AVAILABILITY OF GROUND WATER IN THE BRANCH RIVER BASIN, PROVIDENCE COUNTY, RHODE ISLAND

U.S. GEOLOGICAL SURVEY. Water Resources Division.

WATER-RESOURCES INVESTIGATIONS 18-74

PREPARED IN COOPERATION WITH THE
RHODE ISLAND WATER RESOURCES BOARD

U.S. DEPARTMENT OF THE INTERIOR
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Rogers C. B. Morton, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

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FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

Multiply English units	By	To obtain SI units
Length		
feet (ft)	0.3048	metres (m)
miles (mi)	1.609	kilometres (km)
inches (in)	2.54	centimetres (cm)
Area		
acres	.004047	square kilometres (km^2)
square miles (mi^2)	2.590	square kilometres (km^2)
Volume		
gallons (gal)	3.785	litres (l)
cubic feet (ft^3)	.02832	cubic metres (m^3)
Flow		
feet squared per day (ft^2/day)	.0929	metres squared per day (m^2/day)
cubic feet per second (ft^3/s)	.02832	cubic metres per second (m^3/s)
feet per day (ft/day)	.3048	metres per day (m/day)
gallons per minute (gpm)	.06309	litres per second (l/s)
million gallons per day (mgd)	.04381	cubic metres per second (m^3/s)

AVAILABILITY OF GROUND WATER IN THE BRANCH RIVER BASIN, PROVIDENCE COUNTY, RHODE ISLAND

By H. E. Johnston and D. C. Dickerman

ABSTRACT

Stratified glacial drift consisting largely of sand and gravel constitutes the only aquifer capable of supporting continuous yields of 100 gpm (6.3 l/s) or more to individual wells. The aquifer covers about a third of the 79 mi^2 (205 km^2) study area, occurring mainly in stream valleys that are less than a mile wide. Its saturated thickness is commonly 40 to 60 ft (12 to 18 m); its transmissivity is commonly 5,000 to 8,000 ft^2/day (460 to 740 m^2/day). The aquifer is hydraulically connected to streams that cross it and much of the water from heavily pumped wells will consist of infiltration induced from them. Potential sustained yield from most parts of the aquifer is limited chiefly by the rate at which infiltration can be induced from streams or low streamflow, whichever is smaller. Ground-water withdrawals deplete streamflow; and if large-scale development of ground water is not carefully planned and managed, periods of no streamflow may result during dry weather.

Potential sustained yield varies with the scheme of well development, and is evaluated for selected areas by mathematically simulating pumping from assumed schemes of wells in models of the stream-aquifer system. Results indicate that sustained yields of 5.5, 3.4, 1.6, and 1.3 mgd (0.24, 0.15, 0.07, and 0.06 m^3/s) can be obtained from the stratified-drift aquifer near Slatersville, Oakland, Harrisville, and Chepachet, respectively. Pumping at these rates will not cause streams to go dry, if the water is returned to streams near points of withdrawal. A larger ground-water yield can be obtained, if periods of no streamflow along reaches of principal streams are acceptable.

Inorganic chemical quality of water in the stream-aquifer system is suitable for most purposes; the water is soft, slightly acidic, and generally contains less than 100 milligrams per litre of dissolved solids. Continued good quality ground water depends on maintenance of good quality of water in streams, because much of the water pumped from wells will be infiltrated from streams.

INTRODUCTION

This report deals with ground-water resources of the part of the Branch River basin in northwestern Rhode Island upstream from the U.S. Geological Survey gaging station at Forestdale, RI, an area of 79 mi^2 or 205 km^2 (fig. 1). It is one of a series prepared in cooperation with the Rhode Island Water Resources Board to provide quantitative information on the availability of large supplies of ground water in Rhode Island.

The area is a thinly populated section where either surface-water or ground-water resources are available to meet long-term needs of public-supply systems. The area has several ponds, lakes, reservoirs, and a moderate amount of swampy area; it is drained by several perennial streams. Reservoirs that impound the principal streams originally were constructed to supply water for power generation, processing, and waste disposal for textile mills, but are used now largely for recreation.

Two additional reservoirs have been proposed: one on Tarkiln Brook in the eastern part of the basin would provide 5.4 mgd (0.24 m^3/s); the other on Nipmuc River in the northern part of the basin would provide 9.0 mgd or 0.39 m^3/s (Metcalf and Eddy, 1967). Most of the water would augment public-supply systems in northern Rhode Island. Neither site is in an area where large scale development of ground water is feasible.

Precipitation, the source of virtually all water in the area, as recorded at Greenville, RI, (fig. 1) between 1941-68, ranges from 30 to 60 in (76 to 152 cm) and averages 46 in (117 cm). Half is returned to the atmosphere by evaporation and transpiration, chiefly during the growing season (April to October). Nearly all the remaining half, representing the water available for withdrawal by man, is discharged from the area as runoff. Runoff during the same period, as measured at the Forestdale gage, ranged from 12 to 36 in (30 to 91 cm) annually and averaged 23 in (58 cm). Average runoff of 23 in (58 cm) is equivalent to 1.1 mgd/mi^2 (0.05 m^3/s), or 87 mgd (3.81 m^3/s) from the 79 mi^2 (205 km^2) study area.

Ground-water resources in the basin are relatively undeveloped, and, as a consequence, data necessary for describing accurately the hydraulic properties of the aquifer and for making accurate estimates of potential ground-water yield are sparse.

Water occurs in three hydraulically interconnected aquifers: bedrock, till, and stratified glacial drift. Each aquifer yields usable quantities of water to wells, but only the stratified drift can continuously supply 100 gpm (6.3 l/s) or more to individual wells. Most wells constructed in the till and bedrock yield sufficient water to satisfy domestic and other needs requiring only a few gallons per minute; yield generally does not exceed 20 gpm (1.31 l/s).

Principal emphasis is placed upon evaluation of the hydrology and hydraulic characteristics of the stratified-drift aquifer. The water-yielding characteristics of till and bedrock are considered briefly, because they contribute water to recharge the stratified drift.

Surface water and ground water are so intimately interrelated that they cannot be considered as separate water resources. One cannot be developed without having impact on the other. Pumping several million gallons per day from wells can cause noticeable depletion of streamflow, and regulation of streamflow can significantly affect the yields of some wells that derive most of their water from stream infiltration.

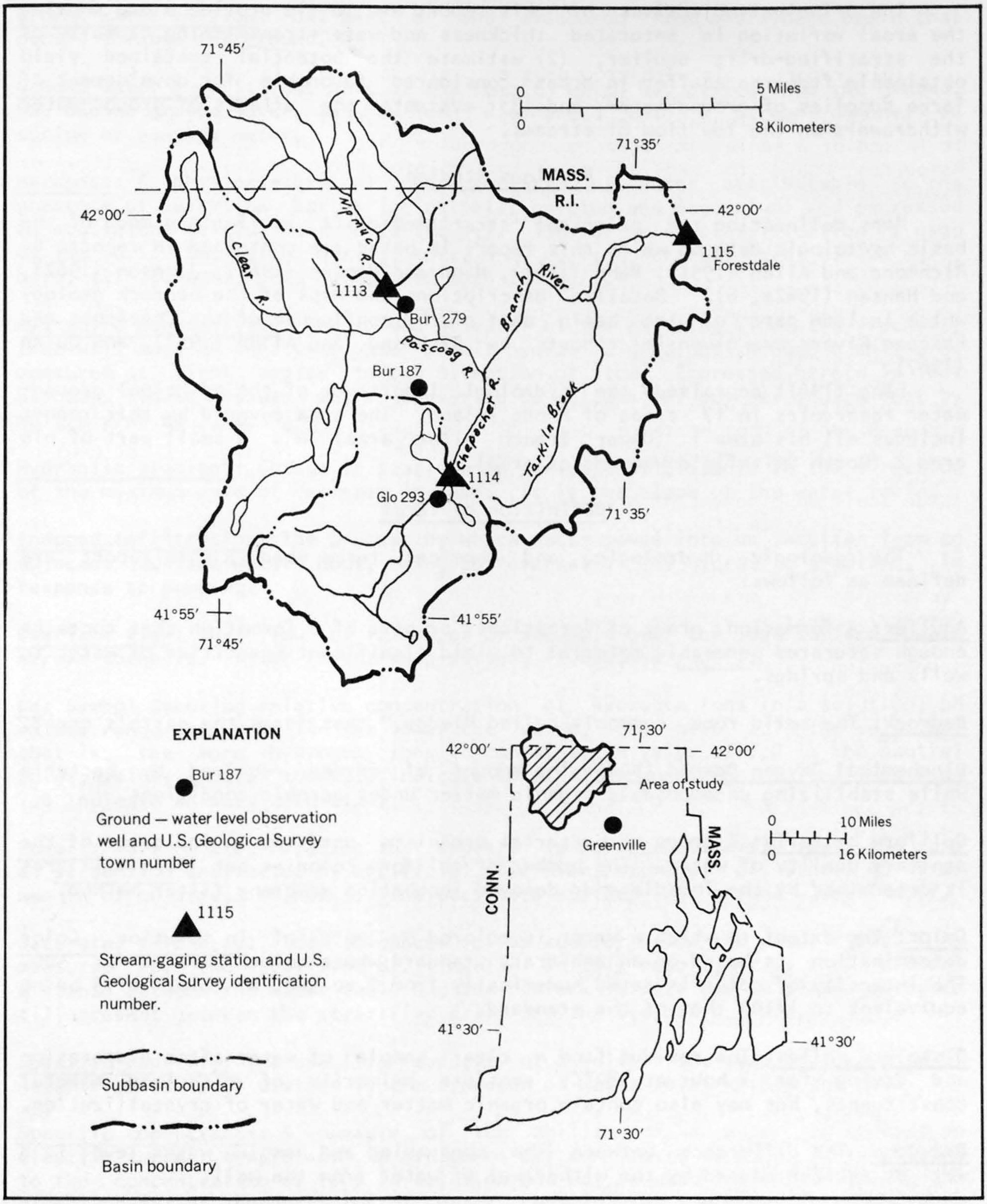

Figure 1. — Location of the Branch River basin.

The principal objectives of this report are to (1) provide a map showing the areal variation in saturated thickness and water-transmitting capacity of the stratified-drift aquifer, (2) estimate the potential sustained yield obtainable from the aquifer in areas considered favorable for development of large supplies of ground water, and (3) evaluate the effects of ground-water withdrawals on the low flow of streams.

Previous Studies

Maps delineating the principal stratified-drift aquifer and much of the basic hydrologic data on which this report is based are contained in reports by Richmond and Allen (1951), Hahn (1961), Hahn and Hansen (1961), Johnson (1962), and Hansen (1962a, b). Detailed descriptions and maps of the bedrock geology which include part of the basin east of the confluence of the Chepachet and Pascoag Rivers are given in reports by Richmond and Allen (1951), and Quinn (1967).

Lang (1961) appraised the hydrologic importance of the principal ground-water reservoirs in 17 areas of Rhode Island. The area covered by this report includes all his area 1 (Upper Branch River area) and a small part of his area 2 (North Smithfield-Woonsocket area).

Definition of Terms

The geologic, hydrologic, and chemical terms used in this report are defined as follows:

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.

Biochemical Oxygen Demand (BOD): The amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions.

Coliform bacteria: A group of bacterial organisms used as an indicator of the sanitary quality of water. The number of coliform colonies per 100 millilitres is determined by the immediate or delayed incubation membrane filter method.

Color: The extent to which a water is colored by material in solution. Color determination is based on an arbitrary standard whose color is rated at 500. The intensity of color is rated numerically from 0 to 500, a color of 5 being equivalent to 1/100 that of the standard.

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

Drawdown: The difference between the nonpumping and pumping water level in a well or aquifer caused by the withdrawal of water from the well.

Ground-water evapotranspiration: Ground water discharged into the atmosphere in the gaseous state by direct evaporation and by transpiration of plants.

Ground-water outflow: That part of the discharge from a drainage basin that occurs through the ground.

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

Hardness: A physical-chemical characteristic of water attributable to the presence of alkaline earths (principally calcium and magnesium) and expressed as equivalent calcium carbonate ($CaCO_3$). The following classification is used by the U.S. Geological Survey: soft, 0-60 mg/l; moderately hard, 61-120 mg/l; hard, 121-180 mg/l; very hard, more than 180 mg/l.

Hydraulic conductivity: The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Expressed herein in feet per day. These values may be converted to gallons per day per square foot by multiplying by 7.48.

Hydraulic gradient: Change in static head per unit of distance in the direction of the maximum rate of decrease in head. It is the slope of the water table.

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.

Overland flow: The flow of rainwater or snowmelt over the land surface toward stream channels. After it enters a stream, it becomes runoff.

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

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.

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.

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 electric current, expressed in micromhos per centimetre at 25°C. It is related to the concentration of ions in solution and may be used for approximating the dissolved-solids concentration of water. Multiplying the specific conductance of waters in the study area by a factor of 0.55 gives an approximate measure of dissolved solids, in milligrams per litre.

Specific yield: Ratio of volume of water a fully saturated rock or unconsolidated material will yield by gravity drainage, given sufficient time, to total volume of rock or unconsolidated material; commonly expressed as 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.

Surface runoff: That part of the runoff of a drainage basin that has not passed beneath the surface since precipitation. It is also defined as that part of runoff which travels over the soil surface to the nearest stream channel.

Till: Predominantly nonsorted, nonstratified, unconsolidated sediment deposited directly from glaciers.

Transmissivity: Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. It is equal to the product of hydraulic conductivity and saturated thickness. 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.

Acknowledgments

The authors are indebted to the well drillers for records of wells, and to the Woonsocket Industrial Park and the Harrisville and Pascoag Fire Districts, for information on their wells and access to their land and equipment for measurements and tests. Special acknowledgment is made to those who permitted test borings to be drilled on their property.

WATER USE

Approximately 3.0 mgd (0.13 m^3/s) of surface water and 1.3 mgd (0.06 m^3/s) of ground water was used in 1968. All but 10 to 15 percent (Murray, 1968) was used for nonconsumptive purposes and was available for reuse. Most of the surface water was withdrawn and used by industry for processing and cooling.

Wells owned by 12 public-supply systems and 1 industrial park pumped 0.75 mgd (0.03 m^3/s), of which 0.65 mgd (0.03 m^3/s) was pumped from the stratified-drift aquifer. Privately owned wells pumped 0.55 mgd (0.02 m^3/s), chiefly from the bedrock aquifer.

Evaluation of long-term needs of public water-supply systems indicates that requirements will be about 3 mgd (0.13 m^3/s) by the year 2020 (Metcalf and Eddy, 1967).

