HYDROLOGY, WATER QUALITY, AND GROUND-WATER-DEVELOPMENT ALTERNATIVES IN THE CHIPUXET GROUND-WATER RESERVOIR, RHODE ISLAND

By Herbert E. Johnston and David C. Dickerman

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4254

Prepared in cooperation with the
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UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION FACTORS

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

Multiply inch-pound unit	By	To obtain metric (SI) unit
Length		
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
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)	0.06308	liter per second (L/s)
gallon 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		
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$^{\circ}F = 1.8\ ^{\circ}C + 32$$

GLOSSARY

ANISOTROPY: The condition of having different properties in different directions.

AQUIFER TEST: A test involving the withdrawal of measured quantities of water from, or addition of water to, a well (or wells) and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition.

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.

BEDROCK: The solid rock, commonly called "ledge," that forms the earth's crust.

CASING: A tubular retaining structure, generally metal, which is installed in the excavated hole to maintain the well opening.

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

CUBIC FOOT PER SECOND: The rate of discharge representing a volume of 1 cubic foot passing a given point during 1 second and is equivalent to 7.48 gallons per second or 448.8 gallons per minute or 0.2832 cubic meters per second.

CUBIC FEET PER SECOND PER SQUARE MILE: The average number of cubic feet of water flowing per second from each square mile of area drained, assuming that the runoff is distributed uniformly in time and area.

DISCHARGE: The volume of water that passes a given point within a given period of time. MEAN DISCHARGE is the arithmetic average of individual daily mean discharges during a specific period.

DISSOLVED SOLIDS: The residue from a clear sample of water after evaporation and drying for 1 hour at 180 degrees 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.

DRAWDOWN(S): 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.

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

FLOW DURATION CURVE: A cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded.

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.

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 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.

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.

GROUND-WATER EVAPOTRANSPIRATION: Ground water discharged into the atmosphere in the gaseous state by direct evaporation and by transpiration by plants.

GROUND-WATER OUTFLOW: That part of the discharge from a drainage basin that occurs through the ground. SUBSURFACE OUTFLOW is also used to describe ground-water outflow.

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

HYDRAULIC CONDUCTIVITY (K): 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 7.48.

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.

ISOTROPY: That condition in which all all significant properties are independent of direction.

LEAKY CONFINED AQUIFER: An aquifer confined by an areally extensive layer of sediment that has much lower hydraulic conductivity than the aquifer.

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

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.

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." "NGVD of 1929" is referred to as "sea level" in this report.

RECHARGE: The processes of addition of water to the zone of saturation, that zone beneath the water table.

RECHARGE AREA: An area in which water is absorbed that eventually reaches the zone of saturation.

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.

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.

RUNOFF IN INCHES: Shows the depth to which the drainage area would be covered if all the runoff for a given time period were uniformly distributed on it.

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.

SATURATED ZONE: That part of the water-bearing material in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

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 a water to conduct an electrical current, expressed in micromhos per centimeter at 25 degrees C. 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 micromhos per cm at 25 degrees C). 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): The 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 a decimal or percentage.

STAGE: The height of a water surface above an established datum plane.

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.

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 predominantly nonsorted, nonstratified material deposited directly by a glacier; it is constituted of varying proportions of sediment particles that range in size from boulders to clay.

TRANSIENT STATE: Non equilibrium water levels or heads; water levels and aquifer storage vary with time.

TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Expressed herein in cubic feet per day per foot or, more simply, feet squared per day. To convert values to gallons per day per foot, multiply them by 7.48. Replaces the term "Coefficient of Transmissibility."

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

WATER TABLE: The surface in an unconfined aquifer at which the pressure is atmospheric. It is the level at which water stands in wells that just penetrate the upper part of the aquifer.

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

WELL SCREEN: The intake section of a well that obtains water from unconsolidated materials such as sand. It allows water to flow freely into the well and prevents sand from entering with the water.

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ABSTRACT

A moderate to highly permeable stratified-drift aquifer consisting chiefly of sand and gravel underlies the valleys of the Chipuxet River and Chickasheen Brook in the towns of Exeter and South Kingstown, Rhode Island. The thickest and most transmissive part of this aquifer forms a major ground-water reservoir that can deliver high yields (100 to 1,200 gallons per minute) to properly located and constructed wells.

Model simulations predict that the ground-water reservoir could sustain a continuous yield of more than 8 million gallons per day. Withdrawal at this rate without return flow to streams, however, would cause streams that flow across the reservoir to have little or no flow much of the time and could cause excessive lowering of ground-water levels.

The Rhode Island Water Resources Board has conducted a program of exploratory drilling and aquifer testing in the ground-water reservoir to identify potential sites for public-supply wells that could supply a total of as much as 3 million gallons per day. Part or all of the pumped water may be exported from the Chipuxet River basin for water supply in other communities, for sewage transport, or for a combination of these uses.

Analysis of aquifer-test data from test wells and from public-supply wells owned by the University of Rhode Island and the Kingston Fire District indicate that a combined yield of 3 million gallons per day is readily obtainable from wells at the five sites under consideration for development. In fact, if it were not for water quality considerations, 3 million gallons per day could be pumped from the University well field alone.

A 2-dimensional, digital-simulation model of the stream-aquifer system was used to evaluate the hydrologic effects of pumping 3 million gallons per day from five different combinations of wells. Model results predict that the proposed alternative withdrawal schemes would cause ground-water levels, at distances of more than about 400 feet from pumping centers, to be lowered a maximum of about 1 foot in the vicinity of streams and 3 to 4 feet at points away from streams.

Model results also predict that withdrawals from each of the five combinations of wells would reduce the flow of the Chipuxet River downstream from pumping wells by a rate nearly equal to the pumping rate within a few days after pumping began. All of the wells are within a few hundred feet of the Chipuxet River.

Based on evaluation of streamflow data, it is estimated that continuous pumping of 3 million gallons per day from wells upstream of the U.S. Geological Survey stream gage on the Chipuxet River would result in periods of little or no flow at the gage for periods of 3 consecutive days on the average of 1 year in 3, and for periods of 90 consecutive days on the average of 1 year in 20. The gage is near the downstream end of the Chipuxet basin and four of the five proposed pumping centers are upstream from the gage. Maintenance of continous flow at the gage will require that aggregate withdrawals from wells upstream of the gage be less than 3 million gallons per day during some dry-weather periods.

The chemical quality of ground water and surface water in the study area is generally suitable for most uses. The water is soft, slightly acidic, and typically has a dissolved-solids content of less than 100 milligrams per liter. However, ground water is highly susceptible to contamination and, in fact, has been locally contaminated, as indicated by elevated concentrations of chemicals in a plume of leachate-contaminated ground water that extends from the now-closed West Kingston sanitary landfill to Hundred Acre Pond. Elsewhere, nitrate and manganese are significant contaminants in ground water.

Concentrations of nitrate exceed natural levels (0.1 milligram per liter or less) throughout much of the study area, but generally are lower than the Federal and State limits of 10 milligrams per liter established for this constituent in drinking water. The nitrate seems to be derived largely from fertilizers applied to agricultural land, which overlies much of the study area. At the proposed Liberty Lane pumping center, which is adjacent to a potato field, nitrate concentrations in excess of 10 milligrams per liter have been observed in water samples from several test wells.

Concentrations of manganese in ground water from most parts of the study area do not exceed the limit of 0.05 milligrams per liter recommended for drinking water. However, concentrations in water from some heavily pumped public-supply wells have increased significantly above this limit after the wells were put into production. Concentrations in a University of Rhode Island supply well at Thirty Acre Pond increased from less than 0.01 to as much as 3 milligrams per liter. It is hypothesized that manganese enrichment of ground water is related to the quantity of infiltration induced through organic-rich sediments that line the bottoms of ponds and some stream reaches. The source of the manganese is believed to be either the organic rich sediment or coatings of manganese oxide on aquifer sediments.

INTRODUCTION

This is a report of an investigation of the Chipuxet ground-water reservoir, a body of highly permeable and porous sand and gravel that occupies an area of approximately 3 mi^2 in the valleys drained by the Chipuxet River and Chickasheen Brook. The area is located in the headwaters of the Pawcatuck River basin in the towns of South Kingston and Exeter, Rhode Island (fig. 1). The ground-water reservoir is one of several in the Pawcatuck River basin (Allen and others, 1966; Gonthier and others 1974) and is one of five in which the Rhode Island Water Resources Board (RIWRB) has done exploratory drilling and aquifer testing. Other ground-water reservoirs being investigated include the Queen-Usquepaug, Beaver-Pasquiset, Lower Wood, and Upper Wood.

Exploratory work by the RIWRB is being done to identify sites at which high capacity wells can be developed to yield water of suitable quality for public supply. Selected favorable sites are being purchased by the RIWRB and will be retained for development as needed to meet future public water-supply needs of southern Rhode Island communities. Test drilling and aquifer testing, which began in 1970, have been completed in the Chipuxet, Beaver-Pasquiset, Lower Wood, and Upper Wood ground-water reservoirs. Some drilling and aquifer testing have been completed in the Queen-Usquepaug ground-water reservoir.

The goal of the RIWRB investigations in the Pawcatuck River basin is to identify and preserve sites from which a combined average daily yield of 22 Mgal/d, and a combined maximum pumping capacity of 44 Mgal/d, can be developed. The excess of pumping capacity over the average daily yield is to provide for meeting peak demands. The average and maximum yields sought in individual ground-water reservoirs are as follows (W. B. Allen, Rhode Island Water Resources Board, oral commun., 1975):

Ground-water reservoir	Average daily yield (Mgal/d)	Maximum pumping capacity (Mgal/d)
Chipuxet	3	6
Beaver-Pasquiset	3	6
Lower Wood	6	12
Upper Wood	6	12
Queen-Usquepaug	4	8
	22	44

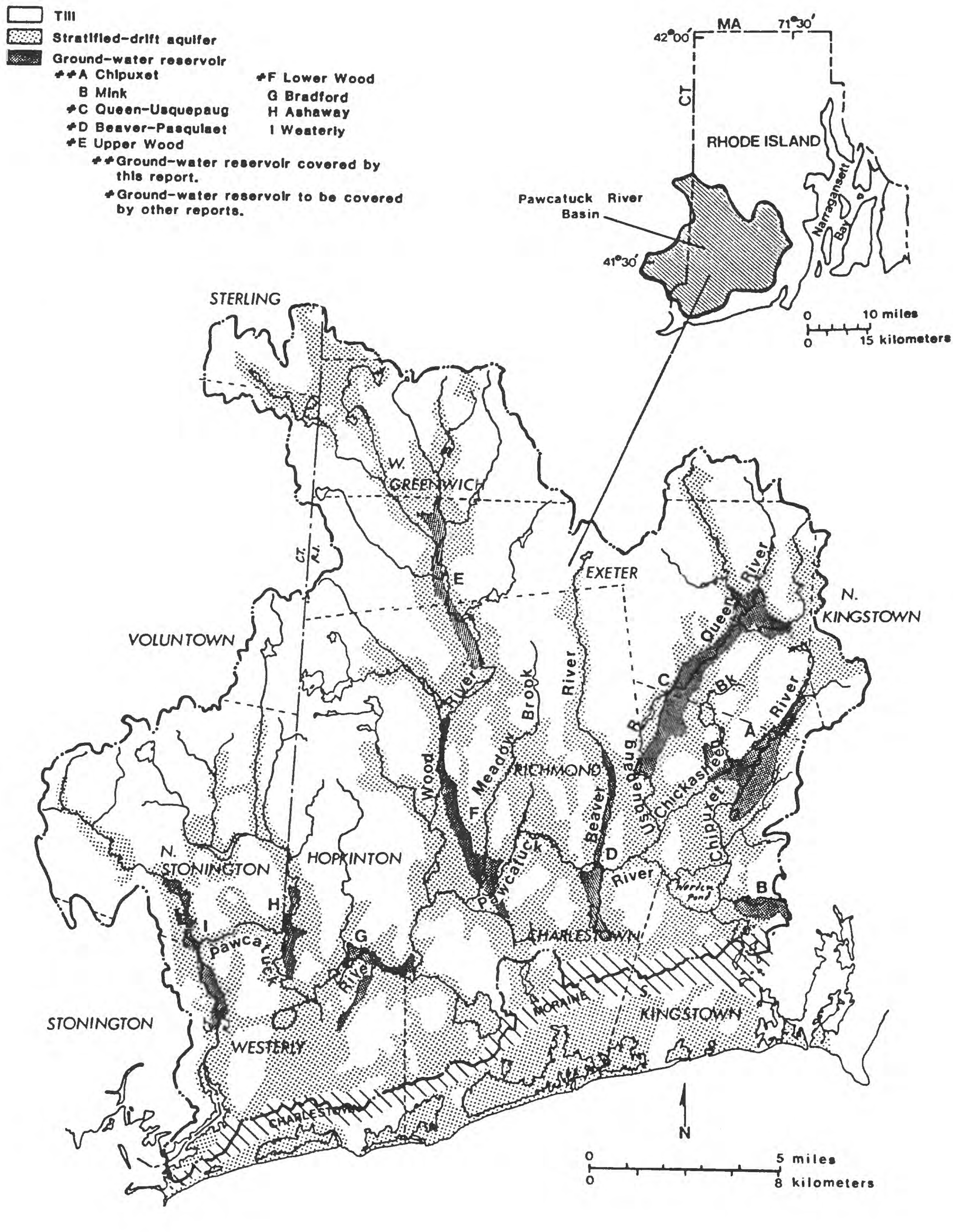

Figure 1.--Location of Chipuxet ground-water reservoir and other major ground-water reservoirs in the Pawcatuck River basin and generalized surficial geology.

In selecting the desired average daily yields in the above table, consideration was given to the low flows of streams. The yields are equal to or less than the 98-percent flow duration[1] of streams that drain the ground-water reservoirs. In the Chipuxet ground-water reservoir, the combined flow of streams along the southern boundary of the reservoir at their 98-percent-duration flows is estimated to be 4 Mgal/d.

Studies by the U.S. Geological Survey (Allen and others, 1966; Gonthier and others, 1974) indicate that ground-water reservoirs in the Pawcatuck River basin could continuously sustain a yield in excess of 65 Mgal/d. This potential yield greatly exceeds foreseeable municipal supply needs in the basin. The U.S. Army Corps of Engineers (1979, table 7-65), for example, estimates that, by the year 2020, the total demand by public water-supply systems in the towns of Charlestown, Exeter, Hopkinton, Richmond, South Kingstown, and Westerly, which lie wholly or partly within the Pawcatuck River basin, will be about 9 Mgal/d.

Because of the abundant ground-water resources in the Pawcatuck basin, it has been proposed that 5 to 11 Mgal/d be pumped to communities outside the basin where available resources are considered inadequate to meet future needs (Metcalf and Eddy, Inc., 1967, p. 10; Rhode Island Statewide Planning Program, 1969, p. 74). If the proposals are implemented, part or all of the water would be pumped from public-supply systems that include well sites owned and (or) tested by the RIWRB. Some of the water exported would likely be taken from the Chipuxet ground-water reservoir.

A potential problem with exporting ground water from the Pawcatuck basin, or from one subbasin to another within the Pawcatuck basin, is that improperly planned and coordinated withdrawals from individual ground-water reservoirs could result in substantially reduced streamflow downstream from pumping centers and (or) excessive declines in ground-water levels near pumping centers. For example, Allen and others (1966, p. 51, 62) demonstrated that 8.6 Mgal/d could be pumped continuously from the Chipuxet ground-water reservoir, but that withdrawal at this rate would cause streams that flow across the reservoir to have little or no flow much of the time.

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[1] As used herein, the 98-percent flow duration of a stream is the average daily flow equaled or exceeded on 98 percent of the days over a period of several years.

The yields sought by the RIWRB were selected in expectation that withdrawal and export of water at these rates would cause minimal depletion of streamflow and minimal lowering of ground-water levels near and downstream from pumping centers. However, the spatial and temporal effects of ground-water withdrawals can be determined only after the locations of wells, and their potential pumping rates and pumping regimens, are known. In addition, these effects can be determined with reasonable accuracy only if the hydraulic characteristics of the aquifer, streamflow variation, recharge rates, and other geologic and hydrologic factors are known.

To obtain the required geohydrolgic information and assess how alternative ground-water management schemes would affect streamflow and water levels in the five areas under investigation, the RIWRB entered into agreements with the U.S. Geological Survey and the University of Rhode Island, Department of Civil and Environmental Engineering, to do hydrologic studies. The agreements with the University of Rhode Island called for modeling studies, and with the U.S. Geological Survey called for hydrologic and modeling studies.

Hydrologic studies began in 1975. These included collection and analysis of geologic and hydrologic data resulting from the drilling and aquifer-test program conducted by the RIWRB, and collection and analysis of additional data on the flow and quality of streams and the quality of ground water. Geohydrologic data reports have been completed in three of the study areas--Chipuxet (Dickerman, 1976), Beaver-Pasquiset (Dickerman and Johnston, 1977), and Lower Wood (Dickerman and Silva, 1980). Results of aquifer tests in the Chipuxet study area have been described by Dickerman (1984). A preliminary study of the source and causes of enrichment of manganese in water pumped from supply wells in the Chipuxet area has also been completed (Silvey and Johnston, 1977).

The University of Rhode Island and the U.S. Geological Survey have cooperated on modeling studies on an informal basis. A model of the Chipuxet ground-water reservoir was developed by the University of Rhode Island (Kelly and Ozbilgin, 1982; Kelly, 1983) and a model of the Beaver-Pasquiset ground-water reservoir was developed jointly by the U.S. Geological Survey and the University of Rhode Island. The models are used to simulate the effects of ground-water development.

Purpose and Scope

The purpose of this report is to describe the (1) hydrology, (2) water quality, and (3) ground-water-development alternatives.

The scope of the work done for this report includes (1) estimation of the areal distribution of hydraulic conductivity of the stratified-drift aquifer from lithologic logs and aquifer-test analyses; (2) computation of potential yields of large-diameter wells at selected sites; (3) collection and analysis of streamflow data to obtain low-flow statistics and to determine the rate of ground-water seepage to streams during periods of low flow; (4) analysis of water-budget data to estimate recharge rates for stratified drift and till; (5) discussion of the hydrologic effects of alternative ground-water-development schemes by means of a digital model of the Chipuxet ground-water reservoir; and (6) collection and analysis of water-quality data from wells and streams.

Data for this study were collected by the RIWRB and U.S. Geological Survey chiefly during 1970-76.

Previous Studies

Substantial geohydrologic information is available from earlier studies of areas that include part or all of the Chipuxet ground-water reservoir area. Surficial and bedrock geology have been mapped by Kaye (1960), Moore (1964), and Power (1957, 1959). Reconnaissance studies of the availability of ground water were done by Bierschenk (1956), Hahn (1959), and Lang (1961). A comprehensive quantitative hydrologic study of the availability of ground water in the Upper Pawcatuck River basin, which includes the major ground-water reservoirs in the Chipuxet River, Usquepaug and Queen Rivers, and Mink-Brook areas was completed by Allen and others (1966). Most of the data on which the present report is based are contained in geohydrologic data reports by Allen and others (1963) and Dickerman (1976). Additional hydrologic data for the Chipuxet ground-water reservoir area are being obtained by the U.S. Geological Survey as part of the ongoing Pawcatuck River basin study. These data are contained in annual reports titled "Water Resources Data for Massachusetts, New Hampshire, Rhode Island, and Vermont" (U.S. Geological Survey, 1974), and "Water Resources Data for Massachusetts and Rhode Island" (U.S. Geological Survey, 1975 to present). The data include records of discharge, temperature, and specific conductance of the Chipuxet River at West Kingston since 1973; measurements of low flow at miscellaneous sites in the Chipuxet River basin, and records of water level fluctuations in observation wells.

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WATER USE

The Chipuxet ground-water reservoir is drained by the Chipuxet River and Chickasheen Brook, which are headwater streams of the Pawcatuck River. In 1979, pumpage from wells and streams in the area drained by the Chipuxet River and Chickasheen Brook averaged 1.14 MGal/d (table 1). Virtually all of the withdrawals were from the thick, permeable part of the stratified-drift aquifer that forms the Chipuxet ground-water reservoir. Of the total amount withdrawn, 1.09 Mgal/d was derived from ground water and 0.05 Mgal/d was derived from surface water. Seventy-eight percent of the water withdrawn was from public supply systems at two pumping centers in the stratified-drift aquifer. These centers contain three University of Rhode Island wells near 30 Acre Pond, and one Kingston Fire District well near the point where Kingston Road crosses the Chipuxet River (fig. 13). Of the remaining water withdrawn, 9 percent was from industrial wells, 4 percent from domestic wells, and 9 percent from irrigation. On an average annual basis, irrigation pumpage amounts to only 0.10 Mgal/d, but water is actually withdrawn at a rate of 0.43 Mgal/d over an 8-week period during an average year. During drought years the irrigation rate remains the same, except that water is then typically withdrawn over a 20-week period.

Eighty-six percent (0.98 Mgal/d) of the water withdrawn from the study area in 1979 was not available for reuse downstream in the Pawcatuck River basin. As much as 0.72 Mgal/d was exported from the basin through the South Kingstown-Narragansett regional sewer system, which discharges to Narragansett Bay east of the study area. The remaining 0.26 Mgal/d was lost to the atmosphere by evapotranspiration or was otherwise consumed. Table 1 summarizes 1979 average annual withdrawal, water loss, and water available for reuse downstream.

Table 1.--Estimated average daily water use in the Chipuxet River and Chickasheen Brook drainage basins in 1979.

Supply	Source	Withdrawals	Losses[1]	Available for reuse
		Million gallons per day		
Public and institutional				
Kingston Fire District	Well	0.18	0.14	0.04
University of Rhode Island	Wells	.71	.71	.0
Self supplied				
Industry	Wells	.10	.02	.08
Domestic	Wells	.05	.01	.04
Irrigation	Well, pond, and streams	.10	.10	.0
		1.14	0.98	0.16

[1] Includes (1) water pumped from the Chipuxet River basin as sewage--0.61 Mgal/d from the University of Rhode Island; 0.11 Mgal/d from the Kingston Fire District; and (2) water lost to the study area by evapotranspiration or other consumptive process. Estimates of consumptive use are based on data given by Murray and Reeves (1977).

HYDROLOGY

Streamflow

Streamflow is the part of precipitation remaining in a drainage basin after all natural and artificial consumptive demands have been satisfied. Streamflow, plus a generally small quantity of subsurface outflow, constitute virtually all of the water available for development in the basin. Natural consumptive demands include the natural discharge of water to the atmosphere by evaporation and transpiration. Artificial consumptive demands include withdrawals of water from wells and streams that is not returned to the ground or to streams within the basin.

Based on measurements of precipitation at Kingston and of streamflow of the Pawcatuck River at Wood River Junction, 57 percent of the average annual rainfall on the study area eventually becomes streamflow. During the period 1941-78, annual precipitation at the National Weather Service station at Kingston, R.I., ranged from 31 to 68 inches and averaged 46 inches. At the U.S. Geological Survey gaging station on the Pawcatuck River at Wood River Junction about 10 miles downstream from the study area, runoff during this same period ranged from 15 to 41 inches and averaged 26 inches. The difference between long-term average precipitation and runoff gives an approximate measure of the amount of water returned to the atmosphere by the combined processes of evaporation and transpiration. Thus, 19.9 inches, or about 43 percent of the water that falls on the study area, is returned to the atmosphere.

The discharge of the Chipuxet River was measured 3.1 miles upstream from its mouth at station number 01117350 (fig. 2) from February 1958 to July 1960 and from September 1973 to September 1983. The surface and subsurface drainage boundaries of the Chipuxet River basin do not coincide in all areas. A water-table map prepared by Allen and others (1966, pl. 3) shows that ground water in the northern part of the basin flows from parts of the surface drainage area into adjacent basins drained by the Queen and Annaquatucket Rivers. In addition, it was determined during the present study that ground water also flows from the upper reaches of the Chickasheen and White Horn Brook surface drainage areas into the Chipuxet River. Thus, although the surface drainage area upstream from the Chipuxet River gage is 9.99 mi^2, the subsurface drainage area is 10.6 mi^2.

The Chipuxet River is a gaining stream--that is, ground water flows into it under natural hydraulic gradients. Chickasheen Brook is a gaining stream downstream from Waites Corner Road, but upstream from this road to the vicinity of Barber Pond it is a losing stream. In the losing reach, the water table is below the bed of the stream most or all of the year, which results in leakage of part of the flow into the underlying aquifer. A reach of White Horn Brook upstream from Route 138 also loses water to the underlying aquifer most of the time.

EXPLANATION

▲ Continuous-record stream-gaging station

△ Miscellaneous discharge-measurement site

Figure 2.--Location of continuous-record stream-gaging stations and miscellaneous discharge-measurement sites.

Estimates of long-term flow characteristics of the Chipuxet River were made by correlating the short-term record for the Chipuxet River at West Kingston (01117350) with three long-term records for stations located farther downstream in the Pawcatuck River basin (fig. 2). These stations are the Pawcatuck River at Wood River Junction (01117500), the Wood River at Hope Valley (01118000), and the Pawcatuck River at Westerly (01118500). Low-flow discharge measurements have been made at six sites on streams that drain the Chipuxet ground-water reservoir (fig.2).

Records of streamflow measurements are published in reports by Allen and others (1963), Dickerman (1976), and in annual water-resources data reports of the Geological Survey.

Duration of Streamflow

Flow-duration curves are one method of depicting the variability of streamflow. They show the percentage of time that specified flows were equaled or exceeded in a given period. Duration curves shown in figure 3 for (1) the Pawcatuck River at Wood River Junction (curve 1) for which a long-term record (water years 1942-78) is available, (2) the Chipuxet River at West Kingston for flow conditions adjusted for the effects of ground-water diversions upstream of the gage (curve 2), and (3) the Chipuxet River at West Kingston for actual flow conditions, which are affected by average annual ground-water diversions (in 1978) of 1 Mgal/d (curve 3). The short-term streamflow records for the Chipuxet River were adjusted to the period 1942-78 (water years) by a method described by Searcy (1959).

Frequency and Duration of Low Flow

Of particular interest to this study are the frequencies with which specified low flows may be expected to recur and the length of time they may be expected to last. It is during periods of low streamflow that the impacts of ground-water withdrawals will be most noticeable on streamflow.

For this study, low-flow frequency and duration data for the Chipuxet River at West Kingston were developed for nonpumping conditions using a relation between flow duration and low-flow frequency. Flow-duration and low-flow frequency data were compiled for the Pawcatuck River at Wood River Junction, Wood River at Hope Valley, and the Pawcatuck River at Westerly. The average percentage of time that streamflows at these stations equaled or exceeded specified consecutive days of low flows for selected recurrence intervals was determined and tabulated (table 2). This relation was then used in conjunction with the Chipuxet River flow-duration curve for no ground-water diversions (Curve 2 in fig. 3) to determine low-flow frequency data for natural stream conditions for the Chipuxet River (table 3).

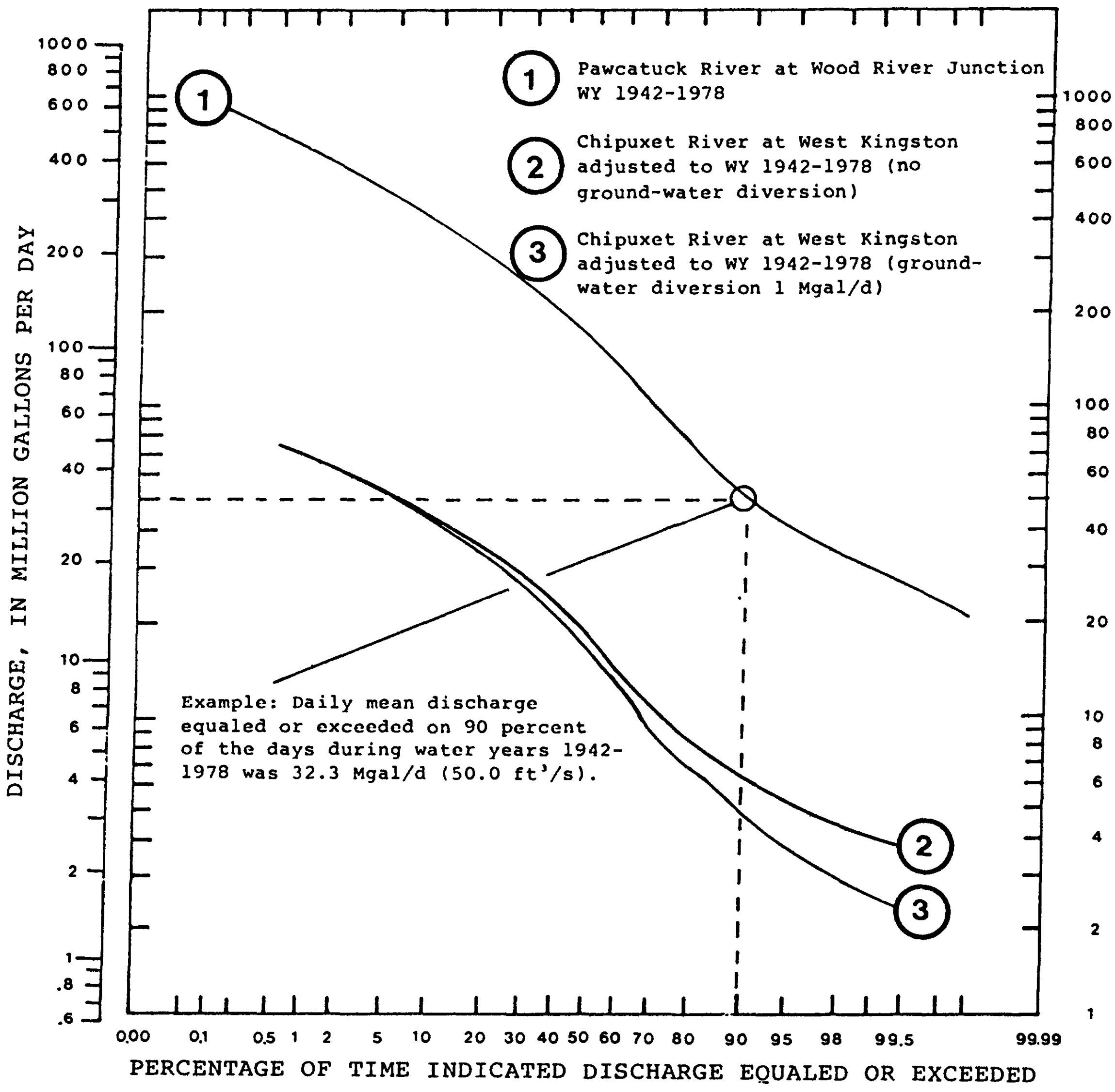

Figure 3.--Flow-duration curves for the Pawcatuck River at Wood River Junction and the Chipuxet River at West Kingston, 1942-1978 water years.

Table 2.--Average duration of lowest mean flows of streams in the Pawcatuck River basin and average percentage of time in which streamflow equaled or exceeded the lowest mean flow for indicated recurrence interval.

[As an example, for any unmeasured site on an unregulated stream, the 30-consecutive-day lowest mean flow that could be expected to recur on the average every 2 years is equivalent to the flow equaled or exceeded 91 percent of the time.]

Period of low flow (number of consecutive days)	Recurrence interval, in years [1]					
	1.2	2 (Median year)	3	5	10	20
3	88	96	98	99	99.5	99.7
7	86	94	97	98	99.1	99.6
14	84	93	96	98	99.0	99.1
30	80	91	94	96	98	99.0
60	76	87	92	94	97	98
90	70	83	88	91	95	97
120	66	78	84	88	93	95
183	56	69	74	79	85	90
365	30	40	47	52	56	61

[1] Based on records for water years 1942-78 at continuous-record gaging stations on the Pawcatuck River at Wood River Junction, Wood River at Hope Valley, and Pawcatuck River at Westerly.

