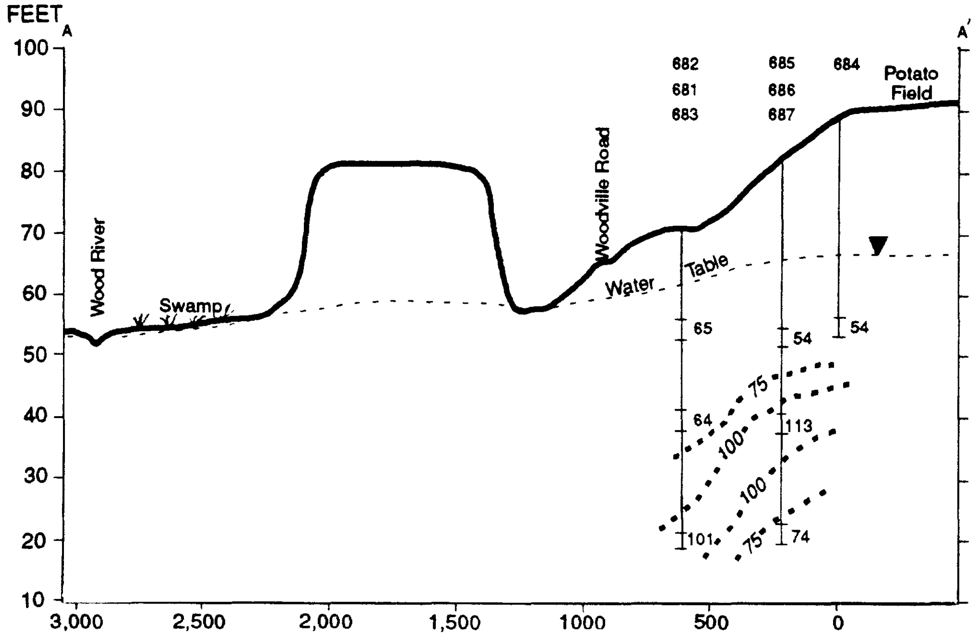


A. Location of aldicarb observation wells.

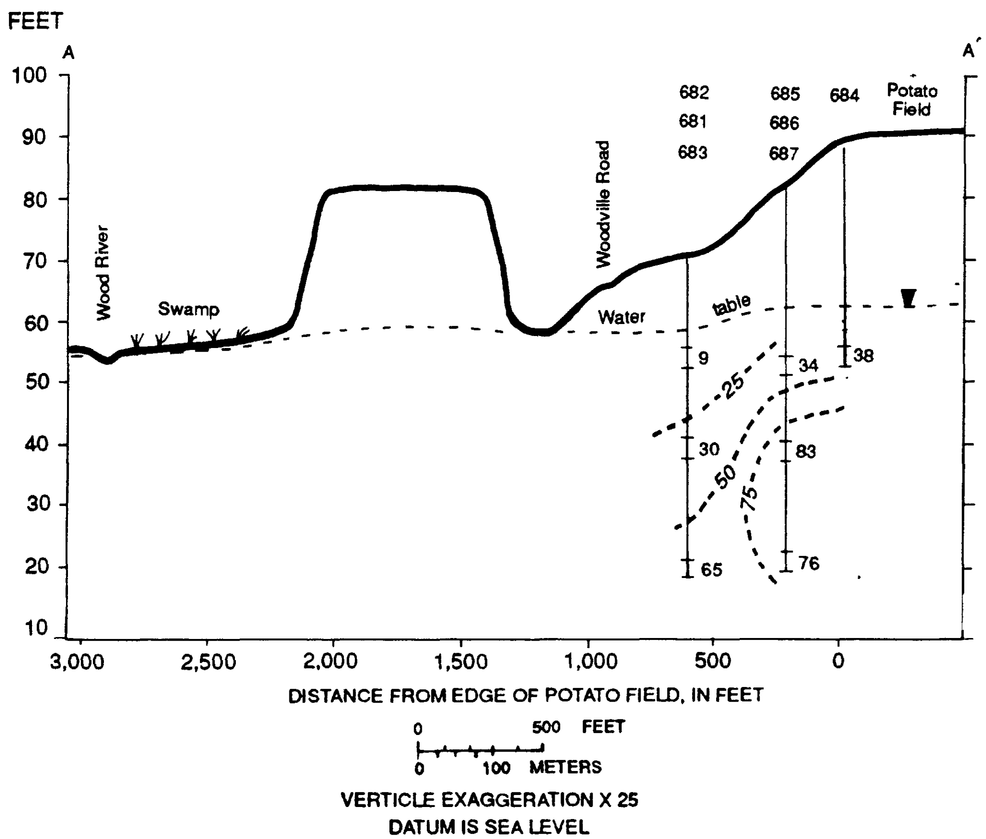


B. Total aldicarb residues on April 23, 1984.

Figure 12.--Well locations and approximate water-table configuration at aldicarb sampling site, and hydrologic sections showing total aldicarb residues.



C. Total aldicarb residues on July 16, 1984



D. Total aldicarb residues on December 17,1985

Table 6.-- Description of wells used to sample ground water for selected pesticides.

[Well locations are shown in figure 12; - -, no data available]

Local well number	Elevation of land surface (feet)	Altitude of water table (feet)	Depth to water table Dec 17, 1985 (feet below) land surface)	Screened interval (feet below land surface)	Approximate distance from field in feet	U = Upgradient D = Downgradient
RIW 688	[a]93	63	30.1	39.1-42.1		U
RIW 684	90.0	63.0	27.0	32.9-35.9	edge of field	D
RIW 685	82.8	62.9	19.9	27.6-30.6	100	D
686	82.6	62.9	19.7	40.9-43.9	100	
687	82.5	62.9	19.6	59.0-62.0	100	
RIW 682	70.6	59.0	11.6	14.3-17.3	500	D
681	70.7	59.0	11.7	28.6-31.6	500	
683	70.7	59.0	11.7	48.4-51.4	500	
RIW 689	64.8	58.5	6.3	18.2-21.2	1,500	D
690	64.6	58.4	6.2	39.0-42.0	1,500	
RIW 255	80.4	- -	- -	25.8[b]	1,800	D

a Value in feet from topographic map. Values in tenths of feet leveled.

b Dug well, open end tile. Sampled at spigot on house. Water source is well point driven inside dug well. Depth of well point unknown.

Table 7.-- Summary of measurements for selected pesticides in ground water near Woodville, R. I., 1984-85.

(See figure 11 for site location and figure 12 for well locations. Analyses are given in micrograms per liter; <, less than; --, no data available)

Local well number	Date	**Aldicarb sulfoxide**	**Aldicarb sulfone**	**Carbofuran**	**Oxamyl**
RIW 688	84-04-23	<1	<1	<1	<1
	84-07-16	<1	<1	<1	<1
	85-12-17	<1	--	--	--
RIW 684	84-04-23	18	14	<1	2
	84-07-16	35	19	<1	2
	85-12-17	24	14	<1	1
RIW 685	84-04-23	30	19	2	<1
	84-07-16	32	22	1	1
	85-12-17	21	13	<1	<1
RIW 686	84-04-23	92	56	7	<1
	84-07-16	69	44	4	<1
	85-12-17	50	33	3	<1
Replicate RIW 686	84-04-23	94	56	7	<1
	84-07-16	69	45	4	1
RIW 687	84-04-23	36	22	2	<1
	84-07-16	46	28	3	<1
	85-12-17	47	29	3	<1
RIW 682	84-04-23	41	19	4	<1
	84-07-16	43	22	4	<1
	85-12-17	6	3	<1	<1
Replicate RIW 682	84-04-23	34	18	3	<1
	84-07-16	41	22	3	<1
RIW 681	84-04-23	34	18	3	<1
	84-07-16	42	22	4	<1
	85-12-17	18	12	1	<1
RIW 683	84-04-23	64	33	6	<1
	84-07-16	66	35	6	<1
	85-12-17	42	23	3	<1
RIW 689	84-04-23	<1	<1	<1	<1
	84-07-16	<1	<1	<1	<1
	85-12-17	<1	<1	<1	<1
RIW 690	84-04-23	<1	<1	<1	<1
	84-07-16	<1	<1	<1	<1
	85-12-17	<1	<1	<1	<1
RIW 255	84-04-23	<1	<1	<1	<1
	84-07-16	<1	<1	<1	<1

On each of the three sampling dates, no aldicarb residues were detected in the upgradient observation well (RIW 688), the downgradient domestic supply well (RIW 255), or the two downgradient observation wells farthest (1,500 ft) from the potato field (RIW 689 and 690) (fig. 12, table 7). The data are insufficient to determine if these downgradient wells are outside the path of the contaminant plume, or if the contaminant plume had not reached these wells by the last sampling date.

Samples from downgradient observation wells within approximately 500 ft of the potato field showed significant aldicarb residues on all three sampling dates (fig. 12, table 7). Aldicarb concentrations for all of these samples equal or exceed the RMCL of 9 ug/L. In some cases, the concentration exceeds the RMCL by an order of magnitude. The maximum concentration of total aldicarb residue measured was 150 ug/L (well RIW 686, table 7).

Hydrogeologic sections showing aldicarb concentrations in contaminated wells on the three sampling dates are shown in figure 12. The data are insufficient to warrant a high level of confidence in the placement of the lines of equal values. However, the episodic nature of aldicarb use, with application only in the spring, suggests that the maximum zones of contamination may move through the ground-water system as three-dimensional slugs surrounded by zones of less contaminated water. Recharge during the year between applications of aldicarb could dissolve and transport additional residues from the unsaturated zone to the saturated zone, but would probably have lower concentrations of the pesticide than recharge that occurs during and shortly after application. Because farm records indicate that aldicarb was not applied in 1982 and 1984, the zones of maximum contamination shown in figure 12 may primarily represent residues from aldicarb application in April 1983.

Length of the ground-water flow path between recharge area and discharge area may affect the concentration of aldicarb in the saturated zone. In shallow zones of the aquifer, where ground water travels a relatively short distance from recharge area to discharge area, flushing of contaminants may take place relatively quickly. Deeper zones of the aquifer, with longer ground-water flow paths, should require longer periods of time for contaminated ground water to move through and discharge from the aquifer. The maximum depth to which the aquifer is contaminated by aldicarb at the study site is not known. The approximate saturated thickness of the stratified-drift aquifer ranges from 140 to 260 ft in the vicinity of the contaminated wells shown in figure 12. Sampling for aldicarb took place within the upper 50 ft of the saturated zone, and aldicarb was found to the bottom of the sampled zone.

Variations in hydraulic conductivity between layers and lenses of sediment in the aquifer affect the distribution of contaminated ground water. Because aldicarb residues do not sorb significantly to sediment, their movement in the saturated zone is controlled primarily by the rate of ground-water flow. The contaminants move more rapidly through highly permeable zones within the aquifer. Lithologic logs for the contaminated wells do not suggest obvious variations in hydraulic conductivity that would explain the vertical distribution of contaminants shown in figure 12. However, a thin layer of relatively high hydraulic conductivity that exerts a significant influence on contaminant movement can easily be overlooked during drilling and sampling (Freeze and Cherry, 1979, p. 398).

Water-table altitudes for cluster wells RIW 685-687 and 681-683 (table 6) indicate that equipotential lines are approximately vertical and ground-water flow is approximately horizontal in this zone of the aquifer. During recharge, the vertical component of flow is more significant than the horizontal component. It is assumed that ground-water flow is from east to west along section A-A' (figure 12). However, the water-table contours are generalized, and the actual ground-water flow direction may not lie within the plane of section A-A'.

Research from laboratory studies indicates that the half-life of aldicarb residues in Long Island's ground water is approximately 2 to 3 years (Porter and others, 1984, p. 18). If these rates are applicable to stratified-drift aquifers in Rhode Island, it may take a decade or more for aldicarb concentrations in the more contaminated zones sampled to decrease to levels below the RMCL of 9 ug/L.

The Rhode Island Department of Health (RIDH) has monitored public and private wells for aldicarb since 1984. Public water-supply systems are monitored annually. Private wells located within 0.5 mi of agricultural areas where aldicarb has been used are eligible for sampling (Lee, R. G., Rhode Island Department of Health, written commun., 1987). As of May 1987, water from 1,053 private wells has been tested for aldicarb (Lee, R. G., Rhode Island Department of Health, written commun., 1987). Statewide, aldicarb has been detected in water from 185 wells or 18 percent of the wells tested. Aldicarb concentrations exceeded the RMCL of 9 ug/L in water from 49 wells, or 26 percent of the wells in which aldicarb was detected. The maximum concentration that has been detected in private well water in Rhode Island is 103 ug/L.

Other Pesticides

Ground-water samples collected by the Survey near Woodville were tested for six other carbamate pesticides in addition to aldicarb and aldicarb residues. Carbaryl, 3-hydroxycarbofuran, 1-naphthol, and methomyl were not detected in any of the samples. Carbofuran was detected in samples from wells located between approximately 100 and 500 ft downgradient from the potato field (table 7). Oxamyl was detected in samples from wells within approximately 100 ft downgradient from the potato field (table 7). The minimum detection limit for each of these six pesticides is 1 ug/L.

Like other carbamate pesticides, carbofuran affects the nervous system. An RMCL of 0.036 mg/L (36 ug/L) has been established for carbofuran (U.S. Environmental Protection Agency, 1985, p. 46987). The maximum concentration of carbofuran detected in ground water from the sampling site near Woodville was 7 ug/L (table 7).

Oxamyl is one of several synthetic **organic chemicals** under consideration for regulation. Establishment of an RMCL for this pesticide requires additional data on human exposure and potential health effects (U.S. Environmental Protection Agency, 1985, p. 47013). The maximum concentration of oxamyl detected in ground water near Woodville was 2 ug/L, in a sample taken from the observation well at the edge of the potato field (table 7).

Numerous other pesticides are used in Rhode Island in agricultural areas, on transportation rights-of-way, and on residential lawns and gardens. The potential extent of ground-water contamination by pesticides in this study area is not known, because ground water samples were analyzed for a limited number of pesticides within a small part of the stratified-drift aquifer.

Low-Level Radionuclides and Other Contaminants

Industrial waste disposal at a site near Wood River Junction has contaminated ground water within the stratified-drift aquifer in an area extending from the disposal site to the Pawcatuck River (fig. 11). Site history and ground-water contamination have been described by Ryan and Kipp (1985), and geohydrologic data for the site have been compiled by Ryan and others (1985). Ground-water contamination was first detected at the site in 1976, when the RIWRB was investigating potential areas in the lower Wood River ground-water reservoir for large-capacity supply wells (Johnston, H. E., U.S. Geological Survey, oral commun., 1987).

Contaminant-Plume Configuration and Movement

The plume of contaminated ground water delineated by Ryan and Kipp (1985) extends from the source area northwestward approximately 1,500 ft to the Pawcatuck River, where it turns southwestward and extends approximately 800 ft downstream through a swampy area on the west side of the river, for a total distance of 2,300 ft. The plume is approximately 300 ft wide and is confined to the upper 80 ft of saturated thickness, where the aquifer consists of medium to coarse sand and gravel. No contamination has been detected in the fine sands and silts underlying the coarser materials. The depth of the base of the plume increases with distance from the source area, until reaching a maximum depth of 80 ft below land surface between 1,400 and 1,500 ft from the source area. Beyond this point, the base of the plume gradually rises to within about 10 ft of land surface at its farthest mapped extent.

Ground water flows westward and northwestward from the till uplands east of the contaminant source area toward the Pawcatuck River. The shape of the contaminant plume itself shows the direction of ground-water flow. The rate of ground-water movement in the vicinity of the contaminant plume has been estimated to range from approximately 1.9 to 2.6 ft/d (Ryan and Kipp, 1985, p. 26). Beneath the Pawcatuck River and the contiguous swampy area west of the river, ground water moves vertically upward, discharging into the river and swamp. Dilution precludes detection of contaminants once they have entered the river (Ryan and Kipp, 1985, p. 29).

Types of Contaminants

Contaminants in the ground water include common **cations** and **anions** at concentrations above background levels, metals, nutrients, radionuclides, and other constituents. Maximum values of several properties and constituents in ground water were measured in 1977, while the industrial plant was still processing material:

Specific conductance	14,500 uS/cm
Hardness (as $CaCO_3$)	3,200 mg/L
Calcium	1,040 mg/L
Magnesium	146 mg/L
Potassium	28 mg/L
Nitrate (as N)	2,200 mg/L

(Dickerman and Silva, 1980, p. 177-178). Comparison of these values with median values for ground water in table 4 shows that values for contaminated water were as much as several orders of magnitude greater than values for uncontaminated ground water in the lower Wood River study area.

After liquid waste discharges ended in 1980, concentrations of many contaminants decreased, but were still well above background levels (Ryan and Kipp, 1985). From 1981-83, the following ranges of chemical and radiochemical constituents were measured in the contaminated ground water:

Potassium	3-25 mg/L
Nitrate (as N)	4-660 mg/L
Boron	20-490 ug/L
Strontium-90	4-290 pCi/L (picocuries per liter)
Technetium-99	75-1,350 pCi/L

(Ryan and Kipp, 1985; Ryan and others, 1985).

Table 8 shows values for selected constituents and properties measured in water from observation wells near the middle of the contaminant plume, at the edge of the plume, and outside the plume, during the winter of 1981-82. Values for the well outside the plume are believed to be typical of uncontaminated ground water in the area.

Radionuclides

Ground-water contamination at this waste-disposal site has been of particular interest to investigators and the public because of the radiochemical constituents present. Measurements of gross alpha or beta activity give a general indication of radioactive contamination. In 1977, the maximum level of gross beta activity measured was 1,518 pCi/L (Dickerman and Silva, 1980, p. 177-178). During 1981-83, measured concentrations of gross beta emitters ranged from 5 to 1,500 pCi/L (Ryan and others, 1985). No gamma emitters above detection levels have been found. Dissolved solids concentrations of up to 3,500 mg/L have interfered with the detection of alpha emitters (Ryan and Kipp, 1985, p. 30).

Strontium-90, a beta emitter, is a byproduct of the nuclear fission process. Concentrations of strontium-90 in the contaminant plume range from 4 to 290 pCi/L (Ryan and others, 1985). Strontium-90 resembles calcium in its chemical behavior and its metabolism by animals. It is incorporated into organic molecules within the body. The MCL for strontium-90 in drinking water is 8 pCi/L (U.S. Environmental Protection Agency, 1977, p. 7-8).

A simplified solute-transport model has predicted that it will take approximately 10 years for natural ground-water flow and radioactive decay to reduce the strontium-90 concentration to the USEPA MCL at this site (Kipp and others, 1986, p. 529). Monitoring will be necessary to determine the actual cleanout time.

Table 8.--Representative values of selected constituents and properties in ground water at the low-level radionuclide contamination site near Wood River Junction, R. I.

(Analyses are given in milligrams per liter, except as indicated; ug/L, micrograms per liter; <, less than; uS/cm at 25°C, microsiemens per centimeter at 25 degrees Celsius; pCi/L, picocuries per liter. See figure 11 for site location. Source, Ryan and Kipp, 1985, p. 32.)

