Availability of Ground Water in the Lower Pawcatuck River Basin, Rhode Island

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AVAILABILITY OF GROUND WATER IN THE LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND

By JOSEPH B. GONTHIER, H. E. JOHNSTON, and G. T. MALMBERG

ABSTRACT

The lower Pawcatuck River basin in southwestern Rhode Island is an area of about 169 square miles underlain by crystalline bedrock over which lies a relatively thin mantle of glacial till and stratified drift. Stratified drift, consisting dominantly of sand and gravel, occurs in irregularly shaped linear deposits that are generally less than a mile wide and less than 125 feet thick; these deposits are found along the Pawcatuck River, its tributaries, and abandoned preglacial channels. Deposits of stratified sand and gravel constitute the principal aquifer in the lower Pawcatuck basin and the only one capable of sustaining yields of 100 gallons per minute or more to individual wells.

Water available for development in this aquifer consists of water in storage—potential ground-water runoff to streams—plus infiltration that can be induced from streams. Minimum annual ground-water runoff from the sand and gravel aquifer is calculated to be at least 1.17 cubic feet per second per square mile, or 0.76 million gallons per day per square mile. Potential recharge by induced infiltration is estimated to range from about 250 to 600 gallons per day per linear foot of streambed for the principal streams. In most areas, induced infiltration from streams constitutes the major source of water potentially available for development by wells.

Because subsurface hydraulic connection in the sand and gravel aquifer is poor in several places, the deposits are conveniently divisible into several ground-water reservoirs. The potential yield from five of the most promising ground-water reservoirs is evaluated by means of mathematical models. Results indicate that continuous withdrawals ranging from 1.3 to 10.3 million gallons per day, and totaling 31 million gallons per day, are obtainable from these reservoirs. Larger yields may be recovered by different well placement, spacing, construction and development, pumping practice, and so forth.

Withdrawals at the rates indicated will reduce streamflow downstream from pumping centers but generally will not result in streams going dry, provided the water is returned to the basin. Export of water from the basin

will require careful consideration of the effects of such withdrawals on low streamflow. Export from the Pawcatuck basin of 27 million gallons per day, estimated to be available from ground-water reservoirs in the upper Pawcatuck basin, in addition to 37.5 million gallons per day available in the lower Pawcatuck basin, will markedly reduce low streamflow. The 90-percent duration flow of the Pawcatuck River at Westerly would be reduced from 75 million gallons per day to perhaps as little as 21 million gallons per day.

The chemical quality of water from both the sand and gravel aquifer and associated streams is suitable for most purposes. The water is soft, slightly acidic, and typically has a dissolved-solids content of less than 75 milligrams per liter. Some treatment may be required locally for removal of iron and manganese to meet recommended standards of the U.S. Public Health Service for drinking water.

INTRODUCTION

Increasing water demand in Rhode Island will require eventual development of all major water resources and will require transfer of water from rural areas, where there is a water surplus, to more populous areas lacking adequate supplies. In anticipation of these requirements, the Rhode Island Water Resources Board and the U.S. Geological Survey are jointly supporting studies of individual drainage basins throughout the State to determine the potential yield of the major aquifers (identified by Lang, 1961). Because of the relatively small anticipated local demand for water in the Pawcatuck basin, the Rhode Island Water Resources Board is planning to export ground water to meet an expected increase in demand of several million gallons per day in the communities along Narragansett Bay to the east.

Ground-water resources in the lower Pawcatuck River basin are largely untapped. The only major pumping centers in the basin are those near the Pawcatuck River at Westerly and Bradford, which are owned by the town of Westerly. Pumpage in the basin in 1966 averaged approximately 5 mgd (million gallons per day), of which 4.25 mgd was from wells in the sand and gravel deposits and 0.75 mgd was from wells in till and bedrock. Nearly half (2.25 mgd) of the water pumped was used by the Westerly public-supply system; most of the remainder was used by self-supplied industries for processing, cooling, sanitation, and fire protection. Much of the pumped water was recycled in the basin as sewage and industrial effluent. It is estimated that public-supply requirements in the study area will be 8 mgd by the year 2020 (Metcalf & Eddy, 1967).

The purpose of this report is to estimate the potential availability of ground water in the lower Pawcatuck River basin, describe areas most favorable for installation of high-capacity wells and large-scale development, calculate a sustained rate of withdrawal for each of these areas, and describe the effect of ground-water pumpage on low streamflow.

To accomplish these objectives, it was necessary to (1) define the areal variation in thickness and water-transmitting capacity of the sand and gravel aquifer, (2) determine the minimum annual rate of ground-water recharge from precipitation, (3) ascertain the potential recharge from induced infiltration when the water table is lowered below the stream level, and (4) develop mathematical models simulating parts of the aquifer with the greatest potential for large-scale withdrawals. A brief review is presented of the data on chemical quality of water in the aquifers and in the streams that provide induced recharge to the aquifers under pumping conditions. Use of secondary aquifers will also help ease water problems—till will yield enough for domestic supplies and bedrock is capable of providing as much as 50 gpm (gallons per minute)—but these sources are not discussed in this report.

This report describes the 169 square-mile Rhode Island part of the Pawcatuck River basin from Kenyon (fig. 1) downstream to the stream-gaging station at Westerly. The principal tributaries, in downstream order, are the Beaver River, White Brook, Wood River, Tomaquag Brook, and Ashaway River.

The river valleys are underlain principally by sand and gravel of glaciofluvial origin and the intervening hills, 200–500 feet above mean sea level, by till and bedrock. In common with many stream valleys in southern New England, ancestral streams have cut deep valleys in the bedrock surface. During retreat of the last continental glacier, the prominent Charlestown moraine, a 100-foot high ridge of till and stratified drift, was deposited across these valleys; it now forms the drainage divide between the basin and Block Island Sound. North of the moraine, valleys cut in bedrock were filled with glaciofluvial deposits of sand and gravel that are locally more than 100 feet thick. The adjustment of the drainage to the terrain after the retreat of the glacier ultimately resulted in the modern Pawcatuck River system.

The glaciofluvial sand and gravel deposits are highly permeable and absorb precipitation readily. For this reason, these deposits are commonly saturated with water to within a few feet of the land surface. Much of the water in this material is available to wells, and, where local conditions are favorable, high-capacity

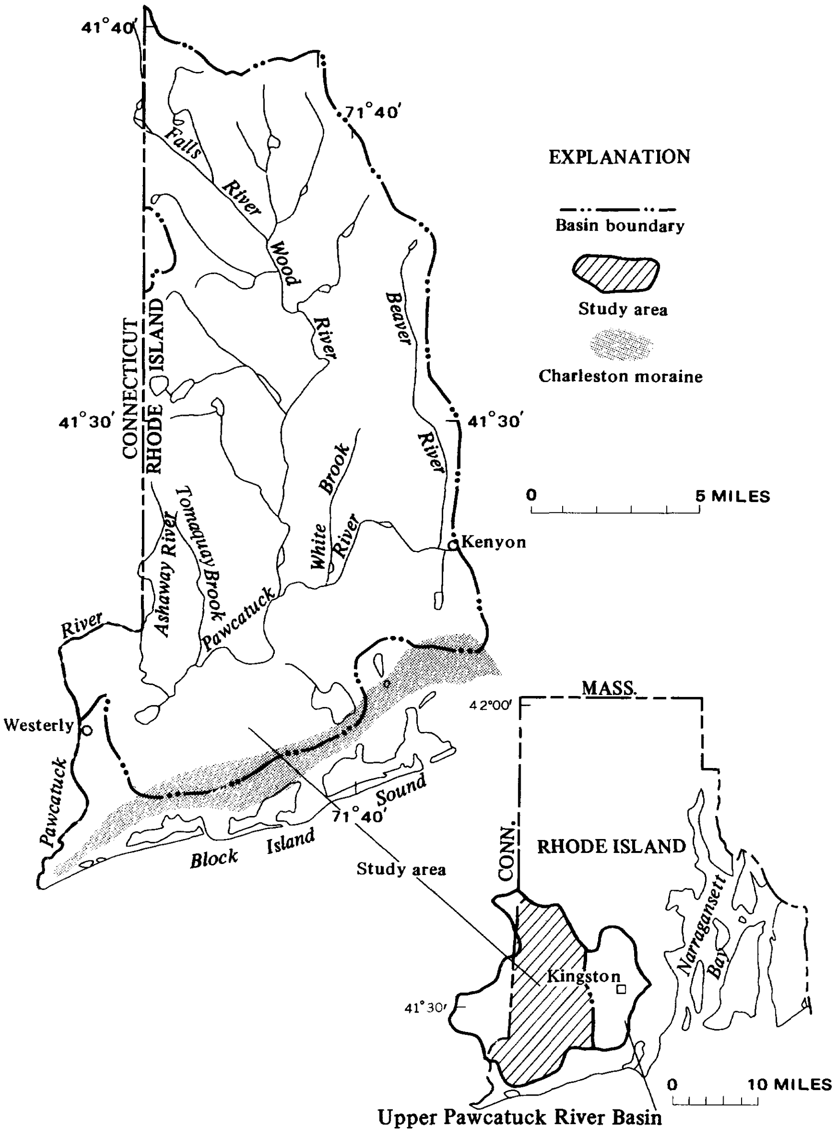


FIGURE 1.—Generalized drainage-basin map of the study area.

wells capable of pumping several hundred gallons per minute can be developed.

The critical aspects of ground-water availability from the major sand and gravel aquifer are the relatively small size of the aquifer and the relationship of aquifer yield to streamflow. It is shown that pumping wells may decrease streamflow and that decreasing streamflow may reduce the amount of water available for development by wells in some areas.

This report is based on original hydrologic investigations and inventory in 1966 and 1967, on descriptions of surficial geology by Feininger (1962, 1965), Kaye (1960), and Schafer (1965, 1968), and on reconnaissances of ground-water conditions by Bierschenk (1956), Bierschenk and Hahn (1959), Johnson, Mason, and DeLuca (1960), Johnson (1961a, 1961b), LaSala and Hahn (1960), LaSala and Johnson (1960), Mason and Hahn (1960), and Randall, Bierschenk, and Hahn (1960). Preliminary estimates of potential ground-water yield in the study area are given by Lang (subareas 13 and 14, 1961). Allen, Hahn, and Brackley (1966) estimated that 25 mgd of ground water is available in the upper Pawcatuck River basin.

Appreciation is expressed to the well drillers, private citizens, corporations, and engineering consultants who provided information and helpful discussion. Personnel of the Water and Sewer Division of the Westerly Department of Public Works, the Rhode Island Department of Natural Resources, and the Rhode Island Department of Public Works deserve special recognition for their cooperation.

THE HYDROLOGIC SYSTEM

The lower Pawcatuck River basin, Rhode Island, receives water from (1) precipitation and from (2) surface and subsurface inflow from the upper Pawcatuck River basin and parts of the lower Pawcatuck River basin in Connecticut. Subsurface inflow from the upper Pawcatuck basin, however, is negligible. The total inflow leaves (1) as surface outflow, (2) as subsurface outflow through valleys buried beneath the Charlestown moraine along the south edge of the study area and through the stream fill beneath the Pawcatuck River at Westerly, and (3) as evaporation and transpiration. Approximate values for inflow and outflow are indicated in table 1. A summary of annual precipitation and runoff for the entire Pawcatuck River basin is given in figure 2.

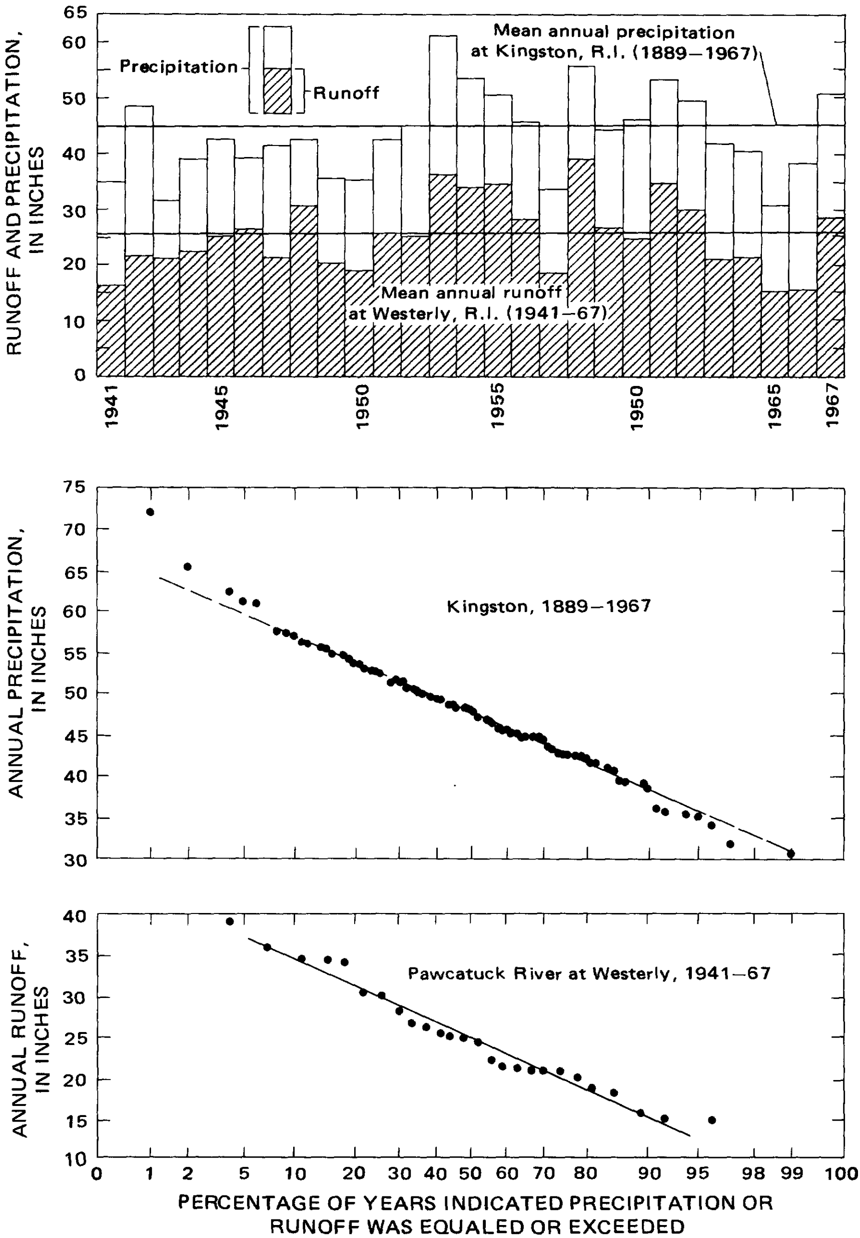


FIGURE 2.—Precipitation and runoff in the Pawcatuck River basin, Rhode Island.

TABLE 1.—*Approximate water budget for the lower Pawcatuck River basin, Rhode Island (1942–66)*

	Cubic feet per second	Millions of gallons per day
Inflow		
A. Precipitation[1]	525	339
B. Surface flow from upper Pawcatuck basin (72 mi^2)[2]	132	85
C. Surface flow from area of lower basin in Connecticut (54 mi^2)[3]	100	65
D. Subsurface flow from area of lower basin in Connecticut	3	2
Total	760	491
Outflow		
E. Surface flow at Westerly (from 295 mi^2)	548	354
F. Subsurface flow	10	6
G. Evaporation and transpiration [(A+B+C+D)−(D+E)]	202	131
Total	760	491

[1] Based on average precipitation of 41.73 in. at Kingston, R.I.
[2] Estimate based on average runoff of Pawcatuck River at Wood River Junction of 1.84 cfs per sq mi.
[3] Estimate based on average runoff of Pawcatuck River at Westerly of 1.86 cfs per sq mi.

