# Water Resources of the New Jersey Part of the Ramapo River Basin

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1974

*Prepared in cooperation with the New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply*

U.S. DEPARTMENT OF THE INTERIOR

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*By* JOHN VECCHIOLI *and* E. G. MILLER

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# WATER RESOURCES OF THE NEW JERSEY PART OF THE RAMAPO RIVER BASIN

By JOHN VECCHIOLI and E. G. MILLER

## ABSTRACT

The Ramapo River, a major stream in the Passaic River basin, drains an area of 161 square miles, 70 percent of which is in Orange and Rockland Counties, N.Y., and 30 percent is in Bergen and Passaic Counties, N.J. This report describes the hydrology of the New Jersey part of the basin and evaluates the feasibility of developing large ground-water supplies from the stratified drift in the Ramapo River valley by inducing recharge to the aquifer from the river. The ground water and surface water of the basin are considered as a single resource because the development of either ground water or surface water affects the availability of the other.

Precambrian gneiss, sparsely mantled with Pleistocene glacial drift, underlies the basin west of the Ramapo River in New Jersey. To the east, bedrock consists of the Watchung Basalt and of shale, sandstone, and conglomerate of the Brunswick Formation of Triassic age. Glacial drift occurs nearly everywhere in the eastern part of the basin, and deposits of stratified drift more than 100 feet thick occur in the Ramapo valley.

Average annual runoff at Pompton Lakes accounts for 25 inches of the 45 inches of annual precipitation in the New Jersey part of the basin, and the remaining 20 inches is accounted for by evapotranspiration. Streamflow is highly variable—particularly in the area underlain by gneissic rocks—because of the low storage capacity of the rocks and the rough topography. Many of the small tributaries go dry during extended periods of no precipitation.

Small domestic supplies of ground water can be obtained nearly everywhere, but the Brunswick Formation is the only consolidated-rock aquifer in the basin that can be depended upon to yield 100–200 gallons per minute to wells. Supplies of more than 1,000 gallons per minute are available from wells tapping the stratified drift in the Ramapo valley. The drift supplies 75 percent of the ground water pumped for public supply in the basin.

Sustained ground-water yield in upland areas, based on stream base-flow recession, is estimated to be 200,000–300,000 gallons per day per square mile for the drift-covered Brunswick Formation and about 100,000–200,000 gallons per day per square mile for the gneiss and basalt. Potential sustained yield of the stratified drift in the valley depends on the availability of the streamflow and on the induced rate of infiltration.

Pumping from the stratified drift results in a reduction in streamflow, which may be undesirable, mainly because of prior downstream water rights. On the basis of the storage available in the stratified drift and an analysis of daily flow during the drought period of October 1964 to September 1967

at Pompton Lakes, 20–25 million gallons per day of Ramapo River water are available for development after existing downstream water requirements are supplied. However, some low-flow augmentation will be necessary to insure downstream rights. Rates of infiltration computed from seepage losses observed near Mahwah indicate that at least 11 million gallons per day, on an average basis, can be infiltrated from the river by the pumping of wells tapping the stratified drift. The use of recharge pits and spreading areas would increase the rate of infiltration. Losses from the Ramapo River could be minimized by returning treated sewage effluent directly to the river or, preferably, by recharging the stratified-drift aquifer with the treated effluent.

Ground-water quality and surface-water quality at times of low-flow vary according to the type of rock from which the water is obtained. Water from the gneiss is low in dissolved solids—less than 127 mg/l (milligrams per liter)—and soft to moderately hard—less than 94 mg/l. Water from the Brunswick Formation is more mineralized—total dissolved-solids content is as much as 278 mg/l and hardness as much as 188 mg/l. Water from the stratified drift is generally intermediate in quality—that is, total dissolved-solids content is as much as 215 mg/l and hardness as much as 155 mg/l. Dissolved-solids content and hardness of surface water in the basin varies inversely with the amount of stream discharge.

Data in this report include construction features and yield characteristics of wells selected for this study, chemical quality of ground and surface water, streamflow variability, lithology of the valley fill, ground-water withdrawals, and the effect of ground-water pumpage on streamflow.