STREAMFLOW

Knowledge of streamflow characteristics is required to evaluate potential streamflow-depletion effects resulting from ground-water withdrawals, and to determine streamflow potentially available for diversion to wells as induced infiltration. Determination of the ground-water runoff component of streamflow also provides a measure of ground-water recharge.

Records of mean daily flow and station descriptions at gaging stations on Nipmuc River near Harrisville, Chepachet River at Chepachet, and Branch River at Forestdale are published in annual reports of the Geological Survey. (See SELECTED REFERENCES.) Flow-duration curves, which show the percentage of time specified flows were equaled or exceeded in a given period, were prepared from data at these stations (fig. 2). Short-term (1964-68) flow-duration records of Nipmuc and Chepachet Rivers are adjusted to the period 1941-68 by correlation (Searcy, 1959) with the record at the Branch River gage. Streamflow at the Branch River gage was affected by regulation prior to 1958, but nearly identical flow-duration curves are obtained for periods when streamflow was regulated (1941-57) and when it was essentially unregulated (1958-68), indicating that effects of regulation do not significantly impair usefulness of the 1941-68 curve for predicting duration of flow.

Low-flow characteristics of streams are particularly important, because streamflow-depletion effects resulting from ground-water withdrawals are most severe during periods of dry weather. Low-flow frequency curves for the Branch River at Forestdale (fig. 3) show how often specified low flows are expected to recur and for what periods of consecutive days they are expected to last.

Streamflow measurements were made at several points in the Branch River basin (fig. 4) during low-flow periods in August and September 1968. Measurements were made in Nipmuc River basin when streamflow was equivalent to that equaled or exceeded 82 percent of the time. All other measurements were made when the unregulated streamflow was equivalent to that equaled or exceeded 93 percent of the time.

Components of Runoff

Runoff in the study area consists of surface runoff and ground-water runoff. Surface runoff is derived from precipitation and snowmelt that has flowed directly over land surface or has fallen directly upon swamps, ponds, lakes, streams, and stream impoundments. Unless detained in surface storage, most of it leaves Branch River basin as streamflow within a few days. Ground-water runoff is the part of precipitation that has percolated to the water table and flowed slowly through the ground to springs, swamps, ponds, lakes, and streams. Because it reaches streams gradually, it sustains flow of unregulated streams during dry weather. Ground-water runoff provides a measure of ground-water recharge. It is water that could have been intercepted by wells.

Separation of hydrographs of Nipmuc and Chepachet Rivers gives hydrographs of the components of surface- and ground-water runoff (fig. 5). The ground-water runoff component was determined by means of rating curves prepared by plotting mean daily streamflow against mean daily ground-water level on days when all or most of the runoff was judged to consist of ground water. Mean daily ground-water level was determined from three observation wells, Bur 187, Bur 279, and Glo 293 (fig. 1). A table of mean daily ground-water levels was then used in conjunction with the curves to construct a continuous hydrograph of ground water contribution to streamflow in the basins during 1968.

Measured runoff during the 1968 calendar year was 24.5 in (62 cm) from Nipmuc River basin and 25.8 in (66 cm) from Chepachet River basin. Hydrograph separation indicates ground-water runoff made up 10.6 in (27 cm), or 43 percent, of the runoff from Nipmuc River basin and 13.3 in (34 cm), or 52 percent, of the runoff from Chepachet River basin. In terms of runoff per unit area, ground-water runoff averaged 0.51 and 0.63 mgd/mi^2 (0.02 and 0.03 m^3/s), respectively, from Nipmuc and Chepachet River basins.

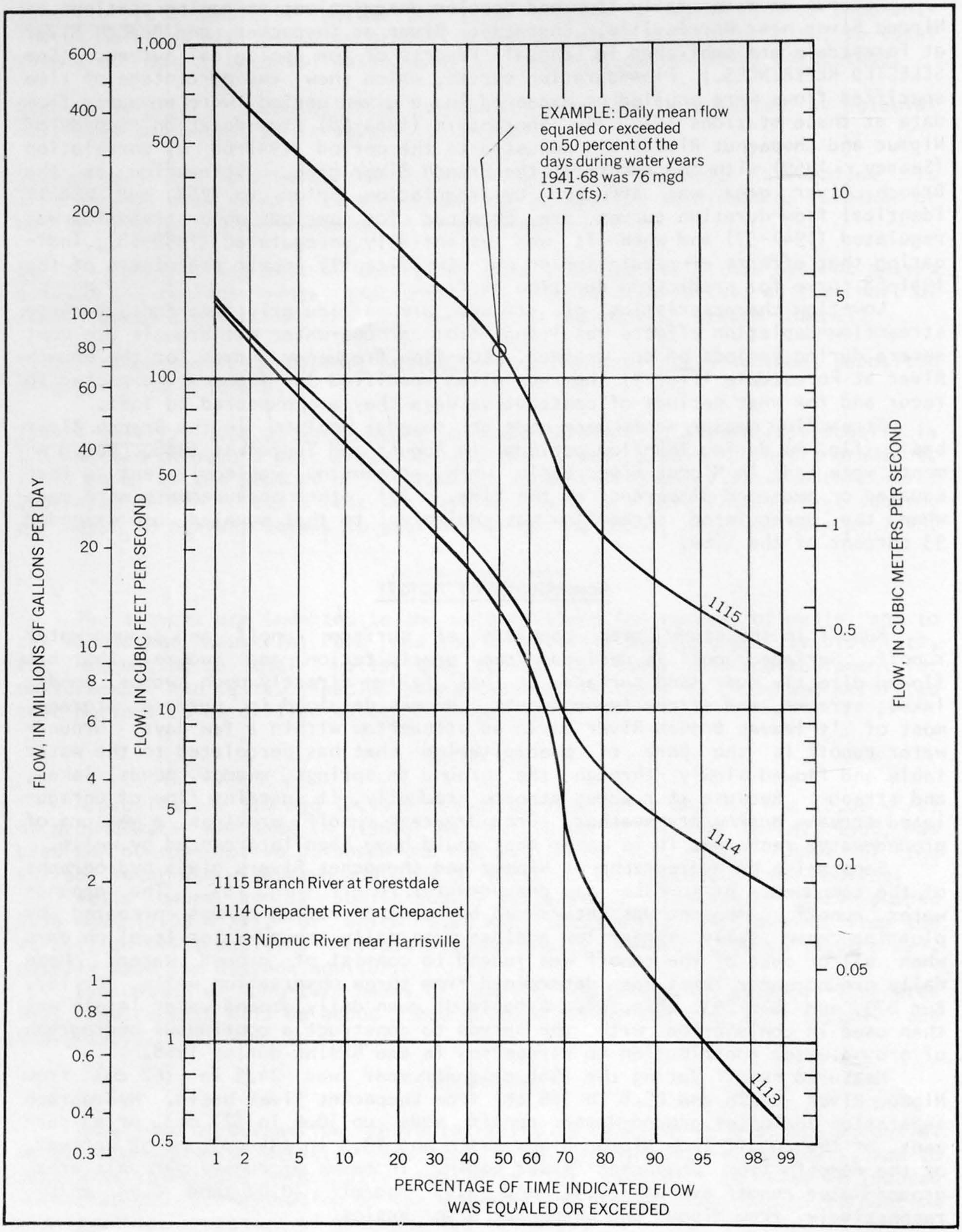

Figure 2. — Duration of daily mean streamflow of the Branch, Chepachet, and Nipmuc Rivers, 1941-68 water years.

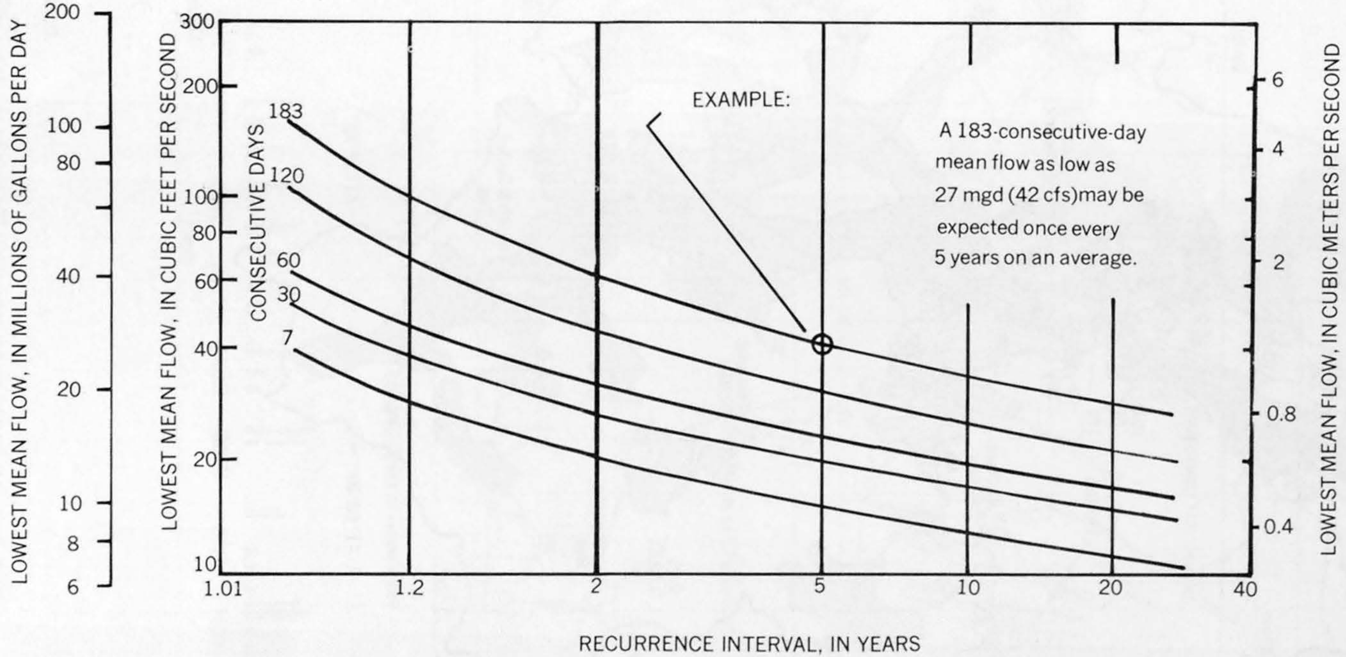

Figure 3. — Recurrence intervals of low flows of the Branch River at Forestdale, 1941-67 water years.

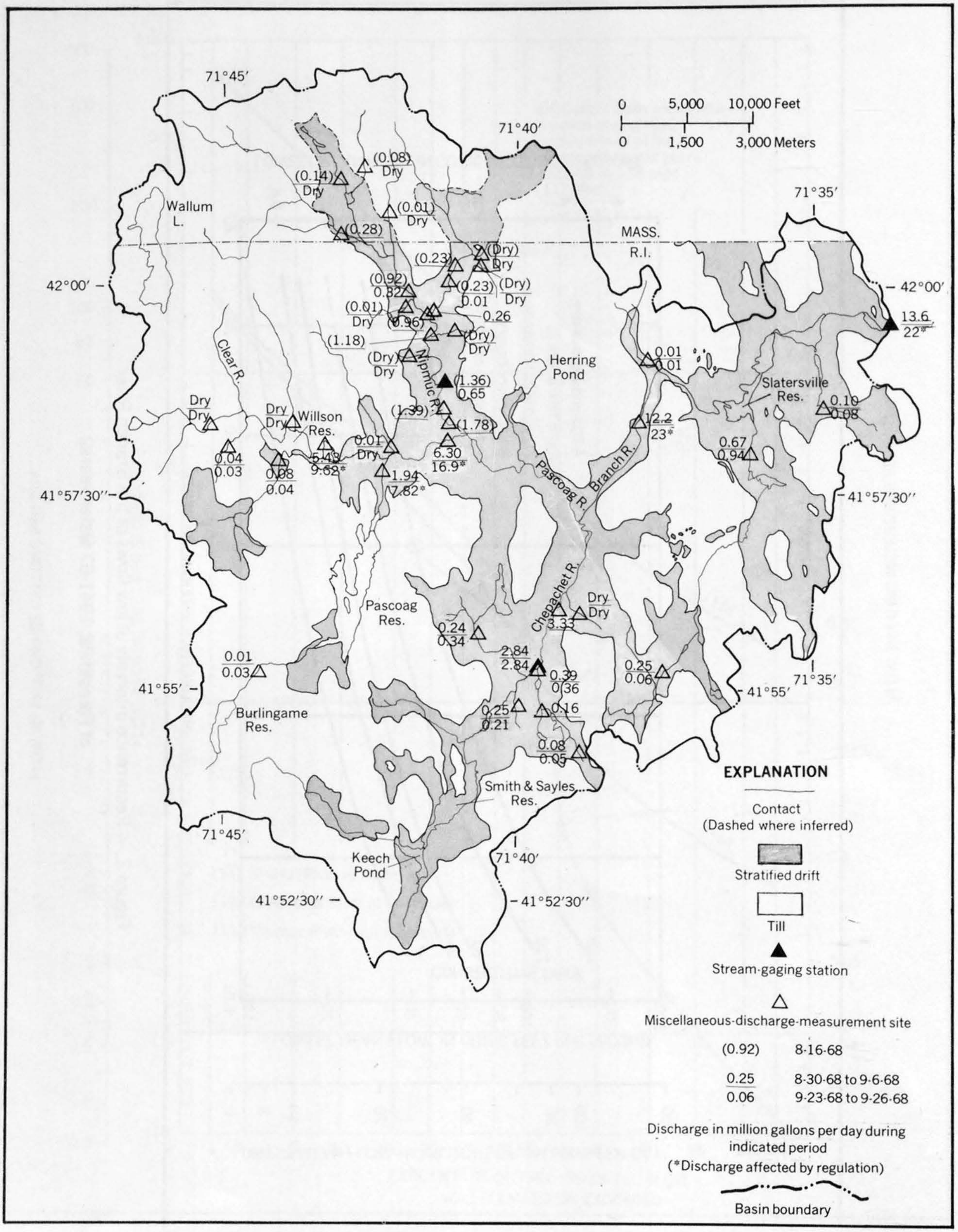

Figure 4. — Low-flow measurements at selected sites in the Branch River basin, August and September, 1968.