THE MAJOR AQUIFER

Glacial outwash deposits of unconsolidated gravel, sand, silt, clay, and mixtures thereof fill depressions in the underlying till and bedrock and are saturated with water to within a few feet of the land surface. These deposits form the principal aquifer in the lower Pawcatuck River valley. This material accumulated in small highly irregular patches in deep valleys of ancient drainage channels and other depressions (pl. 1). The most extensive accumulation is at Ellis Flats near the junction of the Pawcatuck and Wood Rivers, where the deposits have an area of several square miles. Outcrops in most other areas are sinuous and usually less than a mile in width. Thickness of the outwash deposits varies abruptly within short distances. The thickest deposits occur along the axis of buried valleys, where accumulations of more than 100 feet have been measured (pl. 2).

More than 70 percent of the water received in the study area is from precipitation, the distribution of which is similar to that recorded at Kingston, 6 miles to the east in the upper Pawcatuck basin. Measurements at this location from 1889 to 1967 indicate that average precipitation was somewhat greater than during the 25-year period used to compute a water budget for the study area. During the longer period, precipitation averaged 45 inches, ranging from an average monthly low of 2.8 inches in July to an average monthly high of 4.6 inches in November.

Of the precipitation that replenishes the water resources of the study area directly, approximately half is returned to the atmosphere by evaporation and transpiration. Most of the remainder either (1) moves as overland runoff directly to streams, ponds, and swamps or (2) percolates to the water table and moves laterally toward surface-water bodies, where it is discharged as ground-water runoff. Five to 10 cfs (cubic feet per second), or 3 to 6 mgd, less than 2 percent of the precipitation, is estimated to discharge as subsurface outflow through buried valleys beneath the Charlestown moraine and through channel fill beneath the Pawcatuck River at Westerly. The areas through which subsurface flow occurs beneath the Charlestown moraine are those where the water table (pl. 3) immediately north of the surface drainage divide slopes southward.

Logs of many wells drilled in outwash deposits indicate a great variation in materials both laterally and vertically. The general lack of sharply defined stratification and lithologic changes prevents accurate projection of individual units over any significant distance. Because of vertical and horizontal differences in lithology, test drilling is usually required to determine the most favorable areas for installation of high-capacity wells. Data from well logs and geologic maps defining the character of aquifer materials, supplemented by hydraulic data from pumping tests, detail local differences in lithology and permeability. Where the outwash deposits have significant areal extent and depth, are composed predominantly of sand and gravel of moderate to high permeability, and are hydraulically connected to a stream, they form an aquifer suitable for the development of high-capacity wells. In most areas, streams are close enough to the aquifers to be connected to them, for present drainage follows preglacial and glacial drainage systems. The most suitable areas for development of ground water are along or near streams where the aquifer exceeds 50 feet in thickness.

Irregularities of the underlying till and bedrock surface isolate and segment the aquifer and retard movement of water from one area to another. Five areas along the Pawcatuck, Wood, Beaver, and Ashaway Rivers with the greatest potential for development of ground water are shown on plate 4.

WATER-BEARING CHARACTER

Water in the sand and gravel deposits occurs chiefly under unconfined, or water-table, conditions but locally is confined beneath beds of clay and silt. The areal distribution of confining beds is indicated on plate 4.

The saturated thickness of the aquifer, as shown on plate 2, is calculated as the difference in altitude between the bedrock surface, adjusted for the overlying layer of till, and the water table. Saturated thickness increases from the perimeter of the glaciofluvial deposits to more than 120 feet in the upper reaches of the Wood River basin near Ten Rod Road. It is more than 40 feet throughout much of the study area.

The capacity of an aquifer to transmit water is governed by its hydraulic conductivity and saturated thickness. The hydraulic conductivity of a porous material is a measure of the relative ease with which a fluid will pass through it under a given gradient. The term hydraulic conductivity replaces the field coefficient of permeability, introduced by Meinzer and Wenzel (1942, p. 7). If the porous medium is isotropic and the fluid is homogeneous, the medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path (Lohman and others, 1972). Hydraulic conductivity is commonly expressed in feet per day; it may also be expressed in gallons per day per square foot.

Transmissivity is the rate of transmission of water through a unit width of aquifer at the prevailing temperature and under a unit hydraulic gradient. In essence it is the product of hydraulic conductivity and the saturated thickness of the aquifer. Transmissivity is expressed in feet squared per day (ft^2 per day) or gallons per day per square foot; both units are given in this report.

The transmissivity of the sand and gravel aquifer in the lower Pawcatuck River basin is estimated from analyses of specific capacity and aquifer-test data (table 2) and from the lithologic logs of wells and test borings. Estimates of transmissivity based on lithologic logs are made by assigning values of hydraulic conductivity given below to materials described in logs.

Lines connecting points of equal transmissivity, based on these data, show the approximate areal variation of transmissivity (pl.

TABLE 2.—*Summary of transmissivity of the sand and gravel aquifer*

Well (for location see pl. 3)	Transmissivity: Squared feet per day	Transmissivity: Gallons per day per foot	Remarks
Cha 337	6,975	52,300	Computed from specific capacity, using drawdown adjusted for effects of partial penetration and well loss (Butler 1957. Walton 1962).
349	11,600	87,000	Do.
351	12,500	94,000	Do.
Hop 411	18,000	135,000	Do.
412	13,850	104,000	Computed from aquifer test, using Weeks method modified from Hantush (Weeks 1964).
Ric 325	6,400	48,000	Computed from specific capacity, using drawdown adjusted for effects of partial penetration and well loss (Butler 1957; Walton 1962).
Wes 255	21,350	160,000	Do.
256	21,950	164,000	Do.
525	40,000	300,000	Do.

4). Of course, the water-bearing character of the sand and gravel aquifer is not known at every location, so that the lines of equal transmissivity shown on plate 4 must be considered only as approximations.

Average hydraulic conductivity of aquifer materials in the Potowomut-Wickford area, Rhode Island (Rosenshein and others, 1968), are as follows.

Material	*Approximate hydraulic conductivity*: *Feet per day*	*Approximate hydraulic conductivity*: *Gallons per day per square foot*
Gravel	500	3,500
Sand and gravel	200	1,500
Sand	100	800
Fine sand	50	400

GROUND-WATER RECHARGE

Under natural conditions, the principal sand and gravel aquifer is recharged mainly by precipitation that percolates through overlying soils to the water table. Some recharge also is derived from subsurface inflow from adjacent areas of till-covered bedrock. The amount of recharge received from this source is not known, but it is probably only a small percentage of total recharge.

Natural recharge to the aquifer cannot be measured directly, but a partial measure is obtainable by evaluation of the ground-water runoff component of streamflow. Most of the recharge is eventually released to streams as ground-water runoff. Some of the recharge is discharged directly from the water table as ground-water evapotranspiration, and a small amount also is discharged from the aquifer as subsurface outflow. Although some of the water now lost to ground-water evapotranspiration and subsurface outflow is recoverable by wells, the amount that could be intercepted is not easily determined. For purposes of this report, estimates of ground-water recharge are based on evaluation of ground-water runoff, and this part of ground-water recharge is effectively the part available for development by wells.

Estimates of recharge to the sand and gravel aquifer are based on streamflow measurements made during August 1966 after a period of no precipitation and when the flow was composed almost entirely of ground-water runoff. From long-term streamflow records, it is estimated that the measured discharges represent flows that are equaled or exceeded 90–98 percent of the time at the respective measurement sites. Therfore, ground-water runoff was near minimum, and it may be concluded that annual average ground-water runoff, and consequently recharge, is at least equal to the measured discharges. Analysis of low-flow measurements at sites strategically located (fig. 3) indicate that the minimum annual ground-water runoff from sand and gravel deposits averages 1.17 cfs per sq mi, or 0.76 mgd per sq mi (table 3).

INDUCED INFILTRATION

When a well is pumped, the water table around the well declines in a shape somewhat like that of an inverted cone. If a well is near a stream hydraulically connected to the aquifer, expansion of the cone of depression to the stream in response to pumping will induce recharge from the stream. Thereafter, the cone develops asymmetrically, and the hydraulic gradient between the stream and well becomes steep in comparison to the gradient on the opposite side of the well. All other things remaining equal, flow toward the well will increase in proportion to the hydraulic gradient. When pumping starts, all pumpage is derived from storage. At this stage natural ground-water flow toward the river

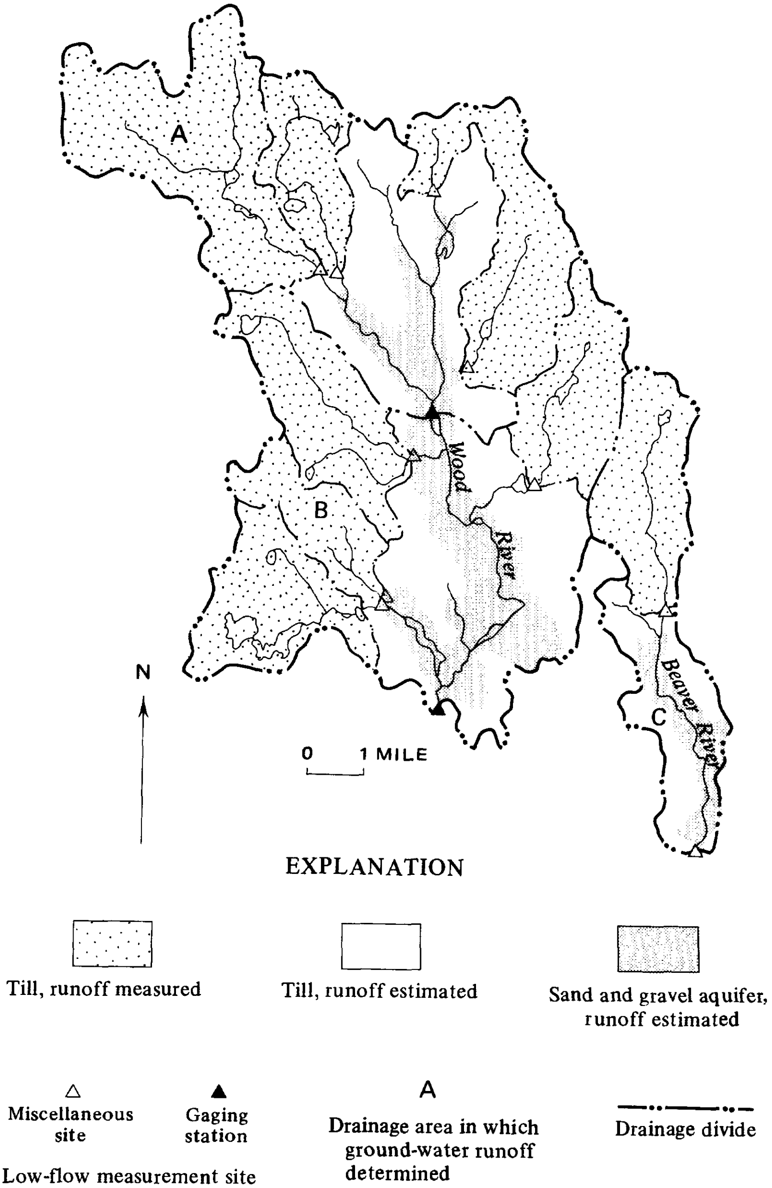


FIGURE 3.—Low-flow measurement sites in the Wood and Beaver River basins.

is intercepted by the cone of depression and is diverted toward the pumping well. When the cone of depression reaches the streams, however, the natural gradient is reversed and induced infiltration from the stream begins to supply a small part of the pumpage. As pumping continues, infiltration from the stream increases under the drive of hydraulic pressure, and eventually practically all the pumpage may be derived from the stream. Capability of ground water to sustain a large continuous demand, therefore, may be directly dependent on the low flow of the stream.

In areas that satisfy prerequisites for inducing recharge, the amount of streamflow that can be induced to recharge an aquifer is governed by the hydraulic characteristics of the aquifer, the amount of water that will leak through the streambed, the number, spacing, and location of wells, and the rate of ground-water withdrawal.

TABLE 3.—*Ground-water runoff from glacial deposits in the Wood and Beaver River basins, August 1966*

	Drainage area above Wood River gage near Arcadia	Drainage area of Wood River between gages near Arcadia and Hope Valley	Drainage area of Beaver River above miscellaneous measurement site at Shannock Hill Road
A. Date of measurements	8-2-66	8-2, 3-66	8-29-66
B. Area of till from which ground-water runoff measured ... sq mi	23.5	22.3	5.53
C. Ground-water runoff from B ... cfs	3.96	2.97	1.10
D. Ground-water runoff per unit area from till, C/B ... cfs per sq mi	0.17 (2.3 in.)	0.13 (1.8 in.)	0.20 (2.7 in.)
E. Area of till from which ground-water runoff estimated ... sq mi	8.5	7.9	3.45
F. Ground-water runoff from E=D×E ... cfs	1.45	1.03	0.70
G. Ground-water runoff from total area of till=C+F ... cfs	5.41	4.00	1.80
H. Total drainage area ... sq mi	35.2	37.2	11.2
I. Ground-water runoff from H ... cfs	[1]10.20	[1]11.80	3.77
J. Area of sand and gravel aquifer from which ground-water runoff estimated ... sq mi	3.2	7.0	2.2
K. Ground-water runoff from J=I-G ... cfs	4.79	7.80	1.97
L. Ground-water runoff per unit area from sand and gravel aquifer, K/J ... cfs per sq mi	1.50 (20.4 in.)	1.10 (14.9 in.)	.90 (12.2 in.)

[1] Estimated from hydrograph separation.

The amount of water that will seep through the streambed is governed by the vertical hydraulic conductivity and thickness of the streambed, the area of streambed through which infiltration occurs, the viscosity of the infiltrating water (viscosity is temperature dependent), and the head difference between the stream and the local water table. The physical factors involved are illus-

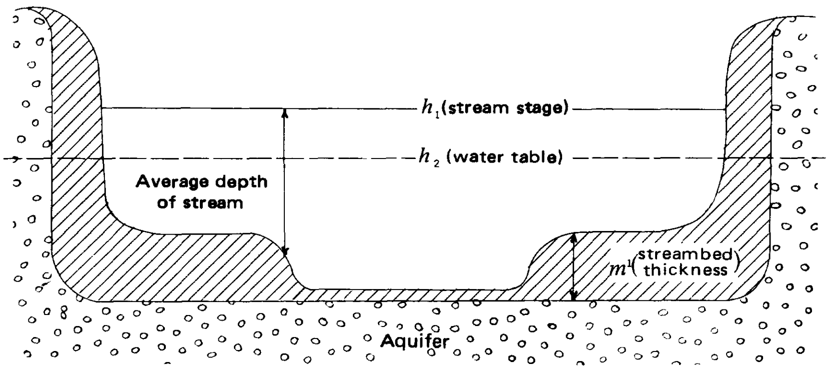


FIGURE 4.—Idealized diagram showing factors affecting streambed infiltration. Streambed infiltration (Q_1) = $\frac{K'IA}{m'}$; K' = vertical hydraulic conductivity of streambed, I = vertical hydraulic gradient ($\frac{h_1-h_2}{m'}$), and A = area of infiltration.

trated in figure 4. The change in viscosity produced by temperature ranges of about 20°C, typical of streams in the study area, will cause infiltration rates to vary as much as 50 percent. The effect of temperature change on infiltration rates is illustrated in figure 5.

Streambeds throughout most of the study area are composed of sand and gravel. Hydraulic connection between the aquifer and stream is probably good in areas where the underlying aquifer consists of similar materials. Furthermore, because most areas favorable for large-scale development of ground water are within a few hundred feet of a stream, a large fraction of the water pumped from high-capacity wells in the lower Pawcatuck River basin will be derived from streamflow.