Table 3.--Estimated low-flow discharge at selected recurrence intervals for the stream-gaging station on the Chipuxet River at West Kingston under natural (nonpumping) streamflow conditions

[Based on flow-duration curve 2, figure 3, and the relation shown in table 2]

Period of low flow (number of consecutive days)	Recurrence interval, in years											
	1.2	2 (median year)	3	5	10	20	1.2	2 (median year)	3	5	10	20
	Cubic feet per second						Million gallons per day					
3	6.8	5.0	4.4	4.1	3.7	3.5	4.4	3.2	2.8	2.6	2.4	2.3
7	7.2	5.4	4.7	4.4	4.0	3.6	4.6	3.5	3.0	2.8	2.6	2.3
14	7.6	5.6	5.0	4.4	4.1	4.0	4.9	3.6	3.2	2.8	2.6	2.6
30	8.4	6.1	5.4	5.0	4.4	4.1	5.4	3.9	3.5	3.2	2.8	2.6
60	9.0	7.0	5.8	5.4	4.7	4.4	5.8	4.5	3.7	3.5	3.0	2.8
90	10.6	7.8	6.8	6.1	5.2	4.7	6.8	5.0	4.4	3.9	3.4	3.0
120	11.9	8.6	7.6	6.8	5.6	5.2	7.7	5.6	4.9	4.4	3.6	3.4
183	15.6	10.8	9.5	8.5	7.4	6.4	10.1	7.0	6.1	5.5	4.8	4.1
365	27.7	22.5	19.5	17.2	15.6	13.9	17.9	14.5	12.6	11.1	10.1	9.0

Two commonly used indexes of low flow are the 7-day low flow with a 10-year recurrence interval and the 30-day low flow with a 2-year recurrence interval. In Rhode Island, water-quality standards established for streams by the Department of Environmental Management are indexed to the 7-day, 10-year flow (P. Albert, Rhode Island Department of Environmental Management, oral commun., 1979). Table 2 shows that the lowest mean flow for 7 consecutive days that may be expected to recur on the average of once in 10 years is equivalent to the flow equaled or exceeded 99.1 percent of the time (2.6 Mgal/d).

Components of Streamflow

Streamflow includes surface-water runoff and base flow. Surface-water runoff includes that part of precipitation and snowmelt that flows directly over the land surface to streams, and that part of precipitation that falls directly on swamps, ponds, lakes, and streams. Except where detained in surface storage in swamps, ponds, and reservoirs, surface runoff generally is discharged from the basin within a few days.

Base flow is that part of streamflow contributed predominantly by seepage of ground water into streams, but at times may include significant quantities of drainage from storage in swamps, ponds, and reservoirs. During summer and fall, and during winter periods when air temperatures are consistently below freezing, base flow of streams in the study area consists almost entirely of ground-water runoff. This component of streamflow is commonly referred to as ground-water runoff.

The ground-water runoff component of streamflow is derived from the fraction of precipitation that percolates to the water table to become ground-water recharge. Because most of the precipitation recharge to aquifers in the study area eventually discharges to streams, measurement of ground-water runoff provides a means of estimating recharge. Use of measurements of ground-water runoff to arrive at estimates of ground-water recharge is discussed in a later section of this report.

Allen and others (1966, table 5) used hydrograph-separation methods to determine that the base flow of the Chipuxet River at West Kingston was 10.2 Mgal/d during water year 1959. This is equivalent to 20.3 inches (0.96 Mgal/d/mi^2) of base flow from the 10.6 mi^2 subsurface drainage area and is 68 percent of total runoff of 29.72 inches (15.0 Mgal/d).

Average annual base flow of the Chipuxet River at West Kingston is estimated to be about 18 inches. This value was determined by correlating discharge (converted to inches) at the gage at West Kingston with that measured for the Pawcatuck River at Wood River Junction during 1959, and 1974-78. Measured discharge during this 6-year period at West Kingston averaged 20 ft^3/s, which was increased to 22 ft^3/s to adjust for out-of-basin discharge of ground-water withdrawals (see table 1) of 1.5 ft^3/s (0.98 Mgal/d). A discharge of 22 ft^3/s is equivalent to 28 inches of water on the 10.6-mi^2 subsurface drainage area. During this same period, average discharge at Wood River Junction was 202 ft^3/s, which is equivalent to 27.3 inches of water on the 100-mi^2 drainage area above the gage.

The ratio of runoff at West Kingston to that at Wood River Junction of 1.03 (28.2 inches/27.3 inches = 1.03) for the 6-year period was assumed to apply to long-term (1941-78) average annual runoff (26.1 inches) at Wood River Junction. Thus average annual runoff at West Kingston is estimated to be 26.9 inches (26.1 inches x 1.03 = 26.9 inches) for the longer 1941-78 period.

It was further assumed that the ratio of base flow to total flow of the Chipuxet River in water year 1959 of 0.68 (or 68 percent) is representative of long-term conditions. Thus it was applied to estimated long-term average annual runoff to compute the average annual base flow to be 18.3 inches (26.9 inches x 0.68 = 18.3 inches).

This value compares closely with average annual base flows determined by base-flow-separation methods applied to long-term streamflow records for the Pawcatuck River at Wood River Junction. Bierschenk (1956, p.23) estimated average annual base flow for the period 1945-54 to be about 17 inches; Lord (1975, table 2.1) estimated base flow for the period 1941-68 to be 18.4 inches.

Relation of Runoff to Geology and Topography

Surficial geology and topography play a primary role in determining the proportion of total runoff that leaves a drainage basin as surface-water runoff or as ground-water runoff to streams. Relatively steep slopes and soils of low permeability characteristic of areas underlain by till generally impede infiltration of precipitation so that total runoff from these areas consists predominantly of surface runoff. Low to moderate slopes and soils of high permeability characteristic of areas underlain by stratified drift, on the other hand, result in high rates of infiltration so that total runoff from these areas is derived predominantly from ground water.

The relation between the type of surficial deposits that underlie a drainage basin and the percentage of total runoff derived from ground water has been studied on Long Island, New York, and in several basins in southern New England. A study on Long Island shows that ground water supplies about 95 percent of the total annual runoff from basins underlain entirely by stratified drift, provided storm drainage systems are not extensively developed in the basins (Pluhowski and Kantrowitz, 1964, p. 35). Studies in Connecticut show that the percentage of runoff derived from ground water is predictably less from basins underlain by till than from basins underlain by both till and stratified drift, and is greater in those basins having a higher percentage of stratified drift (Randall and others, 1966; Thomas and others, 1967; Cervionne and others, 1972; Ryder and others, 1970). Regression analysis of the geologic and hydrologic data from 26 basins in Connecticut and from one basin in Massachusetts indicates that ground-water runoff to streams from areas underlain by till constitutes about 35 percent of the total runoff from till areas (Mazzaferro and others, 1979, p. 46).

Because climate, surficial geology, and topography are much the same in Rhode Island as in Connecticut and Long Island, New York, it is reasonable to assume that ground-water runoff will also constitute about 35 and 95 percent of the average annual runoff from areas underlain by till and stratified drift, respectively, in Rhode Island.

Based on this assumption, calculations were made of the average annual rates of ground-water runoff to streams from till and stratified drift in the 100-mi^2 area above the gage on the Pawcatuck River at Wood River Junction (table 4).

To test the validity of the computed averages, they were applied to the ground-water drainage area upstream from the Chipuxet River gage. This area is 10.6 mi^2, of which 4.5 mi^2 is underlain by till and 6.1 mi^2 is underlain by stratified drift. The computed average annual ground-water runoff at the gage is thus 7.93 Mgal/d--2.62 Mgal/d from till (0.43 Mgal/d/mi^2 x 4.5 mi^2 = 2.62 Mgal/d) and 5.31 Mgal/d from stratified drift (1.18 Mgal/d/mi^2 x 6.1 mi^2 = 5.31 Mgal/d). Allen and others (1966, table 5), computed base flow (mostly ground-water runoff) of the Chipuxet River to be 10.2 Mgal/d during the 1959 water year, a slightly wetter-than-average year. Total runoff during water year 1959 at the Pawcatuck River gage at Wood River Junction was 1.4 inches above the long-term (1941-78) average runoff of 26.1 in.

Computed ground-water runoff of about 20 percent less than that measured by Allen and others (1966) is accounted for, in part, by the fact that some of the measured base flow included drainage from storage in swamps and ponds, and, in part, by slightly above-average total runoff during water year 1959. In any event, the assumption that ground-water runoff from stratified drift and till averages 1.18 and 0.43 Mgal/d/mi^2 (24.8 and 9.1 inches), respectively, seems to be reasonable and conservative.

Table 4.--Estimated long-term (1941-78) average annual ground-water runoff from areas underlain by till and stratified drift in the Pawcatuck River basin upstream of Wood River Junction.

[Ground-water runoff is assumed to constitute 35 percent of average annual runoff from till and 95 percent of average annual runoff from stratified drift.]

Average annual runoff at Wood River Junction (1941-78)		Source of ground water: Till		Source of ground water: Stratified drift	
(in./yr)	(Mgal/d/mi^2)	(in./yr)	(Mgal/d/mi^2)	(in./yr)	(Mgal/d/mi^2)
26.1	1.24	9.1	0.43	24.8	1.18

Hydrogeology

The Chipuxet River and Chickasheen Brook basins, which contain the Chipuxet ground-water reservoir, are underlain by igneous and metamorphic bedrock of mainly granitic composition. Deep, narrow channels were cut into the bedrock surface by preglacial streams and were further deepened by the scouring action of advancing glacial ice. Contours on the bedrock surface (pl. 1) show that preglacial channels of Chickasheen Brook and the Chipuxet River converge to a single channel between Liberty Lane and Larkin Pond. This channel, marked approximately by the 100-foot contour, continues southward from the study area into Block Island Sound.

The bedrock surface is largely concealed beneath a mantle of unconsolidated glacial deposits. These deposits were derived from the underlying granitic bedrock and, therefore, are mineralogically similar to granite.

During the advance of the glacier, unsorted, unstratified drift (glacial till) was deposited beneath the glacial ice. Till covers most of the bedrock surface in hilly upland areas and is found locally on the bedrock surface in valley areas. In upland areas it is generally about 20 feet thick; in lowlands, where it commonly underlies stratified drift, it is generally less than 10 feet thick, and is absent in many places.

During the retreat of the glacier, sorted, stratified drift was deposited in valley areas by meltwater streams issuing from the glacier. These deposits range in thickness from a few feet near valley walls to as much as 200 feet near the axis of the preglacial channel in the southern part of the study area. The vertical distribution of till and stratified drift is illustrated by geologic sections drawn parallel (fig. 5) and perpendicular (figs. 6 to 8) to the axis of the Chipuxet River valley. Figure 5, a geologic section along the approximate trace of the preglacial channel of the Chipuxet River, illustrates the lithologic heterogeneity of the complexly interbedded aquifer system. Locations of the geologic sections and wells are shown in figure 4.

During the early stages of glacial retreat, the ice front stalled a few miles inland from the present-day coastline. Thick deposits of sediment accumulated along this front. The deposits completely filled several southward sloping channels of streams that once drained southern Rhode Island and resulted in the formation of a hummocky ridge known as the Charlestown moraine (fig. 1). The moraine blocked the southward flow of streams, caused lakes to form immediately north of the moraine, and resulted in the formation of the Pawcatuck River, which begins at Worden Pond. The Pawcatuck River carries the runoff from most of southern Rhode Island to Block Island Sound around the western end of the moraine at the Connecticut state line.

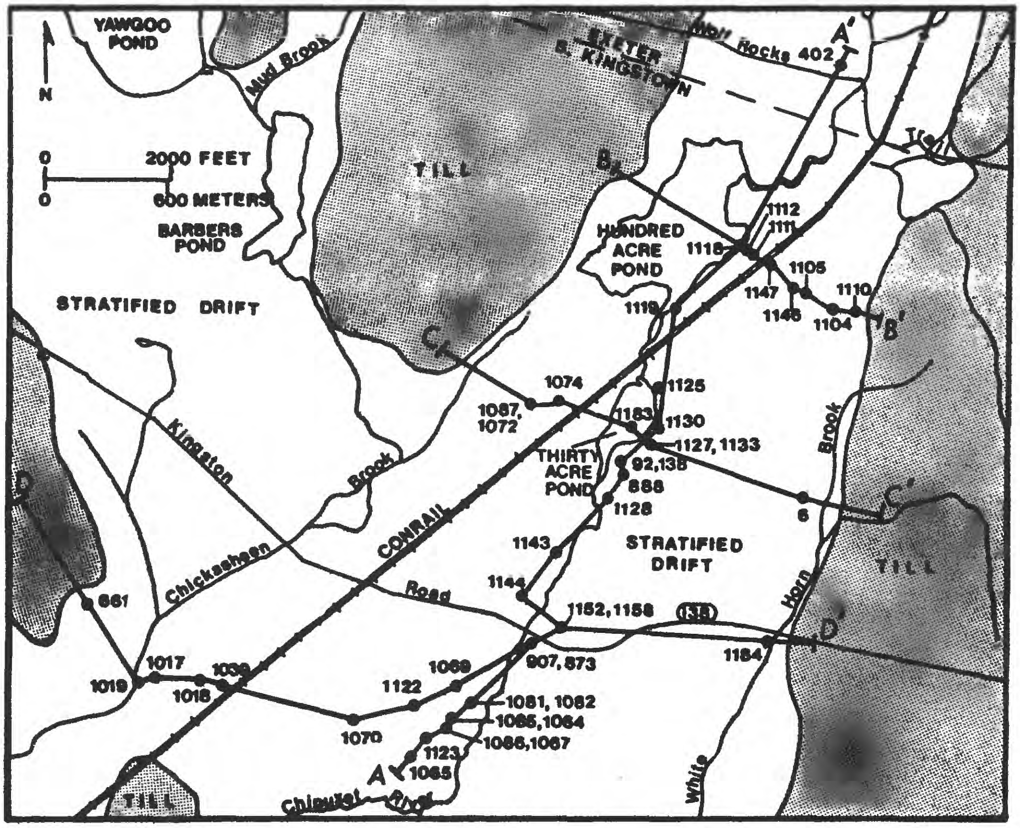

Figure 4.--Locations of five generalized geologic sections of the Chipuxet River valley (See figures 5, 6, 7, and 8 for geologic sections). (From Dickerman, 1984)

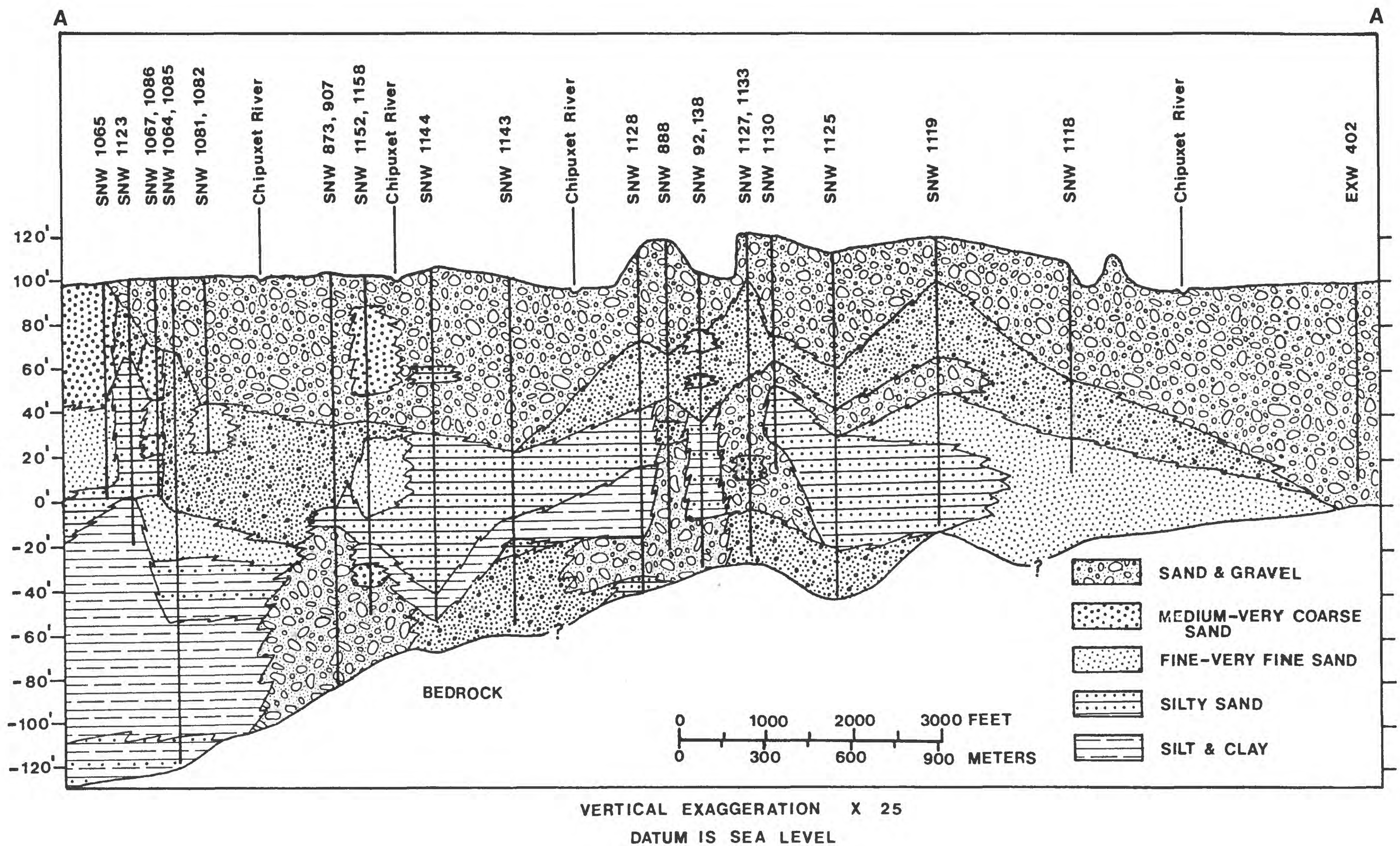

Figure 5.--Geologic section (A-A') of the Chipuxet River valley showing the lighologic heterogeneity of the complexly interbedded aquifer system (See figure 4 for line of section). (From Dickerman, 1984)

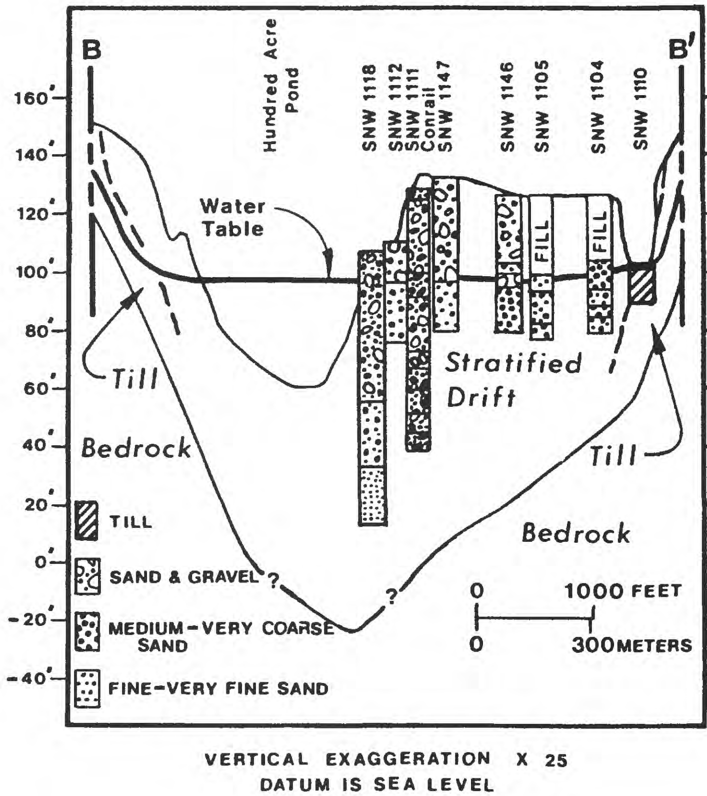

Figure 6.--Generalized geologic section (B-B') of the Chipuxet River valley at the Hundred Acre Pond site (See figure 4 for line of section). (From Dickerman, 1984)

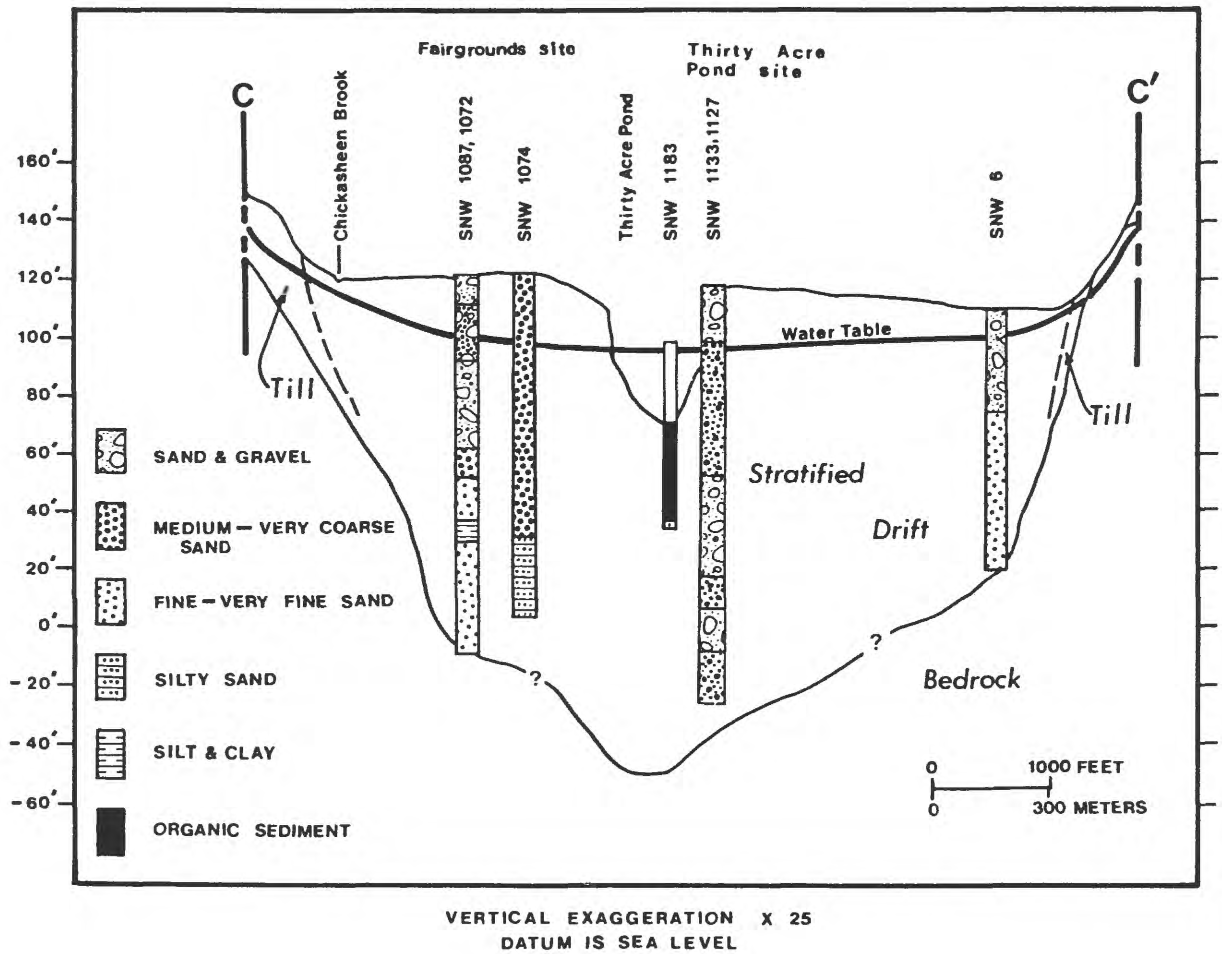

Figure 7.--Generalized geologic section (C-C') of the Chipuxet River valley through the Thirty Acre Pond site and the Fairgrounds site (See figure 4 for line of section). (From Dickerman, 1984)

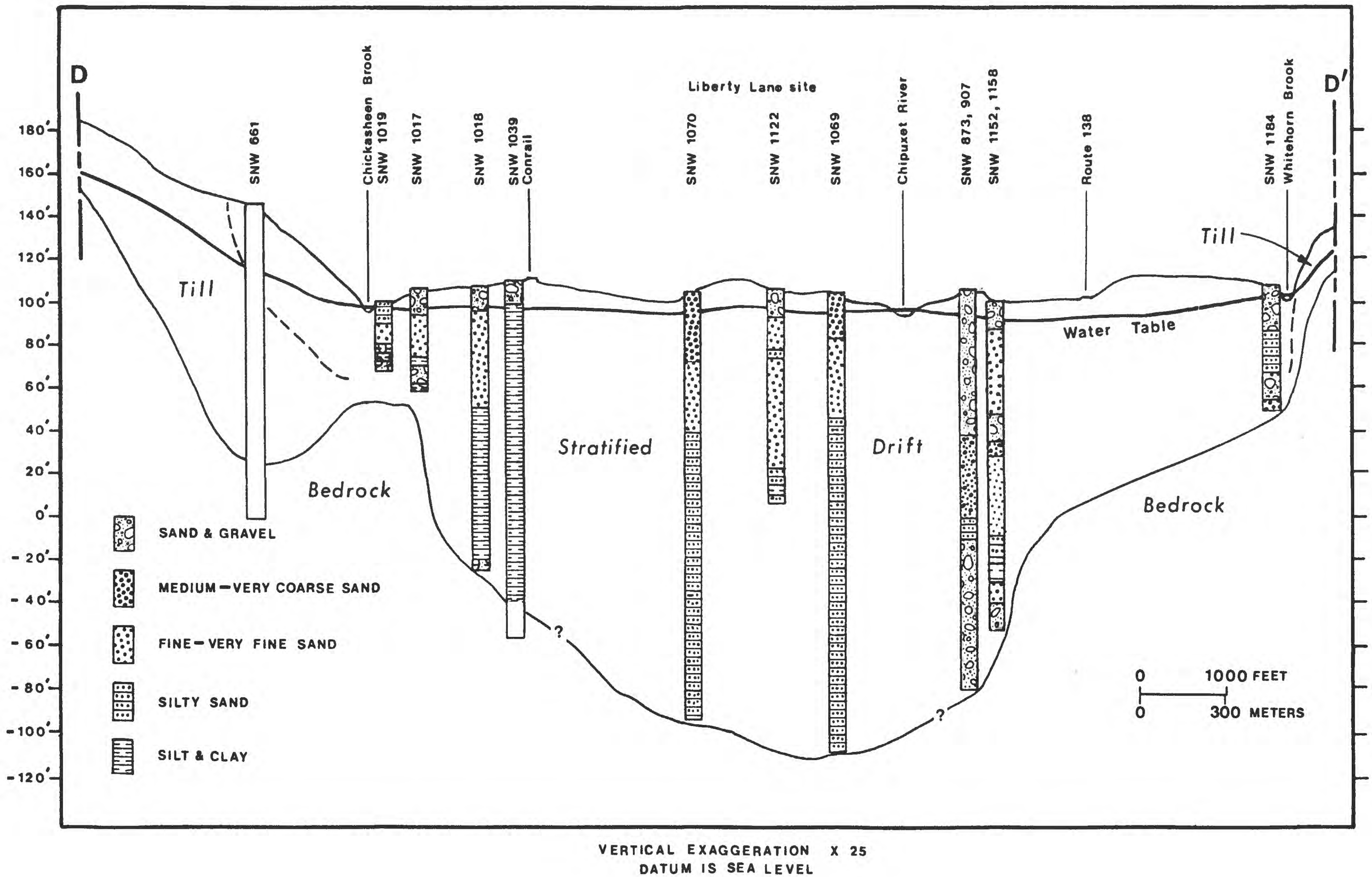

Figure 8.--Generalized geologic section (D-D') of the Chipuxet River valley near the Liberty Lane site (See figure 4 for line of section). (From Dickerman, 1984)

Most of the valley area between the moraine and Larkin Pond, now occupied by Worden Pond and the Great Swamp, was part of a glacial lake. Deposits in this area consist primarily of fine to very-fine sand, silt, and clay. These deposits contain a large volume of water but have low permeability. They may be expected to yield water at relatively low rates to wells. North of Larkin Pond, these deposits interfinger with generally coarser and more permeable sediments of the Chipuxet ground-water reservoir.

Bedrock, till, and stratified drift are the principal aquifers in the study area as well as elsewhere in the Pawcatuck River basin. Although this report is primarily concerned with the stratified-drift aquifer, a brief discussion of the till and bedrock aquifers is included, because they are in hydraulic connection with the stratified-drift aquifer and contribute to recharge to it by subsurface inflow along its margins.

Bedrock

The bedrock aquifer has low porosity and permeability. Water is contained in a network of irregular, widely spaced fractures and joints that decrease in size and number with depth. Effective porosity of the fractured bedrock is estimated to be less than 1 percent.

Despite its low permeability, the bedrock aquifer yields supplies adequate for domestic needs to wells drilled at most locations. Allen and others (1963, table 12) reported yields for 52 wells that penetrate bedrock in the upper Pawcatuck River basin. Yields range from 0.5 to 50 gal/min; median yield is 10 gal/min. Depth of bedrock penetrated by these wells ranges from 14 to 580 feet; median depth of penetration is 77 feet.

The low median yield and relatively large median depth of bedrock penetration indicate that the average hydraulic conductivity of the bedrock is low. Analysis of specific-capacity data for wells of similar depth and yield in crystalline bedrock of eastern Connecticut indicate average transmissivity of bedrock there to be about 33 ft^2/d [1] (Randall and others, 1966; Thomas and others, 1967). Because bedrock in eastern Connecticut is similar to that in the study area, it is reasonable to assume that transmissivity of the bedrock in the study area is in the same order of magnitude.

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[1] The unit "ft^2/d" is a reduction of the unit "cubic feet per day per foot of aquifer thickness."

Till

The till in the study area is a poorly sorted, nonstratified deposit composed mainly of sand and various proportions of clay, silt, gravel, cobbles, and boulders. Clay content of the till generally is very small. Till covers 57 percent of the subsurface drainage area upstream of the U.S. Geological Survey stream gage on the Chipuxet River at State Route 138 (pl. 1). It is tapped by several dug wells used to supply small domestic and farm needs. Yields of these wells are low and typically do not exceed 1 to 3 gal/min. Moreover, many of these wells go dry during droughts, making them unreliable as sources of water.

The water table in the till generally is close to the surface and has a shape similar to that of the land surface. Depths to water range from less than 1 foot below land surface in low areas in the spring months to as much as 29 feet below land surface near hilltops during fall months, and average about 12 feet. During the year, water levels fluctuate from 2 feet in low areas to as much as 20 feet beneath hilltops; the average annual fluctuation is about 5 feet. The slope of the water table generally is steep; gradients typically are in the range of 0.03 to 0.05 ft/ft. The gradients remain about the same from season to season.

The till ranges in thickness from a few inches near bedrock exposures to a maximum of 100 feet at the southwest edge of the study area (pl. 1); average thickness is about 20 feet.

