Hydrologic Characteristics and Sustained Yield of Principal Ground-Water Units Potowomut-Wickford Area Rhode Island

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1775

Prepared in cooperation with the Rhode Island Water Resources Coordinating Board

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By J. S. ROSENSHEIN, JOSEPH B. GONTHIER, *and* WILLIAM B. ALLEN

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By J. S. ROSENSHEIN, JOSEPH B. GONTHIER, and WILLIAM B. ALLEN

ABSTRACT

The Potowomut-Wickford area comprises about 60 square miles in the south-central part of Rhode Island. The area contains a sand and gravel aquifer whose transmissibility ranges from less than 10,000 to more than 300,000 gpd per ft (gallons per day per foot). The parts of the aquifer having large transmissibility are localized enough that they can be treated as separate ground-water reservoirs having limited areal extent and definite hydrologic boundaries. These reservoirs underlie parts of three small river basins: the Potowomut, Annaquatucket, and Pettaquamscutt.

Ground-water runoff from the basins forms a large part of the streamflow. Hydrograph separation, using ground-water rating curves, shows that in 1962 and 1963 ground-water runoff constituted 48 and 52 percent, respectively, of the discharge of the Potowomut River and 53 and 51 percent of the Annaquatucket River. Hydrologic budgets for 1962 and 1963 indicate that ground-water recharge in the Potowomut River basin was 17.1 inches in 1962 and 10 inches in 1963 and that ground-water evapotranspiration for those years was 3.2 and 3.7 inches, respectively. Ground-water recharge in the Annaquatucket River basin for these same years, was 20.9 and 13.2 inches, and ground-water evapotranspiration, 2.0 and 2.2 inches.

Additional rates of ground-water recharge were extrapolated for the 22-year period 1942–63, using graphical relations defined by ground-water rating curves and records of long-term water levels and streamflow. During this period, ground-water recharge in the Potowomut River basin ranged from 10 to 21 inches and averaged 15 inches, and that in the Annaquatucket River basin, ranged from 12 to 25 inches and averaged 18 inches. Lowest rates of recharge occurred in 1944, 1949, 1957, and 1963.

The well fields of the U.S. Navy and of the Kent County Water Authority tap the principal ground-water reservoir underlying the Potowomut River Basin. In 1963, 4 mgd (million gallons per day) was pumped from the reservoir. Of this pumpage, an estimated 1.6 mgd, or 2.5 cubic feet per second, was obtained from influent seepage of streamflow from the upstream reaches of the Hunt and Potowomut Rivers. The streambeds of these rivers have an estimated average vertical permeability of 17 gpd per square foot at 60°F, and have an average potential-infiltration rate of about 370,000 gpd, or about 0.6 cubic feet per second for 1,000

feet of streambed for each 1-foot difference in head between the stream stage and the water level in the aquifer.

A mathematical model was used to simulate hydrologic conditions of the principal ground-water reservoir in 1963. Computations with the model indicate that the reservoir can safely sustain a yield of 8 mgd, or 5,600 gallons per minute, during exceptionally dry years. This yield can be withdrawn using the existing pumping facilities. During exceptionally dry years in the future, a difficult water-management problem may arise, for such sustained withdrawal will result in no streamflow in a sizable reach of the Hunt and Potowomut Rivers for as much as 160 days.

The Potowomut River basin also contains an additional ground-water reservoir that is virtually untapped. During critically dry periods—such as the one of 1963—the estimated supplemental yield of this secondary reservoir, based on mathematical-model analysis, should be about 5 mgd for pumping periods of about 100 days. However, for the additional ground-water reservoir to be developed without significantly decreasing the sustained yield of the principal ground-water reservoir, careful management involving reuse in the basin of the pumpage from the secondary reservoir will be necessary.

The North Kingstown Water Commission well field at Belleville Pond taps the ground-water reservoir underlying the Annaquatucket River basin. Computations, using a mathematical model, indicate that this ground-water reservoir can safely sustain a yield of 3.6 mgd, or 2,500 gallons per minute, in exceptionally dry years. Of this yield, about half can be obtained by the existing pumping facility. To obtain the sustained yield of the reservoir, two additional pumping centers would have to be constructed.

The ground-water reservoir underlying the Pettaquamscutt River basin may be capable of safely sustaining a yield of 1.3 mgd. Development of the southern part of the reservoir may result in problems of saline-water intrusion.

The chemical quality of water from both the Potowomut-Wickford aquifer and the associated streams is suitable for most purposes. The water is soft and has a dissolved-solids concentration of generally less than 70 parts per million. Some treatment may be required locally for the removal of iron and manganese to meet recommended standards of U.S. Public Health Service for drinking water.

INTRODUCTION

An evaluation of the water resources of the Potowomut-Wickford area has been in progress since 1961 as part of a cooperative program between the Rhode Island Water Resources Coordinating Board and the U.S. Geological Survey. The purpose of the evaluation is to provide a technical appraisal to serve as a basis for coordinated development and responsible management of ground-water and related surface-water resources of the area. The aims of the evaluation are (1) to define hydrologically the relation between surface- and ground-water runoff and the degree of connection between streams and significant subsurface water units; (2) to determine and map variations in water-yielding characteristics of the principal ground-water units; (3) to determine the potential ground-water yield in critical periods by use of a water budget; (4) to predict a sustained yield of the principal subsurface reservoirs and of existing pumping centers through the use of mathematical models and the study of reservoir hydrology; (5) to define areas favorable for development of additional pumping centers and the estimated sustained yield from these areas; and (6) to pinpoint special problems such as changes in streamflow and in water quality, that could arise from extensive subsurface-reservoir development.

ACKNOWLEDGMENTS

The authors thank all persons who contributed time, information, and assistance during the collection, processing, and evaluation of data used in this report. J. C. Clifford, Rhode Island Department of Health, furnished results of chemical analyses on many of the water samples collected for this investigation. The U.S. Navy, Department of Defense, furnished records of pumpage, production wells, and test holes, and provided use of their facilities for aquifer-performance tests. The Kent County Water Authority and the North Kingstown Water Commission provided similar information about their water supplies and the use of their facilities.

The investigation was made by the U.S. Geological Survey under the general supervision of R. C. Heath, district chief for New York. C. E. Knox, district chief for central New England, supervised collection and processing of streamflow and temperature records. G. R. Schiner served as project chief during part of the investigation and was responsible for preliminary evaluation.

GENERAL ASPECTS

The Potowomut-Wickford area comprises about 60 square miles in the southeastern part of the State (fig. 1). The average annual precipitation for the area, as recorded at Hillsgrove Airport (fig. 1), is about 43 inches. It ranged from about 30 to 57 inches in the 25-year period 1940–64. During this period the average annual precipitation was equaled or exceeded about 42 percent of the time.

Parts of the area contain ponds and marshes. Some of the ponds and associated streams are used for recreational fishing, boating, and swimming. These streams form five small basins, the largest of which is the Potowomut River basin. All are controlled to some degree by small impoundments that are the result of previous mill operations. Water rights to part of the streamflow are probably allocated to these interests.

Small quantities of water are generally diverted from the streams and ponds, and in low-flow periods these diversions may constitute a sizable part of the total discharge. Much of this diversion is not

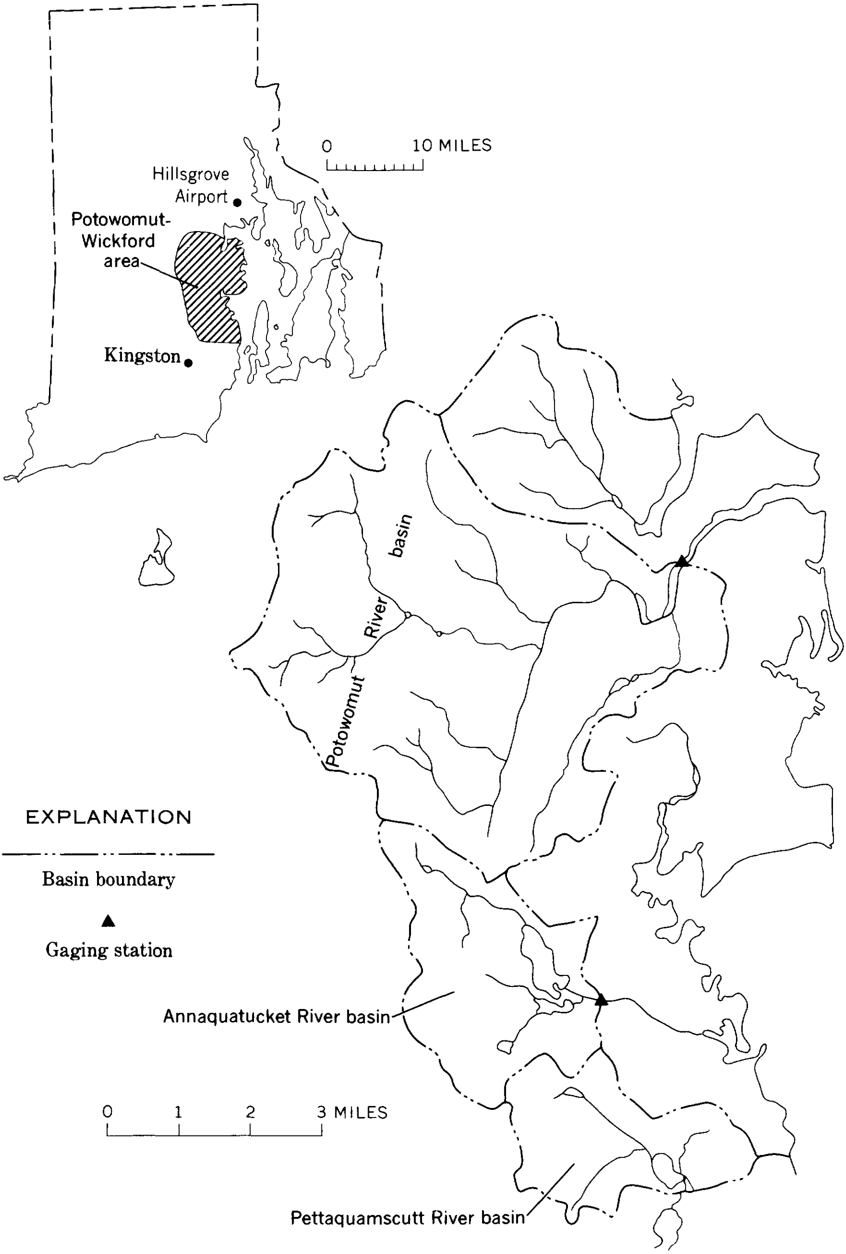

FIGURE 1.—Location of the Potowomut-Wickford area, Rhode Island, and the river basins significant to this study.

returned directly to the streams. During most of the year, a part of the streamflow consists of water discharged from detention storage in natural marshes and ponds, as well as from manmade impoundments. The rest of the flow is derived from direct runoff of precipitation and from base runoff consisting largely of ground-water discharge.

