Availability of Ground Water Upper Pawcatuck River Basin Rhode Island

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1821

Prepared in cooperation with the Rhode Island Development Council and the Rhode Island Water Resources Coordinating Board

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By WILLIAM B. ALLEN, GLENN W. HAHN, *and* RICHARD A. BRACKLEY

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AVAILABILITY OF GROUND WATER, UPPER PAWCATUCK RIVER BASIN, RHODE ISLAND

By William B. Allen, Glenn W. Hahn, and Richard A. Brackley

ABSTRACT

The upper Pawcatuck River basin is a 70-square-mile area in south-central Rhode Island consisting of broad, rolling hills and narrow valleys in the north and flat-floored plains in the south. It is drained by the Pawcatuck River and its two major tributaries, the Usquepaug-Queen River and the Chipuxet River.

Analysis of the water budget for the basin shows that approximately 94 mgd (million gallons per day) or about 63 percent of the precipitation flows out of the basin as streamflow. Of this amount, about 66 mgd is from ground-water seepage.

Two ground-water reservoirs composed of glacial deposits of sand and gravel and capable of substantial yields are in the basin. The larger reservoir underlies the central part of the Usquepaug-Queen River valley. This reservoir ranges in width from 3,000 to 4,000 feet and is 32,000 feet long. A large part of the reservoir contains sand and gravel more than 100 feet thick, having a permeability of more than 1,000 gallons per day per square foot. The yield of this reservoir is estimated to be about 17 mgd.

The smaller ground-water reservoir is in the Chipuxet River valley. It is about 4,000 feet wide and 16,000 feet long. A large part of this reservoir contains sand and gravel more than 150 feet thick having a permeability of more than 1,000 gallons per day per square foot. The yield of the Chipuxet reservoir is estimated to be about 8.6 mgd.

Mineral content of water from both of the reservoirs is generally less than 200 parts per million of dissolved solids. However, in the Chipuxet ground-water reservoir the dissolved solids are somewhat higher, and the iron content is a problem.

Only about 1.5 mgd of water is used in the basin. Most of it is used for public supplies and is obtained from wells not tapping the Usquepaug-Queen or Chipuxet ground-water reservoirs. Estimates of the 25 mgd of ground water potentially available are believed to be conservative, and substantially larger quantities may actually be available when development takes place.

INTRODUCTION

Water to supply the needs of Rhode Island may be obtained from the ground or from streams, ponds, and manmade reservoirs. State officials recognize that there will be an ultimate need for the development and utilization of all water resources of consequence in Rhode Island. Therefore, plans are underway to develop water resources now for future needs. Surface-water reservoirs have been proposed for the western, northern, and southern parts of the State (Metcalf and Eddy, Engineers, 1957). Previous ground-water investigations have indicated that substantial supplies of water are stored in various ground-water reservoirs throughout Rhode Island (Lang, 1961). These reservoirs consist of glacial deposits of sand and gravel, generally in stream valleys. Lang's report suggests that moderate to large supplies of ground water are available from some of these ground-water reservoirs, especially those in the central and southern parts of the State, where conditions are favorable for the infiltration of water from surface streams and ponds. Accordingly, the Rhode Island Water Resources Coordinating Board and the U.S. Geological Survey are currently (1964) supporting studies in three areas—the upper Pawcatuck River basin, the Potowomut-Wickford area, and the South Branch Pawtuxet River area—all in central Rhode Island.

The purpose of this report is to describe the ground water potentially available for development from two ground-water reservoirs in the upper Pawcatuck River basin. One of these reservoirs is in the Usquepaug-Queen River valley and the other in the Chipuxet River valley.

SCOPE

The upper Pawcatuck River basin investigation included (1) delineation of the surface-subsurface geohydrologic system and determination of its capacity to transmit water, (2) definition of the movement of water through the system, and (3) determinaton of the quantities of water in the system available for development. The available water in both the surface system and the subsurface system depends largely on storage and the rate of replenishment. In the surface system water is stored in ponds, swamps, and streams; in the subsurface system, it is stored in sand, gravel, and other porous materials. The rate of replenishment of both the surface and subsurface systems depends upon the amount, distribution, and variation of precipitation.

The cooperative investigation of the upper Pawcatuck River basin was started with the Rhode Island Development Council and completed with the Rhode Island Water Resources Coordinating Board. The fieldwork was done from July 1957 to June 1960; the most intensive phase of the field investigation was during the 2-year period from January 1958 to December 1959. The nature of the fieldwork, history of the investigation, and the geologic and hydrologic data collected during the study are included in a basic-data report on the area by Allen, Hahn, and Tuttle (1963).

This report on the investigation was prepared under the supervision of Ralph C. Heath, district geologist. The work relating to the surface-water sections of the report was done under the supervision of Charles E. Knox, district engineer. Quality-of-water analyses were made in the Geological Survey's laboratory at Albany, N.Y., under the direction of Felix Pauszek, district chemist. John Bredehoeft, research geologist, aided in the determination of the yield of the ground-water reservoirs.

LOCATION

The upper Pawcatuck River basin is in the south-central part of Rhode Island. (See fig. 1.) It lies almost entirely within Washington County, is about 15 miles long and 7 miles wide, and has an area of about 70 square miles. It consists of the drainage basin of the Pawcatuck River upstream from a point about half a mile east of the village of Kenyon.

GEOHYDROLOGIC SYSTEM

Water occurs in the upper Pawcatuck River basin in the streams that drain the area, in ponds, and swamps, and in the glacial deposits and bedrock that underlie the basin. The streams, ponds, and swamps form the most obvious and readily observable part of the geohydrologic system. They form, in fact, what might be referred to as the surface part of the system. The glacial deposits and the bedrock together form the subsurface part of the system. Both the surface and the subsurface parts of the system are hydraulically interconnected, and water moves from one to the other in response to both natural and manmade hydraulic gradients.

Plate 1 is an idealized block diagram that shows the principal streams, swamps, and ponds, and the glacial deposits and bedrock.

SURFACE SYSTEM

LAND SURFACE

The upper Pawcatuck River basin is in the Seaboard Lowland section of the New England physiographic province (Fenneman, 1938, p. 358, 370) and is a part of the Glaciated Appalachian ground-water region (McGuinness, 1963, p. 754). The north half is characterized by low, rolling hills and relatively narrow southward-trending valleys. The south half is a broad, flat-floored plain, at altitudes of 90 to 100 feet, with small isolated hills standing as much as 140 feet above the level of the plain. The south boundary of the basin runs along an

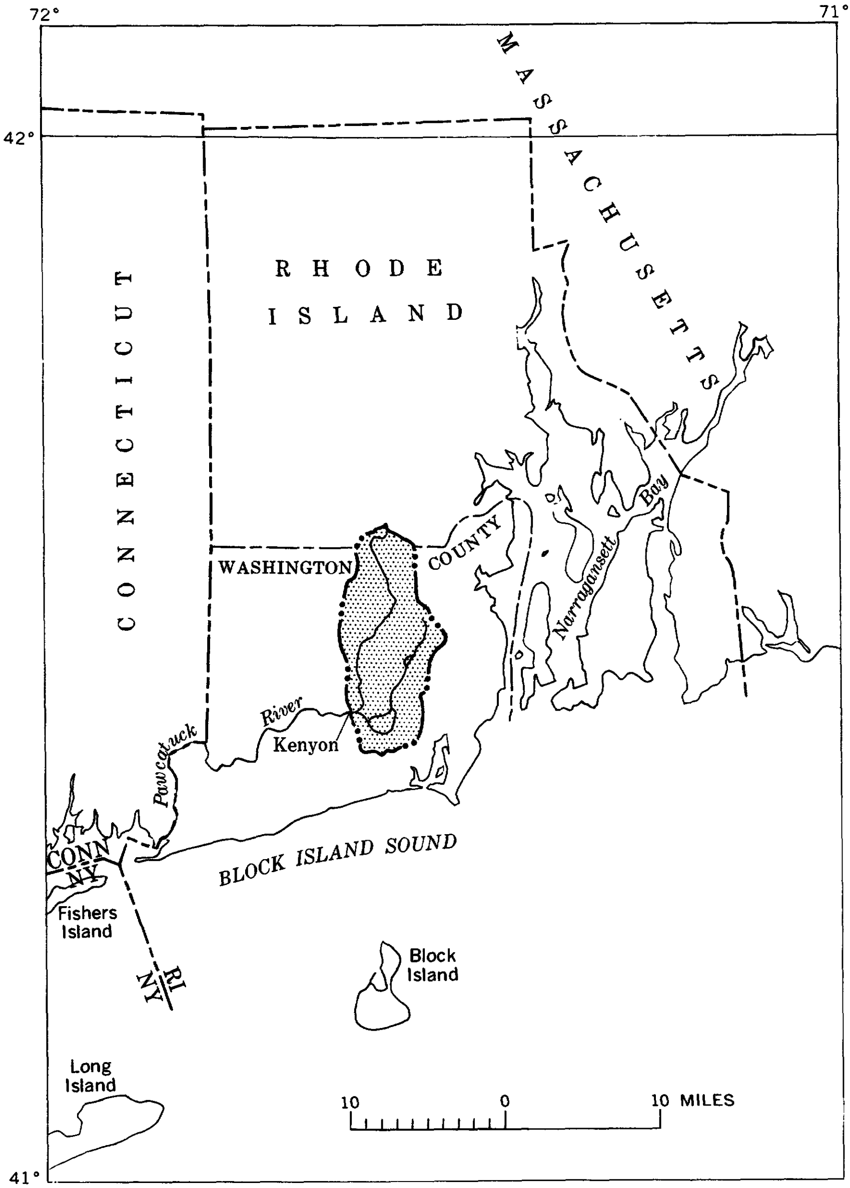


FIGURE 1.—Location of area.

irregular hilly area referred to as the Charlestown moraine. Altitudes along the moraine are as much as 200 feet above sea level. The total relief of the land surface in the basin is about 460 feet, ranging from about 90 feet above mean sea level along the Pawcatuck River at the outlet, to more than 550 feet on the hilltops along the northwest boundary of the basin. The topography of the area is depicted on plate 1.

STREAMS, PONDS, AND SWAMPS

The upper Pawcatuck River basin is drained by the Pawcatuck River and its two principal tributaries—the Usquepaug-Queen River and the Chipuxet River. The Queen River rises in the northern part of the basin and flows generally southwest. Downstream from Glen Rock Reservoir the same stream is called the Usquepaug River. The Usquepaug-Queen River flows through Great Swamp into the Pawcatuck River about half a mile upstream from the outlet of the basin. The Chipuxet River rises in the northeastern part of the basin and flows southwest through Great Swamp and Wordens Pond into the Pawcatuck River. Smaller tributary streams flow into the Usquepaug-Queen River and the Chipuxet River.

There are a number of ponds and reservoirs in the upper Pawcatuck River basin, the majority of which have surface areas of less than one-tenth of a square mile. Wordens Pond in the southern part of the basin is the largest, with an area of about 1½ square miles. Yawgoo Pond in the central part is the second largest, with an area of about one-fourth of a square mile. Other important ponds are Barbers, Hundred Acre, Larkin, and Tucker Ponds.

There are large swampy areas in the basin. Great Swamp, adjacent to Wordens Pond, is the largest. Other smaller swamps, such as Bear and Locke Swamps, occur along the Usquepaug-Queen River. The principal streams, ponds, and swamps are shown on plate 1.

At the outlet of the basin the Pawcatuck River flows between two hills composed of till-covered bedrock (fig. 2). The river valley in this area is less than a quarter of a mile wide, and the bedrock is close to the land surface. Because of this narrows, or gap, little or no water passes out of the basin as ground-water underflow. Thus, the total runoff from the basin discharges through the stream channel. During the course of the investigation a stream-gaging station was maintained a short distance downstream from the narrows to measure the outflow from the basin.

SUBSURFACE SYSTEM

The subsurface geohydrologic system in the upper Pawcatuck River basin consists of unconsolidated rocks—principally glacial deposits of

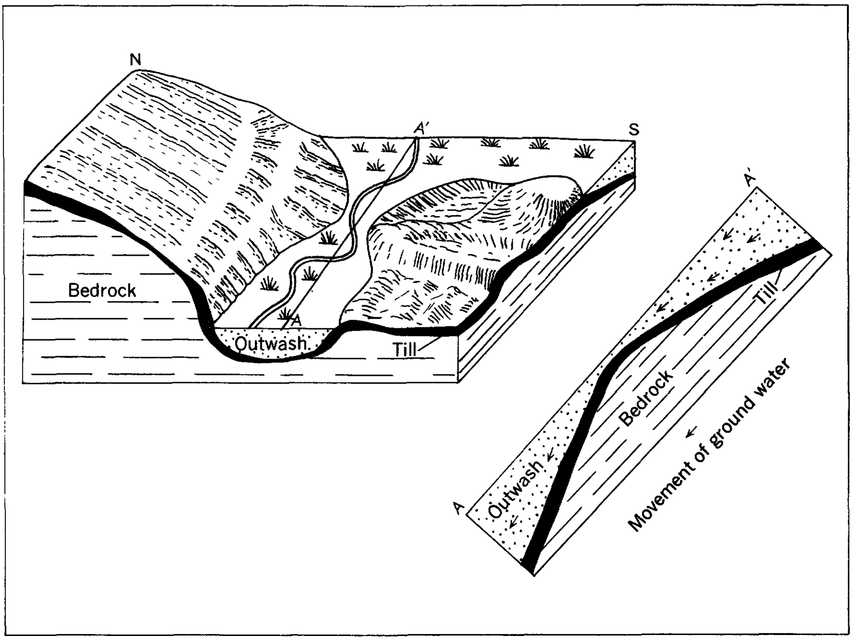


FIGURE 2.—Topographic and geologic conditions at outlet of upper Pawcatuck River basin.

gravel, sand, silt, and clay—and consolidated rocks called bedrock. The principal types of rocks in the basin and their yields are shown in table 1.

BEDROCK

The consolidated rocks in the upper Pawcatuck River basin are classified as crystalline rocks because they are composed of closely fitting mineral crystals. They are metamorphic and igneous rocks, such as gneiss, schist, and granite, of Paleozoic or younger age. They have been mapped, subdivided, and studied in detail by Power (1959) in the north half of the basin (Slocum quad.) and by Moore (1964) in the south half (Kingston quad.). The bedrock is dense and compact, has a porosity of less than 1 percent, and has a very low permeability.

BEDROCK SURFACE

The surface of the bedrock in the upper Pawcatuck River basin is very irregular. An idea of its irregularity may be obtained by examining the vertical sections on plate 1. The bedrock surface slopes to the south from an altitude of about 450 feet above sea level at the north end of the basin to about 100 feet above sea level at the south end. The predominant features are the two southward-trending bedrock

TABLE 1.—*Principal types of rocks and the yields of wells*

Age	Principal types of rocks		Approximate thickness (feet)	Yields of wells (gallons per minute)
Recent (within past 10,000 yr).	Swamp, alluvial, and wind-blown sand deposits.		0-10+	Little or none.
Pleistocene (glacial epoch from 10,000 to 1 million yr).	Stratified deposits	Lacustrine deposits of silt and clay in Great Swamp.	0-200+	Generally 1 to 5, but sometimes less.
	Stratified deposits	Outwash deposits of sand and gravel in Chipuxet River and Usquepaug-Queen River areas.		Highest yield. Gravel from 700 to 2,000. Coarse sand and gravel from 100 to 700. Sand from 5 to 100.
	Till—unsorted mixtures of clay, silt, sand, and gravel.		0-100+	Generally from 1 to 5.
	Mixed till and outwash.		0-200+	Generally from 5 to 100.
Paleozoic or younger (240 million yr ago).	Crystalline rocks such as schist, gneiss, and granite.		Many thousands (underlie entire area).	Generally 1 to 5.

valleys now occupied by the Usquepaug-Queen and Chipuxet Rivers which join beneath Wordens Pond and pass out of the basin beneath the Charlestown moraine. The bottoms of these valleys decline from an altitude of about 200 feet above sea level at the north to about 100 feet below sea level at the south. The approximate position of these bedrock valleys is shown on the vertical sections of plate 1. Their position is also apparent on plate 2 from the lines showing the saturated thickness of stratified glacial deposits. The greatest thicknesses of deposits occur in the valleys. In the north half of the basin the bedrock valleys are only partly filled with glacial deposits, and their location can be seen at the land surface. In the south half of the basin the bedrock valleys are almost completely filled with glacial deposits, and their position is not apparent at the land surface. Because the bedrock valleys contain glacial deposits, it is apparent that they were formed before Pleistocene glaciation at a time when the bedrock surface was being eroded by streams. The bedrock surface is most irregular in the uplands where the present land surface is a subdued replica of the bedrock surface and least irregular in the lowlands. However, some high places on the bedrock surface do not underlie hills so that estimates of depth to bedrock cannot be made on the basis of topography alone.

WATER-BEARING CHARACTERISTICS OF THE BEDROCK

As previously mentioned the bedrock is dense and compact; it has a porosity of less than 1 percent and is relatively impermeable. Thus, the primary physical character of the various rock types has little effect on the movement of ground water. Some of the test holes drilled during the course of this investigation penetrated the top 10 to 20 feet of the bedrock; others ended above bedrock. Most of the test holes were drilled in the preglacial bedrock valleys. The upper surface of the bedrock penetrated in these holes generally was appreciably weathered and fractured. The fracturing did not appear to be related to the type of bedrock. In granite quarries horizontal or gently dipping fractures are wider and more numerous than the vertical or steeply dipping fractures; they also appear to be less numerous with depth. Small quantities of ground water move through the bedrock largely along secondary openings such as fractures. Most wells drawing water from bedrock yield less than 5 gpm (gallons per minute).

UNCONSOLIDATED DEPOSITS

The unconsolidated deposits in the upper Pawcatuck River basin consist of gravel, sand, silt, clay, and till that were laid down by an ice sheet that covered the area many thousands of years ago. Some of the unconsolidated deposits at or near the land surface in lowland areas have been deposited in swamps or along streams in the past 10,000 years or since the glacial epoch and are considered to be of Recent age. The glacial deposits of Pleistocene age include till—a heterogeneous mixture of gravel, sand, silt, and clay laid down directly by the glacial ice—and stratified deposits of gravel, sand, silt, and clay laid down and sorted by water from the melting glacial ice. The till occurs as a discontinuous veneer over the bedrock. In the uplands it is generally about 20 feet thick; in the lowlands, where it underlies the stratified deposits, it is generally not more than 10 feet thick. The stratified deposits are largely restricted to the lowlands and valleys. In the northern part of the basin the stratified drift is about 50 feet thick; whereas in the southern part it is as much as 190 feet thick. The unconsolidated deposits have been mapped in detail in the Kingston quadrangle by Kaye (1960) and in the Slocum quadrangle by Power (1957).