Part of the till is saturated most or all of the year. Data for more than 100 wells (Allen and others, 1963, table 12) that tap till in the upper Pawcatuck River basin, which includes the study area, indicate that the saturated thickness of till ranges from zero to as much as 63 feet, and averages about 7 feet. Periodic water-level measurements made over several years in 17 wells (Allen and others, 1963, table 5) indicate that average saturated thickness may range from as little as 1 foot during dry months in the fall and winter to as much as 12 feet during wet months in the spring.

Hydraulic conductivity of the till is low, which causes yields of shallow dug wells to be low. Pumping tests on a few dug wells and laboratory measurements of hydraulic conductivity of several sediment samples indicate a range of hydraulic conductivity for till of 0.07 to 47 ft/d [1] and a median of 0.7 ft/d (Allen and others, 1966, p. 9). The product of this median value and the 7-foot average saturated thickness of till gives a value for transmissivity of 5 ft^2/d. If this value is multiplied by a minimum average saturated thickness of 1 foot and a maximum average saturated thickness of 12 feet, transmissivity ranges from 0.7 to 8 ft^2/d.

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[1] The unit "ft/d" is a reduction of the unit "cubic foot per square foot per day."

The specific yields of six samples of relatively undisturbed till from the upper Pawcatuck River basin were determined in the laboratory (Allen and others, 1963, table 12). The values ranged from 3.8 to 21.5 percent and averaged 11.1 percent. If the average specific yield of till is, in fact, about 10 percent, a 1-foot decline in the water table would result in release of 1.2 inches of water from storage. During the growing season, when water levels decline an average of about 5 feet, 6 inches (or 0.29 $Mgal/d/mi^2$) of water would be released from storage.

Because of the relatively high specific yield of the till aquifer, it functions as an important storage reservoir that annually absorbs several inches of precipitation. Much of this recharge is gradually discharged as ground-water runoff to nearby streams, or as ground-water flow to the underlying bedrock or adjacent bodies of stratified drift. Recharge to the stratified-drift aquifer by subsurface flow from till is discussed further in the section on recharge to the stratified-drift aquifer.

Stratified Drift

The lithology of the stratified-drift aquifer in the Chipuxet ground-water reservoir is known from lithologic logs of more than 100 wells and test borings. The aquifer is composed of complexly interstratified lenses of silt, sand, gravel and mixtures of these grain sizes. Individual lenses generally are of small areal extent and typically are only a few inches to a few feet thick. The upper part of the aquifer--that which is more than 50 feet above sea level--generally is coarser than the lower part. The upper part of the aquifer consists chiefly of medium to coarse sand and gravel. The lower part of the aquifer consists largely of fine to medium sand and contains more lenses of silt and silty sand. Lenses of coarse sand and gravel are present only locally in the lower part of the aquifer (figs. 5 to 8). A map of the aquifer is shown on plate 1 (part A).

Water-table conditions prevail in the aquifer, which is in good hydraulic connection with overlying perennial streams. The shape of the water-table surface is indicated by water-level contours on plate 1 (part B). These contours show that the water table slopes toward streams, ponds, and swamps, which are areas of ground-water discharge. Periodic measurements of water levels in 25 wells in stratified drift in and near the study area in 1958 and 1959 by Allen and others (1963, table 6) show that, in general, the water table fluctuates 3 to 4 feet annually during years of near normal precipitation. The annual water-level fluctuation ranges from as little as 1 foot near streams to as much as 11 feet near the till boundary of the aquifer.

Depth to water below land surface in the spring, when water levels are highest, ranges from less than 1 foot to as much as 28 feet and averages about 8 feet. Depth to water in the late summer and fall, when water levels are lowest, ranges from about 1 foot to as much as 32 feet and averages about 11 feet.

Saturated thickness of the aquifer ranges from a few feet near its contact with till to as much as 200 feet near the axis of the buried bedrock channel in the vicinity of Larkin Pond. The saturated thickness of the aquifer can be determined at any point in the aquifer by subtracting the altitude of the bedrock surface (pl. 1, part C) from the altitude of the overlying water-table surface (pl. 1, part B).

As a consequence of the interstratification of fine- and coarse-grained sediments, the average hydraulic conductivity of the stratified-drift aquifer is much less vertically than horizontally. The aquifer is, therefore, anisotropic with respect to hydraulic conductivity. The degree of anisotropy varies from place to place because of differences in the number, thickness, areal extent, and hydraulic conductivity of individual lenses of fine-grained units in the sediment column.

A principal effect of the rather strong aquifer anisotropy is that pumping from wells causes rapid water-level drawdown over rather large areas. The effect is similar to the response to pumping from a leaky confined aquifer. For example, during an aquifer test at Thirty Acre Pond on May 20, 1974, pumping from test well SNW (South Kingstown well) 1133 produced a measurable drawdown in observation well SNW 1131 within 5 minutes after pumping began (Dickerman, 1976, table 14). The observation well, which is 980 feet from the pumped well and on the opposite side of the pond, was screened from 115 to 120 feet below the water table. During the same test, measureable drawdown also occurred in a shallow observation well (SNW 1135), located 91 feet from the pumped well, within one minute after pumping began. Rapid drawdown in this well, which was screened from 3 to 4 feet below the water table, provides evidence that the aquifer is unconfined.

If the aquifer at Thirty Acre Pond were isotropic and had a storage coefficient of 0.2, a typical value for unconfined aquifers, measurable drawdown would not have occurred at a distance of 980 feet for nearly 24 hours after pumping began. The storage coefficient could not be determined at this site because of recharge effects from the pond.

Storage coefficient and specific yield

The capacity of an unconfined (water table) aquifer, such as the stratified-drift aquifer in the study area, to take in and release water from storage is governed by its storage coefficient, which is effectively equal to its specific yield. Typically, the specific yield of unconfined aquifers composed of granular materials is in the range of 0.1 to 0.3 (Lohman, 1979, p. 53).

The specific yield of 39 samples of unconsolidated, disturbed samples of sediment from the upper Pawcatuck River basin was determined by laboratory methods by Allen and others (1963, tables 1 and 12). A summary of their results is given in table 5. Laboratory determinations of specific yield of disturbed samples are likely to be larger than those obtained by field methods (Lohman, 1979, p. 54). Therefore, specific yields given in table 5 may be higher than those for similar, undisturbed materials in the study area. If so, they may be assumed to represent the approximate upper limits for specific yields of these types of materials. The average specific yield of 29 samples ranging in grain size from very fine sand to gravel is 27 percent. Inasmuch as the upper 50 feet or so of the stratified-drift aquifer in the study area is composed predominantly of sand and gravel, the average specific yield of this part of the aquifer probably does not exceed 27 percent.

Storage coefficients also were determined from analysis of aquifer-test data (table 9). Values determined at nine sites ranged from 0.004 to 0.27. However, values smaller than 0.11 are not indicative of the true specific yield of the stratified-drift aquifer (Dickerman, 1984). For values greater than 0.11, specific yield averaged 0.18. Williams and Lohman (1949, p. 213, 220) stated that the true value of specific yield is obtained only after the saturated material has been drained for a long time. They conclude that, even for sand-size materials, 2 months to more than 1 year would be required for drainage to reach equilibrium and, thus, give the maximum specific yield. In the Chipuxet aquifer, for example, a specific yield of 0.09 was determined from aquifer-test analysis of SNW 1085 at the Liberty Lane site after pumping 24 hours. Specific yield determined for a 124-hour test on SNW 1082, also located at the Liberty Lane site, was 0.14 (table 9). Based on values from analytical and laboratory analysis, 0.2 seems to be a reasonable average specific yield for the stratified-drift aquifer.

Hydraulic conductivity and transmissivity

The capacity of an aquifer to transmit water is governed by its transmissivity (T), which is the product of the average horizontal hydraulic conductivity (k) and the saturated thickness (b) of the aquifer. For purposes of this study, b is defined as the vertical distance between the water table and the bedrock surface.

The vertical hydraulic conductivities of the beds of streams and ponds and of the aquifer materials immediately beneath these water bodies are also of importance because they determine the rate at which water can be induced to flow into the aquifer by nearby pumping wells. Both laboratory and field methods were used to determine hydraulic properties of the aquifer in the study area.

Table 5.-- Specific yield of sediments from the upper Pawcatuck River basin.

[From Allen and others, 1963; a dash indicates no data]

Material	Number of samples	Specific yield (percent)		
		Low	Average	High
Stratified drift				
Gravel	1	--	27.9	--
Sand and gravel	3	20.4	22.7	25.1
Sand, medium to coarse	15	12.5	26.9	39.2
Sand, fine to very fine	10	16.3	29.2	41.3
Sand, silty	2	12.5	19.1	25.7
Silt	1	--	25.7	--
Silt, organic (swamp deposit)	1	--	39.3	--
Till	6	3.8	11.1	21.5

The capacity of the stratified-drift aquifer to transmit water was determined by analysis of (1) lithologic logs, (2) specific-capacity data for wells 8 inches or larger in diameter, and (3) aquifer-test data. Estimates of average hydraulic conductivity and transmissivity determined from lithologic logs provide values that are applicable to a radial distance within a few feet of the well, whereas values determined from specific-capacity or aquifer-test data apply to a radial distance within several hundred feet of the pumped well. Results of these analyses were used to prepare the map of hydraulic conductivity (pl. 1, part A), which is a modification of part of the map of hydraulic conductivity prepared for the upper Pawcatuck River basin by Allen and others (1966, pl. 2).

Estimates from lithologic logs.--The transmissivity of a layer of sediment is the product of its hydraulic conductivity and its saturated thickness. At any point in the study area, the transmissivity of a column of the stratified-drift aquifer extending from the water table to the bedrock surface is equal to the sum of the transmissivities of each layer of material in the column.

The transmissivity of an aquifer can be estimated by assigning reasonable values of hydraulic conductivity to individual layers of saturated sediment described in lithologic logs of wells or test borings. The transmissivities of individual layers are summed to obtain a measure of the transmissivity of that part of the total aquifer thickness penetrated by the well or boring. Because lithologic logs have been recorded for wells throughout much of the study area, transmissivity (T) or average hydraulic conductivity (k) (where k = T/b), can be estimated at many points in the stratified-drift aquifer. Values of hydraulic conductivity assigned to sediments in the study area to estimate transmissivity are given in table 6.

Values of transmissivity determined from analysis of the lithologic logs of wells provide a rough, but generally conservative, estimate of the water transmitting capacity of an aquifer. At 7 of 14 sites where transmissivity was determined from both lithologic logs and analysis of aquifer-test data, values determined from logs were lower than those determined from aquifer tests (table 9). Estimates from logs are useful because they provide a check on the reasonableness of values obtained from specific-capacity and aquifer-test methods. An example of how transmissivity was estimated from a lithologic log is shown in table 7.

Table 6.--Values of hydraulic conductivity used to estimate transmissivity from lithologic logs in the Chipuxet River basin ground-water reservoir.

[Modified from Rosenshein and others, 1968]

Material	Hydraulic conductivity (ft/d)
Gravel	470
Sand and gravel	200
Very coarse sand	160
Coarse sand	135
Medium sand	105
Fine sand	55
Very fine sand	20
Silt [1]	4
Clay, till (hardpan) [1]	.1

[1] The hydraulic conductivities of silt, clay, and till are based on values published in Geological Bulletin 13 (Allen and others, 1963, p. 8-10). Values were determined by laboratory analysis of samples at the U.S. Geological Survey Hydrologic Laboratory.

Table 7.--Example showing how transmissivity and average hydraulic conductivity are estimated from the lithologic log of a hypothetical well.

Depth below land surface (ft)	Aquifer material	Assumed hydraulic conductivity, k (ft/d)	Saturated thickness, b (ft)	Transmissivity, T = k x b (ft^2/d)
0-20	Gravel	470	10	4,700
20-40	Sand, fine	55	20	1,100
40-50	Sand, very fine	20	10	200
50-70	Sand and gravel	200	20	4,000
70-90	Silt	4	20	80
90-95	Sand, medium	105	5	525
			85	10,605

Average k = T/b = (10,605 ft^2/d)/(85 ft) = 125 ft/d

Estimates of hydraulic conductivity based on lithologic logs of wells in the Chipuxet River basin were used to map areal differences in hydraulic conductivity at four depth intervals in the stratified-drift aquifer (figs. 9a and 9b). These figures show that the hydraulic conductivity of the upper 50 feet of the aquifer is generally higher than at greater depths. They also show that lenses of highly permeable sand and gravel (indicated by zones in which hydraulic conductivity is greater than 100 ft/d) occur locally near the base of the aquifer. It is possible that other lenses of highly permeable material remain to be found in untested areas.

Estimates from specific-capacity data.--The specific capacity of a 100-percent efficient well--that is, one in which drawdown inside the well is the same as that in the aquifer immediately outside the well--is proportional to the transmissivity of the aquifer. Most wells are less than 100-percent efficient, which means that drawdown due to pumping is greater inside than immediately outside the well. Therefore, transmissivity computed from specific capacity is generally on the low side.

Specific-capacity data were used to estimate transmissivity at aquifer-test sites as an additional means of checking the reasonableness of values obtained by analysis of aquifer-test data. Values determined by both methods (table 9) are in reasonably close agreement. However, at 11 of 13 sites where transmissivity was determined by both methods, values determined from specific capacity were lower than those determined from aquifer tests.

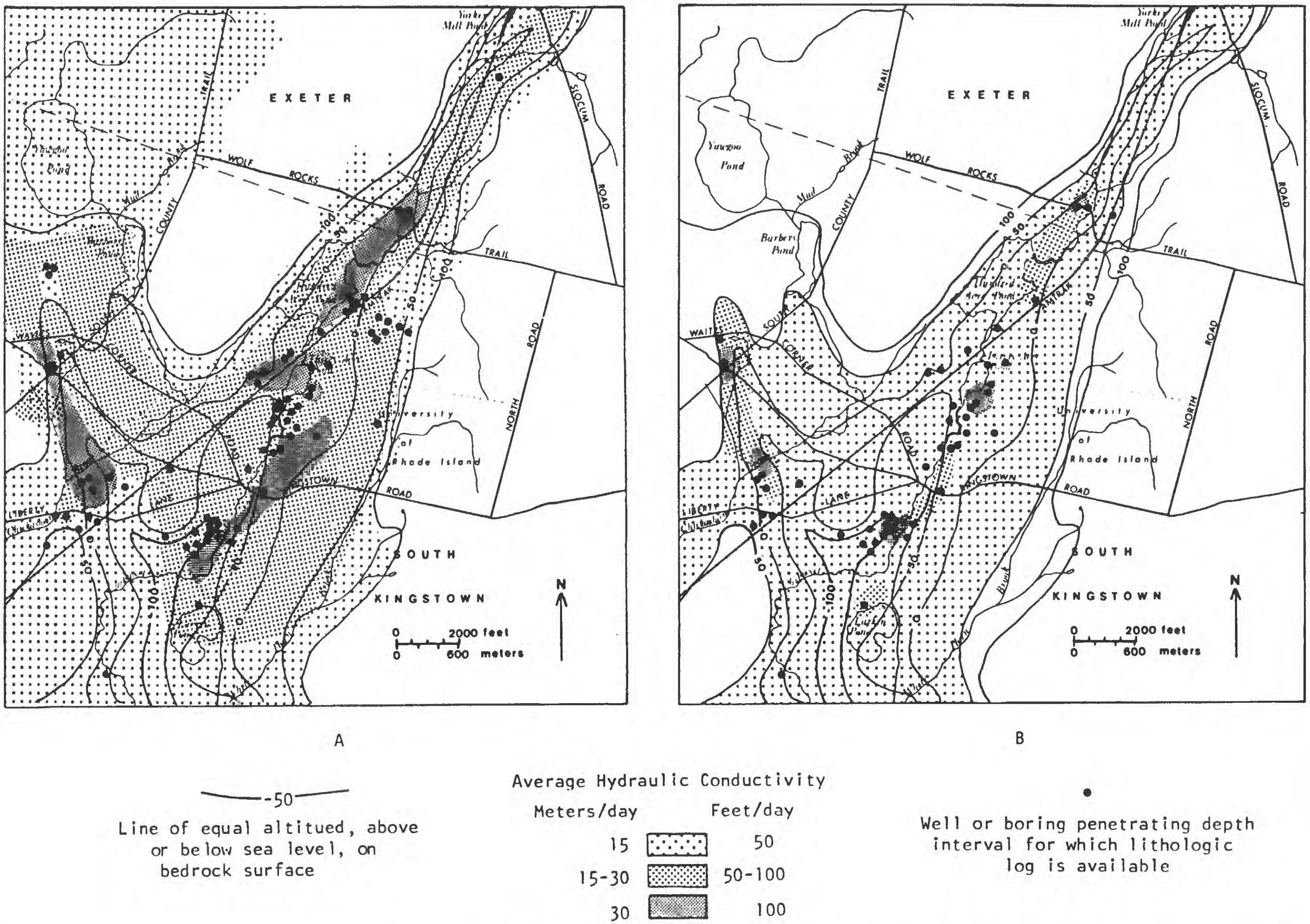


Figure 9a.--Hydraulic conductivity of stratified drift estimated from lithologic logs: A, in the interval 120 to 50 feet above sea level (about 0 to 50 feet below the water table), and B, in the interval 50 to 0 feet above sea level (about 50 to 100 feet below the water table).

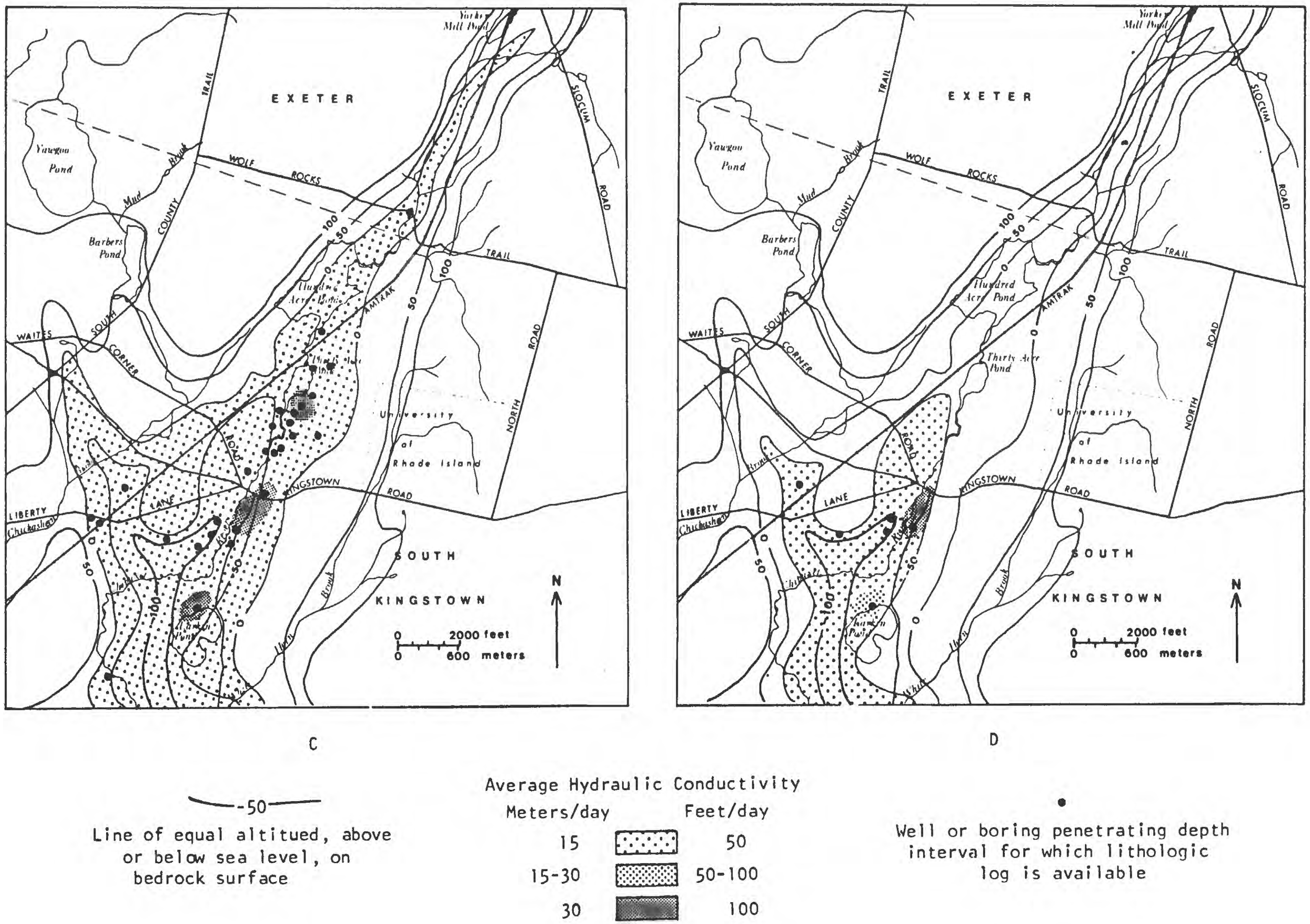


Figure 9b.--Hydraulic conductivity of stratified drift estimated from lithologic logs: C, in the interval 0 to -50 feet below sea level (about 100 to 150 feet below the water table), and D, in the interval -50 to -100 feet below sea level (about 150 to 200 feet below the water table).

Determinations from aquifer tests.--An aquifer test is a controlled field experiment made to determine the hydraulic properties of water-bearing rocks. It involves the pumping of a well at a known constant rate, and measurement of water-level changes in the pumped well and nearby observation wells. Water-level measurements are made before, during, and after the pumping period. Analysis of aquifer-test data by appropriate analytical methods yields values of average transmissivity, horizontal and vertical hydraulic conductivity, and storage coefficient for that part of the aquifer within a radius of several hundred feet of the pumped well.

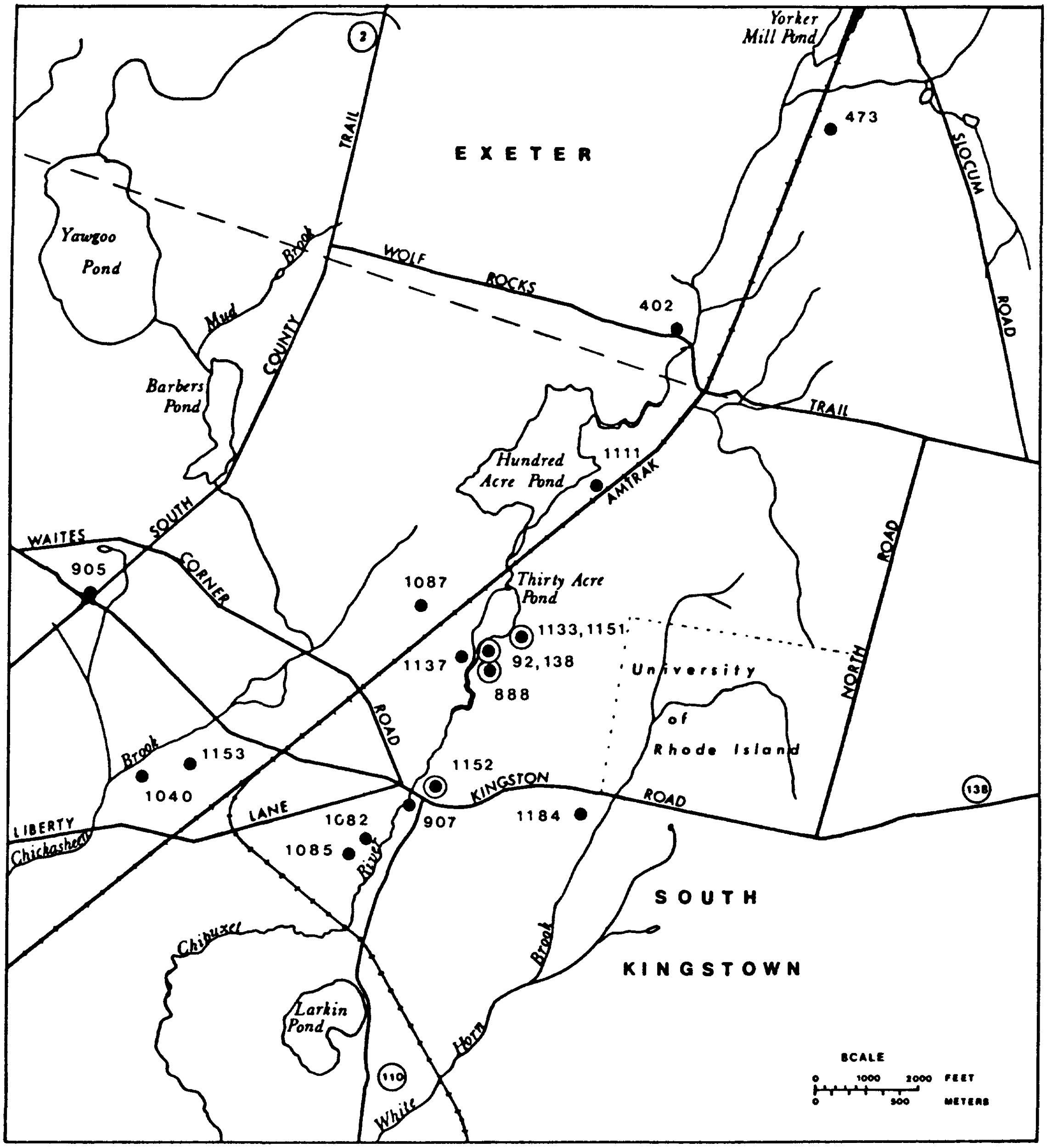
Eighteen aquifer tests, seven of which were done as part of this study, have been made in the thick, permeable parts of the stratified-drift aquifer. For these tests, the wells were pumped continuously at rates ranging from 100 to 910 gal/min for periods of 4 to 124 hours. The pumped wells ranged in depth from 55 to 176 feet and most had 10 to 30 feet of screen exposed near the bottom of the well.

Transmissivity of the stratified-drift aquifer determined from these tests ranged from 5,000 to 39,100 ft^2/d. Average horizontal hydraulic conductivity ranged from 90 to 595 ft/d, whereas average vertical hydraulic conductivity ranged from 6 to 52 ft/d. Horizontal hydraulic conductivity was obtained by dividing transmissivity by aquifer thickness, which was assumed to be the distance from static water level to the bottom of the screen in the pumped well.

Detailed descriptions of the aquifer tests, and a discussion of the methods used to analyze the data, are described in a separate report by Dickerman (1984). Locations of the aquifer-test sites are shown in figure 10. A summary of the well construction and pumping test data is given in table 8; results of aquifer tests analyses are given in table 9.

Yield of wells

The yield of a well is affected by many complexly inter-related factors and cannot be determined accurately in advance of construction. A rough estimate of the potential yield obtainable from a well in the stratified-drift aquifer can be determined, however, using data from a lithologic log or from plate 1. If a lithologic log is available, average hydraulic conductivity can be estimated by the method illustrated in the section on determining transmissivity from logs. If plate 1 is used, saturated thickness at a selected site is determined by subtracting the bedrock altitude from the water-table altitude, and the hydraulic conductivity is estimated from the map. An example of how to estimate the potential yield of a large-diameter well is shown in figure 11.



EXPLANATION

AQUIFER-TEST SITES

92 ◉ Supply well

● 1087 Test well

(Figure is USGS town identification number)

Figure 10.--Location of aquifer-test sites in the Chipuxet River ground-water reservoir.

Table 8. Well construction anad pump-test data for pumping wells tested in the Chipuxet River stratified-drift aquifer.
[From Dickerman, 1984; a dash indicates no data]

Pumping well[1]	Diameter[2] (inches)	Screened interval[3,4] (feet)	Static water level[4] (feet)	Date of aquifer test	Length of test (hours)	Pumping rate (gallons per minute)	Draw-down (feet)	Specific capacity (gallons per minute per foot)
				TOWN OF EXETER				
402	8	17-87	1.04	01-06-60	24	610	7.36	83
473	24X18	74-84	15.00	03-06-67	24	460	43.96	10
				TOWN OF SOUTH KINGSTOWN				
92	18X12	111-131	8.88	03- -49	20	800	9.00	89
138	18X12	50-70	9.80	05- -48	4	235	39.54	6
888	18X12	113-138	21.30	05- -58	72	800	6.00	133
905	8	13-37	4.08	12-07-59	24	290	13.26	22
	8	55-76						
907	8	10-62	6.76	01-27-60	24	395	11.74	34
	8	124-176						
1040	24X18	45-65	5.00	10-26-60	45.5	725	26.00	28
1082	8	40-70	5.50	01-25-71	124	550	26.50	21
1085	8	65-90	3.38	10-08-70	24	610	35.00	17
1087	8	60-85	21.83	11-30-70	100	290	26.00	11
1111	8	53-60	28.00	12-11-73	40	360	—	—
1133	8	80-95	24.26	05-20-74	96	650	26.94	24
1137	8	42-55	4.75	06-10-74	48	100	21.90	5
1151	24X18	75-95	25.10	10-21-74	48	910	7.45	122
1152	18X12	48-63	10.00	03-18-65	66	515	33.00	16
1153	8	52-62	8.50	05-07-74	24	300	32.50	9
1184	12X8	48-58	11.50	11-09-76	9	205	20.67	10

[1] Local well number based on the town in which it is located.
[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, the gravel pack.
[3] Bottom of screened interval is well depth.
[4] Feet below land-surface datum.

Table 9. Summary of hydraulic properties determined from aquifer tests for the stratified-drift aquifer in the Chipuxet River basin.
[From Dickerman, 1984; a dash indicates no data]

Pumping well[1]	Transmissivity estimated from: Lithologic log (square feet per day)	Transmissivity estimated from: Adjusted specific capacity[2] (square feet per day)	Observation well: Number[1,3]	Observation well: Screened interval (feet)	Method[4]	Hydraulic properties determined by analytical methods: Transmissivity (square feet per day)	Hydraulic conductivity: Horizontal[5] (feet per day)	Hydraulic conductivity: Vertical (feet per day)	Storage coefficient[6]
				TOWN OF EXETER					
402	37,600	19,600	397	10-13	a	37,400	435	--	--
			397	10-13	b	39,100	455	--	--
					Site average-----	38,200	445	--	--
473	6,800	5,400	474	(7)	c	7,700	110	--	--
				TOWN OF SOUTH KINGSTOWN					
92	20,000	17,000	--	--	--	--	150	--	--
138	9,400	—	--	--	--	--	--	--	--
888	27,000	28,600	--	--	--	--	--	--	--
905	8,300	6,800	900	(8) 10	b	6,600	90	--	--
907	33,700	10,700	--	--	c	28,700	170	--	--
1040	9,000	13,800	1026, 1037	42-60, 54-64	d	14,000	235	--	0.02
1082	12,600	9,000	1064, 1067	83-95, 67-77	c				
			1068, 1069	74-84, 21-31		9,000	140	--	.11
			1068	74-84	a	7,700	120	--	.13
			1068	74-84	b	8,100	125	8	.16
			1069	21-31	b	9,500	145	27	.17
					Site average-----	8,800	135	18	0.14
1085	15,500	10,900	1064	83-95	b	13,700	160	--	--
			1067	67-77	b	17,000	200	24	.08
			1068	74-84	b	14,700	170	13	.11
			1069	21-31	b	13,800	160	11	.07
					Site average-----	14,800	170	16	0.09
1087	12,000	8,400	1072, 1074	80-92, 73-85	c	8,900	140	--	.13
1111	8,100	20,000	1114, 1116	45-50, 55-61	c	19,000	595	--	.27
1133	11,600	--	92, 1131	111-131, 120-125,	f				
			1128, 1130	144-157, 100-104		27,000	387	--	--
			1130	100-104	e	19,200	240	3	--
			92, 1128	111-131, 144-157,	e				
			1130, 1131	100-104, 120-125		24,900	355	6	--
			92, 1128	111-131, 144-157	c				
			1130, 1131	100-104, 120-125		27,000	385	--	.06
					Site average-----	26,300	375	6	0.06
1137	10,000	6,200	1138	47-53	g	5,000	100	--	.004
			1139	43-48	g	7,700	150	--	.005
					Site average-----	6,400	125	--	0.004
1151	16,900	26,700	92, 888	111-131, 113-138	c				
			1128	114-157		28,600	410	--	.03
			92, 888	111-131, 113-138	f				
			1128	114-157		25,800	370	--	--
					Site average-----	27,200	390	--	0.03
1152	6,200	6,600	1161	(8) 60	b	21,000	400	48	.03
			1162	(8) 60	b	21,000	400	52	.10
			1162	(8) 60	c	21,600	400	--	.04
					Site average-----	21,200	400	50	0.06
1153	13,400	6,000	--	--	--	--	250	--	--
1184	4,800	4,700	1188	(7)	c	6,900	145	--	.009

1 Local well number based on town in which it is located.

2 Drawdown in Exeter well 473 and South Kingstown wells 905, 907, 1082, 1085, 1087, 1152, 1153, and 1184 was adjusted for the effects of partial penetration and dewatering. Drawdown in Exeter well 402 was adjusted only for dewatering; drawdown in South Kingstown wells 1040, 1111, and 1137 was adjusted for well loss, partial penetration and dewatering; and drawdown in South Kingstown wells 92, 888, and 1151 were unadjusted.