The area is primarily suburban and contains some industry and a large military establishment in its south-central part. Water supply is obtained chiefly from wells; the leading source is sand or gravel. Principal withdrawals are concentrated in four centers of pumping, each of which is adjacent to either a stream or a pond. Also, part of the pumpage is probably supplied by indirect diversion of either streamflow or pond storage into the subsurface reservoirs. Much of the pumpage is either used outside the area or not returned to the area; therefore, this water is not available for reuse.

Responsible planning and coordinated management of the water resources of the area require a fairly accurate estimate of the quantities of water available for development and, especially, of the quantity available for use during exceptionally dry periods when demands are large. They also require an understanding of how the natural water system in the area operates. The principal sources utilized are the subsurface reservoirs in the area. The demands on these reservoirs are increasing. The streams traversing the reservoirs form a water-collecting system that extends beyond the actual area containing the ground-water reservoirs. Some of the water potentially available for development from the subsurface reservoirs is streamflow derived from the upper reaches of the basins. The entire drainage area can therefore serve as a catchment basin for a ground-water reservoir. Diversion of some of this water and part of the overflow from the underground reservoirs will affect stream discharge and pond and marsh storage.

Integrated development of the water resources in the Potowomut-Wickford area will depend on the following factors:

1. The amount of usable water in underground and related surface storage.
2. The rate of ground-water renewal by natural recharge from precipitation and by recharge from indirect diversion of streamflow and of water stored in ponds and marshes.
3. The thickness of the saturated material.
4. The rate of flow of water through the subsurface reservoirs.
5. The hydraulic head, or drawdown, in the underground reservoir available to move the water to the points of withdrawal.
6. The overall effects of long-term withdrawals on the water system.

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7. Changes in the quality of water with continued withdrawal.
8. Limitations placed on rates of withdrawal owing to management decisions based on the amount of streamflow allocated for pollution abatement, the amount of water obligated by water rights, the extent of channel and conservation improvement, and the demands for recreation.

HYDROLOGIC UNITS

SURFACE UNITS

The Potowomut-Wickford area comprises parts of about five basins, of which only three have major hydrologic significance to the scope of this investigation. The three major basins (fig. 1) are the Annaquatucket, Pettaquamscutt, and Potowomut. In the 3 years of detailed study, the daily flows of the Annaquatucket and Potowomut Rivers were recorded by gaging stations near their mouths. The flow of tributaries and that of the Maskerchugg and Mattatuxet Rivers and Mill Creek were obtained at partial-records stations. Discharge measurements were made at these stations during periods of low flow, when the discharge should consist chiefly of ground-water runoff. All the discharge records are published in reports, issued annually, of the U.S. Geological Survey. These reports are entitled "Surface Water Records of Massachusetts, New Hampshire, Rhode Island, Vermont." Discharge records of the Potowomut River from 1941 to 1960 are published in water-supply papers of the U.S. Geological Survey entitled "Surface Water Supply of the United States; Part 1–A, North Atlantic Slope Basins, Maine to Connecticut." The magnitude and frequency of floods on the Potowomut River are published in Green (1964) and their flow duration, in Allen (1953).

STREAM DISCHARGE AS RELATED TO SUBSURFACE UNITS

The discharge of the streams draining the Potowomut-Wickford area consists chiefly of two components: (1) direct runoff of precipitation, which forms surface runoff, and (2) ground-water runoff. Because of the hydrologic conditions in the area, a sizable part of the ground-water runoff consists of natural overflow derived from the permeable deposits forming the principal subsurface reservoirs. By measurement of streamflow from the basins, a major part of the natural ground-water discharge from the basins is recorded. Adequate identification of the components of discharge by appropriate hydrograph separation provides an estimate of the quantity of water contributed by each component. This estimate can then be used in a water-budget analysis (p. 13) to determine the recharge to the reservoirs and the variations in perennial yield of these reservoirs.

STREAM DISCHARGE AS RELATED TO SURFACE- AND GROUND-WATER RUNOFF

Surface- and ground-water runoff from the area were defined by using the discharge records for Potowomut River near East Greenwich, R.I., and Annaquatucket River at Belleville, R.I. Runoff characteristics of the various rock materials drained by the streams and the contribution of each rock type to the ground-water runoff were not specifically identified.

The separation into components of the hydrograph of the total runoff for the Potowomut River is shown on plate 1. Ground-water runoff was determined by developing a ground-water rating cure for the basin. Periods of base runoff judged to consist chiefly of ground-water discharge were identified. The logarithms of discharges in these baseflow periods were plotted against the average ground-water stages in observation wells Nok 44 and 250. A line was fitted to these points by using the numerical method of least squares (Searcy and Hardison, 1960; Chow, 1964). By this process, two ground-water rating curves were developed, one for the period of mid-spring through summer and the other for the period of fall through early spring. Adjustments were made to the curves to minimize the amount of runoff from channel storage to be included with the ground-water runoff. The monthly surface- and ground-water runoff is summarized in figure 2. In 1962 and 1963, 48 and 52 percent, respectively, of the total flow consisted of ground-water discharge.

The separation, by components, of the hydrograph of the total runoff for the Annaquatucket River are shown on plate 1. The ground-water rating curves for this separation were made by plotting the discharges of the Annaquatucket River against the water levels in observation well Nok 450. The monthly surface and ground-water runoff is summarized in figure 3. In 1962 and 1963, 53 and 51 percent, respectively, of the total flow was ground-water drainage.

SUBSURFACE UNITS

The geologic materials underlying the Potowomut-Wickford area consist chiefly of four types: (1) stratified sand or gravel interbedded with very fine sand and silt; (2) till, a poorly-sorted mixture of silt, sand, and gravel with some clay; (3) stratified sand or gravel interbedded with various amounts of till; and (4) bedrock composed of crystalline and metamorphosed sedimentary rocks. The properties and the areal extent of these materials have been described in some detail

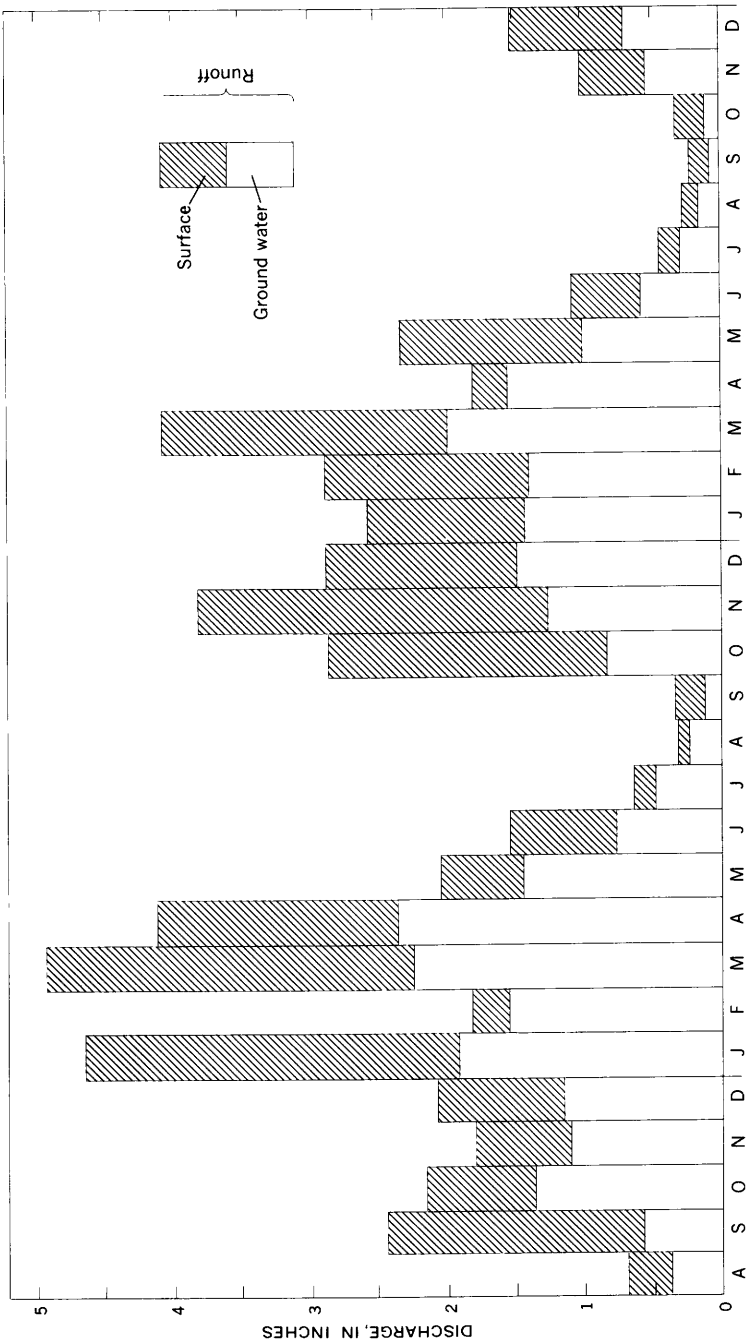

FIGURE 2.—Summary of monthly surface and ground-water runoff in the Potowomut River near East Greenwich, R.I., August 1961–December 1963.