Constituent or property	Observation well in middle of plume **Feb. 17, 1982**	Observation well on edge of plume **Feb. 3, 1982**	Observation well outside of plume **Dec. 23, 1981**
Alkalinity-$CaCO_3$	7	3	9
Boron (ug/L)	230	50	< 10
Cadmium (ug/L)	1	2	< 1
Calcium	720	50	4.1
Chloride	180	9.2	5.0
Copper (ug/L)	4	2	5
Fluoride	< .1	< .1	< .1
Hardness	1900	130	16
Iron (ug/L)	250	20	310
Lead (ug/L)	5	6	1
Magnesium	23	1.5	1.4
Manganese (ug/L)	600	67	1600
Nickel (ug/L)	14	1	2
Nitrate (NO_2+ NO_3)	580	37	.18
pH (units)	5.6	5.7	5.6
Phosphorus (ortho as P)	< .01	< .01	< .01
Potassium	21	3.4	2.5
Silica	< .1	11	6.9
Sodium	25	7.8	4.4
Specific conductance (uS/cm) at 25°C	4260	376	77
Strontium-90 (pCi/L)	222	6.7	2.9
Sulfate	50	14	14
Water temperature (°C)	12.0	11.5	10.5
Zinc (ug/L)	50	11	16

GROUND-WATER-DEVELOPMENT ALTERNATIVES

The impact of alternative schemes of ground-water development on ground-water levels, pond levels, and streamflow in the lower Wood River ground-water reservoir was evaluated with a two-dimensional ground-water flow model. The model was used to simulate the interaction between surface water and ground water in the stream-aquifer system. Steady-state simulations of theoretical pumpage were made for long-term average annual hydrologic conditions (1941-76) and simulated drought conditions (1963-66).

Conceptual Model

A **conceptual model of the stream-aquifer system** in the lower Wood River ground-water reservoir was developed chiefly from geohydrologic data contained in a report by Dickerman and Silva (1980). In developing the lower Wood River model, the complexity of the real system has been simplified. The goal has been to keep the conceptual model as simple as possible while retaining the essential features of the real stream-aquifer system. Simplifying assumptions included in the conceptual model of the flow system are:

(1) Ground-water flow in the stratified-drift aquifer is horizontal, and there is no ground-water flow either to, or from, the underlying bedrock. Although ground-water flow in the stratified drift is not strictly horizontal, this assumption applies reasonably well to most of the model area. The result of this assumption is that the model can not accurately simulate ground-water heads in areas with significant vertical water flow.

(2) Recharge directly on the stratified-drift aquifer from precipitation was uniformly distributed over the modeled area at the rate of 27 in. per year for average conditions, and reduced by 25 percent to simulate drought conditions, except in discharge areas such as swamps.

(3) Recharge to the stratified drift from till/bedrock uplands was applied along the perimeter of the model near the geologic contact between the till and the stratified drift. Recharge from uplands was applied at a rate of 27 in. per year and evenly spread out over nodes adjacent to till/bedrock areas not drained by streams. In upland areas drained by streams, recharge was input to the model at a single node located where the mouth of the stream crosses the geologic contact between the till and the stratified drift.

(4) The elevation of surface water in ponds and streams does not vary with time.

(5) Ground-water discharges from the aquifer are to surface-water bodies through leaky ponds and streambeds, by evapotranspiration, and to discharging wells.

(6) Ground-water evapotranspiration decreases linearly with depth of water table from a maximum at land surface to zero at 4 feet or more below land surface. The evapotranspiration rate used in the model is 22.6 in., as determined by the Thornthwaite method.

(7) All pumping wells are considered to be screened throughout the entire saturated thickness of the aquifer and are 100-percent efficient. To compensate for these idealized well-construction characteristics, maximum allowable drawdown under pumping conditions is limited to 25 percent of the initial saturated thickness.

Although these basic assumptions do not always represent actual field conditions of the stream-aquifer system, the authors believe that any deviations from them probably do not introduce large errors in conceptualization of the system or in digital simulations.

The part of the lower Wood River study area selected for simulation covers 8 mi^2 of stratified drift and is outlined in figure 1. The real system and corresponding conceptual model of the ground-water flow system are shown schematically in figure 13.

Digital Model

Digital models that simulate ground-water flow are widely used in the analysis and management of water resources. A digital model of a stream-aquifer system is a simplified mathematical representation of a complex geohydrologic system. The digital model is a computer program designed to solve equations that govern ground-water flow. The model can be used to evaluate the effects of different stresses imposed on the stream-aquifer system. Accurate simulation of the flow system is essential to anticipate response of the aquifer to applied stresses, especially for stream-aquifer systems.

A finite-difference model developed by McDonald and Harbaugh (1984), was used in this study to simulate the ground-water flow system and its response to imposed stresses. The model uses a block-centered, finite-difference method to approximate numerically the differential equations that describe the flow of ground water. Solution of these equations requires subdivision of the modeled area into a grid of rectangular blocks called nodes. The grid network (fig. 14) of the model consists of 32 rows and 72 columns, and defines 2,304 nodes. Only the nodes representing the stratified-drift aquifer are considered "active" and are involved in the numerical computations. The grid has variable spacing, with node dimensions ranging from 400 to 1,200

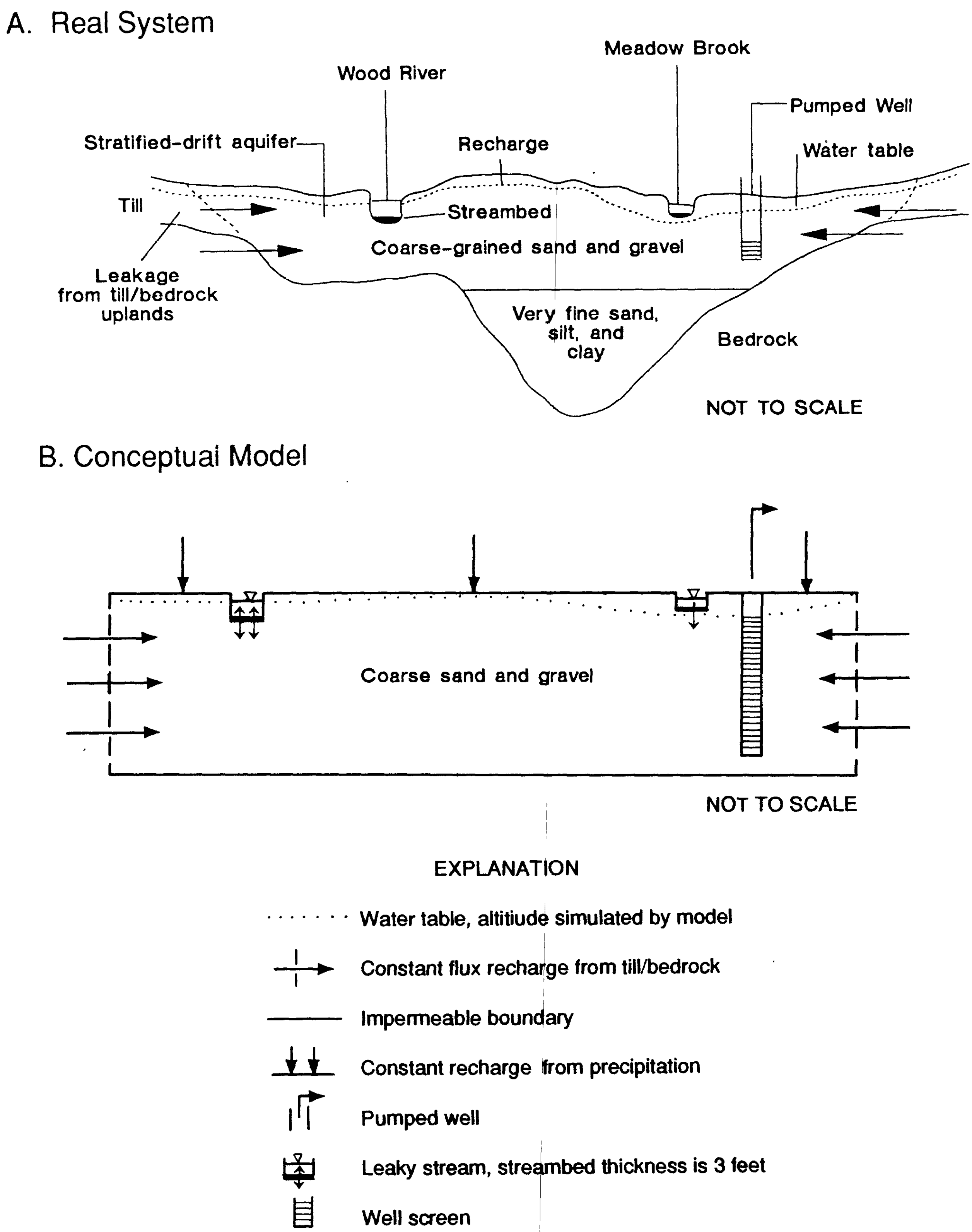


Figure 13.--Idealized conceptual model of steady-state ground-water flow.

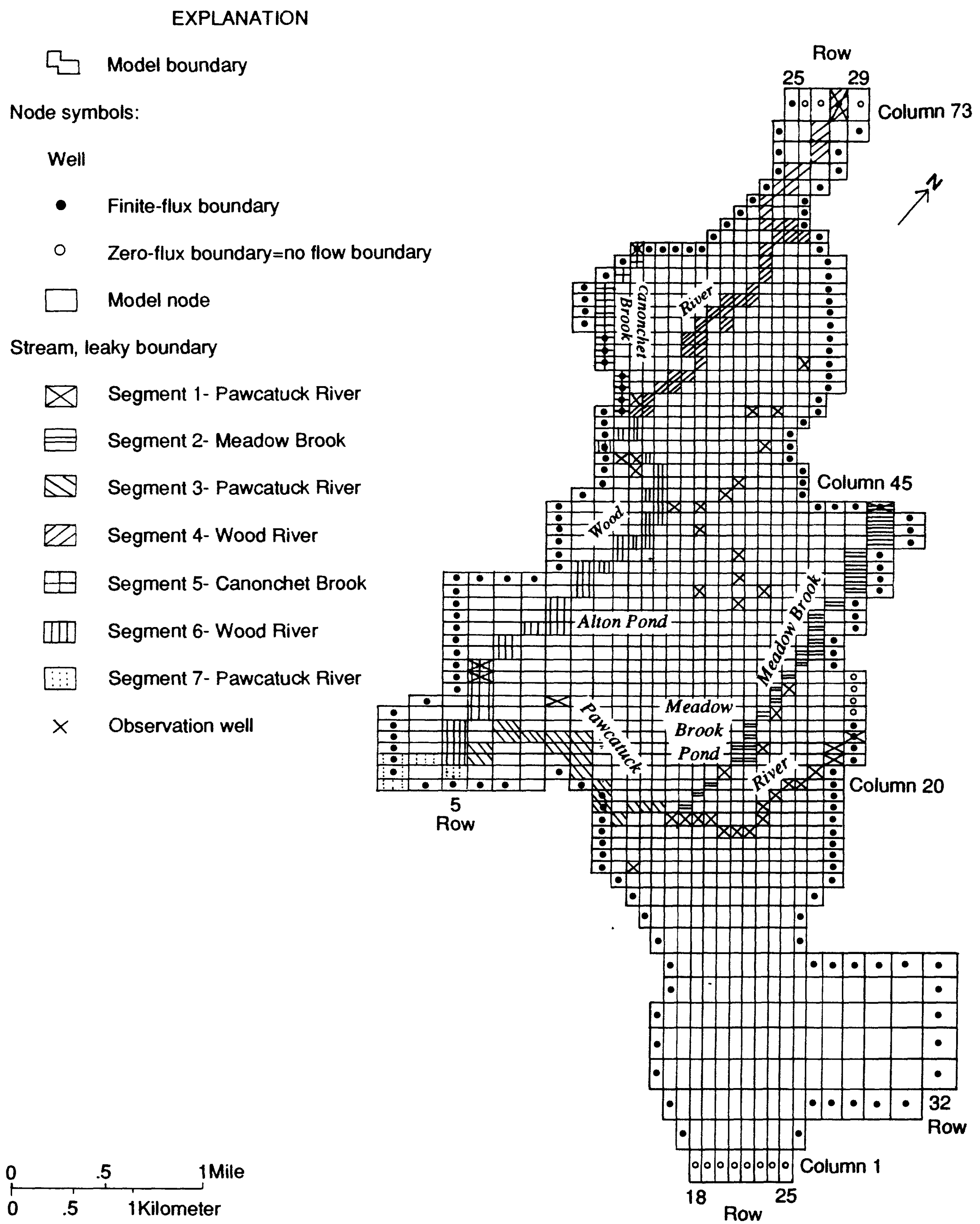


Figure 14.--Finite-difference grid and boundary conditions of the lower Wood River ground-water-flow model.

feet on a side. The grid is finer in the central part of the model where the aquifer is thickest and hydraulic properties are higher. The grid is coarser along the western and eastern parts of the model where values are lower and the aquifer is thinnest. A finite-difference equation that approximates flow in the block is evaluated at each node of the grid, and the set of equations for the entire system is solved simultaneously. The solution technique used in the model is the **strongly implicit procedure** (SIP) developed by Stone (1968).

Boundary Conditions

One important aspect of model construction is to represent conditions at model boundaries as accurately as possible. Boundary conditions in the lower Wood River ground-water model are shown in figure 14. Most of the eastern and western model boundaries coincide with the geologic contact between the stratified drift aquifer and the till-covered bedrock valley walls (figs. 10 and 14). This geologic contact was simulated in the model as a **finite-flux boundary** located at the first node within the stratified drift. These finite-flux boundaries were used to simulate long-term average annual recharge (27 inches) from ground-water inflow from till/bedrock uplands to the active model area. The southern end of the model is simulated as a no-flow boundary (**zero-flux boundary**) along the drainage divide. The northern boundary near the U.S. Geological Survey gaging station near Hope Valley was also zero flux.

The bottom boundary of the aquifer is the contact between the highly permeable stratified drift and the less permeable till-covered bedrock or the fine-grained lake deposits shown in figure 4. In the model, the till/bedrock and fine-grained lake deposit contacts are simulated as no-flow boundaries. The top boundary of the aquifer is the water table and is computed by the model.

Initial Conditions and Input Parameters

The first step in the modeling process was to select a period of time during which recharge to the aquifer, ground-water discharge, and water-table altitude represented long-term average conditions. Data collected during 1976-77 indicated that precipitation, streamflow and water levels were near long-term average annual conditions during late October 1976. Initial conditions of the model were set to reflect October 1976 water-table and streamflow conditions. The near long-term average annual conditions of October 1976 (about 8 percent below long-term average annual conditions) were assumed to represent steady-state aquifer conditions. Therefore, the model was compared to water-level data collected in October 1976 and to average streamflow conditions.

The flow equations require that the hydraulic properties of the aquifer and other hydrologic characteristics be defined for the entire model area. The grid network was superimposed on maps of each parameter, and average numeric values were selected for each active node in the modeled area. In the lower Wood River model, values were assigned to appropriate nodes for aquifer hydraulic conductivity, streambed hydraulic conductivity, streambed thickness, stream altitude, precipitation recharge, evapotranspiration, ground-water inflow from till/bedrock uplands, aquifer-bottom altitude, and land surface elevation.

Aquifer horizontal hydraulic conductivity used in the model is shown in figure 15. Initial model input values of hydraulic conductivity determined from aquifer tests and estimates from lithology were modified during model calibration. Hydraulic conductivities shown in figure 15 are the final result of the model calibration procedure.

Surface-water bodies (ponds and streams) simulated in the model are identified in figure 14 as stream nodes. Since aquifer nodes in the model are wider than natural ponds or streams, leakage to or from stream nodes was reduced to compensate for actual pond or stream width. Flow between surface-water bodies and the aquifer is calculated in the model using effective streambed hydraulic conductivity values (see stream-aquifer interconnection section).

The recharge rate from precipitation to the stratified-drift aquifer was set at the long-term average: 27 in/yr. The October 1976 water-table map (fig. 2) drawn using 33 observation wells, was used to estimate hydraulic head at each node. Surface-water altitudes of ponds and streams were estimated by interpolating between contours shown on the water-table map in figure 2. Initially, streambed thickness was set at 1 ft, and streambed vertical hydraulic conductivities were set equal to the vertical hydraulic conductivity of the aquifer near the stream, which was determined by aquifer test analysis.

A **leaky boundary** condition was assigned to Canonchet Brook, Meadow Brook, the Pawcatuck River, and the Wood River to simulate the interaction of the stream-aquifer system.

Steady-State Calibration

Calibration of a ground-water flow model refers to the process of adjusting model input data until differences between computed heads and measured heads are within acceptable limits. Acceptability of the lower Wood River model was determined by comparing simulated and observed ground-water heads, and by comparing model-determined streamflow to estimated long-term streamflow based on discharge measurements at the outflow point of the study area at Burdickville. This repetitive trial and error procedure was used for calibrating the steady-state model.

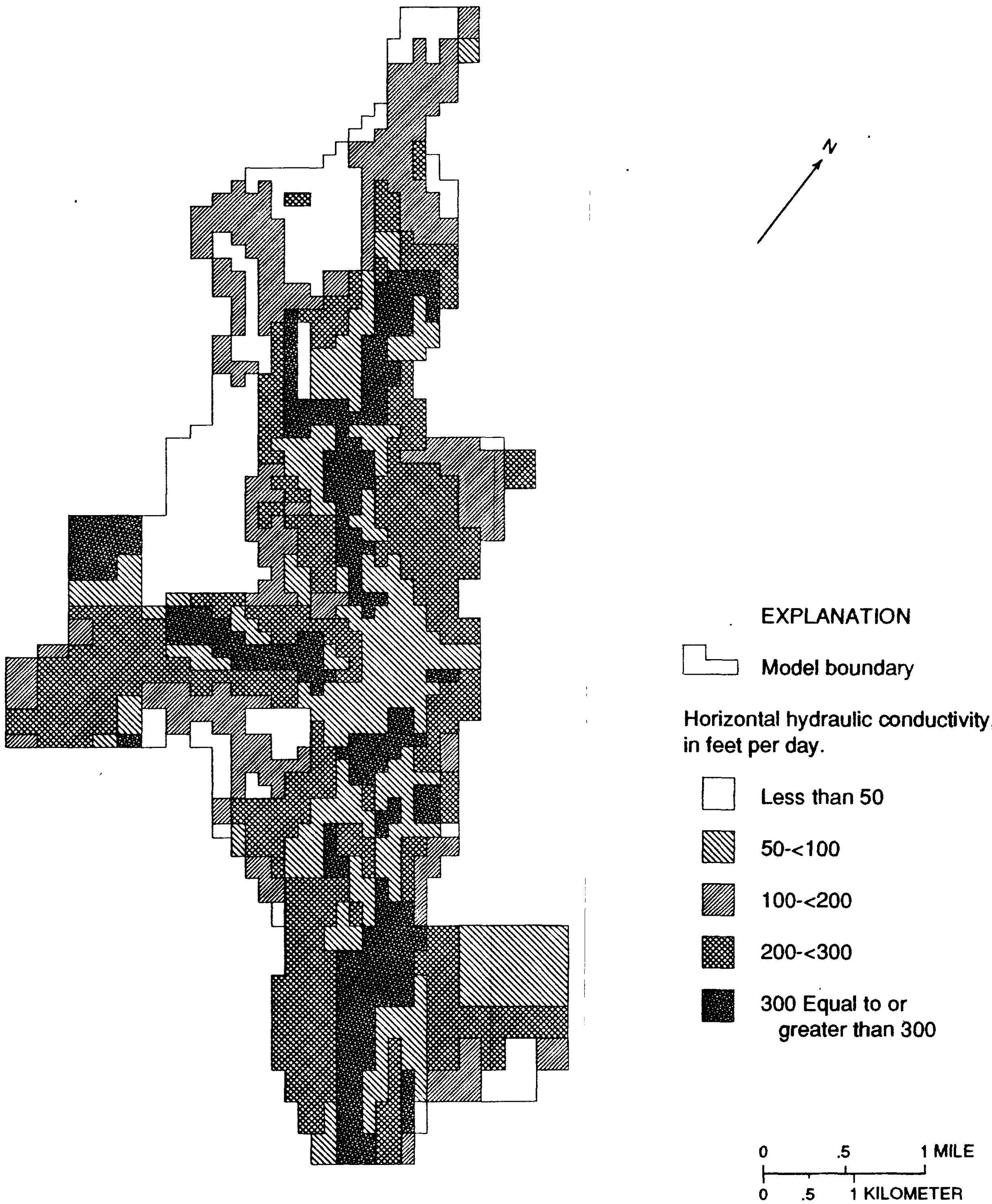


Figure 15.--Horizontal hydraulic conductivity of the stratified-drift aquifer used in digital model.