The character of the streambeds of the Wood and Pawcatuck Rivers during a period of low flow was determined by probing and sampling. In backwater reaches where stream velocity is low, bottom sediments consist of a mixture of loose silt, sand, and organic muck ranging from a few hundredths of a foot to several feet thick. In most stream reaches, however, the central parts of streambeds are composed of loose sand and gravel, and accumulations of silty organic muck are present only along the edges of the stream channel (fig. 6). The vertical hydraulic conductivity of streambed sediments was determined at 13 sites on the Wood and Pawcatuck Rivers with a variable-head permeameter. The thickness of streambed penetrated ranged from 0.5 to 3 feet and averaged about 1 foot. In many places, the streambed is indistinguishable from the underlying aquifer. Values of vertical hydraulic conductivity (adjusted to 15.6°C or 60°F) obtained for fine-grained sediments near stream banks and in backwater areas typically were in the range of 0.1 to 0.7 feet per day (1 to 5 gpd per sq ft). Those for coarse-grained sediments typically were in the range of 0.7 to 2.7 (5 to 20 gpd per sq ft), but were as high as 70 feet per day (525 gpd per sq ft).

For the purpose of estimating potential induced infiltration through streambeds in the study area, average vertical hydraulic gradients of 0.1 and 1.3 feet per day (1 and 10 gpd per sq ft) were assumed for fine-grained and coarse-grained streambed materials,

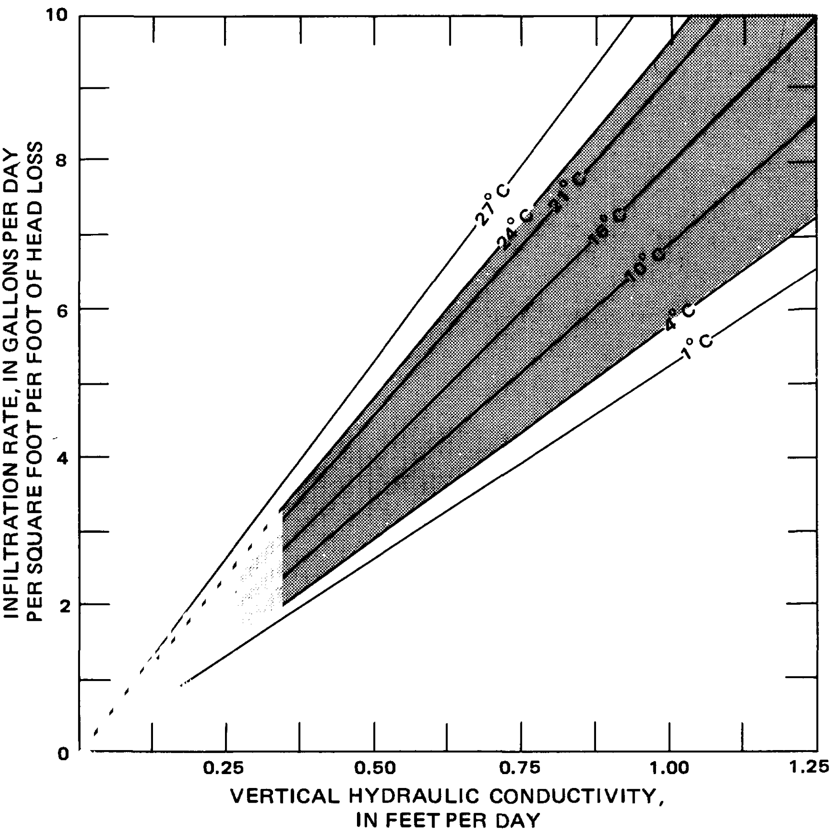


FIGURE 5.—Effect of water temperatures typical of streams in study area on streambed infiltration rates.

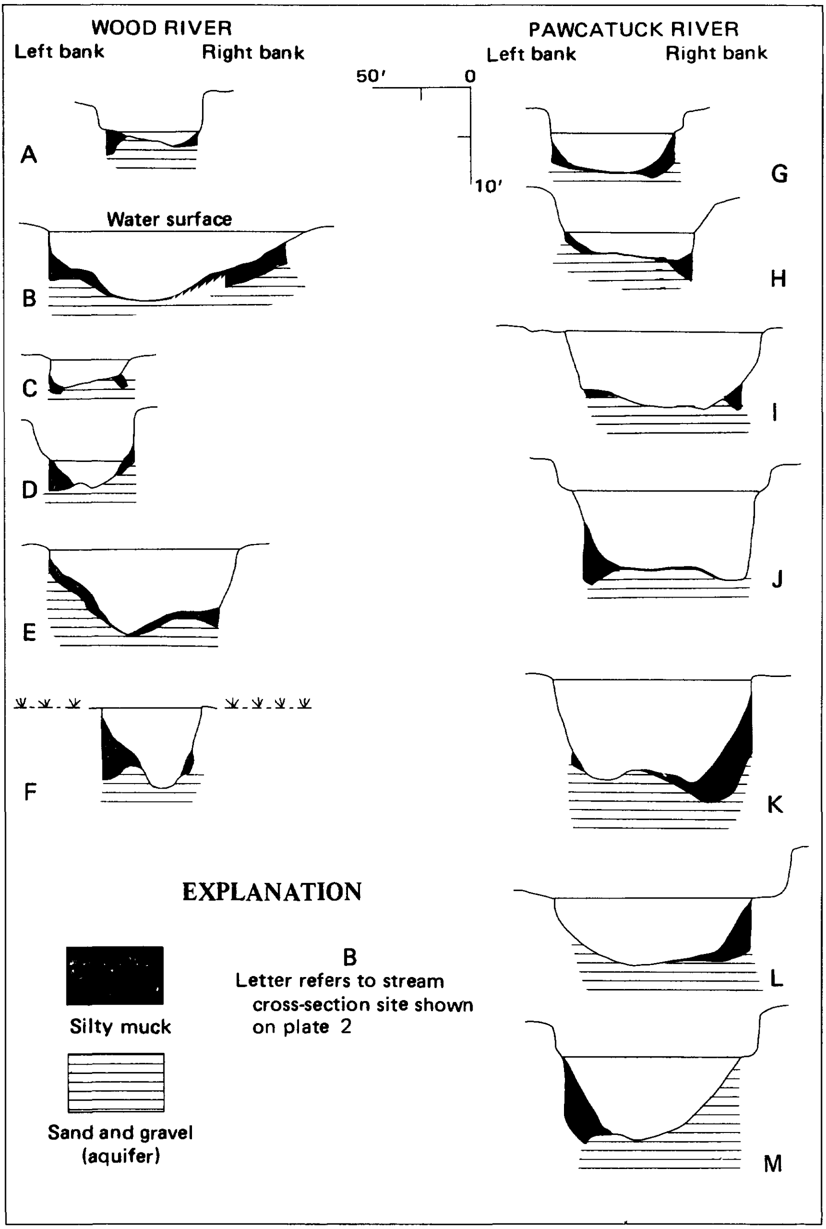


FIGURE 6.—Selected cross-sections of the Wood and Pawcatuck Rivers.

respectively. These values were assigned to descriptions of bottom sediments recorded at 5 to 10 foot intervals across each of the stream sections shown in figure 6 and were multiplied by the water depth at these intervals. A weighted value of potential infiltration per linear foot of stream was obtained at each site for infiltration through the full thickness of the streambed, that is, when the water table is lowered to the bottom of the stream. Based on these determinations, it is estimated that potential infiltration through the bed of the Wood River is at least 250 gpd per linear foot upstream from the stream gage near Arcadia to the Kent County line and at least 500 gpd per linear foot downstream from the gage to the Pawcatuck River. Potential infiltration through the bed of the Pawcatuck River is estimated to be at least 600 gpd per linear foot. These values are used to estimate potential recharge from stream infiltration in areas considered favorable for large-scale development of ground water. (See table 4, col. 6.)

FACTORS AFFECTING YIELD

Many complexly interrelated factors affect the yield obtainable from the sand and gravel aquifer in the lower Pawcatuck basin. The physical factors of principal importance, however, are the amount of water available without "mining" the resource, the water transmitting properties of the aquifer and streambed sediments, and the scheme of development.

Where the ground-water reservoirs are of small volume, the amount of water available for continuous development is governed largely either by the amount of infiltration that can be induced into them from streams or by the amount of streamflow into them during droughts, whichever is least. Infiltration capacity is a principal limiting factor in downstream areas, as along the lower reaches of the Pawcatuck River, where low streamflow commonly exceeds the rate at which it can be induced into the aquifer. Stream inflow during periods of low flow is a principal limiting factor in headwater areas.

Where ground-water reservoirs are of moderate to large size, as in the Wood River basin (areas B and C, pl. 4), water available for continuous development is significantly affected by the storage capacity of the reservoirs. As with a surface reservoir, storage affects the rate of withdrawal that can be maintained during periods of below average recharge (or inflow).

Assuming that 20 percent of the volume of the sand and gravel aquifer is occupied by water that will drain to wells, a value typical of most aquifers of this type, lowering ground-water levels by pumping will result in recovery of about 42 million gallons per square mile for each foot the water table is lowered. In ground-water reservoir B cited above, for example, the area of sand and gravel aquifer is about 7 square miles. Lowering the ground-water levels an average of 10 feet in this reservoir by pumping will result in recovery of nearly 3 billion gallons, enough to support a continuous withdrawal of 16 mgd for 6 months.

The main drawback, however, to effective utilization of ground-water-reservoir storage is that it may greatly alter the low-flow regimen of streams within the reservoir area and upstream from points of return flow. In ground-water reservoir B, which is in the upper part of the Wood River basin, lowering ground-water levels an average of 10 feet below normal summer and fall levels would result in little or no streamflow within the reservoir area for extended periods of time.

The water transmitting properties of the aquifer and streambed sediments limit the rate at which streamflow can leak into the aquifer and move to wells. Because much of the water potentially available for development consists of influent seepage from streams, these properties impose limits on ground-water yield, particularly in those small reservoirs that are traversed by streams of high average flow.

The yield obtained from a ground-water reservoir will depend in large part also on the scheme of development. Different patterns of well placement, number of wells, penetration, efficacy of well construction and development, and pumping regimens will result in different yields. In most areas, maximum yield is obtainable from wells placed close to and alined parallel to streams. Well fields designed in this fashion will intercept most of the potential ground-water runoff and will induce maximum infiltration from streams.

In addition to physical factors imposed by nature and those related to engineering skill in development, political, legal, and economic considerations may be of prime importance in governing yield; however, analysis of these administrative problems is beyond the scope of this report.

In the following section, estimates of potential reservoir yield are given for hypothetical schemes of development in five principal ground-water reservoirs in the study area. Only the physical factors affecting aquifer yield are modeled.

MATHEMATICAL MODELS

Hydrologic conditions in at least five areas (pl. 4) in the lower Pawcatuck River basin are favorable for moderate to large-scale development of water from the sand and gravel aquifer. Hydraulic connection between these five areas is poor, and, therefore, in the following analyses they are considered as separate ground-water reservoirs.

To test the feasibility of developing part or all of the water estimated to be available for development, parts of the aquifer in each ground-water reservoir are simplified into geometric models. Using schemes of hypothetical production wells, together with image wells simulating the effects of hydrologic boundaries, the potential yield of each production well is determined by means of mathematical analysis. Estimates of ground water available for development and results of mathematical analyses are summarized in table 4.

Water potentially available for development in each of the five areas is assumed to be equivalent to (1) ground-water runoff from the sand and gravel aquifer plus (2) streamflow into the ground-water reservoir equaled or exceeded about 90 percent of the time, or, the potential recharge from induced infiltration of streamflow, whichever is smallest. All pumped water is assumed to be returned to the basin downstream from the ground-water reservoir of origin. Return of the pumped water to the ground-water reservoir by well injection or infiltration from settling ponds, septic tanks, or other means may increase the potential supply at the expense of reducing the chemical quality of the water. No attempt is made in the model analysis to establish a network of wells to intercept all ground-water runoff and maximize induced infiltration. To do so would require many wells unevenly spaced and pumped at different rates. Only the most favorable areas for developing high-capacity wells in each ground-water reservoir are modeled, and the effects of pumping from these areas are based on a reasonable number of wells and practical pumping rates. (See pl. 5 and tables 5–8.)

The lack of historical data on the response of the water table to pumping prevents verification of the models; therefore, the models are designed to give a conservative estimate of the potential sustained pumping rate. Linear model boundaries are used to simulate either the barrier effects of the irregular and relatively impermeable till and bedrock along the valley walls or the recharge

TABLE 4.—*Availability of water for development and pumping potential for selected areas in the lower Pawcatuck River basin*

Ground-water reservoir (for location, see pl. 4) (1)	Area of sand and gravel aquifer (sq mi) (2)	Ground-water runoff from sand and gravel aquifer[1] (mgd) (3)	Surface-water inflow to aquifer area exceeded approximately 90 percent of the time (mgd) (4)	Length of principal streams in aquifer area (ft) (5)	Potential recharge by induced infiltration[2] (mgd) (6)	Total water available for development (cols. 3 + 4 or cols. 3 + 6, whichever is least) (mgd) (7)	Pumping potential indicated by model analysis (8): Model No. on pl. 4	Pumping potential indicated by model analysis (8): Pumping rate (mgd)
A	4.2	3.2	21	8,000	4.8	8	1	1.3
							2	4.9
B	7.0	5.3	9	[3]24,000	6	14	3	5.2
				[4]30,000	15		4	4.4
C	7.2	5.5	52	[4]26,000	13	24	5	3.6
				[5]9,000	5.4			
D	4 5	3.4	59	27,000	16.2	20	6	1.3
E	[6]2.8	2.1	69	17,000	11.2	13	7	4.6
							8	2.4
							9	3.3

[1] Based on ground-water runoff rate of 0.76 mgd per square mile determined from table 3.
[2] Assumes water table is lowered to bottom of stream throughout entire reach.
[3] Wood and Fall Rivers above stream gage near Arcadia.
[4] Wood River below stream gage near Arcadia.
[5] Pawcatuck River.
[6] Does not include area in Connecticut.

effects of infiltration from meandering streams. Barrier boundaries are placed somewhat closer than their true positions are thought to be. Recharge boundaries are placed somewhat farther than actual distances from pumped wells to sources of recharge. For a given rate of pumping, drawdown is increased by barrier boundaries and decreased by recharge boundaries. Drawdown in a pumping well reflects the effects of recharge and barrier boundaries and other pumping wells. Image wells are used to simulate the effects of the boundaries. The drawdown at each pumping well caused by image wells and other real or hypothetical pumping wells is determined from the distance versus drawdown relationships for the weighted average transmissivity, coefficient of storage, pumping time, and pumping rate applied to each model. The physical description of each model and the relationship between distance and drawdown is given in the following section of this report and on plate 5.

In three areas (model 4 in area B, and models 8 and 9 in area E, pl. 5) the long dimension of the ground-water reservoir, parallel to the axis of the valley, is modeled as though it were bounded only by a single barrier boundary. It is assumed that the recharge-boundary effect of stream infiltration is cancelled by the barrier-boundary effect of the opposite valley walls, even though the recharge boundary is dominant. This assumption builds additional conservatism into the models, facilitates mathematical computation, and is consistent with the methods applied to these models in order to estimate drawdowns. On the side of the model where it is assumed that the recharge boundary cancels the barrier-boundary, the model is constructed as though the aquifer is unbounded.

A 200-day pumping period, during which pumpage is sustained from model storage or from a combination of storage and continuous recharge from a line source, is used in the model analyses. This period corresponds approximately to the growing season (about 180 days) when, in fact, pumpage from wells in the study area is sustained largely from ground-water reservoir storage and induced infiltration from streams. Most of the direct precipitation recharge to ground-water reservoirs occurs during the nongrowing season. It is assumed that computed pumping rates can be sustained indefinitely, provided they do not exceed the limits of availability established in table 4.