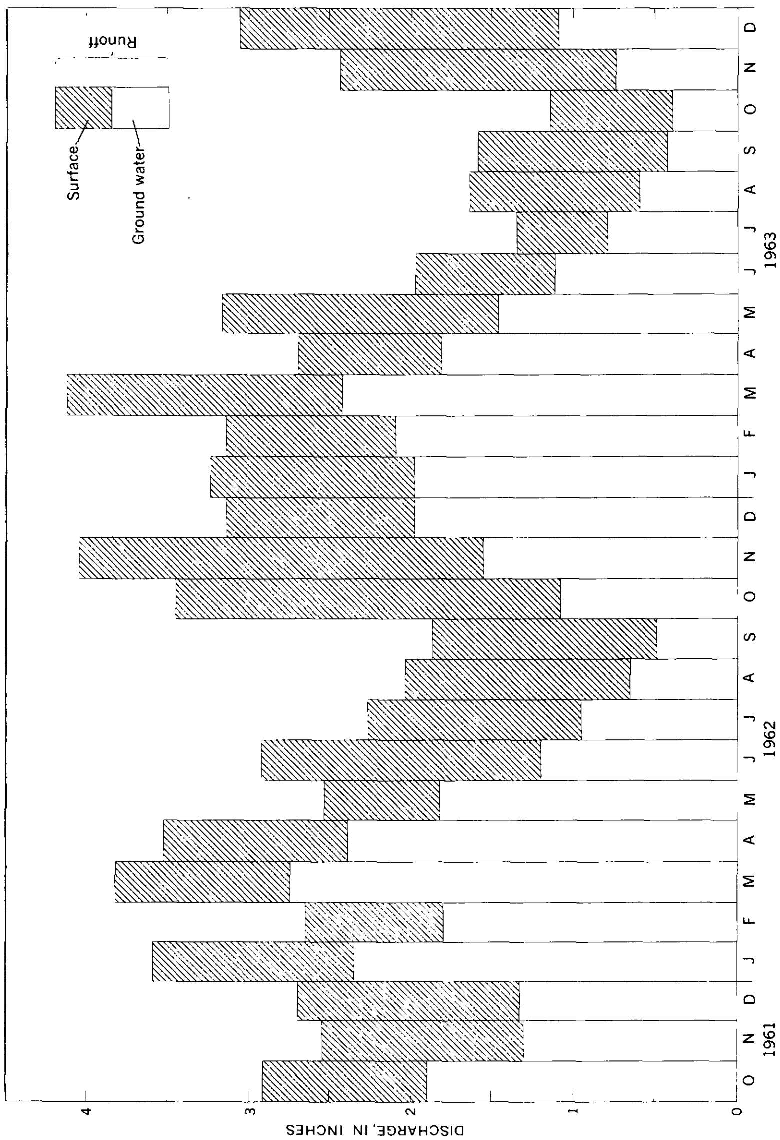

FIGURE 3.—Summary of monthly surface and ground-water runoff (adjusted for subsurface drainage area) in the Annaquatucket River at Belleville, R.I., October 1961–December 1963.

by Powers (1957, 1959), Quinn (1963), Shafer (1961), Smith (1955), and Williams (1964). Of these materials, only those composed dominantly of stratified sand or gravel are sufficiently permeable to yield appreciable quantities of water for development. These materials form the Potowomut-Wickford aquifer and constitute the principal subsurface reservoirs referred to in this report.

WATER-YIELDING CHARACTERISTICS

The significant hydrologic properties of the Potowomut-Wickford aquifer are summarized on plates 2 and 3 and in table 1. The areal variation in the coefficient of transmissibility is shown on plate 2. Some of the data used to prepare this map were obtained from analyses of pumping and specific-capacity tests. The theory on which the determinations are based and the methods of analysis used were described in detail by Bentall (1963a, b, c), Bolton (1963), and Ferris, Knowles, Brown, and Stallman (1962), Walton (1962), and Weeks (1964).

Additional estimates of transmissibility were computed from descriptions of the various geologic materials penetrated by wells. The computations were based on the relation between transmissibility (T), in gpd per ft (gallons per day per foot), permeability (P), in gpd per sq ft (gallons per day per square foot), and saturated thickness (m), where $T=Pm$. An analysis by multiple regression (Jenkins, 1963), using the data for the wells listed in table 1, determined representative values of permeability to be assigned to materials; the descriptions of which were recorded chiefly by drillers. The values obtained from the analysis are listed in the table below and are judged to be applicable to the stratified deposits underlying the Potowomut-Wickford area. The above permeabilities were arbitrarily adjusted downward when applied to wells at locations underlain chiefly by stratified deposits interbedded with various amounts of till.

Material	*Permeability (gpd per sq ft)*
Gravel	3,500
Sand and gravel	1,500
Sand	800
Fine sand	400

The transmissibility of the Potowomut-Wickford aquifer ranges from less than 10,000 to more than 300,000 gpd per ft. The areas of largest transmissibility are concentrated in three elongate sections, one each in the Potowomut, Annaquatucket, and Pettaquamscutt River basins. The transmissibility decreases markedly outward from each section toward till-bedrock boundaries. Because of these factors, each

TABLE 1.—*Summary of hydraulic properties of the Potowomut-Wickford aquifer*
[Well: For location see pl. 4]

Well	Coefficient of trans-missibility (gpd per ft)	Coefficient of storage	Remarks
Egr 3	300,000	....	Computed from specific capacity using drawdown adjusted for effects of partial penetration and well loss (Butler, 1957; Walton, 1962).
10	350,000	....	Do.
96	170,000	....	Do.
147	93,000	....	Do.
157	220,000	0.05	Computed from aquifer test using Bolton's curves (Bolton, 1963).
165	69,000	.14	Do.
170	200,000	.10	Computed from aquifer test using Weeks method modified from Hantush (Weeks, 1964); ratio of vertical to horizontal permeability, 1:100.
171	52,000	....	Computed from specific capacity using drawdown adjusted for effects of partial penetration and well loss (Butler, 1957; Walton, 1962).
172	170,000	....	Do.
173	350,000	....	Do.
174	200,000	....	Do.
180	220,000	....	Do.
182	67,000	.18	Computed from aquifer test using composite curve and Theis nonequilibrium method (Ferris and others, 1962).
184	67,000	.18	Do.
185	67,000	.18	Do.
Nok 11	45,000	....	Computed from aquifer test using Bolton's curves (Bolton, 1963).
26	200,000	....	Computed from specific capacity using drawdown adjusted for effects of partial penetration and well loss (Butler, 1957; Waton, 1962).
69	10,000	....	Do.
72	50,000	....	Do.
73	21,000	....	Do.
156	380,000	.14	Computed from aquifer test using composite curve and Theis nonequilibrium method (Ferris and others, 1962).
157	380,000	.14	Do.
1158	380,000	.14	Do.
1235	90,000	....	Computed from specific capacity using drawdown adjusted for effects of partial penetration and well loss (Butler, 1957; Walton, 1962).
1264	21,000	....	Do.
1266	45,000	....	Do.
1269	53,000	....	Do.
1272	24,000	....	Do.
War 33	350,000	....	Do.
514	270,000	.10	Computed from aquifer test using composite curve and Theis nonequilibrium method (Ferris and others, 1962).
515	270,000	.10	Do.

area of large transmissibility can be considered to form a separate subsurface reservoir.

The saturated thickness of the permeable deposits is shown on plate 3. The map was prepared by using the difference between the altitude of the unit's water table (pl. 4) and its base, generally the bedrock surface. The saturated thickness controls the amount of drawdown, or hydraulic head, available for reservoir development and, in part, the volume of water in storage in the aquifer. The saturated thickness ranges from less than 20 feet to more than 120 feet and in areas of large transmissibility is more than 80 feet.

The water-supply capability of various parts of the aquifer can be estimated from the transmissibility and saturated-thickness maps (pls. 2, 3). The yield of a supply well is dependent on drawdown at the well due to characteristics of aquifer transmissibility and the well construction. (For a more complete discussion of these factors see p. 26 and the explanation on pl. 2.) The graphs and the equation shown on plate 2 permit estimation of these effects and of the possible well yields from the various parts of the aquifer that were not evaluated by mathematical models. The graphs based on aquifer characteristics were computed by using 12-inch-diameter wells and a 200-day pumping period during which there was no recharge. The anticipated drawdown of the aquifer for smaller diameter wells will be somewhat larger, and that for larger diameter wells, somewhat smaller.

NATURAL DISCHARGE AND RECHARGE

Natural discharge from the subsurface units occurs chiefly as overflow to ponds and streams and as direct evapotranspiration. A hydraulic gradient toward the surface units exists in most of the aquifer, as indicated by the slope of the water table shown on plate 4. In response to this gradient, water flows from the areas of higher hydraulic head toward the streams and ponds where it discharges. This flow, under natural conditions, can be approximately described by a modified form of Darcy's law in which the flow (Q) is proportional to transmissibility (T), the hydraulic gradient (I), and the length of flow section (L), where $Q = TIL$. Most of the discharge is recorded as a component of streamflow. The rest occurs as subsurface underflow out of the area and eventually discharges into Greenwich Bay and the west passage of Narragansett Bay.

Water is also discharged directly from the subsurface units by evapotranspiration. This loss occurs chiefly in the growing season, from May through September, when, in general, the evapotranspiration is greatest and the ground-water runoff to the streams and ponds is decreased. In this season the natural water level (pl. 1) in the subsurface units declines continuously as less water is taken in than is discharged. This excess of discharge not offset by recharge is derived from ground-water storage. A corresponding decrease in streamflow and in pond and marsh storage also occurs when local precipitation does not produce significant amounts of surface runoff.

Recharge to the subsurface units occurs chiefly from October through April. Under natural conditions recharge is effectively equal to the discharge plus the change in subsurface storage. An accounting of this recharge can be made if the discharge from the units can be defined. The accounting is commonly referred to as a hydrologic budget and can be expressed in relation to ground-water recharge as follows (Rasmussen and Andreasen, 1959; Schicht and Walton, 1961; Olmsted and Healy, 1962):

Ground-water recharge=ground-water runoff+ground-water evapotranspiration±change in ground-water storage+subsurface underflow.

Detailed estimates of ground-water recharge (tables 2, 3) for the period August 1961–December 1963, were computed on a monthly basis by using the above equation. Ground-water runoff was determined from the streamflow records obtained at the gaging stations on the Potowomut and Annaquatucket Rivers. Ground-water evapotranspiration was determined from the ground-water rating curves (pp. 16, 17) by using the differences in the ground-water runoff recorded at these stations during the growing season and that to be expected for an equivalent ground-water stage during the nongrowing season. Change in storage was determined from the changes in ground-water levels multiplied by a coefficient called gravity yield. Two coefficients were used in an attempt to account for anticipated variation in gravity yield with time, especially during prolonged periods of drainage. The coefficients used in these computations were 0.10 for October–April and 0.15 for May–September. This use has caused some inconsistencies in computed changes in ground-water storage and is probably the chief cause for negative values of recharge computed for some summer months. The inconsistencies produced by the use of two coefficients probably do not exceed 10 percent and do not significantly affect any computations based on rates of recharge shown in the tables.

Subsurface underflow bypassing each gaging station was computed by using Darcy's law (p. 12) and the appropriate data from plates 2 and 4. The underflow at the gaging station on the Potowomut River is about 0.10 cfs (cubic feet per second), or 0.06 inch per year, and at the gaging station on the Annaquatucket River, about 0.14 cfs, or 0.30 inch per year.