The first step in calibrating the steady-state model of the lower Wood River ground-water reservoir was to compare computed model heads at 3 nodes with long-term average annual heads measured in observation wells RIW 600, RIW 231, and CHW (Charlestown well) 265 (fig. 2). These comparisons show that model heads are 0.26 ft below the long-term average in the northern part of the model (RIW 600), 0.05 ft above in the central part (RIW 231), and 0.18 ft below in the southern part (CHW 265). Data used for this comparison are shown in table 9.

Table 9.-- Comparison of measured long-term average-annual and simulated steady-state water-level altitudes

Well number	Node		Long-term average annual water-level altitude in feet above sea level (a)	Steady-state-model water-level altitude, in feet above sea level (b)	Difference in water-level altitude, in feet (b-a)
	Row	Column			
RIW 600	27	59	66.00	65.74	-0.26
RIW 231	23	36	60.93	60.98	.05
CHW 265	22	9	51.90	51.72	- .18

The next step in calibrating the steady-state model was to compare computed model heads with water level measurements made in 33 observation wells in October, 1976. These water levels represent conditions that approach, but are about 8 percent below long-term average annual conditions. Differences between computed model heads and measured heads in 33 observation wells ranged from -7.10 to 1.80 ft (table 10). Head differences were less than 1.80 ft at 80 percent of the observation well nodes, and less than 3.00 ft at all but three well nodes. Final **steady-state** water-table contours for these computed model heads are shown in figure 16 for nonpumping conditions. Figure 16 can be used to compare the position of the water table under conditions of no large-scale aquifer development to simulations in which the aquifer is stressed by high-capacity wells.

Stream-aquifer interconnection in the model is simulated using a stream routing package developed for the modular model (D. E. Prudic, U.S. Geological Survey, written commun., 1986). This package is similar to one developed by Ozbilgin and Dickerman (1984) for a two-dimensional model (Trescott and others, 1976), and was used in place of the river package that comes with the modular model. The new stream package is more realistic because it routes streamflow through the aquifer system; whenever simulated flow in the stream ceases, the simulation of induced infiltration to the aquifer system also ceases. Another advantage of the stream package is that it is much easier to read and evaluate model output of streamflow.

Table 10.--Measured and simulated water-table altitudes for selected observation wells showing differences between observed and computed heads, October 1976.

Node		Observed water-table altitude, in feet above sea level	Model water-table altitude, in feet above sea level	Water-table difference, in feet
Row	Column			
6	29	39.9	41.0	-1.10
6	30	49.0	49.0	.00
9	27	44.9	52.0	-7.10
12	47	56.4	56.0	.40
13	13	42.5	49.0	-6.50
13	46	52.7	53.0	- .30
13	47	48.9	49.0	- .10
13	64	67.1	68.0	- .90
16	17	40.7	41.0	- .30
16	43	55.8	54.0	1.80
18	36	58.2	60.0	-1.80
18	41	56.5	59.0	-2.50
18	43	56.6	58.0	-1.40
20	21	50.1	49.0	1.10
20	44	56.6	59.0	-2.40
21	35	58.2	60.0	-1.80
21	37	58.5	61.0	-2.50
21	39	58.6	61.0	-2.40
21	45	60.9	60.0	.90
22	51	63.3	62.0	1.30
23	23	47.2	49.0	-1.80
23	36	59.2	61.0	-1.80
23	48	62.6	62.0	.60
24	26	51.3	53.0	-1.70
24	51	64.3	63.0	1.30
25	28	52.3	56.0	-3.70
25	47	67.4	66.0	1.40
26	55	65.7	65.0	.70
27	71	61.3	61.0	.30
28	23	44.1	45.0	- .90
28	73	63.4	63.0	.40
29	24	46.0	46.0	.00
30	43	75.5	75.0	.50

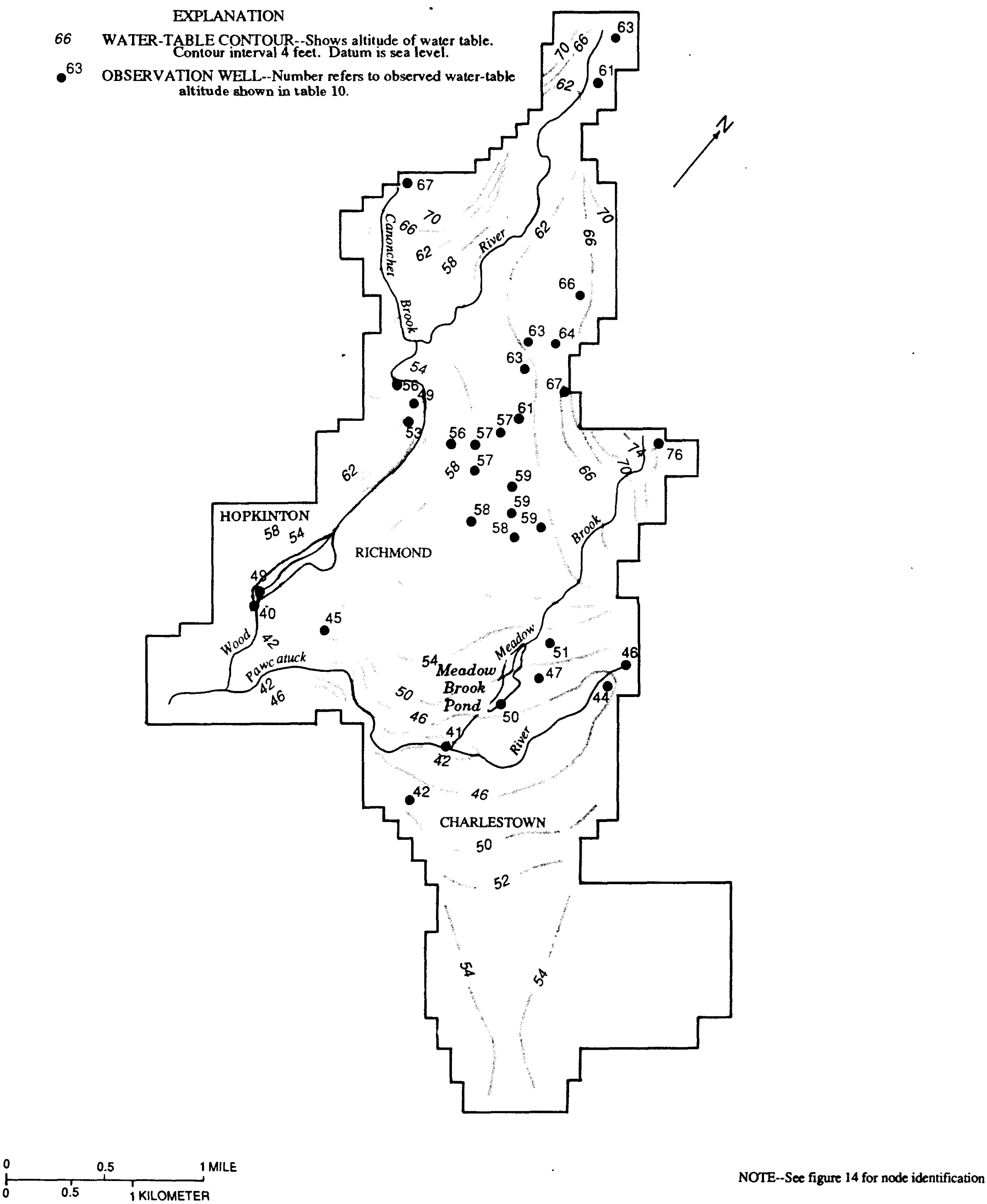


Figure 16.--Simulated position of steady-state water table for nonpumping long-term average-annual streamflow and water-table conditions.

The third step in calibrating the steady-state model was to compare computed model streamflow with long-term average annual streamflow. Streams in the lower Wood River model were divided into seven stream segments (fig. 14). Ponded areas along streams were also modeled as stream nodes. Initial values of effective streambed hydraulic conductivity from aquifer tests produced modeled streamflow too high, and values were adjusted until stream discharge was within acceptable limits. Final effective streambed hydraulic conductivities used in the calibrated model ranged from 8 to 12 ft/d, with streambed thickness set at 3 ft.

Results of the final nonpumping steady-state simulation show that modeled flow is in close agreement (4.3 percent) with estimated long-term average annual streamflow leaving the lower Wood River study area. Simulated steady-state discharge from the model at the study outlet near Burdickville was 385 ft^3/s, which is 21 ft^3/s below estimated long-term average annual streamflow (406 ft^3/s). Of the 385 ft^3/s, 362 ft^3/s was input into the model as stream inflow on the basis of the long-term average annual water budget for the study area (table 1), and 23 ft^3/s was calculated by the model as net ground-water leakage to streams. Of the 21 ft^3/s difference, 3.4 ft^3/s was calculated by the model as evapotranspiration. Part of the remaining difference of 17.6 ft^3/s is due to the model's inability to account for overland runoff from till/bedrock uplands that drains to streams and then flows across areas of stratified drift. This is because calculated flow in the model includes only discharge from ground-water runoff. Standard measurement error (plus or minus 5 percent) for discharge measurements used to estimate long-term average annual streamflow, plus the fact that it is an estimate, probably accounts for any remaining differences.

The final step in the model calibration was to determine if simulated steady-state inflows and outflows of water to the modeled area were in balance. In the ground-water budget, the mass balance of inflows (sources) and outflows (discharges) from the simulated model should be less than 0.1 percent (Konikow, 1978). The mass-balance calculation checks the numerical accuracy of the model solution. The lower Wood River model had a mass-balance discrepancy of -0.06 percent for the steady-state model, indicating that there were no significant errors in numerical computations. Table 11 shows the simulated steady-state water budget for the aquifer. Model results were within acceptable limits, and the model was considered calibrated and acceptable for use in pumping simulations.

During calibration, aquifer bottom elevations were modified where data were sparse (in Indian Cedar Swamp, in the southern part of the model) as was hydraulic conductivity near till/bedrock contacts along the western and eastern sides of the model. Early model runs resulted in heads that were too high in Indian Cedar Swamp. The initial assumption that precipitation recharge would be uniformly distributed over the modeled area was therefore altered, and recharge was eliminated from all discharge areas. The modeled heads then fell within acceptable limits. Results of the final steady state model run show that, of the total recharge to the stratified-drift aquifer under long-term average natural (nonpumping) conditions, 53 percent is derived from precipitation, 35 percent from till/bedrock uplands, and 12 percent from leakage from streams.

Table 11. --Simulated nonpumping steady-state ground-water budget for the lower Wood River two-dimensional model, October 1976.

Sources (Cubic feet per second)		**Discharges** (Cubic feet per second)	
Recharge	15.6	Ground-water runoff	26.2
Ground-water inflow from till/bedrock uplands	10.3	Evapotranspiration	3.4
Stream infiltration	3.7		
Total sources	29.6	Total discharge	29.6

Sensitivity Analysis

To assess the limitations of the conceptual model, an analysis of the sensitivity of the model to changes in model input was made. Changes were varied within the probable range of expected values for individual input. The analysis provides a measure of the sensitivity of model results to changes in values of input parameters, as well as a check on the reasonableness of the calibrated steady-state model.

Principal input parameters of aquifer horizontal hydraulic conductivity (Ka), streambed vertical hydraulic conductivity (Ks), and precipitation recharge (Rp) were independently increased or decreased by a constant factor throughout the entire model area. Differences between calibrated final steady-state values and changed parameter values of aquifer head (water levels) and ground-water discharge were used to evaluate model sensitivity. Input-parameter values to the calibrated model are represented in sensitivity figures (figs. 17-19) by a zero line on the vertical axis of each model row or column tested.

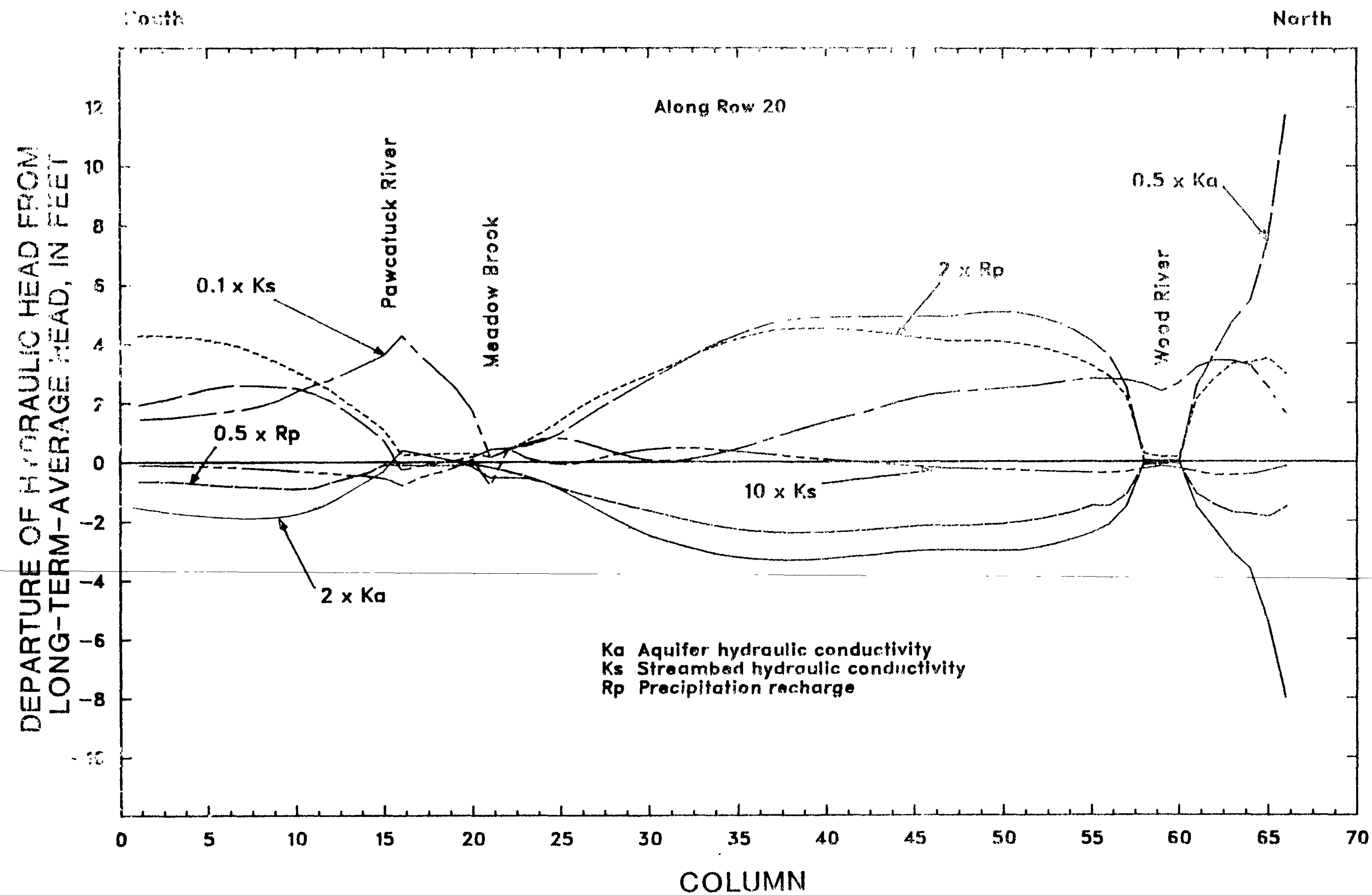


Figure 17.--Effects of varying aquifer, streambed, and precipitation input parameters on the results of the steady-state model, North-South along row 20.

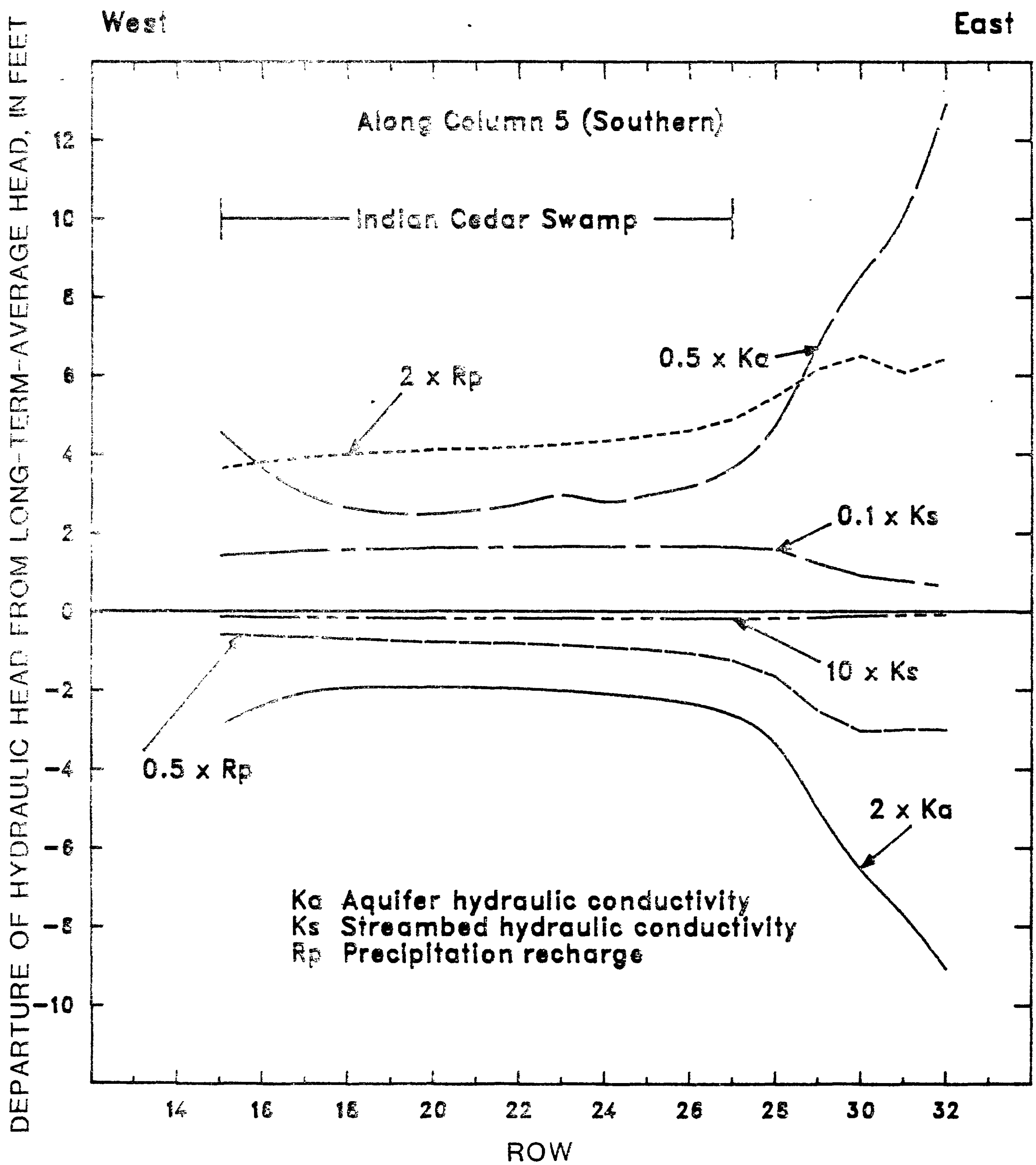


Figure 18.--Effects of varying aquifer, streambed, and precipitation input parameters on the results of the steady-state model, East-West along column 5.