3 Well or wells used in analysis.

4 (a) Delayed yield (Boulton, 1954), described in Lohman (1979, p. 34-40); (b) vertical movement (Stallman, 1963, 1965), described in Lohman (1979, p. 34-40); (c) modified nonleaky confined (Cooper and Jacob, 1946), described in Walton (1962, p. 9); (d) nonsteady flow leaky confined (Hantush, 1960), described in Lohman (1979, p. 32-34); (e) nonsteady radial flow leaky confined (Cooper, 1963), described in Lohman (1979, p. 31-32); (f) steady state leaky confined (Jacob, 1946b), described in Walton (1962, p. 5-6); (g) non-equilibrium formula (Theis, 1935), described in Walton (1962, p. 6).

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

6 Values smaller than 0.11 were determined from drawdown data within the first few minutes of the start of pumping. They are not indicative of the true storage coefficient of the aquifer. Values greater than 0.11 are believed to approach the true storage coefficient (specific yield) of the stratified-drift aquifer in the Chipuxet River basin.

7 Screened interval unknown.

8 Well finish, open end.

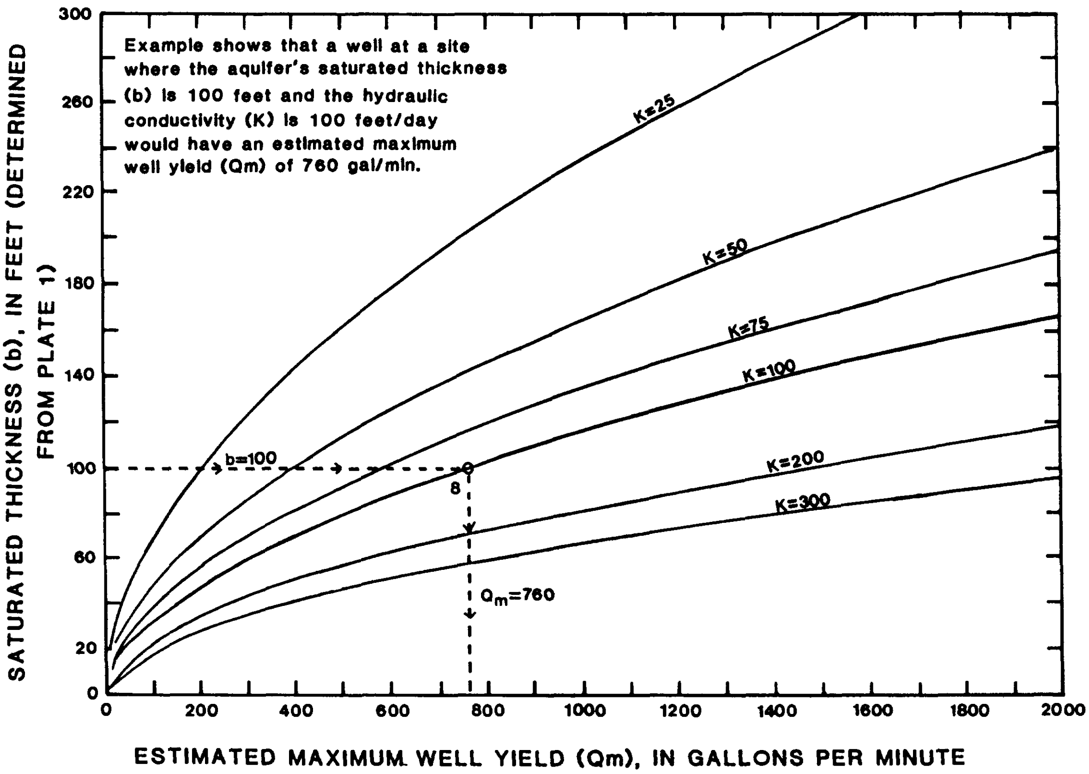


Figure 11.--The potential yield of a large-diameter well screened in the lower 30 percent of the saturated zone.

The values of well yield for figure 11 were calculated for a pumping period of 200 days, assuming that (1) withdrawal is entirely from storage in an aquifer of infinite areal extent, (2) specific yield of the aquifer is 0.2, (3) well diameter is 1 foot, (4) available drawdown is 70 percent of the saturated thickness penetrated by the well, (5) the ratio of horizontal to vertical hydraulic conductivity is 10 to 1, and (6) well efficiency is 90 percent. Computed drawdown for the indicated pumping rates include adjustments for effects of partial penetration and dewatering of the aquifer.

The yields of high capacity supply wells in the study area generally have been determined from pumping tests lasting from 1 to 3 days. Maximum tested yields of large-diameter wells are shown on figure 12. Some of the wells could have been pumped at higher rates.

Yields determined from tests lasting a few days do not necessarily provide an adequate basis for predicting long-term yield. Drawdown caused by other pumping wells or geologic boundaries, such as less permeable bedrock valley walls, may combine to reduce the yield of a well over a long period of time. Estimates of long-term well yield are best determined by mathematical models discussed later in the report.

Because well yield is proportional to water-level drawdown in the aquifer adjacent to a well, comparison of specific capacities (the yield per foot of drawdown in a well) provides a more useful means of comparing the relative yielding capabilities of wells. The specific capacities of 18 large-diameter wells drilled in the Chipuxet ground-water reservoir ranged from 5 to 133 gal/min/ft; the median was 16 gal/min/ft (table 8).

Five potential sites and four existing sites are under consideration by the RIWRB as possible sources of a total 3 Mgal/d public-supply system in the Chipuxet River basin (fig. 27). Data from aquifer tests at each of the sites were used to estimate optimum pumping rates and potential yields obtainable from existing or hypothetical large-diameter wells at these sites (table 10). The effect of pumping selected combinations of these wells on ground-water levels and streamflow is discussed in the section on ground-water modeling. The estimated aggregate yield obtainable from these nine wells is in excess of 6 Mgal/d. Despite the availability of a total yield of more than double that sought, water-quality considerations may preclude development of supplies at one site and limit full development of potential yield at others.

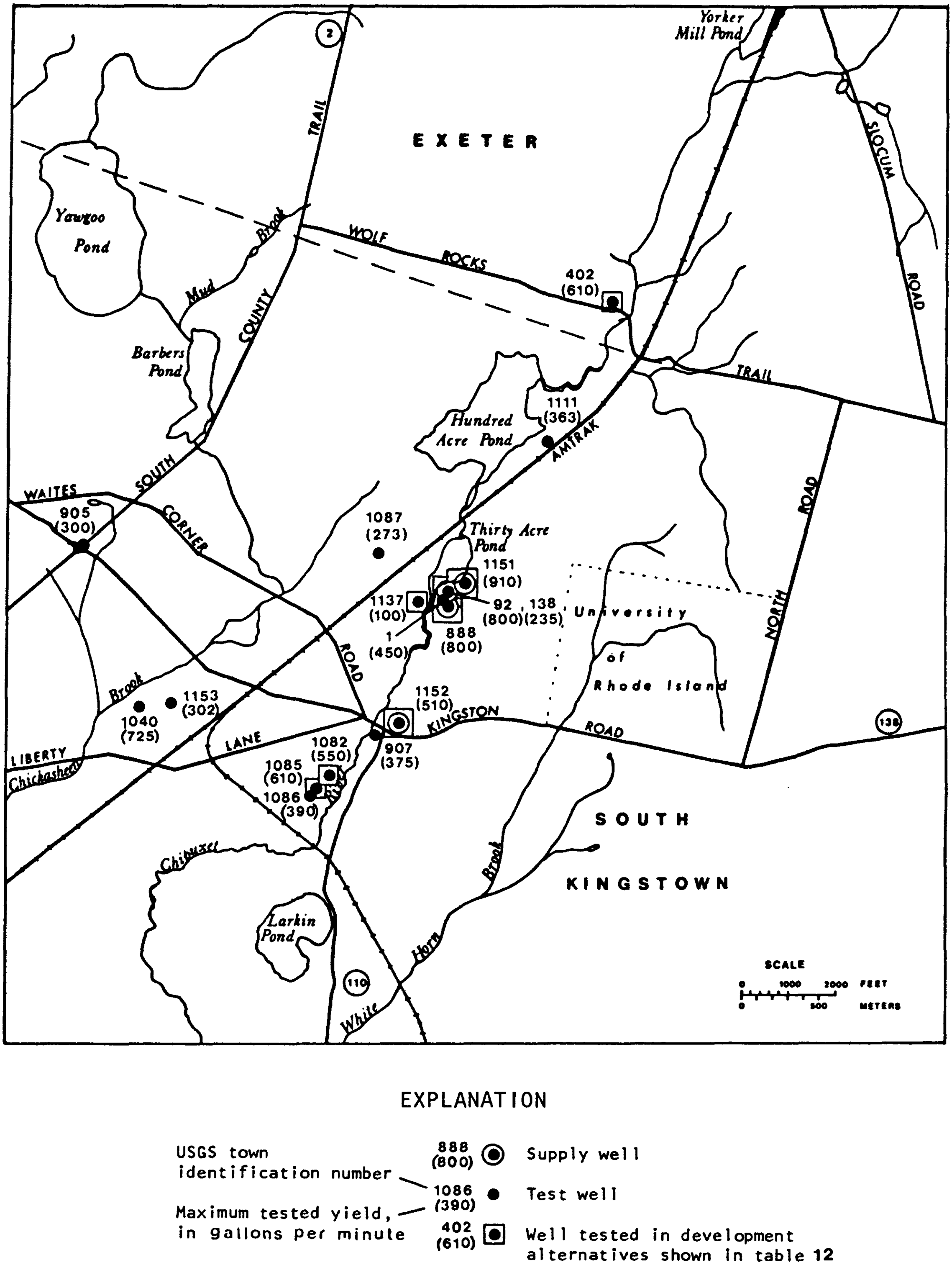


Figure 12.--Maximum yields of large-diameter wells tested in the stratified-drift aquifer.

Table 10.--Potential yield of large-diameter wells at selected sites in the Chipuxet ground-water reservoir

[At sites of test wells, potential yield is estimated for a hypothetical well for which gravel pack construction, diameter, slot size, and length of screen are assumed. Slot sizes for the screens in supply wells SNW 92 and 888 were estimated. See table 8 for additional data on test wells and supply wells. Potential yield at the site of SNW 1142, a 2.5-in. diameter test well 300 ft southwest of SNW 1137 is assumed to be equal to that at the site of SNW 1137.]

Site	USGS town number of test well(*) or supply well(**) at site	Assumed(*) or actual(**) well diameter[1] (in.)	Assumed(*) or actual(**) screen depth (ft)	Estimated(*) or actual(**) specific capacity[2] (gal/min/ft)	Approximate length of static water column above top of screen (ft)	Estimated optimum pumping rate[3] (gal/min)	Potential yield[4] (MGal/d)
Town of Exeter							
Wolf Rocks Trail	402 *	24 x 18*	55-85*	34*	54	1,200	1.3
Town of South Kingston							
Thirty Acre Pond --East Side	92**	18 x 12**	111-131**	89**	102	700	.76
do.	888**	18 x 12**	113-138**	99**	92	800	.86
do.	1151**	24 x 18**	75-95**	122**	50	1,200	1.3
Thirty Acre Pond --West Side	1137*	24 x 18*	45-55*	12*	40	250	.27
do.	1142*	24 x 18*	45-60*	12*	35	250	.27
Kingston Fire District	1152**	24 x 18**	48-63**	16**	38	250	.27
Liberty Lane	1085*	24 x 18*	67-87*	35*	62	475	.51
do.	1082*	24 x 18*	43-58*	24*	38	450	.51
Old Fairgrounds	1087*	24 x 18*	60-70*	24*	38	400	.43
Hundred Acre Pond	1111*	24 x 18*	50-68*	49*	22	600	.65

1 The larger number is the diameter of the gravel pack; the smaller number is the diameter of the casing and screen.

2 Estimates for hypothetical supply wells are based on analysis of aquifer-test data.

3 The pumping rate that would cause water to flow through screen openings at a velocity of about 0.1 ft/s.

4 The product of optimum pumping rate and an assumed pumping period of 1,080 minutes (18 hours)/day.

The optimum pumping rate, as used herein, is the maximum rate at which a well can be pumped without producing appreciable drawdown due to well loss. Well loss is a component of drawdown in a well that occurs when velocity of flow through the well screen and in the well bore is high enough to cause turbulent flow. A large component of drawdown due to well loss increases the depth from which water must be pumped and thereby increases the cost of pumping.

The potential yields of wells given in table 10 are computed as the product of optimum pumping rate and a pumping period of 1,080 minutes (18 hours), assuming that wells would be pumped only part of a day. Higher yields than those indicated could be obtained if the higher cost of less efficient wells and longer pumping periods are assumed.

Natural Recharge and Discharge

Natural recharge to aquifers in the Chipuxet and Chickasheen Brook basins results chiefly from percolation of precipitation to the water table. Some recharge also occurs locally from naturally losing stream reaches. Natural losses of streamflow occur where the water table is below the bed of a stream. Natural discharge from aquifers in the basins occurs as ground-water runoff to streams, ground-water evapotranspiration, and subsurface outflow.

For any given period, recharge to a basin is equal to ground-water discharge from it plus or minus any net change in ground-water storage. Because recharge cannot be measured directly, it is generally determined by measuring or calculating components of discharge and changes in storage. A water budget showing monthly components of ground-water discharge and changes in storage was computed for the Chipuxet basin for water year 1959 to arrive at monthly and annual estimates of recharge (table 11). Because total runoff during water year 1959 was slightly above average (see section on relation of runoff to geology and topography) the estimate of annual recharge of 25 inches is assumed to be above average.

The budget is modified from Allen and others (1966, table 5). The principal modifications of their data are (1) conversion of values in inches to correspond to a subsurface drainage area of 10.6 mi2, (2) reduction of monthly ground-water evapotranspiration, and (3) addition of monthly values of subsurface outflow, pumpage exported, and change in ground-water storage.

Approximately 26 percent of the ground-water evapotranspiration computed by Allen and others (1966) was for the months of December, January, and February, during which average monthly temperatures were below freezing. Because ground-water evapotranspiration during these months was probably negligible, values for these months have been reduced to zero.

Changes in storage were determined from monthly water-level data for 34 wells--13 wells in till and 21 wells in stratified drift in the Upper Pawcatuck River basin (Allen and others, 1963, table 6). Storage changes in till were computed as the product of an assumed average specific yield of 0.1, the area of till (6.1 mi2) in the subsurface drainage area, and the average change in water level in 13 till wells. Storage changes were similarly determined for the 4.1 mi2 area of stratified-drift, using an average specific yield of 0.2 and the average change in water level computed for 21 wells.

An estimate of average annual recharge to the Chipuxet River basin may be obtained, if average annual values can be determined for components of ground-water discharge. Over a period of many years, net changes in ground-water storage tend to be negligible in a basin such as the Chipuxet River basin, where consumptive water use by man is relatively small and constant. Consequently, average annual recharge is essentially equal to average annual discharge.

In the Chipuxet River basin, ground-water discharge occurs as ground-water runoff, ground-water evapotranspiration, subsurface outflow, and by pumping from wells. Average annual ground-water runoff is estimated to be 18.3 inches (see section on components of streamflow). In table 11, values are given for subsurface outflow (0.24 in.), ground-water evapotranspiration (5.39 in.), and consumptive ground-water withdrawals (0.60 in.). These values are representative of long-term average conditions. Long-term average annual discharge and recharge are thus estimated to be 24.5 inches (18.3 in. + 0.24 in. + 5.39 in. + 0.60 in.= 24.53 in.).

Rates of recharge to individual aquifers differ. Average annual rates of recharge to the till and stratified-drift aquifers are estimated to be greater than 9 and 25 inches, respectively. These are conservative estimates based on the assumption that recharge is equivalent to the average annual rates of ground-water runoff from these aquifers, which were estimated in the streamflow section (table 4).

Recharge to the bedrock aquifer occurs by downward movement of water from the overlying till and stratified-drift aquifers, so that the maximum rate of recharge to the bedrock is controlled by that of the overlying aquifer. The stratified-drift aquifer also receives recharge by ground-water inflow from till and bedrock aquifers that lie at topographically higher altitudes, and by seepage from losing streams that flow across it.

Table 11.--Monthly ground-water budget for the Chipuxet River basin, 1959 water year

[computations in inches are for a subsurface drainage area of 10.6 mi^2]

Date	Ground-water discharge					Change in storage[1]	Recharge	
	a	b	c	d	e (e = a+b+c+d)	f	g (g = e + f)	
	Subsurface outflow[2]	Pumpage exported[3]	Ground-Water evapo-transpiration	Base flow[4]	Total dis-charge			
	(in.)	(in.)	(in.)	(in.)	(in.)	(in.)	(in.)	(Mgal/d)
1958								
October	0.02	0.05	0.67	1.55	2.29	0.96	3.25	19.3
November	.02	.05	.44	1.86	2.37	-.39	1.98	12.2
December	.02	.05	.00	1.63	1.70	.10	1.80	10.7
1959								
January	.02	.05	.00	1.43	1.50	-.46	1.04	6.2
February	.02	.05	.00	1.53	1.60	1.06	2.66	17.5
March	.02	.05	.56	2.59	3.22	2.52	5.74	34.1
April	.02	.05	.64	2.77	3.48	-.63	2.85	17.5
May	.02	.05	.79	2.02	2.88	-2.00	.88	5.2
June	.02	.05	.70	1.53	2.30	-.31	1.99	12.2
July	.02	.05	.61	1.58	2.26	-.26	2.00	11.9
August	.02	.05	.64	1.03	1.74	-2.37	-.63	-3.7
September	.02	.05	.34	.75	1.16	-1.41	-.25	-1.5
Total	.24	.60	5.39	20.27	26.50	-3.19	23.31	11.8

1 See text for explanation of method of determination.

2 Subsurface flow out of the 10.6-mi^2 subsurface drainage area.

3 Pumpage from University of Rhode Island well field at Thirty Acre Pond (Allen and others, 1966, table 12) discharged as sewage to White Horn Brook south of State Route 138.

4 Mostly ground-water runoff; includes some drainage from swamps and ponds.

Recharge contributed by ground-water inflow from till and bedrock can be estimated by substituting estimated values of average transmissivity and hydraulic gradient for till and bedrock aquifers into a modified form of the Darcy equation. This equation may be expressed as:

$$Q = TIL \qquad (1)$$

where

Q is flow,in cubic feet per day;

T is transmissivity in feet squared per day;

I is hydraulic gradient in feet per foot; and

L is length, in feet, of the section through which flow occurs.

Average transmissivity of the till is estimated to be 5 ft^2/d--the product of the previous estimate of hydraulic conductivity of 0.7 ft/d and and average saturated thickness of 7 ft. Average transmissivity of the bedrock is assumed to be equal to the previous estimate of 33 ft^2/d. The hydraulic gradient (slope of the water table) in both till and bedrock aquifers near the perimeter of the stratified-drift aquifer averages 0.04 ft/ft. Substituting these values into the above equation gives values for ground-water inflow to the stratified drift of 1.52 ft^3/d per foot of distance along the perimeter of the till-stratified drift contact. The till-stratified drift contact upstream of the Chipuxet River gage is 76,600 feet; therefore, average annual inflow to the stratified drift aquifer in this area is about 116,000 ft^3/d (0.87 Mgal/d).

Induced Recharge

Under natural water-table gradients, water flows from the stratified-drift aquifer into perennial streams in the study area. If natural gradients near these streams are reversed by pumping wells, recharge may be induced into the aquifer from the streams.

The amount of recharge induced in this manner is dependent on a number of factors including (1) the average vertical hydraulic conductivity of the streambed and that of the underlying aquifer, (2) the streambed area of infiltration, (3) the depth of the stream, (4) the viscosity of the infiltrating water, which is temperature dependent, and (5) the difference in head between the stream surface and that in the underlying aquifer.

Earlier studies have shown that streambeds in the Pawcatuck River basin are generally composed of coarse sand and gravel (Allen and others, 1966, p.41; Gonthier and others, 1974, p. 14). Test drilling in the basin suggests that these streambed materials probably are coarser and more permeable than many of the beds contained in the underlying aquifer. Beds of very-fine sand, silty sand, and silt ranging in thickness from only a few inches to several feet were penetrated in most test wells. These fine-grained units, even where only a few inches thick, may cause greater resistance to the vertical flow of water than the streambed materials themselves.

In the lower Pawcatuck River basin, the vertical hydraulic conductivity of streambed materials was measured at several sites with a vertical-head permeameter (Gonthier and others, 1974, p. 15). The measurements for coarse-grained streambed sediments ranged from 0.7 to 2.7 ft/d, whereas values for less abundant fine-grained streambed sediments found adjacent to stream banks and in ponded areas ranged from 0.1 to 0.7 ft/d.

In this study, no determinations were made of streambed hydraulic conductivity, but average vertical hydraulic conductivities of aquifer materials in the vicinity of aquifer test sites were determined to range from 6 to 50 ft/d (table 9).

No data are available to demonstrate the effect of viscosity on stream infiltration rates in the study area. In theory, however, it can be shown that infiltration during cold winter months, when water temperatures are near freezing may be as much as 50 percent lower than during warm summer months when stream temperatures can be as high as 68°F (20°C) (Gonthier and others, 1974, p. 15). This assumes, of course, that stream stages and all other factors remain constant. Typically, however, stream stages are higher in the winter than in the summer so that increases in infiltration caused by higher stream stages partially offset reductions in infiltration rates caused by low water temperatures. The most severe effects of low water temperatures would occur during periods of low streamstage in cold winter months.

Infiltration of streamflow to the University of Rhode Island supply wells located adjacent to Thirty Acre Pond was examined by means of a 3-dimensional ground-water-flow model of the well field as part of this study. Combined pumpage of 373 gal/min (Q_1, in fig. 13), equivalent to the average rate of withdrawal from the well field in 1974, was simulated for supply wells SNW 92 and 888. Variations in percentage of induced recharge over 30-day simulation periods are shown in figure 13. Figure 13 also shows how the percentage of induced recharge varies by pumping the same wells (SNW 92 and 888) at double (Q_2) the 1974 rate, and by pumping a well (SNW 1087) at 373 gal/min (Q_3) at a site 1,200 feet west of Thirty Acre Pond.

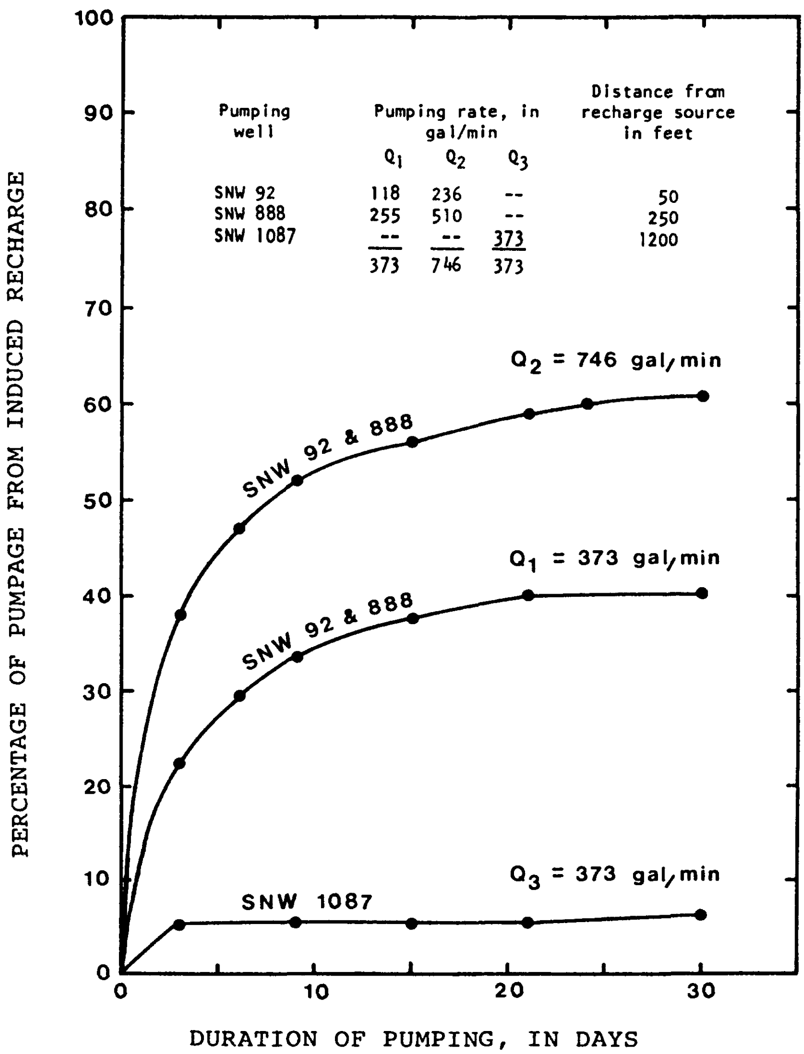


Figure 13.--Simulated withdrawals from wells in the vicinity of Thirty Acre Pond showing how percentage of pumpage induced from a recharge source varies with pumping rate, duration of pumping, and distance from a recharge source.

It is evident from figure 13 that induced recharge began to infiltrate the aquifer almost immediately after pumping started in supply wells SNW 92 and 888. Continuous pumpage from these wells at 373 gal/min caused infiltration to continue to increase for about 20 days. Infiltration of induced recharge to these wells leveled off at about 40 percent of the pumping rate. However, increasing the pumpage from SNW 92 and 888 to 746 gal/min caused infiltration of induced recharge to reach 40 percent of the pumping rate after only 3 days, and began to level off after 30 days at slightly more than 60 percent of the pumping rate.

The graph for well SNW 1087 is significant to the problem of manganese enrichment which is discussed in the water-quality section. Manganese enrichment is shown to be related to the process of induced infiltration. In the example shown in figure 11, it is evident that pumping well SNW 1087 at the rate of 373 gal/min results in a comparatively small percentage of water from induced recharge. Most of the water pumped from this well is potential ground-water runoff that is intercepted before reaching streams.

Potential Yield Of Ground-Water Reservoir

The yield obtainable from the Chipuxet ground-water reservoir is a variable quantity determined by (1) the amount of water potentially available for development, (2) the hydraulic characteristics of the aquifer and streambed materials, (3) the scheme of development by wells, (4) the volume of the aquifer, and (5) the disposition of the used water.

Water potentially available for development perennially from the Chipuxet ground-water reservoir is equal to the amount of natural discharge that can be captured plus the amount of additional recharge that can be induced from streams and other surface-water bodies as a result of lowering ground-water levels by pumping.

Natural discharge potentially available for capture includes (1) ground-water runoff to streams (2) subsurface outflow from the southern end of the ground-water reservoir area, and (3) water lost to the atmosphere by evapotranspiration directly from the water table in areas where the water table is within a few feet of the surface. Estimates of ground-water discharge from the Chipuxet ground-water reservoir area for water year 1959 are given in table 11.

The discharge in table 11 is computed for an aquifer area of 10.6 mi^2. Ground-water runoff from this area was determined by multiplying the area by the average annual rate of ground-water runoff from stratified drift (1.11 $Mgal/d/mi^2$) determined previously. Ground-water evapotranspiration was estimated similarly as the product of this area and the annual rate of ground-water evapotranspiration (0.35 $Mgal/d/mi^2$) computed for water year 1959 (table 11). Subsurface outflow was estimated using equation 1.

The rate at which water from inflowing streams can be induced to leak through streambeds into the underlying aquifer is a principal limiting control most of the time. Potential leakage rates seem to be too low to allow for capture of all of the inflow during periods of normal or above normal flow. However, leakage rates are high enough so that virtually all of the inflow can be induced to leak into the aquifer during periods of low flow.

The hydraulic characteristics of the aquifer determine how many wells are needed, where they must be located, and how they must be pumped to intercept maximum amounts of potential ground-water runoff and to cause maximum infiltration of streamflow. In general, maximum infiltration results from continously pumped lines of wells located close to, and aligned parallel to, the streams. The specific yield of the aquifer and the aquifer volume determine the volume of water available from the aquifer during periods when there is little or no recharge from precipitation or stream infiltration. The volume of the stratified-drift aquifer in the area shown on plate 1 is approximately 13.3 billion cubic feet. If specific yield is assumed to be 0.20 for the entire thickness, the aquifer contains 2.7 billion cubic feet (20 billion gallons) of water. Allen and others (1966, p. 1) demonstrated by means of image-well model analysis, that a yield of 17 Mgal/d could be obtained from storage for a period of 180 days. This is equivalent to 0.4 billion cubic feet or about 15 percent of the water in aquifer storage.

The scheme of well development is perhaps most critical in determining the yield obtainable from the ground-water reservoir. The amount that can be withdrawn is very dependent on the location, number, and depth of wells and on the rate and duration of pumping.

The potential sustained yield of the Chipuxet ground-water reservoir was estimated by Allen and others (1966, p.51) to be in excess of 8 Mgal/d. Model simulations, discussed later, indicate that a yield of 8 Mgal/d can, in fact, be pumped from sites already tested by the RIWRB. Allen and others (1966, p. 62) pointed out, however, that withdrawal at this rate would cause streams to go dry for extended periods during late spring, summer, and fall.

The potential sustained yield obtainable from the ground-water reservoir could conceivably be much greater than 8 Mgal/d, if all of the water pumped from it were returned by way of septic systems, recharge pits, or other methods. Of course, this would result in degradation of the quality of the water, possibly to the extent that it might be rendered unsuitable for drinking water supplies.

QUALITY OF WATER

The chemical quality of water in the Chipuxet ground-water reservoir and in the streams that drain it is generally suitable for most uses. Water in the ground and in streams is soft, slightly acidic, and typically has a concentration of less than 100 mg/L of dissolved solids. Although locally contaminated by man's activities, the contaminants for the most part do not significantly impair the use of the water for most purposes, including drinking. A summary of the quality of surface water and ground water is given in table 12. The source and significance of the most commonly found chemical constituents and properties of water are summarized in table 13. The water quality is good to excellent, as indicated by comparison of median concentrations of constituents in ground-water and surface-water samples in table 12 with the limits recommended for these constituents in drinking water shown in table 13.