Transmissivity of the model aquifer is a weighted average value determined from plate 4. Specific yield of the aquifer in each area is assumed to be 0.20. Hypothetical wells are assumed to be screened in the lower half of the aquifer and to have an effective radius of 1 foot. Data obtained from the mathematical models are summarized in tables 5–8.

Estimates of sustained pumping rates obtained by model analysis are judged to be reasonable, but as results are not verified, they must be considered only rough approximations. The location of wells in the models are selected in part for ease in computation and are not necessarily the best location for production wells. In general, the most advantageous placement of production wells is in aquifer materials of highest transmissivity and in areas close to streams. To obtain the water indicated available by the model analysis more or fewer wells may be required than used in the scheme modeled.

A procedure for estimating potential well yield and approximating drawdown at any site in the aquifer is given on plate 4.

PAWCATUCK–BEAVER RIVER VALLEYS NEAR KENYON (GROUND-WATER RESERVOIR A)

The ground-water reservoir in the Beaver River basin south of Hillsdale and in the vicinity of the Pawcatuck River north of Pasquiset Pond covers an area of 4.2 square miles. Within this area, saturated sand and gravel in the bedrock valley of the ancestral Beaver River is about 40 feet thick; near Kenyon it is about 90 feet thick. The ground-water reservoir is approximately 7 miles long and 2,000 to 3,000 feet wide. Transmissivity is about 5,300 ft^2 per day (40,000 gpd per ft) in much of the area, but near Kenyon it increases to about 12,000 ft^2 per day (90,000 gpd per ft). The total quantity of water available on a continuous basis is estimated to be 8 mgd (table 4). Approximately 3.2 mgd of the total supply estimated to be available is from ground-water runoff to the Beaver and Pawcatuck Rivers, and the remaining 4.8 mgd is potentially available from seepage from the Beaver and Pawcatuck Rivers.

The thickest section of the ground-water reservoir is simplified into two models (models 1 and 2 on pl. 4), each designed to simulate withdrawals from storage under conditions of continuous recharge from the Pawcatuck River. Mathematical models (models 1 and 2, pl. 5) of the ground-water reservoir indicate that a continuous yield of 1.3 mgd can be developed from three wells, each pumping 305 gpm along a 9,000 foot reach of the Beaver River, and that a continuous yield of 4.9 mgd can be developed from an array of nine wells, each pumping 380 gpm from the area between the Pawcatuck River and Pasquiset Pond (table 5).

TABLE 5.—*Summary of data obtained from mathematical models in the sand and gravel aquifer in ground-water reservoir A (Beaver River and Pawcatuck River valleys near Kenyon)*

[Data are given in feet. Effective radius of wells, 1 ft; screen length, 50 percent of saturated thickness of aquifer at well; pumping period, 200 days]

		Drawdown due to						
Hypothetical pumping well	Saturated thickness of aquifer at well	Pumping the well	Interference from image wells and other hypothetical wells	Dewatering	Partial penetration	Well loss	Total drawdown	Water level in well above or below (—) top of screen[1]
Model 1. Beaver River north of Kenyon								
[Weighted transmissivity (*T*) 6,700 ft² per day (50,000 gpd per ft); discharge, 305 gpm per well]								
A --	70	11 90	12.50	7.07	9.93	0.89	42.29	—7.29
B --	82	11.90	14.72	6.82	10.56	.89	44.89	—3 89
C --	90	11.90	9.14	3.29	7.68	.89	32.90	12.10
Total discharge ---915 gpm (1.3 mgd)								
Model 2. Pawcatuck River near Kenyon								
[Weighted transmissivity (*T*) 6,900 ft² per day (52,000 gpd per ft); discharge, 380 gpm per well.]								
A --	82	14.04	1.84	1.94	5.63	1.00	24.45	16.55
B --	82	14.04	2.90	2.25	6.06	1.00	26.26	14.74
C --	60	14.04	1.84	2.96	5.95	1.00	25.79	4.21
D --	85	14.04	17 74	10.54	13.37	1.00	56.69	—14.19
E --	90	14.04	15.79	7.91	11 92	1.00	50.67	5.67
F --	90	14.04	14.43	6.99	11.20	1.00	47.66	—2.66
G --	87	14.04	16.47	8.95	12 46	1.00	52.91	—9.41
H --	87	14.04	14 43	7.40	11.35	1.00	48.20	—4 70
I --	82	14.04	12.24	6.59	10.37	1.00	44.24	—3.24
Total discharge ---3,420 gpm (4.9 mgd)								

[1] To keep water level above screen in all wells while maintaining same total discharge, the pumping rate would have to be increased in some wells and decreased in others.

Continuous pumping at rates of 1.3 and 4.9 mgd from the areas represented by models 1 and 2 will reduce the natural low flow of both the Beaver and Pawcatuck Rivers. Upper reaches of the Beaver River may go dry near pumping centers during late summer and fall; lower reaches will have continuous flow except possibly for periods of a few days during protracted summer droughts. The 90-percent flow duration (about 23 mgd) of the Pawcatuck River below its confluence with the Beaver River will be reduced by about 25 percent.

WOOD RIVER VALLEY NORTH OF WYOMING (GROUND-WATER RESERVOIR B)

The sand and gravel aquifer forms a ground-water reservoir approximately 7 miles long and 4,000 to 5,000 feet wide between the village of Wyoming and Louttit Pond in the Wood River basin. The saturated thickness of the aquifer exceeds 40 feet throughout most of the central part of the reservoir and locally is as much as 125 feet. Transmissivity of the aquifer averages 5,300 ft^2 per day (40,000 gpd per ft), but in areas of maximum saturated thickness, transmissivity is as much as 11,300 ft^2 per day (85,000 gpd per ft).

The potential supply of water available for continuous development is estimated to be 14 mgd (table 4). This amount includes 5.3 mgd of ground-water runoff and 9 mgd of potential seepage from the Falls and Wood Rivers.

The ground-water reservoir is modeled in two parts (models 3 and 4 on pl. 4), one (model 3) to simulate withdrawals from ground-water storage under conditions of continuous recharge from the Wood River, the other (model 4) to simulate withdrawal from ground-water storage only. Model 4 is designed on the assumption that one side of the ground-water reservoir is bounded by an impermeable valley wall; the other sides of the reservoir model are left unbounded on the assumption that the barrier effect created by the other wall of the valley is canceled by the recharge from the river. Analysis of the models indicate that 5.2 mgd can be pumped continuously from four wells, each producing 900 gpm, in the northern part of the reservoir, and that an additional 4.4 mgd can be obtained from five wells, each pumping 610 gpm, in the southern part of the ground-water reservoir. Data obtained from the mathematical model are summarized in table 6.

Pumping the ground-water reservoir, as indicated in the models, will result in withdrawal of approximately 70 percent of the total water available for development. A substantial increase in pumping capacity will require a large number of additional wells in low productive areas of the ground-water reservoir. Withdrawal of 9.6 mgd of ground water will decrease the flow of the Wood River both by inducing infiltration from the river and by capturing potential ground-water runoff to the river. The streamflow of the Wood River that is exceeded 90 percent of the time under natural conditions will be reduced about 50 percent at Hope Valley if development and operation of the ground-water reservoir is done in a manner indicated in figure 7.

Construction of a proposed dam and reservoir on the Wood

River above the gaging station at Arcadia for streamflow regulation and public-supply use will change the downstream flow characteristics. Potential seepage losses affecting the availability of ground water in downstream well fields will have to be reevalu-

TABLE 6.—*Summary of data obtained from mathematical models in the sand and gravel aquifer in ground-water reservoir B (Wood River valley from Plain Road to Wyoming) and C (Wood River valley from Hope Valley to Wood River Junction)*

[Data are given in feet Effective radius of wells, 1 ft; screen length, 50 percent of saturated thickness of aquifer at well; pumping period, 200 days]

		Drawdown due to						
Hypothetical pumping well	Saturated thickness of aquifer at well	Pumping the well	Interference from image wells and other hypothetical wells[1]	Dewatering	Partial penetration	Well loss	Total drawdown	Water level in well above or below (—) top of screen[2]
Model 3. Wood River between Plain Road and Parris Brook								
[Weighted transmissivity (T) 7,350 ft² per dav (55,000 gpd per ft); discharge, 900 gpm per well]								
A --	95	31.50	+4.81	8.17	11.62	4.95	51.43	—3.93
B --	110	31.50	1.10	7.22	14.72	4.95	59.49	—4.49
C --	122	31.50	1.10	6.17	15.08	4.95	58.80	2.20
D --	125	31.50	+4.81	5.96	12.70	4.95	50.30	12.20
Total discharge								3,600 gpm (5.2 mgd)
Model 4. Wood River between Parris Brook and Wyoming								
[Weighted transmissivity (T) 6,700 ft² per day (50,000 gpd per ft); discharge, 610 gpm per well]								
A --	80	23.12	4.57	7.93	11.25	2.09	48.96	—8.96
B --	120	23.12	6.72	5.08	13.25	2.09	50.26	9.74
C --	110	23.12	7.10	5.95	13.04	2.09	51.31	3.69
D --	98	23.12	6.72	6.89	12.24	2.09	51.06	—2.06
E --	90	23.12	4.57	6.49	10.80	2.09	47.07	—2.07
Total discharge								3,050 gpm (4.4 mgd)
Model 5. Ellis Flats								
[Weighted transmissivity (T) 8,760 ft² per day (65,000 gpd per ft); discharge, 275 gpm per well]								
A --	70	8.11	7.68	2.35	5.73	0.67	24.54	10.46
B --	70	8.11	13.89	5.34	8.63	.67	36.64	—1.46
C --	62	8.11	15.43	8.04	9.98	.67	42.23	—11.23
D --	58	8.11	16.43	10.71	11.13	.67	47.05	—18.05
E --	58	8.11	16.74	11.20	11.39	.67	48.11	—19.11
F --	70	8.11	15.88	6.75	9.70	.67	41.11	—6.11
G --	82	8.11	13.66	4.07	8.16	.67	34.67	6.33
H --	85	8.11	11.02	2.84	6.94	.67	29.58	12.92
I --	85	8 11	3.15	.86	3.84	.67	16.63	25.87
Total discharge								2,475 gpm (3.6 mgd)

[1] + indicates buildup due to recharging image wells.

[2] To keep water level above screen in all wells while maintaining same total discharge, the pumping rate would have to be increased in some wells and decreased in others.

ated when the operating procedure for the reservoir is established and the nature of streamflow below the dam is reestablished.

WOOD RIVER VALLEY SOUTH OF HOPE VALLEY (GROUND-WATER RESERVOIR C)

Near the confluence of the Wood River and Diamond Brook, the preglacial channel of the Wood River arcs southeast of the present course, beneath Ellis Flats, Wood River Junction, and Indian Cedar Swamp and emerges in Block Island Sound. That part of the buried valley between Hope Valley and Indian Cedar Swamp is shown as ground-water reservoir C on plate 4. The axis of the buried valley is indicated approximately by the zone of maximum saturated thickness on plate 2. Ground-water reservoir C is approximately 8 miles long and ranges from 2,000 to 5,000 feet in width.

Saturated thickness of the aquifer is 60 feet or more along most of the axis of the buried valley, and near Wood River Junction the saturated thickness is as much as 90 feet. Transmissivity of the aquifer is 8,000 ft^2 per day (60,000 gpd per ft) or more along the axis of the valley and is as high as 12,000 ft^2 per day (90,000 gpd per ft) in the thickest part of the reservoir.

Water potentially available to wells is estimated to be 24 mgd (table 4). Of this amount, 5.5 mgd is estimated to be available from ground-water runoff. Seepage from the Wood and Pawcatuck Rivers to a cone of depression established by pumping wells is estimated to be 18 mgd, consisting of about 13 mgd from the 5 mile reach of Wood River between Hope Valley and Alton and about 5 mgd from a 1.7 mile reach of the Pawcatuck River in the vicinity of Wood River Junction.

Over much of the distance between Hope Valley and the confluence of the Wood and Pawcatuck Rivers, the Wood River flows along the edge of the ground-water reservoir, where the saturated thickness of the aquifer is less than 40 feet. To develop maximum potential infiltration from this reach of the river will require infiltration galleries or many shallow closely spaced wells along the river.

Surface flow of the Wood River past the gaging station at Hope Valley is equal to or more than 22 mgd 90 percent of the time. There is additional inflow to the area of 30 mgd or more in the Pawcatuck River 90 percent of the time, or a total inflow of 52 mgd 90 percent of the time.

Part of the ground-water reservoir extending beneath Ellis Flats is modeled (model 5, pl. 4) to simulate withdrawals largely from aquifer storage but includes some infiltration from the Pawcatuck River. Withdrawals are simulated from a line of nine pumping wells, each pumping 275 gpm (mathematical model 5, pl. 5). Results of the simulated pumping (table 6) indicate that the aquifer area modeled can be pumped at a continuous rate of 3.6 mgd at the well spacing indicated. Pumping at the indicated rate is less than 20 percent of the amount estimated to be available from this ground-water reservoir. Pumping ground-water from upstream reservoirs will have no appreciable effect on the potential pumping capacity indicated in the model analysis because it can be sustained entirely by capture of potential ground-water runoff.

PAWCATUCK RIVER VALLEY NEAR BRADFORD (GROUND-WATER RESERVOIR D)

Sand and gravel deposits along the Pawcatuck River and in a buried bedrock valley south of Bradford form a ground-water reservoir about 4.5 square miles in area. The northern part of the ground-water reservoir along the Pawcatuck River is an irregularly shaped area that locally is as much as a mile wide. The Pawcatuck River winds its way across the north edge of the area and is in hydraulic continuity with the ground-water reservoir for about 5 miles.

Near the river, the saturated thickness of the aquifer is about 45 feet, and the coefficient of transmissivity is generally less than 6,000 ft^2 per day (45,000 gpd per ft). Because of the thin saturated section and moderate transmissivity in this part of the aquifer, development of a large supply of water will require a large number of shallow closely spaced wells pumped at low rates, collector wells, infiltration galleries, or other specialized techniques.

South of Bradford, the aquifer in a preglacial channel is about 3 miles long, half a mile wide, and locally has a saturated thickness of as much as 100 feet. Transmissivity of the saturated material in this part of the ground-water reservoir is estimated to be 10,700 ft^2 per day (80,000 gpd per ft). The greater saturated thickness and higher transmissivity of these deposits probably provide the best chance for development of substantial quantities of ground water with the fewest number of wells.

The total ground water available from the Pawcatuck River valley near Bradford is roughly estimated to be 20 mgd (table 4) based on a calculated value of 3.4 mgd ground-water runoff and 16.2 mgd potentially available from induced infiltration. Streamflow into the Bradford area is estimated to be 59 mgd 90 percent of the time, or more than three times the estimated potential infiltration rate.

The buried valley south of Bradford is selected for mathematical simulation because this part of the ground-water reservoir contains the maximum saturated thickness and has the highest coefficient of transmissivity. A model of the area south of Bradford is designed to simulate pumping from a ground-water reservoir about a quarter of a mile wide and 1½ miles long, bounded on the east and west by barrier boundaries formed by relatively impermeable valley walls and on the north by a recharge boundary formed by the Pawcatuck River. The area includes the Bradford well field, which supplies part of the town of Westerly.

Ground-water withdrawals from the model are simulated by three hypothetical wells spaced about 2,000 feet apart, as shown in model 6 on plate 5. Results of model operation shown in table 7 indicate that a yield of 1.3 mgd can be sustained with this scheme of development.