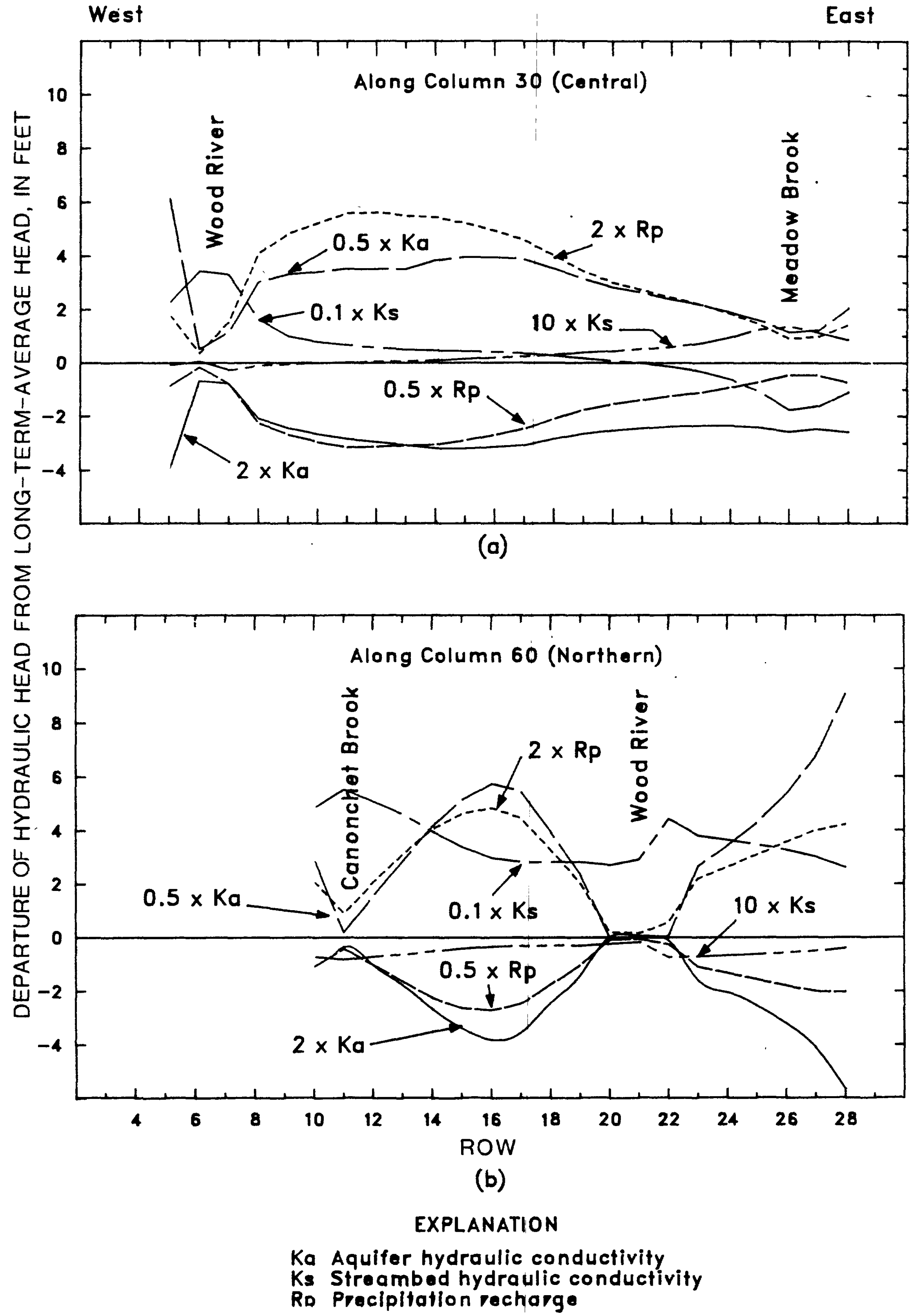


Figure 19.--Effects of varying aquifer, streambed, and precipitation input parameters on the results of the steady-state model, East-West along columns 30 and 60.

The results of the sensitivity analysis are shown in four profiles in figures 17-19. The north-south profile (fig. 17) extends along row 20 through the center of the model. The east-west profiles extend along columns 5, 30, and 60 across the southern, (fig. 18) central, (fig. 19a) and northern (fig. 19b) parts of the model. These profiles show how steady-state heads are affected by increases or decreases in each model input parameter value. A brief discussion of the effects of individual parameters on ground-water discharge and heads follows:

(1) Aquifer horizontal hydraulic conductivity times 2.0 (2 x Ka): Doubling the horizontal hydraulic conductivity of the aquifer produces little or no change in water levels near streams and 2- to 4-ft decreases in water levels in areas away from streams. The effect of lowering water levels was equivalent to partial dewatering of the aquifer. Total ground-water discharge from the aquifer to streams showed a small increase of 2 percent. Raising the aquifer horizontal hydraulic conductivity by a factor of 2 caused 2 nodes to go dry and numerical solution convergence time to double.

(2) Aquifer horizontal hydraulic conductivity times 0.5 (0.5 x Ka): Halving the horizontal hydraulic conductivity resulted in little or no change in water levels near streams, and 3- to 5-ft increases in water levels in areas away from streams. Total ground-water discharge from the aquifer to streams decreased by 1.5 percent. Lowering the aquifer horizontal hydraulic conductivity by a factor of 2 produced slightly larger changes in water levels in the aquifer, indicating that the model is more sensitive to lower than to higher values.

(3) Streambed vertical hydraulic conductivity times 10.0 (10 x Ks): Increasing the vertical hydraulic conductivity of the streambed by an order of magnitude had little to no effect on computed water levels (plus to minus 0.5 ft) or ground-water discharge (1 percent increase).

(4) Streambed vertical hydraulic conductivity times 0.1 (0.1 x Ks): Decreasing the vertical hydraulic conductivity of the streambed by an order of magnitude increased water levels throughout the aquifer by 2 to 3 ft, and decreased ground-water discharge from the aquifer to streams by 1.6 percent. Lowering the streambed vertical hydraulic conductivity by a factor of 10 produces much larger changes in water levels in the aquifer, indicating that the model is much more sensitive to lower than to higher values.

(5) Precipitation recharge times 0.5 (0.5 x Rp): Halving the recharge rate from precipitation results in little to no change in water levels near streams, 2- to 4-ft decreases in water levels in areas away from streams, and decreased ground-water discharge from the aquifer to streams by 2 percent.

(6) Precipitation recharge times 2.0 (2 x Rp): Doubling the recharge rate from precipitation results in little to no change in water levels near streams, and 3- to 6-ft increases in water levels in areas away from streams. Total ground-water discharge from the aquifer to streams increased by 5 percent. Increasing precipitation recharge by a factor of 2 produced larger changes in water levels and more than doubled changes in ground-water discharge, indicating that the model is more sensitive to higher than to lower values.

In summary, the sensitivity analyses have shown that water levels near streams are significantly affected only by large decreases in streambed vertical hydraulic conductivity, and that changing other model input parameters has little or no effect on water levels near streams (figs. 17, 19). The analyses have shown also that water levels and ground-water discharge are most sensitive to large increases in precipitation recharge. Differences between calibrated steady-state model values and the values input for the sensitivity analysis illustrate the range in simulated response associated with what is believed to be the maximum uncertainty in each parameter.

Simulated Effects of Ground-Water Development

Hypothetical Ground-Water Pumpage During Average Conditions

Various development alternatives were simulated under long-term average annual conditions from a selected number of operational and hypothetical wells in the lower Wood River ground-water reservoir. Selected sites consisted of two operational wells and nine hypothetical wells. Hypothetical wells were located at 8-in. test well sites, where aquifer tests were conducted as part of this study. The objective of each hypothetical pumping simulation was to withdraw as much water as possible from the lower Wood River ground-water reservoir without (1) causing water level declines that would lower the initial saturated thickness of the aquifer by more than 25 percent, or (2) causing flow in any stream reach to cease.

Table 12 shows estimated maximum pumping rates for individual wells and summarizes simulated pumpage for each well for selected development alternatives. Estimated maximum pumping rates for individual wells range from 1.0 to 2.0 Mgal/d. These pumping rates are not additive because additional drawdown caused by interference between multiple pumping wells was not considered (see footnote 1 to table 12). However, these maximum rates do provide some measure of potential short-term emergency well yields. Total pumpage for selected development alternative simulations ranges from 6.0 to 11.0 Mgal/d (table 12). Individual wells were pumped at constant rates of 1.0 Mgal/d for all simulations.

For modeling purposes, all pumpage was assumed to be exported from the study area. However, if pumpage is returned to the flow system upstream of withdrawal points rather than exported from the study area, ground-water level and streamflow declines will be less than those predicted by the model. Therefore, model results shown here are on the conservative side, with higher total pumpage possible under return-flow conditions.

Ground-water-development alternatives were simulated at eleven sites: nine field sites where wells were pulled from the ground after aquifer tests, and two operational pumping well sites. The field-tested wells were pumped during aquifer tests conducted as part of this study. During these tests, wells were pumped at rates ranging from 0.46 to 0.91 Mgal/d (table 13). Well RIW 8, an operational 18- by 24-in.-diameter gravel-packed well owned by Carroll Products, was tested at 0.5 Mgal/d. Locations of all wells are shown in figure 2. Ground-water quality problems are known to exist at some of the sites.

During the process of evaluating the lower Wood River ground-water reservoir's potential long-term yield, more than 20 development alternatives were tested with the model. Wells tested during each development alternative were pumped simultaneously. The number of wells pumped concurrently during various development alternatives ranged from a minimum of 1 well to a maximum of 13 wells. Pumping rates for individual wells ranged from 0.50 to 2.0 Mgal/d. The seven pumpage scenarios shown in table 12 are not the only development alternatives possible, and other combinations of wells and pumping rates may produce similar total yields. Pumping was limited to a single well at each site where a field-site aquifer test had been conducted or an operational well installed. In the model, simulated wells are fully penetrating, whereas operational wells are partially penetrating.

Table 12.--Selected ground-water-development alternatives tested for steady-state conditions for the stratified-drift aquifer in the lower Wood River ground-water reservoir.

[ft, feet; in., inches; Mgal/d, million gallons per day; ---, not pumped]

		Data from large diameter test well						Pumping periods simulated[2]						
								Average condition						Drought condition[3]
								Development alternative (pumpage, in Mgal/d)						
Pumping site	Model node	Well number	Screen interval (ft)	Screen slot size (in.)	Pumping rate (Mgal/d)	Water level above screen (ft)	Estimated maximum pumping rate[1] (Mgal/d)	1	2	3	4	5	6	7
Haberek	23,61	RIW 550	65-73 73-85	0.040 .030	0.49	50	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Perreault	22,48	RIW 434	86-96 96-101	.040 .060	.83	75	2.0	---	1.0	1.0	1.0	1.0	1.0	---
James I	19,44	RIW 442	111-116 116-126	.040 .060	.90	101	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Macleod	22,39	RIW 458	84-94 94-104	.060 .030	.80	55	1.5	---	1.0	1.0	1.0	1.0	1.0	---
Hale and Trumpeto II	23,30	RIW 576	66-76 76-81 81-91	.040 .020 .040	.81	52	2.0	1.0	---	1.0	1.0	1.0	1.0	1.0
Town of Richmond	21,28	RIW 583	55-80	.020	.46	47	1.3	---	---	---	1.0	1.0	1.0	---
Hale and Trumpeto I	25,28	RIW 481	99-104 104-114	.100 .040	.89	91	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Carolina Realty	24,26	RIW 500	85-100	.030	.59	77	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Agency Realty and Mortgage Company	23,22	RIW 510	105-115 115-120	.040 .030	.91	95	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Carroll Products	23,20	RIW 8	55-75	---	.50	42	1.0	---	---	---	---	1.0	1.0	---
United Nuclear Corporation	25,12	CHW 351	60-75	.160	1.00	48	1.6	---	---	---	---	---	1.0	---
							TOTAL	**6.0**	**7.0**	**8.0**	**9.0**	**10.0**	**11.0**	**6.0**

1 Estimated maximum pumping rates are not additive because interference between wells was not considered. Estimates are based on specific capacity projected from drawdown at 1 foot radius and water available above the top of the well screen. Optimum size well required to pump estimated maximum is one 18- by 24- inch gravel packed well.

2 Wells were pumped continuously during all simulations.

3 Recharge and streamflow reduced 25-percent to simulate drought condition.

Two additional pumping sites, not shown in table 12, also were tested. Model results indicate that the Carolina Management site (well RIW 423 at model node 27,55) is capable of pumping about 0.4 Mgal/d under long-term average conditions. Because it was located too close to the bedrock valley wall, the Carolina Management site caused nodes near the model boundary to go dry when pumping 0.5 Mgal/d or more. For purposes of this study, if a well site would not produce at least 0.5 Mgal/d, it was eliminated from further testing. The second site, the James II site (well RIW 567 at model node 17,43), is capable of pumping 1.0 Mgal/d simultaneously with the James I site (well RIW 442 at model node 19,44). However, if the near by Perreault site (well RIW 434 at model node 22,48) is pumped simultaneously with the two James wells, drawdown becomes excessive due to well interference and nodes near the model boundry go dry.

Although pumpage scenarios were tested for more than 20 development alternatives, only scenarios 1 to 7 are discussed in detail in this report. Additional scenarios were not discussed because test results did not meet criteria set for pumping simulations or because total pumpage for the scenario was less than 6 Mgal/d.

Development alternatives

Development-alternative 1.--Development-alternative 1 (table 12) was run to test the ability of the lower Wood River ground-water reservoir to sustain an average daily yield of 6 Mgal/d. During this simulation, six wells were pumped at constant rates of 1.0 Mgal/d. Locations of wells and contours of the position of the steady-state water table for development-alternative 1 are shown in figure 20. Total pumpage of 6 Mgal/d produced drawdowns at pumped well nodes that ranged from 2.4 ft at well RIW 510 (node 23, 22) to 6.6 ft at well RIW 442 (node 19, 44). The areal extent of drawdowns greater than or equal to 2 ft is shown in figure 21. Under long-term average recharge conditions, the 2-ft draw-down area covers approximately 2.5 mi^2. Because they respond like large dug wells, small kettle-hole ponds that lie within the areas influenced by pumping should experience declines in pond levels similar to drawdowns shown in figure 21.

Elevated manganese concentrations have been measured at one site east of Meadow Brook Pond (RIW 510). Water quality at the other five sites appears to be suitable for most uses; however, only common constituents and properties have been measured at these sites. Some of the sites evaluated for this development alternative are overlain by agricultural areas, and the possibility of ground-water contamination by pesticides should be considered.

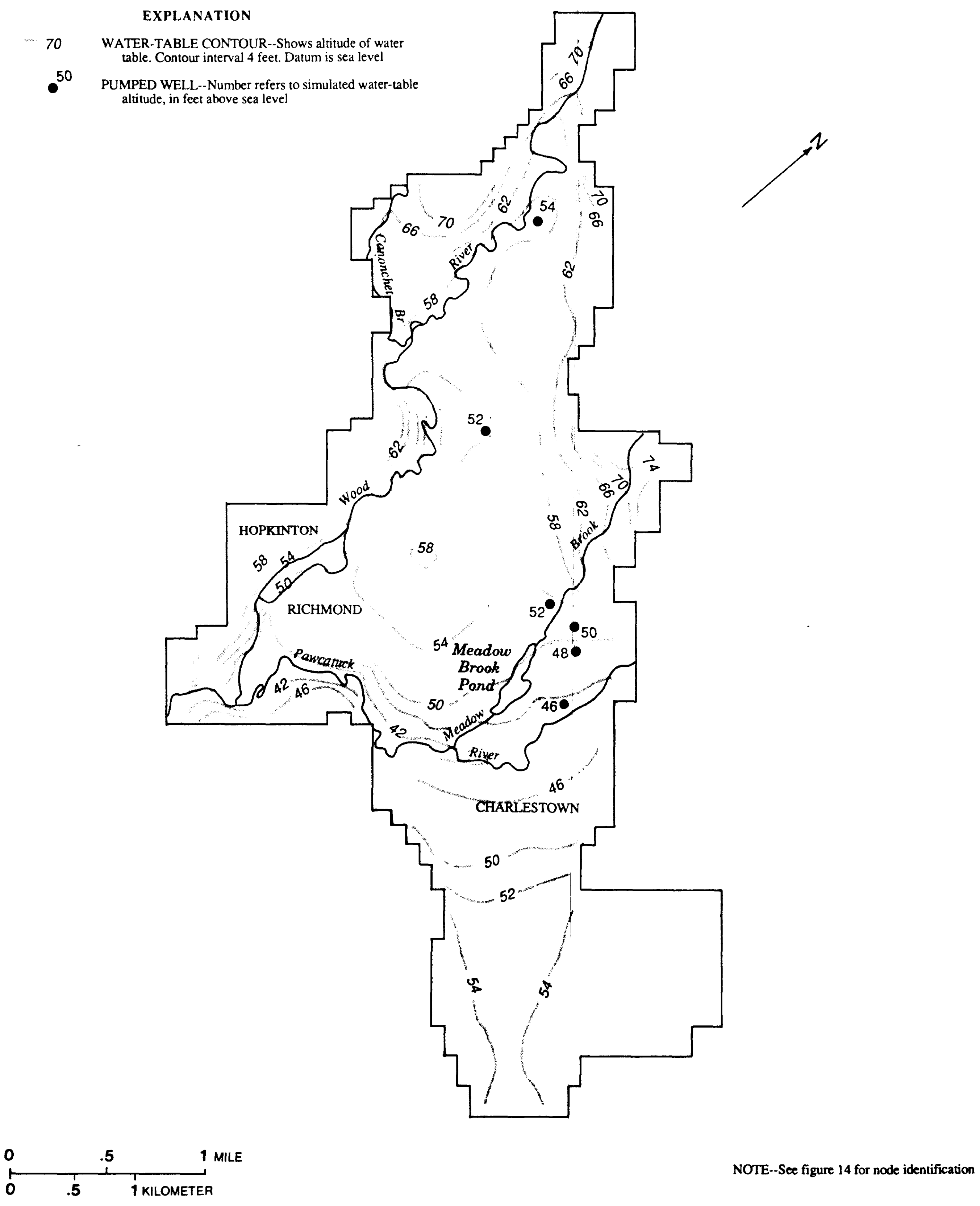


Figure 20.--Simulated position of steady-state water table for long-term average-annual streamflow and water-table conditions for development alternative 1, pumping 6.0 million gallons per day.