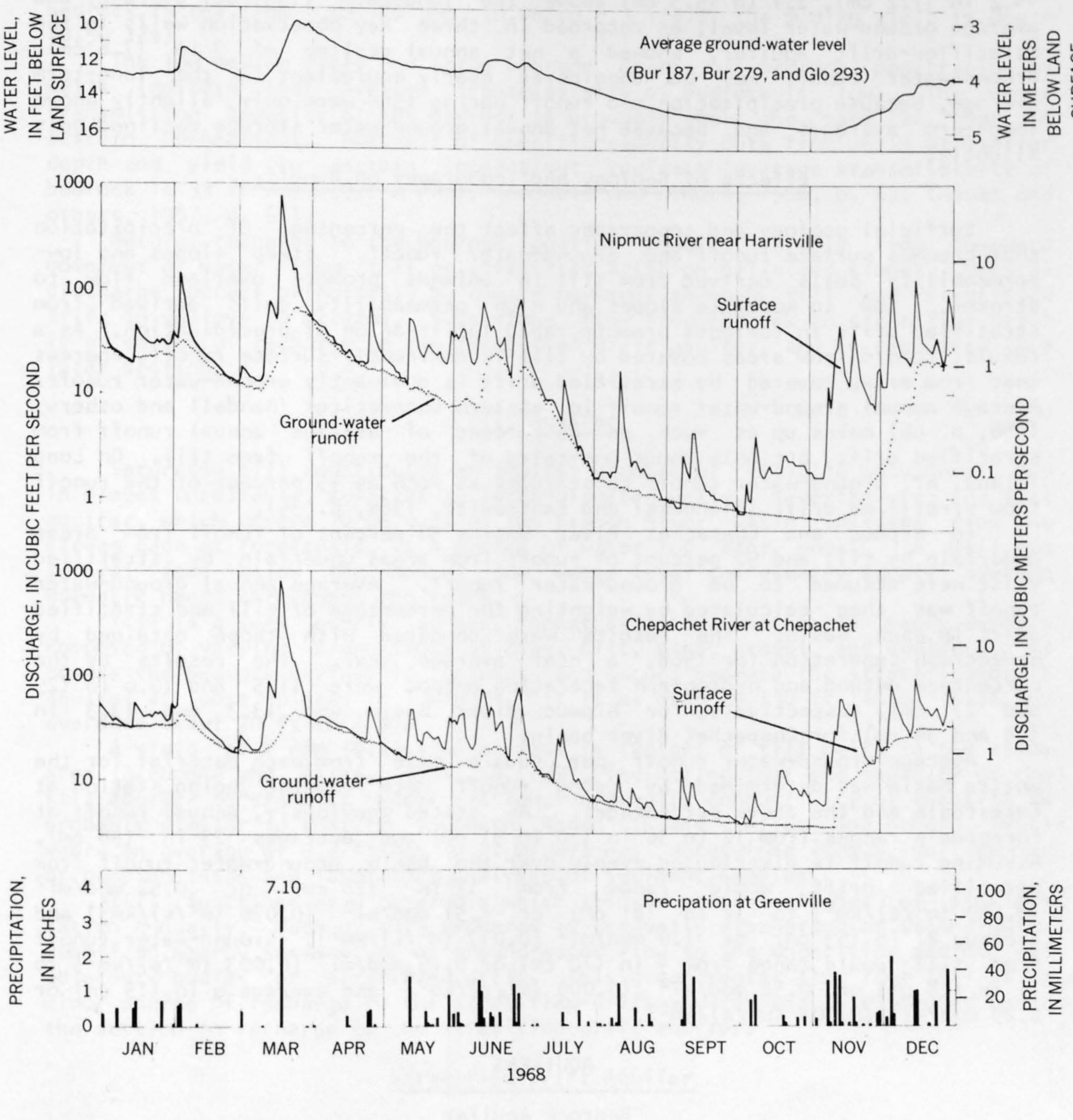

Figure 5. — Separation of runoff into components of ground-water and surface runoff, average ground-water level, and precipitation.

During 1968, runoff from Branch River basin was 25.3 in (64 cm), 2.2 in (5.6 cm) above the long-term (1941-68) average; precipitation at Greenville was 48.2 in (122 cm), 2.1 in (5.3 cm) above the long-term (1939-68) average; and average ground-water level, as recorded in three key observation wells in the stratified-drift aquifer, showed a net annual decline of 3 in (7.6 cm). Ground-water runoff may be considered nearly equivalent to the long-term average, because precipitation and runoff during 1968 were only slightly above long-term averages and because net annual ground-water storage declined only slightly.

Effects of Geology and Topography on Runoff

Surficial geology and topography affect the percentage of precipitation that becomes surface runoff and ground-water runoff. Steep slopes and low-permeability soils derived from till in uplands promote overland flow to streams. Low to moderate slopes and high permeability soils derived from stratified drift in lowlands promote rapid infiltration of precipitation. As a result, runoff from areas covered by till is dominantly surface runoff, whereas that from areas covered by stratified drift is dominantly ground-water runoff. Average annual ground-water runoff in eastern Connecticut (Randall and others, 1966, p. 66) makes up as much as 86 percent of average annual runoff from stratified drift, but only about one-third of the runoff from till. On Long Island, NY, ground-water runoff constitutes as much as 95 percent of the runoff from stratified drift (Pluhowski and Kantrowitz, 1964, p. 35).

In Nipmuc and Chepachet River basins 30 percent of runoff from areas underlain by till and 90 percent of runoff from areas underlain by stratified drift were assumed to be ground-water runoff. Average annual ground-water runoff was then calculated by weighting the percentage of till and stratified drift in each basin. The results were compared with those obtained by hydrograph separation for 1968, a near average year. The results by the percentage method and hydrograph separation method were 11.5 and 10.6 in (29 and 27 cm), respectively, for Nipmuc River basin and 13.3 and 13.3 in (34 and 34 cm) for Chepachet River basin.

Average ground-water runoff per square mile from each material for the entire basin was determined by using runoff data from the gaging station at Forestdale and the above percentages. As stated previously, annual runoff at Forestdale ranges from 12 to 36 in (30 to 91 cm) and averages 23 in (58 cm). Assuming runoff is distributed evenly over the basin, ground-water runoff from stratified drift would range from 11 in (28 cm) or 0.52 mgd/mi^2 [0.009 $(m^3/s)/km^2$] to 32 in (81 cm) or 1.51 mgd/mi^2 [0.026 $(m^3/s)/km^2$] and average 21 in (53 cm) or 1.0 mgd/mi^2 [0.017 $(m^3/s)/km^2$]. Ground-water runoff from till would range from 4 in (10 cm) or 0.19 mgd/mi^2 [0.003 $(m^3/s)/km^2$] to 11 in (28 cm) or 0.52 mgd/mi^2 [0.009 $(m^3/s)/km^2$] and average 6 in (15 cm) or 0.29 mgd/mi^2 [0.005 $(m^3/s)/km^2$].

AQUIFERS

Bedrock Aquifer

Water in igneous and metamorphic bedrock occurs almost exclusively in a network of irregularly spaced fractures, which decrease in size and number downward and become sparse below a depth of about 300 ft (91 m). The probability of obtaining significant quantities of water from bedrock below a depth of about 250 ft (76 m) is small.

Reliable domestic supplies can be obtained from bedrock almost anywhere in the study area. Yield of 129 wells penetrating an average of 160 ft (49 m) of bedrock ranges from 1 to 100 gpm (0.06 to 6.3 l/s); the median yield is 8 gpm (0.50 l/s).

The low median yield and large average depth of bedrock penetration by wells indicate that average transmissivity of bedrock is low. The water transmitting capacity of the bedrock is probably about the same as that in eastern Connecticut. Analysis of specific-capacity data from wells of similar depth and yield in eastern Connecticut indicate average transmissivity of bedrock is 33 ft^2/day (3.1 m^2/day) (Randall and others, 1966, p. 63; Thomas and others, 1967, p. 61).

Natural recharge to the bedrock aquifer results largely from downward movement of water from till or stratified drift on hills and slopes. Natural discharge occurs principally by upward movement through till and stratified drift in valleys to streams. Subsurface flow from bedrock to stratified drift is a source of recharge to the stratified-drift aquifer, and is discussed in a later section.

Till Aquifer

Saturated till constitutes an aquifer capable of yielding only small, and in places unreliable, supplies to large-diameter wells. Nevertheless, the till aquifer, which covers 70 percent of the Branch River basin upstream from the stream gage at Forestdale, is a source of water for many homes. A well dug several feet below the annual low water level can usually supply average domestic needs throughout the years.

Till is a very poorly sorted, nonstratified, dominantly sandy deposit composed of varying proportions of clay, silt, sand, gravel, and boulders. It covers the bedrock surface in uplands and occurs beneath the stratified-drift aquifer at most places in lowlands. It is as much as 130 ft (40 m) thick and averages about 20 ft (6.1 m).

A yield of 2 gpm (0.13 l/s) or less is typical of till wells in the study area (Richmond and Allen, 1951, p. 39), indicating that the capacity of the till aquifer to transmit water is low. Hydraulic conductivity of the till is probably similar to that in southern Rhode Island (Allen and others, 1966) where an average of 0.7 ft/day (0.21 m/day) was determined from a small number of pumping tests and laboratory analyses of sediment samples.

Till functions as a reservoir which absorbs several inches of precipitation annually. Much of this recharge is gradually discharged as ground-water runoff to nearby streams, or as ground-water flow to the underlying bedrock and adjacent bodies of stratified drift. This ground-water flow from till is a minor source of recharge to the stratified-drift aquifer and is discussed under the section on recharge to the stratified-drift aquifer.

Stratified-Drift Aquifer

Stratified drift consists of layers of sorted gravel, sand, silt, and clay that were deposited from glacial meltwaters. These materials cover about 30 percent of the basin, chiefly in valleys (pl. 1) which served as glacial melt-water channels. Areal extent, saturated thickness, and transmissivity of the stratified-drift aquifer in the Rhode Island part of the basin are shown on the geohydrologic map (pl. 1).

Saturated thickness of the stratified-drift aquifer generally is 40 to 60 ft (12 to 18 m) near the axes of principal stream valleys. Maximum known saturated thickness is at Chepachet, where a well 177 ft (54 m) deep penetrated 25 ft (7.6 m) of unsaturated and 110 ft (33 m) of saturated stratified drift and 42 ft (13 m) of bedrock.

Lithologic composition of the stratified drift is known from logs of 103 wells and borings and from examination of exposures. The aquifer consists chiefly of sand and gravel interbedded with a moderate amount of silt and very little clay. The sediments are moderately well to well sorted and occur in lenticular beds of small areal extent. In a few places, as in Chepachet River valley between Keech Pond and Chepachet, fine to medium sand, silt, and a few thin interbeds of clay cover as much as 50 ft (15 m) of coarse sand and gravel.

The water table slopes toward streams, ponds, swamps, and reservoirs, which are sites of ground-water discharge, as shown on water-table maps (Hahn and Hansen, 1961; Johnson, 1962). During dry weather in summer and fall, maximum depth to the water table is commonly no more than 10 ft (3 m) in areas of low topographic relief; it is as much as 50 ft (15 m) below the surface locally, however, in areas of moderately high relief. The water table fluctuates annually from 1 to 3 ft (0.3 to 0.9 m) in valley bottoms and from 7 to 10 ft (2.1 to 3 m) in hilly areas.

Storage and Transmission Characteristics

Specific yield and transmissivity are hydraulic characteristics that determine the capacity of an aquifer to store and transmit water. The specific yield of unconfined sand and gravel aquifers is generally between 10 and 25 percent (Johnson, 1967). An average specific yield of 20 percent is assumed for the stratified-drift aquifer in all subsequent computations. An aquifer having a specific yield of 20 percent will yield from storage about 42 million gallons (159 million litres) of water from an area of 1 mi^2 (2.6 km^2) over which the water table is lowered an average of 1 ft (0.3 m).

The stratified-drift aquifer in the basin contains several billion gallons of water in storage, much of which is available for use. Utilizing ground-water storage by lowering the water table several feet below normal late summer and fall level, however, will effectively stop all ground-water runoff from the aquifer area affected by pumping. In addition, during periods of low flow, most or all of the streamflow in the area affected by pumping may leak into the aquifer, resulting in lengthy periods of little or no streamflow.

In following sections, estimates are made of quantities of water that can be obtained from the stratified-drift aquifer without unduly depleting streamflow during periods of low flow. The estimates would not provide for optimum use of ground-water storage.

The ability of an aquifer to transmit water to wells is determined by its transmissivity. The transmissivity of the stratified-drift aquifer was estimated from lithologic logs of 103 wells and borings and from specific-capacity data for 5 wells. These estimates were used as control points in constructing a transmissivity map of the aquifer (pl. 1). Each layer in lithologic logs was assigned a value of hydraulic conductivity which was multiplied by saturated thickness of the layer to get transmissivity. Transmissivities of individual layers were then summed to get the transmissivity of the part of the aquifer described in the log. Hydraulic conductivity was estimated from a relationship between aquifer test data and lithologic logs in southeastern Rhode Island (Rosenshein and others, 1968, p. 10).

Material	Hydraulic conductivity (ft/day)	(m/day)
Gravel	470	143
Sand and gravel	200	61
Sand	110	34
Fine sand	50	15

Specific capacity, expressed in gallons per minute per foot of drawdown, is determined in part by the ability of an aquifer to transmit water and may be used to estimate transmissivity. Derivation of transmissivity from specific capacity is not exact because drawdown is commonly affected by head loss related to well construction characteristics, partial penetration of the aquifer by the well, dewatering of the aquifer, and geohydrologic boundaries. The combined effect of these factors is usually to decrease specific capacity, and transmissivity computed from unadjusted specific capacity is usually less than the actual transmissivity of the aquifer near the well.

The estimates of transmissivity (table 1) are based on specific-capacity data computed from drawdowns that have been reduced to account for effects of well loss, partial penetration, and dewatering (Walton, 1962). Average hydraulic conductivity (transmissivity divided by saturated thickness) computed from specific-capacity data is in reasonable agreement with that computed from lithologic logs of borings near the pumped wells (table 1).

Hydraulic conductivity of the aquifer determined from all lithologic logs and specific-capacity data ranges from 13 to 480 ft/day (4 to 146 m/day) and averages 170 ft/day (52 m/day).