Most water samples for which data are summarized in table 12 were collected between 1950 and 1974; the analyses are published in a companion geohydrologic data report (Dickerman, 1976). Most of the analyses were made in the laboratories of the Rhode Island Department of Health and the U.S. Geological Survey.

Source of Constituents in Ground Water and Surface Water

Dissolved gases and chemicals in pristine ground water and surface water are derived from precipitation and from the soils and aquifer materials with which the water has been in contact. The type and concentration of constituents are determined by the dissolving power of the water, the composition of the soil and aquifer materials, and the time of contact. Most natural waters contain the positively charged ions (cations) of calcium, magnesium, sodium, and potassium and the negatively charged ions (anions) of bicarbonate, chloride, sulfate, and nitrate.

Man's activities, such as disposal of wastes to streams, application of deicing salts to highways, application of fertilizers to lawns and crop lands, and subsurface disposal of sewage, generally cause concentrations of these principal ions to increase in water. They also contribute constituents such as manmade organic chemicals that do not occur in nature.

Table 12. --Summary of chemical and physical properties of surface water and ground water in the Chipuxet ground-water reservoir area

[Chemical constituents in milligrams per liter, except as noted; a dash indicates no data]

	Surface water				Ground water				
	Samples	Low	Median	High	Wells	Samples	Low	Median[1]	High
Silica(SiO_2)	3	3.8	5	10.0	6	7	7.3	11	19
Iron (Fe)	17	.00	.23	.80	64	101	.00	12	100
Manganese (Mn)	17	.00	.00	.05	64	102	.00	.04	73
Calcium (Ca)	3	3.2	5.2	7.5	21	34	3.2	15	160
Magnesium (Mg)	3	1.3	1.6	4.1	21	34	1.0	4.2	62
Sodium (Na)	2	4.6	--	6.7	21	34	3.2	9.2	60
Potassium (K)	2	.9	--	1.3	21	34	1.0	2.6	30
Bicarbonate (HCO_3)	11	3	8	25	12	17	8	15	68
Sulfate (SO_4)	3	7.5	12	14	23	37	3	27	500
Chloride (Cl)	17	5	17	22	60	95	4	16	206
Fluoride (F)	1	--	.2	--	57	83	.0	.1	1.3
Nitrate (NO_3-N)	19	.00	.29	.8	66	100	.00	1.5	25
Dissolved solids (residue at 105°C)	--	--	--	--	18	31	32	133	966
(residue at 180°C)	11	36	58	116	10	14	38	74.5	137
Hardness (as $CaCO_3$)	11	12	19	30	61	94	11	51	640
Non-carbonate	3	4	19	26	6	6	16	25	54
Alkalinity (as $CaCO_3$)	6	0	5	17	55	88	3	10	128
Specific conductance (micromhos/cm @ 25°C)	24	47	85.5	172	46	73	37	175	1400
pH (units)	16	5.4	6.2	7.2	25	37	5.3	6.0	7.2
Color (Platinum cobalt units)	9	15	35	80	49	75	0	5	70
Methylene blue active substance (MBAS)	--	--	--	--	15	25	.00	.04	.32

1 Value is median of all lows and highs, and is based on a maximum of two values (low and high) per well.

Table 13.--Source and significance of common consituents of water
[A dash indicates no limiting value has been established]

Chemical constituent or physical property	Maximum limit for drinking water (mg/L)	Principal sources	Significance
Silica (SiO_2)	--	Dissolved from practically all rocks and soils.	High concentrations precipitate as hard scale in boilers, water heaters, and pipes. Inhibits deterioration of zeolite-type water softeners and corrosion of iron pipes.
Iron (Fe)	[1] 0.3	Dissolved from minerals that contain oxides, sulfides, and carbonates of iron. Decaying vegetation, iron objects that are in contact with water, sewage, and industrial waste are also major sources.	On exposure to air, iron in ground water oxidizes to a reddish-brown precipitate. More than about 0.3 mg/L stains laundry and utensils, causes unpleasant odors, and favors growth of iron bacteria. Iron in water is objectionable for food and textile processing. Most iron-bearing waters, when treated by aeration and filtration, are satisfactory for domestic use.
Manganese (Mn)	[1] .05	Dissolved from many rocks and soils. Commonly associated with but less common than iron.	More than 0.05 mg/L oxidizes on exposure to air to a black precipitate. Manganese has the same undesirable characteristics as iron, but is more difficult to remove.
Calcium (Ca)	--	Dissolved from rocks and soils, especially those containing calcium silicates, and carbonate and clay minerals.	Hardness and scale-forming properties of water are caused principally by dissolved bicarbonates and sulfates of calcium and magnesium. (See hardness.) Hard water is objectionable for electroplating, tanning, dyeing, and textile processing. It also causes scale formation in steam boilers, water heaters, and pipes.
Magnesium (Mg)	--	Dissolved from rocks and soils, especially those containing magnesium silicates, clay minerals, and carbonate lenses.	See Calcium.
Sodium (Na) and potassium (K)	--	Dissolved from practically all rocks and soils. Sewage, industrial wastes, road salt, and sea water are also major sources. Most home water softeners increase the amount of sodium in water by exchanging it for calcium and magnesium.	Quantities found in the fresh water of the report area have little effect upon the usefulness of water for most purposes; however, more than 50 mg/L may cause foaming in steam boilers. Twenty mg/L of sodium is the maximum permitted for people limited to a very restricted sodium diet.
Carbonate (CO_3) and bicarbonate (HCO_3)	--	Dissolved from carbonate and calcium silicate minerals by reaction with carbon dioxide in water. Decaying vegetation, sewage, and industrial wastes are also important sources.	Carbonates of calcium and magnesium cause hardness, form scale in boilers and pipes, and release corrosive carbon dioxide. (See hardness.) Water of low mineral concentration and low bicarbonate concentration in proportion to carbon dioxide is acidic and corrosive.
Sulfate (SO_4)	[1] 250	Dissolved from rocks and soils containing sulfur compounds, especially iron sulfide; also from sulfur compounds dissolved in precipitation, and sewage and industrial wastes.	Sulfates of calcium and magnesium cause permanent hardness and form hard scale in boilers and hot water pipes.
Chloride (Cl)	[1] 250	Dissolved from rocks and soils in small amounts. Other sources are animal wastes, sewage, road salt, industrial wastes, and sea water.	Large amounts in combination with calcium will result in a corrosive solution and in combination with sodium will give water a salty taste.
Fluoride (F)	[2] 2.0	Dissolved from various minerals of widespread occurrence. Added to public water supplies by fluoridation.	About 1.0 mg/L reportedly reduces the incidence of tooth decay in young children; larger amounts may cause mottling of tooth enamel, depending on average water intake and climate.

[1] Secondary maximum contaminant level established for public water systems by the U.S. Environmental Protection Agency (1979). This constituent or property primarily affects aesthetic rather than health aspects of water quality. At considerably higher concentrations (higher or lower values in the case of pH), health implications may also exist.

[2] Maximum contaminant level established for public water supplies by the Rhode Island Department of Health, Division of Water Supply (1977).

Table 13.--Source and significance of common consituents of water--Continued
[A dash indicates no limiting value has been established]

Chemical constituent or physical property	Maximum limit for drinking water (mg/L)	Principal sources	Significance
Nitrate (NO_3; expressed as N)	[2] 10	Sewage, industrial wastes, fertilizers, and decaying vegetation are major sources. Lesser amounts are derived from precipitation and solution processes.	Values higher than the local average may indicate contamination by man. Water containing more than 10 mg/L (as N) reportedly causes methemoglobinemia, which can be fatal to infants (Comly, 1945).
Specific conductance	--	Dissolved constituents in water that will ionize.	Specific conductance is a measure of the capacity of water to conduct an electric current. Specific conductance of water in the report area x 0.65 gives an approximate measure of dissolved solids in milligrams per liter.
Dissolved solids	[1] 500	Includes all dissolved mineral constituents derived from solution of rocks and soils; locally augmented by mineral matter in sewage and industrial wastes.	Water containing more than 500 mg/L is undesirable for public and private supplies and many industrial supplies. Ground water generally has a higher concentration of dissolved solids than surface water.
Hardness (as $CaCO_3$)	--	Primarily due to calcium and magnesium and to a lesser extent to iron, manganese, aluminum, barium, and strontium. There are two classes of hardness, carbonate (temporary) and noncarbonate (permanent). Carbonate hardness refers to the hardness balanced by equivalents of carbonate and bicarbonate ions; noncarbonate refers to the remainder of the hardness.	Hard water uses more soap to lather and deposits soap curds on bathtubs. Hardness forms scale in boilers, water heaters, radiators and pipes, causing a decrease in rate of heat transfer and restricted flow of water. Water having a very low hardness may be corrosive. Waters of hardness up to 60 mg/L are considered soft; 61 to 120 mg/L, moderately hard; 121 to 180 mg/L hard; more than 180 mg/L, very hard.
Hydrogen ion (pH)	[1] 6.5-8.5	Water having high concentrations of acids, acid-generating salts, and free carbon dioxide has a low pH. Where carbonates, bicarbonates, hydroxides, phosphates, and silicates are dominant, the pH is high. The pH of most natural waters ranges between 6 and 8.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote alkaline characteristics; values lower than 7.0 indicate acid characteristics. Acid waters and excessively alkaline waters corrode metals.
Detergents as methylene blue active substance (MBAS)	--	MBAS is a measure of the concentrations of detergents in water. Primary sources of alkyl benzene sulfonate (ABS) and linear alkyl sulfonate (LAS) are synthetic household detergent residues in sewage and waste waters.	High concentrations of ABS causes undesirable taste, foaming, and odors. Indicates presence of sewage or industrial waste. After mid-1965 ABS was gradually replaced by LAS, which is more degradable.
Color	--	May be imparted by iron and manganese compounds, algae, weeds, and humus. May also be caused by inorganic or organic wastes from industry. True color of water is considered to be only that remaining in solution after the suspended material has been removed.	Water for domestic and some industrial uses should be free of perceptible color. Color in water is objectionable in food and beverage processing and many manufacturing processes. Usually expressed in units of color (platinum-cobalt method) rather than in milligrams per liter.
Dissolved oxygen (D.O.)	--	Derived from the atmosphere and from photosynthesis by aquatic vegetation. Amount varies with temperature and pressure and decreases during breakdown of waste material. Concentration can be expressed in mg/L or as a percentage of saturation.	Dissolved oxygen in surface water is necessary for support of fish and other aquatic life. It causes precipitation of iron and manganese in well water and can cause corrosion of metals.
Temperature	--	Fluctuates seasonally in streams and shallow aquifers. At depths of 30 to 60 feet, ground-water temperature remains within 4°F or 5°F (2°C or 3°C) of mean annual air temperature and increases gradually with depth. May fluctuate where affected by induced infiltration. Disposal of water used for cooling or industrial processing may cause local temperature anomalies.	Affects the usefulness of water for many purposes. For most uses, especially cooling, water of uniformly low temperatures is desired. A rise of a few degrees in the temperature of a stream may limit its capacity to support aquatic life. Warm water carries less oxygen in solution and is more corrosive than cold water.

Precipitation

The quality of precipitation in the study area has not been determined. However, its chemical composition is probably generally similar to that determined by Thomas and others (1968, table 3) for precipitation collected at three stations in the towns of Ledyard, Chesterfield, and Noank in southeastern Connecticut between July 1963 and December 1964. The following table summarizes the median concentrations of chemical constituents and physical properties determined at these stations. Twenty four to thirty eight analyses were made for each constituent.

Property or constituent	Concentration
Calcium (Ca)	1.5
Magnesium (Mg)	.2
Sodium (Na)	1.9
Potassium (K)	.4
Bicarbonate (HCO_3)	0
Sulfate (SO_4)	6.2
Chloride (Cl)	1.2
Dissolved solids (Residue on evaporation at 180°C)	15
Hardness as $CaCO_3$	4
Specific conductance (micromhos/cm @ 25°C)	52
pH (units)	4.7

Streams

The average quality of uncontaminated streamflow is intermediate between that of precipitation and ground water. During periods of substantial direct runoff, the chemical composition of natural streamflow may resemble that of precipitation, whereas during periods of low base flow, its composition is representative of the average composition of ground-water runoff upstream from the sampling point. Most of the samples of streamflow for which analyses are available were taken during periods of low base flow. As a consequence, streamflow data summarized in table 12 probably represent the average quality of ground water in the study area. If analyses were available for a wide range of streamflow conditions, it is likely that the median values reported in table 12 for surface water would be lower. It is of interest to note that the low values for chemical constituents in surface-water samples are not substantially different from values listed above for precipitation.

A U.S. Geological Survey water-quality monitor that provides a continuous record of temperature and specific conductance of streamflow was installed at the gaging station on the Chipuxet River at West Kingston in October 1973. Mean daily values of these parameters have been published annually (U.S. Geological Survey) since 1973 . Because specific conductance, a measure of electrical conducatance of a solution, is proportional to the concentration of dissolved constituents in water, the monitor provides a record of daily variations and longterm trends in water quality of the Chipuxet River.

The variation in specific conductance of the Chipuxet River at West Kingston during water year 1975 is shown in figure 14. The graph demonstrates that specific conductance is lowest when streamflow is highest and constituted of both direct runoff and ground-water runoff, and highest when streamflow is lowest and constituted chiefly of ground-water runoff. For streams in the study area, multiplication of specific conductance by a factor of 0.65 gives an approximate measure of dissolved-solids concentration in milligrams per liter. During water years 1973-80, specific conductance ranged from 37 to 180 micromhos/cm, indicating a range in dissolved solids concentration of the river water of 24 to 117 mg/L. This compares with a range of 36 to 116 mg/L of dissolved solids indicated in table 12.

The record of temperature fluctuations during water year 1975 is also shown in figure 14. Freezing-point temperature (32°F or 0°C) is reached, or nearly reached, during several days in winter; maximum temperatures in the summer months are typically 81° to 82°F (27° to 28°C). The maximum water temperature recorded at this station from October 1973 to September 1980 was 86°F (30°C) on August 2, 1975.

Hundred Acre and Thirty Acre Ponds through which the Chipuxet River flows become thermally stratified in summer (Guthrie and Stolgitis, 1977, p. 205). During these warm months, a layer of warm water (the epilimnion) is near the surface; below it lies a transition layer (the thermocline) in which temperature decreases rapidly with depth; and below this is a layer (the hypolimnion) of relatively uniformly colder water. In late Autumn, the temperature in the upper layer drops and mixing takes place until the entire pond is nearly uniform in temperature. Measurements made as part of this study on November 12, 1976, showed that temperature of Thirty Acre Pond was 39°F (4°C) from top to bottom.

Figure 15 shows that thermal stratification affects the chemical character of the pond water. On August 8, 1955, dissolved oxygen ranged from about 6 mg/L in the top layer to less than 1 mg/L in the bottom layer. The pH also decreased with depth. Alkalinity, on the other hand, increased from about 1 mg/L in the top layer to about 7 mg/L in the bottom layer. The change in quality with depth of Thirty Acre Pond is believed to be related to the occurrence of manganese in nearby supply wells which induce recharge from the pond. This relation is discussed in the following section on iron and manganese in ground water.

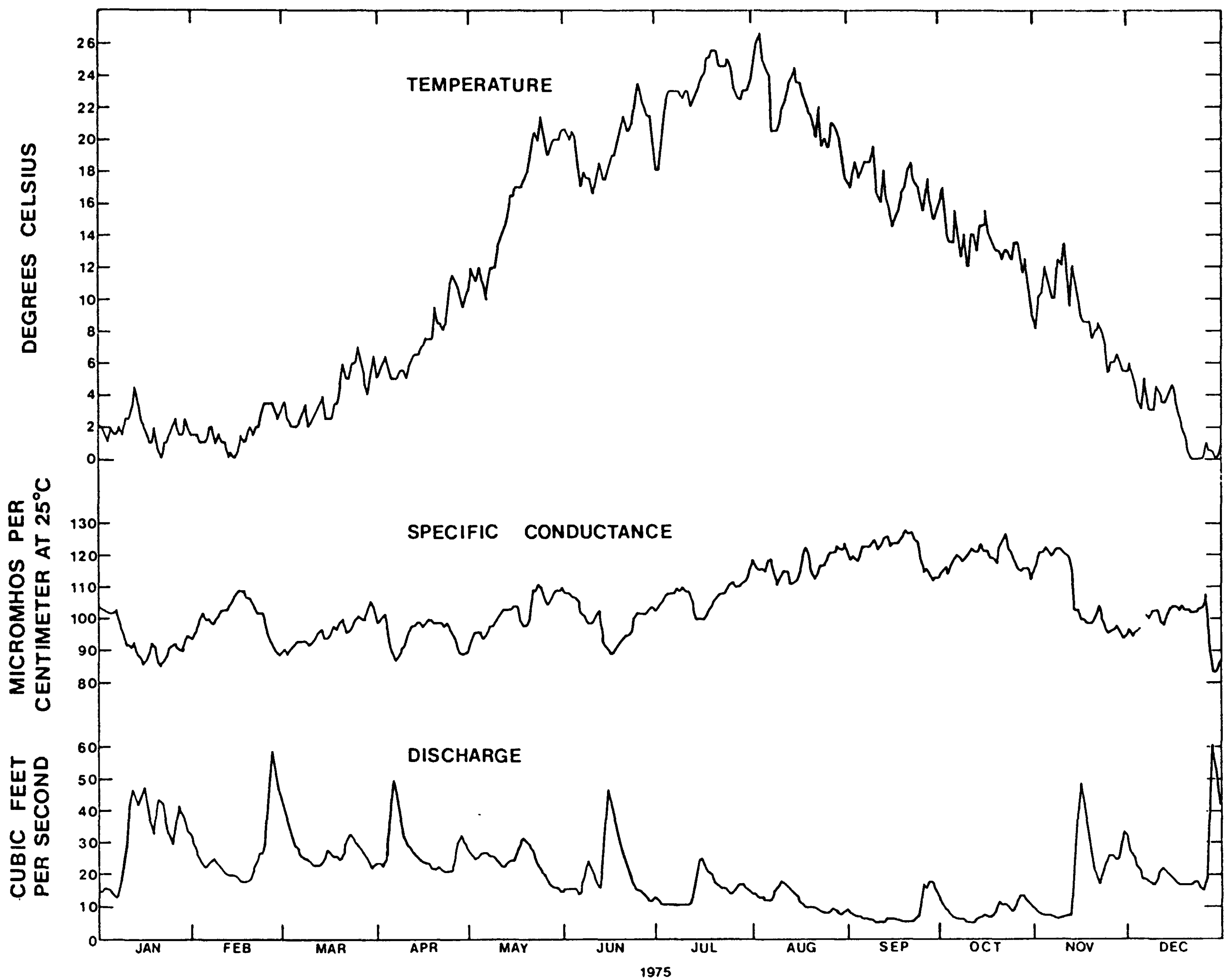


Figure 14.--Relation of discharge, temperature, and specific conductance of the Chipuxet River at West Kingston.

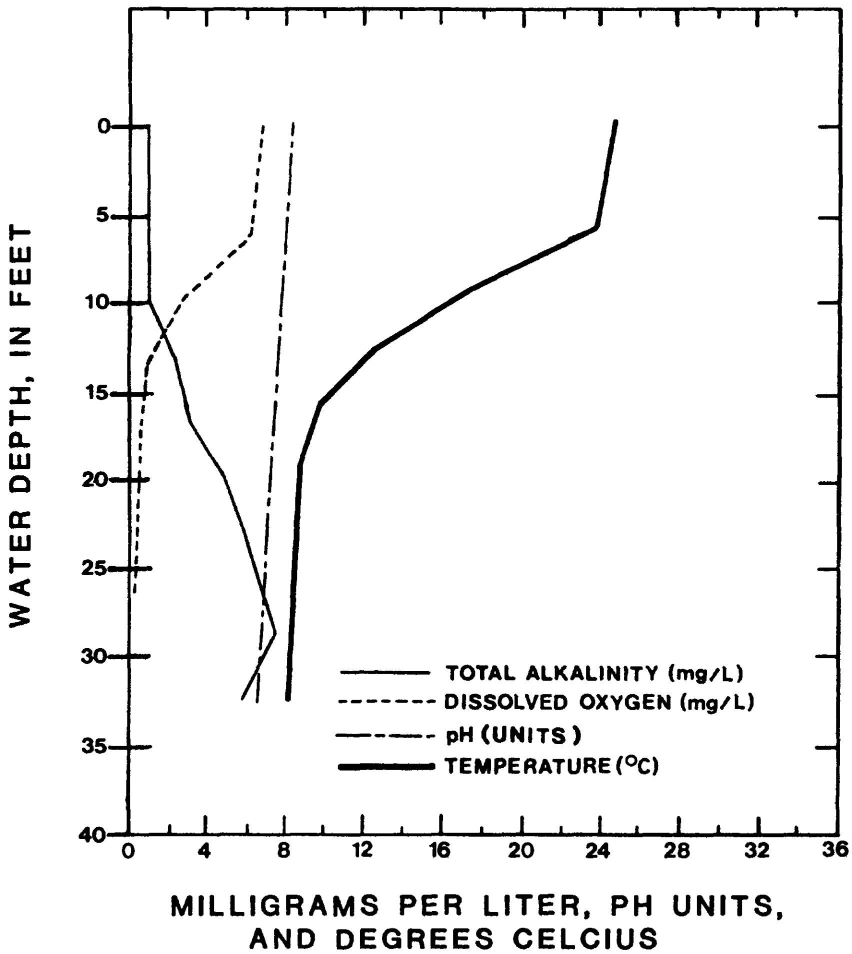


Figure 15.--Variation in quality of water with depth in Thirty Acre Pond on August 8, 1955. (From Guthrie and Stolgitis, 1977)

Ground Water

The natural quality of ground water generally is strongly influenced by the composition of the soils and rocks through which it moves. In the Chipuxet River basin, however, the bedrock and the overlying glacial deposits and soils derived therefrom consist chiefly of relatively insoluble silicate minerals. As a result, even though the dissolving power of precipitation is substantial, uncontaminated ground water contains only low concentrations of dissolved mineral matter. The low values listed for ground water in table 12 are believed to be representative of relatively uncontaminated ground water in the study area. These values are not substantially different from those listed above for precipitation, which suggests that a major part of the natural dissolved-solids concentration in ground water may be derived from precipitation.

The high concentrations of constituents listed for ground water in table 12 are for samples taken from wells downgradient from the now-closed West Kingston landfill (Kelly, 1975, fig. 7). These are representative of the most contaminated water in the study area.

Iron and Manganese

Iron and manganese are generally present in natural ground waters in the stratified-drift aquifer in concentrations that are below limits established for drinking water. However, both are present locally in excessive concentrations. The highest concentrations of these constituents, shown in table 12, are for water samples collected from observation wells that tap a plume of contaminated ground water downgradient from the now-closed West Kingston landfill. Excessive levels of iron are also reported to be locally present in uncontaminated ground water near the base of the aquifer (Allen and others, 1966, p. 58), and concentrations of manganese (but not iron) have increased with time in three of four University of Rhode Island supply wells.

Some of the analyses for iron and manganese summarized in table 12 were made on samples that were not filtered at the time of collection. If the unfiltered samples contained suspended sediment, as water from newly constructed wells commonly does, most or all of these constituents may have been derived from oxides of iron and manganese that occur as coatings on sediment particles. Some of the analyses for iron and manganese in water taken from observation wells near the West Kingston landfill, for example, may have been made on unfiltered samples (Kelly, 1975, p. 32). Thus, the high values for iron and manganese reported in table 12 could be much higher than are actually dissolved in ground water.

The high concentrations of iron and manganese reported to be present in ground water near the base of the aquifer by Allen and others (1966) were determined for unfiltered samples taken from newly constructed wells. A potentially productive depth interval (124 to 176 ft) in U.S. Geological Survey test well SNW 907 drilled near the U.S. Geological Survey gage at West Kingston was reported to yield water containing 4.5 mg/L total iron and 0.16 mg/L total manganese. This depth interval should be resampled before discounting it as a potential source of water because of the reported high levels of iron and manganese.

Allen and others (1966) also reported concentrations of 2.0 mg/L iron and 0.33 mg/L manganese in water pumped July 15, 1960 from well SNW 888, screened near the base of the aquifer at Thirty Acre Pond. (See fig. 16A for location.) Inasmuch as the sample was taken soon after the well was put into production, the water may have contained suspended sediment. Moreover, the analysis was made by the State, which generally does not filter samples taken from public-supply wells for chemical analysis. In 19 subsequent analyses of water from this well, iron ranged from 0.00 to 0.15 mg/L, with a median value of 0.03 mg/L (Dickerman, 1976, table 20). If the ground water near the base of the aquifer originally did contain excessive dissolved iron, downward movement of iron-free water from above may have caused concentrations to diminish.

The change in manganese concentration in water pumped from supply wells at Thirty Acre Pond after the wells were put into production is illustrated in figure 16C. Because manganese enrichment of water from heavily pumped municipal and industrial supply wells is a common and troublesome problem in Rhode Island, a study of the problem was made at the Thirty Acre Pond well field (Silvey and Johnston, 1977).

Results of the study indicate that the increase in manganese concentration of the water pumped from the supply wells is caused by the passage of induced stream and pond infiltration through organic-rich sediments that line the pond and river bottom (fig. 16B). As the water passes through the organic sediments, dissolved oxygen and nitrate (oxidized) nitrogen contained in the infiltrating water are depleted, causing the water to change from an oxidized to a reduced state. The reduced infiltrate is able to maintain in solution high concentrations of dissolved manganese and iron derived from biochemical decomposition of organic matter and from dissolution of oxides and other forms of manganese and iron present as coatings and stains on aquifer materials.

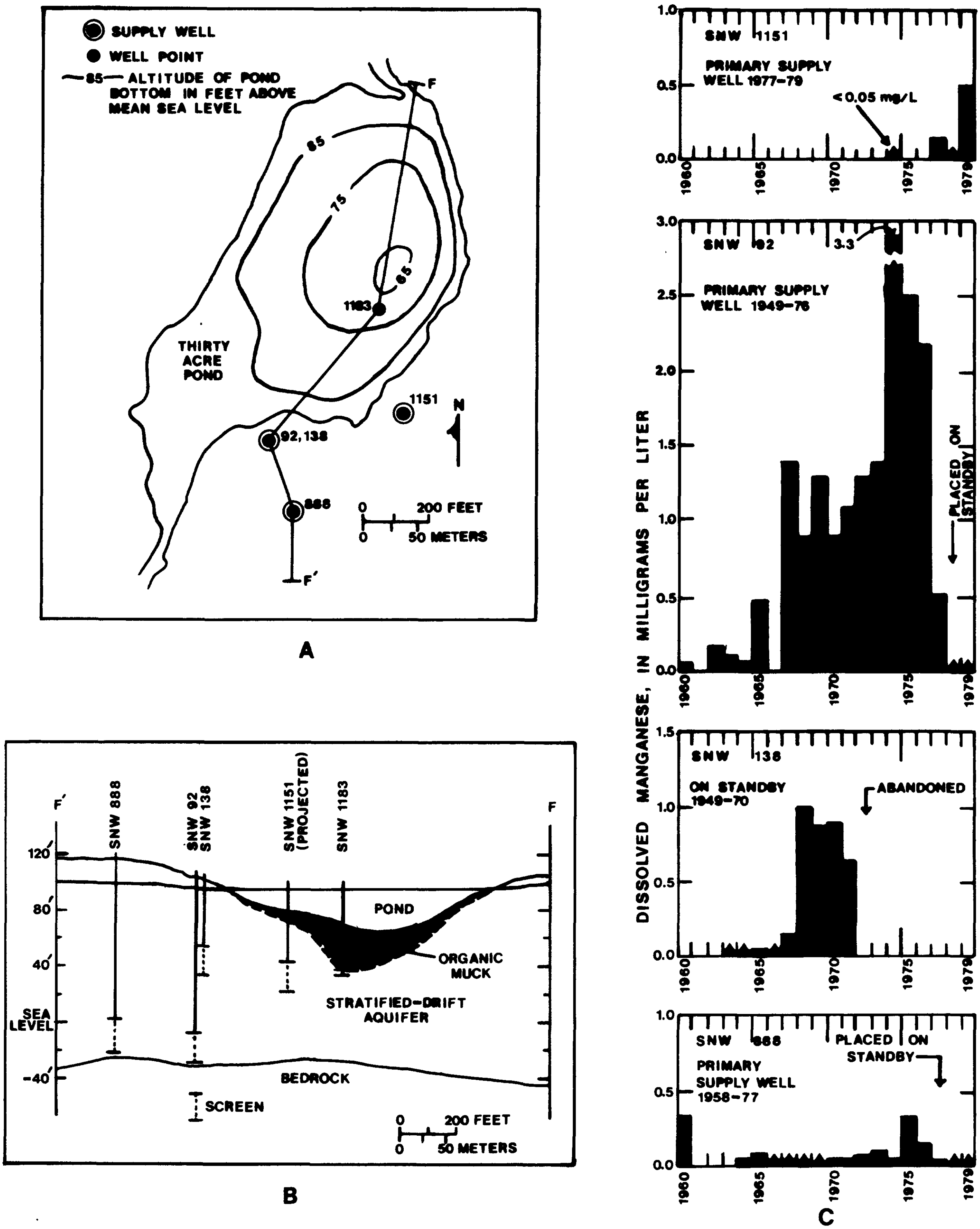


Figure 16 A.--Map of Thirty Acre Pond showing location of University of Rhode Island supply wells, altitude of pond bottom, and line of section through pond.

16 B.--Section through Thirty Acre Pond.

16 C.--Graphs showing maximum annual concentration of manganese measured in water from supply wells SNW 92, 138, 888, and 1151 from 1960-79.

Concentrations of dissolved manganese and iron as high as 1.2 and 40 mg/L, respectively, were measured in water samples obtained at a depth of 3.5 to 5.8 feet below the firm, sandy pond bottom. These were obtained from a well point located about 50 feet from supply well SNW 92 where the pond bottom was overlain by 1.5 feet of silty muck mixed with partly decomposed vegetal matter. Water depth at this sampling site was 2 to 3 feet. It is believed that higher concentrations of manganese may be generated beneath deeper parts of the pond where organic-rich sediments are as much as 25 feet thick (fig. 16B).

In addition, water in the deep part of Thirty Acre Pond through which most of the infiltration is believed to occur, is in a reduced state (as indicated by low dissolved oxygen and high alkalinity) during the summer (fig. 15). Infiltration of this reduced water, which probably contains elevated concentrations of dissolved iron and manganese, will further increase the concentration of manganese in the ground water.

Once in solution the manganese, but not the iron, is transported with the infiltrating water to supply-well intakes. The iron precipitates before reaching well intakes. Why the manganese remains in solution and the iron doesn't has not been determined for this site, but solubility diagrams for iron and manganese indicate that manganese is soluble over a wider range of conditions than iron (Hem, 1970).

A flow-net analysis of the well field (fig. 17) indicates that during 1974-75, when only wells SNW 92 and SNW 888 were being pumped, most of the infiltrating pond and river water was going to well SNW 92. Meanwhile, water going to well SNW 888 was chiefly ground water that was intercepted before discharging into the river and pond. This pattern of flow is consistent with the high manganese concentration in water from well SNW 92 and the low concentration in SNW 888.

In 1977, a new well (SNW 1151) was put into use and both SNW 92 and SNW 888 were used sparingly thereafter. Now that most of the infiltration is being diverted to well SNW 1151, the manganese concentration in water from well SNW 92 has dropped sharply and the manganese concentration of water from the new well has begun to increase (fig. 16C).