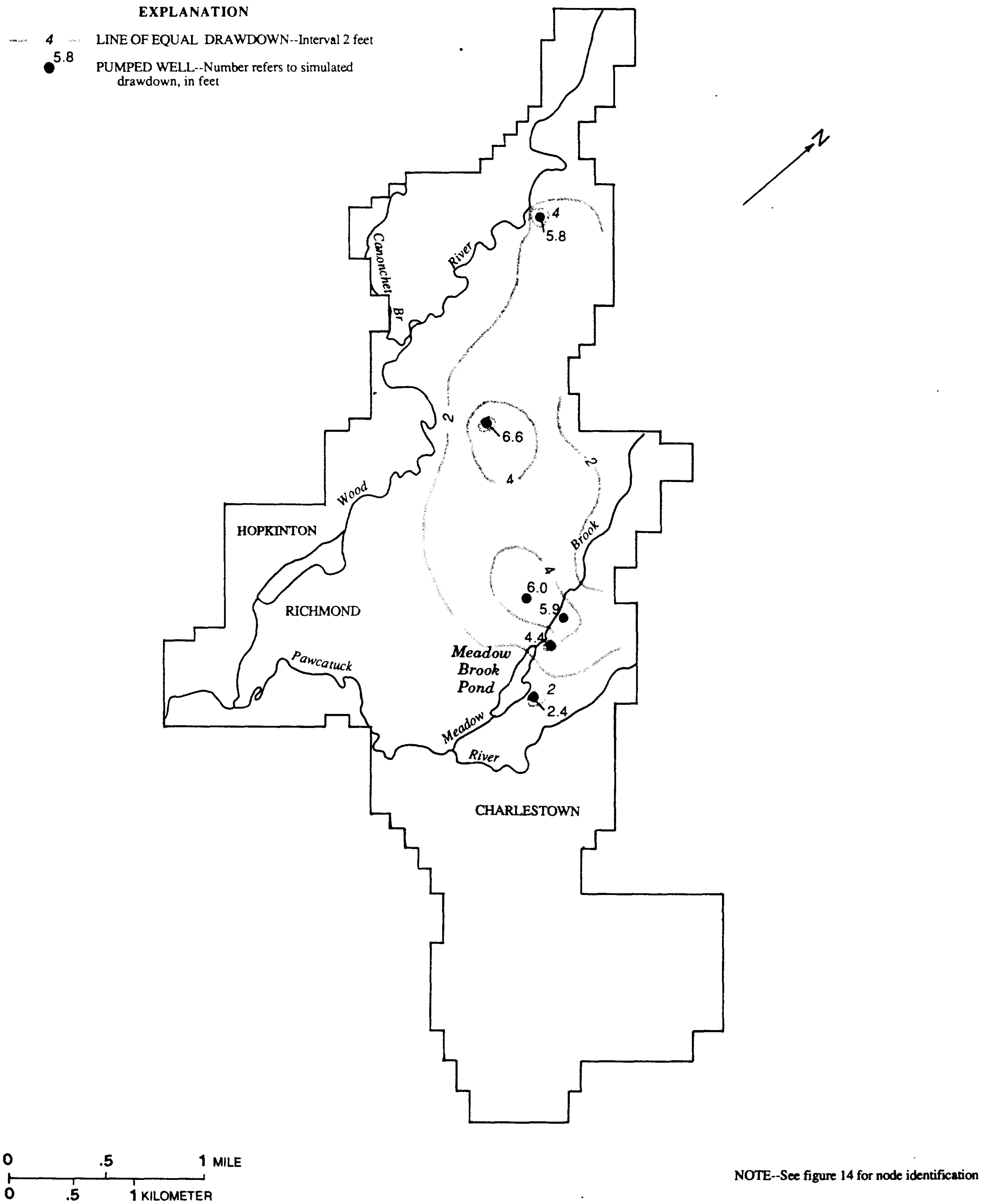


Figure 21.--Simulated steady-state drawdown for long-term average-annual streamflow and water-table conditions for development-alternative 1, pumping 6.0 million gallons per day.

Development-alternative 1 shows that the lower Wood River ground-water reservoir can sustain an average daily yield of 6 Mgal/d with minimal effect on streamflow, pond levels, and ground-water levels under long-term-average annual hydrological conditions. Criteria for streamflow depletion and reduction in aquifer saturated thickness for hypothetical simulations were met with development-alternative 1. The combination of six pumped wells used in this simulation is only one of several scenarios shown in table 12 that would produce a yield of 6 Mgal/d.

Development-alternatives 2 to 5.--Pumping scenarios given in development-alternatives 2 to 5 (table 12) show that the lower Wood River ground-water reservoir is capable of sustaining an average daily yield of 7 to 10 Mgal/d under long-term-average annual hydrological conditions. The needs of the RIWRB to obtain an average daily yield of 6 Mgal/d from the basin can be met with each of these pumpage scenarios. Using different combinations of wells, one to four wells could be eliminated from alternatives 2 to 5, respectively, and each pumping scenario could still meet the 6-Mgal/d goal of the RIWRB. No stream reaches went dry and reduction in aquifer saturated thickness was less than 25 percent for each pumpage scenario. Development-alternatives 2 to 5 provide flexibility in the design and management of the lower Wood River ground-water reservoir to sustain an average daily yield of 6 Mgal/d.

Development-alternative 6.--In order to test the maximum pumping capacity of the lower Wood River aquifer, ground-water withdrawals were gradually increased to see if the ground-water reservoir could sustain pumpage equal to the total simulated ground-water runoff (16.9 Mgal/d) available within the modeled area. Development-alternative 6 (table 12) shows that the lower Wood River ground-water reservoir can sustain a maximum yield of 11 Mgal/d from 11 wells at tested sites. During this simulation, each of the 11 wells were pumped at a constant rate of 1.0 Mgal/d. Well locations and contours of the steady-state-pumping water table are shown in figure 22. Total pumpage of 11 Mgal/d produced drawdowns at pumping well nodes that ranged from 3.1 ft at well RIW 510 to 13.4 ft at well RIW 458 (table 13).

Table 13 shows a comparison between measured drawdown from aquifer tests and maximum predicted model drawdown at pumping nodes near 8-in. test sites and operational well sites. Model drawdowns are shown at each pumped node. Also shown are pumped node drawdowns adjusted to a 1-ft well radius by extrapolation using the Thiem equation (Trescott and others, 1976, p. 10). For example, pumped-node drawdown of 12.6 ft at well RIW 442, adjusted for a well with a 1-ft radius, becomes 19.0 ft. Drawdowns were adjusted to a 1-ft well radius because this is the radius of a typical **gravel packed well** installed in Rhode Island. Table 13 also shows pumping rates and drawdowns for aquifer tests conducted as part of this study, for comparison with pumping rates and drawdowns simulated under steady-state-pumping

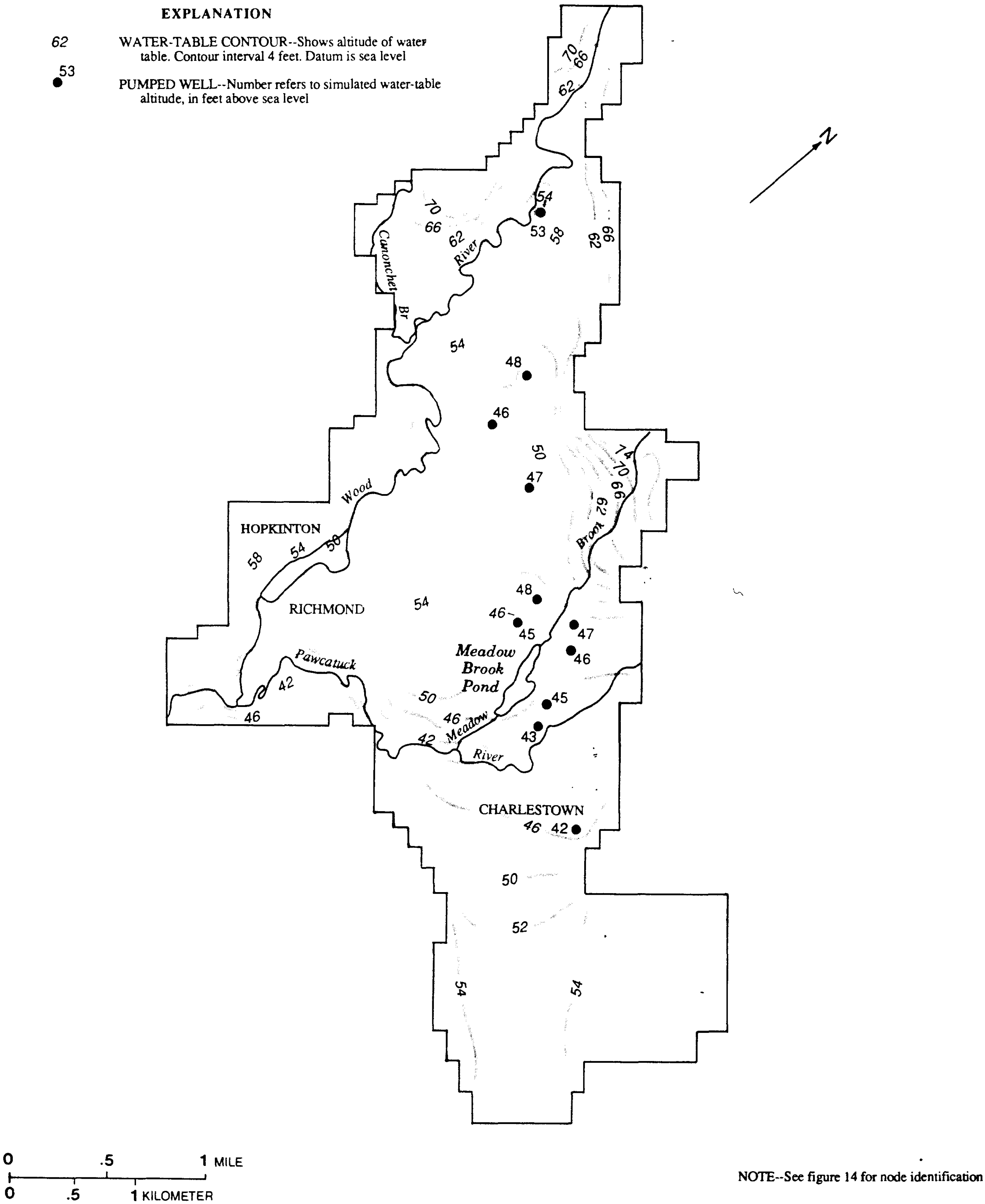


Figure 22.--Simulated steady-state drawdown for long-term average-annual streamflow and water-table conditions for development-alternative 6, pumping 11.0 million gallons per day.

Table 13.--Comparison of drawdowns from aquifer tests with simulated steady-state drawdowns during maximum pumpage of 11 million gallons per day, in the lower Wood River ground-water reservoir.

[d, days; Mgal/d; million gallons per day; ft; feet; --, not known]

			AQUIFER TEST			MODEL SIMULATION				
Pumping site	Model node	Well number	Time (d)	Pumping rate (Mgal/d)	Drawdown[1] (ft)	Time (d)	Pumping rate (Mgal/d)	Drawdown[1,2] (ft)	Drawdown at pumped node (ft)	Drawdown[3] (ft)
Haberek	23,61	RIW 550	2	0.49	10.1 (6.0)	Infinity	1.0	10.8 (6.0)	6.5	13.7
Perreault	22,48	RIW 434	2	.83	1.5 (5.0)	Infinity	1.0	16.2 (5.0)	12.9	18.1
James I	19,44	RIW 442	2	.90	9.3 (5.0)	Infinity	1.0	16.7 (5.0)	12.6	19.0
Macleod	22,39	RIW 458	2	.80	12.8 (5.5)	Infinity	1.0	15.3 (5.5)	13.4	16.5
Hale and Trumpeto II	23,30	RIW 576	2	.81	8.4 (4.9)	Infinity	1.0	12.5 (4.9)	10.3	13.7
Town of Richmond	21,28	RIW 583	2	.46	8.1 (4.8)	Infinity	1.0	15.7 (4.8)	11.3	18.1
Hale and Trumpeto I	25,28	RIW 481	2	.89	2.1 (5.2)	Infinity	1.0	11.2 (5.2)	8.7	12.6
Carolina Realty	24,26	RIW 500	1.8	.59	10.2 (5.0)	Infinity	1.0	8.3 (5.0)	6.3	9.4
Agency Realty and Mortgage Company	23,22	RIW 510	2	.91	10.6 (5.0)	Infinity	1.0	5.0 (5.0)	3.1	6.1
Carroll Products	23,20	RIW 8	1	.50	-- --	Infinity	1.0	-- --	2.8	7.3
United Nuclear Corporation	25,12	CHW 351	0.3	1.00	14.1 (2.0)	Infinity	1.0	12.5 (2.0)	5.8	13.7
			Total	[4]9.84		Total	[5]11.0			

1 Number in parentheses ( ) is distance from pumped well to observation well in feet.
2 Drawdown at model pumped node adjusted to radius shown in parenthesis ( ).
3 Drawdown at model pumped node adjusted to 1 foot radius.
4 Wells not pumped simultaneously.
5 Wells pumped simultaneously.

conditions. In the stratified-drift aquifer, maximum drawdown did not exceed 20 percent of the initial saturated thickness of the aquifer at any node during any pumping simulation. Maximum simulated drawdown, for a well adjusted to a 1-ft radius during total pumpage of 11 Mgal/d in the lower Wood River area was 19.0 ft (nodal drawdown was 12.6 ft at node 19,44; see table 13) of an available 100 ft of saturated thickness.

Figure 23 shows the simulated decline in the altitude of the water table for development-alternative 6 and delineates the areal extent of drawdown zones of 2 ft or more. If these drawdowns are compared with those shown in figure 21 for development-alternative 1, the 2-ft-drawdown zones are similar, whether pumping 6 Mgal/d or 11 Mgal/d. Shallow kettle-hole ponds within the study area probably would experience declines in pond levels similar to drawdowns shown in figure 21 and 23 when pumping 6 and 11 Mgal/d, respectively.

All criteria were met with development-alternative 6. Water level declines were not excessive, the initial saturated thickness of the aquifer was reduced less than 25 percent, and no stream reaches went dry under long-term-average conditions.

Three of the 11 sites tested for development-alternative 6 have water quality unsuitable for most uses. One site (CHW 351) is adjacent to the low-level-radionuclide contamination plume. Large-scale pumping at this location could induce contaminated water into the well. The other two sites (RIW 8 and 510) have elevated concentrations of iron and manganese. Water quality at the other eight sites appears to be suitable for most uses; however, some of the sites are overlain by agricultural areas, and pesticide contamination is a possibility. If the three sites with unacceptable water quality are not used, the ground-water reservoir can sustain withdrawals of 6 to 8 Mgal/d from eight sites under long-term-average hydrological conditions.

Increased Pumpage (10.0 Mgal/d) near Meadow Brook Pond.--Six wells near Meadow Brook Pond were pumped at high rates to evaluate ground-water movement between the contamination plume from the low-level-radionuclide contamination site in Charlestown and Meadow Brook Pond in Richmond (fig. 24). The purpose of this particular pumping scenario was to determine if ground water within the contamination plume could be diverted under the Pawcatuck River and into pumping wells on the other side of the river under extremely heavy pumping--a condition that could occur during a severe drought.

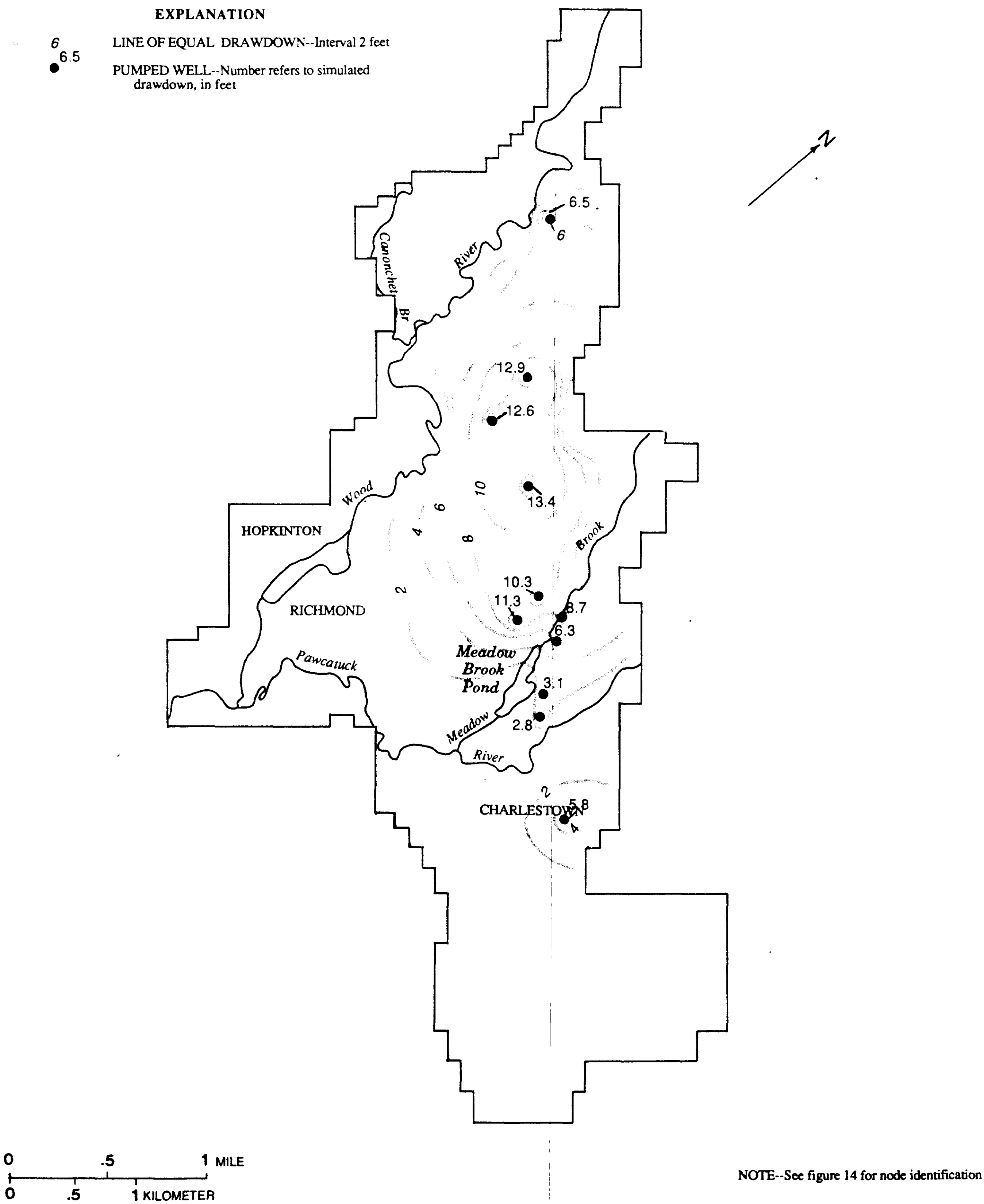


Figure 23.--Simulated steady-state drawdown for long-term average-annual streamflow and water-table conditions for development-alternative 6, pumping 11.0 million gallons per day.