Table 1.--Transmissivity and average hydraulic conductivity of stratified-drift aquifer estimated from specific-capacity data and lithologic logs
(See plate 1 for location of wells and page v for metric conversion factors)

Well no.	Bur 9	Bur 149	Bur 359	Nsm 310		Nsm 356
Diameter of well (in)	12	12	24	8[a]	24	24
Pumping rate (gpm)	350	350	400	500	675	353
Length of test (hrs)	29	8	20	120	47	93
Reported drawdown (ft)	17	8	18.9	30.8	39.5	28.5
Drawdown, adjusted[b] (ft)	9.3	4.8	9.1	13.3	16.1	13.9
Specific capacity, adjusted (gpm/ft)	37	72	44	37	42	25
Transmissivity, estimated (ft^2/day)	7,100	12,900	7,800	8,400	6,800	4,900
Saturated thickness of aquifer (ft)	38	27	30	59	59	48
Average hydraulic conductivity, estimated (ft/day)	190	480	250	150	115	100
Average hydraulic conductivity, estimated from lithologic logs[c] (ft/day)	210	210	160	150	150	100

[a] 8-in casing and screen removed for construction of 24-in gravel-packed well.
[b] Drawdown adjusted for well loss, dewatering, and partial penetration.
[c] Number of lithologic logs in immediate vicinity of pumped well used to obtain average hydraulic conductivity: Bur 9, 15 wells; Bur 149, 5 wells; Bur 359, 7 wells; Nsm 310, 6 wells; and Nsm 356, 2 wells.

Natural Recharge and Discharge

Natural recharge to the stratified-drift aquifer results from infiltration and percolation of precipitation to the water table and from subsurface inflow from till and bedrock. Natural discharge occurs as ground-water runoff to streams, ground-water evapotranspiration, and subsurface outflow from the basin.

Recharge to the aquifer is equal to discharge plus or minus changes in aquifer storage. Over a period of many years, however, net changes in storage in an undeveloped aquifer tend to be so small that average annual recharge is effectively equal to average annual discharge.

In the section on components of runoff, ground-water discharge to streams is estimated to average 1.0 mgd/mi^2 [0.17 $(m^3/s)/km^2$] or 21 in (53 cm) annually. Ground-water evapotranspiration is estimated to average 0.1 mgd/mi^2 [0.002 $(m^3/s)/km^2$] or 2 in (5.1 cm) annually, similar to that determined in southeastern Rhode Island (Rosenshein and others, 1968) for Annaquatucket River basin which is largely covered by stratified drift. Discharge from the aquifer as ground-water underflow beneath Branch River at Forestdale is negligible. Average annual discharge and recharge are, therefore, estimated to be 1.1 mgd/mi^2 [0.019 $(m^3/s)/km^2$] or 23 in (58 cm) annually.

That part of the 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. The equation may be expressed in the form $Q = TIL$; where Q is flow, in ft^3/day; T is transmissivity, in ft^2/day; I is hydraulic gradient in ft/ft; and L is length, in ft, of the section through which flow occurs.

Average transmissivity of the till is estimated to be 3.5 ft^2/day (0.3 m^2/day), the product of the previous estimate of hydraulic conductivity of 0.7 ft/day (0.2 m/day) for till and estimated average saturated thickness of 5 ft (1.5 m). Average transmissivity of the bedrock is assumed equal to the previous estimate of 33 ft^2/day (3.1 m^2/day). 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 (0.04 m/m), or about 200 ft/mi (38 m/km).

Substituting these values into the above equation gives values for ground-water inflow to the stratified-drift aquifer of 740 $ft^3/day/mi$ (13 $m^3/day/km$), from the till aquifer and 7,000 $ft^3/day/mi$ (123 $m^3/day/km$), from the bedrock aquifer. The perimeter of the stratified-drift aquifer above the stream gage at Forestdale, including the part of the basin in Massachusetts, is about 116 mi (187 km). Total ground-water inflow is, therefore, about 0.9 million cubic feet per day, or 6.7 mgd (0.29 m^3/s). This is the equivalent of about 5.3 in (135 mm) of recharge annually to the 26.5 mi^2 (68.6 km^2) of stratified-drift aquifer above the gage.

These calculations indicate about 23 percent of natural recharge to the stratified-drift aquifer is from ground-water inflow from till and bedrock. The remaining 77 percent is from infiltration of precipitation.

From a practical standpoint recharge available for development by wells is equal to ground-water runoff. Discharge of ground water to the atmosphere by evapotranspiration may be prevented if the water table is lowered below roots of plants. However, prevention of substantial amounts of ground-water evapotranspiration would require that the water table be lowered several feet below streambeds throughout the growing season resulting in periods of little or no streamflow for periods of 6 months or more.

Recharge from Induced Infiltration

Water flows naturally from the stratified-drift aquifer to the streams. Reversal of the water-table gradients by pumping from wells will reduce the ground-water runoff to streams and, if the duration of pumping is sufficient, it will cause the water to move from the stream into the aquifer. The most heavily pumped wells will derive a significant part of their yield from this induced infiltration, because the sites that are favorable for high-capacity wells are generally no more than a few hundred feet from a stream.

The cone of influence of a continuously pumping well close to a stream having a good hydraulic connection with the aquifer will spread beneath the stream until sufficient head loss and streambed area are developed to cause the water to infiltrate the aquifer at a rate nearly equal to the pumping rate. Under such conditions, the cone of influence will stabilize, and the well yield will be sustained largely by induced infiltration (Walton, 1964).

In the narrow parts of the aquifer along the Branch River, well yields will be supported mainly by induced infiltration because the aquifer storage is too small to support large withdrawals. Consequently, the maximum dependable yield will be governed chiefly by low streamflow entering the area of pumping influence or by the amount of infiltration that can be induced.

The amount of infiltration induced is dependent largely upon the vertical hydraulic conductivity of the streambed, the viscosity of the water as determined by its temperature, the streambed area of infiltration, the position of the water table beneath the stream, and the hydraulic properties of the aquifer.

The reported measurements of the infiltration rates of streambeds in New England are scant. Rosenshein and others (1968), using a pumping test method, determined the hydraulic conductivities of 3 and 16 ft/day (0.9 and 4.9 m/day) for the sand and gravel bed of a river in southeastern Rhode Island. These would permit infiltration at rates of 0.87 and 5.66 mgd/acre/ft of head loss [2.87 and 18.7 $(m^3/s)/km^2/m$], respectively. Ryder and others (1970), by direct measurement of the streamflow loss, determined an infiltration rate equivalent to 2.57 mgd/acre/ft of head loss [8.47 $(m^3/s)/km^2/m$] at 10°C for a streambed consisting of sand and gravel in southwestern Connecticut. These values are generally higher than those which have been obtained for streams in glaciated areas in other parts of the country and perhaps are not representative of the average conditions in the study area. Schicht (1965), for example, lists the infiltration rates (adjusted to a stream temperature of 4°C) for eight stream reaches in Illinois, Indiana, and Ohio that range from 0.037 to 1.010 mgd/acre/ft of head loss [0.12 to 3.33 $(m^3/s)/km^2/m$]; the median is 0.183 mgd/acre/ft of head loss [0.60 $(m^3/s)/km^2/m$].

The beds of streams that drain the stratified-drift aquifer consist chiefly of sand and gravel. The infiltration rates of these streambeds very likely are within the ranges of 0.037 to 5.66 mgd/acre/ft of head loss [0.12 to 18.7 $(m^3/s)/km^2/m$]. For purposes of computing the recharge from the induced infiltration, a value of 0.2 mgd/acre/ft of head loss [0.66 $(m^3/s)/km^2/m$] was assumed. Bottoms of reservoirs and other stream impoundments are subject to less scour than streambeds and their infiltration rates per foot of head loss are expected to be smaller. Accordingly, a value of 0.04 mgd/acre/ft of head loss [0.13 $(m^3/s)/km^2/m$] was assumed for them.

Computations of potential recharge from induced infiltration can be made by the following equation (Schicht, 1965, p. 50):

$$R_i = I_t s_r A_r$$

where

R_i = potential recharge by induced infiltration, in mgd
I_t = average infiltration rate of streambed for a particular surface water temperature, in mgd/acre/ft
s_r = average head loss within streambed area of infiltration or average depth of water in stream for a particular stream stage, depending upon the position of the water table, in ft
A_r = streambed area of infiltration, in acres

The maximum potential infiltration for a given stream reach and the infiltration rate can be approximated by substituting average stream depth into the term s_r.

Ground-Water Withdrawals and Streamflow Depletion

Streamflow depletion caused by ground-water withdrawals from the stratified-drift aquifer is likely to be the most significant consequence of extensive ground-water development in the Branch River basin. During periods of low streamflow, large ground-water withdrawals may reduce natural streamflow below that required by downstream users for supply or waste dilution. If sustained withdrawal from a well exceeds flow in a nearby stream, the reach of stream within the cone of pumping influence may go dry.

The impact of ground-water withdrawals on streamflow in the study area will be determined chiefly by the rate and duration of withdrawals, location of wells, and disposition of the pumped water.

The relation of stream depletion to duration of pumping, and the distance between a well and stream, can be estimated from graphs (fig. 6) constructed from an equation by C. V. Theis (1941). Distances and hydraulic characteristics used in constructing the graphs are representative of conditions likely to exist in the study area. In the example, if the source of recharge is a stream, streamflow is being reduced by an amount equal to 51 percent of the pumping rate.

Figure 6 shows that the greatest impact on streamflow will result from sustained pumping from wells placed close to streams. Ultimately, of course, withdrawal of water from any well in the Branch River basin, if not returned to the basin, will deplete streamflow by an amount approximately equal to that withdrawn.

Stream depletion caused by ground-water withdrawals can be minimized by (1) concentrating withdrawals in the lower part of the basin where streamflow is large, (2) returning pumped water to streams near points of withdrawal, (3) pumping from wells no nearer than several hundred feet from streams during critically dry periods, and (4) releasing water from existing reservoirs during dry periods in amounts adequate to offset depletion.

Existing pumping centers are scattered, and most of the small amount of water pumped is returned to the ground through onsite disposal systems to become available for reuse. Ground-water withdrawals caused relatively little streamflow depletion in 1968.

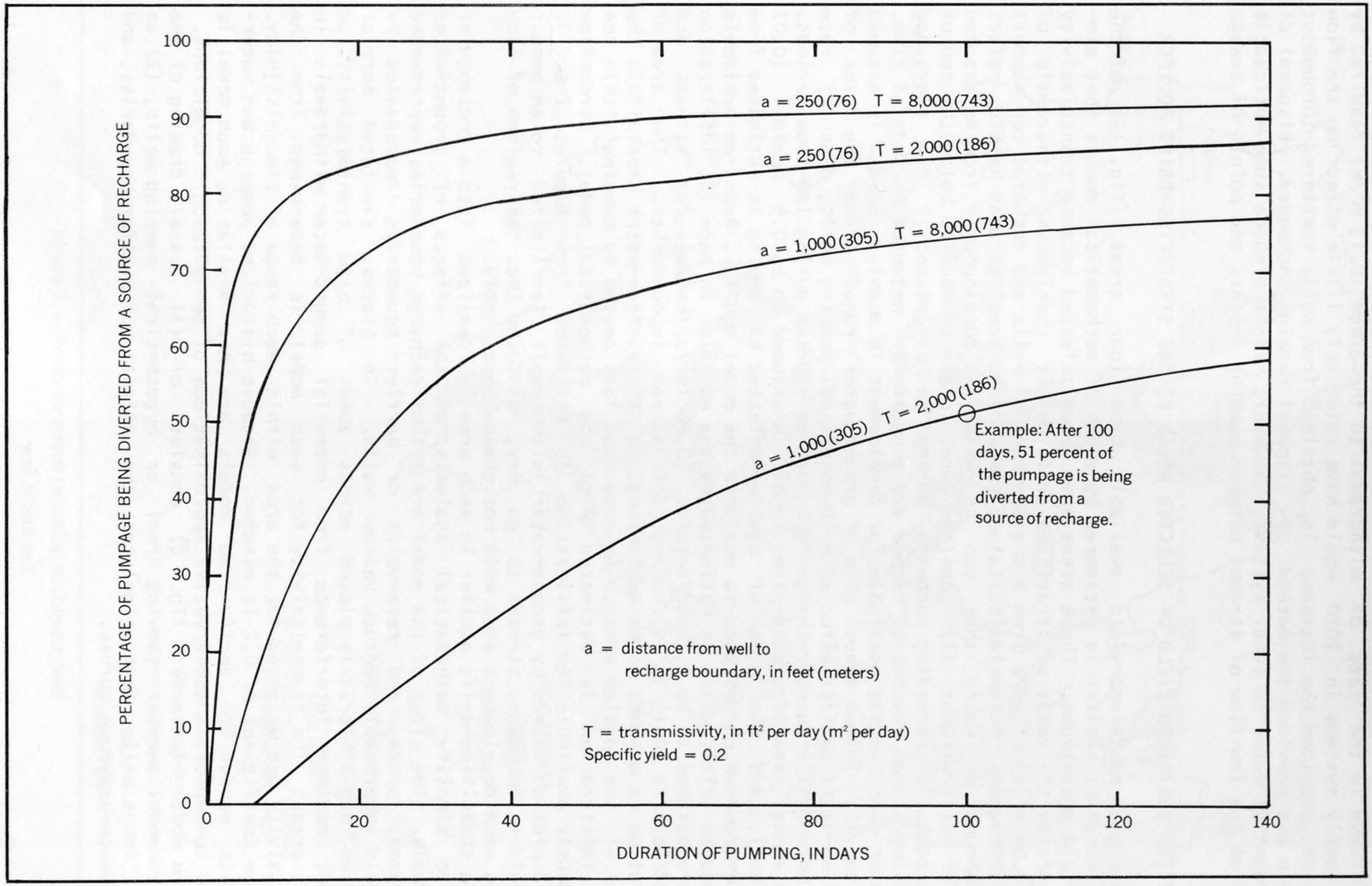

Figure 6. — Relation between duration of pumping and percentage of pumpage being diverted from a source of recharge for selected values of aquifer transmissivity and distance between a well and a recharge boundary.

Increase in the rate of withdrawal to the 3 mgd (0.13 m^3/s) required by public supply systems in 2020 would have relatively little effect on the flow of streams, provided the increase is obtained from wells scattered throughout the basin and provided the method of disposal remains unchanged. Disposal of this amount of water to sewer systems, however, might produce some noticeable effects on the low-flow of streams between pumping centers and points of sewage return.

POTENTIAL SUSTAINED YIELD OF SELECTED AREAS OF THE STRATIFIED-DRIFT AQUIFER

Potential sustained yield available from four areas (fig. 7) of the stratified-drift aquifer is estimated by means of mathematical models that simulate field conditions. These areas have been selected because transmissivity and saturated thickness of stratified drift permit continuous withdrawals of 1 mgd (0.04 m^3/s) or more from a small number of wells and recharge can support such withdrawals. Potential sustained yield of an area, as used herein, refers to the amount of water that can be withdrawn continuously from an assumed system of wells without (1) causing water levels to decline below the top of well screens, (2) exceeding recharge during an exceptionally dry year, and (3) causing stream reaches to become dry annually for extended periods of time.