The hydrologic significance of recharge in 1962 and 1963 is not apparent with respect to defining the quantity of ground-water available to the area during critically dry periods. To define this significance more precisely, additional ground-water budgets were computed. Graphical relations were established between water levels in observation well Nok 255 for October 1961-December 1963 and those for the same period in observation wells Nok 44, Nok 250, and Nok 450. The relations were used to extrapolate the records of water levels in wells

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TABLE 2.—*Ground-water hydrologic budget of the Potowomut River basin, Rhode Island, August 1961–December 1963*

[All items expressed in inches, except where noted. Precipitation data are from U.S. Weather Bur. sta. 6698 at T. F. Green Airport, Warwick, R.I. Runoff data are from U.S. Geol. Survey gaging sta. 1-1170, Potowomut River near East Greenwich, R.I. Surface drainage area, 23 sq mi; subsurface drainage area, 23.2 sq mi. Ground-water recharge per square mile: mgd, million gallons per day]

	Precipitation	Runoff	Ground-water runoff	Ground-water evapotranspiration	Change in ground-water storage	Ground-water recharge excluding underflow	Ground-water recharge per square mile (mgd)
1961							
August	3.86	0.68	0.38	0.72	−0.70	0.40	0.22
September	7.92	2.42	.58	.60	+2.45	3.63	2.10
October	2.39	2.14	1.34	.08	−1.26	.16	.09
November	3.10	1.78	1.08	Negligible	+.11	1.19	.69
December	3.16	2.06	1.13	do	−.02	1.11	.62
1962							
January	4.70	4.60	1.88	Negligible	+1.49	3.37	1.89
February	5.16	2.13	1.52	do	−.31	1.21	.75
March	1.93	4.90	2.21	do	+.85	3.06	1.72
April	3.85	4.09	2.31	0.02	−.24	2.09	1.21
May	2.14	2.03	1.42	.41	−1.42	.41	.23
June	5.52	1.53	.75	.65	−.70	.70	.40
July	1.62	.64	.47	.71	−1.37	[1] −.19	0
August	2.73	.31	.23	.67	−1.21	[1] −.31	0
September	3.67	.34	.12	.56	−.41	.27	.16
October	11.89	2.84	.82	.13	+.95	1.90	1.07
November	4.49	3.81	1.23	Negligible	+1.24	2.47	1.43
December	2.63	2.86	1.47	do	+.11	1.58	.89
Total	50.33	30.08	14.43	3.15	−1.02	17.06	
1963							
January	3.40	2.55	1.41	Negligible	−0.02	1.39	0.78
February	3.15	2.86	1.38	do	+.18	1.56	.97
March	3.78	4.04	1.80	do	+.65	2.45	1.37
April	1.62	1.80	1.53	0.16	−.76	.93	.54
May	4.69	2.31	.99	.64	−.25	1.38	.77
June	3.54	1.07	.57	.68	−1.15	.10	.06
July	3.35	.45	.28	.69	−1.31	[1] −.34	0
August	1.56	.26	.15	.61	−1.06	[1] −.30	0
September	4.10	.23	.08	.51	−.86	[1] −.27	0
October	1.63	.32	.12	.40	−.43	.09	.05
November	6.53	1.01	.52	Negligible	+.31	.83	.48
December	2.15	1.51	.69	do	+.59	1.28	.72
Total	39.50	18.41	9.52	3.69	−4.11	10.01	

[1] See text page 13.

TABLE 3.—*Ground-water hydrologic budget of the Annaquatucket River basin, Rhode Island, October 1961–December 1963*

[All items expressed in inches, except where noted. Precipitation data are from U.S. Weather Bur. Sta. 4266 at Kingston, R.I. Runoff data are from U.S. Geol. Survey gaging sta. 1-1171, Annaquatucket River at Belleville, R.I. Surface drainage area, 6.4 sq mi; subsurface drainage area, 9 sq mi. Ground-water recharge per square mile: mdg, million gallons per day]

	Precipitation	Runoff adjusted for subsurface drainage area	Ground-water runoff	Ground-water evapotranspiration	Change in ground-water storage	Ground-water recharge excluding underflow	Ground-water recharge per square mile (mgd)
1961							
October	3.14	[1] 2.92	[1] 1.90	[1] 0.10	[1] −1.10	[1] 0.90	0.50
November	3.66	2.54	1.31	Negligible	−.42	.89	.52
December	3.32	2.70	1.33	do	+.25	1.58	.89
1962							
January	6.64	3.60	2.36	Negligible	+1.76	4.12	2.31
February	3.84	2.65	1.81	do	+.25	2.06	1.28
March	2.21	3.83	2.75	do	+.02	2.77	1.55
April	3.09	3.52	2.38	do	−.37	2.01	1.16
May	1.89	2.53	1.83	0.13	−1.71	.25	.14
June	5.54	2.93	1.20	.35	−.94	.61	.35
July	1.77	2.27	.95	.42	−1.24	.13	.07
August	4.08	2.03	.65	.47	−1.17	[2] −.05	0
September	3.86	1.87	.49	.45	−.07	.87	.50
October	8.26	3.45	1.08	.13	+1.27	2.48	1.39
November	4.88	4.05	1.56	Negligible	+1.45	3.01	1.74
December	3.75	3.14	1.99	do	+.64	2.63	1.47
Total	49.81	35.87	19.05	1.95	−.11	20.94	
1963							
January	3.65	3.24	1.98	Negligible	−0.08	1.90	1.07
February	3.31	3.14	2.09	do	−.04	2.05	1.27
March	3.60	4.12	2.42	do	+.08	2.50	1.40
April	2.17	2.70	1.82	0.10	−.89	1.03	.60
May	4.82	3.18	1.47	.27	−.56	1.18	.66
June	1.45	1.98	1.12	.38	−1.06	.42	.24
July	4.69	1.35	.80	.46	−1.10	.16	.09
August	2.81	1.64	.59	.47	−1.28	[2] −.22	0
September	3.93	1.59	.43	.45	−.65	.23	.13
October	1.94	1.15	.39	.13	−.28	.24	.13
November	6.89	2.46	.75	Negligible	+.86	1.61	.93
December	2.78	3.07	1.10	do	+.77	1.87	1.05
Total	42.04	29.62	14.96	2.24	−4.23	13.19	

[1] Estimated.
[2] See page 13.

Nok 44, Nok 250, and Nok 450 from 1954 to 1961. These extended water levels and their appropriate ground-water rating curves for the Potowomut and Annaquatucket Rivers were used to compute the ground-water budgets in table 4 by the method described on page 12. Additional estimates of ground-water recharge for the period 1942–55 (table 5) were obtained by defining the relations of (1) ground-water recharge in the Potowomut River basin to runoff of the Potowomut River (fig. 4), and (2) ground-water recharge in the Annaquatucket River basin to ground-water recharge in the Potowomut River basin (fig. 5). The data used to define these relations were taken from tables 2, 3, and 4.

Ground-water recharge in both the Potowomut and the Annaquatucket River basins varied markedly during the 22-year period 1942–63. Estimated annual recharge in the Potowomut River basin ranged from about 10 to 21 inches and averaged 15 inches. In the Annaquatucket River basin, recharge ranged from about 12 to 25 inches and averaged about 18 inches.

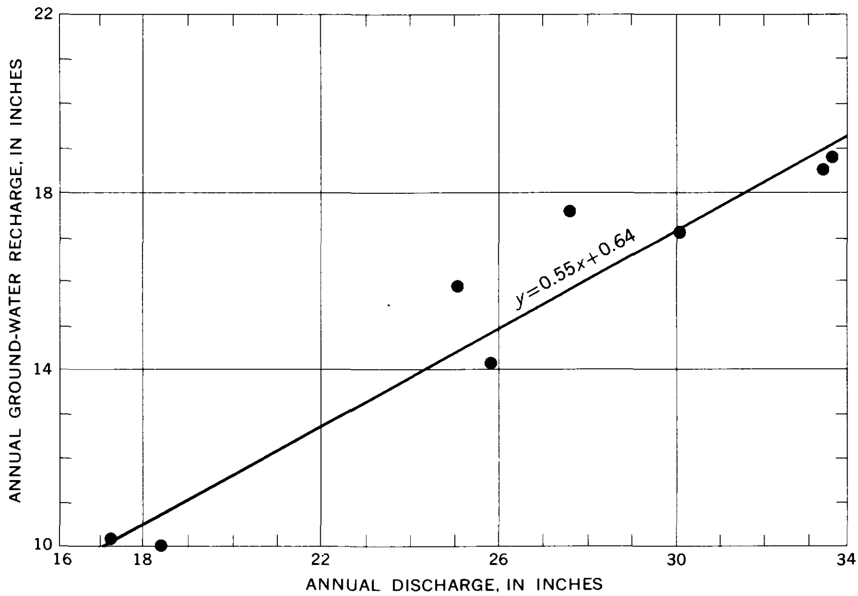

FIGURE 4.—Relation of runoff of the Potowomut River to ground-water recharge in the Potowomut River basin.

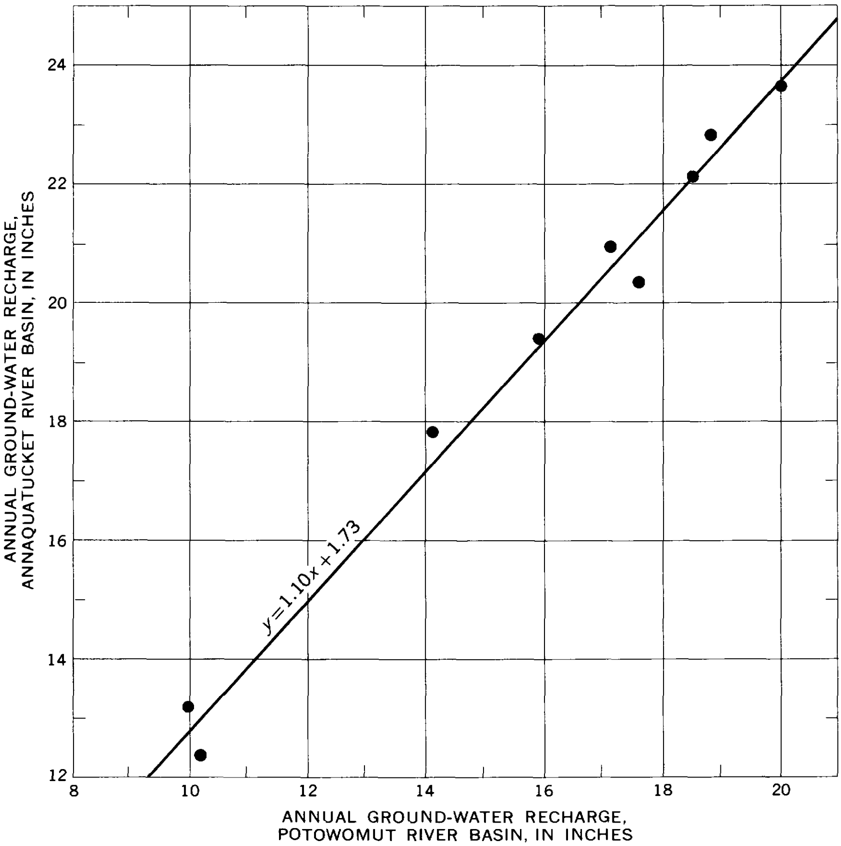

FIGURE 5.—Relation of ground-water recharge in the Potowomut River basin to that in the Annaquatucket River basin.