TABLE 7.—*Summary of data obtained from mathematical models in the sand and gravel aquifer in ground-water reservoir D (Pawcatuck River valley near Bradford)*

[Data are given in feet. Effective radius of wells, 1 ft; screen length, 50 percent of saturated thickness of aquifer at well; pumping period, 200 days]

Hypothetical pumping well	Saturated thickness of aquifer at well	Drawdown due to					Total drawdown	Water level in well above or below (—) top screen [1]
		Pumping the well	Interference from image wells and other hypothetical wells	Dewatering	Partial penetration	Well loss		
Model 6. Bradford well field								
[Weighted transmissivity (T) 7,350 ft² per day (65,000 gpd per ft); discharge, 310 gpm per well]								
A	65	11.07	9.07	4.78	7.87	0.61	33.40	—0.90
B	78	11.07	17 39	9.98	11.82	.61	49.87	—10.87
C	100	11.07	12.89	3.87	9 28	.61	37.72	12.28
Total discharge							930 gpm (1.3 mgd)	

[1] To keep water level above screen in all wells while maintaining same total discharge, pumping rate would have to be increased in some wells and decreased in others.

Development of 1.3 mgd will have no appreciable effect on the natural low flow of the Pawcatuck River, and development of upstream ground-water reservoirs will have little or no effect on the ground-water yield at Bradford.

PAWCATUCK–ASHAWAY RIVER VALLEYS NEAR ASHAWAY (GROUND-WATER RESERVOIR E)

Ground-water reservoir E (pl. 4) near Ashaway consists of 2.8 square miles underlain by sand and gravel capable of yielding large quantities of water. The sand and gravel fills a depression in the bedrock about 4 miles long and 2,000 to 3,000 feet wide. The saturated thickness is more than 80 feet at most places along the axis of the buried valley and locally reaches a thickness of more than 100 feet (pl. 2).

The transmissivity of the aquifer in the Ashaway River valley is about 6,900 ft^2 per day (52,000 gpd per ft) and in the Pawcatuck River valley ranges from about 6,700 to 9,600 ft^2 per day (50,000 to 72,000 gpd per ft). The potential supply of ground water is estimated to be 2 mgd from ground-water runoff and about 11 mgd from induced recharge, or a total of about 13 mgd (table 4). Ninety percent of the time, flow of the Pawcatuck and Ashaway Rivers entering the area is estimated to be 62 mgd and 7 mgd, respectively.

To illustrate potential ground-water yield, pumpage is simulated from arrays of hypothetical wells in three areas of the ground-water reservoir (models 7, 8, and 9, pl. 4). North of the confluence of the Ashaway and Pawcatuck Rivers a rectangular area (model 7) 7,500 ft long and 1,500 ft wide is modeled to simulate pumping from eight wells equally spaced and each pumping 395 gpm for a total of 4.6 mgd (table 8). The area modeled is bounded on the east by a barrier formed by the relatively impermeable valley walls and on the south by a recharge boundary formed by the Pawcatuck River. The boundaries on the north and west side of the model are left unbounded, on the assumption that the effects of recharge from the Ashaway River are offset by the barrier effects of the opposite valley wall. With the assumed array of wells, approximately 4.6 mgd can be pumped from the northern part of the ground-water reservoir.

Because most of the pumpage from the area represented by model 7 will be diverted from the Ashaway River, its natural low flow will be reduced considerably by ground-water withdrawals of 4.6 mgd. During drought, flow of the Ashaway River would probably cease in the vicinity of pumping centers.

TABLE 8.—*Summary of data obtained from mathematical models in the sand and gravel aquifer in ground-water reservoir E (Pawcatuck-Ashaway River valleys near Ashaway)*

[Data are given in feet. Effective radius of wells, 1 ft; screen length, 50 percent of saturated thickness of aquifer at well; pumping period, 200 days]

Hypothetical pumping well	Saturated thickness of aquifer at well	Drawdown due to: Pumping the well	Drawdown due to: Interference from image wells and other hypothetical wells	Drawdown due to: Dewatering	Drawdown due to: Partial penetration	Drawdown due to: Well loss	Total drawdown	Water level in well above or below (—) top of screen [1]
Model 7. Ashaway River near Ashaway								
[Weighted transmissivity (*T*) 6,900 ft² per day (52,000 gpd per ft); discharge, 395 gpm per well]								
A --	105	15.30	11.79	4.87	10 65	1.00	43.60	8.90
B --	100	15.30	15.62	7.31	12.74	1.00	51.97	—1.97
C --	82	15.30	17.29	12.27	14.17	1.00	60.03	—19.03
D --	85	15.30	18.06	12.22	14.39	1.00	60.98	—18.48
E --	90	15.30	17.04	9.93	13.35	1.00	56.62	—11.62
F --	103	15.30	14.25	6.21	11.92	1.00	48.68	2.82
G --	100	15.30	9.27	4.11	9.56	1.00	39.24	10.76
H --	70	15.30	3.87	3.75	7.24	1.00	31.16	3.84
Total discharge							3,160 gpm	(4.6 mgd)
Model 8. Pawcatuck River near Potter Hill								
[Weighted transmissivity (*T*) 6,700 ft² per day (50,000 gpd per ft); discharge, 415 gpm per well]								
A --	100	15.46	11.73	5.27	10.82	1.24	44.52	5.48
B --	102	15 46	15.20	6.93	12.53	1.24	51.36	— 36
C --	98	15.46	15.20	7.38	12.68	1.24	51.96	—2.96
D --	90	15.46	11.73	6.19	10.54	1.24	45.16	—.16
Total discharge							1,660 gpm	(2.4 mgd)
Model 9. Pawcatuck River southeast of Potter Hill								
[Weighted transmissivity (*T*) 9,600 ft² per day (72,000 gpd per ft); discharge, 330 gpm per well]								
A --	85	8.91	13.59	4.19	8.43	1.00	36.12	6.38
B --	85	8.91	16.08	5.46	9.61	1.00	41 06	1.44
C --	85	8.91	17.40	6.23	10.27	1.00	43.81	—1.31
D --	85	8.91	17.84	6.51	10.50	1.00	44.76	—2.26
E --	85	8.91	17.40	6.23	10.27	1.00	43.81	—1.31
F --	81	8.91	16 08	5.89	9.75	1.00	41.63	—1.13
G --	70	8.91	13.59	5.66	8.89	1.00	38.05	—3.05
Total discharge							2,310 gpm	(3.3 mgd)

[1] To keep water level above screen in all wells while maintaining same total discharge, the pumping rate would have to be increased in some wells and decreased in others.

On the east bank of the Pawcatuck River east and southeast of Potter Hill, two areas (pl. 4) are modeled to simulate pumping from a line of wells in a narrow strip of aquifer bounded on the east by the wall of the buried valley and unbounded on the other three sides.

A model of the northern part of this area is designed to simulate pumping each of four wells at 415 gpm, or 2.4 mgd (table 8), in a rectangular area 4,000 ft long and 1,000 ft wide.

The southern part of the ground-water reservoir is similarly modeled as a rectangular area 4,000 ft long and 1,500 ft wide, with an array of seven wells, each pumping 330 gpm, or 3.3 mgd (table 8). The combined withdrawal of about 6 mgd from these two areas is but a fraction of the flow in the Pawcatuck River during low flow. Low flow in the Pawcatuck River will be sufficient to supply infiltration to satisfy pumping of 6 mgd from the southern half of the ground-water reservoir, if all ground-water reservoirs are developed and pumped as indicated.

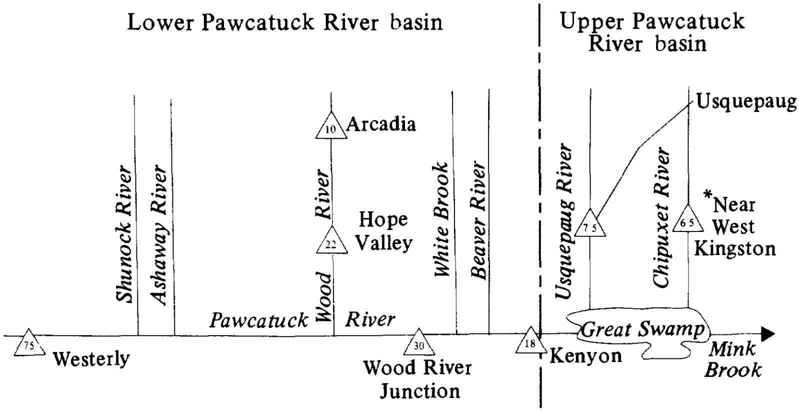
FUTURE GROUND-WATER DEVELOPMENT

Analysis of the models indicate that there is sufficient ground water available to meet the expected water requirements in the lower Pawcatuck River basin in the foreseeable future. The overall capacity of the hydrologic system will not be exceeded by pumping for local needs.

Large-scale development of one or more of the several ground-water reservoirs for local use or for export to communities on Narragansett Bay may deplete streamflow significantly in some reaches. If the pumped water is used locally and returned to the hydrologic system at or near its point of withdrawal, effect on streamflow will be minimized. Careful management will be required if the pumpage is exported from the basin or consumptively used within the basin, for the aquifer and the streams react as a unit to any change imposed on the system. Large diversions at any site along the river will reduce the low flow at downstream sites, and, if pumping greatly exceeds the rates indicated in the model analysis, the available water supply and dependable pumping rate at downstream sites will be reduced proportionally.

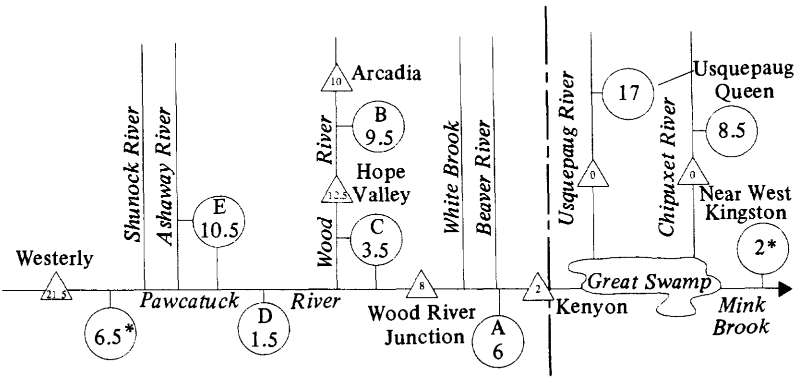
Figure 7A is a schematic diagram of the Pawcatuck River and its tributaries and shows the approximate natural flow equaled or exceeded 90 percent of the time at several gaging stations.

Figure 7*B* illustrates the effects of pumping the principal ground-water reservoirs at low flow, assuming all pumpage is consumptively used or exported from the Pawcatuck River basin.



*Estimated discharge of Chipuxet River, Chickasheen Brook, and White Horn Brook at downstream edge of Chipuxet Valley aquifer.

A



*Reported dependable yield

B

FIGURE 7.—Approximate flow of streams exceeded 90-percent of the time under natural conditions and ground-water development. *A*, Natural flow of streams that is exceeded 90 percent of the time. All figures are given to the nearest half million gallons per day. *B*, Approximate flow of streams exceeded 90 percent of the time if all the ground-water reservoirs are pumped at the rates indicated in the circles and the water is exported from the basin. All figures are given to the nearest half million gallons per day.

In the upper basin, potential ground-water yields of the Chipuxet and Usquepaug-Queen River valley reservoirs are based on model analyses by Allen, Hahn, and Brackley (1966). The yield in the

Mink Brook area is the reported dependable yield of the Wakefield Water Company well field. In the lower basin, potential ground-water yields are based on model analyses described in this report, except at Westerly, which is the reported dependable yield of the municipal well fields. All pumpage is assumed to be derived from ground-water runoff and induced infiltration, and the flow downstream from each ground-water reservoir is reduced accordingly. Part of the pumpage undoubtedly would be supplied from ground-water storage and salvage of natural discharge from evapotranspiration, and, therefore, streamflow at the gaging stations would probably be somewhat more than indicated. Pumping the ground-water yield of 25 mgd in the upper basin (Allen and others, 1966) will dry up the stream at the Usquepaug-Queen and Chipuxet gaging stations during low flow and will reduce flow entering the study area at Kenyon (fig. 7).

Despite the gross approximations used in calculating low flow, the values are highly significant because they indicate that there is sufficient water available in the lower basin to meet the sustained pumping capacity, indicated in the model analysis, 90 percent or more of the time, regardless of upstream development. Whether or not low flow is adequate to meet downstream surface-water requirements after such withdrawal of ground-water is attained is beyond the scope of this report.

Observation wells strategically located and complete records of pumping from ground-water reservoirs where large-scale development is planned would provide information required for construction and verification of analog or digital models. Such models would permit more accurate analysis of those ground-water reservoirs and better management of them.

CHEMICAL QUALITY OF WATER

Water in the sand and gravel aquifer and in streams that flow over it in the lower Pawcatuck basin is generally of chemical quality suitable for most purposes. Analyses of water samples from 11 wells and 12 streams provide a representative indication of the chemical character of the water likely in the study area (tables 9 and 10).

The ground-water samples had a dissolved-solids content that

TABLE 9.—*Chemical analyses*

Local well No. (see pl. 3 for site location)	Latitude (N.)	Longitude (W.)	Date of collection	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)
Cha 337	41°26'42"	71°37'47"	5–23–67	--	14.0	.03	.05
Exe 114	41°33'18"	71°42'32"	6– 1–67	9	5.6	.02	.04
Hop 411, 417[1]	41°23'54"	71°47'32"	5–23–67	--	13 0	.12	.04
Hop 418	41°31'36"	71°42'09"	6– 1–67	14	10.0	.06	.03
Hop 241	41°31'36"	71°42'09"	6– 1–67	12	6.6	.51	1.5
Ric 7	41°26'12"	71°43'14"	5–24–67	--	8.4	.06	.23
Ric 16	41°28'11"	71°40'12"	5–24–67	--	12.0	.03	.02
Ric 325	41°26'58"	71°41'46"	5–23–67	--	9.4	.06	.02
Wes 167–194[1]	41°23'38"	71°45'17"	5–29–67	9	4.6	.01	.04
Wes 525	41°23'36"	71°50'25"	5–29–67	9	8.8	.02	.03
Wgr 279	41°37'50"	71°46'00"	6– 1–67	--	15.0	.30	1.0

[1] Composite sample.