Water continuously available for development in modeled areas is assumed equal to (1) minimum annual rate of ground-water runoff from the area of stratified-drift aquifer affected by hypothetical pumping wells, plus (2) rate of the potential induced recharge from surface sources during low-flow periods. Minimum annual rate of ground-water runoff is assumed to be 0.5 mgd/mi^2 [0.02 $(m^3/s)/km^2$], and the area of aquifer affected by pumping is estimated from distance-drawdown curves used to evaluate the model aquifer. Recharge available from induced infiltration is estimated by the equation on page 18. Infiltration rates are assumed to be 0.2 mgd/acre/ft [0.66 $(m^3/s)/km^2/m$] for streams and 0.04 mgd/acre/ft [0.13 $(m^3/s)/km^2/m$] for stream impoundments. The area of infiltration is assumed to be equivalent to the surface-water area within the confines of the modeled areas. Average head loss caused by pumping within the area of infiltration is estimated with the mathematical model. Streamflow continuously available for infiltration is estimated from figures 2 and 3. Stream depletion caused by ground-water withdrawals is limited to an amount that would seldom cause streams to go dry, assuming that the regimen of flow entering each development area will not change appreciably.

The stratified-drift aquifer in each area is idealized into a rectangular model to simplify mathematical analysis of the effects of ground-water withdrawals. The sides of the model are either recharge boundaries represented by streams, ponds, and reservoirs or barrier boundaries represented by relatively impermeable bedrock valley walls. In places, simulated barrier boundaries are arbitrarily placed across zones of high transmissivity to represent maximum interference from potential ground-water withdrawals in adjacent areas. The transmissivity for each model is determined from the transmissivity map weighted for the area within each range of transmissivity. A storage coefficient of 0.2 is assumed. Because historical pumpage and water-level data needed to verify the models are not available, each model is designed to represent conservative approximations of geohydrologic conditions.

Each model (example, fig. 8) consists of (1) a scale drawing of the idealized model aquifer showing real or hypothetical pumping wells, (2) an array of image wells that simulates the effects of aquifer boundaries, and (3) distance-drawdown curves.

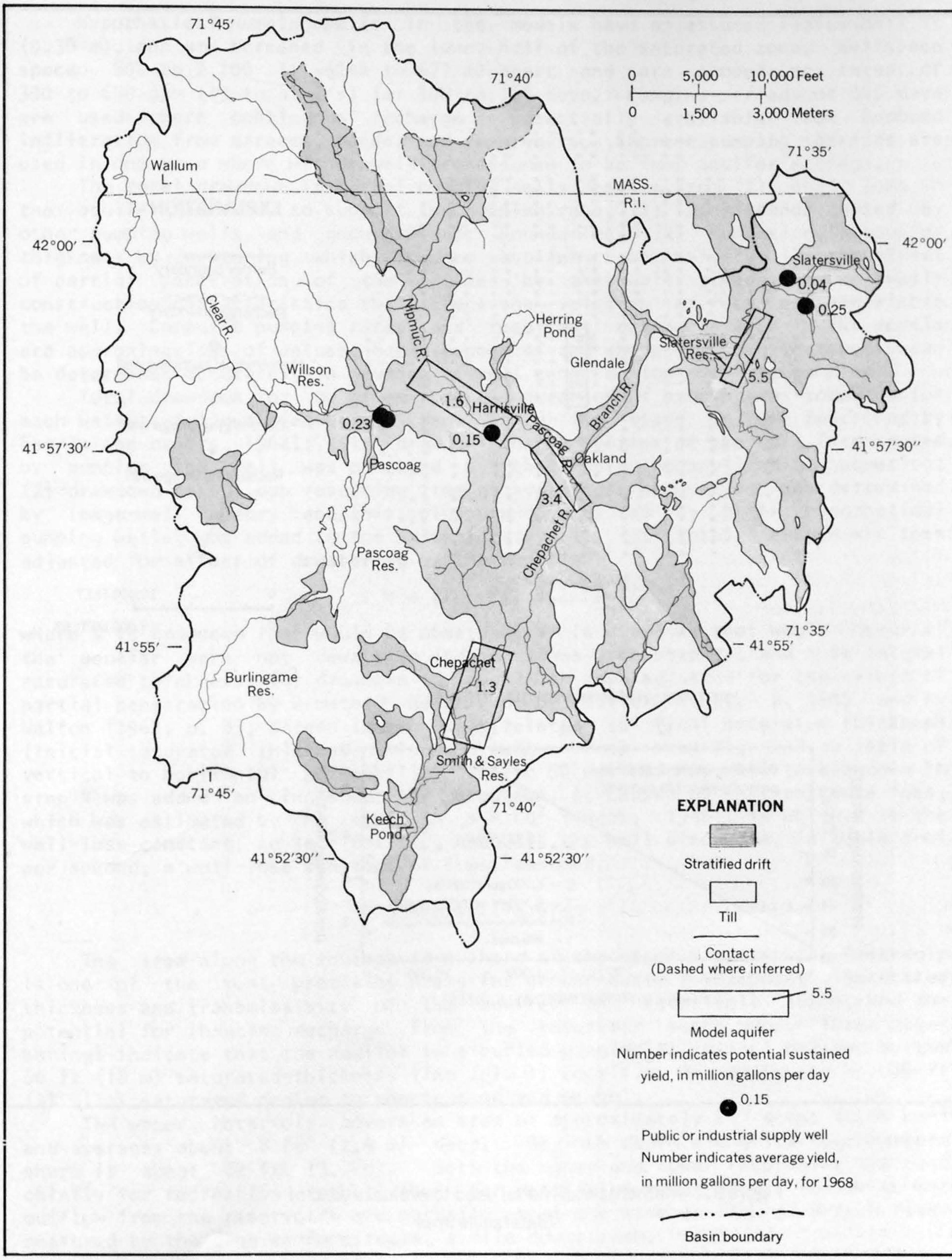

Figure 7. — Areas for which potential sustained yield was evaluated.

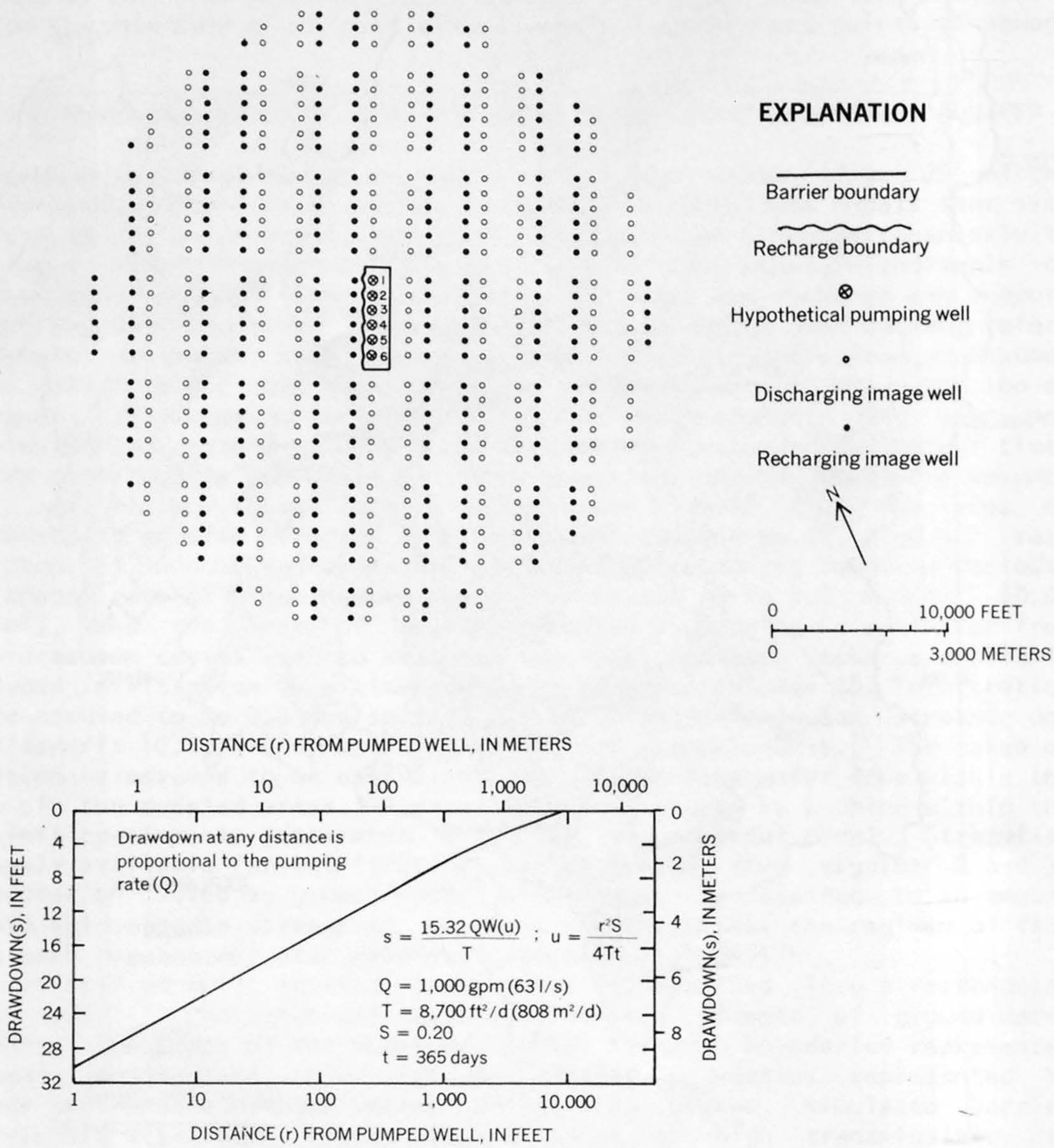

Figure 8. — Mathematical model used to evaluate yield of Slatersville area.

Hypothetical pumping wells in the models have an assumed radius of 1 ft (0.30 m), and are screened in the lower half of the saturated zone. Wells are spaced 800 to 2,200 ft (244 to 671 m) apart and are pumped at rates of 300 to 650 gpm (19 to 41 l/s) for 100 to 365 days. Pumping periods of 365 days are used where continuous recharge is potentially available from induced infiltration from streams, ponds, and reservoirs. Shorter pumping periods are used in one area where withdrawals are assumed to be from aquifer storage.

The total drawdown in actual pumping wells results from (1) head loss in the aquifer necessary to support the pumping rate, (2) interference caused by other pumping wells and geohydrologic boundaries, (3) reduction in aquifer thickness by dewatering, which reduces aquifer transmissivity, (4) the effect of partial penetration of the aquifer by the well screen, and (5) well-construction characteristics that affect the velocity of flow into and within the well. Computed pumping rates and resultant drawdowns used in the models are approximations of values, because none of the above drawdown increments can be determined accurately in advance of well construction and test pumping.

Total drawdown for a given rate and duration of pumping was computed for each well as follows (equations and theory for steps 1-3 are described by Ferris and others, 1962): (1) drawdown in the aquifer at the well face caused by pumping the well was computed by the Theis nonequilibrium equation; (2) drawdown or buildup resulting from geohydrologic boundaries was determined by image-well theory and this, plus drawdown caused by other hypothetical pumping wells, was added to the value in step 1; (3) total drawdown was then adjusted for effect of dewatering by the equation

$$s = m\left[1 - \sqrt{(1 - 2s'/m)}\right]$$

where s is drawdown that would be observed, s' is drawdown that would occur if the aquifer were not dewatered (the drawdown from step 2), and m is initial saturated thickness; (4) drawdown in step 3 was then adjusted for the effect of partial penetration by a method described by Butler (1957, p. 160) and by Walton (1962, p. 8); screen length was related to final saturated thickness (initial saturated thickness minus drawdown from step 3), and a ratio of vertical to horizontal permeability of 1 to 50 was assumed; (5) to drawdown in step 4 was added an increment of drawdown, s, caused by well-entrance loss, which was estimated by the equation $s = CQ^2$ (Jacob, 1946), in which C is the well-loss constant, in sec^2 per ft^5, and Q is the well discharge, in cubic feet per second; a well-loss constant of 1 was assumed.

Slatersville Area

The area along the southeastern shore of the upper Slatersville Reservoir is one of the most promising areas for ground-water development. Saturated thickness and transmissivity of the aquifer are relatively large, and the potential for inducing recharge from the reservoir seems good. Three auger borings indicate that the aquifer in a buried preglacial channel defined by the 60 ft (18 m) saturated-thickness line (pl. 1) consists of as much as 75 ft (23 m) of saturated medium to coarse sand and gravel.

The upper reservoir covers an area of approximately 147 acres (0.59 km^2) and averages about 8 ft (2.4 m) deep. Maximum depth along its southeastern shore is about 12 ft (3.7 m). Both the upper and lower reservoirs are used chiefly for recreation rather than for regulating river flow. Inflow to and outflow from the reservoirs are normally about the same as flow of Branch River measured by the gage at Forestdale, a mile downstream.

The water which is available for infiltration from surface inflow to the reservoir and reservoir storage is larger than can be developed by wells. The surface inflow to the reservoir is 76 mgd (3.3 m^3/s) for more than 50 percent of the time and 9 mgd (0.4 m^3/s) for more than 99 percent of the time (fig. 2). The ground-water runoff available for development during dry years from an area of 0.5 mi^2 (1.3 km^2) of stratified drift is about 0.25 mgd (0.01 m^3/s).

The model aquifer (fig. 9) used to evaluate potential sustained yield of the Slatersville area is designed to simulate the hydraulic connection between the aquifer and the overlying surface reservoir. A weighted transmissivity of 8,700 ft^2/day (810 m^2/day) is assumed. A recharge boundary simulates recharge from a reservoir area of about 65 acres (0.3 km^2).

Simulated withdrawals (table 2) from a line of six wells close to the reservoir and spaced 800 ft (244 m) apart indicate that a continuous yield of as much as 5.5 mgd (0.24 m^3/s) is obtainable. At a withdrawal rate of 5.5 mgd (0.24 m^3/s), drawdown beneath the reservoir would result in infiltration of nearly 8 mgd (0.35 m^3/s) if the infiltration rate of the reservoir bottom is 0.04 mgd/acre/ft of head loss [0.13 (m^3/s)/km^2/m], as assumed. Since the potential rate of infiltration exceeds the design withdrawal rate, model results are probably reasonable.

Sustained ground-water withdrawal of 5.5 mgd (0.24 m^3/s) will deplete surface outflow from upper and lower Slatersville Reservoirs by nearly the same rate. Low flow of the Branch River at Forestdale (fig. 3) is 7.1 mgd (0.31 m^3/s) on the average of once every 25 years. Thus, if runoff continues as in the past, withdrawal of 5.5 mgd (0.24 m^3/s) will seldom, if ever, cause outflow from reservoirs to cease.