One way of reducing manganese concentrations in the combined water supply taken from the well field at Thirty Acre Pond would be to pump a larger percentage of the total supply from well SNW 888, less from well SNW 1151, and perhaps a small amount from SNW 92. Also, the addition of one or more additional wells on the opposite side of the pond would increase the opportunity to intercept potential ground-water runoff to the pond and stream, thereby reducing the amount of water passing through organic bed materials.

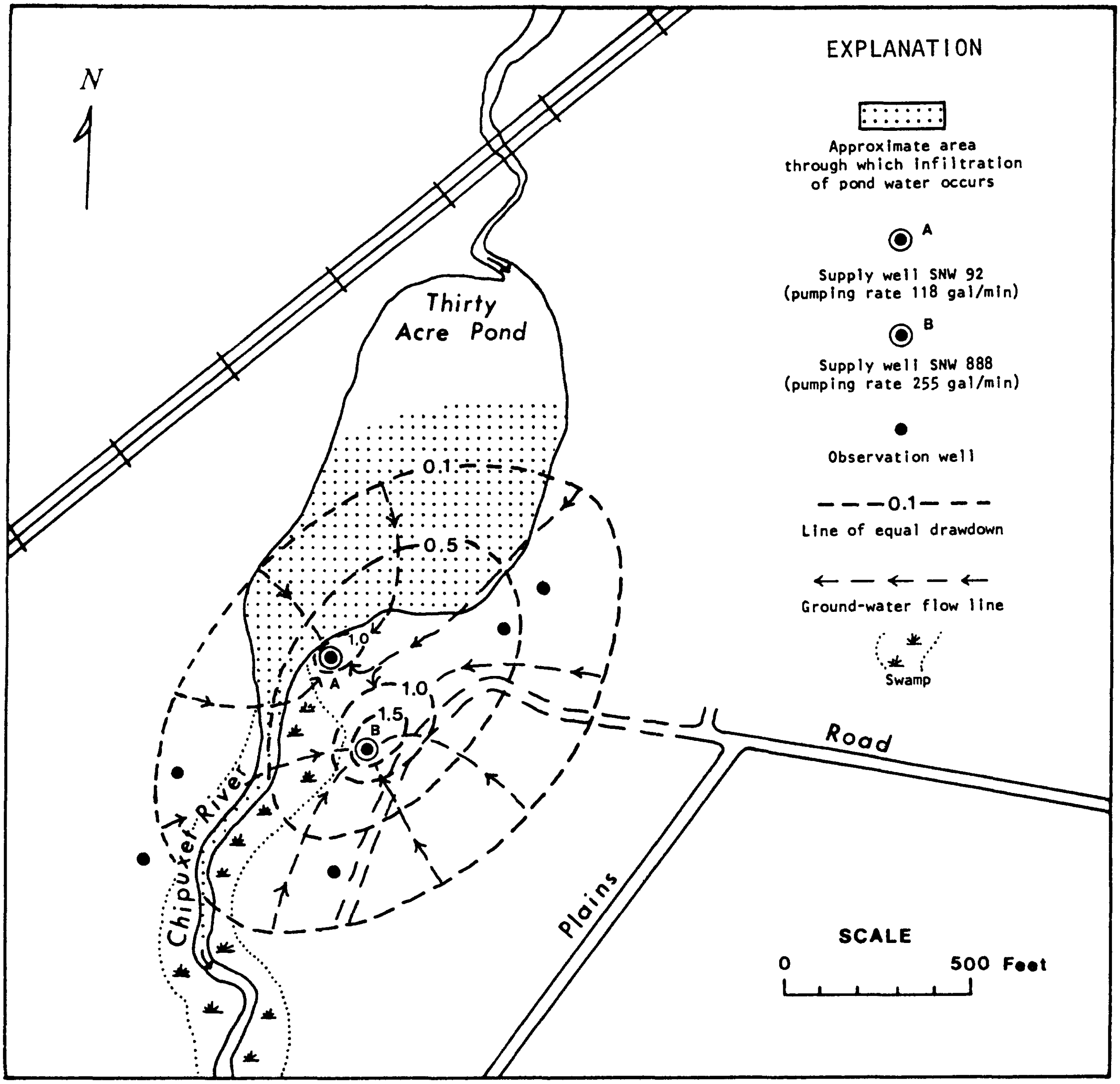


Figure 17.--Ground-water flow pattern and area of river and pond infiltration estimated for average pumping and drawdown conditions in the University of Rhode Island well field, October 1974-December 1975. (Modified from Silvey and Johnston, 1977)

Based on the study at Thirty Acre Pond, it is concluded that the manganese-enrichment problem can be minimized by avoiding siting supply wells adjacent to water bodies having organic-rich bottom sediments. Where this is not feasible, the problem may be minimized by siting the well(s) as far as possible from the recharge source so as to maximize interception of potential ground-water runoff and minimize induced stream infiltration. An example of how distance from a recharge source can affect the percentage of the pumpage that is induced as recharge is given in figure 11 (see section "Induced Recharge"). A less practical alternative for wells such as SNW 92 is to reduce the average daily withdrawal rate so as to minimize induced recharge.

Elsewhere in Rhode Island, the problem of manganese enrichment also seems to be caused by infiltration of organically polluted streamflow (Johnston and Dickerman, 1974). Maintenance of good quality streamflow in the study area is, therefore, also a means of preventing manganese enrichment in supply wells.

The Rhode Island Department of Health has established water-quality class segments for streams in the Chipuxet River basin that will ultimately require that no waste discharges be made to surface water other than noncontact cooling water (Rhode Island Statewide Planning Program and Rhode Island Department of Health, 1976, p. IV-2, fig. 7). Achievement of this goal will assure that water available for infiltration is of high quality.

Nitrate

Nitrogen, which is present in ground water chiefly in the oxidized form as nitrate (NO_3), is a common contaminant in water in the stratified-drift aquifer. In many parts of the aquifer, nitrate is significantly above background levels and locally concentrations exceed the maximum contaminant level of 10 mg/L (as elemental nitrogen, N) established for drinking water by the U.S. Environmental Protection Agency (1976) and the Rhode Island Department of Health (1977).

Natural levels 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 do not contain nitrogen. The principal source of nitrate in ground water in the study area seems to be fertilizers added to croplands; however, septic-tank effluent and fertilizers added to lawns are also sources of this constituent.

Concentrations of nitrate (as N) in uncontaminated ground water are generally less than 0.1 mg/L. In water samples taken from most test wells drilled in relatively undeveloped parts of the stratified-drift aquifer in the study area, and elsewhere in the Pawcatuck River basin (Dickerman and johnston, 1977, table 15; Dickerman and Silva, 1980, table 19), concentrations of nitrate (as N) have been less than 0.1 mg/L. In many such water samples, nitrate has been below detectable levels.

The average concentration of nitrate in ground water in the Chipuxet River basin is indicated by the nitrate-concentration of the base flow of streams. As previously noted, base flow in the study area consists chiefly of ground-water runoff. The nitrate (as N) concentration of base flow sampled at eight sites in the study area by the RIWRB on September 29 and October 2, 1972, ranged from 0.10 to 0.61 mg/L; the median value was 0.20 mg/L (Dickerman, 1976, table 23). (The nitrate data given by Dickerman are expressed in terms of nitrate as NO_3 rather than nitrate as N, they can be converted to values expressed as N by dividing them by 4.5.)

The highest value of nitrate determined for base flow in 1972 was for a sample taken from the Chipuxet River at Wolf Rocks Trail. The comparatively high value of 0.61 mg/L may have been caused in part by nitrate-contaminated runoff from agricultural land upstream. A fertilizer source is indicated by data from a study of nitrate levels in streamflow and ground water at a turf farm about 1 mile upstream (Sheehan, 1971). Results of this study showed that, in 1970, levels of nitrate (as N) were as high as 7.0 mg/L in a brook that passes through the turf farm and as high as 6.0 mg/L in water from a well on the farm.

The study by Sheehan (1971) indicates that leaching of fertilizers applied to agricultural lands can greatly increase the concentrations of nitrate in ground water in the study area. Evidence that fertilizers are a major source of nitrate in ground water elsewhere in the study area is also provided by data from the University of Rhode Island well field at Thirty Acre Pond and from the aquifer-test site at Liberty Lane.

At Thirty Acre Pond, nitrate concentrations measured in wells screened at several different depths show that the upper part of the aquifer on both sides of the river is degraded by nitrate (Silvey and Johnston, 1977, p. 22). Concentrations of nitrate (as N) as high as 6.6 mg/L were measured in a drive-point well (SNW 1150) screened from 5.2 to 7.5 feet below the bottom of a 1.5-foot-thick layer of organic-rich material in the swampy flood plain of the river. This well intercepts ground water flowing from adjacent University experimental agricultural plots toward the river. Fertilizers applied to potato fields and to the experimental agricultural plots adjacent to the pond and well field are the only apparent sources for the nitrate.

Pumping supply wells causes downward movement of the shallow, nitrate-degraded ground water. The change in concentration of nitrate with time in water from well SNW 1150 and from three supply wells (SNW 92, SNW 138, and SNW 888) is shown in figure 18. Higher concentrations of nitrate in SNW 138 than in SNW 92 and SNW 888 resulted from the fact that SNW 138 is screened at about mid-depth in the aquifer, whereas SNW 92 and SNW 888 are screened near the bottom of the aquifer (fig. 16-B).

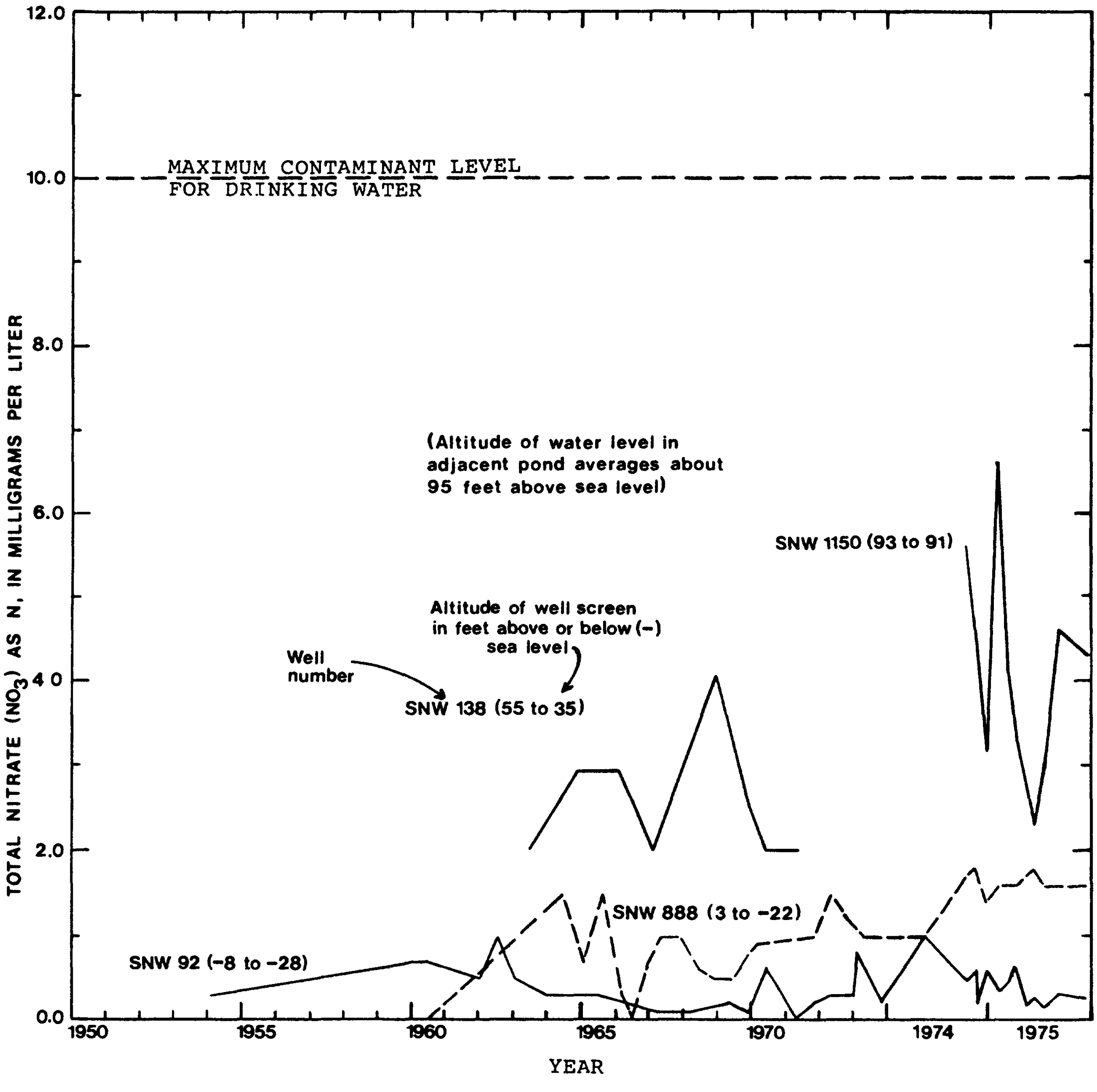


Figure 18.--Variation in the concentration of nitrate in ground water at the University of Rhode Island well field at Thirty Acre Pond from 1954-75. Concentrations have been higher in wells screened in the upper part of the aquifer. (From Silvey and Johnston, 1977)

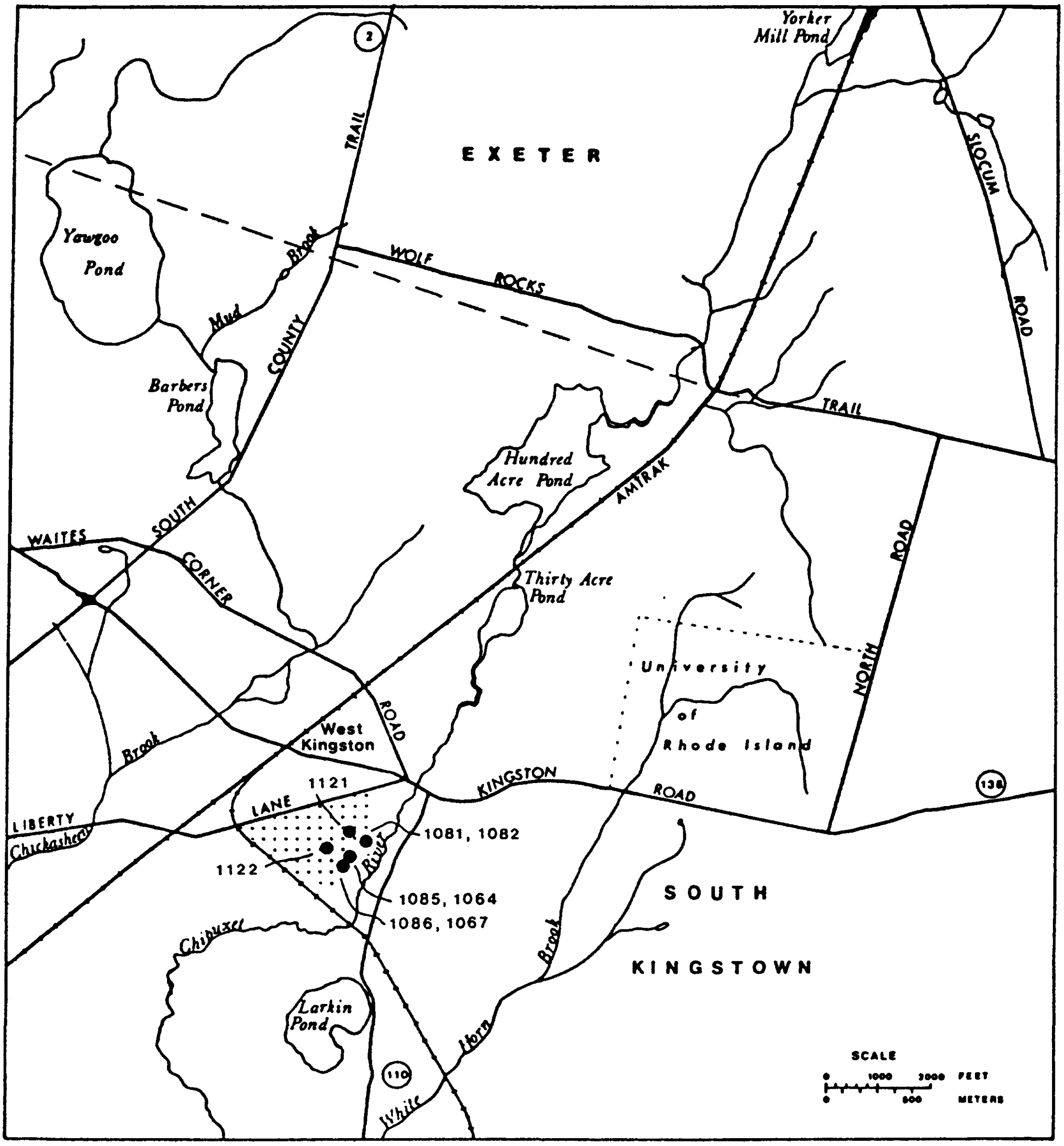
At the Liberty Lane aquifer-test site, analyses of water from exploratory wells SNW 1121 and SNW 1122, which were drilled in a potato field (fig. 19), show that the shallow part of the aquifer is highly contaminated with nitrate. The analyses are shown in the following table. Although the wells are hydraulically downgradient from the village of West Kingston, where sewage is discharged to septic tanks and cesspools, fertilizers applied to the potato field are a more likely source of the nitrate.

Well number	Date sampled	Depth to water (ft)	Screen depth (ft)	NO_3 as N (ng/L)
SNW 1121	02-29-73	8	17-21	24.4
	03-30-73	8	46-50	2.4
SNW 1122	04-02-73	6	17-21	17.8
	04-03-73	6	32-37	3.6

Three 8-inch diameter test wells (SNW 1082, SNW 1085, and SNW 1086) were drilled at the edge of the potato field by the RIWRB. Two of these well sites (SNW 1082 and SNW 1085) are under consideration as possible sites for public-supply wells. Analyses for nitrate in water pumped from the three 8-inch diameter test wells and from a 2.5-inch diameter exploratory well at each site are shown in table 14. The 8-inch diameter wells were drilled 2 to 3 feet from exploratory 2.5-inch-diameter wells and were screened at similar depths.

Data for water samples from the 2.5-inch diameter wells indicate the concentration of nitrate in ground water at the pumping test sites 18 to 34 days before pumping began in the 8-inch wells. For example, at the site of 8-inch well SNW 1086, the nitrate concentration in water from the adjacent 2.5-inch well, SNW 1067, was 3 mg/L 34 days before the start of a pumping test on SNW 1086. During the 168-hour pumping test, the nitrate concentrations in water from SNW 1086 increased to as much as 20 mg/L. It is likely that the nitrate was drawn downward from a shallower depth.

As long as fertilization of the adjacent field continues, it is likely that nitrate levels in ground water will remain high in the Liberty Lane area. Some dilution of nitrate levels will result from infiltration induced from the nearby Chipuxet River, but whether dilution would keep levels substantially below levels of 10 mg/L is uncertain.



EXPLANATION

1086 ●

Test well and USGS town identification number

Potato field

Figure 19.--Location of wells in and adjacent to a potato field at Liberty Lane that yielded water contaminated by nitrate in in 1970-73.

Table 14.--Nitrate in well water at the Liberty Lane aquifer-test site

[A dash indicates no data]

		Well					
		SNW 1082	SNW 1081	SNW 1085	SNW 1064	SNW 1086	SNW 1067
Diameter (in.)		8	2.5	8	2.5	8	2.5
Screen depth (ft)		40-70	54-69	65-90	83-95	60-80	67-77
Pumping rate (gal/min)		550	--	610	--	390	--
Date	Hours pumped	Concentration of NO_3 as N, in mg/L					
09-09-70	--	--	--	--	1.5	--	--
09-17-70	--	--	--	--	--	--	3.0
10-08-70	3	--	--	2.0	--	--	--
10-08-70	--	--	--	3.0	--	--	--
10-09-70	24	--	--	5.0	--	--	--
10-21-70	2	--	--	2.5	--	10.0	--
10-23-70	50	--	--	6.0	--	15.0	--
10-24-70	72	--	--	6.0	--	20.0	--
10-25-70	96	--	--	6.0	--	20.0	--
10-26-70	120	--	--	6.0	--	20.0	--
10-27-70	144	--	--	6.0	--	18.0	--
10-28-70	168	--	--	3.5	--	18.0	--
01-07-71	--	--	2.0	--	--	--	--
01-25-71	4	1.5	--	--	--	--	--
01-27-71	28	2.0	--	--	--	--	--
01-27-71	54	2.0	--	--	--	--	--
01-28-71	76	2.0	--	--	--	--	--
01-29-71	96	3.0	--	--	--	--	--

GROUND-WATER-DEVELOPMENT ALTERNATIVES

Background and Description of Digital Model

Electric-analog models for the analysis of ground-water reservoirs were popular during the 1950's and early 1960's. In the late 1960's, digital-computer models largely supplanted electric-analog models. The rapid growth of digital modeling since then attests to the value of these models both for providing information to allow hydrologists to better understand ground-water flow systems and for assessing the hydrologic effects of different ground-water-development alternatives. Through formal cooperation with the RIWRB and informal cooperation with the U.S. Geological Survey, the University of Rhode Island, Department of Civil and Environmental Engineering, under the direction of Professor William E. Kelly, has developed electric-analog and digital models of the Chipuxet ground-water reservoir.

Digital and electric-analog models of the ground-water reservoir were developed by Geisser (1975). His digital model was subsequently modified by Beckman (1978) to simulate the stream-aquifer system on a monthly or weekly basis. Beckman's modifications were made to improve the accuracy of simulated effects of pumping on streamflow. A user's manual for the digital model was prepared by Kelly and Ozbilgin (1982) and a summary of the work by Geisser and Beckman was published by Kelly (1983) in a report of limited distribution. The model was used to compute changes in ground-water levels and streamflow in time and space in response to selected pumping schemes for wells. The descriptions of the model and of model simulations given herein are taken largely from Kelly (1983).

The digital-simulation model consists of a set of equations, a computer code for their solution, and input data (transmissivities, storage coefficients, boundary conditions, and pumping rates) which represent the geohydrologic system and the problem to be solved. The model uses a finite-difference method in which differential equations describing ground-water flow in two dimensions are solved numerically. The computer code used in the development of the Chipuxet model was developed by Pinder (1970) and is described in a later revision by Trescott (1972).

The area modeled was subdivided into a uniform finite difference grid consisting of squares called nodes, each 400 feet to a side, and to which hydraulic properties were assigned. Model nodes are identified by row and column numbers, as shown in figure 20.

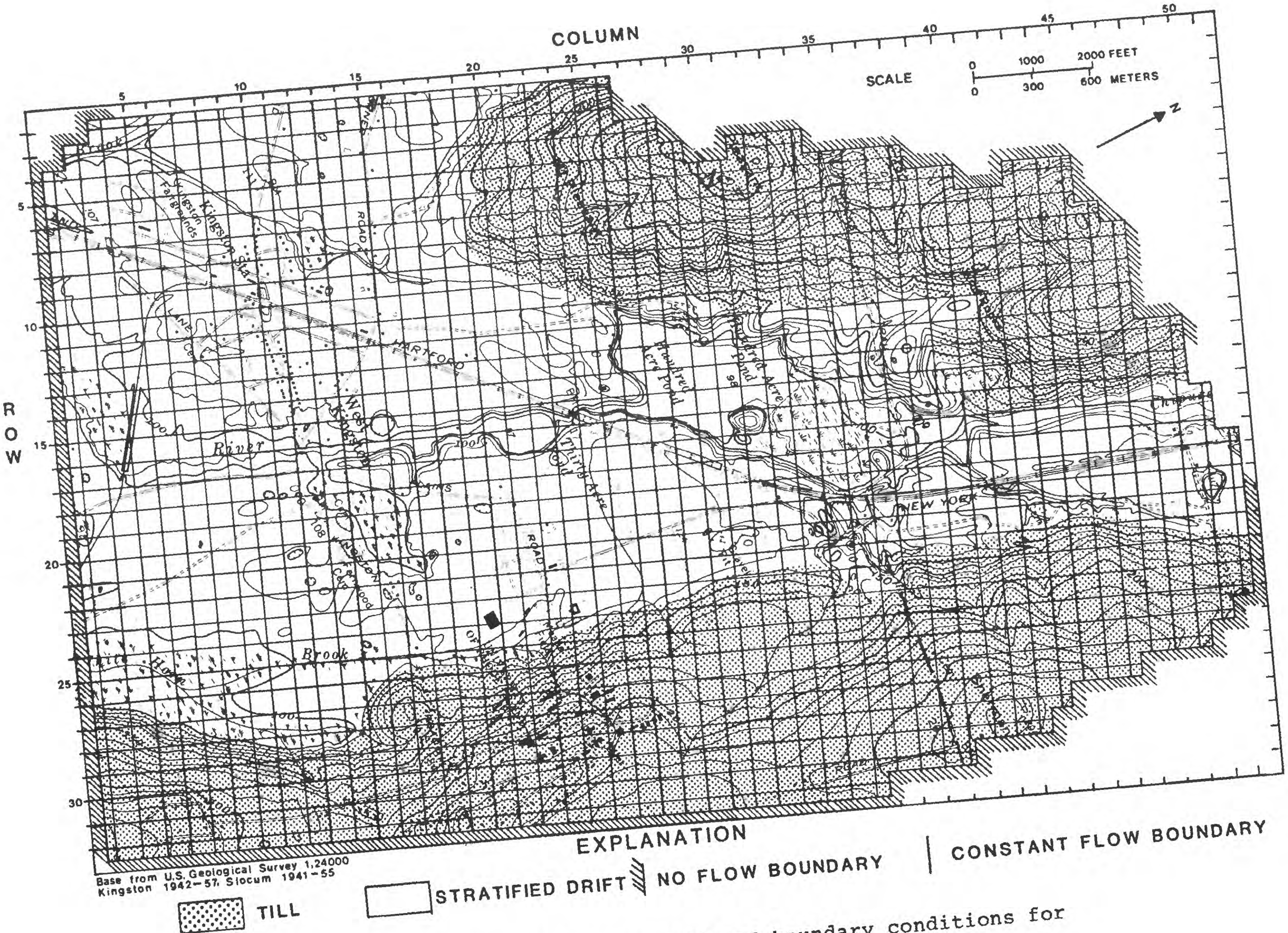


Figure 20.--Finite-difference grid and boundary conditions for Chipuxet aquifer model. (From Kelly, 1983)

Model Assumptions

The complex ground-water flow system is made amenable to mathematical treatment by use of several simplifying assumptions. Assumptions made by Geisser and by Beckman in the digital model analysis are that:

(1) Groundwater flow is essentially horizontal.

(2) The storage coefficients of the till and stratified-drift are typical of a water-table aquifer; Geisser (1975, p. 95) assumed a value of 0.30 for stratified drift; Beckman (1978, p.15) assumed values of 0.05 and 0.25, respectively, for till and stratified drift.

(3) Transmissivity does not change appreciably as saturated thickness changes.

(4) Recharge rates for till and stratified drift are the same.

(5) Seepage rates to or from streams and ponds are controlled by constant heads (fixed water-level altitudes) in the stream and by aquitards of limited areal extent that underlie the stream.

(6) All discharge from the aquifer either is pumped from wells or is ground-water runoff to the Chipuxet River.

The assumption of horizontal flow is probably correct, except in the vicinity of streams and ponds where flow may be nearly vertical. Horizontal flow occurs where the water levels in shallow and deep wells at the same site are essentially equal. A vertical component of flow occurs where water levels in deep and shallow wells differ. No data are available to demonstrate horizontal flow, but Allen and others (1963, p. 50) show that water levels in wells screened near the bottom of the aquifer near the Chipuxet River at West Kingston are as much as 1 foot higher than in wells screened near the water table. This head difference represents the energy required to move water almost vertically from the bottom of the aquifer into the river.

The assumed storage coefficients of 0.05 for till and 0.25 to 0.30 for stratified drift are typical of water-table aquifers and are reasonably close to average values of 0.10 for till and 0.20 for stratified drift estimated from field data. (See sections on till and stratified drift.)

The assumption that transmissivity remains constant as water levels in the aquifer rise and fall is not strictly valid. Transmissivity, being the product of the hydraulic conductivity and saturated thickness of the aquifer, decreases as saturated thickness decreases. However, pumping stresses simulated for this study caused decreases in saturated thickness that are typically less than 5 percent of aquifer thickness. The resulting small change in transmissivity will not appreciably affect model results.

Recharge rates to till and stratified-drift aquifers differ, as shown earlier in this report. Simulated recharge to both aquifers at a uniform average rate in the Chipuxet basin results in more recharge being added to till and less being added to stratified drift than actually occurs. However, experiments with a similar model of the Beaver-Pasquiset ground-water reservoir (D. C. Dickerman, U.S. Geological Survey, and M. M. Ozbilgin, University of Rhode Island, oral commun., 1983) show that use of a basin-wide average recharge rate for both aquifers does not seriously affect the predictive capability of the model.

The assumption that water levels in the Chipuxet River, Hundred Acre Pond, and Thirty Acre Pond are fixed at some constant altitude means that the model will continue to simulate recharge from these water bodies even when they may, in reality, have gone dry. This assumption will produce no significant difference between real and simulated drawdowns for ground-water withdrawals that do not exceed the low flows of streams in the study area. However, simulated withdrawals in excess of low stream flow may result in water-level drawdowns that are less than would be observed in the field.

The assumption that streams and ponds are underlain by aquitards (layers having lower hydraulic conductivity than the aquifer) of limited areal extent allows the model to simulate the effects of head loss resulting from vertical flow of water through aquifer and streambed sediments in which hydraulic conductivity is lower vertically than horizontally.

Not all of the recharge to aquifers discharges to the Chipuxet River and to pumping wells as assumed. Some ground water discharges (1) to the atmosphere by evapotranspiration, (2) to the lower reaches of White Horn Brook and Chickasheen Brook, and (3) as subsurface outflow along the southern boundary of the area modeled. The fact that these discharges are not simulated in the model does not greatly affect drawdown predictions in the vicinity of the pumping centers tested. This is partly because unaccounted-for stream discharge occurs downstream of the pumping centers and partly because drawdowns are controlled largely by induced stream infiltration. However, the model will predict somewhat larger flows in the Chipuxet River downstream from the U.S. Geological Survey gage at Route 138 than actually occur.

Boundary Conditions

Ideally, model boundaries should be chosen so that they coincide with hydrologic boundaries that do not shift during the time frame of the model analysis. In addition, the specified boundary conditions should remain unchanged during all calibration and prediction runs; otherwise, boundary conditions become another variable that could affect simulation results.