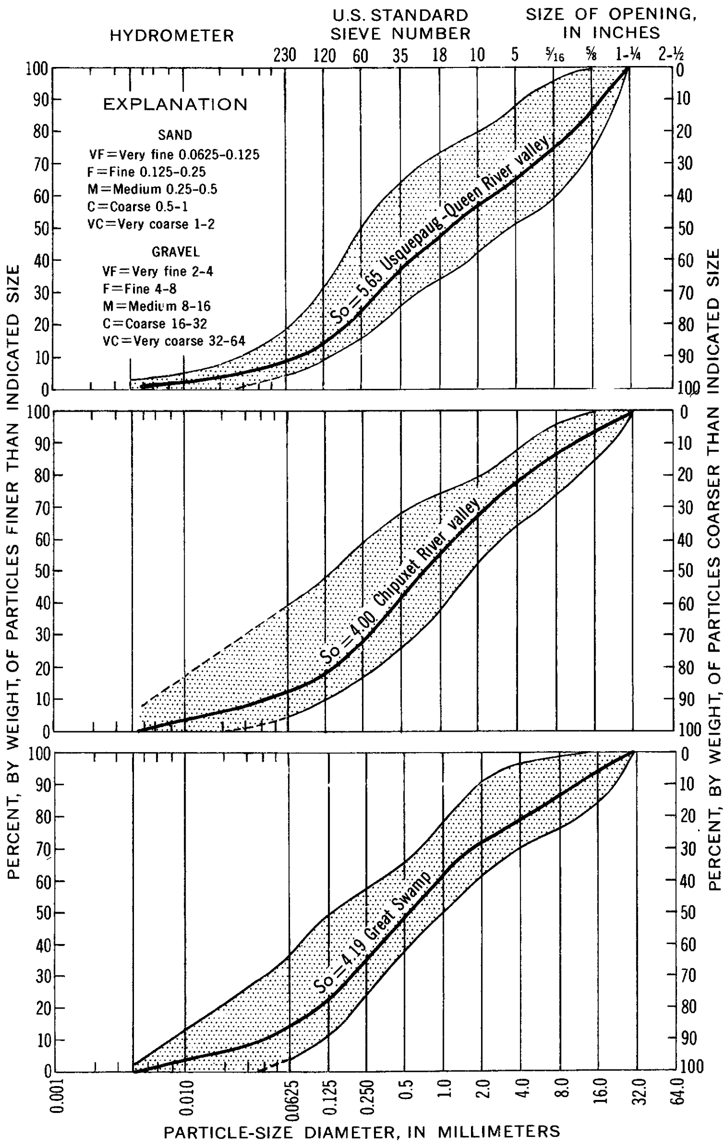
TILL

Till, the principal unconsolidated deposit in the northern part of the upper Pawcatuck River basin, consists mainly of mechanically broken fragments of granite and gneiss. The fragments range in size from clay particles to boulders, depending upon the nature of the source rocks. The hard granites and granite-gneisses, which occur mostly in the northern part of the basin, have rather widely spaced fractures and break chiefly into boulders, large cobbles, and pebbles so that trains of boulders cover the hillsides and form such features as Dumping Rock and Wolf Rocks. The schists are finely foliated and break up easily into sand- and silt-size particles. They are found mostly in the southern part of the basin and result in a till composed generally of fine-grained fragments. Only small amounts of clay are present in the till of the upper Pawcatuck River basin.

Samples of till were collected from test holes drilled in the basin and analyzed for particle-size distribution and grain size (Allen and others, 1963, table 1, p. 8–10). Most of the samples were from the till underlying the stratified deposits. Particle-size distribution curves and sorting coefficients show the distribution of grain sizes and sorting in till from a number of samples in the Usquepaug-Queen River valley, the Chipuxet River Valley, and Great Swamp (fig. 3). The sorting coefficient is the square root of the 75-percent grain size divided by the 25-percent grain size. According to Krumbein and Pettijohn (1938, p. 232), a sorting coefficient value (*So*) of less than 2.5 indicates a well-sorted sediment; a value of 3.0, a normally sorted sediment; and a value of 4.5, a poorly sorted sediment. A comparison of the curves and sorting coefficients shows that the coarsest grained (median grain size of 1 mm) and poorest sorted till occurs in the Usquepaug-Queen River valley. The median grain sizes of the samples collected from the test holes are considerably coarser than those reported by Bierschenk (1956, fig. 5) for samples of till collected from surface exposures in the area.

The wide range in particle sizes of the till in the upper Pawcatuck River basin makes it a poor water-transmitting material. The permeability of till, tested in the laboratory and in the field by pumping tests, ranged from 0.5 to 310 gpd per sq ft (gallons per day per square foot) and had a median value of 5 gpd per sq ft. The median permeability value probably is fairly representative. Locally, however, till may contain lenses of sorted sand and gravel resulting in a permeability considerably greater than the median.

Permeability is defined as the rate at which a unit cube of material will transmit water under a hydraulic gradient of 1 foot per foot. The standard coefficient of permeability used by the U.S. Geological Survey is the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot of an aquifer under a hydraulic gradient of 1 foot per foot, at a temperature of 60° F. The field coefficient of permeability is the same, except that it is measured under prevailing conditions, particularly as to temperature of the water. The water-transmitting capacity of an entire aquifer is referred to as transmissibility. The coefficient of transmissibility is defined as the number of gallons of water transmitted per day through a vertical strip of an aquifer 1 foot wide under a hydraulic gradient of 1 foot per foot (100-



CLAY	SILT	SAND(see explanation)					GRAVEL(see explanation)				
<0.004 mm	0.004-0.0625 mm	VF 0.0625-0.125	F 0.125-0.25	M 0.25-0.5	C 0.5-1	VC 1-2	VF 2-4	F 4-8	M 8-16	C 16-32	VC 32-64

FIGURE 3.—Particle-size distribution and sorting coefficients (*So*) of samples of till from the upper Pawcatuck River basin. Shading shows the range in grain size of several samples from each area.

percent gradient). The coefficient of transmissibility is equal to the field coefficient of permeability multiplied by the thickness of the aquifer, in feet; it is defined mathematically as:

$$T=Pm$$

where T is the transmissibility in gallons per day per foot, P is the permeability in gallons per day per square foot, and m is the thickness of the aquifer in feet.

STRATIFIED DEPOSITS

The stratified deposits of the upper Pawcatuck River basin are divided into three types on the basis of physical characteristics and origin. They are (1) outwash deposits, fine- to coarse-grained materials deposited by streams issuing from the melting ice, (2) lacustrine deposits, fine-grained materials deposited in lakes generally south of the ice front, and (3) mixed deposits, both till and outwash deposited by the ice or deposited by water issuing from the melting ice. In most places the different types of stratified deposits grade into each other, so that the distinction between the types is somewhat arbitrary. The stratified deposits will be discussed here only as they influence the occurrence of ground water.

OUTWASH DEPOSITS

The outwash deposits contain beds or layers of sand and gravel and layers of fine sand and silt of varying thicknesses. They make up about half the stratified materials of the entire basin. Deposits in the Chipuxet River and in the Usquepaug-Queen River valleys grade to the south into lacustrine deposits. They also underlie a small area at the southeast corner of the basin.

Particle-size distribution curves were prepared and sorting coefficients were determined to show the distribution of grain size and sorting in stratified deposits from a number of selected samples of individual beds in Great Swamp, in the Chipuxet River valley, and in the valley of the Usquepaug-Queen River (fig. 4). A comparison of the median grain size and sorting coefficients shows that the outwash deposits in the valley of the Usquepaug-Queen River are slightly coarser (median grain-size diameter of 0.200 against 0.175) and better sorted ($So=2.90$ against 3.26) than those in the Chipuxet River valley. However, the difference is size and sorting is probably not enough to be significant.

In order to determine the water-yielding capacity or permeability of the outwash deposits, samples were tested in the laboratory, and pumping tests were made in the field. The results of the laboratory tests and data collected during pumping tests are published in the basic-data report (Allen and others, 1963, p. 8–10 and 44–50).

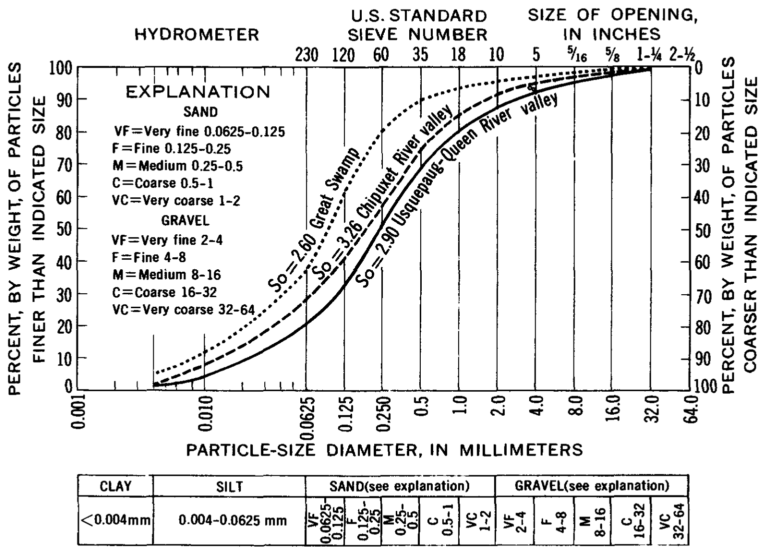


FIGURE 4.—Particle-size distribution and sorting coefficients (*So*) of samples of stratified deposits.

Seven 8-inch diameter test wells were constructed and used for pumping tests to obtain information on the water-transmitting capacity of the sand and gravel outwash deposits. Tests were conducted at six of these wells (Exe 401, Exe 402, Sok 905, Sok 906, Sok 907, and Sok 908). In addition, three pumping tests made by well contractors or consulting engineers while developing water-supply wells (Exe 39, Sok 81, and Sok 1040) were analyzed. Methods used for analyzing pumping tests have been summarized by Ferris, Knowles, Brown, and Stallman (1962). The results of the nine tests are tabulated in table 2. Because none of the tests were made under ideal conditions, the coefficients of permeability and transmissibility determined from the tests are probably rough approximations of the true values.

The specific capacity of a well can also be used to determine the transmissibility (and indirectly the permeability) of an aquifer. The specific capacity is the quantity of water a well yields, in gallons per minute per foot of drawdown. The term is correctly applied only to wells in which the drawdown varies approximately in direct proportion to the yield. The specific capacity of wells is determined by dividing their yield in gallons per minute by the drawdown at the end of the period of pumping. To compare specific capacities of different wells the pumping periods should be of the same length. Specific capacities were determined for the 9 wells on which pumping tests were made and for 7 additional wells, or a total of 16 wells (table 2).

TABLE 2.—*Comparison of coefficients of transmissibility of stratified drift determined by different methods*

[Well numbers in Rhode Island are assigned consecutively in the order in which the wells are inventoried. Three-letter prefixes are added to the numbers for town identification. (See Allen and others, 1963, p. 6.)]

Well No.	Data from pumping tests					Coefficient of transmissibility (gpd per ft)		Saturated thickness of reservoir (feet)	Average field coefficient of permeability (gpd per sq ft)
	Date of pumping test	Length of test (hours)	Pumping rate (gpm)	Drawdown (feet)	Specific capacity (gpm per ft)	Based on specific capacity	Based on analisis of drawdown or recovery data with nonequilibrium formula		
Exe 33	4– 47	24	260	16	16	[1] 30, 000	------------	38	800
39	1– 47	24	400	11	35	70, 000	[1 2] 60, 000	59	1, 000
400	1–12–60	½	60	15	5	[1] 10, 000	------------	25	400
401	2–15–60	24	410	8	51	100, 000	[1] 100, 000	69	1, 500
402	1– 6–60	24	604	7	86	200, 000	[1] 300, 000	87	3, 400
Sok 81	1– 49	24	367	18	20	40, 000	[1 2 3] 66, 000	60	1, 100
84	1– 45	25	800	24	33	[1] 60, 000	------------	55	1, 100
91	3– 49	24	560	23	24	[1] 40, 000	------------	54	700
92	1– 49	24	950	11	86	[1] 150, 000	------------	124	1, 500
887	2– 58	24	1, 100	12	92	[1] 160, 000	------------	48	3, 100
888	5– 58	72	800	6	133	[1] 200, 000	------------	87	2, 100
905	12– 7–59	24	290	13	22	40, 000	[1] 80, 000	77	1, 000
906	12–15–59	24	242	16	15	30, 000	[1] 180, 000	52	3, 500
907	1–27–60	24	393	12	33	60, 000	[1] 200, 000	124	1, 600
908	12–29–59	24	226	22	10	[1] 20, 000	85, 000	53	400
1040	11–26–60	46	725	26	28	[1] 50, 000	[3] 70, 000	60	800

[1] Used in determining average field coefficient of permeability.
[2] Data from Lang, Bierschenk, and Allen, 1960, table 1.
[3] Equilibrium formula.

Coefficients of transmissibility determined from pumping tests and from specific-capacity data are compared in table 2. The values believed to be most accurate were divided by the saturated thickness of the aquifers at the site of the wells to determine the average field coefficient of permeability. The permeability values in table 2 compare favorably with values obtained for other areas in Rhode Island (Lang and others, 1960, table 1).

LACUSTRINE DEPOSITS

The lacustrine deposits in the upper Pawcatuck River basin contain thick and well-sorted beds of fine sand and silt. These deposits underlie Great Swamp, Wordens Pond, and surrounding areas in the southern part of the basin. According to Kaye (1960), most of the southern part of the basin was a lake during the late stages of Pleistocene glaciation. The lake was confined on the south, east, and west by low chains of hills that were ultimately breached on the west at the narrows or gap along the present course of the Pawcatuck River. The lake was fed by water from the melting ice and probably filled with sediments relatively fast so that today only Wordens Pond and Great Swamp remain as present day remnants of it. Data from wells and test holes show that the lake deposits are largely composed of fine sand. Some silt and a little banded clay are present. No coarse sand and gravel are found at depth but are present at the surface at several places around the borders of the glacial lake. To the north of Great Swamp, deltaic beds—deposited by the glacial streams that flowed down the present valleys of the Chipuxet River and Usquepaug-Queen River—interfinger with the lacustrine deposits laid down in the glacial lake and result in deposits consisting of alternating beds of fine- and coarse-grained materials.

An average particle-size distribution curve and an average sorting coefficient value for lacustrine deposits underlying Great Swamp are shown on figure 4. The curve shows that the median-size diameter is in the very fine sand range, and the sorting coefficient indicates that the material is well sorted. Based largely on laboratory determinations, permeability values of the lacustrine deposits range from 1 to 20 gpd per sq ft.

MIXED DEPOSITS

The lithologic characteristics of the unconsolidated deposits in parts of the upper Pawcatuck River basin shown that, in places, there is no sharp dividing line between outwash and till. One grades into the other, so that the deposits as a whole include till and outwash in varying amounts. These gradational or mixed deposits are found along the south and southeast borders of the basin. At the south border of the basin the mixed deposits form an irregular ridge of kame and kettle topography called the Charlestown moraine. A transverse section along this moraine shows that it is composed of mixed till and outwash deposits (pl. 1). Actually the Charlestown moraine contains many more thin gravelly layers in the till and many more thin layers of till in the outwash than are shown on the diagram. The outwash, a minor part of the moraine, generally is poorly sorted and poorly stratified. In the southeastern part of the basin the mixed deposits contain clay, sand, gravel, and boulders which generally are poorly stratified and contain much sandy till. A small area of mixed deposits also occurs along the Chipuxet River valley in the central part of the basin (pl. 2). As seen in surface exposures it contains a coarse sandy to bouldery till. The average size distribution of a number of samples of mixed till and outwash from different parts of the basin shows that the median-size range for both the outwash and till fractions is equivalent to coarse sand but that the till is poorly sorted ($So=4.04$) and the outwash is fairly well sorted ($So=2.91$).

Permeability values of the mixed deposits are based largely on samples tested in the laboratory. Mixed deposits from the Charlestown moraine had permeability values that ranged from less than 1 to 100 gpd per sq ft. Mixed deposits in the southeastern part of the basin had permeability values generally less than 50 gpd per sq ft.

RECENT DEPOSITS

In the upper Pawcatuck River basin the glacial drift is overlain by swamp, alluvial, and wind-blown deposits of Recent age that are sandy, relatively thin, and of limited areal extent. These deposits do not yield appreciable quantities of ground water and are of primary importance only with respect to the infiltration or runoff of precipitation.

SUMMARY OF WATER-TRANSMITTING CAPACITY

The water-bearing characteristics of the deposits underlying the upper Pawcatuck River basin are largely dependent upon porosity and permeability. Porosity is expressed as the ratio of the volume of openings to the total volume of the material. The unconsolidated deposits commonly have spaces or openings between individual grains. The porosity of these deposits in the upper Pawcatuck River basin, according to laboratory tests, ranges from about 25 to 50 percent (Allen and others, 1963, tables 1 and 12). The porosity of the bedrock was not determined but is probably very low.

The permeability of a material depends on the number, size, shape, and degree of interconnection of openings. Some unconsolidated materials such as silt and clay may have a high porosity but, because the openings are very small, the permeability is low. On the other hand well-sorted sand or gravel, which contain large openings, will transmit water readily and therefore have a high permeability. Such deposits of sand and gravel are excellent aquifers. Aquifers not only store water but also transmit it from one place to another in response to hydraulic gradients.

The water-transmitting characteristics of the glacial deposits and the bedrock and the saturated thickness of the unconsolidated deposits are shown on plate 2. The water-transmitting characteristics of the glacial deposits were determined by means of laboratory data, pumping tests, and specific capacity or other miscellaneous data. The most important points at which these data are available and the type of data are shown by circles on the map. The saturated thickness is the difference, in feet, between the altitude of the water table (top of the zone of saturation) and the altitude of the bedrock surface and is shown by isopachous lines on the map.

The unconsolidated deposits in the upper Pawcatuck River basin may be divided into four types on the basis of their capacity to transmit water. The areal occurrence of the different types of deposits is shown on plate 2. This includes (1) areas in which the deposits have average permeabilities of more than 1,000 gpd per sq ft and where properly constructed wells will yield 700 to 2,000 gpm, (2) areas with permeabilities of 100 to 1,000 gpd per sq ft and where wells will yield up to about 700 gpm, (3) areas with permeabilities of 20 to 100 gpd per sq ft and where the yields of wells are generally less than 100 gpm, and (4) areas with permeabilities of less than 1 to 20 gpd per sq ft and where wells generally yield less than 5 gpm. The most permeable deposits are in the central part of the Chipuxet River valley and in the Usquepaug-Queen River valley.

The area covered by the diagonal dashed pattern in the Chipuxet River valley is of special interest. This area is underlain by two aquifers, the lower of which is from 22 to 65 feet thick and is overlain by 30 to 85 feet of fine sand, silt, and clay, which acts as a confining layer. The confining layer is overlain by a surficial aquifer of coarse sand and gravel as much as 68 feet thick. The permeabilities of both these aquifers are substantially more than 1,000 gpd per sq ft. Section *C—C′* on plate 2 crosses the most permeable areas in the Chipuxet River and Usquepaug-Queen River valleys and shows the vertical relations of the two aquifers in the Chipuxet River valley.