Table 2.--Summary of data obtained from mathematical model of the Slatersville area at a withdrawal rate of 5.5 mgd

(Pumping rate, six wells at 640 gpm* each; pumping period, 365 days; effective radius of well, 1 ft; screen length, 25 ft; water available above top of screen, 35 ft; drawdown data are given in feet; see page v for metric conversion factors.)

Hypothetical pumping well	Drawdown due to: Aquifer loss and interference	Drawdown due to: Aquifer dewatering	Drawdown due to: Partial penetration	Drawdown due to: Well loss	Total drawdown in pumped well	Remaining drawdown available above top of screen
1	18.36	4.30	6.02	2.03	30.71	4.29
2	19.12	4.73	5.59	2.03	31.47	3.53
3	19.62	5.20	5.45	2.03	32.30	2.70
4	19.62	5.20	5.45	2.03	32.30	2.70
5	19.12	4.73	5.59	2.03	31.47	3.53
6	18.36	4.30	6.02	2.03	30.71	4.29

*Total withdrawal, 3,840 gpm (5.5 mgd).

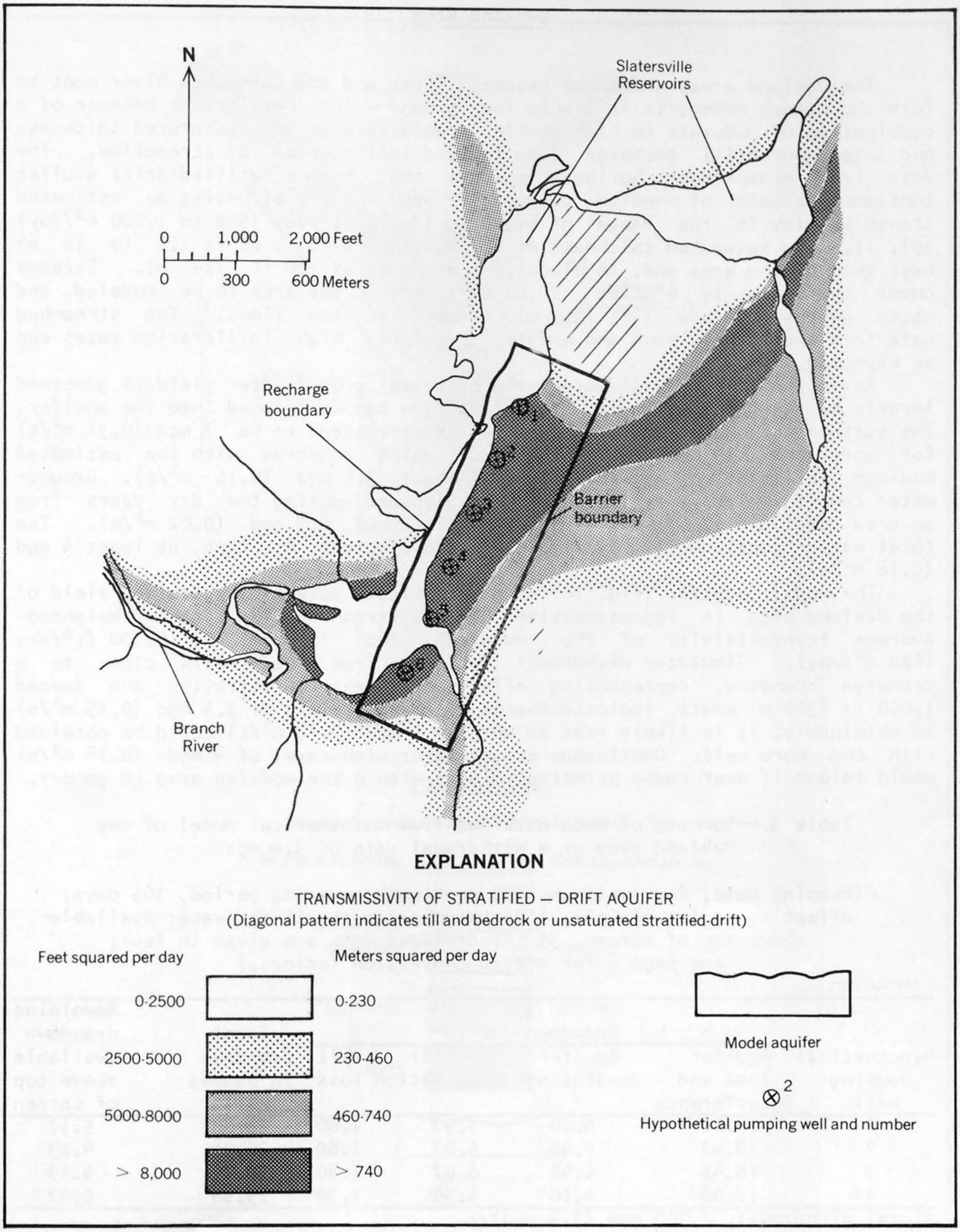

Figure 9. — Model aquifer of the Slatersville area.

The Oakland area, where the Pascoag River and the Chepachet River meet to form the Branch River, is favorable for ground-water development because of a combination of moderate to high aquifer transmissivity and saturated thickness and large potential recharge from induced infiltration of streamflow. The data from nine auger borings indicate that the stratified-drift aquifer consists largely of medium to coarse sand and gravel having an estimated transmissivity in the range of 6,300 to 13,000 ft^2/day (590 to 1,200 m^2/day) (pl. 1). The saturated thickness of the aquifer is 40 to 60 ft (12 to 18 m) over much of the area and, in places, is as great as 80 ft (24 m). Streams cover approximately 6 acres (0.02 km^2) within the area to be modeled, and water depths average 3 ft (0.9 m) or more at low flows. The streambed materials are largely sand and gravel; therefore, high infiltration rates can be expected.

As in the Slatersville area, the potential ground-water yield is governed largely by the rate at which the streamflow can be induced into the aquifer. The surface inflow to the modeled area is estimated to be 7 mgd (0.31 m^3/s) for more than 99 percent of the time, which compares with the estimated maximum infiltration at low flow of about 3.6 mgd (0.16 m^3/s). Ground-water runoff which is available for development during the dry years from an area of 1 mi^2 (2.6 km^2) of aquifer is about 0.5 mgd (0.02 m^3/s). The total water continuously available for development is, then, at least 4 mgd (0.18 m^3/s).

The model aquifer (fig. 10) used to evaluate potential sustained yield of the Oakland area is representative of the stream-aquifer system. Weighted-average transmissivity of the modeled area (pl. 1) is 6,700 ft^2/day (620 m^2/day). Simulated withdrawal (table 3) from four wells close to a recharge boundary, representing effects of stream infiltration and spaced 1,000 ft (300 m) apart, indicate that a continuous yield of 3.4 mgd (0.15 m^3/s) is obtainable. It is likely that as much as 4 mgd (0.18 m^3/s) could be obtained with one more well. Continuous ground-water withdrawal of 4 mgd (0.18 m^3/s) would seldom if ever cause principal rivers within the modeled area to go dry.

Table 3.--Summary of data obtained from mathematical model of the Oakland area at a withdrawal rate of 3.4 mgd

(Pumping rate, four wells at 590 gpm* each; pumping period, 365 days; effective radius of well, 1 ft; screen length, 25 ft; water available above top of screen, 35 ft; drawdown data are given in feet; see page v for metric conversion factors.)

Hypothetical pumping well	Drawdown due to: Aquifer loss and interference	Drawdown due to: Aquifer dewatering	Drawdown due to: Partial penetration	Drawdown due to: Well loss	Total drawdown in pumped well	Remaining drawdown available above top of screen
1	18.08	4.10	5.90	1.80	29.88	5.12
2	18.42	4.42	6.07	1.80	30.71	4.29
3	18.42	4.42	6.07	1.80	30.71	4.29
4	18.08	4.10	5.90	1.80	29.88	5.12

*Total withdrawal, 2,360 gpm (3.4 mgd).

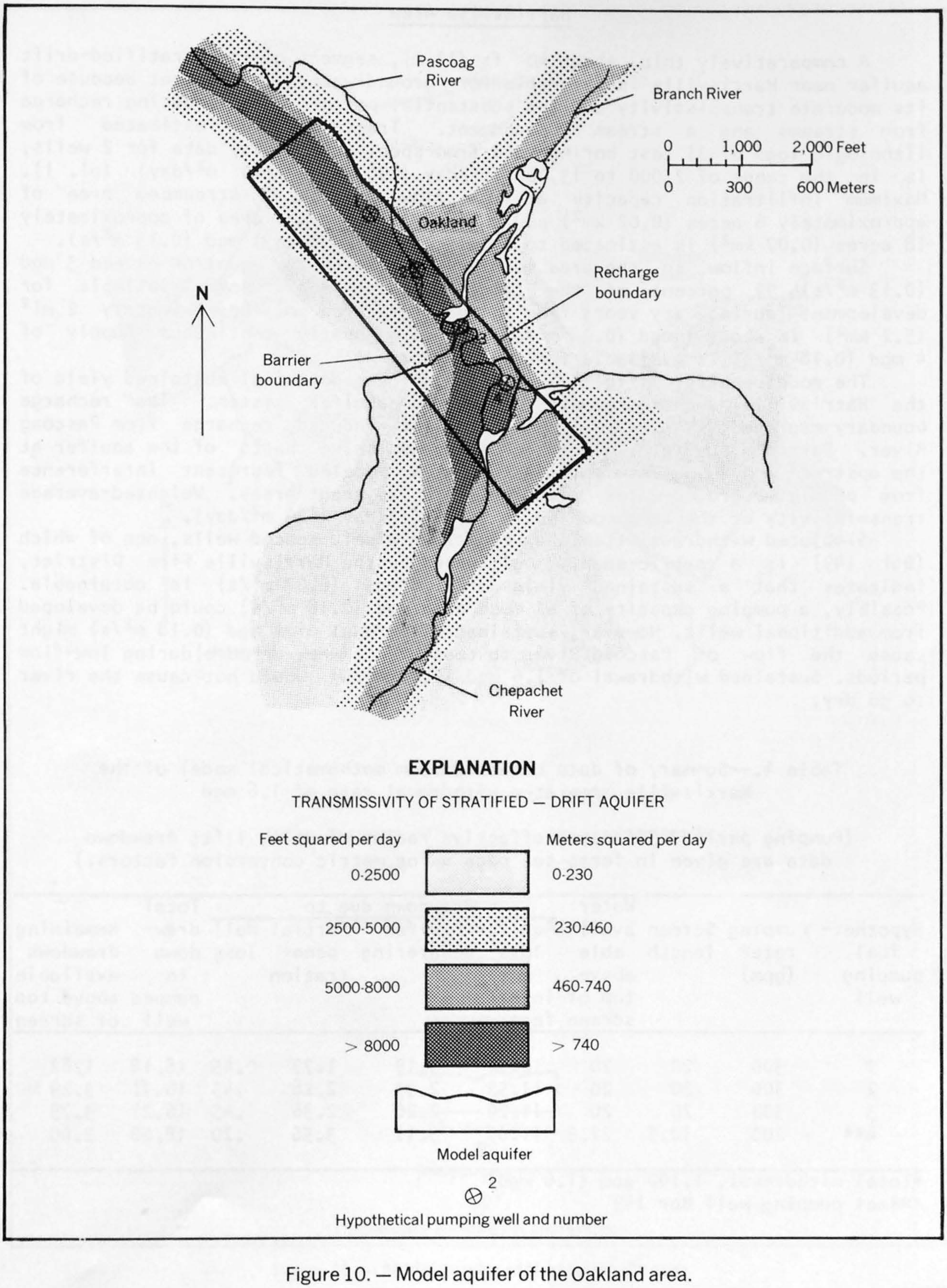

Figure 10. — Model aquifer of the Oakland area.

Harrisville Area

A comparatively thin, about 40 ft (12 m), segment of the stratified-drift aquifer near Harrisville is favorable for ground-water development because of its moderate transmissivity and the substantial potential for inducing recharge from streams and a stream impoundment. Transmissivity, estimated from lithologic logs of 31 test borings and from specific-capacity data for 2 wells, is in the range of 2,000 to 13,000 ft^2/day (190 to 1,200 m^2/day) (pl. 1). Maximum infiltration capacity at low flow through a streambed area of approximately 6 acres (0.02 km^2) and a stream-impoundment area of approximately 18 acres (0.07 km^2) is estimated to be slightly more than 3 mgd (0.13 m^3/s).

Surface inflow to the area modeled is estimated to equal or exceed 3 mgd (0.13 m^3/s) 99 percent of the time. Ground-water runoff available for development during dry years from an aquifer area of approximately 2 mi^2 (5.2 km^2) is about 1 mgd (0.04 m^3/s). Thus, a nearly continuous supply of 4 mgd (0.18 m^3/s) is available for development.

The model aquifer (fig. 11) used to evaluate potential sustained yield of the Harrisville area represents the stream-aquifer system. The recharge boundary represents the approximate effect of induced recharge from Pascoag River. Barrier boundaries placed across transmissive parts of the aquifer at the upstream and downstream ends of the area modeled represent interference from possible ground-water withdrawal in adjacent areas. Weighted-average transmissivity of the area modeled is 6,700 ft^2/day (620 m^2/day).

Simulated withdrawal (table 4) from four widely spaced wells, one of which (Bur 149) is a public-supply well owned by the Harrisville Fire District, indicates that a sustained yield of 1.6 mgd (0.07 m^3/s) is obtainable. Possibly, a pumping capacity of as much as 4 mgd (0.18 m^3/s) could be developed from additional wells. However, sustained withdrawal of 4 mgd (0.18 m^3/s) might cause the flow of Pascoag River to cease for a week or more during low-flow periods. Sustained withdrawal of 1.6 mgd (0.07 m^3/s) would not cause the river to go dry.

Table 4.--Summary of data obtained from mathematical model of the Harrisville area at a withdrawal rate of 1.6 mgd

(Pumping period, 365 days; effective radius of well, 1 ft; drawdown data are given in feet; see page v for metric conversion factors.)