# INTRODUCTION

## PURPOSE AND SCOPE OF REPORT

The study of water resources in the New Jersey part of the Ramapo River basin is part of a statewide program of investigation of the ground-water resources of New Jersey by the U.S. Geological Survey in cooperation with the New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply. Whereas most former studies appraised the availability of ground water within political units, such as counties, the present investigation evaluates the interrelationship of ground and surface water within the drainage basin, a hydrologic unit. The objectives of this study were to define the hydrology of the New Jersey part of the basin and to evaluate the feasibility of developing large ground-water supplies from the stratified drift in the Ramapo River valley by inducing recharge from the river. The possibility of recycling water by using treated-sewage effluent to recharge the drift is also considered briefly.

The data presented and interpreted include the following: The construction features and yield characteristics of selected wells, the amount of ground-water pumpage from each aquifer, the utilization of ground water, and the chemical quality and the availability of both ground water and surface water. The geohydrology of the valley-fill deposits is described in detail, giving particular attention to the hydraulic continuity between these deposits and the Ramapo River. Also, the potential ground-water yield throughout the basin is evaluated.

## ACKNOWLEDGMENTS

Many of the well and water-use data were obtained from the files of the New Jersey Department of Conservation and Economic Development.

Special thanks are expressed to Messrs. Harry Breen, Jr., and N. David Fagerlund, Superintendents of the Township of Mahwah Water Department and the Borough of Oakland Water Department, respectively, who provided so freely of their time and their Departments' personnel and equipment as needed in this study. The authors are also grateful to the officials of the Borough of Ramsey and the Township of Wayne, as well as the Borough of Oakland and the Township of Mahwah, for providing data from their files and allowing the use of their wells for collection of water samples. Mr. Adam F. Rinbrand of Rinbrand Well Drilling Co., Glen Rock, N.J., graciously provided data on many wells. The New York district of the Water Resources Division, U.S. Geological Survey, made streamflow measurements and collected water samples in the New York part of the basin. Though too numerous to list, our thanks are also extended to the many other individuals who provided some of the information used in this report.

## PREVIOUS STUDIES

The water resources of the Ramapo River basin were described briefly by Vermeule (1894) in his study of the water supply of the State of New Jersey. Weston and Sampson (1924) considered the basin as a potential water supply for the city of Bayonne. Tippetts, Abbett, McCarthy, and Stratton (1955) described the water-supply potential of the Ramapo River and, though only generally, the ground-water potential in the basin. The water resources of the basin have also been described by the Bergen County Water Study Committee (1957) and by Neglia, Elam, and Rothenberg (1967). In the New York part of the basin, Perlmutter (1959) made a study of the geology and ground-water resources of Rockland County, and Ayer and Pauszek (1963) evaluated the surface-water supply in that county.

Streamflow measurements made in the basin and water-quality data are published annually by the U.S. Geological Survey. (See U.S. Geological Survey, 1965, 1966.) Every 5 years, the streamflow data are also published by the New Jersey Department of

Conservation and Economic Development in their Special Report Series (Vickers and McCall, 1968).

Previous geologic studies in the basin include those by Kümmel (1898, 1899) on the rocks of the Newark Group and by Salisbury (1902) on the glacial deposits. Kümmel (1940) described the geology of the entire State of New Jersey, and Johnson (1950) revised the geologic map showing the distribution of the various rock units in the State. Distribution of the rock units in the New York part of the basin have also been mapped (New York [State publication], 1961).

## GEOGRAPHY

Headwaters of the Ramapo River, which is a major headwater stream of the Passaic River basin, are near Monroe, N.Y. (fig. 1). The Ramapo drains an area of 160.7 square miles, of which, 112.4 square miles are in New York State (Vermeule, 1894, p. 166). The drainage basin includes parts of Orange and Rockland Counties, in New York, and parts of Passaic and Bergen Counties in New Jersey. (See pl. 1.) For most of its course, the stream follows a low valley in the middle, or just east, of the Highlands, which rise some 700–1,000 feet above the stream. The total channel length of the Ramapo is 34 river miles (Vermeule, 1894, p. 167). The Mahwah River — the Ramapo's major tributary — joins the Ramapo just south of the New York–New Jersey State line. Other smaller tributaries are Stony Brook, in New York, and Darlington, Bear Swamp, Pond, and Haycock Brooks, in New Jersey. Lakes abound in the basin; among the largest are Mombasha and Tuxedo Lakes, in New York, and Ramapo, Pines, and Pompton Lakes, in New Jersey.