HYDROLOGY

Ground water and surface water are components of a complex dynamic system termed the hydrologic cycle. If they are to be evaluated they must be considered not only in relation to each other but also in relation to the other parts of the geohydrologic system.

HYDROLOGIC CYCLE

The hydrologic cycle has been described as the circulation of water from the sea, through the atmosphere, to the land, and thence, with numerous delays, back to the sea by overland and subterranean routes (Meinzer, 1942, p. 1).

The principal elements of the hydrologic cycle as applied to the valley part of the upper Pawcatuck River basin are illustrated on figure 5. All water that falls on the basin is derived from precipitation. Of the precipitation that reaches the ground, part runs off over the land surface (overland runoff) and is stored temporarily in ponds and swamps or moves out of the basin as streamflow. Some of the water infiltrates into the underlying rock and becomes ground water, moving laterally under the influence of gravity to points of discharge such as springs and to seepage areas in swamps and along the bottom and sides of streams. Therefore, much of the flow of streams during periods of no precipitation is derived from ground-water seepage. A part of the precipitation is returned to the atmosphere through the transpiration of plants and by evaporation. Transpiration and evaporation losses can take place at any point in the cycle where water is exposed to the air or is available to plants.

The following sections describe those phases of the hydrologic cycle with which this report is concerned.

SOURCE OF WATER

All water in the upper Pawcatuck River basin is derived from precipitation. The only permanent long-term precipitation station in the basin is maintained by the U.S. Weather Bureau at Kingston. As a part of this investigation precipitation stations were maintained during 1957, 1958, and 1959 at Glen Rock, Wordens Pond, and Lafayette Fish Hatchery. Daily records from these stations are published together with the records at Kingston for 1958–59 in the basic-data report (Allen and others, 1963, table 3).

AMOUNT

The average annual precipitation at Kingston during the period from 1889 through 1962 was 48.39 inches; the range was from 31.76 inches in 1943 to 72.22 inches in 1898. On the average about 30 inches

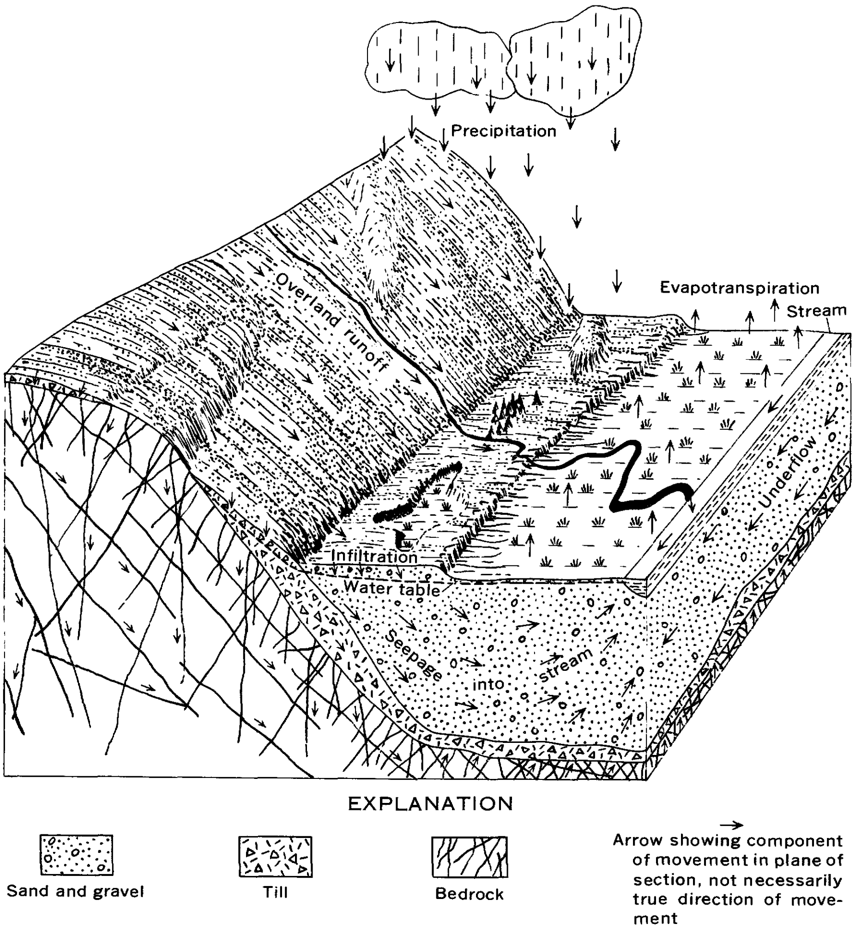


FIGURE 5.—Hydrologic cycle of the valley part of the upper Pawcatuck River basin.

of snow falls annually. The long-term average precipitation at Kingston is equivalent to a sheet of water 48 inches thick over the entire basin each year and is equal to a little more than 160 mgd (million gallons per day) on the entire basin. Of course, only a part of this water is available for use by man.

Because of differences in land-surface altitudes, the precipitation is not evenly distributed over the basin. As shown on figure 6 the precipitation is highest in the northern part of the basin and lowest in the southern part near Wordens Pond. A part or all of this difference is due to differences in land-surface altitudes. The land surface in the northwestern part of the basin reaches altitudes of about 550 feet, whereas near Wordens Pond it averages about 90 feet

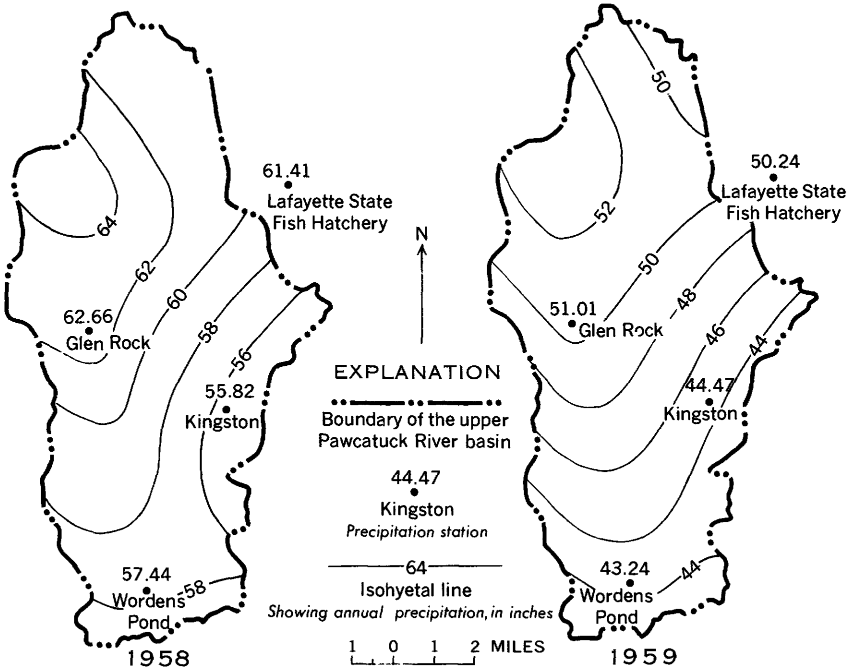


FIGURE 6.—Annual precipitation in the upper Pawcatuck River basin, 1958 and 1959.

above sea level. The differences in precipitation between the northwestern and southern parts of the area were about 6 and 8 inches in 1958 and 1959, respectively.

The year to year variation in precipitation can be great at any one point. For example, at Kingston in 1931, 39.43 inches was recorded and in 1932, 61.21 inches. During a wet year the annual rainfall may be two or more times that of a dry year.

Precipitation at Kingston for 1958 and 1959 was 55.82 and 44.47 inches, respectively. The weighted-average precipitation for the basin, determined by the Thiessen polygon method, was 59.63 inches in 1958 and 47.82 inches in 1959.

SEASONAL DISTRIBUTION

In general, precipitation is rather evenly distributed throughout the year, although in some years 1 or more months receive considerably more or less than the long-term average. (See following table.) June and July generally receive the least precipitation, and January, March, and August receive the most. The high maximum monthly values for August, September, and October are due to hurricanes.

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Seasonal distribution of precipitation, 1889–1962, in inches

Month	Mean	Maximum	Minimum
January	4.23	11.43	0.83
February	3.73	9.44	.67
March	4.25	9.67	.23
April	4.03	9.70	.72
May	3.57	8.95	.67
June	3.02	7.42	.04
July	2.95	11.75	.43
August	4.15	13.56	.79
September	3.72	12.66	.35
October	3.54	12.05	.27
November	4.11	10.25	.41
December	4.11	11.59	.83

TRENDS IN PRECIPITATION

Precipitation trends at Kingston, considered to be representative of trends in the upper Pawcatuck River basin during the period 1889–1962, are plotted on figure 7. Above-average precipitation is represented by a rising line and below-average precipitation by a falling line. Of interest is a comparison of records of cumulative departure from average precipitation at Kingston with that of Providence (Quinn and others, 1948, fig. 2B, p. 42). From 1905 to 1946, precipitation at Providence was generally below average (normal), whereas at Kingston, it was generally above average from the start of the record in 1888 to 1929 and below average from 1939 to 1952.

LOSSES OF WATER TO THE ATMOSPHERE

Water is lost to the atmosphere by evapotranspiration, a term combining evaporation from land and water surface and the transpiration of plants. According to the source of the water lost to the atmosphere, evapotranspiration may be divided into two parts: (1) surface and soil evapotranspiration and (2) ground-water evapotranspiration. The surface and soil evapotranspiration includes evaporation of moisture from the soil, water surfaces, and buildings or other objects and the transpiration of moisture by vegetation, whose roots do not reach the water table. Ground-water evapotranspiration is water lost directly from the water table, both by evaporation and by the transpiration of plants whose roots extend below the water table.

Evapotranspiration is largely controlled by air temperature. For example, during the winter or the nongrowing season when air temperatures are low, evapotranspiration is very small. However, as air temperatures rise in the spring and the growing season starts, evapotranspiration increases rapidly, reaching a maximum in July or early

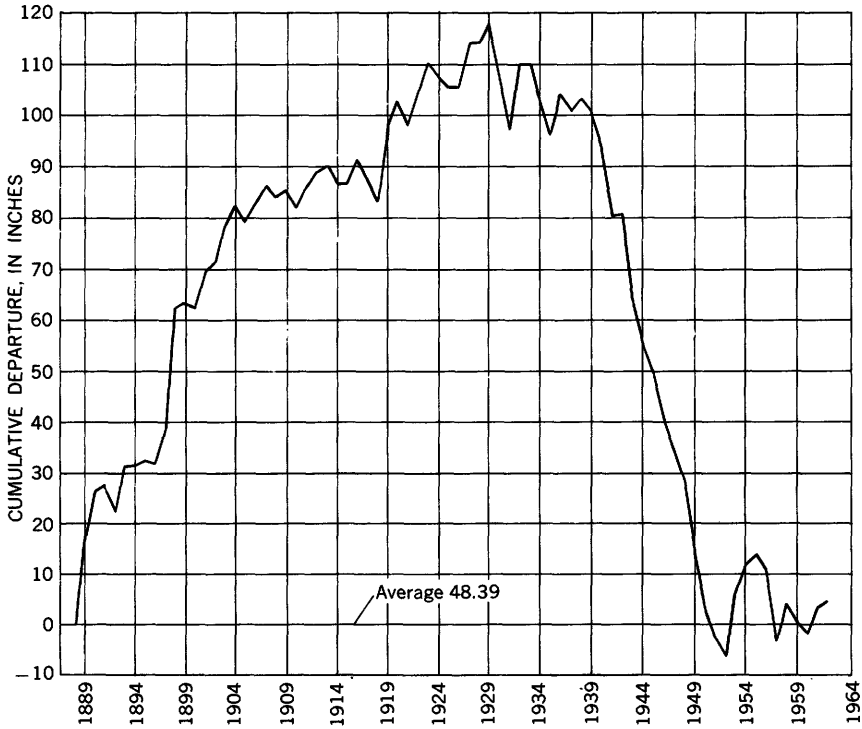


FIGURE 7.—Cumulative departure from average precipitation at Kingston, 1889–1962.

August, and decreases rapidly as the air temperatures drop and the growing season closes in the fall. This seasonal variation of evapotranspiration is approximately the same from year to year.

AIR TEMPERATURE

A knowledge of air-temperature variations in the upper Pawcatuck River basin is pertinent to a study of its water resources because of the dominant influence of air temperature on water losses by evaporation and transpiration.

Air temperatures at Kingston are measured by the U.S. Weather Bureau. According to the Kingston records, the mean annual air temperature is 49°F. January is generally the coldest month, with a mean monthly temperature of 29.5° F. The lowest recorded temperature since 1889 was 23° F below zero on January 11, 1942. July is usually the warmest month, with a mean monthly temperature of 70.1° F. The highest recorded temperature was 99° F on August 9 and 10, 1949.

EVAPOTRANSPIRATION FROM THE LAND SURFACE AND SOIL

The average growing season in the upper Pawcatuk River basin is 180 days from the last killing frost about April 30 to the first killing frost about October 20. Most of the precipitation that falls on the basin during the growing season is evaporated or transpired from the land surface and soil before it is able to infiltrate to the water table. Thus, a large part of the water lost annually by evapotranspiration does not come from the ground-water reservoir. However, in Great Swamp, where the water table is shallow and the capillary fringe extends to the land surface, large quantities of ground water are discharged into the atmosphere by evaporation. Here also, plant roots and rootlets extend into the zone of saturation, and the plants discharge water through their leaves into the atmosphere by transpiration.

Water loss by evapotranspiration from a drainage basin is the difference between the precipitation over the basin and the runoff from the basin, including changes in surface and underground storage, for a given period. In humid regions, where there is generally sufficient water to satisfy the demands of vegetation, the mean annual water loss is principally a function of air temperature (Langbein and others, 1949, p. 7). The relation between mean annual air temperature and mean annual water loss in such regions is shown on figure 8. For the upper Pawcatuck River basin, where the mean annual air temperature is almost 50°F, the average annual water loss by evapotranspiration, as determined from figure 8, is about 24 inches.

Several methods are available for the direct measure of evapotranspiration, but all such methods are expensive and time consuming. No measurements were made in the upper Pawcatuck River basin. Estimates of total evapotranspiration (water loss) for 1958 and 1959, based on precipitation minus runoff, are 22.8 and 22.7 inches, respectively. For the 1959 water year, water loss was about 16.0 inches.

An indication of the seasonal variation in evapotranspiration can be obtained by calculating potential evapotranspiration using a method developed by Thornthwaite and Mather (1957). Potential evapotranspiration is defined as the amount of water that would be lost from a surface fully occupied by vegetation if there were no deficiency at any time of water in the soil for use by the vegetation. By use of air-temperature data at Kingston the monthly potential evapotranspiration for 1958 and 1959 was computed from tables prepared by Thornthwaite and Mather. The averages of the two values for 1958 and 1959 are shown by months on figure 9.

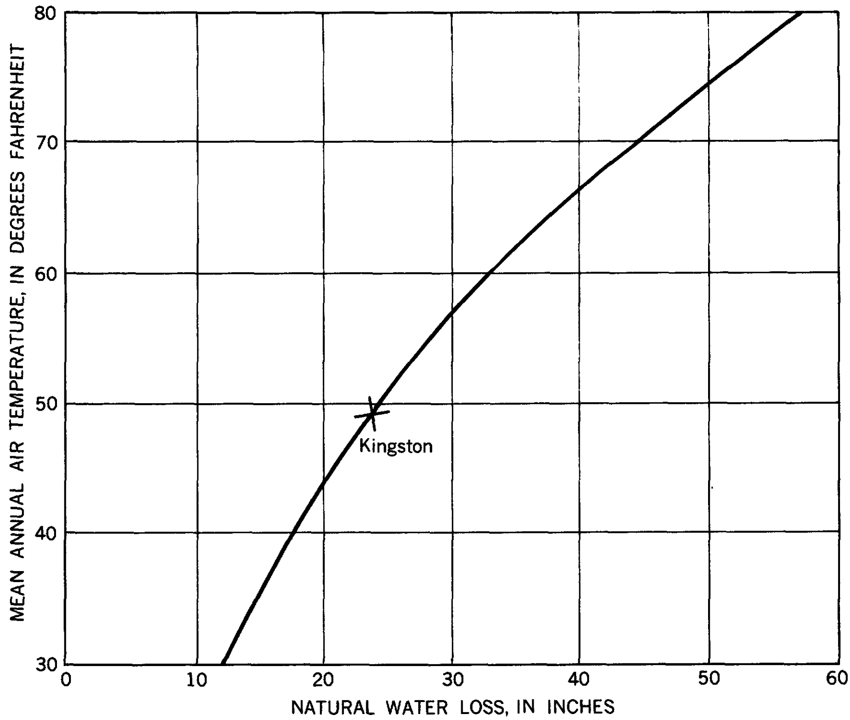


FIGURE 8.—Relation of annual water loss to air temperature in humid areas. (After Langbein and others, 1949.)

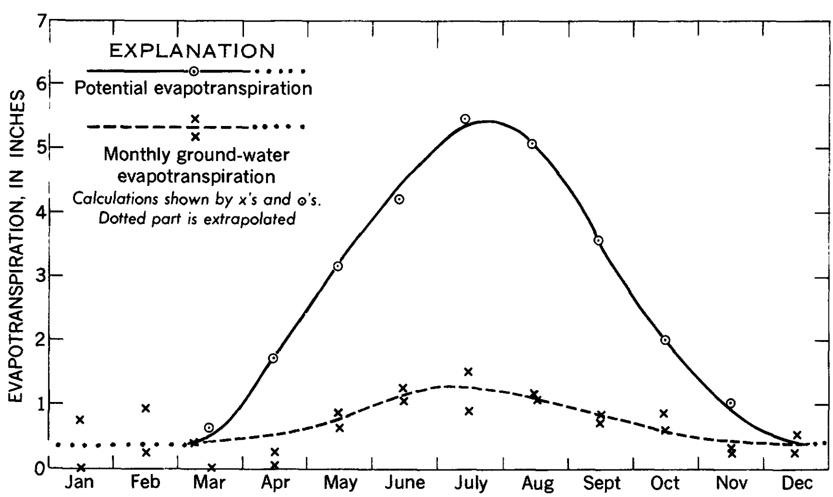


FIGURE 9.—Comparison of total evapotranspiration and ground-water evapotranspiration, by months, for the upper Pawcatuck River basin.

GROUND-WATER EVAPOTRANSPIRATION

Ground water continuously percolates towards streams; however, the roots of plants and soil capillaries intercept and discharge into the atmosphere some of the water which otherwise would reach the streams. Evapotranspiration from the ground-water reservoir is largely a function of the season and the depth to the water table.

In the upper Pawcatuck River basin, ground-water evapotranspiration is very small from November to April, increases rapidly in the late spring, reaches a maximum generally in July, and decreases rapidly as the growing season closes in the fall. The opportunity for evapotranspiration is large in such places as Great Swamp where the water table is within a few feet of the land surface.