TABLE 10.—*Chemical analyses*

Stream (see pl. 3 for site location)	Latitude (N.)	Longitude (W.)	Date of collection	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)
Pawcatuck River at Kenyon.	41°26'43"	71°37'38"	10–17–67	15	7.6	0.58	0.08
Pasquiset Brook near Kenyon.	41°26'38"	71°37'39"	10–17–67	16	9.6	1.0	.09
Beaver River at Shannock Hill.	41°27'51"	71°37'42"	10–17–67	13	9.0	.35	.05
Pawcatuck River at Wood River Jct.	41°26'42"	71°40'53"	10–17–67	13	8.2	.58	.08
Pawcatuck River near Wood River Jct.	41°25'58"	71°41'40"	10–17–67	13	8.0	.54	.07
Cedar Swamp Brook near Wood River Jct	41°25'37"	71°41'44"	10–17–67	12	11.0	.82	.09
Wood River at Arcadia.	41°34'26"	71°43'16"	10–18–67	14	8.8	.30	.04
Wood River at Hope Valley.	41°29'58"	71 42'57"	10–18–67	14	8.0	.34	.05
Wood River at Alton.	41°26'16"	71°43'21"	10–18–67	13	7.4	.37	.04
Pawcatuck River at Burdickville.	41°24'58"	71°43'46"	10–17–67	14	7.9	.44	.06
Pawcatuck River tributary at White Rock.	41°23'46"	71°50'22"	10–16–67	9	9.9	.32	.04
Pawcatuck River at Westerly.	41°23'07"	71°50'00"	10–16–67	12	8.5	.45	.05

of ground water

Calcium (Ca)	Magnesium (Mn)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C)	Hardness as $CaCO_3$) Calcium magnesium	Non-carbonate	Specific conductance (micromhos at 25°C)	pH	Color
9.5	3.1	12.0	1.7	29	12.0	18.0	.2	2.3	94	36	12	143	6.8	4
4.8	.7	2.7	2.3	5	9.3	5.0	.2	4.4	41	15	11	70	6.4	2
6.8	2.0	6.0	1.5	16	17.0	6.2	.1	.8	62	25	12	90	6.7	2
3.8	1.1	4.5	1.5	10	7.3	5.0	.3	4 3	43	14	6	62	6.4	2
5.3	.2	4.3	.7	12	6.5	6.0	.1	.0	36	14	4	56	6.3	4
8.8	1 5	16.0	3.4	8	16.0	23.0	.1	14.3	100	28	22	102	6.2	2
4.1	1.0	4.6	.9	14	5.1	5.3	.1	.8	42	14	2	55	6.6	2
2.4	1.0	4.4	.6	10	4.1	5.1	.1	2.0	36	10	2	47	6 2	4
9.3	2.3	7.0	2.1	10	14.0	13.0	.1	12.0	74	32	24	122	6.3	2
6.5	1.6	12.0	1.2	21	1.3	13.0	.2	2.2	69	22	6	109	6.7	3
4.3	.4	3.4	1.4	16	5.7	3.2	.9	.0	41	12	0	51	6.7	4

of surface water

Calcium (Ca)	Magnesium (Mn)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180°C)	Hardness as $CaCO_3$ Calcium and magnesium	Noncarbonate	Specific conductance (micromhos at 25°C)	pH	Color
4.6	1.4	6.4	1.2	9	10.0	11.0	0.3	0.7	58	18	10	78	6.7	32
4.6	1.7	6.6	.9	12	9.3	12.0	.2	1.0	68	18	8	83	6.7	65
4.0	1.0	4.8	.8	8	7.9	8.8	.2	.9	46	14	8	63	6.8	20
4.6	1.3	9.9	1.3	7	12.0	11.0	.2	.9	64	17	12	93	6.8	30
4.6	1.3	8.6	1.0	14	11.0	11.0	.2	.6	64	17	6	87	6.7	30
3.7	1.2	6.5	.8	6	7.1	9.5	.4	1.7	18	14	9	62	6.3	140
2.5	.6	3.8	1.0	8	5.6	4.9	.2	.6	40	8	2	42	6.8	48
3.1	.8	6.4	.9	8	6.3	10.0	.2	.4	50	10	4	64	6.8	30
3.1	.8	6.4	1.0	8	5.4	11.0	.2	.4	50	10	4	64	6.7	25
4.0	1.1	6.3	1.0	10	8.4	10.0	.3	.5	50	14	6	71	6.6	25
3.8	1.1	4.4	.8	12	8.7	5.0	.1	.3	48	14	4	58	6.8	40
4.5	1.3	7.7	1.2	14	9.9	11.0	.2	.7	60	16	5	82	6.9	35

ranged from 36 to 100 mg/l (milligrams per liter). The principal cations, calcium, magnesium, sodium, and potassium, were present in concentrations of 16 mg/l or less; and the principal anions, bicarbonate, sulfate, and chloride, were present in concentrations of 29 mg/l or less. Hardness ranged from 10 to 36 mg/l, indicating that the water is soft. The pH, ranged from 6.2 to 6.8, which indicates that the water is slightly acidic and that it may be somewhat corrosive.

Iron and manganese were present in a few samples in concentrations that exceed limits (0.3 and 0.05 mg/l, respectively) recommended for these constituents in drinking water (U.S. Public Health Service, 1962). Concentrations of iron ranged from 0.01 to 0.51 mg/l, and the median was 0.06 mg/l; manganese ranged from 0.02 to 1.5 mg/l and the median was 0.04 mg/l.

Surface-water samples were taken at low flow when most of the streamflow consists of ground-water runoff. Accordingly, since the volume of chemical contaminants added to streams in the Pawcatuck basin is small, the chemical quality of surface water is very similar to that of the ground water. The concentration of most constituents, however, is generally slightly less in surface water than in ground water. An exception is iron, which was present in concentrations somewhat greater than those in most of the samples of ground water. Iron ranged from 0.3 to 1.0 mg/l, and the median concentration was 0.44 mg/l.

Adequate protection of the quality of water in the study area requires an awareness of the close relation between surface water and ground water. Contamination of streamflow, especially by chemical constituents, may result in impairment of quality of ground water in areas where streamflow is being induced into the ground by pumping wells. Degradation of ground water quality by direct introduction of a contaminant into an aquifer by way of leaching pits, landfills, or other direct means may, in turn, result in contamination of streamflow. The effects of contaminated ground water on the quality of streamflow are likely to be most significant in headwater areas, where discharge of the contaminated ground water may constitute a substantial part of total streamflow at low flow.

CONCLUSIONS

Unconsolidated deposits of sand and gravel having little uniformity in thickness and lithology and lying unconformably on a highly irregular surface of bedrock and till form a discontinuous aquifer that locally is 100 feet or more thick. Irregularities in the underlying till and bedrock projecting upward to or nearly to the surface separate the aquifer into five or more ground-water reservoirs along the Beaver, Wood, Ashaway, and Pawcatuck Rivers. The irregularities are sufficient obstacles to regional ground-water movement that they prevent significant underflow between reservoirs; however, the reservoirs are hydraulically connected by streams that flow across them.

The principal ground-water reservoirs are basically of two types (1) those of small volume, whose dependable yield is controlled largely by the rate at which streamflow can be induced into them and (2) those of moderate to large volume, whose dependable yield is controlled largely by both the amount of potential ground-water runoff that can be salvaged and by the rate at which streamflow can be induced into them or by the magnitude of the low flow available as influent seepage.

Because most sites favorable for large-scale ground-water development are within a few hundred feet of a stream, prospective patterns of use must consider the fact that ground-water withdrawals may markedly reduce low flows of streams at and downstream from pumping centers.

Mathematical models used to simulate ground-water withdrawals from assumed schemes of wells indicate that a sustained yield ranging from 1.3 to 10.3 mgd is obtainable from a small number of wells in the five principal ground-water reservoirs. The principal conclusions drawn from model analyses are summarized below.

1. A ground-water reservoir of small volume and relatively high transmissivity near the confluence of the Pawcatuck and Ashaway Rivers is capable of sustaining a yield of 10.3 mgd. Most of the water pumped from this reservoir will be from induced infiltration of streamflow. Withdrawals of this magnitude from a scheme of wells similar to that used in the model will have comparatively little effect on the natural low flow of the Pawcatuck River, but may cause the flow of the Ashaway River to cease during extended summer droughts.
2. A ground-water reservoir of relatively large volume in the Wood River valley north of Wyoming is capable of sustaining withdrawals of 9.6 mgd. Pumping at this rate will substantially reduce the low flow of the Wood River within the reservoir area. Reaches of the river near pumping centers may go dry for a week or more during prolonged droughts.

Construction of a proposed surface reservoir in the upper part of the ground-water reservoir will require reassessment of the potential ground-water yield, when the operating procedure of the surface reservoir and resulting changes in streamflow regimen have been established.

3. A ground-water reservoir occupying the preglacial channel of the Beaver River near Kenyon has a capacity to supply dependable yields of 6.2 mgd. Pumping from the ground-water reservoir at this rate, using a scheme of wells such as that used in the model analysis, will substantially reduce the low flow of both the Beaver and Pawcatuck Rivers. Upper reaches of the Beaver River may go dry during late summer and fall; lower reaches will have continuous flow. The 90-percent flow duration (about 23 mgd) of the Pawcatuck River below its confluence with the Beaver River will be reduced by about 30 percent.
4. A ground-water reservoir of relatively large size occupying the buried preglacial valley of the Wood River between Hope Valley and Indian Cedar Swamp will support continuous ground-water withdrawals of 3.6 mgd. This amount is obtainable from a scheme of wells designed primarily to develop potential ground-water runoff and, secondarily, to develop induced recharge from the Wood and Pawcatuck Rivers. A total of 24 mgd, chiefly from induced infiltration, is estimated to be potentially available for development from this reservoir. To obtain as much as 24 mgd, however, would require development from a much larger array of shallow closely spaced wells or the use of infiltration galleries. Development of 3.6 mgd will have no appreciable effect on the low flows of either the Wood or Pawcatuck Rivers.
5. A fifth ground-water reservoir of comparatively small size near the community of Bradford will support continuous withdrawals of 1.3 mgd from a scheme of wells also designed primarily to develop potential ground-water runoff and, to a lesser extent, induced recharge from the Pawcatuck River. A much larger part of the 20 mgd potentially available for development could probably be developed by a larger network of shallow wells or infiltration galleries in the less transmissive parts of the ground-water reservoir near the Pawcatuck River. Withdrawal of 1.3 mgd from this ground-water reservoir will have no appreciable effect on the low flow of the Pawcatuck River.

The results obtained by model analyses are meant to show, by example, the potential for ground-water development in the lower Pawcatuck basin. The calculated dependable yields are neither maximum nor optimum. Indeed, if the surface-inflow regimen to the basin remains unchanged, more ground water could be developed than is indicated. The techniques for accomplishing such development entail the use of different schemes of development, extension of areas of development beyond those modeled, increasing withdrawals during periods of high recharge, institution of artificial-recharge methods, low-flow augmentation from surface reservoirs, and return of all unconsumed water to areas of origin.

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Base from U. S. Geological Survey 1:24,000 Ashaway, Watch Hill, Carolina, Voluntown, Hope Valley, 1942–53; Coventry Center, Slocum, 1941–55; Kingston, 1942–57; and Oneco, 1943–53

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

MAP SHOWING APPROXIMATE CONFIGURATION OF THE BEDROCK SURFACE, LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND

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Base from U. S. Geological Survey 1:24,000
Ashaway, Watch Hill, Carolina, Voluntown,
Hope Valley, 1942–53; Coventry Center,
Slocum, 1941–55; Kingston, 1942–57;
and Oneco, 1943–53

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

MAP SHOWING APPROXIMATE SATURATED THICKNESS OF THE SAND AND GRAVEL AQUIFER, LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND

* U.S. GOVERNMENT PRINTING OFFICE: 1974—543–584/74

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Base from U. S. Geological Survey 1:24,000
Ashaway, Watch Hill, Carolina, Voluntown,
Hope Valley, 1942–53; Coventry Center,
Slocum, 1941–55; Kingston, 1942–57;
and Oneco, 1943–53

SCALE 1:48 000

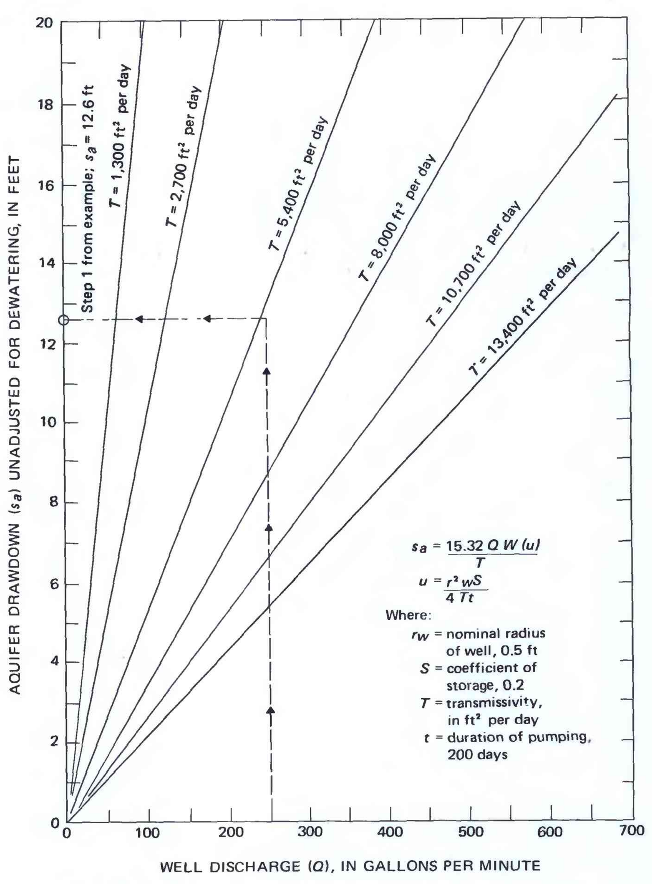
1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 4 5 KILOMETERS

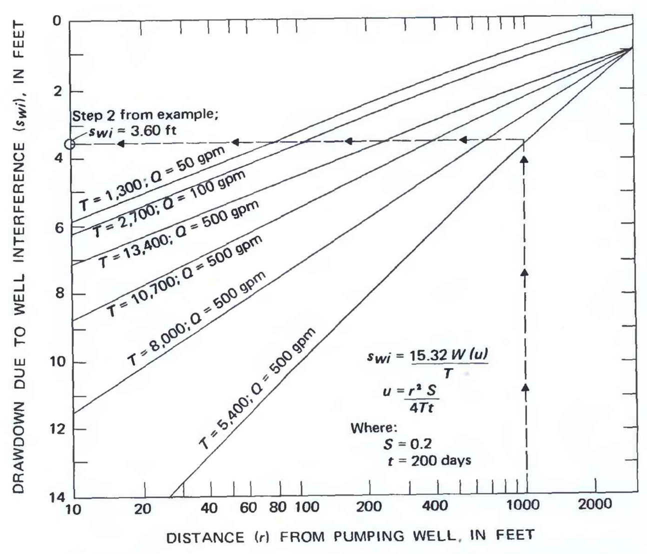
CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

MAP SHOWING APPROXIMATE CONFIGURATION OF THE WATER TABLE IN THE SAND AND GRAVEL AQUIFER, AUGUST 1966, LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND

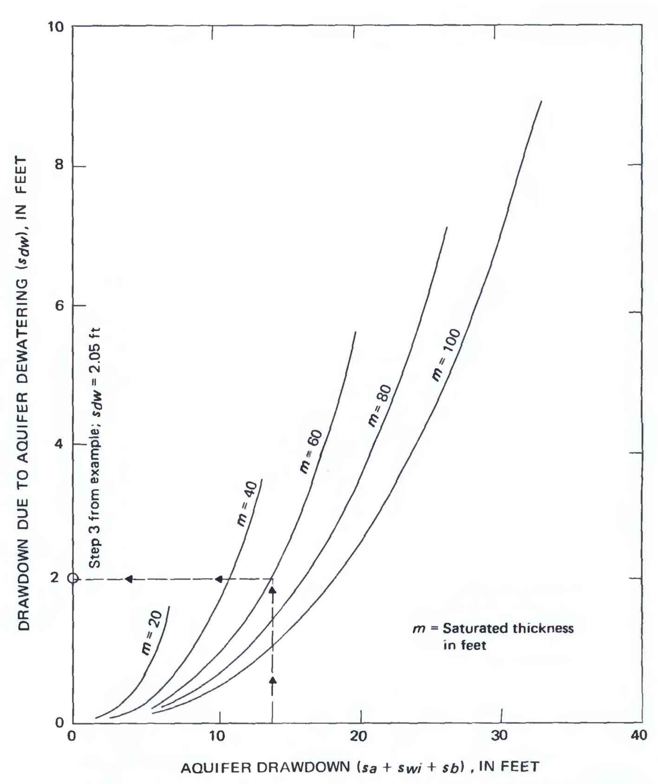
* U.S. GOVERNMENT PRINTING OFFICE: 1974—543-584/74