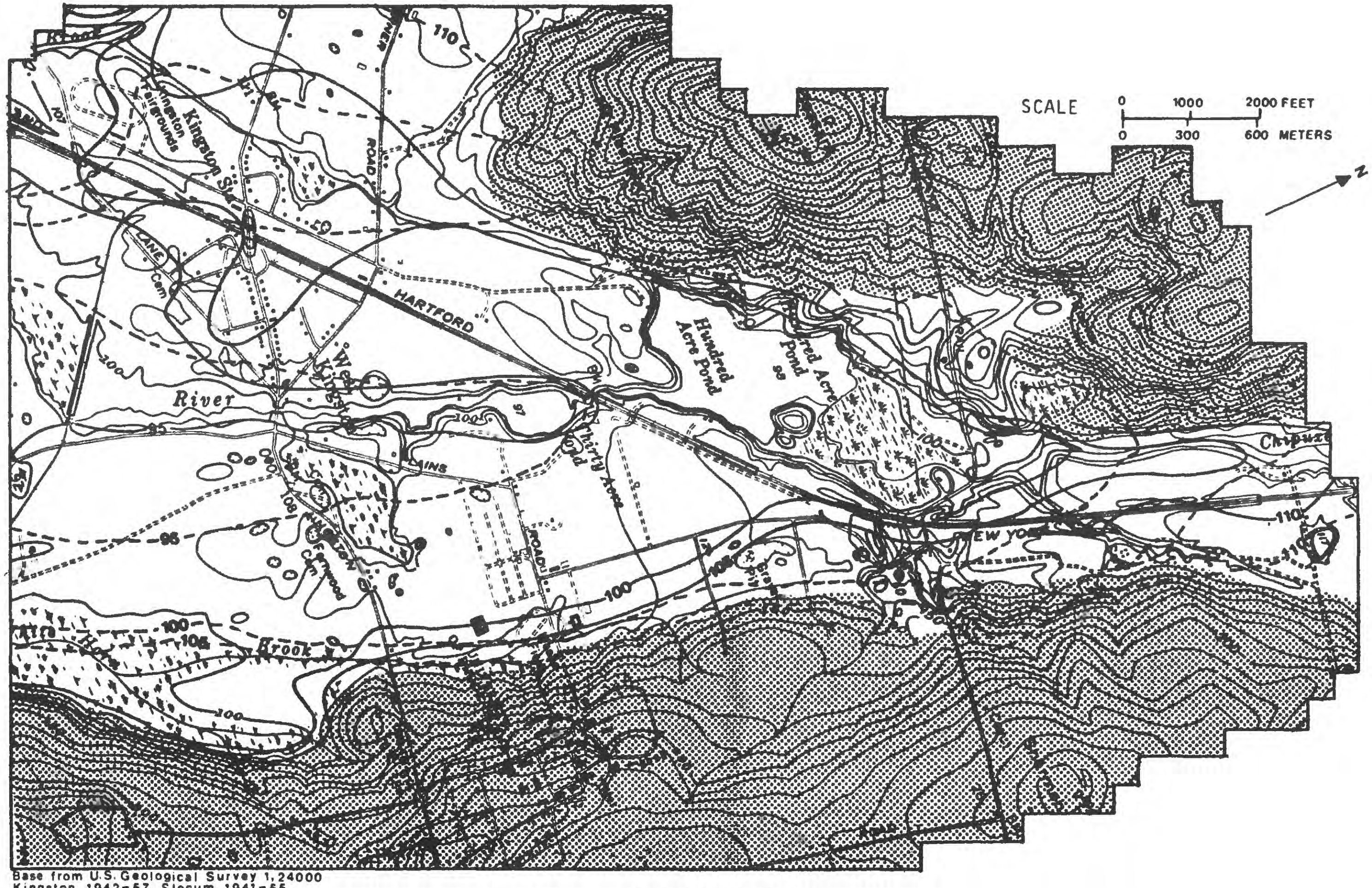
The types of boundaries assumed in the digital model are shown in figure 20. No-flow boundaries were used at natural drainage boundaries and across the southern end of the model area where the water-table map (see fig. 21) shows that there is relatively little subsurface flow out of the modeled area under non-pumping conditions. Constant-flow boundaries are used at the northern and western edges of the model where the water-table map indicates that there is subsurface flow into the modeled area. Initial estimates of subsurface flow were computed from data taken from maps of the water table, saturated thickness, and hydraulic conductivity prepared by Allen and others (1966). The Chipuxet River, Hundred Acre Pond, and Thirty Acre Pond are treated as constant-head boundaries. For the model of steady-state conditions, stream and pond levels were set equal to estimated average annual altitudes. For the model of transient conditions, stream and pond levels were set equal to average monthly altitudes representative of the period simulated.

Calibration Procedure

Calibration refers to the process of adjusting input hydrologic properties (transmissivity, storage coefficients, and recharge rates) to the model until differences between model simulations and field observations are within acceptable limits. The model has been calibrated under both steady-state and transient conditions.

A steady-state condition occurs when there are no changes in ground-water storage with time. A true steady-state condition never occurs in the study area, but is often approximated during dry months in late summer and fall when the rate of change in ground-water storage is small. A near steady-state condition existed in the Chipuxet ground-water reservoir area during August and September 1959. The water-table map shown on plate 1, Part B is based on measurements made in late August 1959.

A transient condition is the true condition of the ground-water flow system in the study area. Because discharge to principal streams occurs continuously and because recharge by precipitation occurs episodically, changes in ground-water storage occur repeatedly. Water levels rise and storage increases when recharge exceeds discharge; they fall and storage decreases when discharge exceeds recharge. These changes are most readily observed in the continuous records of stream discharge obtained at gaging stations and in records of water-level fluctuations in wells.



EXPLANATION

TILL

STRATIFIED DRIFT

MODEL BOUNDARY

– – 100 – – Water-table contour based on model data

——100—— Water-table contour based on measurments made in August, 1959, by Allen and others (1966, plate 3)

Contours show altitude of water table, in feet above sea level.

Contour interval is 5 feet.

Figure 21.--Comparison of water table in August 1959 and simulated steady-state water table. (From Kelly, 1983)

Steady-State Model

The steady-state model was calibrated by adjusting model parameters until simulated water-level altitudes and increase of base flow (which consists mostly of ground-water runoff) within the modeled area agreed reasonably well with water levels measured in late August 1959 and base flow increase measured in September 1959. The measured water table and simulated steady-state water table are compared in figure 21. Discrepancies between simulated and estimated water levels result in part from the fact that Chickasheen Brook and White Horn Brook are not incorporated into the model. Both brooks lose water to the underlying aquifer in their upper reaches during part or all of the year, and gain water from ground-water runoff in their lower reaches. Annual losses and gains were not determined.

Increases in ground-water runoff to a 23,000-foot reach of the Chipuxet River predicted by the steady-state and transient models for a low-flow condition are compared in figure 22. Also shown for comparison is a measured increase in ground-water runoff to the Chipuxet River between miscellaneous measurement site 1 and the Chipuxet River gage during a low-flow period. The measured difference in flow between site 1 and the gage on September 10, 1959, was 6.0 ft^3/s (point A in fig. 22). If there had been no ground-water withdrawals from University of Rhode Island supply wells at Thirty Acre Pond the difference in flow would have been about 6.5 ft^3/s. Figure 22 indicates that the transient model approximates the low-flow condition more closely than the steady-state model.

Initial values of transmissivity for the stratified-drift aquifer were estimated from a map of saturated thickness and average hydraulic conductivity prepared by Allen and others (1966, pl. 2). Only minor adjustments were made to the published values during calibration, because distribution of transmissivity was reasonably well known from field measurements. Subsequent field measurements of aquifer hydraulic properties have required only local modifications to the original maps of aquifer saturated thickness and hydraulic conductivity.

A maximum transmissivity of 20,100 ft^2/d was assigned to the model in the stratified drift areas in the vicinity of Thirty Acre Pond. A uniform transmissivity of 135 ft^2/d was assigned to all till-bedrock areas. Aquifer-test data (table 9) indicate that the transmissivity in the vicinity of Thirty Acre Pond is 28,600 ft^2/d. Estimated transmissivities for till-bedrock areas given earlier indicate that the average transmissivity is probably about 40 ft^2/d. However, the order of magnitude of differences between modeled and estimated transmissivities should have only a minor impact on simulated model results. A sensitivity analysis (fig. 23) shows that uniformly increasing or decreasing initially assigned values of transmissivity in the model by as much as 20 percent causes minor (+ or -0.2 ft) changes in the water level in observation well SNW 6. (See fig. 27 for location of SNW 6.)

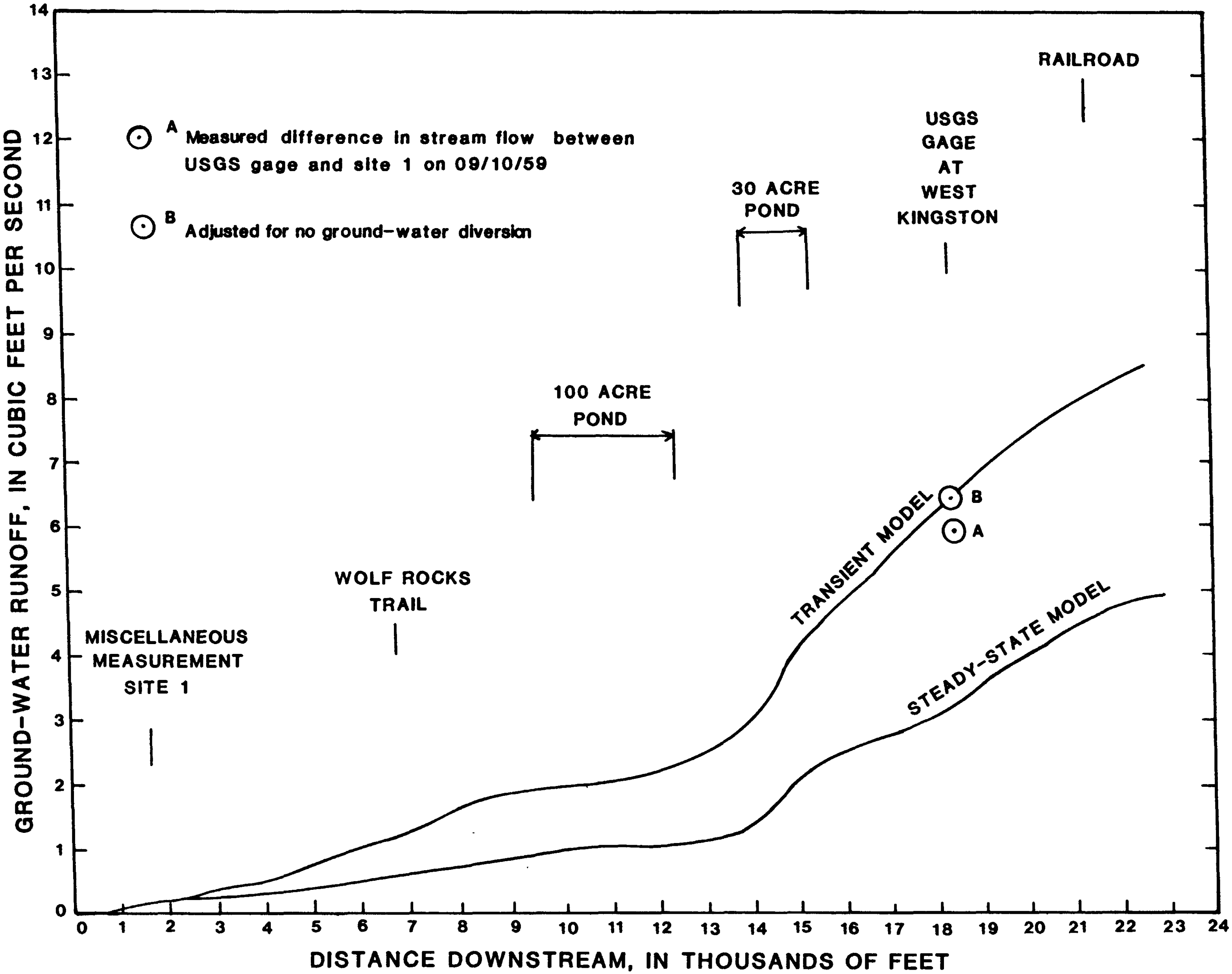


Figure 22.--Predicted and measured increases in low stream flow caused by ground-water runoff to the Chipuxet River from the area modeled. (Modified from Beckman, 1978)

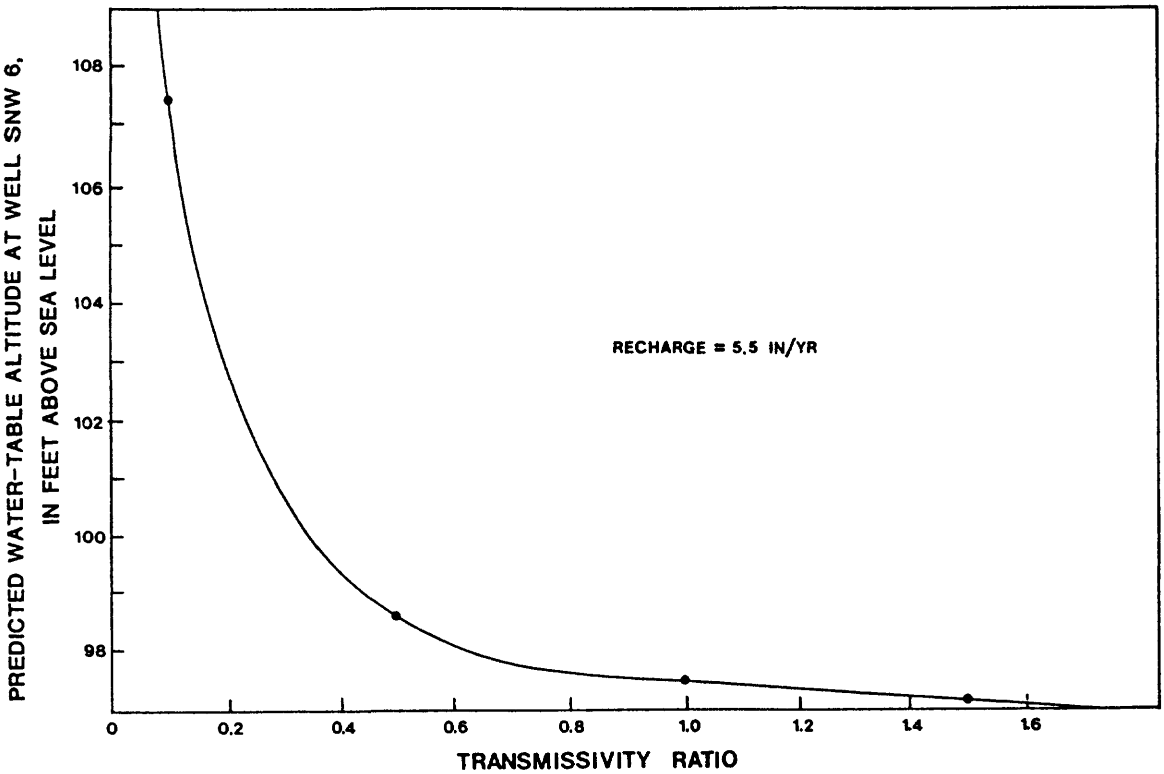


Figure 23.--Water-table altitudes predicted by the calibrated Chipuxet digital model are more sensitive to decreases (ratios < 1.0) than to increases (ratios > 1.0) in aquifer transmissivity. (Adapted from Kelly, 1983)

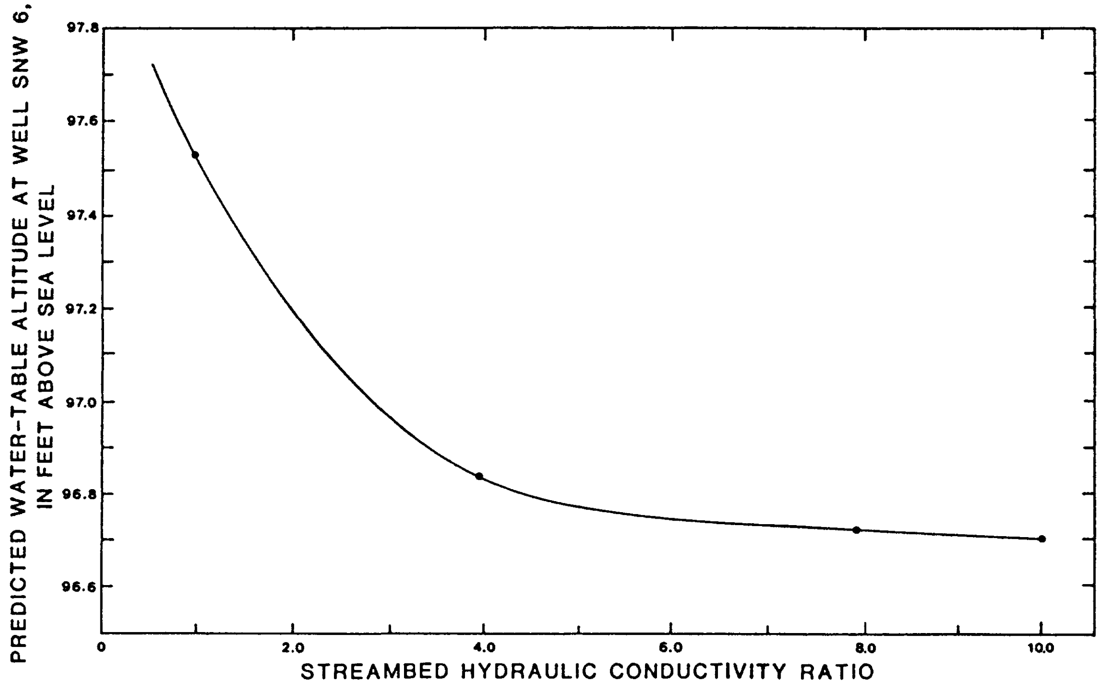


Figure 24.--Water-table altitudes predicted by the calibrated Chipuxet digital model are sensitive to both increases and decreases (ratios > 1.0 or <1.0) in streambed hydraulic conductivity. (Adapted from Kelly, 1983)

Streambeds were modeled as confining beds and arbitrarily assumed to be 1 foot thick. Values of hydraulic conductivity for aquitards used in the digital model were derived by Geisser (1975). He used the electric-analog model to obtain a series of best-fit values. These best-fit values range from 0.08 ft/d in the upper reaches of the modeled area to 0.004 ft/d in the ponds. Sensitivity analysis shows that the water level in SNW 6 is sensitive to small changes in the final values of streambed hydraulic conductivity that were selected (fig. 24).

An additional calibration step involved comparison of the water level in observation well SNW 6 with recharge rates (fig. 25), during several months when near steady-state conditions occurred. Recharge rates were assumed to equal the rate of ground-water runoff to the Chipuxet River. Because most of the water discharged as ground-water runoff during the selected months was derived from ground-water storage, the addition of recharge to the aquifer at a rate equivalent to the rate of discharge results in no change in storage, a steady-state condition. The results of this experiment show reasonably good correlation with the observed water level in the well.

Transient Model

The transient model was calibrated by adjusting values of monthly recharge until good agreement was obtained between the simulated and observed altitudes of the water table at observation well SNW 6 (fig. 26). Recharge rates were also adjusted to produce ground-water runoff that would match the increase in streamflow measured on September 10, 1959.

The constant-head nodes representing the Chipuxet River and the ponds were adjusted on a monthly basis using the mean monthly altitude of the river at the U.S. Geological Survey gage at West Kingston. Altitudes of the river at the gage and for Thirty Acre and Hundred Acre Ponds are known for a wide range of flows. Therefore, the slope of the stream-pond surfaces could be adjusted based on altitudes determined from mean monthly flows at the gage.

A test of the Chipuxet model accuracy was made using data from a construction site at the University of Rhode Island (Kelly, 1983, p.28). In April 1976, a dewatering operation was begun to lower the water table at the site of a new sewage pumping station. The site is about 3,000 feet south of U.S. Geological Survey observation well SNW 6. Continuous ground-water withdrawals were made for 4 months at a reported rate of about 3 Mgal/d. Simulated pumping at the rate of 3 Mgal/d for this same period resulted in good agreement between modeled and observed water-table altitudes at SNW 6.

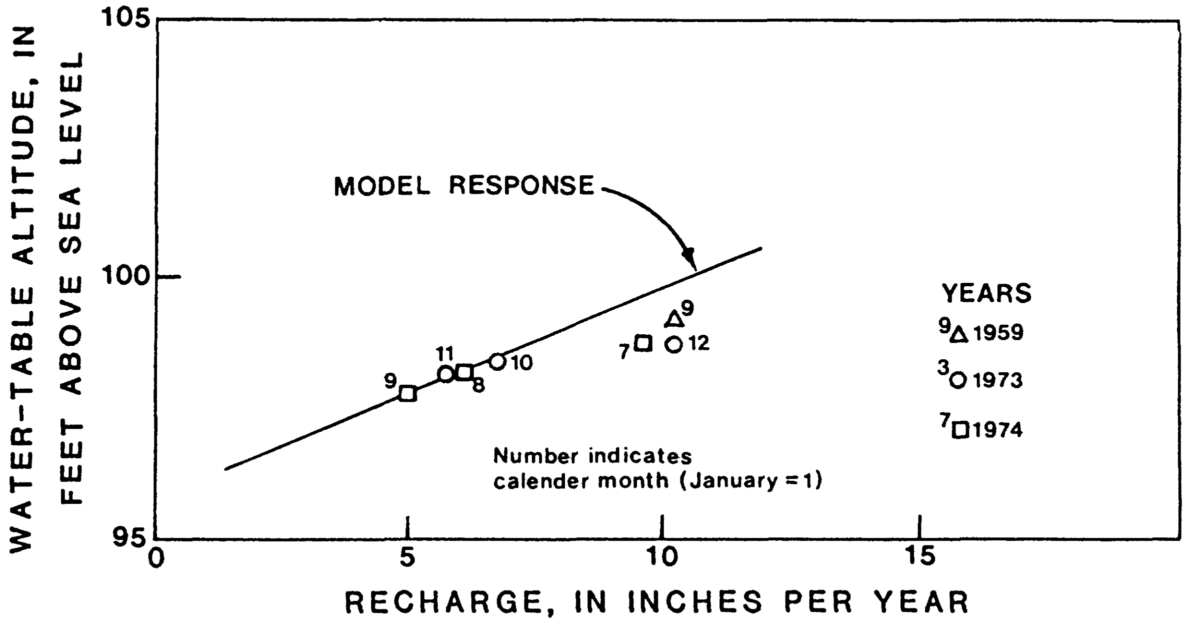


Figure 25.--Comparison of observed and simulated steady-state water levels in observation well SNW 6. (From Kelly, 1983)

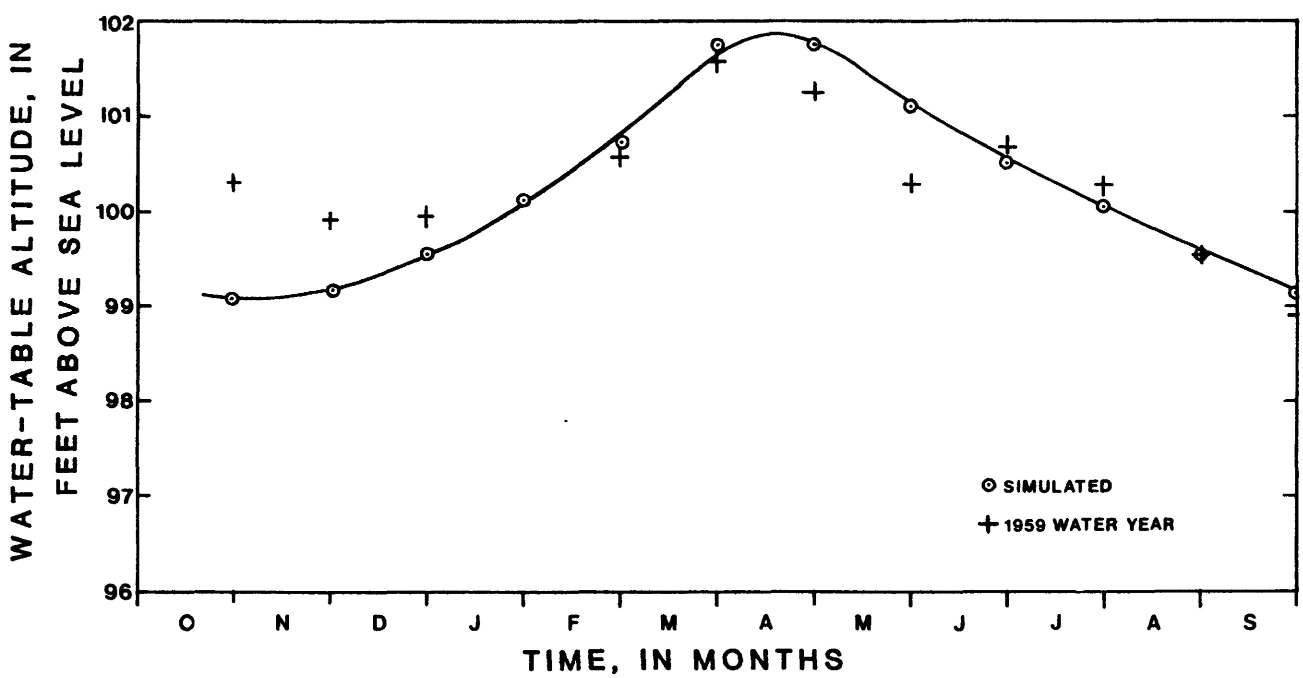


Figure 26.--Simulated and observed water levels at observation well SNW 6 during the 1959 water year. (From Kelly, 1983)

Simulation of Ground-Water Withdrawal Schemes

Withdrawal rates for five alternative schemes for developing an average annual yield of 3 Mgal/d from wells in the Chipuxet ground-water reservoir are shown in table 15; locations of the well sites are shown in figure 27. The sixth alternative scheme shown in table 15 is not proposed for the development; rather it is designed to simulate drawdowns under the much higher withdrawal rates that Allen and others (1966) estimated to be obtainable.

Transient and steady-state simulations were run to determine the effects of pumping on streamflow depletion and drawdown of the water table. A comparison of steady-state and transient simulations of the effects of pumping scheme I on the change in streamflow between the upstream and downstream ends of the modeled area is shown in figure 28. Transient simulations probably are more representative of changes in streamflow that would occur under pumping scheme I. If so, predictions of streamflow depletion and water-level drawdowns by the steady-state model will be conservatively large. It should be noted, however, that the transient model uses average monthly base flows. Some daily low flows of the Chipuxet River will be below monthly averages.

Effect of Withdrawals on Water Levels

The effect of withdrawing ground water at the rate of 3 Mgal/d in each of five development schemes listed in table 15 was determined by using a version of the model in which it was assumed that (1) the water table was flat, (2) no subsurface flow occurred into or out of the modeled area, (3) the storage coefficient of the stratified drift was 0.30, and (4) pumping was for a period of 180 days during which there was no recharge (Geisser, 1975, p.95; Kelly, 1983, p.31). The pumping period of 180 days corresponds approximately to the growing season in the study area during which recharge is typically small.

Simulated drawdown resulting from pumping schemes I and V are shown in figures 29 and 30. Drawdowns for scheme I were least because pumping was spread over a large area of the aquifer. Drawdowns for scheme V were greatest because pumping was concentrated in the well field at Thirty Acre Pond. Drawdowns for schemes II, III, and IV were intermediate. None of the proposed development schemes produces excessive drawdowns.

Drawdowns in the pumped wells for each of the five development schemes are shown in table 16. Results for scheme VI indicate that even for a combined pumping rate of 8 Mgal/d, drawdowns would not be excessive.

Table 15.--Alternative schemes for developing 3 million gallons per day from the Chipuxet ground-water reservoir

[After Kelly, 1982, p. 39; a dash indicates no data.]

Well field	Well site [1]	Yield of well, in Mgal/d					
		Withdrawal scheme					
		I	II	III	IV	V	VI
Wolf Rocks	A	0.50	0.75	---	---	---	1.50
Thirty Acre Pond	B	.50	.75	0.75	1.00	1.00	1.00
	C-D	.50	.50	.75	1.00	1.75	2.50
	E-F	.50	---	.50	---	---	1.00
Kingston Fire District	G	.25	.25	.25	.25	.25	.50
Liberty Lane	H	.35	.35	.35	.35	---	.80
	I	.40	.40	.40	.40	---	.70
Total		3.00	3.00	3.00	3.00	3.00	8.00

[1] See figure 27 for location.

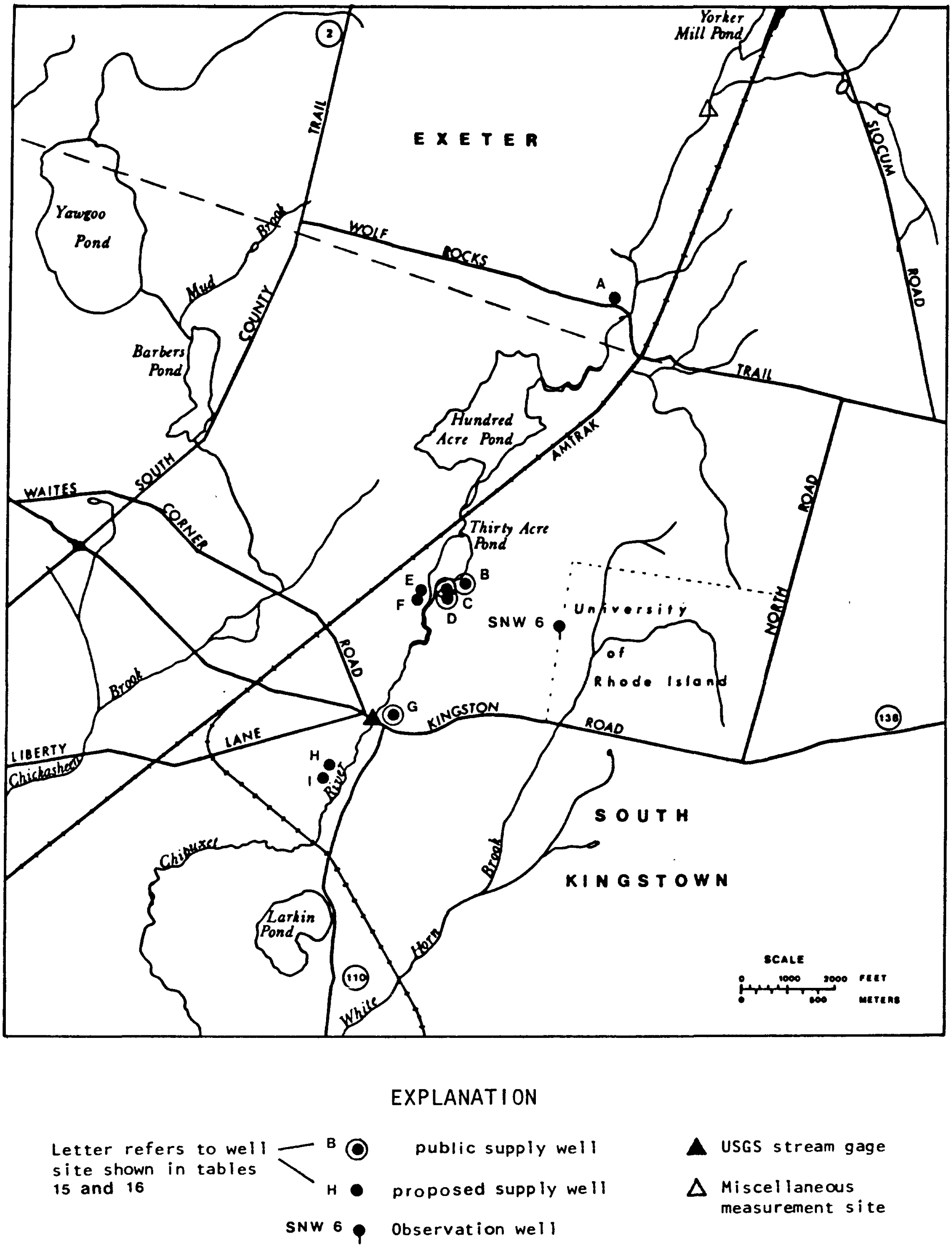


Figure 27.--Location of public-supply wells and proposed public-supply wells within the model area.