In the upper Pawcatuck River basin the relation between monthly average base flow and monthly average ground-water stage for 1958–59 was used to determine ground-water evapotranspiration in a manner similar to that used in the Brandywine Creek Basin of Pennsylvania (Olmsted and Hely, 1962). Figure 10 shows the relation between monthly average base flow and ground-water stage; the winter months tend to plot to the right and the summer months to the left. A straight line drawn along the right side of the plotted points reflects the relation of ground-water runoff to ground-water stage in the absence of evapotranspiration from the zone of saturation. The slope of the relation line is determined by taking pairs of months that have about the same average potential evapotranspiration. The ratio of the change in base flow to change in ground-water stage for each pair of months is as follows:

Pairs of months	Ratio		
	1958	1959	Average
February–December	8.2	−1.4	3.4
March–November	6.7	4.8	5.7
April–October	7.9	5.8	6.8
May–September	6.2	5.4	5.8
June–August	4.9	4.8	4.8
Average	6.8	3.9	5.3

The average ratio of the slope of the relation line is 5.3. A straight line was drawn at this slope along the lower side of the plotted points (ignoring the point for January 1958). The equation for this line is $Rg=5.3\ Hg+50$, in which Rg is the average ground-water discharge to the river, assumed equal to base flow in cubic feet per second, and Hg is the average ground-water stage in inches. Table 3 shows

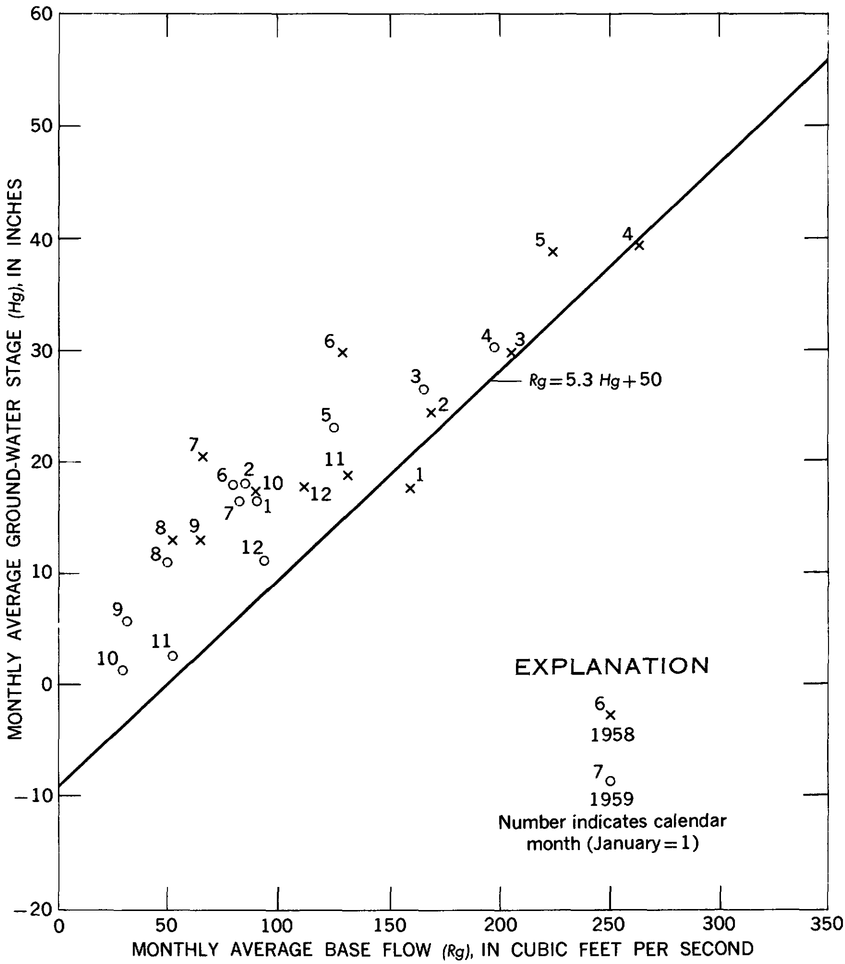


FIGURE 10.—Relation of monthly average base flow to ground-water stage of Pawcatuck River at Kenyon.

the computation of ground-water evapotranspiration losses for the upper Pawcatuck River basin based on the relation line on figure 10. These losses for 1958 and 1959 are plotted on figure 9. The loss of ground water through evapotranspiration in the entire upper Pawcatuck basin amounted to 8.77 inches in the 1959 water year. A water year is defined as the 12-months period ending September 30 of the year designated. For the Chipuxet and Usquepaug basins it was 8.59 and 7.39 inches, respectively (tables 5 and 4).

STREAMFLOW

Water flowing out of the basin in streams consists of water that has moved over the land surface during and immediately after rains and periods of snow melt and ground water that has seeped into the streams. The streamflow represents the water left over after evapotranspiration losses are satisfied.

During the course of the investigation streamflow was measured at two stations in the basin and at one station on Pawcatuck River at Kenyon just beyond the boundary of the basin (fig. 1). Of the two stations within the basin one was on Chipuxet River at West Kingston (lat 41°28′55″, long 71°33′06″), 3.1 miles upstream from its mouth. Discharge records are available at this station from February 1958 to July 1960. The surface drainage area above the station is 9.9 square miles. The other station in the basin was operated on Usquepaug River near Usquepaug (lat 41°28′55″, long 71°36′19″), 1.3 miles upstream from Chickasheen Brook. The surface-drainage area above this station is about 36 square miles. Discharge records are available from February 1958 to July 1960. The third stream-gaging station was on Pawcatuck River at Kenyon (lat 41°26′45″, long 71°37′34″), about half a mile outside the boundary of the basin. The surface-drainage area above this station is about 73 square miles. Discharge records are available from November 1957 to July 1960. Daily discharge records at these stations are published in the basic-data report (Allen and others, 1963, table 8).

Low-flow discharge measurements were made at six sites in the upper Pawcatuck River basin in September and October 1959. These measurements were used to determine the areal distribution of ground-water discharge. The records are given in the basic-data report (Allen and others, 1963, table 9).

The total runoff of the Pawcatuck River at Kenyon for the 1959 water year is about 27 inches (33 billion gallons of water for the year) from a drainage area of 73 square miles. In 1958 and 1959, the runoff was 37 and 25 inches, respectively, or an average of about 31 inches. The total runoff was computed on the basis of the surface-water drainage area.

Hydrographs showing the flow of the Chipuxet, Usquepaug, and Pawcatuck Rivers, water levels in wells Sok 6 and Sok 515, the stage of Wordens Pond, and precipitation at nearby stations, all for 1959, are shown on figure 11. The base-flow parts of the streamflow are also shown on the figure. The overland flow is the difference between total streamflow and base flow. The hydrographs show that runoff is high in March and April, and low in August, September, and October, when evapotranspiration losses are large.

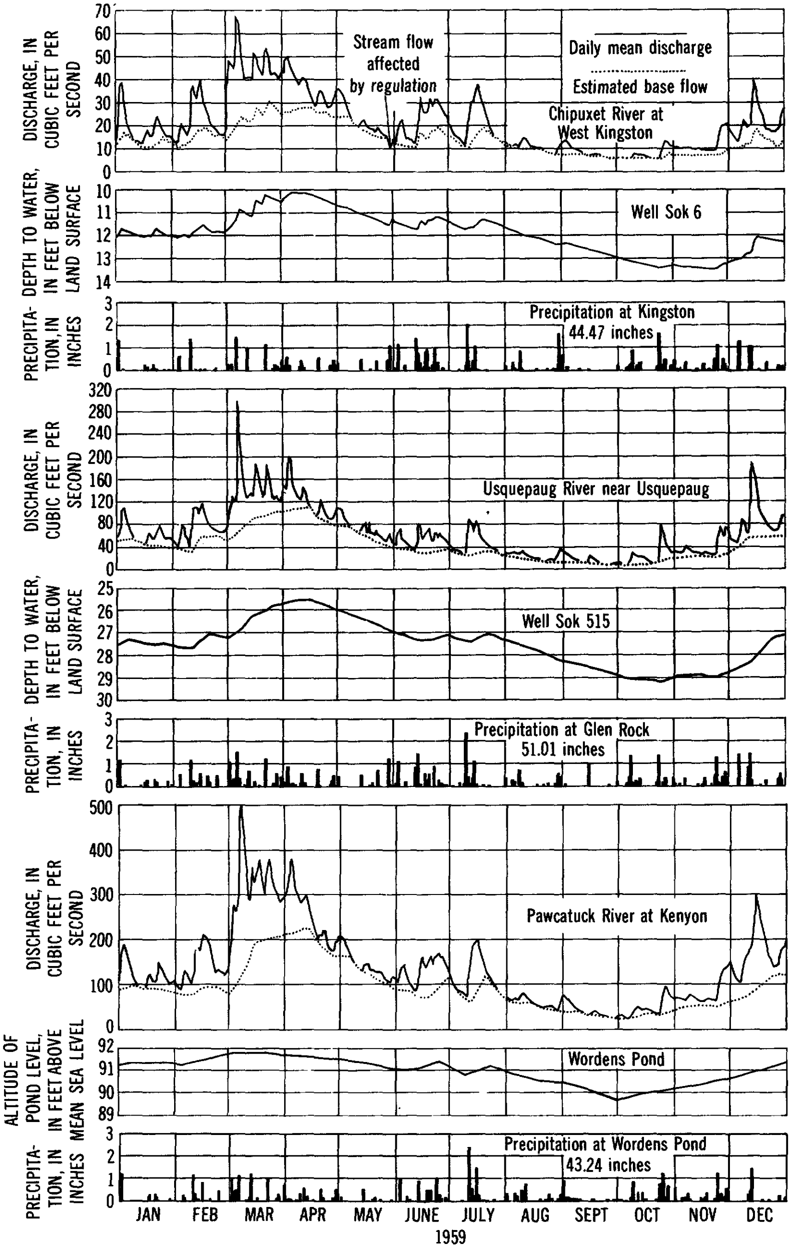


FIGURE 11.—Streamflow, ground-water levels, and precipitation at selected stations and stage of Wordens Pond in 1959.

OVERLAND RUNOFF

Overland runoff consists of water that reaches stream channels promptly during and after precipitation largely by flow over the land surface. It is quite variable, ranging from none during dry periods to very high during periods of heavy precipitation. Overland runoff is a major component of the streamflow shown by the relatively sharp peaks on the stream hydrographs on figure 11. Such flow is derived, of course, only from the surface-water drainage area.

FLOODS

In the upper Pawcatuck River basin there are many swampy areas, and the land adjacent to the various streams is sparsely populated. Past floods have inundated the swamps and other low-lying undeveloped land. Thus, floods have not been a serious problem and will not become one unless there is considerably more development adjacent to the streams. However, the ground-water reservoirs that will be discussed in a later section are in the lower parts of valleys in areas subject to inundation by floods. If supply wells are developed in these reservoirs, floods must be considered in the design and construction of the wells and pumphouses. Floods, as discussed later, may also be important in recharging the ground-water reservoirs.

The probable occurrence of floods can be determined by flood-frequency analyses. The results of such analyses are generally shown in graphs that show the recurrence interval of floods of various magnitudes. The recurrence interval has been defined as the average interval of time within which a given flood discharge will be equaled or exceeded once (American Society of Civil Engineers, 1953, p. 1221). Flood-frequency curves for the Pawcatuck, Usquepaug, and Chipuxet Rivers are shown on figure 12. They are based on data by Green (1964). The use of the curves can be illustrated by referring to the graph for the upper Pawcatuck River at Kenyon, which indicates that a flood discharge of about 800 mgd, or 1,240 cfs (cubic feet per second), will occur, as an annual peak discharge on the average, once in each 10-year period. The recurrence intervals are based on past records at gaging stations in Rhode Island and reflect only the expected conditions. For example, a flood with a recurrence interval of 10 years has a 1 in 10 chance of occurring in any given year. However, such a flood might actually occur in each of several consecutive years.

FLOW-DURATION STUDIES

Many different graphical methods have been devised to show streamflow or some particular aspect of streamflow. One of these, flood-frequency curves, was illustrated and discussed in the preceding sec-

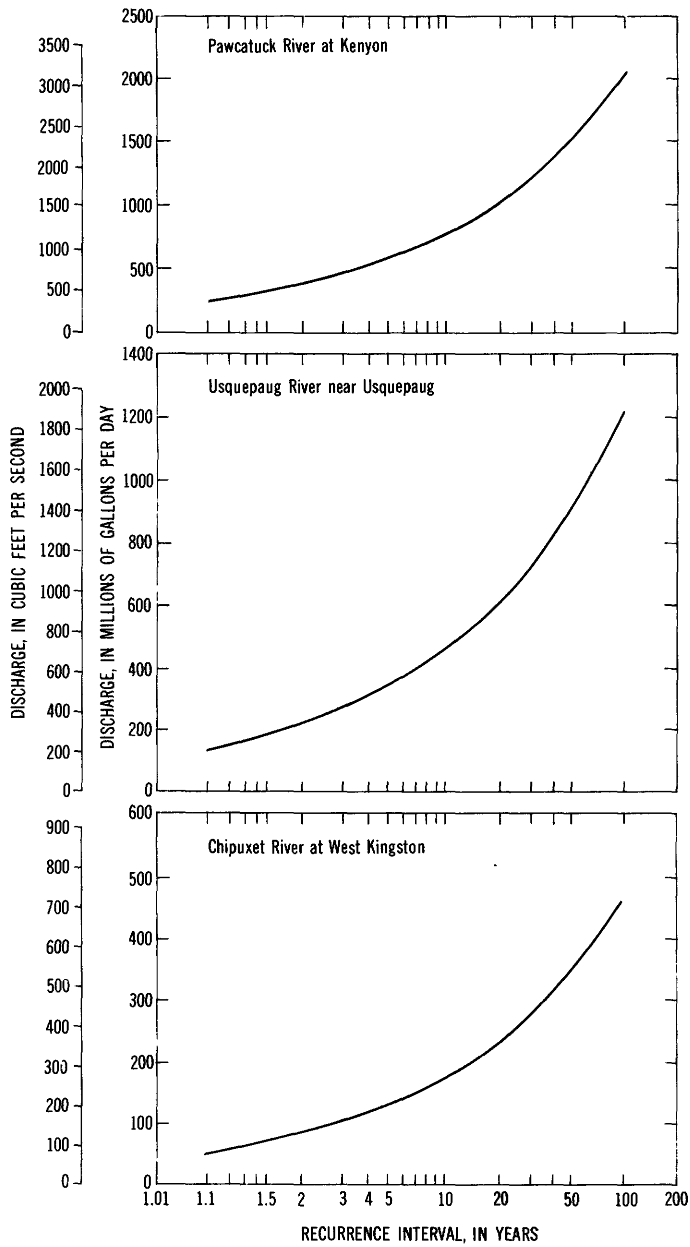


FIGURE 12.—Flood-frequency curves for stations in and near the upper Pawcatuck River basin.

tion. Another valuable method, flow-duration curves, shows the percent of time during which specified discharges are equaled or exceeded in a given period (Searcy, 1959, p. 1). Flow-duration curves were prepared for the three stream-gaging stations in and near the upper Pawcatuck River basin and for the gaging station on Pawcatuck River at Wood River Junction (fig. 13). Because the stations on the Usquepaug and the Chipuxet Rivers and the station on the upper Pawcatuck River were operated for only about 2½ years, it was necessary to correlate the records at these stations with the long-term record at Wood River Junction in order to develop flow-duration curves applicable to the base period, water years 1942–61. Assuming the hydrologic conditions existing during the base period are the same as those which will be experienced in the future, the curves can be used to forecast the percentage of time that specific discharges will be equaled or exceeded. To illustrate, it may be observed from the curve for Pawcatuck River at Kenyon that the discharge is more than 69 mgd (about 108 cfs) more than 50 percent of the time.

The slopes of flow-duration curves can be used for qualitative comparison of runoff characteristics. The moderate slopes of flow-duration curves indicate appreciable amounts of water in storage. The streamflow represented by the high-discharge end of the curves is largely overland runoff and that represented by the low-discharge end is mainly ground-water runoff. The slope of the flow-duration curve for the Chipuxet River is somewhat flatter than the curves for the Usquepaug River and the Pawcatuck River at Kenyon (fig. 13), indicating that there is proportionally more stored water contributing to streamflow in the Chipuxet River valley than in the others.

BASE FLOW

A part of all streamflow in Rhode Island is composed of water that has seeped into the streams from adjoining ground-water reservoirs. Such seepage composes the major part of the base flow of the streams. During winter periods when air temperatures are below freezing and there is no overland runoff from melting snow and during fair-weather periods in the summer, the flow of many streams is composed entirely of ground-water seepage. At other times the flow of streams is composed of overland runoff, ground-water seepage, overflow from swamps, and water derived from pond and channel storage. The last three of these—ground-water seepage, swamp discharge, and pond and channel storage—compose the base flow of the streams. Daily estimates of base flow were made at each of the three stations in and near the upper Pawcatuck River basin. Weather records, ground-water levels, and daily streamflow were compared and evaluated in arriving at the estimated base flows. The estimated base flows for 1959 for

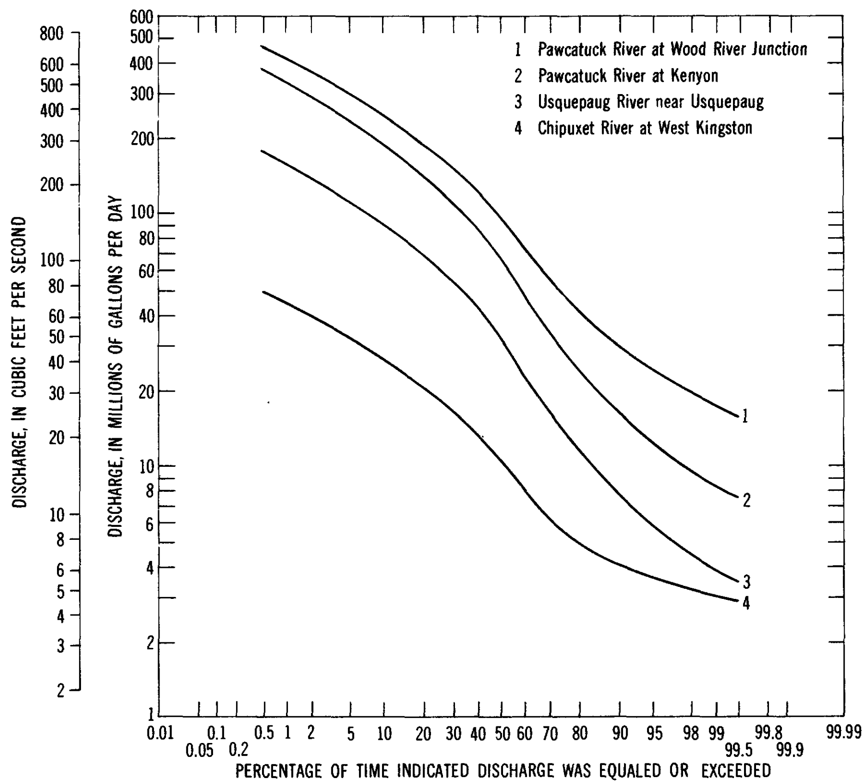


FIGURE 13.—Flow-duration curves for the three stations in and near the upper Pawcatuck River basin and for Pawcatuck River at Wood River Junction, 1942–61 water years.

the three stations are shown on figure 11. They were computed on the basis of the ground-water drainage area.