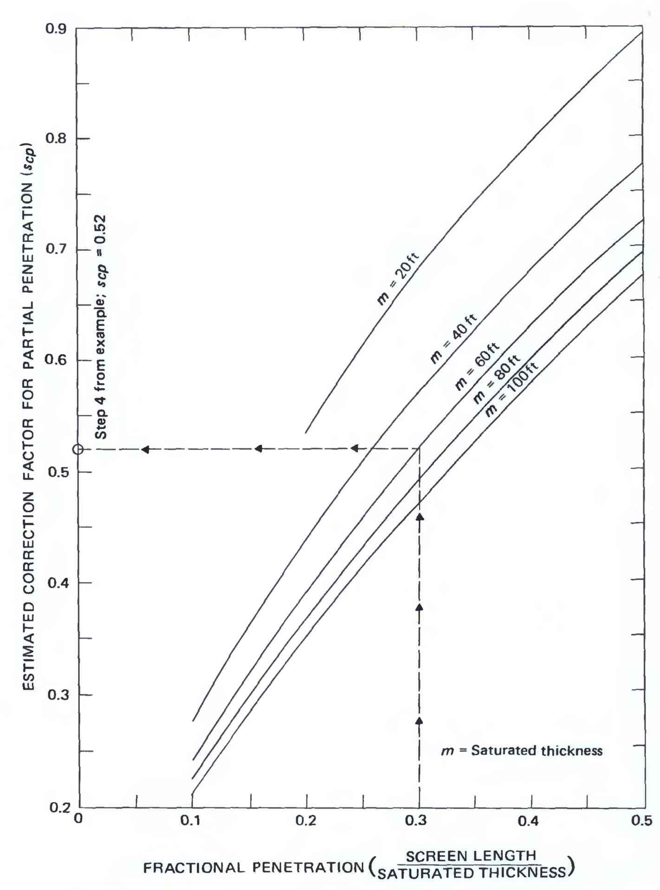
A. RELATION OF WELL DISCHARGE TO DRAWDOWN IN AQUIFER AT WELL



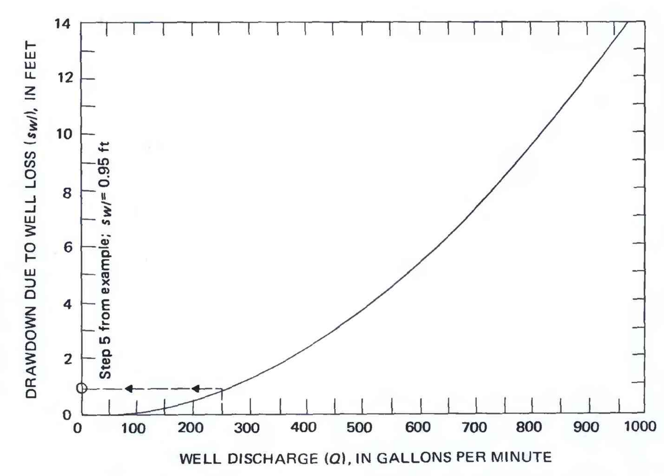
B. RELATION OF DISTANCE FROM PUMPED WELL TO DRAWDOWN DUE TO WELL INTERFERENCE



C. RELATION OF AQUIFER DRAWDOWN TO ADJUSTMENT FOR DEWATERING



D. RELATION OF FRACTIONAL PENETRATION TO ESTIMATED CORRECTION FOR PARTIAL PENETRATION



E. RELATION OF WELL DISCHARGE TO WELL LOSS

ESTIMATING WELL YIELD

(Modified from Rosenshein and others, 1968)

An estimate of the well yield that may be possible at a specified site can be obtained by using the graphs associated with the equation below. The drawdown available for development at the site can be obtained from the accompanying map. In appraising the possible yield of a well, the maximum allowable drawdown should be limited to the saturated thickness at the well available above the screen.

The graphs permit an approximate evaluation of the factors to which most of the observed drawdown in a pumping well is generally attributed. The aquifer drawdown in graph *A* was computed by using a pumping period of 200 days without recharge and should provide a reasonable estimate of drawdown for continuous withdrawal. Drawdown at various distances from the pumped well at rates other than that given in graph *B* can be obtained by the method shown in the example, step 2 (stated below).

For a specified well discharge (*Q*)

$s_{total} = (s_a + s_{wi} + s_b + s_{dw}) / s_{cp} + s_{wl}$, where:

s_{total} is the estimated drawdown to be anticipated in a well for a specified discharge and aquifer transmissivity;

s_a is an increment of drawdown in a proposed well for a specified discharge and aquifer transmissivity—taken from graph *A*;

s_{wi} is the estimated drawdown due to other wells pumping – taken from graph *B*;

s_b is the estimated drawdown due to boundary effects – may be obtained from graph *B* as the drawdown for twice the measured distance from well site to the aquifer boundary (zero transmissivity line);

s_{dw} is the estimated drawdown due to aquifer dewatering for a specified saturated thickness (pl. 2) – taken from graph *C*;

s_{cp} is the estimated correction factor for partial penetration for a specified saturated thickness – taken from graph *D*;

s_{wl} is the estimated drawdown at the specified discharge due to well loss – taken from graph *E*;

Example – Supply well is needed at site where aquifer transmissivity (*T*) is 5,400 ft² per day. From plate 2 the saturated thickness is about 60 feet. Yield desired is 250 gpm and proposed screen length is 18 feet. Screen is to be set in lower part of aquifer. Proposed site of new well is about 1,000 feet from existing well discharging 150 gpm; aquifer transmissivity is the same.

$s_{total} = (s_a + s_{wi} + s_b + s_{dw}) / s_{cp} + s_{wl}$

Step 1: From graph *A* (follow arrows) for a discharge of 250 gpm and $T = 5,400$ ft² per day, s_a is 12.6 feet.

Step 2: From graph *B* at 1,000 feet from existing pumping well for a $T = 5,400$ ft² per day and a well discharge (*Q*) of 500 gpm, s_{wi} is 3.60 feet.

Drawdown at any distance is directly proportional to the pumping rate (*Q*).

In graph *B*, s_{wi} is proportional to *Q*; actual discharge of existing well is 150 gpm;

s_{wi} = 150 gpm/500 gpm x 3.60 feet = 0.3 x 3.60 feet = 1.08 feet.

Because the new well is not near a boundary, s_b is 0;

Step 3: From graph *C* (follow arrows) for $s_a + s_{wi} + s_b$ of 13.68 feet and saturated thickness of 60 feet, s_{dw} is 2.05 feet.

Step 4: To determine s_{cp} an estimate of fractional penetration is needed.

Fractional penetration (graph *D*) $= \frac{18 \text{ feet}}{60 \text{ feet}} = 0.30.$

From graph *D* for a fractional penetration of 0.30 and a saturated thickness of 60 feet, s_{cp} is 0.52.

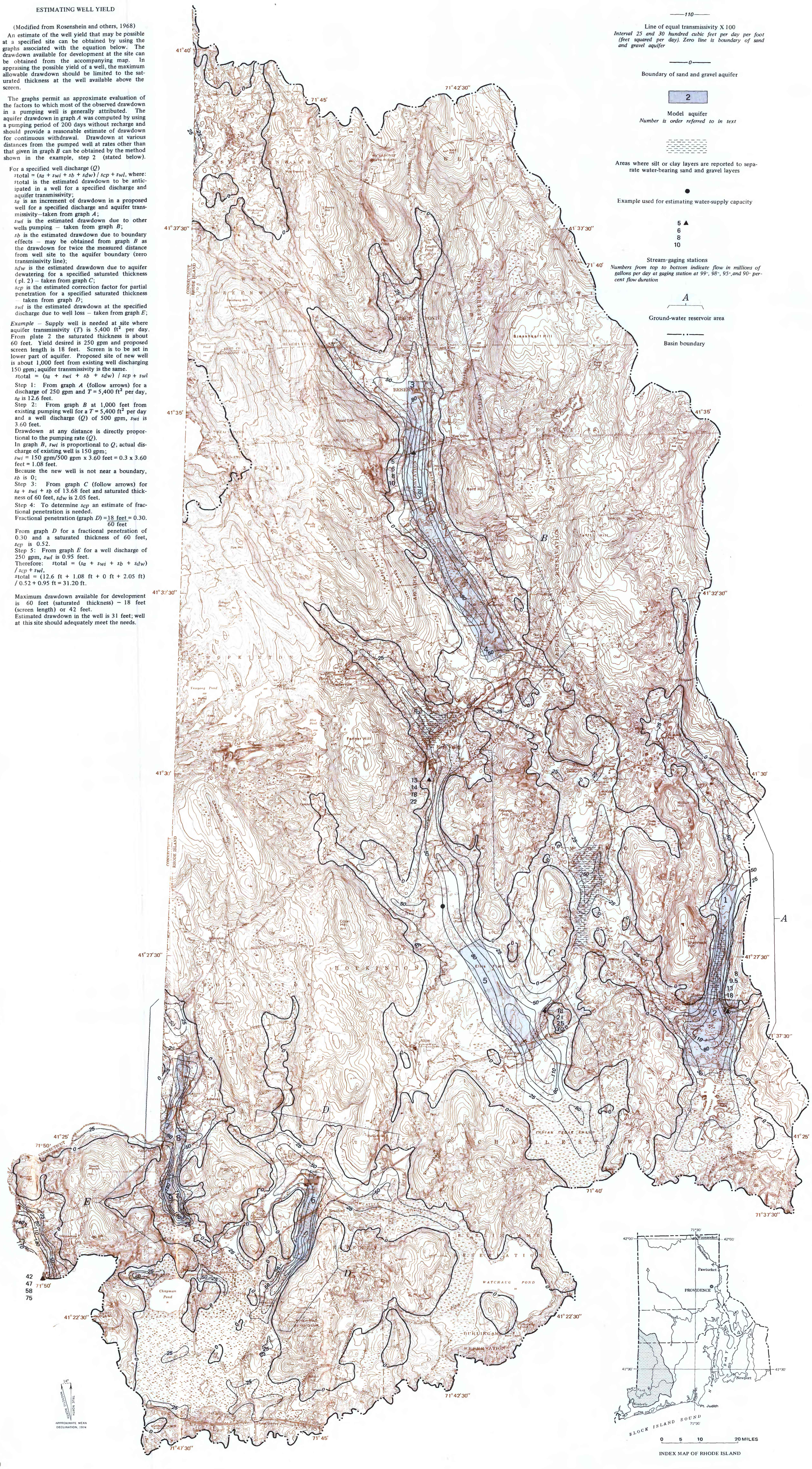
Step 5: From graph *E* for a well discharge of 250 gpm, s_{wl} is 0.95 feet.

Therefore: $s_{total} = (s_a + s_{wi} + s_b + s_{dw}) / s_{cp} + s_{wl}$,

s_{total} = (12.6 ft + 1.08 ft + 0 ft + 2.05 ft) / 0.52 + 0.95 ft = 31.20 ft.

Maximum drawdown available for development is 60 feet (saturated thickness) – 18 feet (screen length) or 42 feet.

Estimated drawdown in the well is 31 feet; well at this site should adequately meet the needs.



EXPLANATION

—110—

Line of equal transmissivity X 100
Interval 25 and 30 hundred cubic feet per day per foot (feet squared per day). Zero line is boundary of sand and gravel aquifer

—0—

Boundary of sand and gravel aquifer

2

Model aquifer
Number is order referred to in text

Areas where silt or clay layers are reported to separate water-bearing sand and gravel layers

Example used for estimating water-supply capacity

5 ▲
6
8
10

Stream-gaging stations
Numbers from top to bottom indicate flow in millions of gallons per day at gaging station at 99-, 98-, 95-, and 90- percent flow duration

A

Ground-water reservoir area

Basin boundary

INDEX MAP OF RHODE ISLAND

Base from U. S. Geological Survey 1:24,000 Ashaway, Watch Hill, Carolina, Voluntown, Hope Valley, 1942–53; Coventry Center, Slocum, 1941–55; Kingston, 1942–57; and Oneco, 1943–53

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

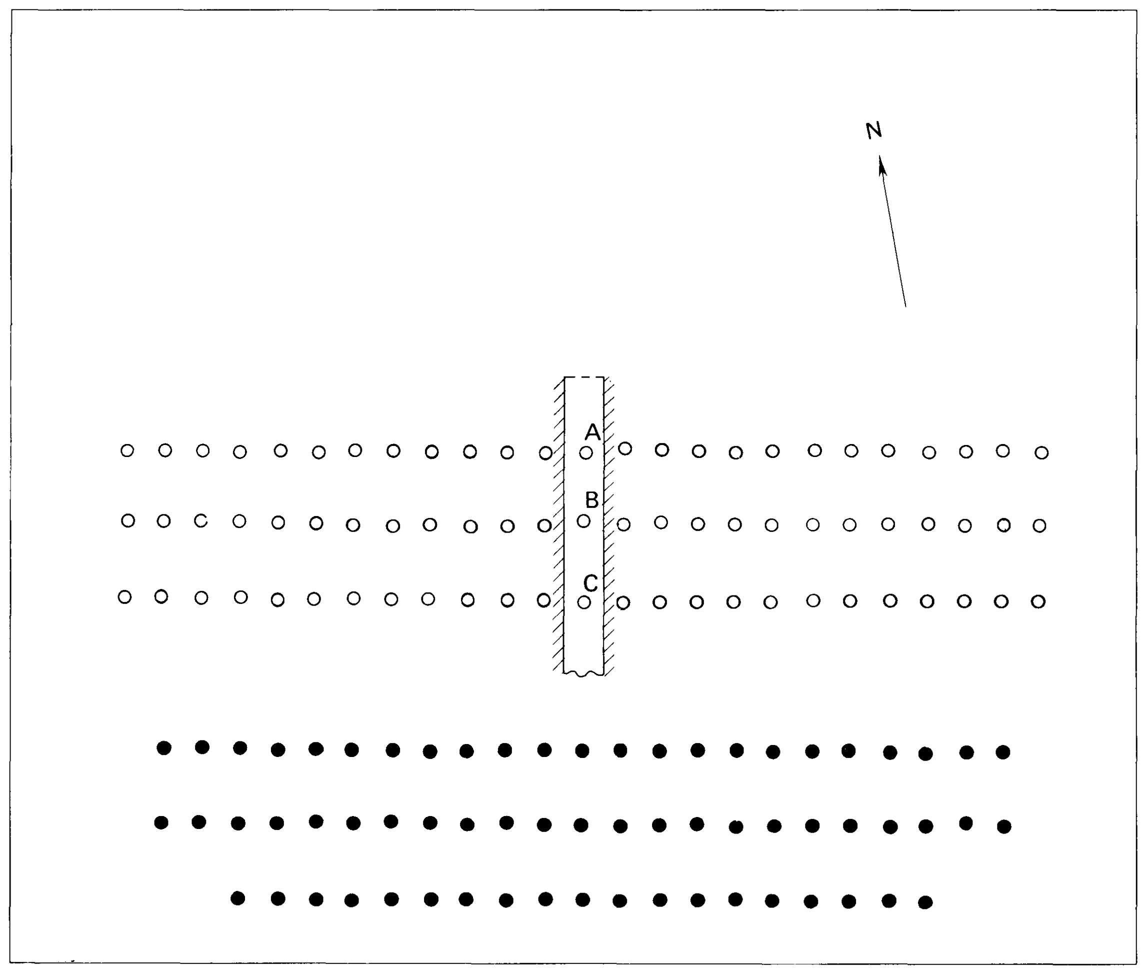
1 .5 0 1 2 3 4 5 KILOMETERS

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

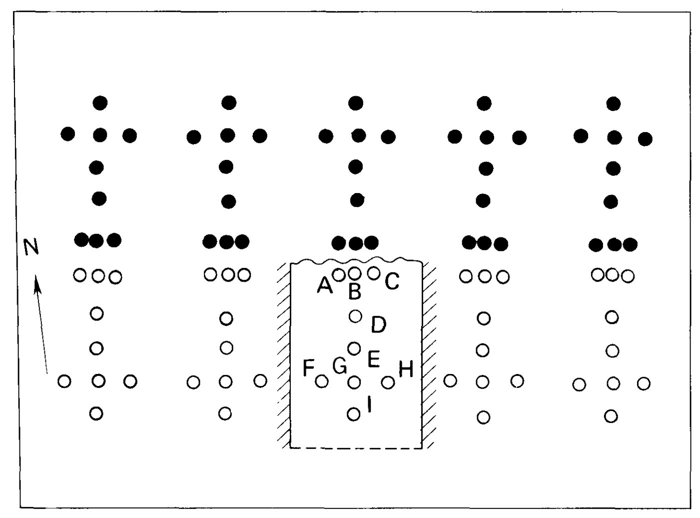
TRANSMISSIVITY OF THE SAND AND GRAVEL AQUIFER IN THE LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND, AND GRAPHS FOR ESTIMATING WELL YIELD