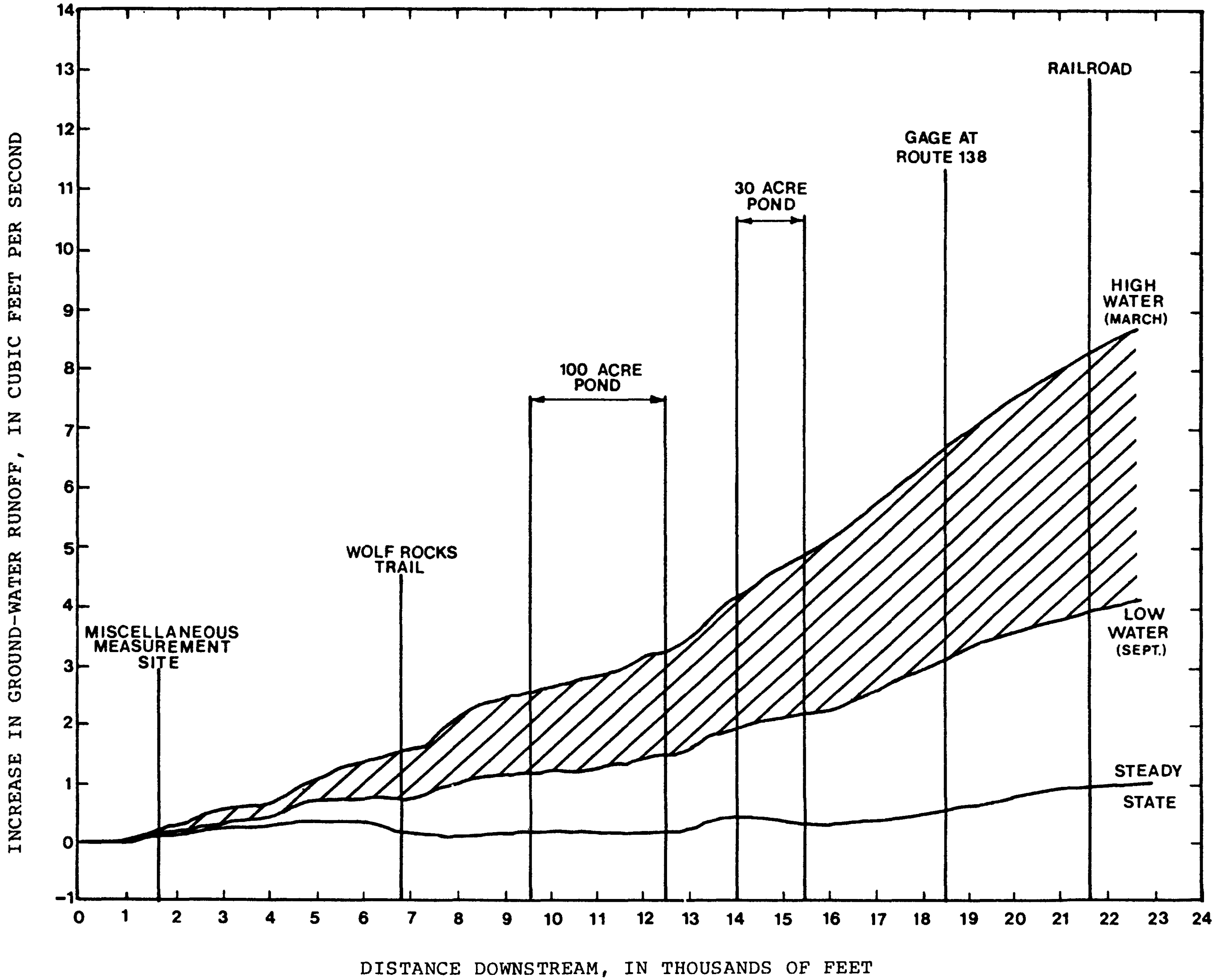
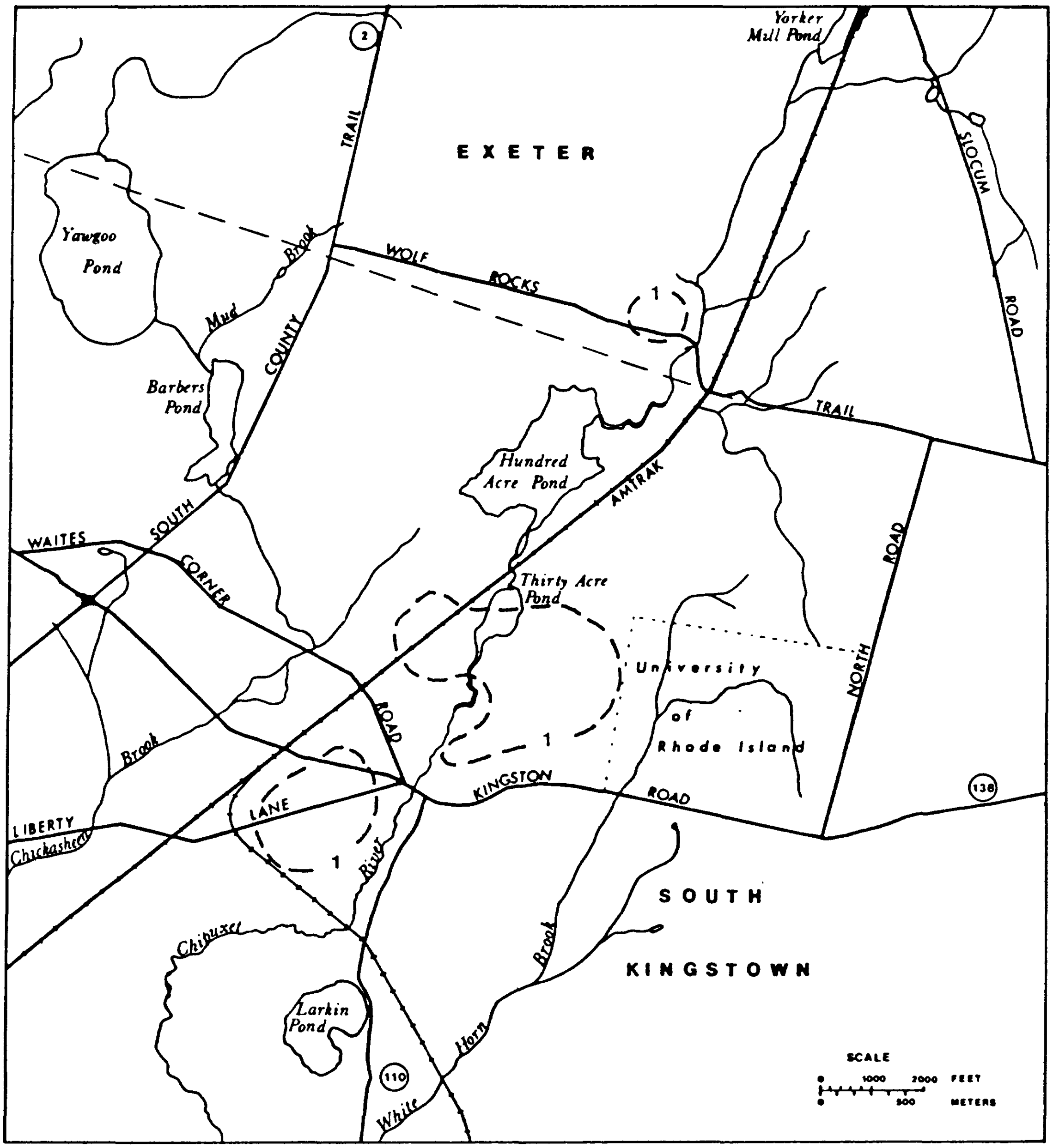


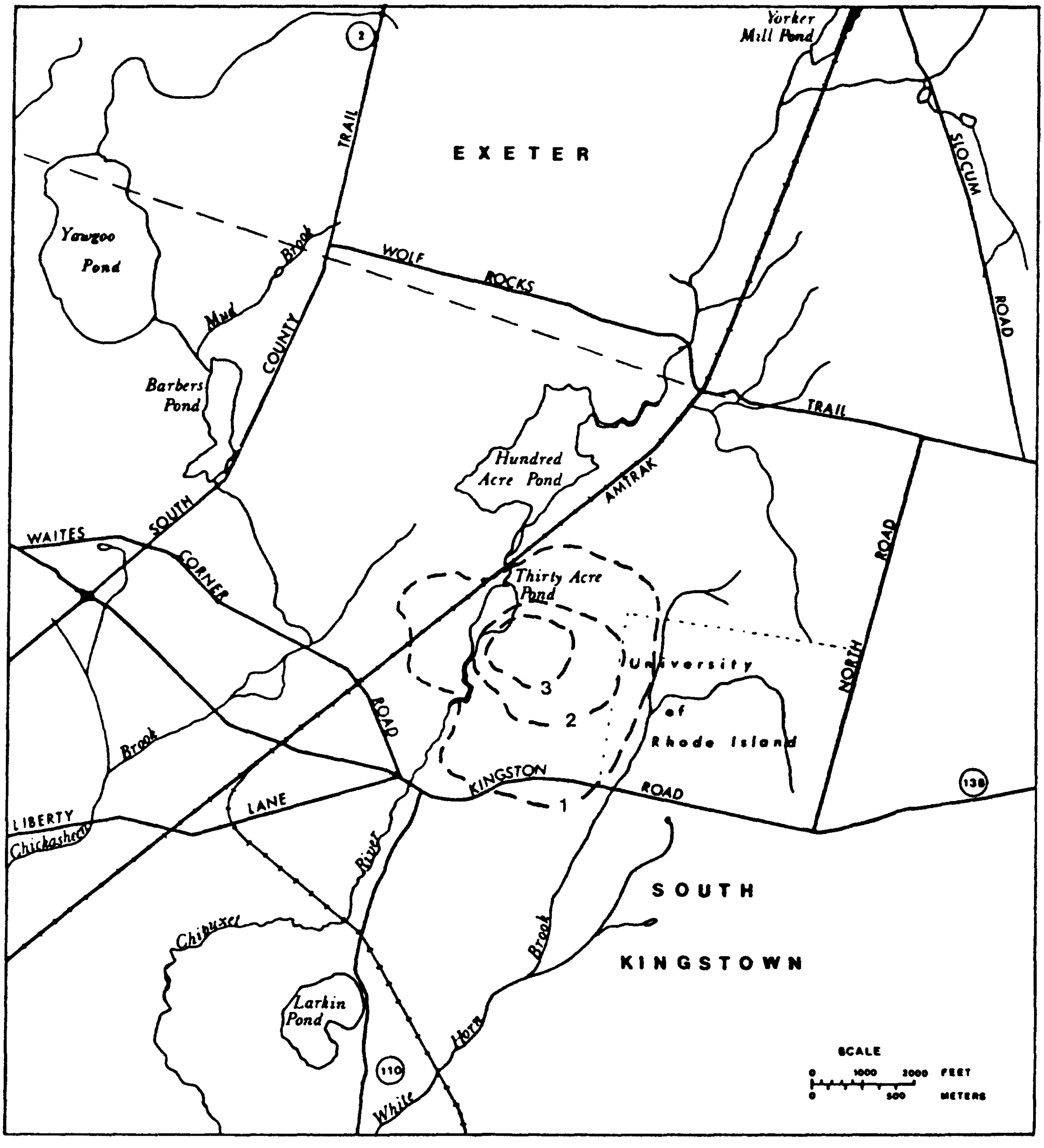
Figure 28.--Comparison of steady-state and transient simulations for increase in ground-water runoff under pumping scheme 1. (From Kelly, 1983)



EXPLANATION

Line of equal water level decline (feet)

Figure 29.--Simulated water-table drawdown caused by pumping well schem 1 for 180 days. (Modified from Geisser, 1975)



EXPLANATION

Line of equal water level decline (feet)

Figure 30.--Simulated water-table drawdown caused by pumping well scheme V for 180 days. (Modified from Geisser, 1975)

Table 16.--Simulated drawdowns in wells after being pumped continuously for 180 days at rates listed in table 15.

[After Kelly, 1982, p. 40; a dash indicates no data.]

Well field	Well site	Drawdown, in feet [1]					
		Withdrawal scheme					
		I	II	III	IV	V	VI
Wolf Rocks	A	6.56	9.88	---	---	---	19.69
Thirty Acre Pond	B	5.53	7.64	8.19	10.53	11.43	13.06
	C-D	6.12	6.11	8.98	11.16	18.78	27.27
	E-F	2.67	---	5.40	---	---	11.36
Kingston Fire District	G	2.81	2.71	2.93	2.87	2.72	5.97
Liberty Lane	H	4.05	4.00	4.09	4.05	---	8.90
	I	4.40	4.36	4.43	4.43	---	8.14

[1] Drawdowns are for a 100-percent efficient well with radius of 0.5 foot and are uncorrected for partial penetration and dewatering.

Effect of Withdrawals on Streamflow

The discussion of the effect of withdrawals on streamflow is taken chiefly from Beckman (1978) and Kelly (1983). Simulated reductions in ground-water runoff to the Chipuxet River within the modeled area caused by pumping schemes I and V are shown for conditions of low flow (fig. 31) and high flow (fig. 32). The low-flow condition is representative of streamflow in September 1959, when mean monthly flow of the Chipuxet River at the gage at West Kingston, adjusted for ground-water diversion, was 8.8 ft3/s. This flow is equivalent to the mean daily flow that is equaled or exceeded about 77 percent of the time. The high-flow condition is representative of streamflow in March 1959, when mean monthly flow, adjusted for ground-water diversion, was 46 ft3/s. This flow is equivalent to the mean daily flow equaled or exceeded about 9 percent of the time.

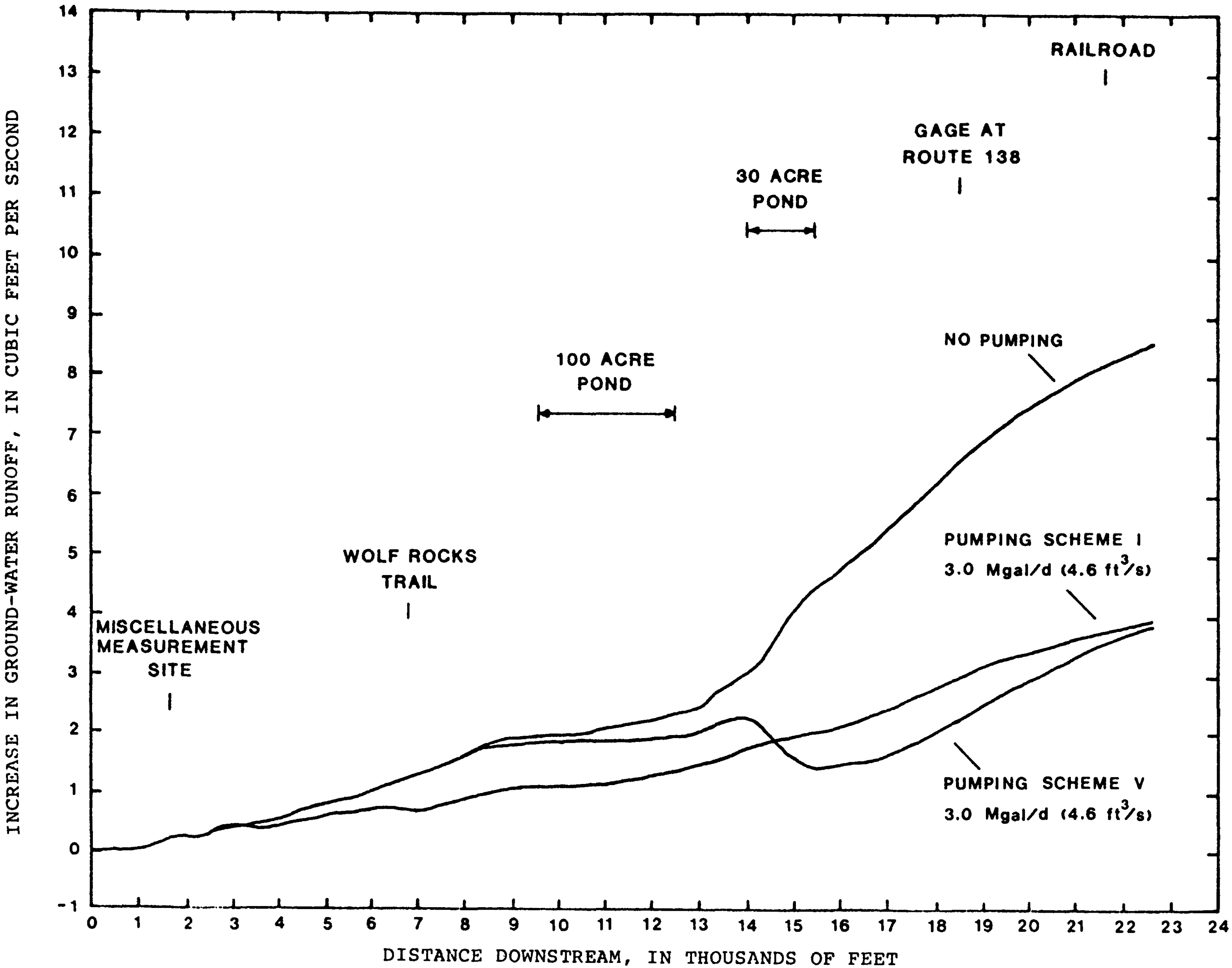


Figure 31.--Simulated effect of pumping schemes 1 and V on increase in ground-water runoff in the Chipuxet River for a low-flow condition similar to that of September 1959. (Modified from Beckman, 1978)

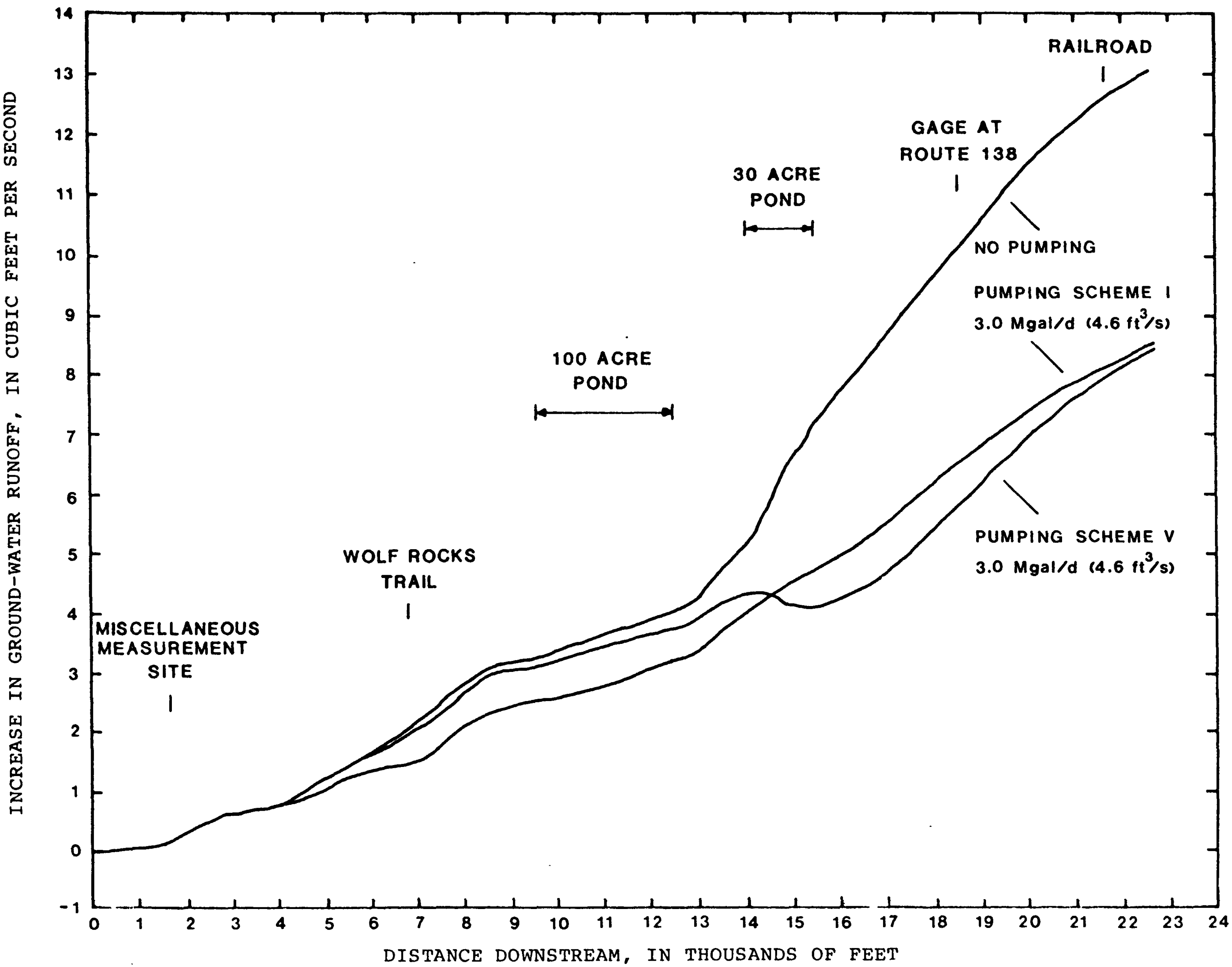


Figure 32.--Simulated effect of pumping schemes 1 and V on increase in ground-water runoff in the Chipuxet River for a high-flow condition similar to that of March 1959. (Modified from Beckman, 1978)

It is evident that upstream reaches of the river are least affected if pumping is concentrated in the lower part of the ground-water reservoir near Thirty Acre Pond. Under conditions of continuous withdrawal, however, all pumping schemes reduce total outflow from the ground-water reservoir by an amount approximately equal to the rate of ground-water withdrawal from wells. It should be noted that underflow entering from the west edge of the model goes into the Chipuxet River, simulating more flow than it may in fact have, especially in the lower reaches.

Simulated effects of pumping schemes I and V on mean monthly flows of the Chipuxet River at West Kingston are shown in figure 33. Scheme I produces less streamflow depletion at the gage than scheme V because some pumping in scheme I occurs downstream of the gage at the Liberty Lane well field.

Figure 33 illustrates the almost immediate reduction of streamflow that occurs in response to pumping from selected wells. This relation may be used in conjunction with table 3 to estimate the effects of pumping on the low flow of the stream at West Kingston as a consequence of pumping any combination of selected wells upstream of West Kingston. For example, in table 3 the estimated 7-day low flow with a 10-year recurrence interval is 2.6 Mgal/d, which is equivalent to the flow equaled or exceeded 99 percent of the time (table 2). Table 3 also indicates that if water is withdrawn at a rate of 3 Mgal/d from wells upstream of West Kingston and exported from the basin, no flow at the gage would occur for periods as long as 90 consecutive days on the average of 1 year out of 20.

Scheme V illustrates that a combined yield of 3 Mgal/d can be obtained from the well fields at Thirty Acre Pond and the Kingston Fire District. However, at the withdrawal rates shown in scheme V, a very large percentage of the pumpage would consist of water induced from the river and pond. In the water quality section, it is shown that undesirably high concentrations of manganese in water from wells in the Thirty Acre Pond well field are related to induced recharge. Scheme I, on the other hand, would result in interception of increased amounts of ground-water runoff to streams and less infiltration of streamflow. Presumably, manganese enrichment of well waters would be less of a problem under scheme I.

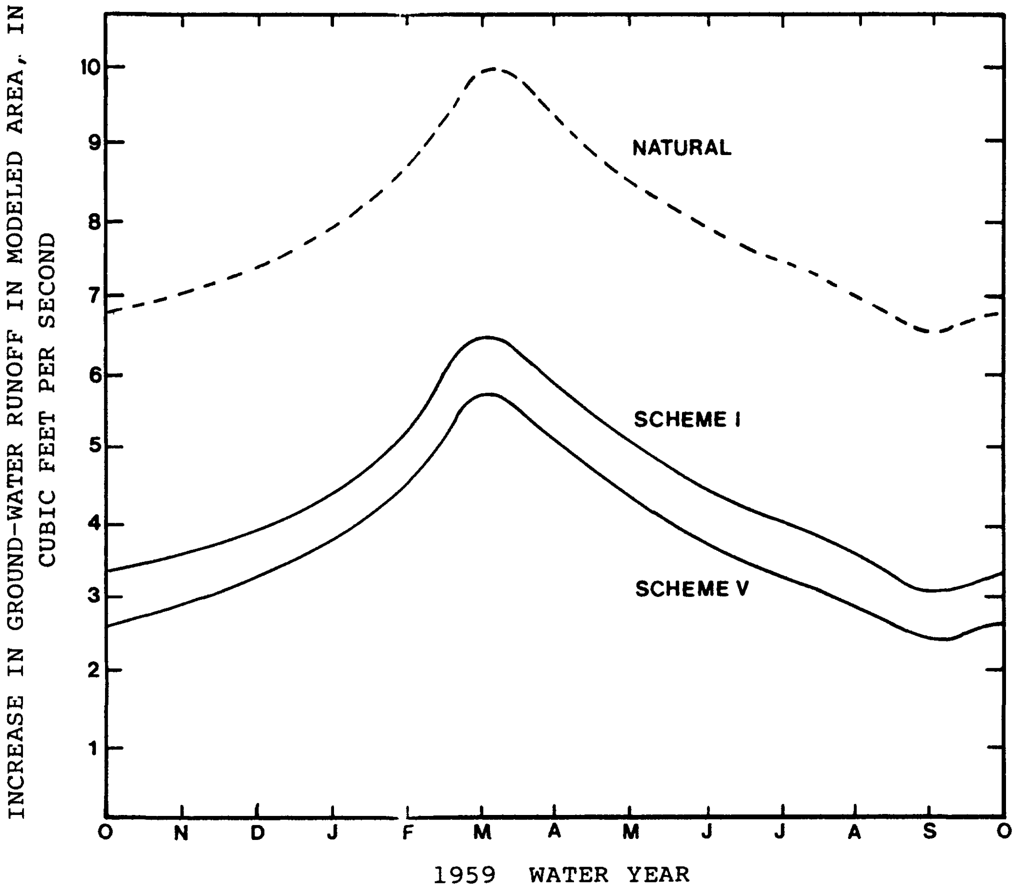


Figure 33.--Simulated effect of ground-water withdrawal on increase in ground-water runoff in the Chipuxet River at West Kingston for streamflow conditions similar to those in water year 1959. (From Kelly, 1983)

SUMMARY AND CONCLUSIONS

A moderately to highly permeable and porous stratified-drift aquifer occupies the valleys of the Chipuxet River and Chickasheen Brook in the towns of Exeter and South Kingston. The thickest and most transmissive part of this aquifer forms a ground-water reservoir that can yield water at high rates to carefully located and constructed large-diameter wells. Supply wells and test wells have been pumped at rates ranging from 100 to 900 gal/min and yields of as much as 1,200 gal/min are obtainable at some sites.

Exploratory drilling and aquifer testing by the Rhode Island Water Resources Board have resulted in identification of sites from which a combined average yield of 3 Mgal/d could be developed for public supply. Some of the tested sites are being acquired and will be preserved for future use. Although the ground-water reservoir could continuously yield as much as 8.6 Mgal/d, withdrawal and export of water from the Chipuxet River basin (as water supply, sewage, or a combination of both) at this rate would cause streams that flow across the ground-water reservoir to have little or no flow much of the time during summer and fall months.

In 1979, 1.14 Mgal/d was withdrawn from the ground-water reservoir. Most of the water used was discharged from the Chipuxet River basin as sewage. Although streamflow was reduced by a like amount, flow at the Chipuxet gage was continous throughout the year. The low flow (98-percent-duration flow) of the Chipuxet River at the gage at West Kingston, near the downstream end of the ground-water reservoir, is 2.8 Mgal/d for nonpumping conditions. It is estimated that continuous withdrawal of 3 Mgal/d from wells upstream of the Chipuxet gage would cause periods of no flow at the gage as long as 7 consecutive days on the average of 1 year in 3, and for as long as 90 consecutive days on the average of 1 year in 20. Supplemental supplies could be obtained from wells in other ground-water reservoirs in the Pawcatuck River basin during low flow. For purposes of this study, it is assumed that this is an acceptable consequence of development.

The Water Resources Board has proposed five alternative schemes for developing 3 Mgal/d from existing supply wells and from wells at other tested sites. The impacts of the five development schemes on ground-water levels and on streamflow were evaluated by a digital model of the Chipuxet ground-water reservoir. The sites evaluated include Wolf Rocks Trail, the University of Rhode Island Well field at Thirty Acre Pond, a site on the west side of Thirty Acre Pond, the Kingston Fire District well field, and a site adjacent to a potato field at Liberty Lane.

Simulated pumping from the model indicates that all schemes for withdrawing 3 Mgal/d will cause relatively insignificant lowering of ground-water levels. Maximum drawdowns are caused by a scheme that concentrates withdrawals at the Thirty Acre Pond and Kingston Fire District well fields. For this scheme, drawdowns will be less than 3 feet beyond a distance of about 900 feet from the pumping center at Thirty Acre Pond.

Model simulations also show that all five pumping schemes will deplete the flow of the Chipuxet River by an amount about equal to the pumping rate soon after pumping begins. More than 3 Mgal/d can be pumped for export most of the time without causing streamflow to cease. However, during low-flow periods the withdrawal rate would have to be reduced if some flow is to be maintained in the Chipuxet River at all times.

Of the five sites tested in the proposed development schemes, two have water-quality problems. Two of three supply wells in the University of Rhode Island well field at Thirty Acre Pond have yielded water containing manganese in concentrations that exceed the maximum concentration of 0.2 mg/L recommended by the Rhode Island Department of Health. Water pumped from test wells at the Liberty Lane site contained excessive concentrations of nitrate nitrogen.

Elevated concentrations of manganese in the well water at Thirty Acre Pond is attributed to infiltration of streamflow through organic sediments on the bottom of the pond and river. Changes in the physical-chemical character of the infiltrating water cause it to dissolve manganese from organic sediments and (or) aquifer materials.

A study of the problem at this site indicates that excessive concentrations of manganese in well water may be partly controlled by regulating pumping so as to minimize the percentage of induced recharge reaching well intakes. At Thirty Acre Pond this means pumping the wells at rates far less than is potentially obtainable from them. Digital model analysis shows that the entire 3 Mgal/d yield sought by the Water Resources Board could be obtained from this well field. Withdrawal at this rate, however, would likely cause water from all of the wells to have elevated levels of manganese.

In general, those schemes that spread withdrawals of 3 Mgal/d over a large area will result in the least amount of induced recharge and, presumably, will minimize manganese contamination of well water. Other ways of avoiding manganese contamination of well water include locating wells as far as possible from sources of infiltration, or, where this is not feasible, locating them adjacent to surface-water bodies not lined with organic-rich sediment.

Test wells in the Liberty Lane area contained nitrate in concentrations that were substantially above background levels and that locally exceeded the mandatory contaminant level of 10 mg/L established for drinking water by the U.S. Environmental Protection Agency (1976). The source of the nitrate seems to be nitrate fertilizers that have been applied to an adjacent potato field. A nitrate level of 28 mg/L was measured in a shallow well drilled in the potato field. Continued application of nitrate fertilizers to the potato field at the same rate will continue to keep nitrate levels high in ground water at this site.

The chemical quality of surface water and ground water in most of the study area is generally good. The concentration of dissolved solids in both is commonly less than 100 mg/L, and few chemical constituents are present in concentrations that would impair the use of the water for drinking or most other purposes.

Much of the area overlying the stratifed-drift aquifer is agricultural land that is used for growing turf, potatoes, and other vegetables. Because leaching of nitrate fertilizers applied to this land is locally known to have resulted in increased concentrations of nitrate in ground water, it is possible that nitrate contamination is much more common than data presented herein indicate.

The high permeability of this water-table aquifer makes it highly susceptible to contamination. If ground-water quality is to be maintained at a level suitable for drinking and other uses, some form of land-use control may have to be implemented in areas of recharge.

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