The estimated base flows include the three components noted above. For the purpose of this study it would be useful to determine how much of the base flow is supplied by ground-water seepage. However, such a determination is not possible at present (1964). The estimated base flows doubtless include a substantial amount of swamp discharge and pond and channel storage during the spring months. During the summer and fall nearly all the base flow is ground-water seepage. However, because of the discharge of substantial amounts of ground water by evapotranspiration, the base flow during this period represents only a part of the total ground-water discharge. (Total ground-water discharge as used here includes both the part that reaches the streams and the part lost through evapotranspiration.) The part of the spring base flow supplied by swamp discharge and from pond and channel storage is probably not substantially (if any) larger than the ground water lost by evapotranspiration during the summer and fall. Therefore, it appears fairly safe to assume that, on an annual basis, the estimated base flow is about equal in amount to the ground-water discharge.

Average monthly values for 1958 and 1959 of precipitation, water loss, and total runoff (overland runoff and base flow) for the three stations in and near the basin are shown on figure 14. The average base flow (ground-water runoff) for the 1959 water year for the Chipuxet River and the Usquepaug River is 68 and 72 percent of the total runoff, respectively. Base flow in the upper Pawcatuck River basin compares favorably with that of the Beaverdam Creek basin in the coastal plain of Maryland, where almost 72 percent of the total runoff was ground-water flow (Rasmussen and Andreasen, 1959, p. 99).

CHANGES IN WATER IN STORAGE

Considerable amounts of water are in storage in the basin in streams and ponds, in the soil zone, and in the zone of saturation. Seasonal changes in storage in two of these—the zone of saturation and stream and ponds—are discussed in the following sections.

CHANGES IN GROUND-WATER STORAGE

The amount of ground water in storage at any time depends on the balance between recharge and discharge. The water level in a well is an indication of the amount of water in storage in the zone of saturation at a particular point. Changes in the amount of water in storage are reflected by changes in water levels in wells. Recharge causes the water level to rise, and discharge causes it to fall.

To determine changes in ground-water storage in the upper Pawcatuck River basin, ground-water levels were measured in 67 observation wells more or less evenly spaced over the basin. Of these wells, six were equipped with continuous recording gages, and the remainder were measured biweekly.

Hydrographs of ground-water levels for 1959 for wells Sok 6 and Sok 515 are shown on figure 11. Ground-water levels (and, therefore, ground-water storage) reached their annual peak in April. The levels declined from this peak more or less continuously throughout the growing season. Because of heavy precipitation in both June and July, some ground-water recharge occurred at the wells as shown by the brief rises in water level.

It was necessary to construct a basin-wide hydrograph of ground-water levels for use in computations of ground-water evapotranspiration. Because ground-water evapotranspiration is affected most directly by ground-water levels in the stratified deposits in the valley

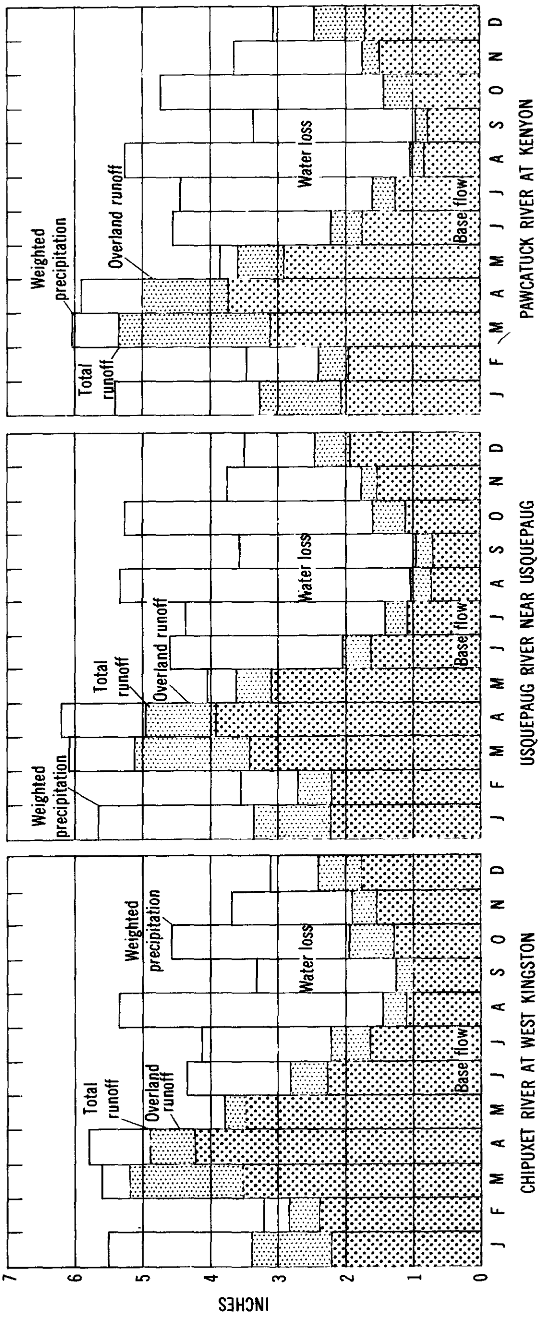


FIGURE 14.—Average precipitation and runoff for the principal streams in the upper Pawcatuck River basin for the 2-year period, 1958–59.

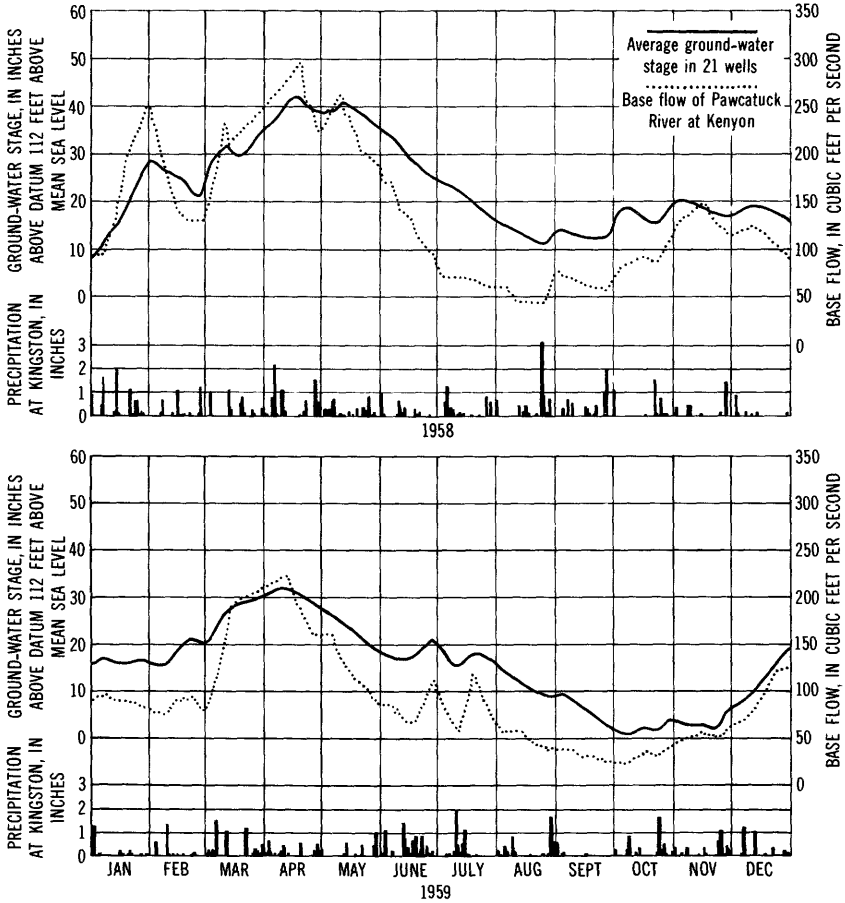


FIGURE 15.—Ground-water stage, base flow, and daily precipitation, upper Pawcatuck River basin, 1958–59.

areas, a composite hydrograph was prepared from the water-level measurements in 21 of the observation wells, all of which are in areas underlain by stratified deposits. The composite hydrographs for 1958 and 1959 shown on figure 15.

The water-level measurements made in the upper Pawcatuck River basin reflect the seasonal variations in ground-water storage in terms of feet of change in the thickness of the zone of saturation. To determine the volumetric change it is necessary to multiply the feet of change of the water table by the specific yield of the material through which the change occurs. The records from 39 wells, more or less evenly spaced over the basin, showed an average decline of the water table of 4.5 feet during the growing season of 1959.

Values of specific yield for selected samples of coarse-grained stratified outwash are reported in tables 1 and 12 of the basic-data report (Allen and others, 1963). The average of these values is about 30 percent. The average specific yield of till and of fine-grained lacustrine deposits doubtlessly is considerably less, possibly as little as 10 percent. Because about 75 percent of the basin is underlain by till and fine-grained lacustrine deposits, 15 percent would probably be a realistic value for the average specific yield of the basin. Based on the average decline of the water table of 4.5 feet and a specific yield of 15 percent, it is estimated that the seasonal change in ground-water storage in 1959 amounted to about 10 billion gallons, or about 54 million gallons per day during the 180 days of the seasonal decline. Although no computations have been made of the total volume of ground water in storage in the upper Pawcatuck River basin, it is apparent that the decline in storage during the growing season of 1959 represents a very small percent of the total.

The water-level measurements in the observation wells and single measurements made in a large number of additional wells were used in drawing the water-table map shown on plate 30. This map represents the position of the water table on August 23, 1959, at a time when water levels were relatively low and were declining seasonally. Because water levels in all wells were not measured on August 23, 1959, it was necessary to estimate the position of the water level in some of the wells shown on plate 3 by comparison of the water-level records of these wells with the long-term records of the wells that were measured.

The hydraulic gradient and direction of ground-water movement can be determined from the water-table contours. Water always moves in the direction of the steepest hydraulic gradient or at right angles to the water-table contours. The contours on plate 3 show that the ground water in the upper Pawcatuck River basin flows towards the streams draining the valleys and in a generally southward direction down the valleys.

CHANGES IN SURFACE-WATER STORAGE

Water is stored on the land surface in the upper Pawcatuck River basin in stream channels, ponds, and swamps. The amount of water in the stream channels is relatively small. The average amount of water in storage in Wordens, Yawgoo, Tucker, Hundred Acre, Larkin, Barbers, and Thirty Acre Ponds is estimated to be about 32 billion gallons. The depletion of surface-water storage during the growing season of 1959 amounted to more than 700 million gallons, or about 4 mgd for a period of 180 days. As in the case of ground-water storage, depletion of surface-water storage is seasonal. The storage is replenished by fall and winter precipitation.

SUMMARY OF THE WATER BUDGET

The preceding sections contain brief discussions of those aspects of the hydrologic cycle that are of direct importance in making determinations of the availability of ground water. It may appear that the most important section of all—that relating to ground-water recharge—has been omitted. However, direct measurement of ground-water recharge, like evapotranspiration losses, is extremely difficult to make. It can be determined most satisfactorily at the present time by measuring the discharge from the zone of saturation. Such discharge, as noted in the preceding sections, involves both seepage into streams (base flow) and evapotranspiration losses directly from the zone of saturation. The ground-water recharge, which is assumed to be equal to the base flow, as well as the other principal elements of the water budget can best be seen from tables 3, 4, and 5.

Tables 3, 4, and 5 summarize the water budget and show the monthly precipitation, water losses, and runoff for the upper Pawcatuck River basin and for the Chipuxet River and Usquepaug-Queen River subbasins for the 1959 water year (October 1958 through September 1959). The runoff is broken down into total runoff, overland runoff, and base flow. The tables also contain computed values of evapotranspiration from ground water (from the zone of saturation) and the average monthly ground-water stage in the stratified deposits.

The values contained in tables 3, 4, and 5 are the most accurate that can be determined at this time with the data and methods presently available. The values for precipitation were determined from measurements at four stations by use of the Thiessen polygon method. The total runoff was measured at continuous stream-gaging stations maintained by the Geological Survey. The average ground-water stages are based on actual measurements but probably do not precisely reflect the average ground-water stage for the different parts of the basin. The separation of the streamflow hydrographs into base-flow and overland-runoff parts involves considerable judgment. Therefore, the values of overland runoff, base flow from the hydrographs, base flow computed for zero evapotranspiration loss, and evapotranspiration from ground water are, at best, only approximations of the true values. For example, it may be noted that the evapotranspiration from ground water is shown in all tables to be less in March and April than in January and February. This is unquestionably wrong and probably reflects errors either in the average ground-water stage

TABLE 3.—*Monthly water budget for the upper Pawcatuck River basin, 1959 water year*

[Surface-drainage area is about 73 sq mi, and subsurface-drainage area is 69 sq mi]

Date	Precipitation (inches) [1]	Water losses [2] (inches)	Total runoff		Overland runoff		Base flow				Evapotranspiration from ground water		Average [6] ground-water stage (inches)
							From stream hydrograph			Computed[5] for zero evapotranspiration (mgd)			
			Inches [3]	Million gallons per day	Inches [3]	Million gallons per day	Inches [4]	Million gallons per day	Percent of total runoff		Inches [4]	Million gallons per day	
1958													
October	4.36	2.22	2.14	87.8	0.74	30.3	1.48	57.5	65	91.1	0.87	33.6	17
November	2.89	.62	2.27	95.6	.26	11.0	2.13	84.6	88	96.9	.31	12.3	19
December	1.81	—.36	2.17	89.1	.42	17.4	1.85	71.7	80	93.7	.57	22.0	18
1959													
January	2.58	.67	1.91	78.2	.49	20.1	1.49	58.1	74	87.8	.77	29.7	16
February	3.47	1.43	2.04	92.3	.84	38.1	1.27	54.3	59	93.7	.92	39.4	18
March	6.82	1.67	5.15	211.2	2.56	104.6	2.75	106.6	50	124.0	.45	17.4	27
April	3.66	—.25	3.91	164.7	.88	37.4	3.20	127.3	77	136.3	.23	9.0	30
May	21.9	—.02	2.21	90.4	.25	10.3	2.07	80.1	89	111.8	.82	31.7	23
June	6.31	4.31	2.00	84.6	.76	32.3	1.32	52.3	62	93.7	1.04	41.4	18
July	4.41	2.59	1.82	74.3	.51	20.7	1.38	53.6	72	89.8	.94	36.2	17
August	3.24	2.37	.87	35.5	.09	3.9	.81	31.6	89	71.1	1.02	39.5	11
September	1.31	.73	.58	24.4	.10	4.4	.50	20.0	82	53.0	.83	33.0	6
Total	43.05	15.98	27.07	94.4	7.90	27.8	20.25	66.6	[7] 71	95.3	8.77	28.7	

[1] Average for basin determined by Thiessen polygan method.
[2] Difference between precipitation and total runoff includes evapotranspiration losses and changes in ground-water and surface-water storage.
[3] Based on surface-drainage area.
[4] Based on subsurface drainage area.
[5] Computed from relationship line in fig. 10. Assumes no evapotranspiration from ground water.
[6] Above an arbitrary datum 112 ft above mean sea level. Values pertain only to stratified outwash deposits.
[7] Average for basin.

TABLE 4.—*Monthly water budget for the Usquepaug-Queen River basin, 1959 water year*

[Surface-drainage area is about 36 sq mi, and subsurface-drainage area is 33 sq mi]

Date	Precipitation (inches) [1]	Water losses [2] (inches)	Total runoff		Overland runoff		Base flow				Evapotranspiration from ground water		Average [6] ground-water stage (inches)
							From stream hydrograph			Computed[5] for zero evapotranspiration (mgd)			
			Inches [3]	Million gallons per day	Inches [3]	Million gallons per day	Inches [4]	Million gallons per day	Percent of total runoff		Inches [4]	Million gallons per day	
1958													
October	5.13	2.68	2.45	49.3	0.82	16.6	1.76	32.7	66	42.8	0.54	10.1	17
November	2.96	.60	2.36	48.8	.29	6.0	2.25	42.8	88	45.6	.15	2.8	19
December	1.96	−.27	2.23	44.9	.39	7.8	2.00	37.1	83	44.2	.38	7.1	18
1959													
January	2.79	.67	2.12	42.6	.56	11.4	1.68	31.2	73	41.1	.53	9.9	16
February	3.82	1.53	2.29	51.0	.82	18.3	1.59	32.7	64	44.2	.56	11.5	18
March	7.28	2.47	4.81	96.9	2.00	40.4	3.05	56.5	58	59.9	.18	3.4	27
April	4.18	.28	3.90	80.8	.78	16.2	3.39	64.6	80	66.6	.10	2.0	30
May	2.34	.03	2.31	46.6	.38	7.6	2.10	39.0	84	53.6	.79	14.6	23
June	6.42	4.66	1.76	36.4	.67	13.9	1.18	22.5	62	44.2	1.14	21.7	18
July	4.27	2.77	1.50	30.2	.51	10.3	1.07	19.9	66	42.0	1.19	22.1	17
August	3.01	2.26	.75	15.2	.15	3.1	.65	12.1	80	32.2	1.09	20.1	11
September	1.46	.90	.56	11.6	.16	3.3	.44	8.3	72	22.5	.74	14.2	6
Total	45.62	18.58	27.04	46.2	7.53	12.9	21.16	33.3	[7] 72	44.9	7.39	11.6	

[1] Average for basin determined by Thiessen polygon method.
[2] Difference between precipitation and total runoff includes evapotranspiration losses and changes in ground-water and surface-water storage.
[3] Based on surface-drainage area.
[4] Based on subsurface drainage area.
[5] Computed from relationship line similar to fig. 10. Assumes no evapotranspiration from ground water.
[6] Above an arbitrary datum 112 ft above mean sea level. Values pertain only to stratified outwash deposits.
[7] Average for basin.