TABLE 4.—*Estimated rate of ground-water recharge, Potowomut and Annaquatucket River basins, 1955–61, and hydrologic significance with respect to annual discharge of the Potowomut River*

Year	Annual discharge Potowomut River (in.)	Percent of time annual discharge was equaled or exceeded [1]	Ground-water runoff (in.)	Ground-water evapotranspiration (in.)	Change in ground-water storage (in.)	Ground-water recharge (in.)	Ground-water recharge (in. per day)	Ground-water recharge (mgd per sq mi)
Potowomut River basin								
1955	33.29	22	16.1	3.6	−1.2	18.5	0.051	0.89
1956	27.64	39	15.1	3.2	−.7	17.6	.048	.83
1957	17.29	87	7.2	3.3	−.3	10.2	.028	.49
1958	38.95	4	17.0	2.7	+.3	20.0	.055	.96
1959	25.14	56	12.6	3.1	+.2	15.9	.044	.76
1960	25.86	52	11.2	3.3	−.4	14.1	.039	.68
1961	33.52	17	15.7	2.5	+.6	18.8	.052	.90
Annaquatucket River basin								
1955	33.29	22	22.1	1.7	−1.7	22.1	0.061	1.06
1956	27.64	39	19.8	1.5	−1.0	20.3	.055	.96
1957	17.29	87	10.9	2.2	−.7	12.4	.034	.59
1958	38.95	4	21.5	1.4	+.7	23.6	.065	1.13
1959	25.14	56	17.7	1.3	+.4	19.4	.053	.92
1960	25.86	52	16.6	1.8	−.6	17.8	.049	.85
1961	33.52	17	20.1	1.6	+1.1	22.8	.062	1.08

[1] Based on 22 years of record.

TABLE 5.—*Extended estimates of ground-water recharge in the Potowomut and Annaquatucket River basins, 1942–54*

[Extended estimates are based on relations shown in figs. 4 and 5]

Year	Annual discharge Potowomut River (in.)	Percent of time annual discharge was equaled or exceeded	Estimated ground-water recharge					
			Potowomut River basin			Annaquatucket River basin		
			Inches	Inches per day	mgd per sq mi	Inches	Inches per day	mgd per sq mi
1942	24.73	61	14.2	0.039	0.68	17.4	0.048	0.83
1943	19.77	74	11.5	.032	.56	14.4	.039	.68
1944	16.81	96	9.9	.027	.47	12.6	.034	.59
1945	24.49	65	14.1	.039	.68	17.2	.047	.82
1946	27.33	44	15.7	.043	.75	19.0	.052	.90
1947	20.36	70	11.8	.032	.56	14.8	.041	.71
1948	30.12	26	17.2	.047	.82	20.7	.057	.99
1949	17.77	91	10.4	.028	.49	13.2	.036	.63
1950	19.36	78	11.3	.031	.54	14.2	.039	.68
1951	28.98	34	16.6	.045	.78	20.0	.055	.96
1952	26.63	49	15.3	.042	.73	18.6	.051	.89
1953	37.54	9	21.3	.058	1.01	25.2	.069	1.20
1954	34.47	13	19.6	.054	.94	23.3	.064	1.11

WITHDRAWALS

Water is withdrawn from the Potowomut-Wickford aquifer chiefly at four pumping centers. These pumping centers consist of (1) two Kent County Water Authority wells near the junction of the Hunt and Potowomut Rivers; (2) two U.S. Navy wells near the junction of the Hunt and Potowomut Rivers; (3) one U.S. Navy well near the junction of Frenchtown Creek and the Hunt River; and (4) two North Kingstown Water Commission wells at Belleville Pond. The available pumping records of these well fields are summarized in figure 6.

About 90 percent of the total pumpage from the aquifer in the Potowomut River basin is from the wells of the Kent County Water Authority and of the U.S. Navy. The average daily pumpage from wells of the Kent County Water Authority was 1.27 mgd (million gallons per day) in 1961, 1.35 mgd in 1962, and 1.50 mgd in 1963. For the same time the average daily pumpage from wells of the U.S. Navy was 2.25 mgd, 2.45 mgd, and 2.51 mgd, respectively. The greatest annual withdrawals from these well fields were in 1944, when the pumpage from the Kent County well field average 2.21 mgd, and that from the U.S. Navy well field, 2.75 mgd.

POTOWOMUT RIVER BASIN

WATER LEVELS AND WELL-FIELD HYDROLOGY

Water levels in the well fields of both Kent County Water Authority and the U.S. Navy have been measured intermittently since 1944. During this investigation, recording gages were installed on wells Egr 2 and War 513 to obtain detailed data on water levels in the cones of depression formed at the pumping centers. Of significance are those levels recorded in 1962, a year of above-average ground-water recharge, and in 1963, one of the lowest years of ground-water recharge recorded in a 22-year period (tables 2–5). In 1962, water levels (fig. 7) in both well fields declined from early April through September—the period when withdrawals exceeded recharge and part of the pumpage was taken from ground-water storage in the aquifer. Recharge to the aquifer during late October–December more than balanced these withdrawals (table 2). By the end of 1962, water levels in the well fields had fully recovered to levels equivalent to those recorded at the beginning of the year; recharge had fully balanced discharge; and storage was replenished. During 1962 a total of 493 million gallons was pumped by the Kent County Water Authority wells, and 896 million gallons by the U.S. Navy wells. In 1963 the total

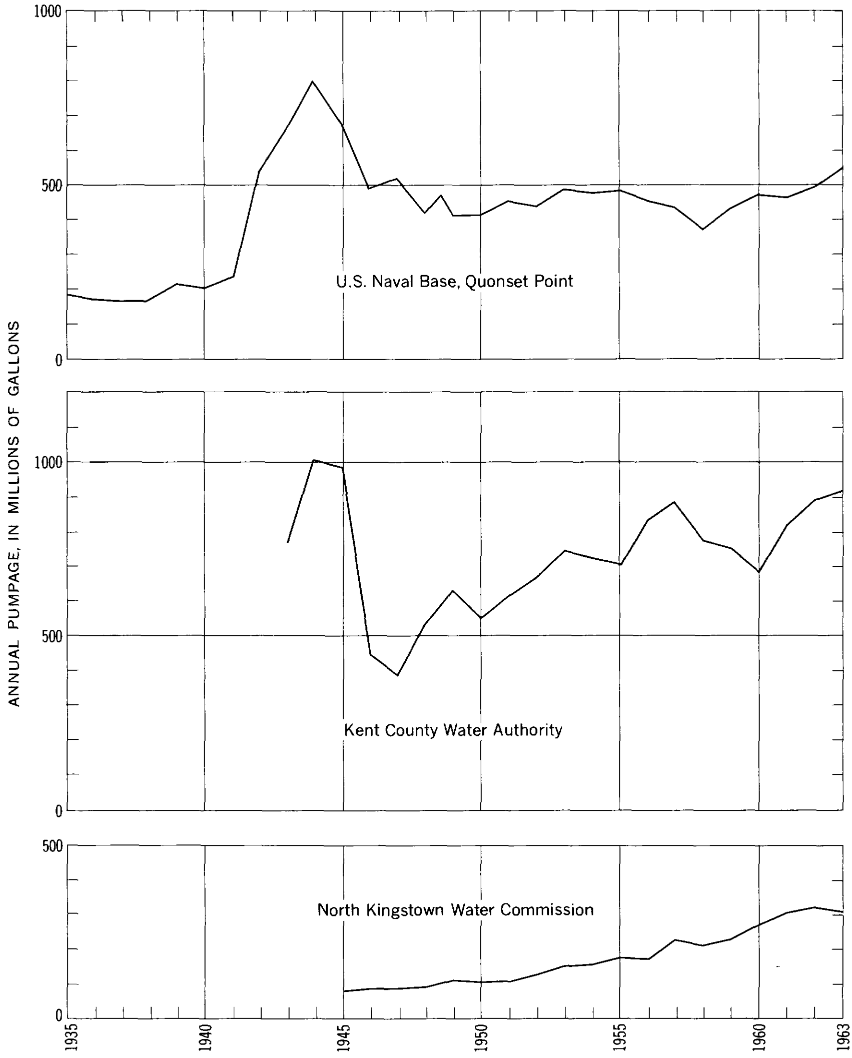

FIGURE 6.—Annual pumpage from the Potowomut-Wickford aquifer from wells of the U.S. Navy, the Kent County Water Authority, and the North Kingstown Water Commission.

withdrawal exceeded recharge, and a net decline in water level was recorded in the cones of depression; at the end of the year the water level in well Egr 2 was 3.62 feet lower than it was at the beginning of the year, and in well War 513, 4.98 feet lower. Part of the withdrawal was obtained from storage in the aquifer. During 1963 about 549 million gallons was pumped by wells of the Kent County Water Authority, and 915 million gallons, by wells of the U.S. Navy.

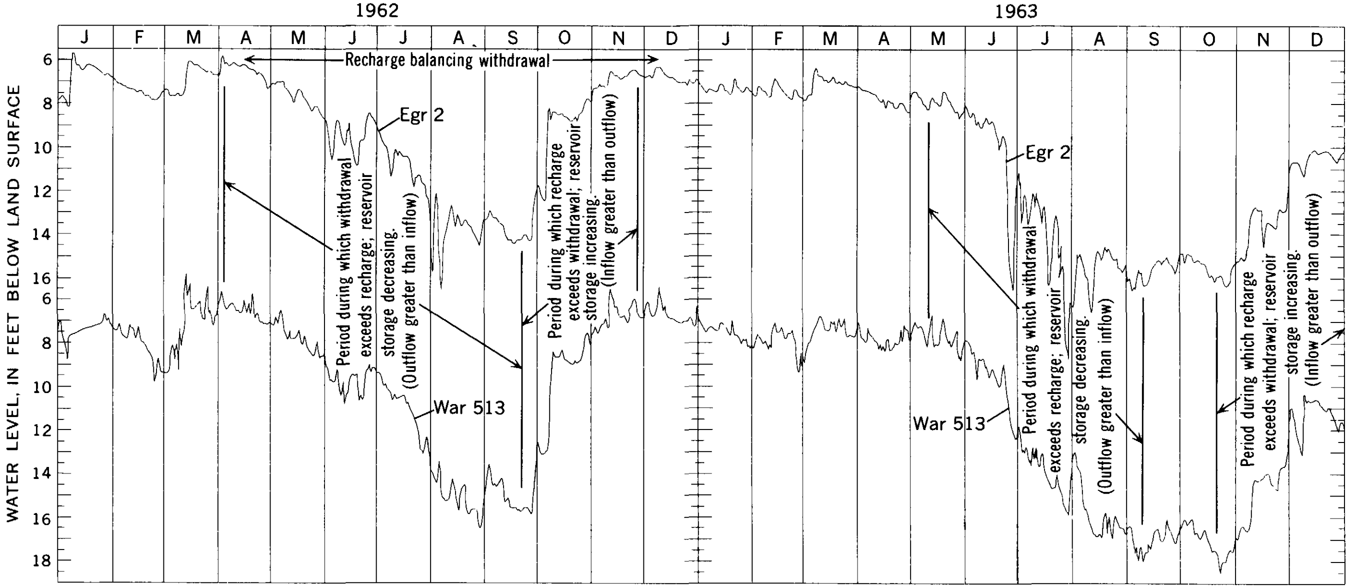

FIGURE 7.—Fluctuation of water levels in wells Egr 2 and War 513, located in cones of depression of the Kent County Water Authority and the U.S. Navy well fields.