Hypothetical pumping well	Pumping rate* (gpm)	Screen length	Water available above top of screen	Drawdown due to: Aquifer loss and interference	Drawdown due to: Aquifer dewatering	Drawdown due to: Partial penetration	Drawdown due to: Well loss	Total drawdown in pumped well	Remaining drawdown available above top of screen
1	300	20	20	12.77	3.19	1.77	0.45	18.18	1.82
2	300	20	20	11.59	2.39	2.28	.45	16.71	3.29
3	300	20	20	11.20	2.20	2.36	.45	16.21	3.79
4**	200	10.5	21.5	11.07	3.17	3.56	.20	18.00	2.00

*Total withdrawal, 1,100 gpm (1.6 mgd)
**Real pumping well Bur 149

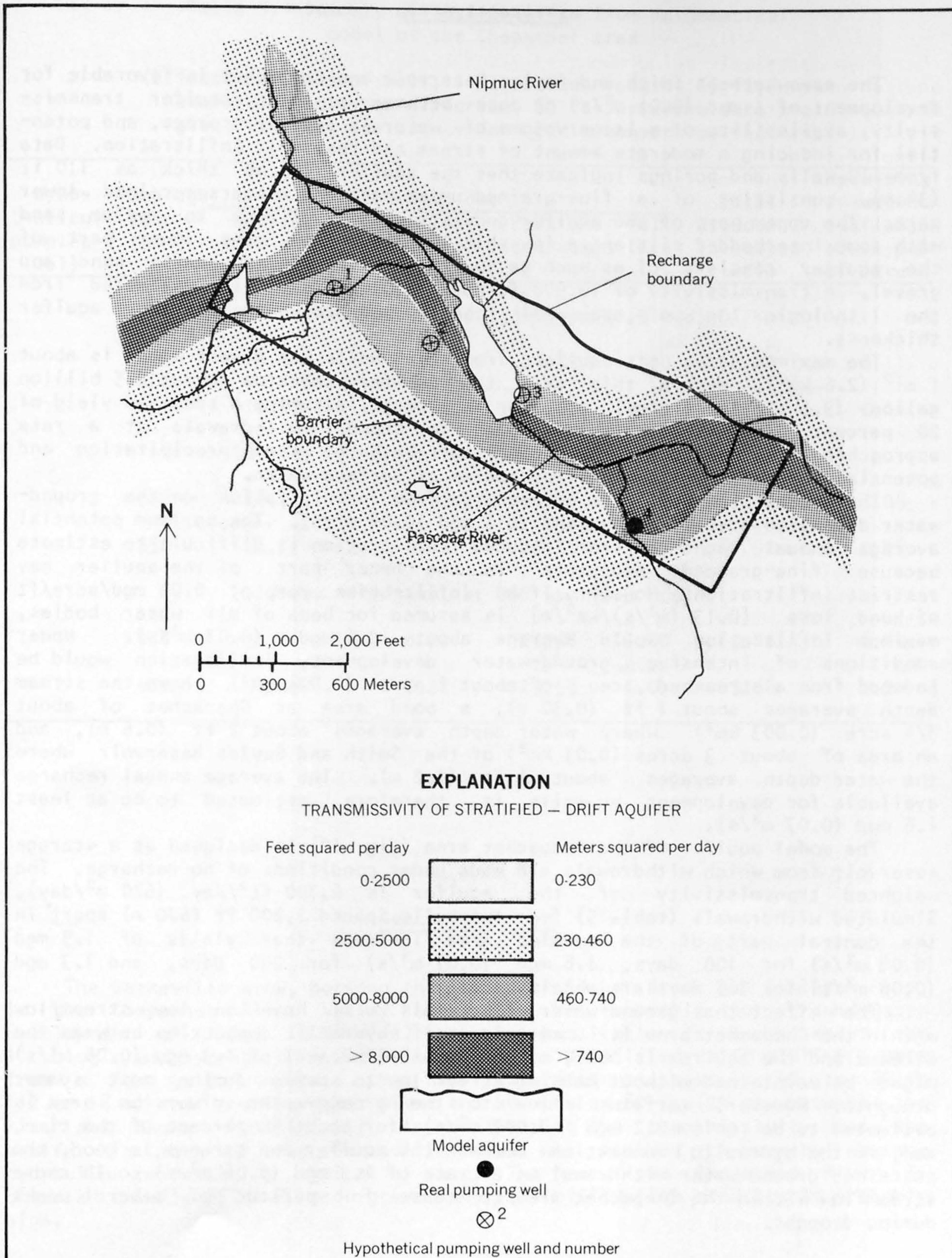

Figure 11. — Model aquifer of the Harrisville area.

Chepachet Area

The area between Smith and Sayles Reservoir and Chepachet is favorable for development of 1 mgd (0.04 m^3/s) or more because of high aquifer transmissivity, availability of a large volume of water in aquifer storage, and potential for inducing a moderate amount of stream and reservoir infiltration. Data from 12 wells and borings indicate that the aquifer is as thick as 110 ft (34 m), consisting of a fine-grained upper part and a coarse-grained lower part. The upper part of the aquifer consists chiefly of fine to medium sand with some interbedded silt and a few thin layers of clay. The lower part of the aquifer consists of as much as 50 ft (15 m) of fine to coarse sand and gravel. A transmissivity of 10,900 ft^2/day (1,010 m^2/day) is estimated from the lithologic log of one well that penetrates the entire aquifer thickness.

The maximum area of aquifer from which wells can divert water is about 1 mi^2 (2.6 km^2). Within this area the aquifer contains about 2.5 billion gallons (9.5 billion litres) of water in storage, assuming a specific yield of 20 percent. This is more than enough to support withdrawals at a rate approaching the average annual rate of recharge from precipitation and potential induced infiltration from bodies of surface water.

The average annual rate of recharge from precipitation on the ground-water diversion area is equivalent to 1 mgd (0.04 m^3/s). The maximum potential average annual recharge from induced infiltration is difficult to estimate because fine-grained sediments in the upper part of the aquifer may restrict infiltration. However, if an infiltration rate of 0.04 mgd/acre/ft of head loss [0.13 $(m^3/s)/km^2/m$] is assumed for beds of all water bodies, maximum infiltration would average about 0.6 mgd (0.03 m^3/s). Under conditions of intensive ground-water development, infiltration would be induced from a streambed area of about 1 acre (0.004 km^2) where the stream depth averages about 1 ft (0.30 m), a pond area at Chepachet of about 3/4 acre (0.003 km^2) where water depth averages about 2 ft (0.6 m), and an area of about 3 acres (0.01 km^2) of the Smith and Sayles Reservoir where the water depth averages about 4 ft (1.2 m). The average annual recharge available for development by wells is, therefore, estimated to be at least 1.6 mgd (0.07 m^3/s).

The model aquifer of the Chepachet area (fig. 12) is designed as a storage reservoir from which withdrawals are made under conditions of no recharge. The weighted transmissivity of the aquifer is 6,700 ft^2/day (620 m^2/day). Simulated withdrawals (table 5) from two wells spaced 2,200 ft (670 m) apart in the central part of the modeled area indicate that yields of 1.9 mgd (0.08 m^3/s) for 100 days, 1.6 mgd (0.07 m^3/s) for 200 days, and 1.3 mgd (0.06 m^3/s) for 365 days are obtainable.

The effect that ground-water withdrawals will have on low streamflow within the Chepachet area is uncertain. If hydraulic connection between the streams and the aquifer is poor, a continuous withdrawal of 1.3 mgd (0.06 m^3/s) might be maintained without causing streamflow to cease during most summer droughts. However, surface inflow to the ground-water diversion area is estimated to be only 0.2 mgd (0.009 m^3/s) for about 99 percent of the time, and, if the hydraulic connection between the aquifer and streams is good, the sustained ground-water withdrawal at a rate of 1.3 mgd (0.06 m^3/s) could cause streamflow within the Chepachet area to cease for periods of several weeks during drought.

Table 5.--Summary of data obtained from mathematical model of the Chepachet area

(Effective radius of well, 1 ft; screen length, 25 ft; water available above top of screen, 65 ft; drawdown data are given in feet; see page v for metric conversion factors.)

Hypo-thetical pumping well	Pumping rate (gpm)	Drawdown due to				Total drawdown in pumped well	Remaining drawdown available above top of screen
		Aquifer loss and interference	Aquifer dewatering	Partial penetration	Well loss		
100-day withdrawal at 1,300 gpm (1.9 mgd)							
1	650	26.91	6.03	23.85	2.10	58.89	6.11
2	650	26.91	6.03	23.85	2.10	58.89	6.11
200-day withdrawal at 1,100 gpm (1.6 mgd)							
1	550	28.22	6.83	25.38	1.49	61.92	3.08
2	550	28.22	6.83	25.38	1.49	61.92	3.08
365-day withdrawal at 900 gpm (1.3 mgd)							
1	450	30.26	8.22	23.58	1.00	63.06	1.94
2	450	30.26	8.22	23.58	1.0	63.06	1.94

Gazzaville Area

The Gazzaville area, between the mouth of Sucker Brook and Gilleran Pond, in the Chepachet River valley seems to be favorable for ground-water development of 1 mgd (0.04 m^3/s) or more, but little is known about the lithologic and hydraulic characteristics of the stratified-drift aquifer. Data from a few wells indicate that its saturated thickness is 40 to 60 ft (12 to 18 m) near the Chepachet River and as much as 80 ft (24 m) between the river and Sucker Pond (pl. 1). In constructing the transmissivity map, the aquifer in much of the Gazzaville area was assumed to have an average hydraulic conductivity typical of sand. The bed of the Chepachet River is composed chiefly of sand and gravel and its infiltration capacity is probably high.

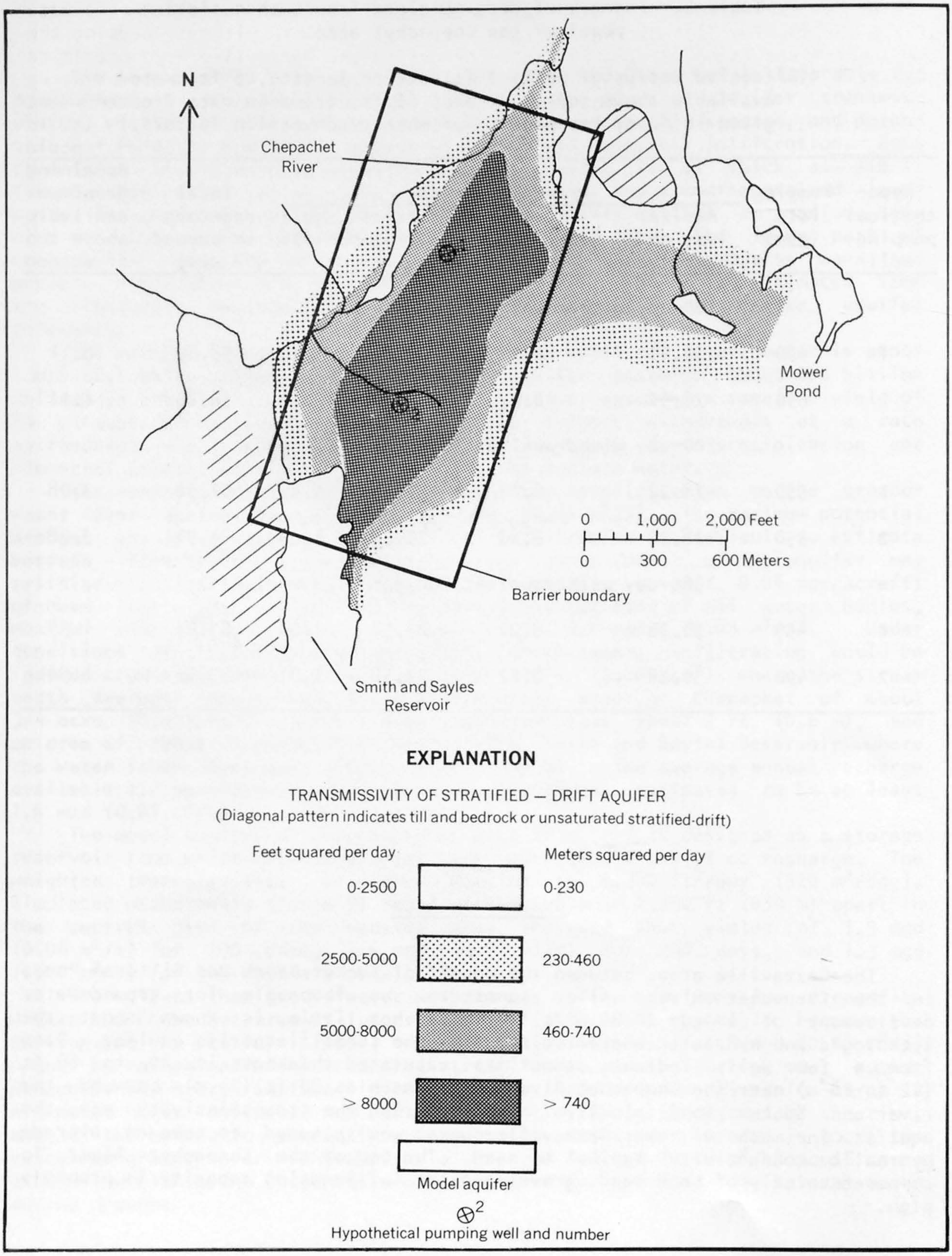

Figure 12. — Model aquifer of the Chepachet area.

It is estimated that ground-water withdrawal could be sustained at a rate of 1.5 mgd (0.07 m^3/s) during periods of dry weather without causing the Chepachet River to go dry. Surface inflow to the Gazzaville area equals or exceeds 1.8 mgd (0.08 m^3/s) 99 percent of the time (fig. 2) and ground-water runoff to the river below the gage is estimated to cause the 99-percent-duration flow at Gilleran Pond to be 2.0 mgd (0.09 m^3/s). It is probable that a combined pumping capacity in excess of 2 mgd (0.09 m^3/s) could be developed from several wells. Sustained withdrawal of as much as 2 mgd (0.09 m^3/s) during dry summer and fall months, however, might cause flow of the Chepachet River to cease for several days on the average of once every 10 years.

CHEMICAL QUALITY OF WATER

The chemical analyses of water from the stratified-drift aquifer indicate that it is suitable for most purposes. The water is soft and typically contains less than 100 mg/l (milligrams per litre) dissolved solids. The principal cations of calcium, magnesium, sodium, and potassium are generally present in concentrations less than 15 mg/l, and the principal anions of bicarbonate, sulfate, and chloride are generally present in concentrations less than 20 mg/l. Iron and manganese occur in concentrations less than or not greatly exceeding the respective limits of 0.3 and 0.05 mg/l recommended for these constituents in public water supplies (U.S. Public Health Service, 1962). The pH, a measure of the hydrogen-ion concentration, generally ranges from 5.5 to 7.0. The water in this pH range is generally somewhat corrosive.

Analyses of the samples collected from streams at 12 sites (figure 13, tables 6 and 7) in the basin during September 1968, at a time when the unregulated streamflow was virtually all ground-water runoff, indicate that the chemical quality of low streamflow was much the same as that of the ground water in the stratified-drift aquifer. However, concentrations of iron and manganese were somewhat higher in the stream samples than in the well samples. The median concentrations of iron and manganese were 0.03 and 0.05 mg/l, respectively, in the ground-water samples and 0.32 and 0.11 mg/l, respectively, in the surface-water samples. The general similarity in chemical quality of ground water and surface water indicates that only small amounts of the constituents in tables 6 and 7 are being added to streams as a result of human activities.