TABLE 5.—*Monthly water budget for the Chipuxet River basin, 1959 water year*

[Surface-drainage area is 9.9 sq mi, and subsurface-drainage area is 9.1 sq mi]

Date	Precipitation (inches) [1]	Water losses [2] (inches)	Total runoff		Overland runoff		Base flow				Evapotranspiration from ground water		Average [6] ground-water stage (inches)
							From stream hydrograph			Computed[5] for zero evapotranspiration (mgd)			
			Inches [3]	Million gallons per day	Inches [3]	Million gallons per day	Inches [4]	Million gallons per day	Percent of total runoff		Inches [4]	Million gallons per day	
1958													
October	4.29	1.35	2.94	16.3	1.28	7.1	1.79	9.2	56	13.2	0.78	4.0	17
November	3.05	.53	2.52	14.4	.52	3.0	2.16	11.4	79	14.1	.51	2.7	19
December	1.72	−.59	2.31	12.8	.56	3.1	1.90	9.7	76	13.7	.78	4.0	18
1959													
January	2.48	.25	2.23	12.4	.70	3.9	1.66	8.5	68	12.7	.82	4.2	16
February	3.01	.55	2.46	15.2	.90	5.5	1.72	9.7	64	13.7	.71	4.0	18
March	6.33	1.02	5.31	29.5	2.54	14.1	3.01	15.4	52	18.7	.65	3.3	27
April	3.54	−.67	4.21	24.0	1.22	7.0	3.25	17.0	71	20.9	.74	3.9	30
May	2.28	−.22	2.50	13.9	.34	1.9	2.33	12.0	86	16.7	.92	4.7	23
June	5.92	3.30	2.62	15.0	.98	5.6	1.79	9.4	63	13.7	.82	4.3	18
July	4.19	1.76	2.43	13.5	.74	4.1	1.84	9.4	70	13.0	.71	3.6	17
August	3.66	2.40	1.26	7.0	.16	.9	1.20	6.1	87	9.9	.75	3.8	11
September	1.18	.24	.94	5.4	.14	.8	.87	4.6	85	6.7	.40	2.1	6
Total	41.65	9.92	31.73	15.0	10.08	4.8	23.52	10.2	[7] 68	13.9	8.59	3.7	

[1] Average for basin determined by Thiessen polygon method.
[2] Difference between precipitation and total runoff includes evapotranspiration losses and changes in ground-water and surface-water storage.
[3] Based on surface-drainage area.
[4] Based on subsurface drainage area.
[5] Computed from relationship line similar to fig. 10. Assumes no evapotranspiration from ground water.
[6] Above an arbitary datum 112 ft above mean sea level. Values pertain only to stratified outwash deposits.
[7] Average for basin.

or the separation of the streamflow hydrographs or reflects inaccuracies inherent in the method of computing ground-water evapotranspiration.

Regardless of the existence of obvious errors in some of the monthly values, the annual values are believed to be of the correct order of magnitude. A possible exception is the water loss from the Chipuxet River (table 5) which appears to be too low. These values show that about 60 percent of the precipitation on the entire upper Pawcatuck basin discharges as streamflow through the Pawcatuck River. Also observe that a little over 70 percent of the total runoff is base flow.

GROUND-WATER RESERVOIRS

Ground water, at least in quantities adequate to supply domestic and other relatively small needs, is available at almost any place in the upper Pawcatuck River basin, either from the bedrock or from the layer of unconsolidated deposits that cover the bedrock. Ground water is available in substantial amounts from two areas in the basin. The larger of these areas occupies the central part of the Usquepaug-Queen River valley, from the vicinity of Exeter State School (now Ladd School) to about a mile south of the village of Usquepaug. For convenience in the following discussion this area will be referred to as the Usquepaug-Queen ground-water reservoir. The smaller area is in the Chipuxet River valley, from the vicinity of Hundred Acre Pond to Larkin Pond. This area is referred to as the Chipuxet ground-water reservoir.

One of the principal objectives of the investigation was to determine the perennial yield of these ground-water reservoirs. The yield of these and similar ground-water reservoirs in the valleys of Rhode Island is supplied from the following sources: (1) Recharge from precipitation falling directly on the reservoirs, (2) ground water that moves into the reservoirs from the adjoining uplands, and (3) infiltration of water from the streams flowing across the reservoirs.

Under natural (nonpumping) conditions the water in the reservoirs consists only of recharge from precipitation on the reservoirs and water moving into them from the adjoining uplands. The water is discharged naturally from the reservoirs either by seepage into streams, by evaporation (where the water table is within several feet of the land surface), or by the transpiration of plants whose roots reach the water table. Under conditions of maximum withdrawal the seepage of water into the streams ceases, evapotranspiration losses are stopped or substantially reduced, and water infiltrates from the streams into the deposits.

In analyzing the yield of ground-water reservoirs it must be recognized that recharge from precipitation is not at a constant rate. Measurement of ground-water levels in the upper Pawcatuck River basin show that most recharge occurs during two distinct periods, one in the fall at the end of the growing season and the other in the spring before plant growth starts. Depending on climatic conditions the recharge between these periods may range from negligible to substantial amounts. In analyzing the yield of a ground-water reservoir it is necessary to assume that no recharge will occur during a certain period. In humid areas such as Rhode Island periods of 90 to 365 days have been assumed in various studies. A period of 180 days is probably most realistic, and such a period is used in the succeeding analysis of the yield of the Usquepaug-Queen and Chipuxet ground-water reservoirs.

The movement of water into the reservoirs from the surrounding uplands is continuous in time but variable in rate. The rate largely depends on the height of the water table in the uplands and, thus, is generally greatest in the spring.

The water available for infiltration from the streams to the ground-water reservoirs ranges between wide extremes. It is greatest in the spring and least in the late summer and early fall. The amount that actually infiltrates depends on the permeability of the deposits in contact with the streams and the hydraulic gradient between the streams and the reservoirs. Observations made during the course of the study revealed relatively coarse-grained material along the bottoms of the streams in the ground-water reservoir areas. Fine-grained material appears to be thin or absent except possibly in ponds and some swampy areas. Thus, conditions appear to be generally favorable for stream infiltration.

It is apparent from the preceding discussion that the yield of the ground-water reservoirs in the upper Pawcatuck River basin involves several factors, all of which vary with time. Estimates of the yield can be arrived at through the application of any one of several different methods, including analog models and mathematical models of varying complexity. The selection of a particular method is dependent on the time and funds available and the required degree of accuracy in the final answer. In selecting an analytical method knowledge of the physical features of a ground-water reservoir, particularly the lateral and vertical variations in permeability, must be considered. Obviously, the final answer can never be more accurate than the least accurate data used in the analysis, regardless of the complexity of the analytical method used.

Careful consideration of the geologic and hydrologic situation in the upper Pawcatuck River basin indicated that estimates of yield sufficiently accurate for most purposes could be obtained with a relatively simple mathematical model. The principal features of this model and how it was used in estimating the yields will be discussed in the following sections devoted to the different reservoirs.

RELATION OF STREAMFLOW TO YIELD OF RESERVOIRS

The water potentially available from any area equals the stream discharge from the area plus any reductions in evapotranspiration losses. Because reductions in evapotranspiration cannot be estimated with any degree of accuracy in advance of the development of a ground-water reservoir, they are not considered in the yield of the reservoirs in the upper Pawcatuck River basin. Drawdowns resulting from pumpage will be less than predicted to the extent that these losses are reduced.

As has been pointed out in preceding sections, stream discharge consists of water that has moved through the ground (base flow) and water that has flowed over the land surface to the streams. The analysis of stream discharges, both with respect to the amounts that are derived from the ground and that flow overland and to long-term variations, is important in estimating yields from the ground-water reservoir.

Three stream-gaging stations were maintained as part of the upper Pawcatuck River basin investigation. Gaging stations on the Usquepaug River and Chipuxet River are of particular significance because for practical purposes they measure the amount of water which is potentially available for ground-water developments from the reservoir areas. Because of the short duration of periods of peak streamflow and the low permeability of the streambeds, it is unlikely that, even under the most favorable natural conditions, all the flow which passes either of these gages could be diverted to the ground-water reservoirs. For these reasons only the base flow was considered to be potentially available for infiltration to the ground-water reservoirs.

The stream-gaging stations in the upper Pawcatuck basin were maintained for approximately 2 calendar years, 1958 and 1959, which included 1 water year, 1959 (October 1, 1958, through to September 30, 1959). Based on precipitation data, stream discharge during the 1959 water year is slightly above average. However, from the standpoint of water-supply developments, it is more important to estimate stream discharge during unusually dry years. In an effort to estimate streamflow in the upper Pawcatuck River basin during dry years, the data from the three stations in the basin were compared with the records from 1941 to 1962 for Pawcatuck River at Wood River Junction.

Because it is assumed in the analysis of the yields that storage in the ground-water reservoirs must be capable of supplying the withdrawals for a period of at least 180 days, only annual and longer term variations in streamflow are of interest. For this reason only annual mean discharge figures were used. Annual mean discharge of

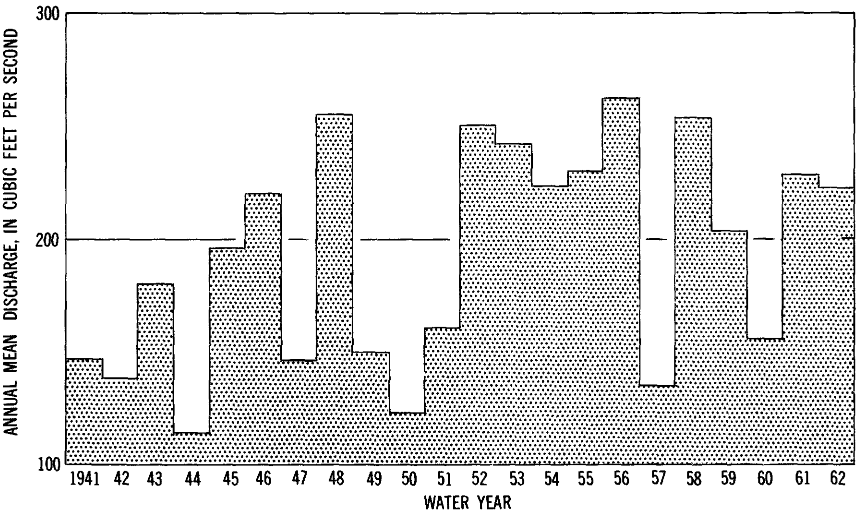


FIGURE 16.—Annual mean discharge of the Pawcatuck River at Wood River Junction for the period 1941–62.

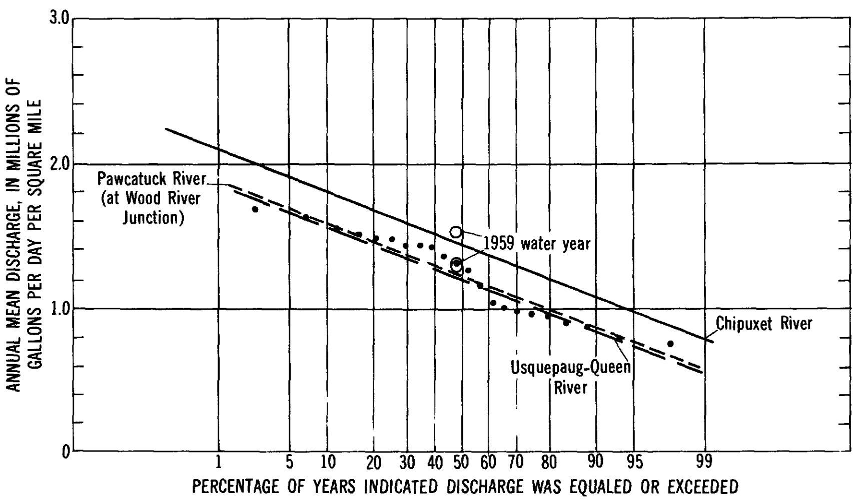


FIGURE 17.—Cumulative probability distribution of annual mean discharges.

Pawcatuck River at Wood River Junction from 1941 through 1962 is shown graphically on figure 16. Annual mean discharge per square mile of drainage basin for the 22 water years shown on figure 16 are plotted on probability graph paper in figure 17. The data are approximately normally distributed.

Because of the proximity of the stations, it is reasonable to assume that the distribution of annual mean discharge of the Usquepaug-Queen and the Chipuxet Rivers is similar to the annual mean discharge of Pawcatuck River at Wood River Junction. Data for the Chipuxet and Usquepaug-Queen Rivers for the 1959 water years are correlated with the 1959 data from the Pawcatuck River on figure 17. Two distribution lines parallel to the distribution line for the Pawcatuck River were drawn through the 1959 data points for the Usquepaug-Queen and the Chipuxet Rivers on the assumption that the distribution of annual mean discharge of these streams is similar to that of the Pawcatuck River. By use of these distribution lines it is possible to estimate the annual mean discharge for the Usquepaug-Queen and Chipuxet Rivers during dry years. Table 6 lists the low annual mean discharges which occur on the average of 1 low year in 10 years and 1 low year in 20 years for both the Chipuxet and the Usquepaug-Queen Rivers.

TABLE 6.—*Summary of actual and estimated annual mean discharge and base flow during average and dry years for the Usquepaug-Queen River and the Chipuxet River*

Average and dry water years	Drainage-basin area (sq mi)		Annual mean—					
			Discharge (mgd)		Discharge per square mile (mgd per sq mi)		Base flow (mgd)	
	Usquepaug-Queen	Chipuxet	Usquepaug-Queen	Chipuxet	Usquepaug-Queen	Chipuxet	Usquepaug-Queen	Chipuxet
1959 (average year)	36	9.9	46	15	1.28	1.52	33	10
On the average:								
1 low year in 10	36	9.9	31	11	.86	1.08	22	7.4
1 low year in 20	36	9.9	27	9.6	.76	.97	19	6.4

USQUEPAUG-QUEEN GROUND-WATER RESERVOIR

A large ground-water reservoir is present in the Usquepaug-Queen River valley. Coarse sand and gravel were deposited as glacial outwash in a preglacial bedrock valley which coincides with the present valley. As indicated on plate 2, coarse outwash deposits with average permeabilities in excess of 100 gpd per sq ft underlie the valley from the vicinity of Exeter State School (Ladd School) to the vicinity of Usquepaug, a distance of approximately 6 miles. These deposits constitute the ground-water reservoir. A major part of the reservoir, as shown on figure 18, consists of well-sorted coarse-grained deposits approximately 100 feet thick with average permeabilities in excess of 1,000 gpd per sq ft.

In order to simplify the mathematical analysis of the yield of the reservoir it was necessary to assume that the reservoir is bounded by straight, parallel impermeable boundaries. These boundaries are shown on figure 18, and their use in the analysis will be described in the following section.

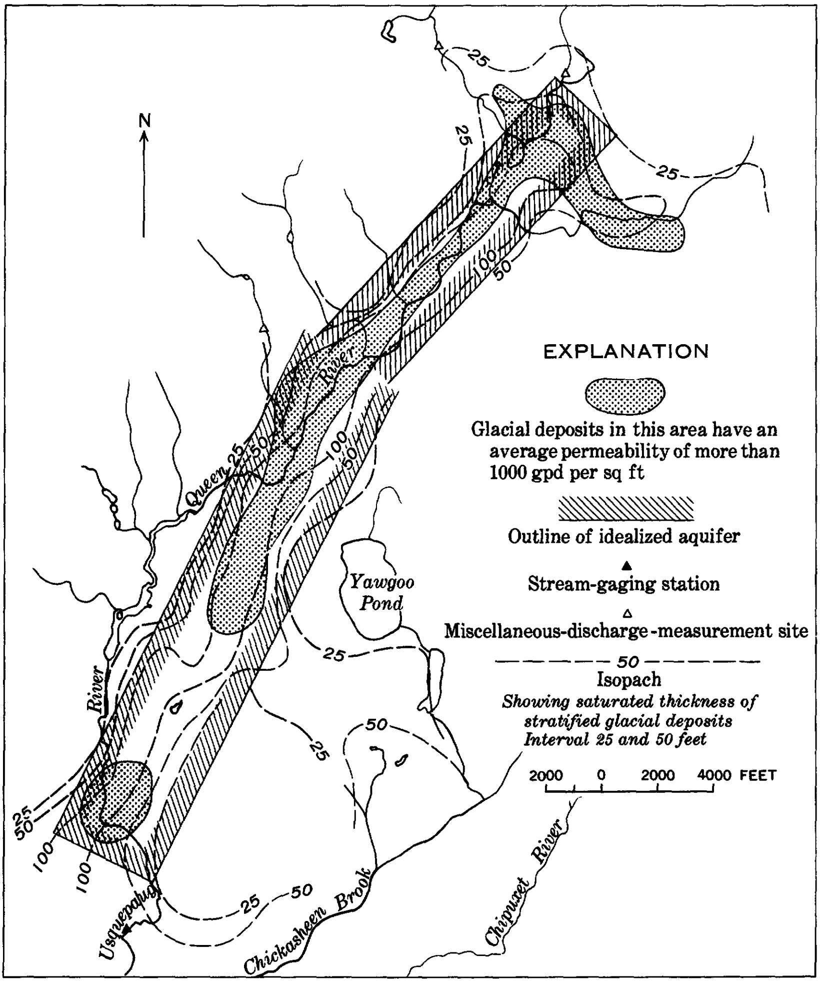


FIGURE 18.—Usquepaug-Queen ground-water reservoir.

PHYSICAL AND HYDROLOGIC FEATURES

The analysis of the estimated yield in the ground-water reservoir is based on the assumption that if the water in storage in the aquifer is sufficient to sustain a certain rate of pumpage for a period of 180 days without recharge, the reservoir will be capable of sustaining this pumpage rate indefinitely. This is felt to be a conservative approach, particularly for the reservoir in the Usquepaug-Queen River valley where large amounts of streamflow are available for infiltration to the ground-water reservoir.

The idealized ground-water reservoir in the Usquepaug-Queen River valley consists of two adjacent rectangular areas, shown on figure 19. To compute the amount of water which might be withdrawn from this reservoir, it is necessary to know the coefficient of transmissibility and the coefficient of storage of the aquifer material. The transmissibility of the outwash deposits can be estimated at any point in the ground-water reservoir by multiplying the average permeability by the saturated thickness of the outwash material, both taken from plate 2. On the basis of the geologic data an average coefficient of transmissibility of 50,000 gpd per ft and a storage coefficient of 0.2 were used for analysis.

In order to make the mathematical analysis a hypothetical system of supply wells is assumed for the idealized reservoir. Figure 19 shows the assumed configuration of pumping wells in the Usquepaug-Queen ground-water reservoir. In order to compensate for the hydraulic effect of the reservoir boundaries it is necessary to introduce an array of imaginary image wells beyond the boundaries (Ferris and others, 1962, p. 147–151). The boundary effects are determined by assuming that the image wells begin pumping at the same time as the supply wells and are pumped at the same rate as the supply wells. The pumping wells and the associated array of image wells for the larger of the two idealized segments of the reservoir in the Usquepaug-Queen River valley are shown on figure 20. Although theoretically the image wells extend to infinity, their effect on the drawdown in the aquifer diminish with distance and become negligible beyond the line shown on the figure.

The two idealized segments of the Usquepaug-Queen ground-water reservoir were treated independently in the analysis of yields. Although this simplification affects computed drawdowns, the effect is insignificant.

Drawdowns were computed using the Theis nonequilibrium equation (Ferris and others, 1962, p. 92–98). Computed drawdowns were corrected for thinning of the aquifer (Ferris, 1949, p. 246–247) using the correction:

$$s' = s + \frac{s^2}{2m}$$

where s' is the actual drawdown that would occur in response to pumping, s is the drawdown that would occur if the aquifer were not dewatered, and m is the saturated thickness of aquifer material before pumping began.