The recharge area supporting the two pumping centers is approximately defined on plate 4 by the boundary of the area of diversion; this area is about 4.7 square miles. Assuming no significant decrease in evapotranspiration occurred in 1962, direct recharge on this area could not have supported a withdrawal of more than 3 mgd, or about 0.8 mgd less than the actual combined average daily withdrawal of the two well fields. Because no net annual decline in water levels was recorded in the cones of depression, this additional recharge had to be supplied from outside the area of ground-water diversion from streamflow derived from the upper reaches of the Potowomut River. On the assumption that a moderate decrease in evapotranspiration occurred in 1963, direct recharge on this area could not have supported an average withdrawal of more than 1.4 mgd, or about 2.6 mgd less than the actual average daily withdrawal. Of this deficit, about 1 mgd was computed as having been derived from storage in the cone of depression, and about 1.6 mgd, or 2.5 cfs, as additional recharge, from stream infiltration.

STREAM INFILTRATION AND WELL-FIELD YIELD

Diversion of streamflow into the cone of depression formed by pumping is commonly referred to as either induced infiltration or recharge by influent seepage of surface water. The quantity of water that can be continuously withdrawn from existing well fields can be significantly controlled by this influent seepage. The amount of seepage depends on (1) area of streambed affected by withdrawal, (2) vertical permeability of streambed and aquifer, (3) viscosity of stream water, and (4) the vertical hydraulic gradient across the streambed. Analysis of data from pumping tests at the U.S. Navy well fields failed to yield adequate information to permit a reasonable estimate of the length of streambed affected by pumping or of the permeability of the streambed. The piezometric map (pl. 4) shows that water levels in the aquifer represented by the 20-foot contour have declined below the Hunt River adjacent to the well fields; however, the total length of the streambed affected by the cones of depression cannot be precisely defined on the basis of available data.

Vertical permeability.—The sediments comprising the streambeds of the Potowomut River basin form a thin veneer over the aquifer. This veneer is as much as 10 feet thick locally and is estimated to average about 2 feet thick. The sediments range from pebble-sized gravel and coarse sand to organically rich very fine sand and silt. In the 12,500-foot reach of the Hunt River upstream from the Potowomut River, field measurements of the vertical permeability of these sediments were made at 11 sites. The measurements were made with a variable-head permeameter. The streambed permeability, adjusted to 60° F, ranged from 0.7 to 114 gpd per sq ft. The smallest permeability was recorded for dense sediment high in organic matter. However, most of the streambed sediments, including those having a high organic content, are not dense. Based on observations of the types of materials composing the streambed and of their areal distribution and measured permeability, the average effective vertical permeability is estimated to be 17 gpd per sq ft at 60° F.

Estimates of vertical permeability of the aquifer in contact with the streambed were obtained from pumping tests by using the method described by Weeks (1964). For well Egr 170, in the new U.S. Navy well field, the ratio of vertical to horizontal permeability was 1:100, and the vertical permeability was 20 gpd per sq ft. For well War 515, in the old U.S. Navy well field, this ratio was 1:25, and the vertical permeability was 130 gpd per sq ft. Additional but much less reliable estimates of vertical permeability were calculated, by using leaky-artesian type curves, from that part of the data from wells Egr 165, 170, and 183 which reflected the marked effects of vertical leakage during the initial stages of the pumping tests. The upper part of the aquifer, described in drillers' records as fine to medium sand, was treated analytically as a leaky confining layer. Estimates of vertical permeability of this upper part were 30, 30, and 31 gpd per sq ft, respectively.

Viscosity.—The effect of the viscosity of stream water on streambed infiltration is a function of temperature. For each 1°F change in water temperature, the infiltration rate should correspondingly change about 1.5 percent (Rorabaugh, 1956). The temperature of the Hunt River near Davisville was recorded during the investigation by using a continuously recording gage. The data collected for 1962 and 1963 indicate that the mean monthly temperature of the Hunt River ranged from 33° to 70°F. The effect of this temperature range probably caused the rate of infiltration to vary from 10 to 19.5 gpd per square foot of streambed.

Vertical hydraulic gradient.—The vertical hydraulic gradient across the streambed depends on the bed thickness (fig. 8) and on the difference in head between the stream stage and the aquifer water level at the stream. The rate of streambed infiltration will therefore vary with the changes in the average depth of water in channels of the Hunt and Potowomut Rivers and with changes in the average rate of withdrawals from adjacent well fields.

Estimates of the infiltration potential of the Hunt and Potowomut

Rivers for 1962 and 1963 are given in table 6. The potential rate of infiltration ranges from about 250,000 gpd (about 0.39 cfs) to about 490,000 gpd (about 0.76 cfs) and averages about 380,000 gpd (about 0.57 cfs). These estimates were computed by using a streambed width of 25 feet, a length of 1,000 feet, and a difference in vertical head of 1 foot. The equation for this computation and the physical factors considered are shown in figure 8.

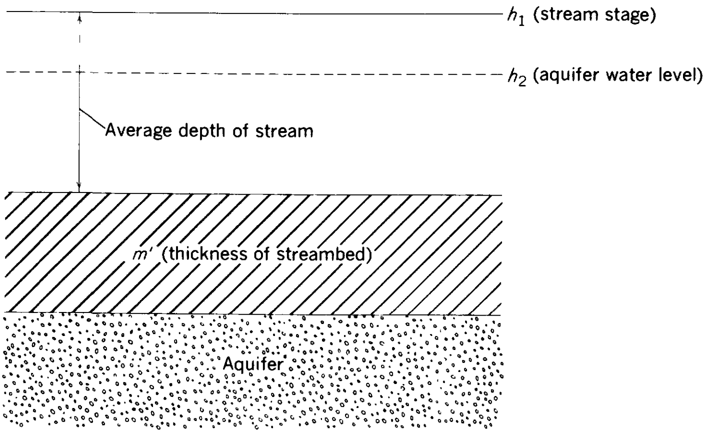

FIGURE 8.—Factors considered in estimating capacity of the Hunt and Potowomut Rivers for induced infiltration ($Q_i=P_zIA$). Q_i=rate of infiltration; P_z=vertical permeability of streambed; I=vertical hydraulic gradient $\left(\frac{h_1-h_2}{m'}\right)$; and A=elemental area of streambed.

TABLE 6.—*Estimated potential-infiltration rate of the Hunt and Potowomut Rivers per 1,000 feet of streambed for each 1-foot difference in head between stream stage and aquifer water level at the stream*

Year and month	Mean monthly stream temperature (° F)	Streambed infiltration rate		Year and month	Mean monthly stream temperature (° F)	Streambed infiltration rate	
		gpd	cfs			gpd	cfs
1962				*1963*			
January	34	260,000	0.40	January	34	260,000	0.40
February	35	265,000	.41	February	33	252,000	.39
March	38	285,000	.44	March	39	290,000	.45
April	49	355,000	.55	April	49	355,000	.55
May	57	405,000	.63	May	57	405,000	.63
June	65	458,000	.71	June	65	458,000	.71
July	66	462,000	.71	July	70	490,000	.76
August	66	462,000	.71	August	68	475,000	.73
September	61	432,000	.67	September	60	425,000	.66
October	53	380,000	.59	October	56	400,000	.62
November	42	310,000	.48	November	48	350,000	.54
December	36	272,000	.42	December	37	278,000	.43

SUSTAINED YIELD

PRINCIPAL GROUND-WATER RESERVOIR

Mathematical model.—The sustained yield of the Potowomut-Wickford aquifer underlying the Potowomut River basin was evaluated by using mathematical models. The part of the aquifer having the largest transmissibility and the greatest potential for water-supply development is southwest of the junction of the Hunt and Potowomut Rivers (pl. 2). Here the aquifer can be treated as if it were a ground-water reservoir (No. 1 on pl. 2) of limited areal extent, of large transmissibility, and of definite hydrologic boundaries. The mathematical model (pl. 5) of the principal reservoir is represented by a rectangular strip of the aquifer 2,000 feet wide and 10,600 feet long. The model has barrier boundaries simulating the effects of aquifer discontinuity and has recharge boundaries simulating effects of recharge chiefly from stream infiltration. The model aquifer contains the principal pumping centers of the basin. Its transmissibility is 125,000 gpd per ft., and its storage coefficient is 0.20. The transmissibility is a reasonably weighted average of the transmissibility of the area represented by the model (pl. 2); also the storage coefficient is sufficiently accurate (table 1) to reproduce the anticipated effects on the reservoir caused by long periods of continuous withdrawal. The model aquifer was used to determine the amount of the available ground-water recharge in the basin that could be safely withdrawn from the reservoir during a 1-year period of critically low recharge.

The maximum possible withdrawal was limited to the effective rate of recharge per square mile occurring on the reservoir catchment area in 1963, one of the four lowest years of recharge recorded in 22 years. The upstream reaches of this area total about 18.6 square miles. The effective rate of recharge on these reaches is equal to the sum of the ground-water runoff plus the ground-water evapotranspiration minus the change in storage, or 9.1 inches. Therefore, the ground-water recharge available for potential development from the reservoir is 5,600 gpm, or 8 mgd.

Model verification.—The effects of actual well-field withdrawals in 1963 on observation wells Egr 2 and War 513 were simulated by the mathematical model. This simulation was used to judge the validity of the results to be obtained in establishing a firm yield of both the existing pumping centers and of the reservoir itself. Data on pumping wells Egr 3, War 33, War 39, and War 40 and on their associated image-well systems were used in conjuction with a distance-drawdown graph (pl. 5, left) to compute the drawdown at the observation wells.

The drawdown computed with the model for 365 days of pumping under hydrologic conditions that existed in 1963 was 3.71 feet in Egr 2 and 5.00 feet in War 513. Actual measured declines in water levels for the same period were 3.62 feet in Egr 2 and 4.95 feet in War 513. Therefore, the mathematical model is capable of providing a fairly accurate estimate of the response of the reservoir to withdrawals during years of critically low recharge.