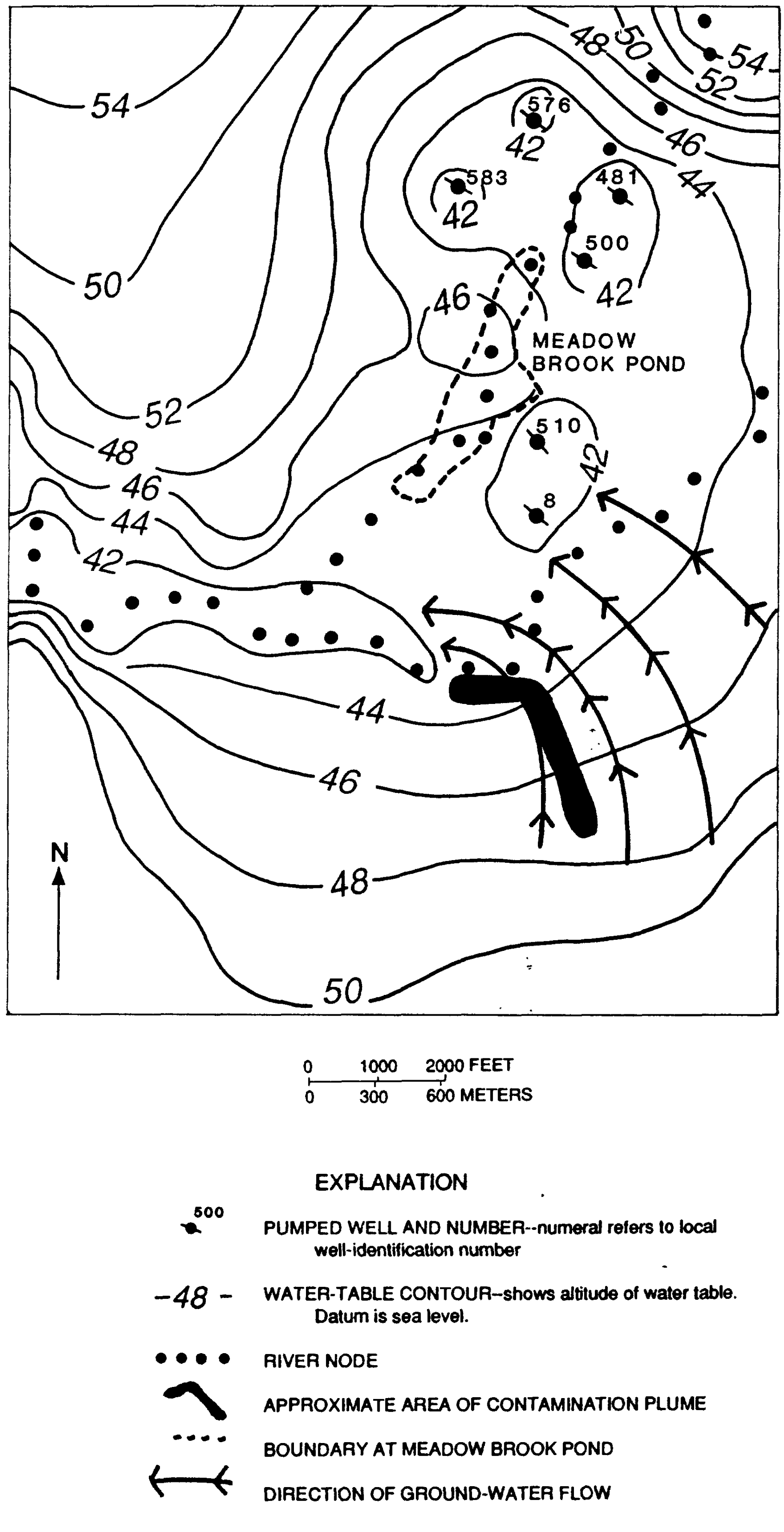


Figure 24.--Simulated position of steady-state water table and direction of ground-water flow in the vicinity of a contamination plume for 10.0 million gallons per day pumpage concentrated near Meadow Brook Pond.

Model results for this simulation (fig. 24) show the position of the steady-state water table and the direction of ground-water-flow in the vicinity of the contamination plume. Ground-water-flow lines in figure 24 indicate that ground water can be diverted under the Pawcatuck River from Charlestown toward two pumping wells (RIW 8 and 510) in Richmond. Figure 24 also shows that ground water diverted under the Pawcatuck River toward wells RIW 8 and 510 is derived from a source north or northeast of the contamination plume.

Each of the six pumped sites in this simulation was assumed to consist of one 18- by 24-in.-diameter well. Each well was pumped at its estimated maximum capacity. Wells RIW 8 and 583 were pumped at 1 Mgal/d, and wells RIW 481, 500, 510, and 576 were pumped at 2 Mgal/d. Figure 25 shows resultant steady-state drawdown for these wells under total pumpage of 10 Mgal/d. Pumpage of 10 Mgal/d caused drawdowns at pumped-well nodes of 4.96 ft (RIW 8) to 17.37 ft (RIW 481) and caused five stream nodes in Meadow Brook Pond to go dry.

The simulation shows that ground water can be diverted from the Charlestown side of the Pawcatuck River to pumped wells near Meadow Brook Pond in Richmond at a combined pumping rate of 10 Mgal/d. However, ground water within the low-level-radionuclide contamination plume in Charlestown is not diverted to RIW wells 8 and 510 in Richmond with the number, locations, and total pumpage of wells used for this scenario.

Stream-Aquifer Interaction

Figure 26 demonstrates the reduction in stream discharge due to ground-water pumpage in the lower Wood River model. Meadow Brook (segment 2, fig. 14) was selected for this figure because it is the stream segment most affected by ground-water pumpage. Profiles of stream discharge along Meadow Brook extend from the northernmost stream node at Pine Hill Road to the mouth of the brook at the Pawcatuck River. These profiles show reductions in streamflow due to simulated ground-water withdrawals for development-alternatives 1 and 6. Figure 26 shows streamflow along Meadow Brook, a naturally losing brook, decreasing by 1.87 ft^3/s under nonpumping average conditions from 9.36 ft^3/s at Pine Hill Road to 7.49 ft^3/s at its mouth. Comparisons of stream discharge profiles along Meadow Brook for development-alternative 1, pumping 6 Mgal/d, and development-alternative 6, pumping 11 Mgal/d, show that streamflow decreases along the same reach by 4.86 ft^3/s and 7.18 ft^3/s, respectively. During testing of development-alternatives 1 through 6, no stream nodes went dry.

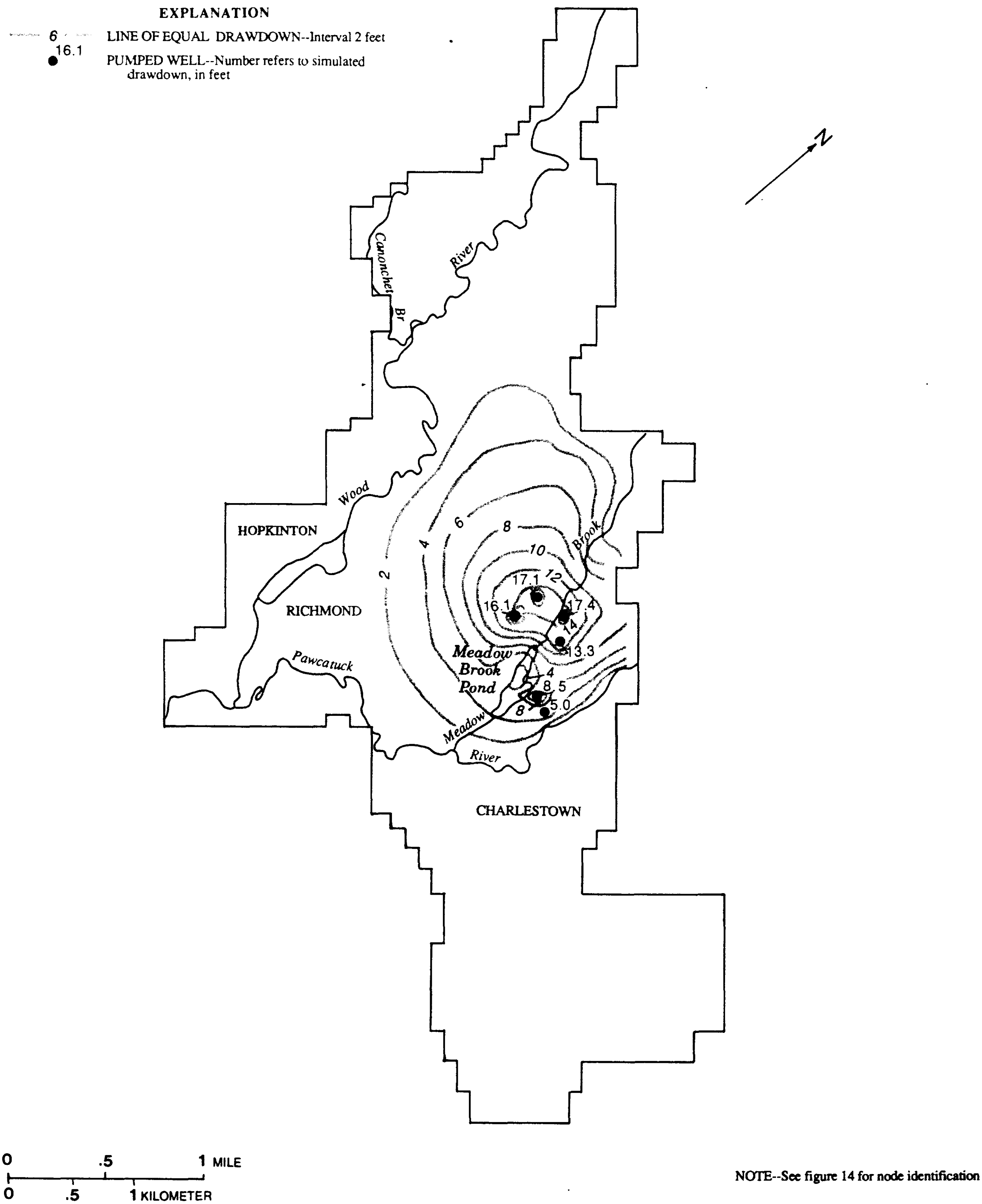


Figure 25.--Simulated steady-state drawdown for 10.0 million gallons per day pumpage concentrated near Meadow Brook Pond.

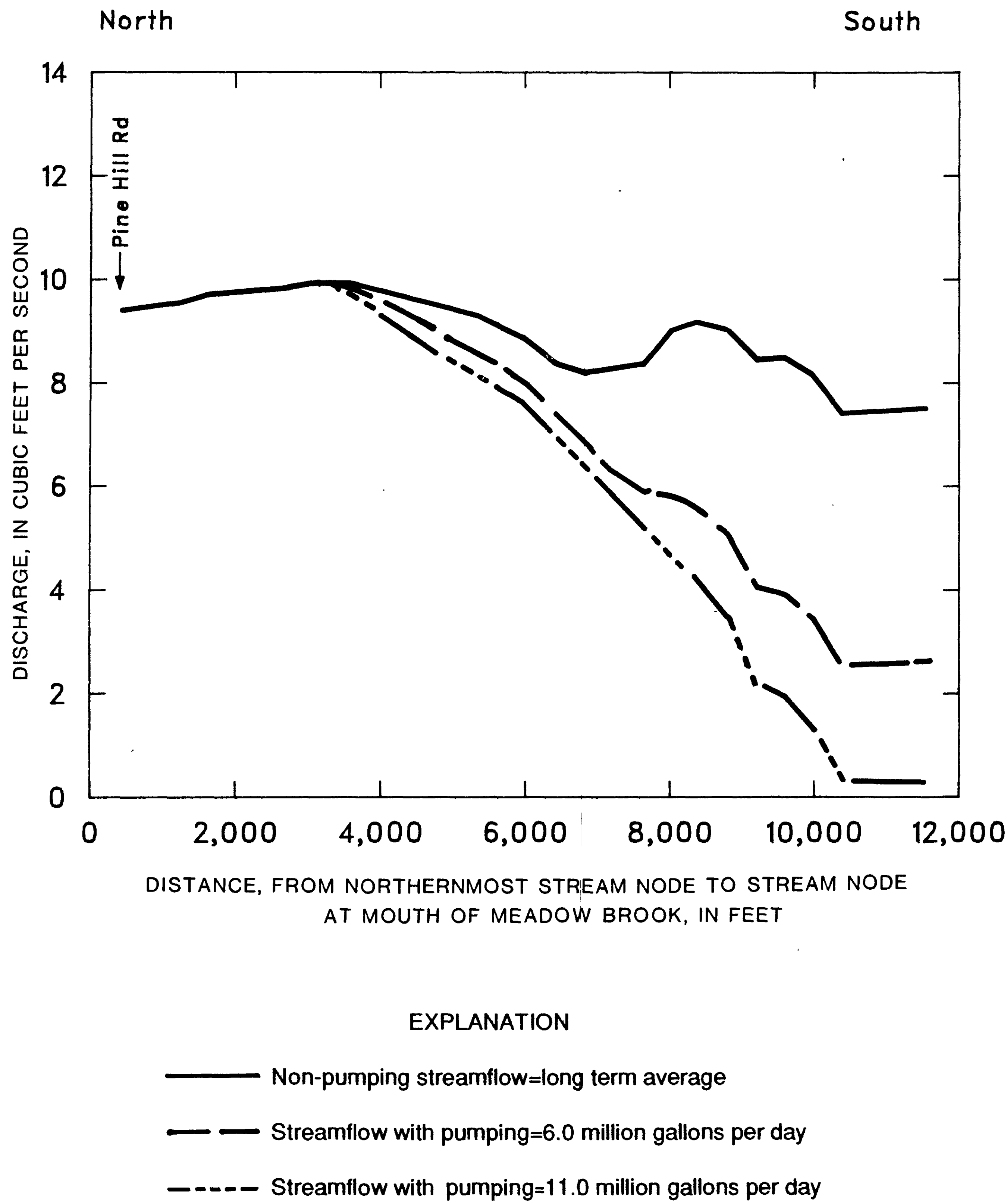


Figure 26.--Comparision of stream discharge profiles for long-term average-annual streamflow and water-table conditions along Meadow Brook showing reduction in streamflow due to simulated ground-water pumpage of 6.0 and 11.0 million gallons per day.

Streamflow depletion along the other six stream segments shown in figure 14 are summarized in table 14 for development-alternative 1, 6, and 7. This table shows changes in stream leakage to, or from, stream segments for nonpumping and pumping conditions for each stream segment for long-term-average and drought hydrological conditions. Table 14 shows that ground-water pumpage did not affect stream leakage along Canonchet Brook during any pumping scenario and that maximum streamflow declines occurred along Meadow Brook, where stream leakage declined by 7.2 ft^3/s during development-alternative 6.

Source of Pumped Water

Pumping scenarios tested show that 96 to 98 percent of all ground-water pumpage will be derived from a combination of intercepted ground-water runoff and induced stream infiltration. The remaining 2 to 4 percent is derived from reduced evapotranspiration. The amount of water that a well derives from intercepted ground-water runoff, induced recharge from streamflow, or reduced evapotranspiration is highly variable.

Generally, the closer a well is located to a surface water body, the larger the percentage of water derived from induced recharge from streamflow. Conversely, the farther away from the surface water body the well is located, the smaller the percentage of water derived from induced recharge from streamflow and the greater the amount derived from intercepted ground-water runoff. Intercepted ground-water runoff is ground water that is moving in the aquifer flow system toward a stream, but is intercepted by a pumped well before it discharges to the stream as ground-water runoff.

For the 20 pumping scenarios tested, water derived from intercepted ground-water runoff ranged from 55.5 to 77.3 percent of the total, and that derived from induced recharge from streamflow ranged from 20.1 to 42.7 percent. Table 15 summarizes the source and relative percentages of water withdrawn from wells for the seven ground-water-development alternatives shown in table 12.

The quality of surface water in the study area appears to be generally suitable for most uses, and, therefore, induced recharge is not expected to have an adverse effect on ground-water quality. However, where organic material covers streambeds, water induced into the aquifer may undergo a change in redox potential that results in increased concentrations of iron or manganese.

Table 14.--Change in stream leakage to or from stream segments for nonpumping and pumping conditions for long-term average and drought hydrological conditions in the lower Wood River ground-water reservoir.

[stream leakage, in cubic feet per second]

Stream segment		Long-term average condition			Drought condition	
		Nonpumping	Pumping		Nonpumping	Pumping
			Development-alternative 1	Development-alternative 6		Development-alternative 7
Name	Number	Stream leakage[1]	Stream leakage[1]	Stream leakage[1]	Stream leakage[1]	Stream leakage[1]
Pawcatuck	1	8	7	5	8	6
River	3	3	2	2	2	2
	7	1	1	0	0	1
subtotal		12	10	7	10	9
Wood	4	5	3	2	3	2
River	6	6	5	4	5	4
subtotal		11	8	6	8	6
Canonchet Brook	5	0.9	0.9	0.9	0.6	0.6
Meadow Brook	2	-1.91	-6.76	-9.08	-2.84	-7.02
Total		21.99	12.14	4.82	15.76	8.58

1 A positive number indicates that ground water leaks from the aquifer into the stream, and a negative number indicates that water from the stream leaks into the aquifer.

Table 15.--Summary of source by percent of water withdrawn from wells during selected ground-water development alternatives in the lower Wood River ground-water reservoir.

[Mgal/d, million gallons per day]

		Source, by percent		
Development alternative[1]	Pumpage, in Mgal/d	Intercepted ground-water runoff[2]	Induced recharge	Reduction in evapotranspiration
1	6.0	55.9	42.2	1.9
2	7.0	61.9	36.4	1.7
3	8.0	58.6	39.7	1.7
4	9.0	55.5	42.7	1.8
5	10.0	56.8	41.5	1.7
6	11.0	58.3	37.9	3.8
[3]7	6.0	58.8	40.4	0.8

1 See table 12 for summary of data on individual pumping sites, pumping rates, and pumping conditions simulated.
2 Water that would have discharged into streams as ground-water runoff, but instead was intercepted by pumping wells before it reached the stream.
3 Simulated drought condition shown for comparison with average condition in development-alternative 1.

Hypothetical Ground-Water Pumpage During Drought Conditions (Development-Alternative 7)

The lower Wood River model was used to test the ability of the ground-water reservoir to sustain an average daily yield of 6 Mgal/d under simulated drought conditions. Drought conditions were simulated in the model by reducing long-term-average recharge from precipitation, inflow from till-covered bedrock uplands, and streamflow by 25 percent. These reduced values approximate the 1963-66 drought--a period considered representative of extreme drought conditions. The 1963-66 drought period represents the lowest consecutive 4 years of precipitation recorded at the National Weather Service Station at Kingston since the station began operation in 1889. Figure 27 shows the position of the simulated steady-state water table for nonpumping drought conditions. This figure is given to compare changes in ground-water head during drought conditions with ground-water head shown in figure 16 for average conditions.

For development-alternative 7 (table 12), the same wells and pumping rates were selected as were tested during development-alternative 1 for average conditions. Location of the six pumped wells, and simulated contours of the position of the steady-state water table for development-alternative 7 are shown in figure 28. Total pumpage of 6 Mgal/d produced drawdowns at pumped well nodes of 2.7 ft at well RIW 510 (node 23, 22) to 7.0 ft at well RIW 442 (node 19, 44). The areal extent of drawdowns greater than or equal to 2 ft is shown in figure 29. Under simulated drought conditions, the 2-ft-drawdown area shown in figure 29 covers about the same 2.5-mi^2 area as shown in figure 21 for pumping under long-term-average conditions. The major difference in drawdown between drought (fig. 29) and long-term-average (fig. 21) pumping simulations is that the areal extent of the 4-ft-drawdown zone approximately doubles in area under drought conditions.