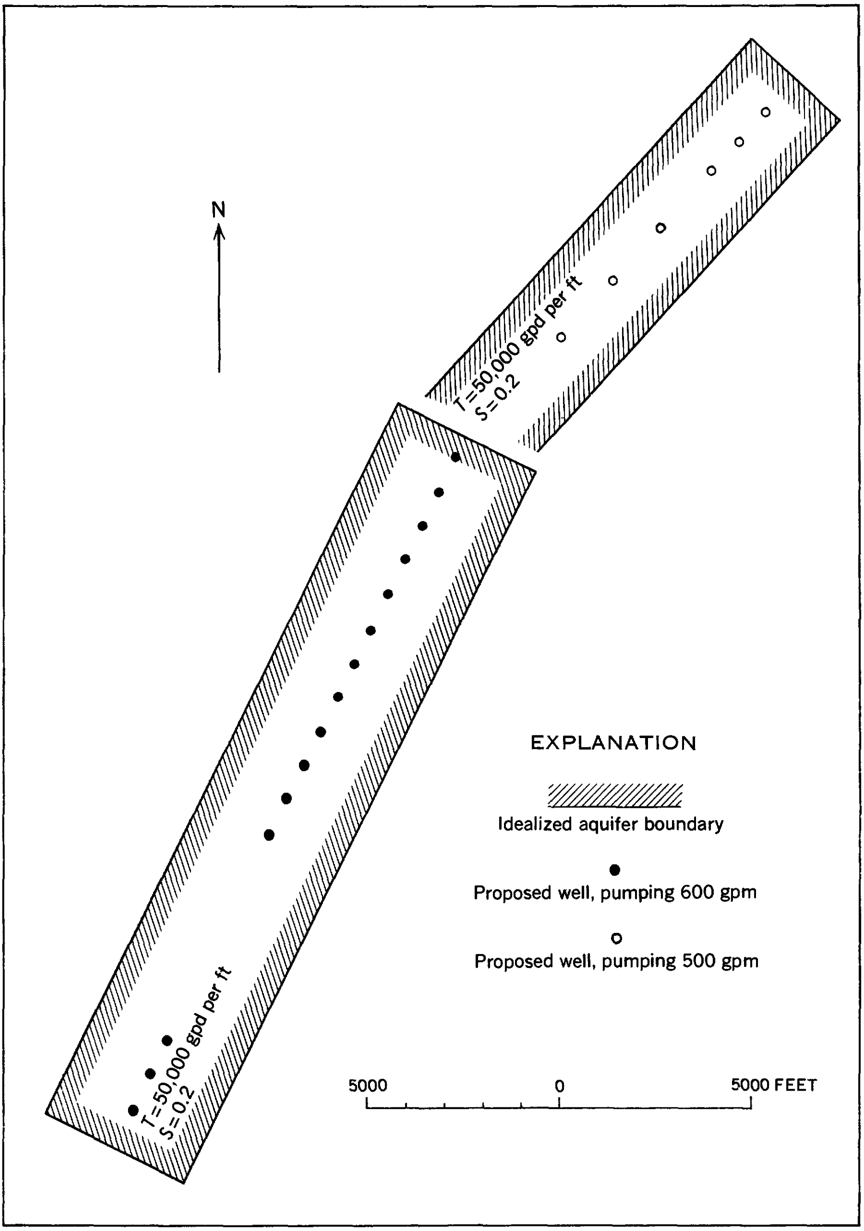


FIGURE 19.—Idealized ground-water reservoir in the Usquepaug-Queen River valley. The wells indicated were assumed for the purpose of analysis.

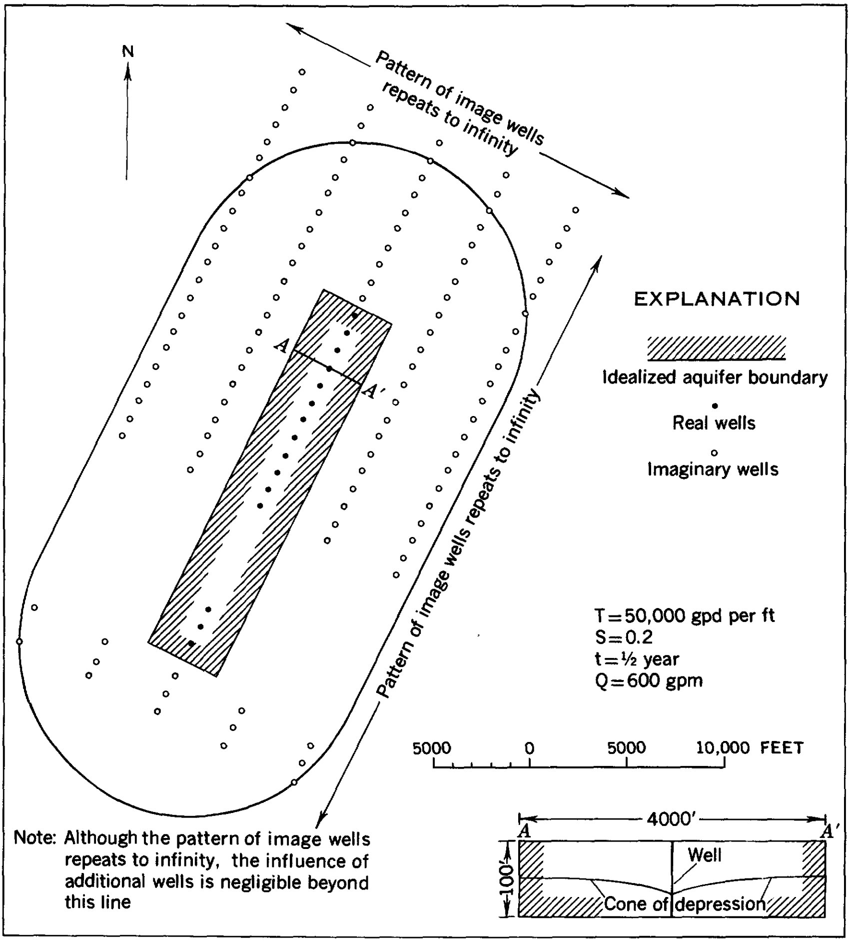


FIGURE 20.—Larger of the two idealized rectangular aquifers in the Usquepaug-Queen River valley showing the assumed pumping wells and the array of imaginary, image wells needed for analysis. T=coefficient of transmissibility, S=coefficient of storage, t=pumping period, and Q=pumping rate.

The analysis indicates that the reservoir storage is sufficient to sustain a total rate of pumpage of approximately 17 mgd. This rate is based on the assumption that the pumpage would be from six wells in the northern part of the reservoir, of which three are spaced 1,000 feet apart and three are spaced 2,000 feet apart, each pumping at a rate of 500 gpm and 15 wells in the southern part of the reservoir spaced 1,000 feet apart, each pumping at a rate of 600 gpm. The locations of the wells are shown on figure 19.

WATER POTENTIALLY AVAILABLE TO THE RESERVOIR

As explained previously, only the base stream discharge—ground-water discharge—was assumed to be potentially available to a ground-water development. A series of miscellaneous stream measurements was made on the major tributaries of the Usquepaug River during September and October 1959 at times when the streamflow was principally base flow. These measurements are summarized in table 7, and the sites of the discharge measurements are indicated on figure 18.

The miscellaneous measurements indicate that approximately 60 percent of the base flow of the Usquepaug-Queen River is contributed along the reach of river underlain by the ground-water reservoir. This is significant because it indicates that 60 percent of the total base flow is presently ground-water discharge which can be diverted directly to wells. In other words, discharge of base flow from the area of ground-water development is available within the reservoir without stream infiltration.

The proposed development and the availability of water in the Usquepaug-Queen River valley is summarized in table 8.

TABLE 7.—*Summary of miscellaneous discharge measurements in the Usquepaug-Queen River basin*

Date of measurement	Locke Brook (mgd)	Fisherville Brook (mgd)	Queen River (mgd)	Total discharge of tributaries (mgd)	Discharge at Usquepaug River gage (mgd)	Percent of Usquepaug discharge contributed by tributaries
9–10–59	0. 56	1. 67	0. 33	2. 56	10. 3	25
10– 7–59	. 93	1. 15	. 39	2. 47	7. 11	35
10–22–59	1. 02	1. 69	. 57	3. 28	9. 69	34

TABLE 8.—*Summary of potentially available water and proposed ground-water development in the Usquepaug-Queen River basin*

[Results in millions of gallons per day except as indicated]

Average and dry water years	Annual mean base flow	Recoverable ground-water discharge base flow from area of proposed development	Proposed pumpage	Necessary infiltration	Amount of ground water available as diverted evapotranspiration	Duration of proposed pumpage possible without recharge (days)
1959	33	19	17	------	Assumed negligible.	180
On the average:						
1 low year in 10	22	13	17	4	--------------	180
1 low year in 20	19	11	17	6	--------------	180

Infiltration from surface streams is necessary during dry years, as indicated in table 8. However, the quantities are relatively small except during the driest years. Little is known about the character of the material lining the stream channels in the ground-water reservoir area. However, 40 gpd per sq ft of area available for infiltration appears to be a reasonable estimate of the infiltration capacity of the lower part of the streambed. Because the reach of stream overlying the proposed area of ground-water development in the Usquepaug-Queen River valley is more than 20,000 feet long and averages 10 feet in width, an area in excess of 200,000 square feet is potentially available for infiltration. This suggests that a conservative estimate of the potential infiltration capacity of the streambed during base-flow conditions is 8 mgd, which is in excess of the amount necessary even in very dry years. At times of high streamflow the infiltration capacity is doubtless many times greater.

As has been pointed out in preceding sections, large quantities of water are returned to the atmosphere by evaporation and transpiration by plants in the upper Pawcatuck River basin. This investigation indicates that during an average year about 7 inches of rainfall are discharged from the Usquepaug-Queen basin as evapotranspiration. This amounts to approximately 120 million gallons per year per square mile. Wherever the water table is lowered 10 feet or more below the land surface by a ground-water development, the amount of water transpired is greatly reduced. The resultant reduction in the quantity of water lost through evapotranspiration from the area of ground-water development makes additional water available for ground-water withdrawal. However, it is extremely difficult to estimate how much of this water can be diverted to a ground-water development. It might amount to as much as 200 to 300 million gallons per year. Therefore, changes in the rate of evapotranspiration resulting from lowering of the water table by wells were disregarded in determining the available ground water because of the difficulties of estimating these changes. (See table 8.)

CHIPUXET GROUND-WATER RESERVOIR

A large ground-water reservoir also occurs in the Chipuxet River valley. Coarse sand and gravel which make up the reservoir were deposited by glacial streams during the last Plesistocene ice advance. An irregular area approximately 4 miles long by 4,000 feet wide is underlain by deposits with average permeabilities in excess of 100 gpd per sq ft. In a major part of the area the average permeability of the coarse outwash deposits exceeds 1,000 gpd per sq ft. The actual ground-water reservoir and the idealized reservoir assumed for purposes of analysis are shown on figure 21. Along the line of section *C–C′*, on plate 2, two aquifers are present where a tongue of fine, less permeable sand and silt is interbedded between two bodies of coarse sand and gravel. Further south the coarse-grained beds grade entirely into fine sand and silt; to the north the fine-grained deposits pinch out, and the coarse sand and gravel form one continuous aquifer.

PHYSICAL AND HYDROLOGIC FEATURES

The irregular ground-water reservoir in the Chipuxet River valley was idealized into the rectangular area indicated on figure 21. This rectangular area neglects a part of the aquifer in the vicinity of Chickasheen Brook, west of the main ground-water reservoir. The saturated thickness of outwash deposits over most of the area ranges from approximately 100 to 150 feet. Because the average permeability of most of the coarse outwash is greater than 1,000 gpd per sq ft, the average transmissibility of the ground-water reservoir is assumed for purposes of analysis to be 100,000 gpd per ft.

The storage capacity of the ground-water reservoir is sufficient to sustain 16 wells pumping 750 gpm for a period of approximately 180 days without recharge. This is a rate of ground-water withdrawal of approximately 17 mgd; however, the water available for replenishment of the reservoir in the Chipuxet River valley does not appear to be adequate to support this rate of withdrawal. The available supply as discussed in the following section can be drawn from eight wells, each pumping 750 gpm, spaced as shown on figure 22. This rate of withdrawal, 8.6 mgd, could be withdrawn from storage in the reservoir without recharge for a period of approximately 1 year.

The quantitative estimates of the storage capacity of the ground-water reservoir were determined using the same procedures as those used for the Usquepaug-Queen ground-water reservoir.

WATER POTENTIALLY AVAILABLE TO THE RESERVOIR

Only the base flow of the Chipuxet River was assumed to be available to a ground-water development in the area. A series of miscellaneous stream discharge measurements was made during September and October 1959 on the Chipuxet River about 4,000 feet upstream from the area designated as the ground-water reservoir (fig. 21). These measurements were made during periods in which most of the stream discharge was base flow. The point at which the measurements were made is shown on figure 21, and the records are summarized in table 9.

The miscellaneous discharge records indicate that approximately 60 percent of the base flow is contributed to the Chipuxet River in

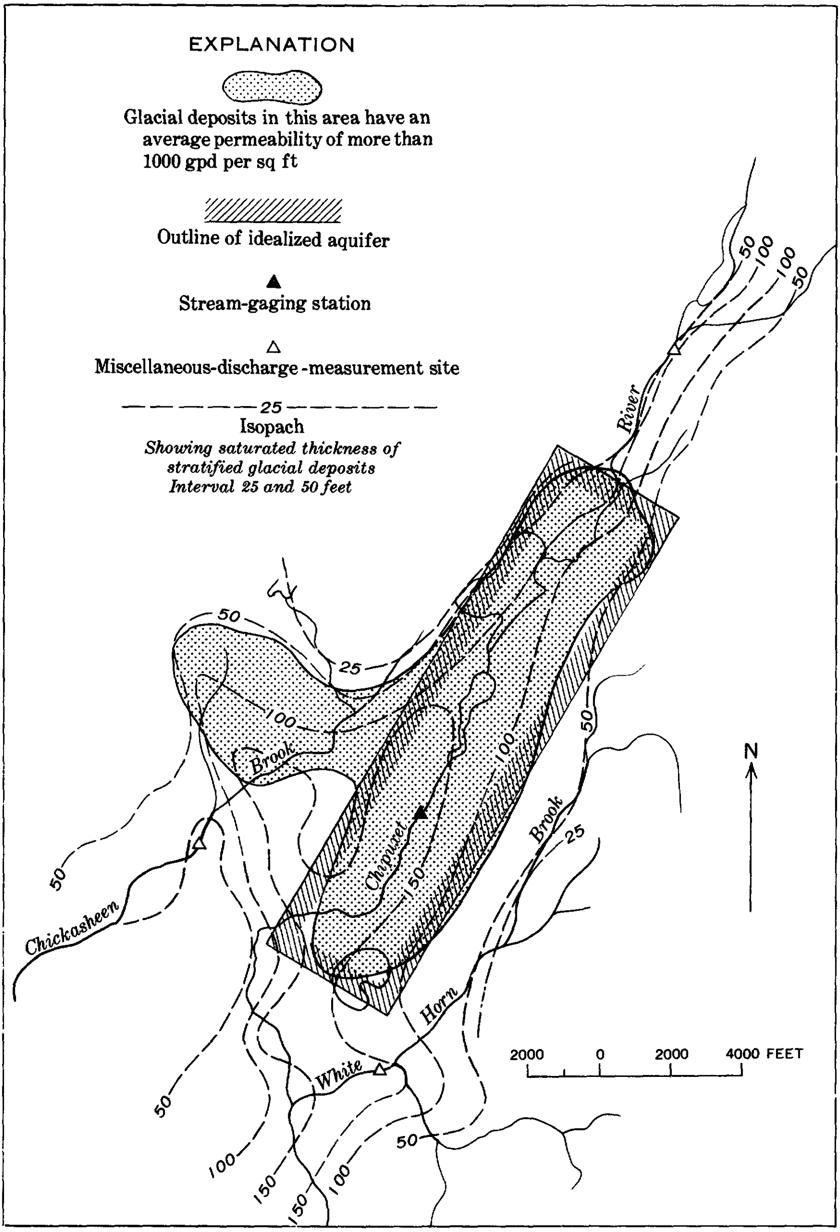


FIGURE 21.—Chipuxet ground-water reservoir.

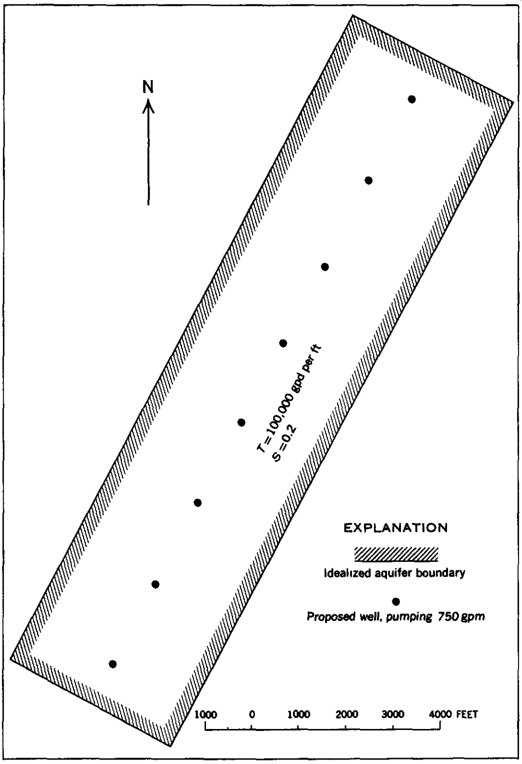


FIGURE 22.—Idealized ground-water reservoir in the Chipuxet River valley with proposed wells indicated.

the reach of river underlain by the ground-water reservoir. This is similar to the situation in the Usquepaug-Queen River valley. Ground-water discharge from the area of proposed development can readily be diverted to wells spaced evenly down the center of the reservoir. This diversion of ground-water discharge to wells would not entail stream infiltration.

The proposed development and the availability of water to the ground-water reservoir are summarized in table 10. As table 10 indicates, the amount of base flow available for infiltration during dry years is not sufficient to balance the proposed pumpage. However, the large storage capacity of the ground-water reservoir would be more than adequate to sustain the development during a dry year.

TABLE 9.—*Summary of miscellaneous discharge measurements of the Chipuxet River*

Date of measurement	Discharge at miscellaneous discharge measurement site (mgd)	Discharge at stream-gaging station on Chipuxet River (mgd)	Percent of Chipuxet River discharge contributed by drainage area above miscellaneous measurement point
9-10-59	1.78	5.61	32
10- 7-59	1.31	3.94	33
10-22-59	1.37	3.81	35

TABLE 10.—*Summary of potentially available water and proposed development in the Chipuxet River valley*

[Results in millions of gallons per day, except as indicated]

Water year	Annual mean base flow	Recoverable ground-water discharge base flow from area of proposed development	Base flow available for infiltration [1]	Proposed pumpage	Necessary infiltration	Amount of ground water available as diverted evapotranspiration	Duration of proposed pumpage possible without recharge (years)
1959	10	6	4.0	8.6	2.6	Assumed negligible.	1
On the average:							
1 low year in 10	7.4	4.4	3.0	8.6	4.2		1
1 low year in 20	6.4	3.8	2.6	8.6	4.8		1

[1] Equals annual mean base flow minus recoverable ground-water discharge.