The present study was limited almost entirely to the New Jersey part of the basin. This area includes almost all of the Township of Mahwah, all of the Borough of Oakland, about half of the Boroughs of Ramsey and Franklin Lakes (all in Bergen County); and a small part of the Borough of Pompton Lakes and the Township of Wayne, and a very small part of the Boroughs of Ringwood, Manaque, and North Haledon (all in Passaic County).

The part of the Ramapo River basin in New Jersey is rather sparsely populated, as compared with most of the other areas in northeastern New Jersey. West of the Ramapo River, most of the area is mountainous and wooded and is poorly suited for urbanization or major development. Practically all development in the New Jersey part of the basin has been east of the river and has been largely residential. East of the river, the topography is hilly,

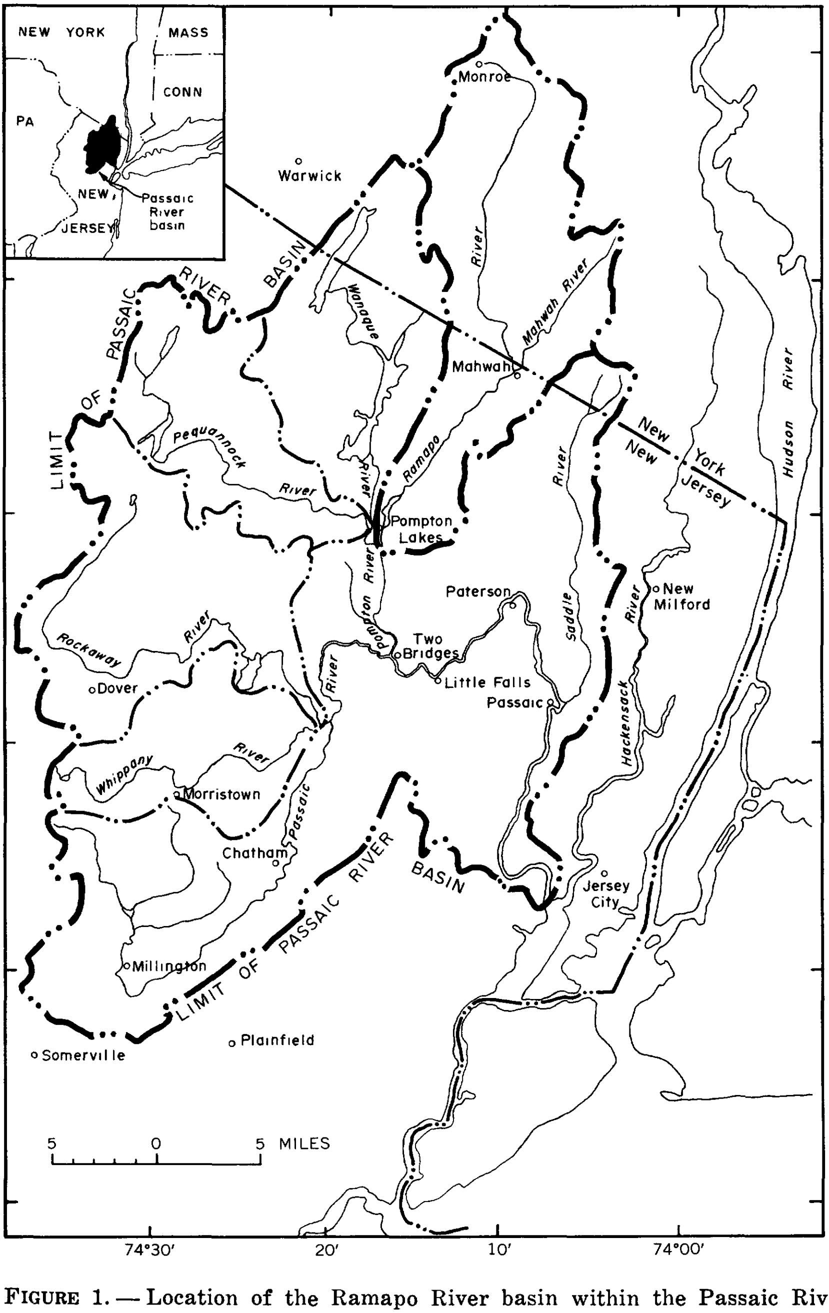


FIGURE 1.—Location of the Ramapo River basin within the Passaic River drainage system.

and much of it is also wooded. One of the notable industries within the basin is a large automobile assembly plant near Mahwah. Continued suburban development of the general area is anticipated.