Reservoir operations.—A study of reservoir operations was made, utilizing the mathematical model and existing pumping facilities, to determine the sustained yield of the existing well fields. The total drawdown in each pumping well is a result of (1) drawdown, adjusted for dewatering, in the aquifer at the well face necessary to support the pumping rate; (2) drawdown in the well due to well loss as a result of well construction; (3) drawdown in the well due to the effects of partial penetration, that is, the well being open to a small percentage of the full saturated thickness of the aquifer; and (4) drawdown in each well due to the other pumping wells, or well interference. Both the drawdown in the aquifer at the well face and the well interference were computed using the mathematical model, simulating the five pumping wells, an associated array of 161 image wells, and the distance: drawdown graph (pl. 5, left). Drawdown due to well loss (s_w) was estimated using the equation $s_w = CQ^2$ (Jacob, 1946), in which C is the well-loss constant (in sec ^{2} per ft ^{5}) and Q is the well discharge (in cubic feet per second). A well-loss constant of 2 was used for wells Egr 3, War 33, War 39, and War 40, and a constant of 1 was used for well Egr 180. These constants were estimated from specific-capacity tests of variable discharges. Drawdown due to partial penetration was estimated using the method described by Butler (1957, p. 160) and by Walton (1962, p. 8).

The results of the evaluation are given in table 7. On an annual basis, the well fields can safely withdraw 5,600 gpm from the ground-water reservoir at the existing pumping centers. The pumpage should not seriously lower the water levels below the tops of the screens in the pumping wells nor excessively dewater the aquifer near these wells. During critical periods this withdrawal equals the ground-water recharge available to the reservoir for development. Streambed infiltration rates are adequate to support the pumpage minus water taken from storage and local recharge with the head differences to be anticipated in the more than 8,000 feet of streambed to be affected by pumping.

Maximum drawdown in the reservoir occurs during mid-May to mid-October. In this period the withdrawals must be balanced entirely by stream infiltration and the water taken from storage. For streamflow alone to completely balance the pumpage, a continuous discharge in the Potowomut River of about 12 cfs would be required; such discharge occurs about 70 percent of the time (Allen, 1953). In abnormally dry years, however, the discharge can be less than 12 cfs for as many as 160 days. In 1949, for example, the discharge was less than 12 cfs for 165 days; in 1957, for 155 days; and in 1963, for 130 days. The amount to be taken from storage to balance the deficit in streamflow during these periods is about half the total withdrawal, or about 4 mgd. The maximum drawdown to be anticipated under these conditions is given in table 7.

Implications of results.—The data given in table 7 indicate that the ground-water reservoir can safely sustain a yield of 8 mgd, or 5,600 gpm (gallons per minute), during periods of critically low ground-water recharge, low ground-water runoff, and low streamflow. This total yield can be withdrawn at the sites of the existing pumping facilities. The data indicate that the Kent County Water Authority well field can safely sustain a yield of 2,450 gpm, and the U.S. Navy well fields, 3,150 gpm. This pumpage requires utilization of only 10–45 percent of the 50 feet of head available for development at the various well sites.

A withdrawal of 8 mgd from the reservoir will have negligible effects on streamflow and on marsh and pond storage during a wet year, such as 1958. However, in exceptionally dry years, such as 1949, 1957, and 1963, this withdrawal will result in no streamflow for as much as 160 days in a sizable reach of the Hunt and Potowomut Rivers. An undetermined decrease in marsh and pond storage should also result.

SECONDARY GROUND-WATER RESERVOIR

A virtually untapped area of large transmissibility underlies the Potowomut River basin north of the junction of Scrabbletown Brook and the Hunt River. This part of the aquifer represents a secondary ground-water reservoir (No. 2 on pl. 2) potentially available for additional large-scale development, in particular for supplemental dry-weather supply. Optimum development of the yield of this reservoir for supplemental dry-weather supply will require operation coordinated with that of the principal ground-water reservoir in the lower part of the basin.

Potential yield of reservoir in critically dry periods.—The potential yield of the reservoir was evaluated by using a mathematical model. In the evaluation, no adjustment was made for the effects of streambed infiltration on reservoir yield. Data collected during this investigation

TABLE 7.—*Summary of data obtained from the mathematical model of the principal ground-water reservoir in the Potowomut River basin*

[Data are in feet except as indicated]

Pumping well	Discharge [1] (gpm)	Screen length	Water level above top of screen	Effective radius of well	Drawdown: In aquifer at well site due to pumping	Drawdown: Due to well loss	Drawdown: Due to partial penetration	Drawdown: Due to well interference	Drawdown: Total in well after 365 days of pumping	Undeveloped-water level in well above screen	Maximum [2] anticipated drawdown in well	Water level in well above screen
Egr 3	1,200	35	55	1	15.86	13.13	10.89	2.95	45.24	9.76	53.14	1.86
180	1,800	30	64	2	22.68	16.08	17.68	Negligible	56.44	7.56	63.41	.59
War 33	1,250	40	63	1	17.47	15.50	13.56	3.58	50.12	12.88	58.05	4.95
39	400	25	13	1	5.07	1.59	5.07	2.33	14.06	−1.06	21.62	−8.62
40	950	30	32	1	11.75	8.96	9.16	1.58	31.45	.55	39.44	−7.44

[1] Total withdrawal, 5,600 gpm (gallons per minute).
[2] Drawdown anticipated at end of 160-day period during which available recharge and stream infiltration is insufficient to balance discharge; appreciable part of pumpage must come from storage in reservoir.

TABLE 8.—*Summary of data obtained from the mathematical model used to estimate potential yield of the undeveloped ground-water reservoir in Potowomut River basin*

[All data except discharge data are given in feet. Discharge: gpm, gallons per minute]

Hypothetical pumping well	Discharge [1] (gpm)	Screen length	Water level above top of screen	Effective radius of well	Drawdown: In aquifer at well site due to pumping	Drawdown: Due to partial penetration	Drawdown: Due to well interference	Drawdown: Due to well loss	Drawdown: Total in pumped well	Water level in well above screen
2	500	40	40	1	20.66	6.96	6.58	3.72	37.92	2.08
3	500	40	40	1	19.52	6.58	6.58	3.72	36.40	3.60

[1] Total withdrawal, 1,000 gpm.

indicate that the rate of streambed infiltration in this part of the basin is considerably less than that elsewhere in the basin.

The effective rate of recharge on the diversion area of the reservoir was 9.1 inches in 1963. The ground-water potentially available for development by the reservoir from recharge alone during critically dry periods is about 1.4 mgd, or 1,000 gpm. In years of low recharge, such as 1963, however, little or no recharge can be expected to occur for periods of as much as 150 days. Therefore, reservoir storage alone may be required to sustain withdrawal during such periods.

The mathematical model (pl. 5, center) of the undeveloped reservoir area represents a rectilinear strip 2,000 feet wide and 7,000 feet long. The model has four barrier boundaries, three of which simulate the effects of transmissibility changes. The northernmost boundary was arbitrarily placed so that the effects of the diversion on the principal ground-water reservoir were minimized (No. 1 on pl. 2). The transmissibility of the model is 70,000 gpd per ft, and the effective saturated thickness, 80 feet. These values are sufficiently conservative to be fairly representative of the characteristics of the part of the aquifer modeled (pls. 2, 3).

Computations (table 8), using the mathematical model, indicated that the reservoir can safely sustain a yield of 1,000 gpm, or about 1.4 mgd, in exceptionally dry years. This yield was computed from data on two wells (wells 2 and 3, pl. 5) 1,000 feet apart in the central part of the reservoir; these wells were pumped for 150 days during which there was no recharge.

Potential yield of reservoir for supplemental dry-weather supply.— With the optimum utilization of both reservoir head and storage, the secondary reservoir may provide a significant supplement to the dry-weather yield of the principal reservoir in the lower part of the basin. This supplemental yield was computed with the mathematical model (pl. 5, center) for pumping periods of 60, 100, 150 days. In the evaluation, the aquifer head available for development was limited by practical considerations to half the saturated thickness, or about 40 feet.

For the optimum utilization of reservoir head, well construction that minimizes factors such as partial penetration, well loss, and well interference is required. The effects of partial penetration and of well loss are significantly influenced by the percentage of the aquifer thickness that is screened in the wells. To maximize reservoir yield and to minimize these adverse effects, hypothetical pumping wells were assumed to be screened the full saturated thickness of the lower half of the reservoir. The effective radius of each pumping well was taken as 1 foot, and the well-loss constant, as 3 sec^2 per ft^5. The pumping wells were spaced, at scale, 1,000 feet apart along the center of the model.

The results of the evaluation are given in table 9. These results indicate that, by optimum use of available drawdown, the reservoir should be capable of providing a supplemental dry-weather yield of about 7 mgd, or 4,800 gpm, for 60 days; about 5 mgd, or 3,500 gpm, for 100 days; and about 4.3 mgd, or 3,000 gpm, for 150 days. However, use of the reservoir for supplemental supply during several consecutively dry years requires that adequate recharge be available to refill the reservoir at the end of the specified periods of supplemental pumping. For example, to refill the reservoir after the 60-day pumping period would require an annual rate of recharge of about 7.3 inches; after the 100-day pumping period, about 8.7 inches; and after the 150-day pumping period, about 11.3 inches. Annual recharge at rates equal to or greater than these amounts is generally available, even during consecutive dry years (tables 4, 5).

TABLE 9.—*Summary of data obtained from the mathematical model used to estimate the potential yield of the secondary ground-water reservoir for supplemental dry-weather supply*

[Drawdown data are given in feet]

Hypothetical pumping well	Drawdown: In aquifer at well due to pumping	Drawdown: Due to well interference	Drawdown: Total in aquifer at well	Drawdown: Due to partial penetration	Drawdown: Due to well loss	Drawdown: Total in pumped well	Water level in well above bottom of screen (ft)
60-day supplemental pumping at 4,800 gpm							
[Discharge, 800 gpm; screen length, 40 ft; water level above top of screen, 40 ft; effective radius of well, 1 ft]							
1	28.91	9.45	38.36	9.74	9.53	57.63	22.37
2	26.49	13.78	40.27	8.92		58.72	21.28
3	26.10	14.97	41.07	8.79		59.39	20.61
4	26.10	14.97	41.07	8.79		59.39	20.61
5	26.49	13.78	40.27	8.92		58.72	21.28
6	28.91	9.45	38.36	9.74		57.63	22.37
100-day supplemental pumping at 3,480 gpm							
[Discharge, 580 gpm; screen length, 40 ft; water level above top of screen, 40 ft; effective radius of well, 1 ft]							
1	23.84	13.92	37.76	8.03	5.01	50.80	29.20
2	21.39	17.82	39.21	7.21		51.43	28.57
3	20.55	19.21	39.76	6.92		51.69	28.31
4	20.55	19.21	39.76	6.92		51.69	28.31
5	21.39	17.82	39.21	7.21		51.43	28.57
6	23.84	13.92	37.76	8.03		50.80	29.20
150-day supplemental pumping at 3,000 gpm							
[Discharge, 500 gpm; screen length, 40 ft; water level above top of screen, 40 ft; effective radius of well, 1 ft]							
1	23.45	19.84	43.29	7.90	3.72	54.91	25.09
2	20.66	23.80	44.46	6.96		55.14	24.86
3	19.54	25.50	45.04	6.58		55.34	24.66
4	19.54	25.50	45.04	6.58		55.34	24.66
5	20.66	23.80	44.46	6.96		55.14	24.86
6	23.45	19.84	43.29	7.90		54.91	25.09

ANNAQUATUCKET RIVER BASIN

The transmissibility of the Potowomut-Wickford aquifer is not adequate to support large-scale development except in one area in the Annaquatucket River basin. This area underlies the North Kingstown Water Commission well field at Belleville Pond. Current withdrawal at the well field, consisting of wells Nok 26 and 1156, is about 1 mgd.