* U.S. GOVERNMENT PRINTING OFFICE: 1974—543-584/74

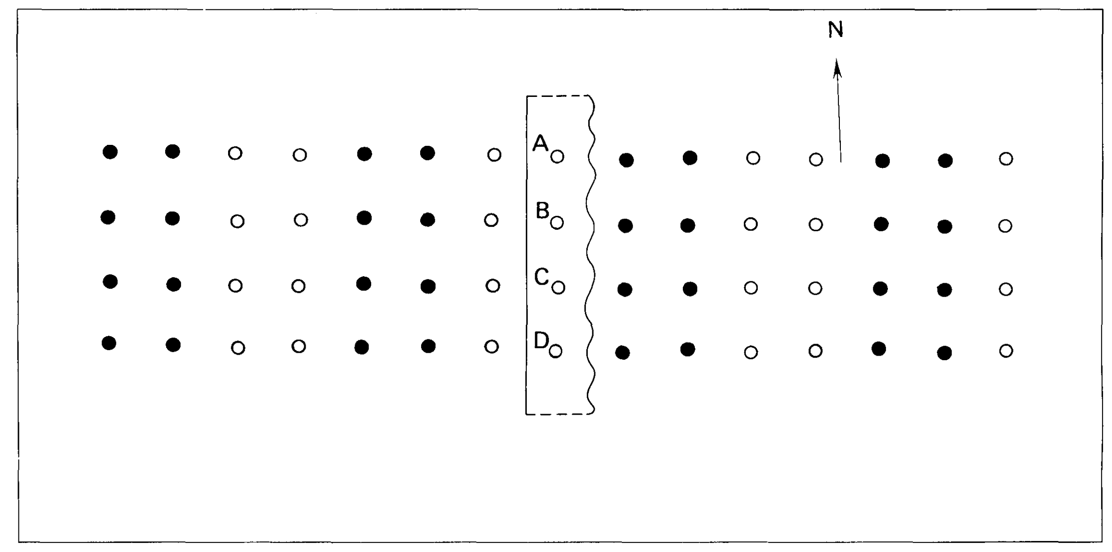
Prepared in cooperation with the
RHODE ISLAND WATER RESOURCES BOARD



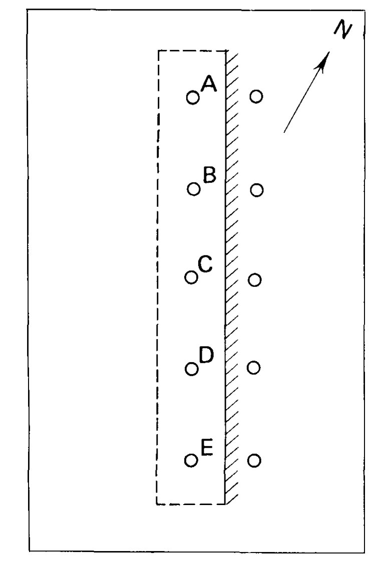
MODEL 1
BEAVER RIVER NORTH OF KENYON
(Model anaylsis summarized in table 5)



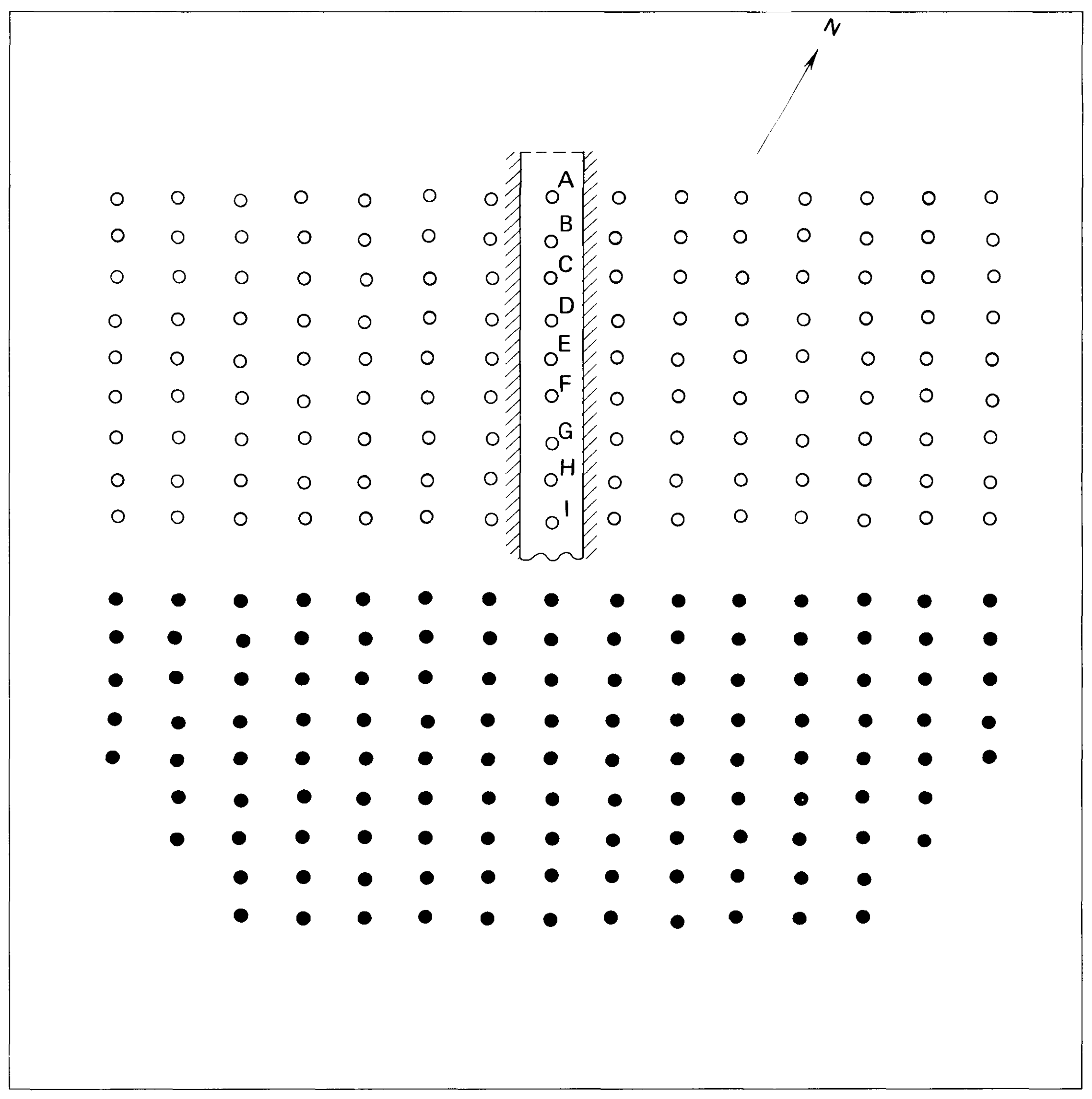
MODEL 2
PAWCATUCK RIVER NEAR KENYON
(Model analysis summarized in table 5)



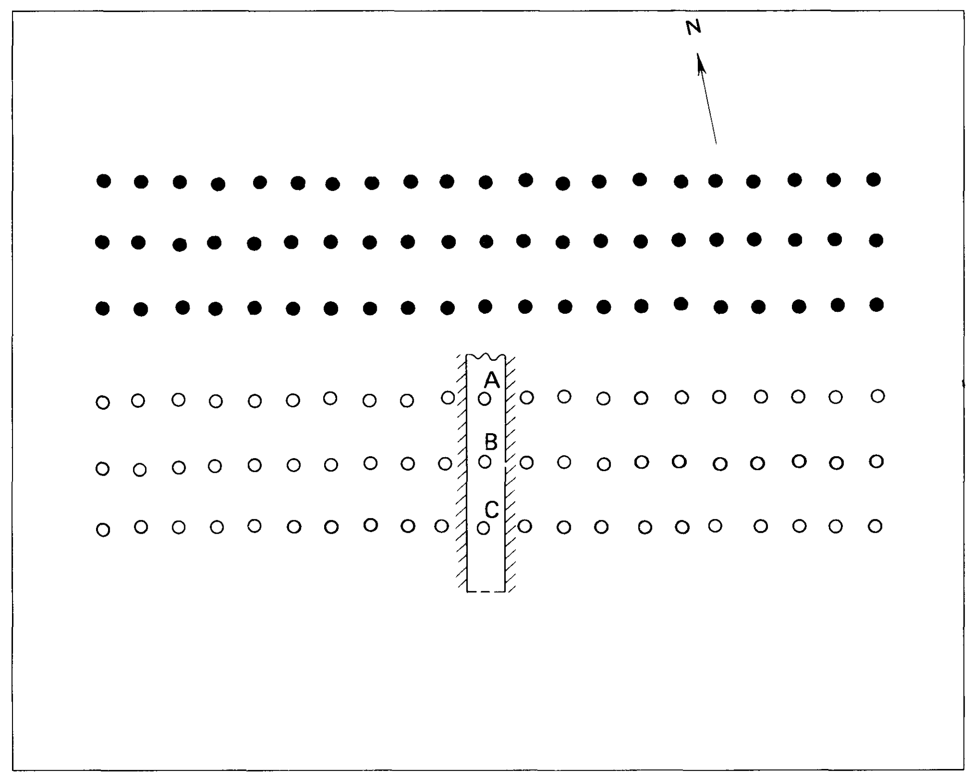
MODEL 3
WOOD RIVER BETWEEN PLAIN ROAD AND PARRIS BROOK
(Model analysis summarized in table 6)



MODEL 4
WOOD RIVER BETWEEN PARRIS BROOK AND WYOMING
(Model analysis summarized in table 6)

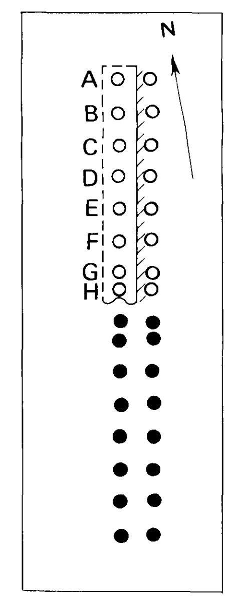


MODEL 5
ELLIS FLATS
(Model analysis summarized in table 6)

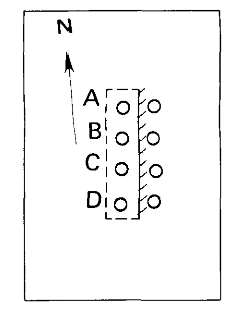


MODEL 6
BRADFORD WELL FIELD
(Model analysis summarized in table 7)

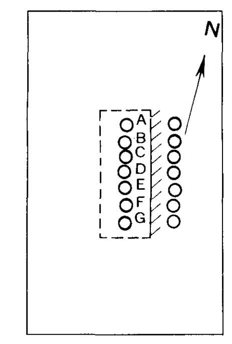
0 4000 8000 12000 16000 FEET



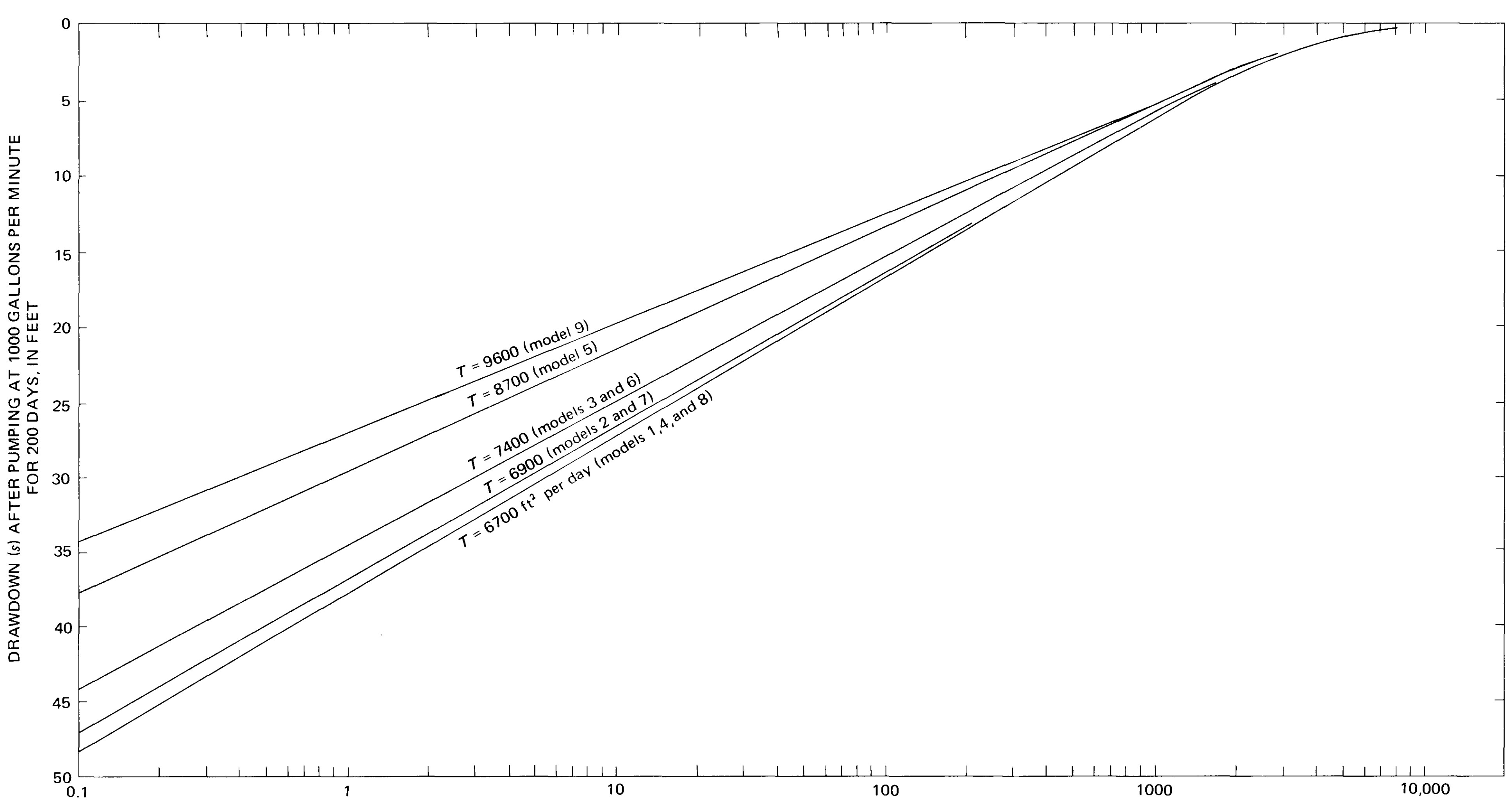
MODEL 7
ASHAWAY RIVER NEAR ASHAWAY
(Model analysis summarized in table 8)



MODEL 8
PAWCATUCK RIVER NEAR POTTER HILL
(Model analysis summarized in table 8)



MODEL 9
PAWCATUCK RIVER SOUTH-EAST OF POTTER HILL
(Model analysis summarized in table 8)



DISTANCE-DRAWDOWN GRAPHS FOR AQUIFER MODELS

EXPLANATION

Barrier boundary

Recharge boundary

Unbounded

○A Hypothetical pumping well and identification

○ Discharging image well

● Recharging image well

MATHEMATICAL MODELS OF SELECTED AREAS, LOWER PAWCATUCK RIVER BASIN, RHODE ISLAND

☆ U.S. GOVERNMENT PRINTING OFFICE: 1974—543-564/74