Stream-discharge profiles along Meadow Brook demonstrate the interaction between the stream and the aquifer under simulated drought conditions pumping at 6 Mgal/d (fig. 30). Nonpumping (natural) simulated streamflow is shown for comparison in figure 30 for long-term-average and drought hydrological conditions. This figure shows that streamflow along Meadow Brook, a naturally losing brook, would decrease by 1.9 ft^3/s under nonpumping average conditions (from 9.4 ft^3/s at Pine Hill Rd. to 7.5 ft^3/s at its mouth) and by 2.8 ft^3/s under nonpumping drought conditions from 7.0 ft^3/s to 4.2 ft^3/s.

Figure 30 also shows that pumping 6 Mgal/d under simulated drought conditions causes flow in Meadow Brook to cease near the mouth of the brook. The stream discharge profile for development-alternative 7, pumping 6 Mgal/d, shows that streamflow would decrease by 7.0 ft^3/s to zero flow at the mouth of Meadow Brook.

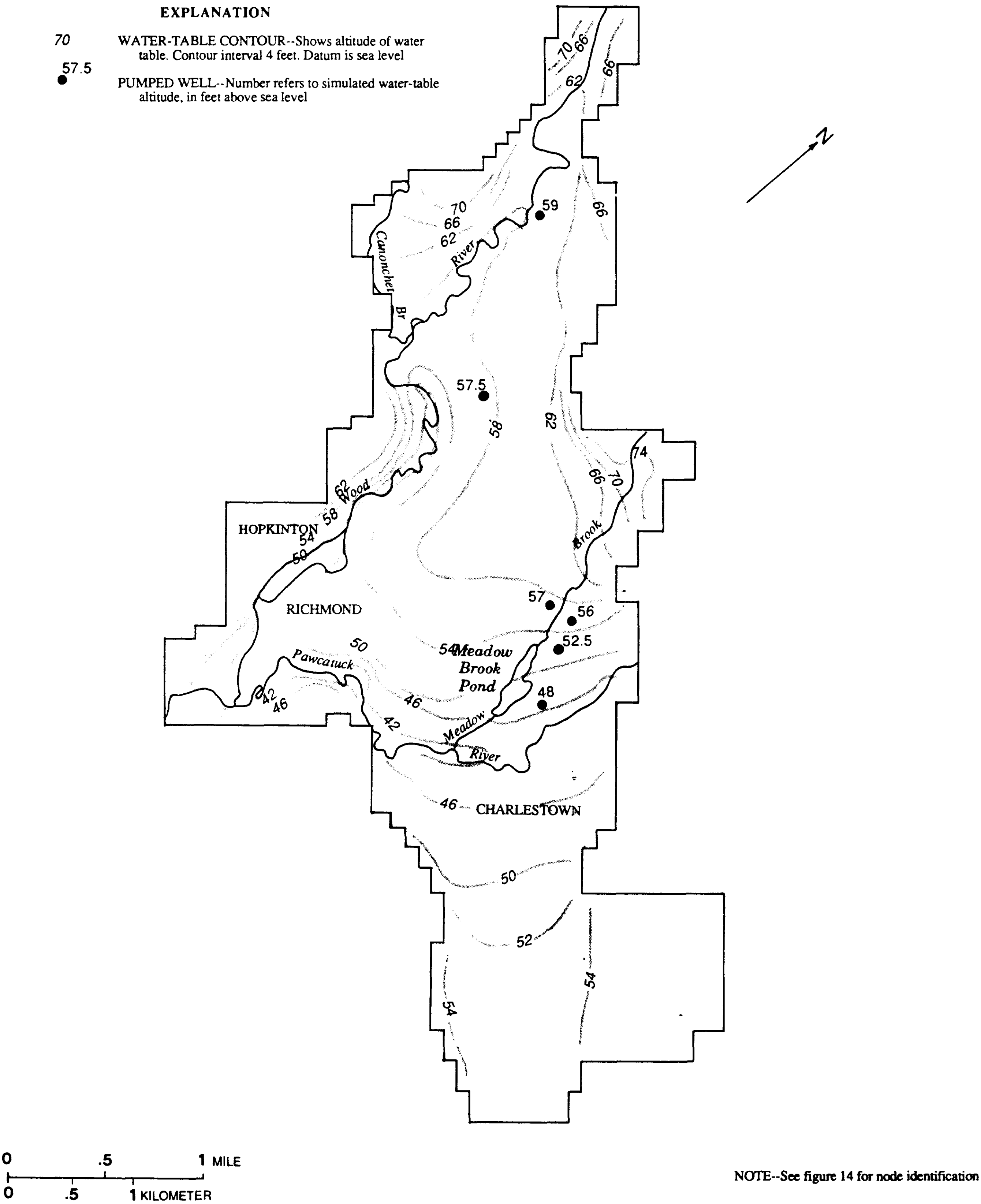


Figure 27.--Simulated position of steady-state water table for nonpumping, drought conditions.

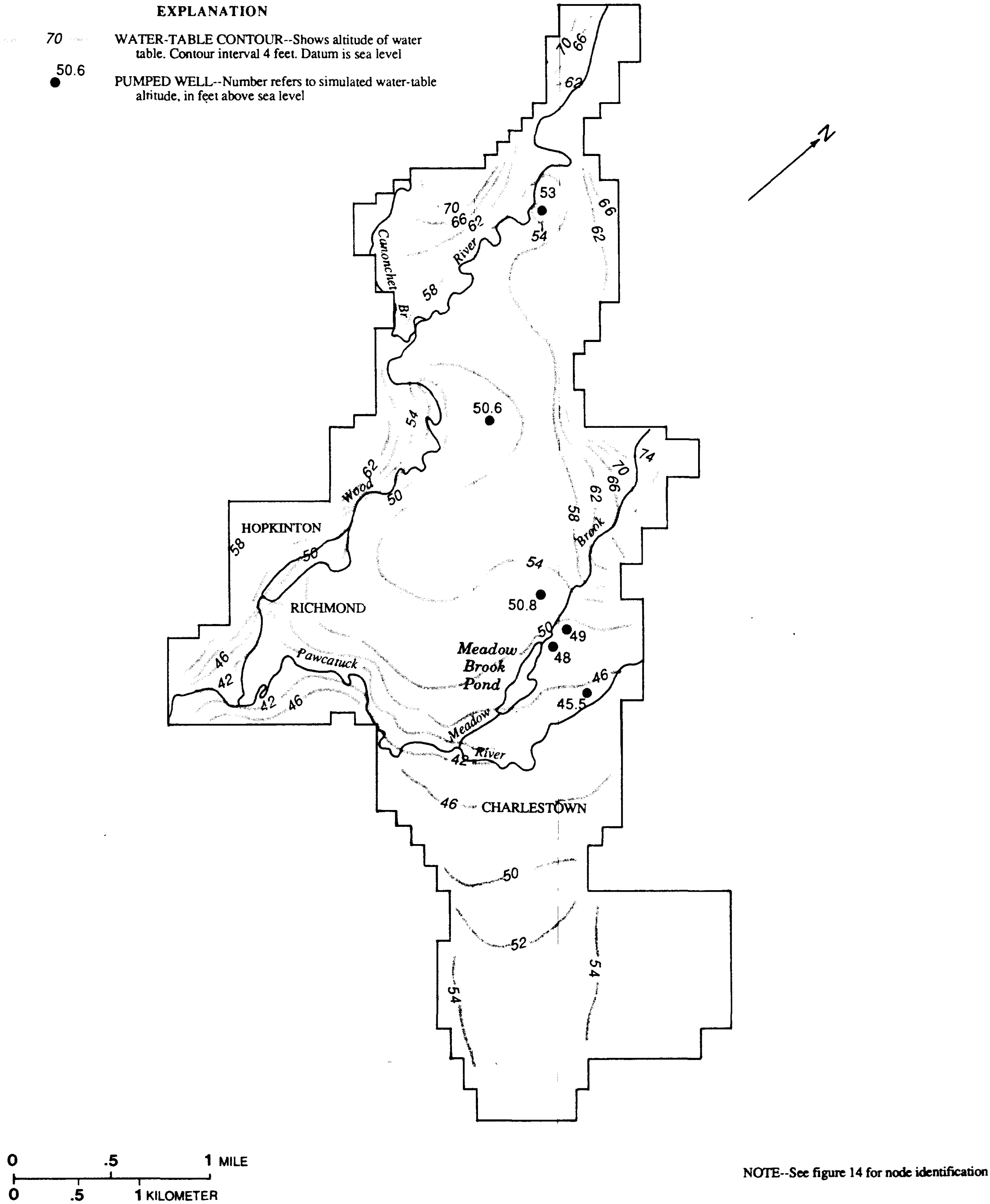


Figure 28.--Simulated position of steady-state water table for a drought conditon for development alternative 7, pumping 6.0 million gallons per day.

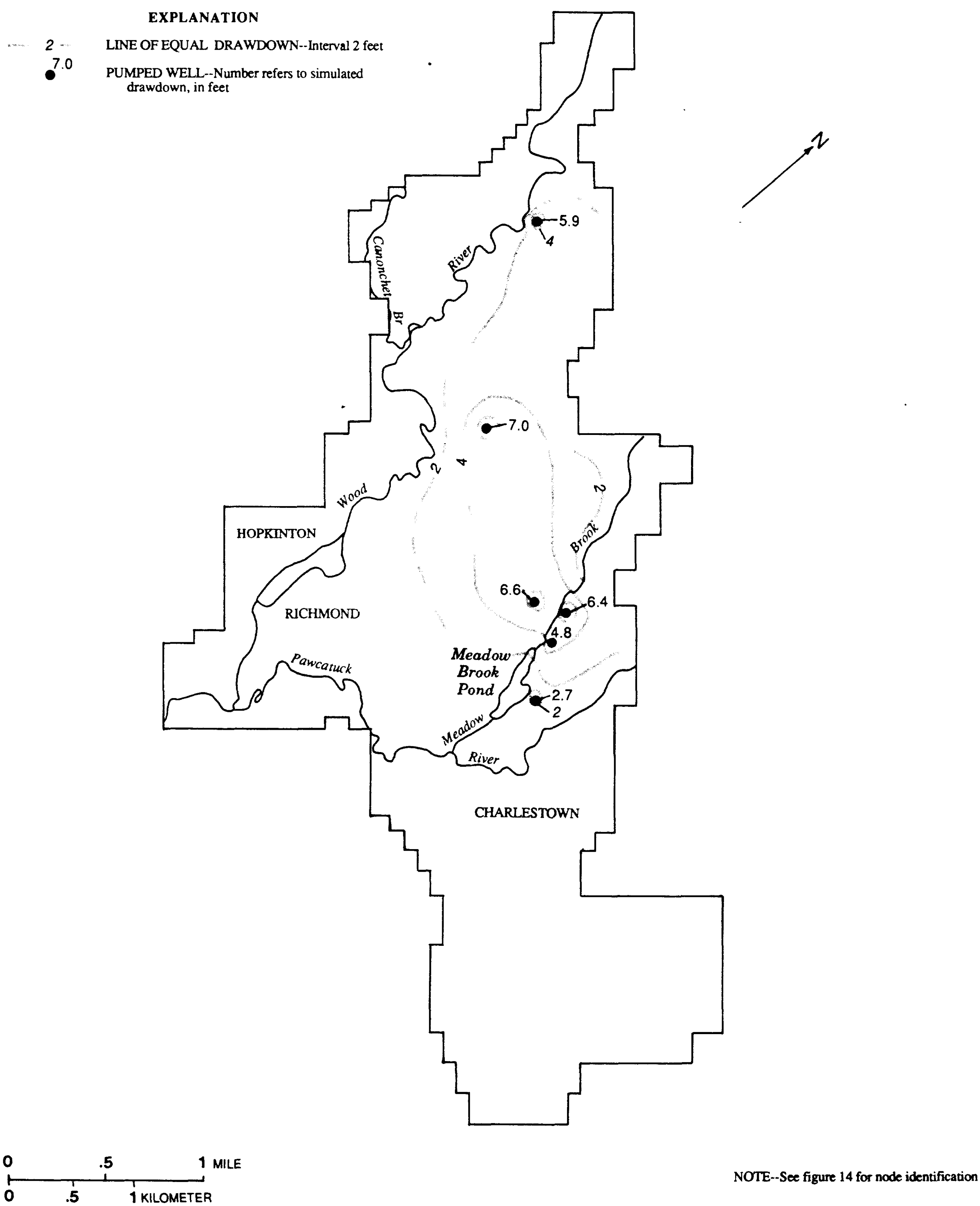


Figure 29.--Simulated steady-state drawdown for a drought condition for development alternative 7, pumping 6.0 million gallons per day.

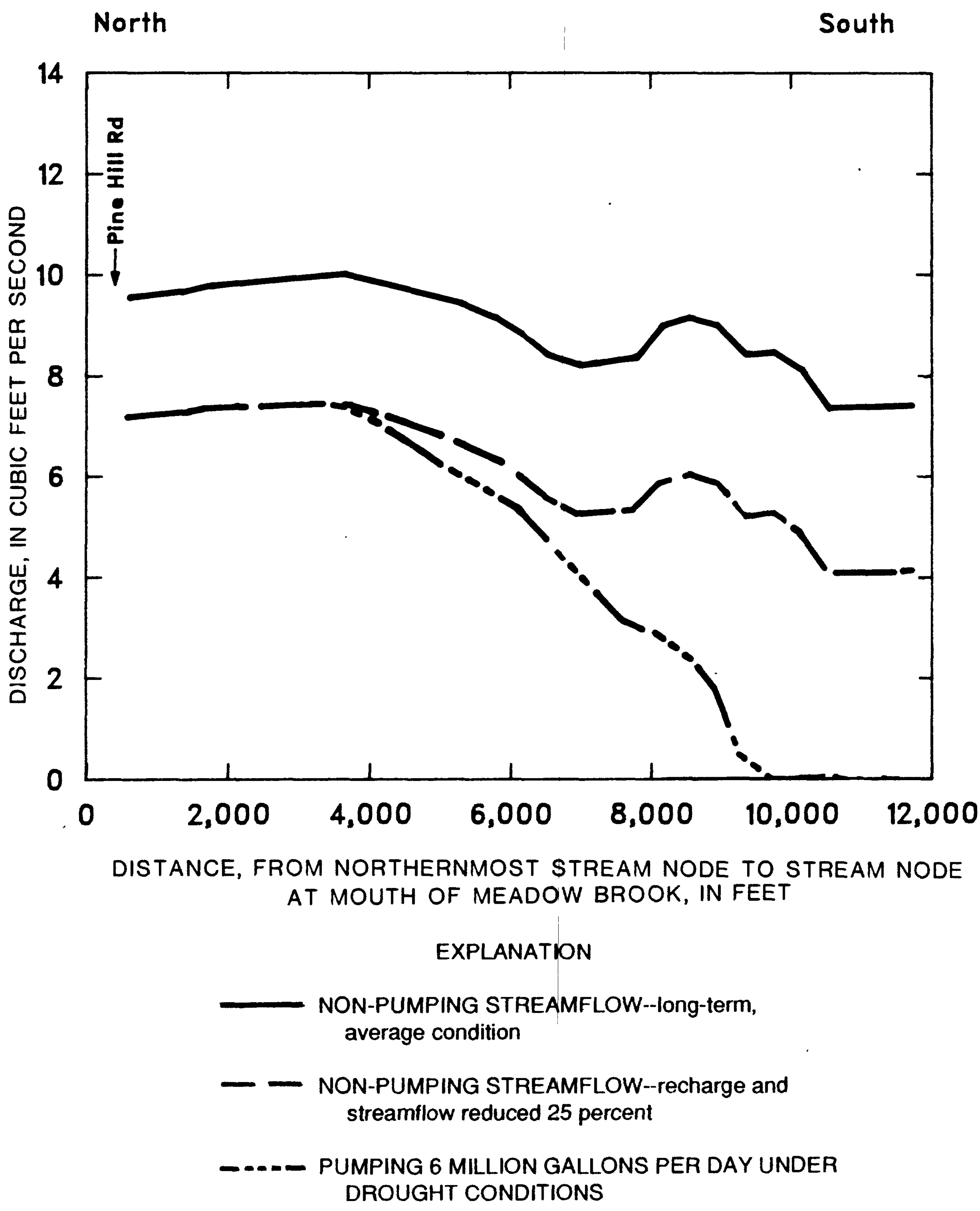


Figure 30.--Comparison of stream discharge profiles for drought conditions along Meadow Brook showing reduction in streamflow due to simulated ground-water pumpage of 6.0 million gallons per day.

The two criteria established for hypothetical pumping simulations could not all be met under drought conditions. The one criterion met was that the initial saturated thickness of the aquifer be reduced by less than 25 percent. Water-level declines were not excessive and the maximum reduction in initial saturated thickness of the aquifer was about 7 percent. The criterion of minimal streamflow depletion with no dry reaches was not met and six pond or brook nodes would go dry along Meadow Brook. However, except for Meadow Brook, streamflow depletion along the other six stream segments shown in figure 14 is minimal. Maintaining some flow in Meadow Brook during drought periods may require reduction of pumpage to less than 6 Mgal/d. However, model results are believed to be conservative inasmuch as simulations were done under steady-state conditions and pumpage was assumed to be exported from the basin. Reduction in pumpage may not be necessary if water pumped from the aquifer is returned to the flow system upstream from ground-water withdrawal points.

SUMMARY AND CONCLUSIONS

This report describes the hydrogeology and water quality of the lower Wood River ground-water reservoir and presents results of steady-state model simulations. The U.S. Geological Survey ground-water-flow model, developed by McDonald and Harbaugh (1984), was used to simulate the steady-state ground-water flow system and its response to imposed stresses.

The lower Wood River study area is located within the Pawcatuck River basin in southern Rhode Island. The predominantly crystalline bedrock of the study area is covered by glacial deposits of till and stratified drift. Till is exposed at the land surface in the upland areas, and stratified drift forms broad lowlands in the major stream valleys. Stratified drift is the only geologic unit capable of producing well yields greater than 350 gal/min. The lower Wood River ground-water reservoir is that part of the stratified-drift aquifer with the greatest potential for ground-water development. The saturated thickness of the stratified-drift aquifer averages 70 ft and has a maximum known saturated thickness greater than 290 ft. Aquifer transmissivity ranges from 8,600 to 36,400 ft^2/d. Horizontal hydraulic conductivity ranges from 125 to 545 ft/d, and vertical hydraulic conductivity ranges from 4 to 210 ft/d. Unconfined conditions prevail in the aquifer, which is hydraulically connected with perennial streams and ponds.

Water available annually for recharge generally is equal to annual runoff (precipitation minus evapotranspiration). Annual precipitation from 1941-76 averaged 45.5 in. Of this amount, 27 in. reached the water table as recharge and the rest (18.5 in.) returned to the atmosphere by evapotranspiration.

The sites most favorable for development of high-capacity wells (those capable of 350 gal/min or more) are located between the Wood River and Meadow Brook in the Ellis Flats area and along the eastern side of Meadow Brook.

Water quality in the lower Wood River study area is generally suitable for most uses. Uncontaminated surface water and ground water contain low concentrations of dissolved mineral matter. Median values for dissolved solids concentrations are 38 mg/L for surface water and 54 mg/L for ground water. Water in the ground and in streams is soft and slightly acidic. Ground-water contamination has been detected in several locations. Significant contaminants identified include nitrate, pesticides, and radionuclides. These contaminants have been introduced by various land-use and waste-disposal activities.