CHEMICAL QUALITY

The chemical characteristics of water depend on the environment through which it has passed. Precipitation contains some dissolved gases such as carbon dioxide and oxygen and usually a very small amount of mineral solids. As the precipitation reaches the ground additional minerals are dissolved, depending mostly on the solubility of the minerals, the time of contact, and the dissolving power of the precipitation.

The suitability of water for many uses depends on its physical and chemical characteristics. Of these characteristics, chemical quality may pose problems of water treatment. Pathogenic organisms and suspended particles are easily removed by treatment, but certain chemical constituents such as cyanides, detergents, and certain dissolved metals are difficult to remove and may require treatment that is so costly as to prevent the use of the supply for many purposes. Industry along the Pawtuxet River in Cranston has faced this problem.

TABLE 11.—*Water-quality characteristics*

Characteristic or constituent	Maximum allowable concentration for drinking water [1] (parts per million)	Source	Remarks
Silica (SiO_2)		Siliceous minerals present in nearly all rocks.	Causes extremely hard scale in pipes and boilers. Used in zeolite-type water softeners.
Iron (Fe)	0.3	Common iron-bearing minerals present in many rocks.	More than about 0.3 ppm will cause reddish-brown color, will stain laundry, plumbing fixtures, and water utensils; is objectionable for food processing and beverages. Imparts taste and favors growth of iron-forming bacteria.
Manganese (Mn)	.05	Manganese-bearing minerals.	Brown to black stain; not as common as iron; generally has same objectionable features.
Calcium (Ca) and magnesium (Mg).		Limestone, dolomite, gypsum.	Causes most hardness.
Sodium (Na) and potassium (K).		Feldspars and other common minerals; ancient brines, sea water; industrial brines and sewage.	More than 50 to 100 ppm in boiler water causes foaming and salty taste.
Bicarbonate (HCO_3) and carbonate (CO_3).		Action of carbon dioxide on carbonate minerals.	In combination with calcium and magnesium form carbonate hardness which decomposes in boiling water with attendant formation of scale and release of corrosive carbon dioxide gas.
Sulfate (SO_4)	250	Gypsum, iron sulfides, and other rarer minerals; common in waters from many industrial wastes.	Sulfates of calcium and magnesium form hard scale and are cathartic and unpleasant to taste.
Chloride (Cl)	250	Found in small to large amounts in all soils and rocks; natural and artificial brines, seawater, sewage.	In high concentrations has salty taste and makes water corrosive.
Fluoride (F)	0.8–1.7	Various minerals of widespread occurrence, in minute amounts.	Optimum concentration tends to reduce decay of teeth of children; larger amounts may cause mottling of the enamel of teeth.
Nitrate (NO_3)	45	Decayed organic matter, sewage, nitrate, fertilizers, nitrates in soil.	Values higher than the local average may suggest pollution. There is evidence that more than about 45 ppm NO_3 may cause methemoglobinemia (infant cynosis). Waters of high nitrate content should not be used for baby feeding (Maxcy, 1950).
Dissolved solids	500	All substances dissolved in water.	More than 500 to 1,000 ppm interfere in many chemical processes.
pH		Hydrogen-ion concentration in water.	Values below 7.0 (neutral) indicate acid waters and a tendency for corrosiveness towards metal.
Specific conductance		Dissolved constituents in water that will ionize.	A quick means of determining the concentration of dissolved solids in water.
Color	20	Action of water in organic matter and industrial wastes.	Unsightly in drinking water.

[1] U.S. Public Health Service (1962).

Minute quantities of some chemical ions such as arsenic, cyanide, phenol, and manganese influence considerably the use of water. Table 11 explains the sources of the more common chemical constituents and describes their effects on use.

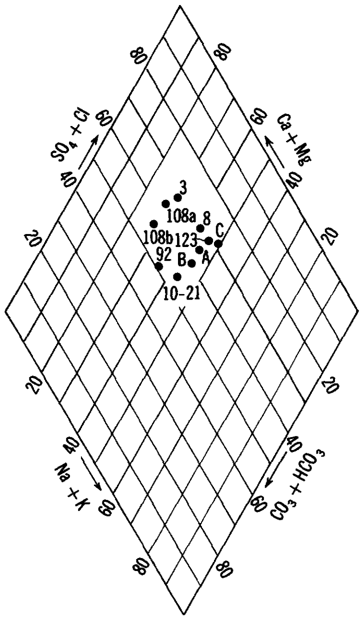
The suitability of water for drinking can be evaluated on the basis of the recommended maximum concentrations established by the U.S. Public Health Service (1962) for different mineral constituents. The concentrations are used by most States for rating municipal water supplies. The maximum allowable concentrations for drinking water are also listed in table 11 for the principal mineral constituents.

The chemical quality of water in the upper Pawcatuck River basin was evaluated on the basis of 53 samples of ground water from wells and springs and 30 samples of surface water from streams including samples collected during this investigation and at several other times.

For the purpose of this study, samples of surface water were collected at 12 sites on 10 streams on October 8, 1958, and April 7, 1959. The time of collection was selected to represent low and high periods of streamflow. Samples of ground water were collected at 14 wells and 1 spring that yield water from stratified deposits, 4 wells and 1 spring that yield water from till, and 1 well that yields water from mixed till and outwash. For most samples the chemical constituents determined included iron (total and dissolved), manganese (total and dissolved), bicarbonate, dissolved solids, total hardness, specific conductance, pH, and color (for surface-water samples). In a few samples chloride, fluoride, and nitrate were also determined. Sampling points are shown on plate 1 and analyses are given in tables 10 and 11 of the basic-data report (Allen and others, 1963). Twenty-one other samples of ground water and six other samples of surface water which were collected during earlier studies are also tabulated.

The cation-anion relation of water samples from streams, stratified deposits, till, and bedrock in the upper Pawcatuck River basin are compared on figure 23. As shown, no one chemical constituent is dominant.

A comparison of the 1924 and 1925 analyses with those made in 1958 and 1959 does not show any significant change. However, this comparison may not be valid because of differences in rate of flow of the stream at the different sampling times. The stream sample collected from Pawcatuck River near Kenyon in August 1925 had a dissolved-solids content of 42 ppm, whereas the dissolved-solids contents of samples collected in October 1958 and April 1959 were 53 and 37 ppm, respectively. A similar comparison on Chipuxet River at West Kingston showed a dissolved-solids content of 36, 27, and 19 ppm in July 1924, October 1958, and April 1959, respectively.



Number or letter	Date of collection	Dissolved solids (ppm)	Source
A	7-28-24	36	Chipuxet River
B	do	32	Queen River
C	8-28-25	42	Pawcatuck River
Exe 10-21	4-23-24	33	Glacial outwash
Nok 123	2-3-54	44	Do
Sok 3	6-12-24	91	Bedrock
8	4-22-25	33	Till
92	2-3-54	86	Glacial outwash
108a	6-12-24	203	Bedrock
108b	4-22-25	216	Do

FIGURE 23.—Chemical character of waters from the upper Pawcatuck River basin.

CHEMICAL CHARACTERISTICS OF SURFACE WATER

The chemical characteristics of surface water differ during periods of high and low flow. At high flow most of the water in streams is overland runoff; at low flow most of the water is ground-water runoff. In Rhode Island overland runoff is generally low in mineral content because of the short period of contact with minerals; ground-water runoff generally has a higher mineral content.

The sampling program in October 1958 was intended to show the chemical composition of the streams under base-flow conditions; that in April 1959, the composition of overland runoff. The sampling dates were selected on the basis of general climatic conditions. Later analysis of the streamflow hydrographs, however, showed that the ratio of base flow to total discharge was nearly the same (roughly 60 to 70 percent) in both October and April. Therefore, both sets of analyses show the composition of mixtures of both base flow and overland runoff.

The location of the stream sampling sites and results of analyses made for this study are shown graphically on plate 3. A pair of columns are shown for color, dissolved solids, hardness, and iron. The left-hand column shows the composition of the samples collected in October 1958 and the right-hand column, the composition of those collected in April 1959. Most of the samples collected in October showed slightly higher concentrations than those collected in April.

As shown, the chemical quality of surface waters is satisfactory for many uses. It ranges from excellent to fair. The range in dissolved solids was from 29 to 116 ppm, and the range in hardness was from 6 to 45 ppm. This moderate range in quality reflects the geology, streamflow conditions, and—in some areas—industrial pollution.

The Chipuxet River is somewhat contaminated by industrial wastes upstream from the ground-water reservoir; and a small stretch of the Queen River, at the upper end of the Usquepaug-Queen ground-water reservoir, has a high nitrate content which may be indicative of bacterial pollution. In the development of the ground-water reservoirs both the chemical composition and concentration of the polluting substances must be considered.

CHEMICAL CHARACTERISTICS OF GROUND WATER

The chemical composition of ground water is dependent largely on the mineral composition of the rocks through which the water has moved and the rate of movement. Ground water in discharge areas and in the deeper parts of aquifers is generally more highly mineralized than ground water in recharge areas and from shallow depths.

The chemical composition of ground water from selected wells in the upper Pawcatuck River basin is shown on figure 19. Iron is the most troublesome constituent and will be a problem in the Chipuxet ground-water reservoir. However, samples collected from well Sok 907, in the Chipuxet ground-water reservoir near West Kingston, showed that the iron and manganese are largely restricted to the lower aquifer. The sample from the lower aquifer contained 4.5 ppm of total iron and 0.16 ppm of total manganese. The upper aquifer, at the same location, had 0.05 ppm of total iron and 0.00 ppm of total manganese. Water from a well at the University of Rhode Island (Sok 888), pumping from the lower aquifer, contained 2.0 ppm of total iron and 0.33 ppm of total manganese when sampled on July 15, 1960 (Allen and others, 1963, table 11). A test well drilled in 1964 for the village of Kingston in the shallow aquifer in the same area at first produced water with a high nitrate content, but extended pumping reduced the content. The source of this nitrate is not known.

In summary, the chemical quality of ground water in the upper Pawcatuck River basin ranges from good to fair. Concentrations of dissolved solids were 226 ppm or less, and usually the water was soft or only moderately hard. Water from several wells contained concentrations of iron, manganese, and nitrate that would be troublesome.

WATER TEMPERATURE

The mean annual temperatures of surface water and ground water are generally within a few degrees of the mean annual air temperature. Temperatures measured in streams generally follow the same pattern as the air temperature except for a slight lag and have a relatively wide fluctuation daily, monthly, and annually when compared with ground-water temperatures. Among the factors controlling stream temperatures are changes in air temperature, thermal pollution, turbidity, color of stream bottom, exposure to sunlight, and amount of ground-water seepage.

In the upper Pawcatuck River basin stream temperatures were not measured periodically. In central Rhode Island continuous records of temperature of the Hunt River have been collected with an automatic recorder since January 1962. These records show that during 1962 the temperature of the water in the Hunt River fluctuated between 33° and 72° F; daily changes were generally less than 4° F. Stream temperatures in the upper Pawcatuck area are probably similar.

A relatively constant temperature makes ground water more desirable for use in cooling or air conditioning than surface water. The temperature of ground water is nearly constant throughout the year except (1) at shallow depths, (2) when affected by man's activities, or (3) where infiltration of surface water occurs.

In the upper Pawcatuck River basin ground-water temperatures were measured biweekly in three public-supply wells during 1958 and 1959 to determine the magnitude of seasonal fluctuations. The records show an annual change of only about 2° to 3° F. Temperature measurements made in 213 wells in the basin, without regard to depth, season of the year, and the possibility of stream infiltration, ranged from 42° to 62° F and averaged 53° F.

UTILIZATION

The estimated daily use of water in the upper Pawcatuck River basin averaged about 1.5 mgd during the period 1958–1959. Most of this water was obtained from wells and was used for public supplies (table 12).

PUBLIC SUPPLIES

The only public-water supply of significant size in the upper Pawcatuck River basin is that of the Wakefield Water Co. The source of this system is four gravel-packed wells (Sok 81, Sok 84, Sok 91, and Sok 887). When pumped together, these wells furnish an average of 860,000 gpd to about 10,000 people and a few small industries. In the summer as much as 2,200,000 gpd is pumped for an additional 10,000 people during short periods. The water is withdrawn from the small ground-water reservoir in the southeastern part of the basin (pl. 2) but is pumped outside the basin. The quality of water from these wells is shown in the basic-data report (Allen and others, 1963, table 11).

The University of Rhode Island pumps an average of about 300,000 gpd of water from three gravel-packed wells (Sok 92, Sok 138, and Sok 888) to a total of about 3,000 students and teachers. Most of this water is returned to the Chipuxet River through White Horn Brook downstream from the Chipuxet ground-water reservoir but is not lost to the basin.

A State institution, Ladd School, pumps about 170,000 gpd of ground water from two gravel-packed wells (Exe 33 and Exe 39) which is used by about 1,200 people within the basin. The village of Kingston is supplied with water from a 36-inch diameter well formerly called Great Spring. The well (Sok 8) supplies water to about 800 people.

TABLE 12.—*Estimated daily withdrawal of water in the upper Pawcatuck River basin*

Usage	Source	Average daily consumption (gallons)	Population served	Treatment
Wakefield Water Co.[1]	Wells (Sok 81, 84, 91, 887)	[2] 860,000	[3] 10,000	Chlorination.
University of Rhode Island	Wells (Sok 92, 138, 888)	300,000	3,000	None.
Ladd School	Wells (Exe 33, 39)	170,000	1,200	None.
Village of Kingston	Well (Sok 8)	40,000	850	None.
Domestic	Wells	50,000	1,000	
Irrigation	Wells, ponds. and reservoirs	[4] 40,000		
Stock	Wells and ponds	30,000		
Industry	Wells, ponds, and reservoirs	4,000		

[1] Pumped outside the basin.
[2] Peak daily withdrawal about 2.2 mgd.
[3] Additional population of 10,000 during summer.
[4] Only in dry year.

OTHER USES

Approximately 1,000 people in the upper Pawcatuck River basin rely on water from privately owned wells most of which are dug and driven. A few springs are also used. Wells, generally dug, and small ponds are used to supply water for farm livestock. In West Kingston one industry uses small amounts of ground water from its own gravel-packed well. In other parts of the basin, ponds and reservoirs are used.

Water is used for irrigating potatoes in the south half of the basin. In the flat plains farmers have dug small basins that intersect the water table, and in places, streams have been dammed as at Glen Rock Reservoir to impound sufficient quantities of water to give a reasonably continuous supply. Much of the irrigation water is lost from the basin by evaporation. Amounts of water used for irrigation are difficult to measure, for irrigation is only practiced in dry years; during this time water is only applied intermittently.

Most of the streams and ponds in the basin are used for recreation. Chipuxet River, Usquepaug-Queen River, Wordens Pond, Hundred Acre Pond, and others are used for canoeing, boating, fishing, swimming, and other recreational activities. The Rhode Island Division of Fish and Game operates a wildlife refuge in Great Swamp. Wordens Pond is a breeding ground for waterfowl.

SUMMARY AND CONCLUSIONS

The upper Pawcatuck River basin contains two extensive permeable ground-water reservoirs. The total yield of these reservoirs is estimated to be 25.6 mgd (17 mgd from the Usquepaug-Queen reservoir and 8.6 mgd from the Chipuxet reservoir). These estimates are believed to represent a conservative appraisal of the ground water potentially available for large-scale development. However, there are always uncertainties involved in the development of a ground-water supply because it is never completely certain what material will be encountered in drilling beneath the earth's surface until the hole is drilled. Obviously a number of assumptions had to be made in order to estimate the amount of ground water potentially available. It is worth reviewing some of these assumptions so that the reader is better able to appraise the reliability of the final estimates. The most significant of the assumptions are discussed below:

1. Only the base flow part of the stream discharge was assumed to be available for development from the ground-water reservoirs. Most of this base flow is water normally contributed to the streams in the areas underlain by the reservoirs. The rest of the base flow would be derived from upstream areas and would enter the reservoirs by infiltration. A part of the overland runoff might also infiltrate the ground-water reservoirs under pumping conditions. However, this was disregarded in the analysis and, therefore, tends to make the estimated yields conservative.
2. The storage capacity of the reservoirs was evaluated on the assumption that if the reservoir could be pumped for approximately 180 days without excessive drawdown this rate of pumpage could be sustained from the assumed well configurations. Drawdowns were considered excessive when the calculated dewatering of the aquifer at the pumping wells exceeded 75 percent of the initial saturated thickness. Properly constructed and developed wells with only small head losses due to well construction were also assumed. Test drilling conducted during the course of this inves-

tigation indicated that highly efficient wells can be readily constructed in the reservoir areas.

3. Water which might be available from a reduction in the rate of evaporation and transpiration due to lowering of the water table could not be considered mathematically in the analysis. Large quantities of the water now lost by evapotranspiration may be salvaged as a result of the lowering of the water table due to pumpage. This factor also tends to make the estimated yields conservative.
4. In the analysis of yields it was assumed that the boundaries of the ground-water reservoirs are impermeable. Actually, substantial quantities of water move into the reservoirs from the surrounding areas. Therefore, the effect of the imaginary image wells will doubtless, be less than was assumed in the analysis. This will result in smaller drawdowns than those anticipated.
5. In the analysis it was assumed that pumping wells would be located on a single line down the center of each area and would be spaced 1,000 feet apart, except for three wells in the Usquepaug-Queen area that were assumed to be spaced 2,000 feet apart. It should be noted, however, that the closer the supply wells are spaced, the larger the amount of ground-water storage that can be utilized. This advantage must be weighed against the cost of constructing the wells and necessary pipelines. Operating experience may actually show that the estimated yield of the reservoirs can be obtained from supply wells spaced as much as 2,000 to 3,000 feet apart.

As can be seen, the assumptions made were for the most part conservative. For this reason the estimate of 25.6 mgd of ground water potentially available is also believed to be conservative. Substantially larger quantities of ground water may actually be available.

Large-scale development of either or both of the ground-water reservoirs would produce a great deal of new data. Any large-scale development should be carefully observed and the data critically analyzed. In the Chipuxet reservoir the iron and industrial contamination problems should be considered. It will almost certainly be desirable to adjust the pattern of development so as to take advantage of the new data and make optimum use of the ground-water reservoirs.

At the proposed pumping rates the streams flowing over the ground-water reservoirs will probably be dry during the late spring, summer, and early fall for continuous periods of several days to a month or more. During this time most of the water pumped will be derived from storage in the ground-water reservoirs.

It is believed that the proposed pumping rates will have little or no affect on Great Swamp and Wordens Pond. However, the annual mean flow at the outlet of the basin near Kenyon will be decreased by the quantity of water pumped from the reservoirs to other areas. Substantial quantities of water will, of course, continue to move into the streams, Great Swamp, and the ponds in the basin as ground-water discharge from the 27-square-mile area downstream from the ground-water reservoirs.

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