The quality of the Clear, Pascoag, and Branch Rivers is affected by industrial discharges, which consist largely of textile wastes. The stream reaches most affected are designated by the letters C and D on figure 13. The contaminants added to streamflow are chiefly organic, which is of significance where the well discharge is likely to be substantially derived from induced infiltration of streamflow. The suspended matter, turbidity, color, and bacteria associated with organic contaminants will be largely or entirely removed from the water as it infiltrates the streambeds and flows through aquifer materials to the wells. Most inorganic chemical constituents in surface water, on the other hand, will not be removed. Water from wells deriving most of their supply from the infiltration of water from streams and reservoirs will have an inorganic chemical composition similar to that of the surface-water body.

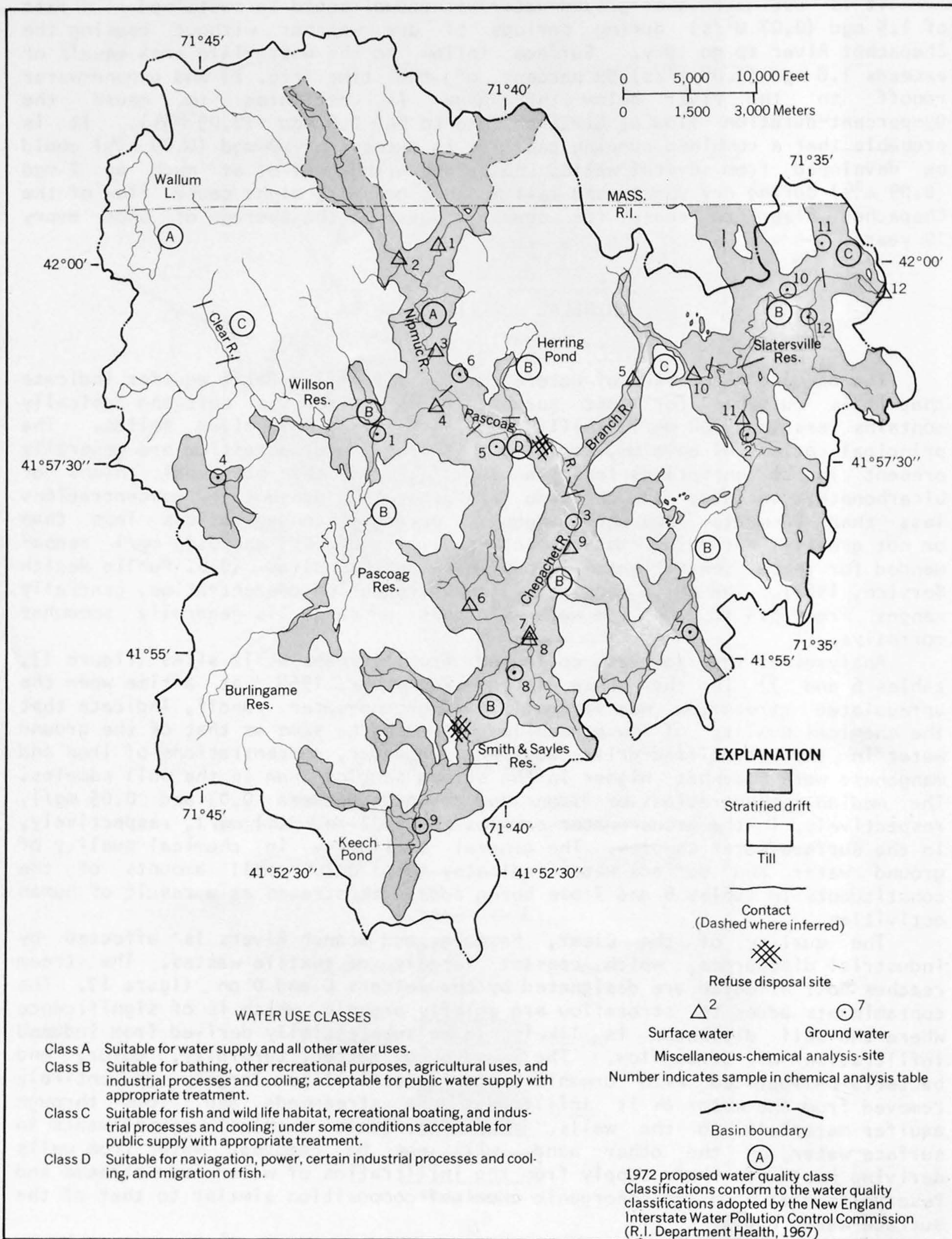

Figure 13. — Water quality classes proposed for stream reaches in the Branch River basin by the Rhode Island Department of Health and location of sampling sites for chemical analyses in tables 6 and 7.

Table 6.--Chemical analyses of water from selected wells

(Chemical analyses in milligrams per litre.)

Sample	Local well number	Water-bearing material	Date of collection	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (Residue on evaporation at 180°C)	Hardness as $CaCO_3$: Calcium, Magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos per cm at 25°C)	pH	Color
1	Bur 9	Sand and gravel	5-13-68	10	10	0.25	0.29	11	2.3	15	3.5	18	19	23	0	10	105	37	22	178	6.4	2
2	Bur 54	do.	5-15-68	11	7.3	.01	.04	4.3	1.0	5.8	1.3	10	7.0	11	.1	.2	48	14	6	73	6.4	3
3	Bur 69	Rock	5-13-68	12	19	.01	.05	12	1.4	8.0	1.2	48	3.8	7.0	.9	.4	84	36	0	113	7.0	2
4	Bur 124	Sand and gravel; rock	5-15-68	8	8.1	.02	.06	1.0	.4	2.2	.6	2	7.0	1.0	.2	.3	25	4	2	29	5.5	1
5	Bur 149	Sand and gravel	5-13-68	9	10	.01	.05	4.6	1.1	5.3	1.0	12	7.0	9.3	.1	.1	46	16	6	66	6.4	2
6	Bur 284	Sand and gravel; rock	5-14-68	12	8.3	.03	.12	5.5	.8	2.3	1.0	4	12	4.0	.2	0	42	16	14	51	5.8	0
7	Glo 28	Sand and gravel	5-15-68	11	4.8	.05	.04	7.3	1.2	8.0	1.2	12	16	11	.1	.0	60	23	13	98	6.4	3
8	Glo 293	Sand	5-15-68	9	6.9	.05	.04	5.0	.5	2.4	1.0	10	7.2	5.4	.1	.0	34	14	6	48	6.6	1
9	Glo 298	do.	5-14-68	20	10	.19	.07	3.0	.3	2.9	.8	16	2.2	1.0	.0	.0	34	8	0	39	6.6	1
10	(*)	Sand and gravel	5-14-68	10	7.4	.04	.06	7.1	1.0	26	1.4	8	9.4	45	.1	1.3	109	22	15	193	6.4	2
11	Nsm 183	do.	5-14-68	11	16	.00	.03	14	5.5	10	1.4	48	15	12	.1	14	117	58	18	177	6.9	2
12	Nsm 310	do.	5-14-68	10	12	.03	.22	4.5	.8	13.6	.8	16	5.0	3.8	.1	1.6	46	14	1	51	6.6	2

*Composite sample from well points Nsm 158, Nsm 159, Nsm 162, and Nsm 165-167.

Table 7.--Chemical analyses of water from selected streams

(Chemical analyses in milligrams per litre.)

Sample	Stream and location	Date of collection	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (Residue on evaporation at 180°C)	Hardness as $CaCO_3$		Specific conductance (micromhos per cm at 25°C)	pH	Color
																	Calcium, Magnesium	Noncarbonate			
1	Round Top Brook near Harrisville	9-4-68	19	6.5	0.37	0.19	3.2	0.7	4.4	0.6	9	6.3	7.1	0.0	0.2	32	11	4	51	7.1	5
2	Chockalog Brook near Harrisville	9-4-68	17	3.8	2.3	.12	3.1	.6	4.1	.7	8	4.3	7.1	.1	.7	40	10	4	45	6.5	90
3	Nipmuc River near Harrisville	9-4-68	17	6.6	.09	.13	4.6	1.0	5.7	.8	8	6.9	11	.1	.5	44	16	9	68	6.6	6
4	Clear River at Harrisville	9-4-68	20	1.4	.25	.14	4.0	.6	10	.9	4	9.2	16	.2	.1	48	12	10	84	6.0	5
5	Pascoag River at Oakland	9-4-68	19	2.7	.59	.11	4.9	.8	13	1.4	13	9.2	18	.2	.9	60	15	4	107	6.6	4
6	Sucker Brook at Chepachet	9-4-68	15	11	.21	.08	8.1	1.8	15	1.8	13	7.4	31	.1	2.2	95	28	17	149	6.7	5
7	Chepachet River at Chepachet	9-4-68	19	5.4	.33	.08	5.4	1.2	8.1	1.8	13	7.2	15	.1	.6	52	18	8	88	6.8	6
8	Tributary to Chepachet River at Chepachet	9-4-68	19	5.5	.33	.15	3.4	.7	4.9	.9	8	6.7	8.2	.1	.1	34	12	5	56	6.8	5
9	Chepachet River at Gazzaville	9-4-68	17	7.1	.17	.06	6.5	1.4	9.6	1.3	12	6.5	21	.1	.4	65	22	12	106	6.8	6
10	Branch River at Nasonville	9-4-68	20	4.1	.46	.09	5.4	1.1	12	1.3	12	8.4	19	.1	.6	61	18	8	107	6.8	6
11	Tarkiln Brook near Oak Valley	9-4-68	20	3.0	.32	.16	3.3	.7	4.7	.9	9	6.7	7.5	.1	.1	32	11	4	52	6.8	10
12	Branch River at Forestdale	9-4-68	22	.1	.21	.09	5.4	1.1	11	1.4	14	7.4	17	.2	.2	52	18	6	96	6.8	6

An indication of the organic content of streamflow of the Clear, Pascoag, and Branch Rivers is provided by analyses of a series of samples collected by Rhode Island Department of Health (1967) over a 2-day period during July 1966. Flows during this period were approximately equivalent to those equaled or exceeded 68 percent of the time. The average 5-day BOD (biochemical oxygen demand) load at 10 sampling sites ranged from 0.9 to 20 mg/l and was 5.0 mg/l, or more, at five sites. Concentration of coliform bacteria ranged from 23 per 100 ml (millilitres) to 2.4 million per 100 ml, and in some samples at 9 of the 10 sites coliform concentration was 2,300 per 100 ml or more.

An indication of the inorganic chemical quality of streamflow in reaches affected by discharges of industrial waste is given by analyses of samples 4, 5, 10, and 12 in table 7. The chemical quality of these samples differs little, if any, from that of samples from stream reaches that do not receive industrial-waste discharges.

Inasmuch as the chemical quality of water pumped from wells may be highly dependent upon the chemical quality of streamflow, continued availability of water of good quality from wells is dependent upon continued availability of water of good quality in streams.

CONCLUSIONS

The stratified-drift aquifer in the part of the Branch River basin in Rhode Island will yield several million gallons of water per day to a reasonably small number of wells having individual yields ranging from 300 to 700 gpm (19 to 44 l/s). The total yield obtainable from the aquifer will depend in large part on where wells are located, how they are pumped, whether the used water is returned to the basin or exported from it, and on acceptable limits of stream depletion during periods of low flow.

Although aquifer characteristics are not well known in some parts of the basin, a moderate number of lithologic logs and specific-capacity data indicate that the aquifer is composed largely of moderately to highly transmissive deposits of sand and gravel. Throughout much of the basin the aquifer has a saturated thickness of 40 to 60 ft (12 to 18 m) and a transmissivity between 5,000 and 8,000 ft^2/day (460 and 740 m^2/day).

Virtually all the water pumped from wells in some areas favorable for development of large supplies will be derived from infiltration induced from streams. Aquifer yield from most of these areas will be dependent on the amount of streamflow continuously available for infiltration during periods of low flow or the rate at which streamflow can be induced into the aquifer.

Although the aquifer contains large amounts of water in storage, effective use of this storage will generally be possible only if extended periods of no streamflow near pumping centers are an acceptable consequence of development. Substantial lowering of ground-water levels necessary to make effective use of aquifer storage will cause streamflow to cease near some pumping centers for extended periods of time during droughts.

Mathematical models simulating ground-water withdrawals in the Slatersville, Oakland, Harrisville, and Chepachet areas indicate that continuous yields of as much as 5.5, 3.4, 1.6, and 1.3 mgd (0.24, 0.15, 0.07, and 0.06 m^3/s), respectively, are obtainable from these areas. The computed yields represent estimates of amounts practically obtainable from a reasonably small number of large-diameter screened wells. They are not necessarily indicative of optimum or maximum yields obtainable from the stratified-drift aquifer. Additional amounts are available from areas not modeled.

Location of wells shown in the mathematical models was chosen for ease of computation and is not necessarily the best possible site for a well. Similar yields may be obtainable in modeled areas with a different arrangement and number of wells.

Ground-water resources potentially available for development are more than adequate to meet anticipated public-supply needs in the study area in the foreseeable future. The total potential ground-water yield of 12 mgd (0.53 m^3/s) obtainable from modeled areas is 4 times the estimated public-supply requirement of 3 mgd (0.13 m^3/s) by the year 2020. More than 12 mgd (0.53 m^3/s) can be developed in the basin, if (1) streamflow depletion resulting from ground-water withdrawals is disregarded, (2) pumpage is returned to streams near points of withdrawal, and (3) releases are made from existing surface reservoirs to offset adverse effects of streamflow depletion.

Optimum development of available ground-water supply in the study area may be determined by the amount of streamflow depletion that can be tolerated. Avoiding undesirable streamflow depletion will require coordinated management of withdrawals from all pumping centers and of releases from surface reservoirs. Management of the complexly interrelated stream-aquifer system may best be accomplished with the aid of electric-analog or digital models. Models of a stream-aquifer system, when based on adequate geohydrologic data, permit rapid evaluation of effects of different schemes of ground-water development and surface-reservoir operation on ground-water levels and streamflow regimen.

The inorganic chemical quality of ground water from the stratified-drift aquifer and associated streams is generally good. The water is soft, slightly acidic, and typically contains less than 100 mg/l dissolved solids. However, because much of the water potentially available to wells is induced infiltration from streams, continued good chemical quality in aquifers will depend largely on continued good chemical quality in streams.

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