Excessive concentrations of iron and manganese in ground water are present locally and are probably derived from natural sources. Concentrations of both constituents in water from two observation wells east of Meadow Brook Pond consistently exceeded USEPA MCL's for drinking water. Median concentrations of iron in these wells were 15 and 12.9 mg/L. Median concentrations of manganese were 0.46 and 0.39 mg/L. Elevated iron and manganese concentrations may be related to the absence of dissolved oxygen in the zone of the aquifer screened by the wells. Meadow Brook Pond and the lower reaches of Meadow Brook are naturally losing surface-water bodies. As surface water infiltrates through the organic-rich sediments, dissolved oxygen is consumed in reactions with the organic material. This creates a reducing environment that enables ground water to dissolve iron and manganese from organic matter and from inorganic coatings on aquifer materials.

Concentrations of nitrate (as N) in uncontaminated ground water generally are less than 0.1 mg/L. No nitrate was detected in 51 of 108 water samples analyzed. The median concentration for all samples was 0.02 mg/L.

The highest concentrations of nitrate were measured at a low-level-radionuclide contamination site near Wood River Junction. While industrial wastes were being discharged at the site, measured concentrations of nitrate in the contaminant plume ranged from 20 to 2,200 mg/L. During 1981-83, after plant processing had ended, nitrate ranged from 5 to 600 mg/L.

A limited amount of sampling for pesticides was done as part of the present study. A network of 10 observation wells was installed in the vicinity of a potato field near Woodville in 1983 to determine whether aldicarb, a carbamate pesticide, was present in the aquifer. Total aldicarb residues in samples from downgradient observation wells within approximately 500 ft of the potato field equaled or exceeded the RMCL of 9 ug/L on all three sampling dates, in some cases by an order of magnitude. The maximum concentration measured was 150 ug/L.

The maximum depth to which the aquifer is contaminated by aldicarb at this location is not known. Sampling for aldicarb was done within the upper 50 ft of the saturated zone, which ranges in thickness from 140 to 260 ft at this location. Aldicarb was found at all sampled depths in this zone.

Ground-water samples from this site were tested for six other carbamate pesticides. Carbaryl, 3-hydroxycarbofuran, 1-naphthol, and methomyl were not detected. Carbofuran was detected in water from wells 100 and 500 ft downgradient from the potato field at a maximum concentration of 7 ug/L. Oxamyl was detected in water from an observation well at the edge of the potato field at a concentration of 2 ug/L. The potential extent of ground-water contamination by pesticides in the study area is not known.

Liquid-industrial-waste disposal at a site near Wood River Junction has contaminated ground-water within the stratified-drift aquifer. The plume of contaminated water is 300 ft wide and 2,300 ft long, extending from the disposal site northwest to the Pawcatuck River. The plume is confined to the upper 80 ft of saturated thickness, where the aquifer consists of medium to coarse sand and gravel. The contaminated ground water discharges to the Pawcatuck River and its contiguous swamp.

Contaminants in the ground water include common cations and anions, metals, nutrients, radionuclides, and other constituents. In 1977, maximum values of several properties and constituents were measured, including specific conductance of 14,500 uS/cm, hardness of 3,200 mg/L (as $CaCO_3$), and nitrate of 2,200 mg/L (as N). After liquid waste discharges ended in 1980, concentrations of many contaminants decreased but were still well above background levels as of 1983. During 1981-83, nitrate concentration ranged from 4 to 660 mg/L (as N), strontium-90 ranged from 4 to 290 pCi/L, and gross beta emitters ranged from 5 to 1,500 pCi/L. No gamma emitters above detection levels have been found.

A simplified solute-transport model has predicted that it will take approximately 10 years for natural ground-water flow and radioactive decay to reduce the strontium-90 concentration to the USEPA MCL for drinking water at this site. Monitoring will be necessary to determine the actual cleanout time.

The lower Wood River ground-water reservoir was simulated with a model that uses a block-centered, finite-difference method to approximate numerically the differentical equations that describe the flow of ground water. The grid network for the model consists of 32 rows and 72 columns, for a total of 2,304 nodes. The solution technique used in the model is the strongly implicit procedure. Most model boundaries coincide as closely as possible with geologic contacts between the stratified drift and the till-covered bedrock valley walls, and were treated as finite-flux boundaries. The bottom boundary of the aquifer is the contact between the highly permeable stratified drift and the less permeable till-covered bedrock or the fine-grained lake deposits. The bottom boundary was modeled as a no-flow boundary. A leaky-boundary condition was assigned to Canonchet Brook, Meadow Brook, the Pawcatuck River, and the Wood River to simulate the interaction of the stream-aquifer system.

The model was calibrated by comparing computed model heads and measured heads, and by comparing model-determined streamflow to measured discharge at three gaging stations and two miscellaneous discharge-measurement sites. Computed and measured head differences in 33 observation wells were less than 1.80 ft at 80 percent of the observation well nodes. Total modeled flow--streamflow input to the model plus ground-water leakage from the aquifer to the stream--was within 4.3 percent of estimated long-term average annual streamflow within the study area. The model had a mass-balance discrepancy of -0.06 percent, indicating no significant errors in numerical computations.

To assess the limitations of the conceptual model, an analysis of the sensitivity of the model to changes in model input was made. Changes were varied within the probable range of expected values for individual input. The sensitivity analyses show that water levels near streams are significantly affected only by large decreases in streambed vertical hydraulic conductivity. The analyses also show that water levels away from streams, as well as ground-water discharge, are most sensitive to large increases in recharge from precipitation.

Ground-water-development alternatives were simulated at 11 well sites under long-term-average annual hydrological conditions and drought conditions to test the maximum yield of the lower Wood River ground-water reservoir. Total pumpage for development alternative simulations ranged from 6 to 11 Mgal/d. Individual wells were pumped at constant rates of 1 Mgal/d for all simulations. Model results are on the conservative side because all pumpage was assumed to be exported from the study area. However, if pumpage were returned to the flow system upstream from withdrawal points rather than exported from the study area, ground-water-level and streamflow declines would be less than predicted.

The objective of each hypothetical pumping simulation was to withdraw as much water as possible from the ground-water reservoir without (1) causing water-level declines that would lower the initial saturated thickness of the aquifer by more than 25 percent, and (2) causing cessation of flow in any stream reach.

Development-alternative 1 shows that the lower Wood River ground-water reservoir can sustain an average daily yield of 6 Mgal/d with minimal effect on streamflow, pond levels, and ground-water levels under long-term-average hydrological conditions. Pumping scenarios for development-alternatives 2 to 5 show that the lower Wood River ground-water reservoir is capable of sustaining an average daily yield of 7 to 10 Mgal/d under long-term-average annual hydrological conditions. Development-alternatives 2 to 5 provide flexibility in the design and management of the ground-water reservoir while sustaining an average daily yield of 6 Mgal/d. All pumping-scenario criteria were met with each of the six development alternatives.

To test the maximum pumping capacity of the lower Wood River aquifer, ground-water withdrawals were gradually increased to see if the ground-water reservoir could sustain pumpage equal to the total ground-water runoff (16.9 Mgal/d) available from the modeled area. Development-alternative 6 shows that the lower Wood River ground-water reservoir can sustain a maximum yield of 11 Mgal/d from 11 wells at tested sites. All pumping-scenario criteria were met with development-alternative 6. However, severe declines in the water levels of shallow ponds are likely. Water quality at 3 of the 11 sites tested for development-alternative 6 is poor and unsuitable for most uses. One site (CHW 351) is adjacent to the low-level radionuclide contamination plume. Ground water at the other two sites (RIW 8 and 510) has elevated iron and manganese concentrations. If the three sites where water quality is poor are not used, the ground-water reservoir can sustain from 6 to 8 Mgal/d from eight sites under long-term average hydrological conditions.

The aquifer is in good hydraulic connection with streams within the study area. Meadow Brook is the stream segment most affected by ground-water pumpage. Streamflow depletion in all other stream segments is minimal. Development alternatives show that 36 to 43 percent of all water withdrawn from wells is derived from induced recharge.

Drought conditions were simulated in the model by reducing long-term average recharge from precipitation, inflow from till-covered bedrock uplands, and streamflow, by 25 percent. These reduced values approximate conditions during the 1963-66 drought--a period considered representative of extreme drought conditions. Development-alternative 7 shows that the ground-water reservoir can sustain a pumping rate of 6 Mgal/d under drought conditions. Withdrawals at this rate did, however, cause six nodes to go dry along the lower reaches of Meadow Brook. Reduction of pumpage to less than 6 Mgal/d may be required to maintain some flow in Meadow Brook during drought periods. However, model results under drought conditions are believed to be conservative inasmuch as simulations were done under steady-state conditions and pumpage was assumed to be exported from the basin. Reduction in pumpage may not be necessary if water pumped from the aquifer were returned to the flow system upstream from withdrawal points.

The lower Wood River ground-water reservoir is a valuable source of water in the Pawcatuck River basin. Development alternatives simulated in this study indicate that the ground-water reservoir can sustain withdrawals of 6 to 11 Mgal/d under long-term-average annual hydrological conditions without excessive streamflow depletion or decreases in aquifer saturated thickness. However, withdrawals of as much as 6 Mgal/d during drought conditions may cause excessive lowering of streamflow and pond levels. Although water quality is suitable for most uses, some promising well sites may be of limited use because of ground-water contamination by nitrate, pesticides, radionuclides, and/or because of elevated concentrations of iron and manganese. The most beneficial ground-water development in the study area can be achieved if water quality and aquifer hydraulic properties are considered simultaneously.

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GLOSSARY

ANION: An ion that has a negative electrical charge; for example, nitrate and chloride ions are anions.

ANISOTROPY: That condition in which all hydraulic properties vary with direction.

AQUIFER: A formation, group of formations, or part of a formation that contains enough saturated permeable material to yield significant quantities of water to wells and springs.

AQUIFER TEST: A controlled field experiment wherein the effect of pumping a well is measured in the pumped well and in observation wells for the purpose of determining hydraulicproperties of an aquifer.

BEDROCK: The solid rock, commonly called "ledge", that underlies unconsolidated material at the earth's surface.

CATION: An ion that has a positive electrical charge; for example, sodium and calcium ions are cations.

COLOR: Color is expressed in units of the platinum-cobalt scale proposed by Hazen (1892, p. 427-428). A unit of color is produced by one milligram per liter of platinum in the form of the chloroplatinated ion. The intensity of color is rated numerically from 0 to 500, a color of 5 being equivalent to 1/100 that of the standard. The extent to which a water is colored by material in solution may indicate the presence of organic material that may have some bearing on the dissolved-solids content.

CONCEPTUAL MODEL, of the stream-aquifer system: A general idea or understanding of an existing stream-aquifer system, that makes it possible to realistically simulate that system mathematically.

CONFINED AQUIFER (ARTESIAN AQUIFER): An aquifer in which ground water is confined under pressure significantly greater than atmospheric. See UNCONFINED AQUIFER.

CONTINUOUS-RECORD GAGING STATION: A site on a stream at which continuous measurements of stream stage are made. These records are converted to daily flow after calibration by flow measurements.

DIGITAL MODEL: A simplified mathematical representation of a complex aquifer system. A computer program designed to solve ground-water flow equations.

DISCHARGE: The volume of water that passes a given point within a given period of time.

DISSOLVED SOLIDS: The residue from a clear sample of water after evaporation and drying for 1 hour at 180 °C; consists primarily of dissolved mineral constituents, but may also contain organic matter and water of crystallization.

DRAINAGE AREA: The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

DRAINAGE BASIN: A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

DRAINAGE DIVIDE: The rim of a drainage basin. Drainage divide, or just divide, is used to denote the boundary between one drainage area and another.

DRAWDOWN: The decline of water level in a well after pumping starts. It is the difference between the water level in a well after pumping starts and the water level as it would have been if pumping had not started.

DURATION OF FLOW, of a stream: The percentage of time during which specified daily discharges have been equaled or exceeded in magnitude within a given time period.

EVAPOTRANSPIRATION: Water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

FINITE-FLUX BOUNDARY: A model-boundary condition that is specified by assigning a fixed value of volumetric flow to recharge (or discharge) wells at appropriate nodes to simulate flow across the boundary.

GAGING STATION: A particular site on a stream, canal, lake, or reservoir where systematic observations of hydrologic data are obtained.

GAINING STREAM: A stream or reach of a stream whose flow is being increased by inflow of ground water.

GLACIOFLUVIAL: Pertaining to streams flowing from glaciers or to the deposits made by such streams.

GNEISS: A coarse-grained rock in which bands rich in granular minerals alternate with bands in which schistose minerals predominate.

GRAVEL PACKED WELL: A well in which filter material is placed in the annular space to increase the effective diameter of the well, and to prevent fine-grained sediments from entering the well.

GROUND WATER: Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

GROUND-WATER DRAINAGE DIVIDE: A line on a water table on each side of which the water table slopes downward in a direction away from the line. It is analogous to a divide between two drainage basins on a land surface. Generally a ground-water divide is found nearly below a surface-drainage divide, but in many localities there is no relation between the two.

GROUND-WATER OUTFLOW: That part of the discharge from a drainage basin that occurs through the ground. The term "underflow" is often used to describe ground-water outflow.

GROUND-WATER RECHARGE: The amount of water that is added to the saturated zone.

GROUND-WATER RESERVOIR: Parts of the sand and gravel aquifer where ground-water is accumulated under conditions that make it suitable for development and use.

GROUND-WATER RUNOFF: That part of the runoff which has passed into the ground, has become ground water, and has been discharged into a stream channel as spring or seepage water.

HARDNESS: A physical-chemical characteristic of water that is commonly recognized by the increased quantity of soap required to produce lather. It is attributable to the presence of alkaline earths (principally calcium and magnesium) and is expressed as equivalent calcium carbonate ($CaCO_3$). The following classification is used by the U.S. Geological Survey: soft, 0-60 mg/L; moderately hard, greater than 60-120 mg/L; hard, greater than 120-180 mg/L; very hard, greater than 180 mg/L.

HEAD, static: The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

HETEROGENEITY: Heterogeneity is synonymous with nonuniformity. A material is heterogeneous if its hydrologic properties vary with position within it.

HYDRAULIC CONDUCTIVITY: The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Expressed herein in feet per day. These values may be converted to gallons per day per square foot by multiplying by 7.482.

HYDRAULIC GRADIENT: The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

INDUCED INFILTRATION: The process by which water moves into an aquifer from an adjacent surface-water body, owing to reversal of the hydraulic gradient, in response to pumping.

INDUCED RECHARGE: The amount of water entering an aquifer from an adjacent surface-water body by the process of induced infiltration.

LEAKY BOUNDARY: A boundary condition that relates boundary flux to boundary head. Its most common use is to represent the interaction between a water table aquifer and a stream or river which is separated from the aquifer by a semipervious streambed layer.

LITHOLOGIC LOG: Description of geologic material collected during sampling of test wells.

LOSING STREAM: A stream or reach of a stream that is losing water to the ground.

METAMORPHISM: Any change in the texture or composition of a rock, after its induration or solidification, produced by exterior agencies, especially by deformation and by rise of temperature.

METASEDIMENTARY: Partly metamorphosed sedimentary rocks.

MICROGRAMS PER LITER (ug/L): A unit for expressing the concentration of chemical constituents in solution. Micrograms per liter represents the weight of solute per unit volume of water. Approximately equal to parts per billion (ppb).

MILLIGRAMS PER LITER (mg/L): A unit for expressing the concentration of chemical constituents in solution. Milligrams per liter represents the weight of solute per unit volume of water. Equal to parts per million (ppm) for concentrations less than 7,000 mg/L. (1 mg/L equals 1,000 ug/L)

ORGANIC CHEMICAL: A chemical compound consisting of carbon. Historically, organic compounds were those derived from vegetable or animal sources. Today, many organic chemicals are synthesized in the laboratory.

OVERDEEPENING: The process by which a glacier gouges basins much deeper than the general level of the subglacial surface.

pH: Symbol denoting the logarithm of hydrogen-ion concentration in a solution to base 10, pH values range from 0 to 14. The lower the value, the more acid the solution; that is, the more hydrogen ions it contains. A value of 7.0 is the neutral point; values greater than 7.0 indicate an alkaline solution; values less than 7.0 indicate an acid condition.

PLUME: An area of an aquifer containing degraded water resulting from migration of a contaminant.

PRECIPITATION: The discharge of water from the atmosphere, either in a liquid or solid state.

RADIONUCLIDE: A species of atom that emits alpha, beta, or gamma rays for a measurable length of time. Individual radionuclides are distinguished by their atomic weight and atomic number.

RECOVERY: The rise of the water level in a well after pumping has stopped. It is the difference between the water level in a well after pumping stops and the water level as it would have been if pumping had continued at the same rate.

REDOX POTENTIAL: A numerical index of the intensity of oxidizing or reducing conditions within a system.

SATURATED THICKNESS: The thickness of an aquifer below the water table. As measured for the stratified-drift aquifer in this report, it is the vertical distance between the water table and the bedrock surface, and in places includes till present between the stratified drift and the bedrock surface.

SEDIMENTARY ROCKS: Rocks formed by the accumulation of sediment in water (aqueous deposits) or from air (eolian deposits).

SEISMIC SHOTPOINT: Location where seismic energy is released.

SPECIFIC CAPACITY: The specific capacity of a well is the rate of discharge of water from the well divided by the drawdown of water level within the well.

SPECIFIC CONDUCTANCE: A measure of the ability of water to conduct an electrical current, expressed in microsiemens per centimeter at 25 degrees Celsius. Specific conductance is related to the type and concentration of ions in solution and can be used for estimating the dissolved-solids content of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65 percent of specific conductance (in microsiemens per centimeter at 25 degrees Celsius. This relation is not constant from stream to stream or from well to well, and it may even vary in the same source with changes in the composition of the water.

SPECIFIC YIELD (Sy): Ratio of the volume of water a fully saturated rock or unconsolidated material will yield by gravity drainage, given sufficient time, to the total volume of rock or unconsolidated material; commonly expressed as percentage.

STEADY STATE: Equilibrium water levels or heads; aquifer storage and water levels do not vary with time.

STORAGE COEFFICIENT: The volume of water an aquifer releases from, or takes into, storage per unit surface area of the aquifer per unit change in head; commonly expressed as a decimal or percentage. In an unconfined aquifer, the storage coefficient is virtually equal to the specific yield.

STRONGLY IMPLICIT PROCEDURE (SIP): A method for iteratively solving a large system of simultaneous linear equations.

STRATIFIED DRIFT: Unconsolidated sediment that has been sorted by glacial meltwater and deposited in layers, or strata.

STREAMFLOW: The discharge that occurs in a natural channel. "Streamflow" is more general than "runoff", as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

TILL: A geologic term for a glacial deposit of predominantly nonsorted, nonstratified material ranging in size from boulders to clay. It is commonly so compact that it is difficult to penetrate with light drilling equipment.

TOTAL RUNOFF: Part of precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversion, storage, or other works of man in or on stream channels. Includes both surface- and ground-water runoff.

TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to the product of the hydraulic conductivity and saturated thickness. Expressed herein in feet squared per day.

UNCONFINED AQUIFER (WATER-TABLE AQUIFER): An aquifer in which the upper surface of the saturated zone, the water table, is at atmospheric pressure and is free to rise and fall.

UNDERFLOW: See "**GROUND-WATER OUTFLOW**".

UNSATURATED ZONE: The zone between the land surface and the water table.

WATER TABLE: The upper surface of the saturated zone.

WATER YEAR: A 12-month period, October 1 through September 30. It is designated by the calendar year in which it ends.

ZERO-FLUX BOUNDARY: A model boundary condition that is specified by assigning a value of zero transmissivity to nodes outside the boundary to simulate no flow across the boundary.