Water levels in the well field have been measured intermittently in observation wells from 1948 to 1962. Water-level fluctuations do not generally show any annual decline in aquifer storage due to pumping; instead, they show that the average annual withdrawal has generally been balanced by an equivalent amount of recharge. Much of this recharge is derived from the part of the aquifer upgradient from the well field. This recharge area cannot be adequately defined with available data. Some recharge can also be derived from Belleville Pond and from Secret Lake. However, several 24-hour pumping tests in the well field indicated no apparent recharge from these sources, and data did not permit a direct evaluation of the recharge potential of these sources.

In the vicinity of the North Kingstown Water Commission well field, the aquifer can be treated by analysis and can be managed by users as if it were a separate ground-water reservoir (No. 3 on pl. 2) of small areal extent, of large transmissibility, and of definite hydrologic boundaries. The potential yield of the reservoir under natural conditions is limited to the amount of ground-water recharge that occurs on an upgradient area of intake of more than 6 square miles. Much of this recharge moves downgradient to be discharged as either influent seepage toward Belleville Pond or as underflow from the reservoir area. In 1963 the effective rate of recharge on the intake area was 13 inches. On the basis of this figure, the amount of ground-water recharge that is potentially available for development from the reservoir during critically dry periods is about 4 mgd, or 2,800 gpm.

Mathematical model.—The sustained yield of the existing well field and the ground-water reservoir was evaluated with a mathematical model. This model represents a rectangular area 1,600 feet wide and 6,000 feet long (pl. 5, right); it has three barrier boundaries that simulate the effects of marked decrease in aquifer transmissibility and one recharge boundary near Belleville Pond that simulates the effects of upgradient recharge. The model aquifer has a transmissibility of 200,000 gpd per ft. and a storage coefficient of 0.20. The transmissibility is a reasonably weighted average for the area represented by the model, and the storage coefficient (table 1) is sufficient to reproduce the response of the reservoir to long periods of continuous withdrawal.

Model verification.—The effects of actual well-field withdrawals were simulated with the mathematical model, and this simulation permitted evaluation of the model's reliability. Data on pumping well Nok 26 and its system of image wells were used to compute the drawdown at observation well Nok 27, which is 110 feet away from the pumped well. The computations were based on pumping conditions during a 215 day period of exceptionally low recharge in 1949. The computed drawdown was 1.93 feet. In this period the observed decline in water level in the cone of depression at well Nok 27 was 0.97 feet. The computed drawdown was adjusted to the conditions of partial penetration at the observation well (Butler, 1957, p. 157–164; Walton, 1962, p. 7–8). The adjusted drawdown was 1.07 feet. This drawdown, although only approximately correct, nearly corresponds to the observed decline and shows that the mathematical model is capable of providing a reliable estimate of the response of the aquifer to withdrawals during years of critically low recharge, such as 1949 and 1963.

Reservoir operations.—Computations (table 10), using the mathematical model, indicate that the existing wells can safely sustain a continuous yield of 1,240 gpm, or 1.8 mgd, in exceptionally dry years. Under similar hydrologic conditions, the ground-water reservoir alone can safely sustain a yield of 2,510 gpm, or 3.6 mgd. This yield was computed by using the model and data from existing pumping wells and from two hypothetical pumping wells (pl. 5, right). Each hypothetical well was placed over the center of the ground-water reservoir 1,000 feet from other pumping wells, and each was pumped at 780 gpm. The effects of withdrawals from the additional pumping centers would be sufficient to reduce the yield of the existing well field from 1,240 gpm to 950 gpm. Actual development of 780 gpm at each additional center could require the use of several wells at each site because of the probable effects on actual production wells from partial penetration and well loss.

PETTAQUAMSCUTT RIVER BASIN

The part of the Potowomut-Wickford aquifer which underlies the Pettaquamscutt River basin has sufficiently large transmissibility to support a moderate-scale development in one area. The ground-water reservoir (No. 4 on pl. 2) in that area is currently being tapped in the North Kingstown Water Commission well field at Pausacaco Pond. Withdrawal from the pumping center is less than 0.1 mgd.

Available hydrologic data do not warrant use of a mathematical model to determine the sustained yield of either the ground-water reservoir or the well field. However, a less reliable but usable estimate of reservoir yield can be obtained by determining the amount of re-

TABLE 10.—*Summary of data obtained from the mathematical model of the ground-water reservoir, Annaquatucket River basin, used to determine the sustained yield of the existing well field*

[Data are in feet except as indicated]

Pumping well	Discharge [1] (gpm)	Screen length	Water level above top of screen	Effective radius of well	Drawdown					Water level in well below top of screen
					In aquifer at well face due to pumping	In aquifer at well face due to well interference	Due to well loss	Due to partial penetration	Total in well after 365 days of pumping	
Nok 26	650	20	23	0.5	8.48	3.20	6.29	8.01	26.26	3.26
1156	590	20	20	0.5	8.28	3.85	5.01	7.96	25.10	5.10

[1] Total withdrawal from wells Nok 26 and 1156, 1,240 gpm.

charge potentially available for development. The area of ground-water diversion upgradient from the reservoir is 2.7 square miles. Partial records of low flow of the Mattatuxet River in the basin indicate that ground-water runoff in the upgradient area is somewhat greater than that from an equivalent area in the Annaquatucket River basin. Based on a moderate increase in the effective rate of recharge in the Annaquatucket basin, recharge in the diversion area averages about 1.8 mgd during abnormally dry years such as 1963. Excluding the induced infiltration from streams and ponds, the ground-water reservoir has, therefore, a potential yield of 1.8 mgd. Because the average transmissibility and the saturated thickness of the reservoir are moderate, only about 70 percent of the potential yield, or about 1.3 mgd, can probably be developed.

Extensive development of the ground-water reservoir is complicated by several factors. The areas of highest transmissibility underlie Pausacaco Pond, and pumping wells, thus, cannot be developed in the most productive part of the aquifer. The south edge of the reservoir underlies the Pettaquamscutt River, which contains brackish water, and extensive development of this part of the reservoir may cause saline-water intrusion.

CHEMICAL QUALITY OF WATER

The chemical quality of raw water in the Potowomut-Wickford area is suitable for most purposes. Water pumped from the Potowomut-Wickford aquifer generally contains less than 70 ppm (parts per million) dissolved solids. The chief anions are bicarbonate, sulfate, chloride, and nitrate, and concentration of any one of these constituents is generally less than 25 ppm. Locally along Narragansett Bay, however, the chloride content may exceed the 250 ppm limit recommended by the U.S. Public Health Service (1962) for drinking water. The chief cations are calcium, sodium, magnesium, and potassium. Each of these cations is generally present in concentrations less than 10 ppm; thus, the water is soft. The hydrogen ion concentration, or pH, ranges from about 5.5 to 7. Water in this pH range is somewhat corrosive. In most parts of the aquifer the iron and manganese contents of the water do not exceed the standards (0.3 and 0.05 ppm, respectively) recommended by the U.S. Public Health Service (1962). Where exceeded, the concentrations of iron are sufficiently low that the water can be readily treated. Locally, where the contents of both iron and manganese exceed the standards, treatment for the constituents could possibly be somewhat difficult.

The water collected from streams in the area during periods of low flow has a chemical quality similar to that of water from wells. These waters differ chiefly in iron and manganese concentrations and in color. The iron and manganese concentrations in stream water generally exceed those in water from wells. The iron content in stream water ranges from 0.03 to 3.7 ppm. The highest iron concentrations occur in Sandhill Brook, in the lower reach of the Hunt River near Davisville, and in the Potowomut River. Of the 49 analyses available, however, only 15 exceeded the standards recommended by the U.S. Public Health Service (1962). The concentration of manganese ranges from less than 0.01 to 0.54. In only 4 of the 34 analyses available did the manganese concentrations exceed the maximum concentration recommended in the U.S. Public Health Service drinking-water standards.

SUMMARY AND CONCLUSIONS

The Potowomut-Wickford area is underlain by a sand and gravel aquifer whose transmissibility ranges from less than 10,000 to more than 300,000 gpd per ft. The areas of large transmissibility occur in four ground-water reservoirs in the Potowomut, Annaquatucket, and Pettaquamscutt River basins. The principal ground-water reservoir of the Potowomut River basin is capable of safely sustaining a yield of 8 mgd, or 5,600 gpm, during periods of exceptionally low recharge. This yield is about twice the current pumpage and can be withdrawn at existing pumping facilities. Part of this sustained withdrawal would be derived from influent seepage of streamflow. If this yield were increased by development of the reservoir, a sizable reach in both the Hunt and the Potowomut Rivers would be dry in exceptionally dry years (such as 1957) for as much as 160 days.

The Potowomut River basin also contains an additional ground-water reservoir that is virtually untapped. This secondary reservoir may be capable of yielding a supplemental supply of as much as 5 mgd during critically dry periods for as much as 100 days. However, to develop this supplemental supply without significantly decreasing the sustained yield of the principal ground-water reservoir will require careful management.

The ground-water reservoir underlying the Annaquatucket River basin is capable of safely sustaining a yield of 3.6 mgd, or 2,500 gpm, during exceptionally dry years. This discharge is about three times the current average daily pumpage and could not be obtained until after two additional 780-gpm pumping centers were developed.

The ground-water reservoir underlying the Pettaquamscutt River basin may be capable of safely sustaining a yield of 1.3 mgd during exceptionally dry years. This sustained yield is about 13 times the current average daily withdrawal. Extensive development of the southern part of the reservoir, however, could result in the intrusion of saline water into the aquifer.

The estimates of safe yield of the subsurface reservoirs are predicated on limiting the withdrawal to the effective average rate of ground-water recharge to the reservoirs during exceptionally dry years. This limitation does not necessarily allow for either optimum use of reservoir storage or recharge occurring during near-normal years of precipitation. The reservoir yields represent a practical limit based on the curent rate of withdrawal coordinated with the current level of planning and development of the water resources of the area. Although such considerations as the feasibility of increasing the total withdrawal through artificial recharge, the regulation of streamflow, and similar programs of water-resource management are not within the scope of this evaluation, adequate interpretation is provided to permit testing of the technical feasibility of specific management programs as the need arises to augment the yield from subsurface reservoirs. Also, the evaluation can serve as a basis to permit the application of the electric analog or digital computer to the analyses of current and future water-resources problems of the area.

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