The Ramapo River basin is a part of the Appalachian Highlands division that includes several physiographic provinces. Of these, parts of the New England and Piedmont provinces characterize the basin. The boundary between these two provinces follows the valley of the Ramapo River in New Jersey, and it continues up the Mahwah River valley in New York.

Within the New Jersey part of the basin, the New England province, known locally as the New Jersey Highlands, consists of the rugged Ramapo Mountains. One of these mountain peaks reaches a maximum altitude of 1,164 feet above mean sea level, half a mile southwest of the State line, in the westernmost part of the basin. Many other peaks, particularly in the northern part of the range, reach altitudes of more than 900 feet; however, in the southern part of the range, the altitudes are lower.

The Piedmont province — that part of the basin southeast of the river — is marked by less rugged hills elongated in a north-south to northwest-southeast direction, and the highest altitude in the province, 750 feet above mean sea level, is that of a ridge near Campgaw that is the northernmost extension of the Watchung Mountains. Extensive swampy areas occur in the headwaters of many of the tributary streams in this part of the basin. Consequently, the drainage divide between the Ramapo River and the Saddle River, to the east, is poorly defined in some places.

## GEOLOGY

Various rock types, representing several geologic time periods and ranging in age from Precambrian to Holocene, crop out in the Ramapo River basin. The areal extent of the various rock units is shown in figure 2.

### PRECAMBRIAN ROCKS

Crystalline rocks of Precambrian age underlie almost all of the basin area west of the Ramapo River in New Jersey, as well as most of the New York part of the basin. These rocks, for the most part, are gneisses — that is, metamorphic granitoid, or granite-like, rocks. The gneisses are part of a mountainous northeast-trending belt across northern New Jersey, known as the New Jersey Highlands. The Ramapo Mountains mark the southeast border of the Highlands. These Precambrian rocks are believed to be deeply buried beneath the Triassic rocks to the east and to underlie all other rocks in northern New Jersey, as they are the oldest rocks known to occur in the area.

### PALEOZOIC ROCKS

Limestones of early and middle Paleozoic age underlie the headwaters area of the Ramapo River in Orange County, N.Y., but they are not known to occur in the New Jersey part of the basin. These limestones are mentioned briefly, however, because of their effect on the chemical quality of the water downstream, as discussed in the section "Surface-Water Quality." (See p. 40.)

### TRIASSIC ROCKS

The Newark Group of Late Triassic age crops out across northern New Jersey in a northeast-trending belt that ranges in width from 32 miles along the Delaware River to 15 miles at the New York State line. From Pompton Lakes north to the New Jersey–New York State line, the Newark Group underlies the entire area east of the Ramapo River, to as far as the Hudson River. These rocks are truncated on the west by a major fault zone, called the Great Border fault, where the rocks of the Newark Group lie against the Precambrian crystalline rocks. The Ramapo River outlines the trend of the fault zone in New Jersey, and the Mahwah River follows the trend of the fault zone in New York.

The Newark Group is made up of both sedimentary and igneous rocks. In the western part of the outcrop area in New Jersey, the Newark Group consists of three units, from oldest to youngest, as follows (Kümmel, 1898): Stockton, Lockatong, and Brunswick Formations. However, in the northeastern part of the State, the Newark Group consists entirely of the Brunswick Formation interlayered with Watchung Basalt, except for a narrow exposure of Stockton Formation that flanks both sides of the Palisade sill (diabase) along the Hudson River.

The Brunswick Formation in the Ramapo River basin is made up largely of sandstone and conglomerate containing interbedded shale. The Brunswick beds in the southwestern part of the outcrop area in New Jersey and at the type locality are chiefly soft red shales. According to Kümmel (1899, p. 48), however, "northward the shales grade into sandstones which are frequently conglomeratic. This is notably the case in Bergen County where every exposure of any extent shows beds of sandstone and even conglomerate interlayered with the shales * * *. The increasing coarseness continues into Rockland County [N.Y.], where the great mass of the formation appears to be sandstone and conglomerate, rather than argillaceous shale."

The Triassic igneous rocks—the extrusive Watchung Basalt of the Newark Group and the intrusive diabase—are commonly called trap rock. These rocks are much harder and more resistant

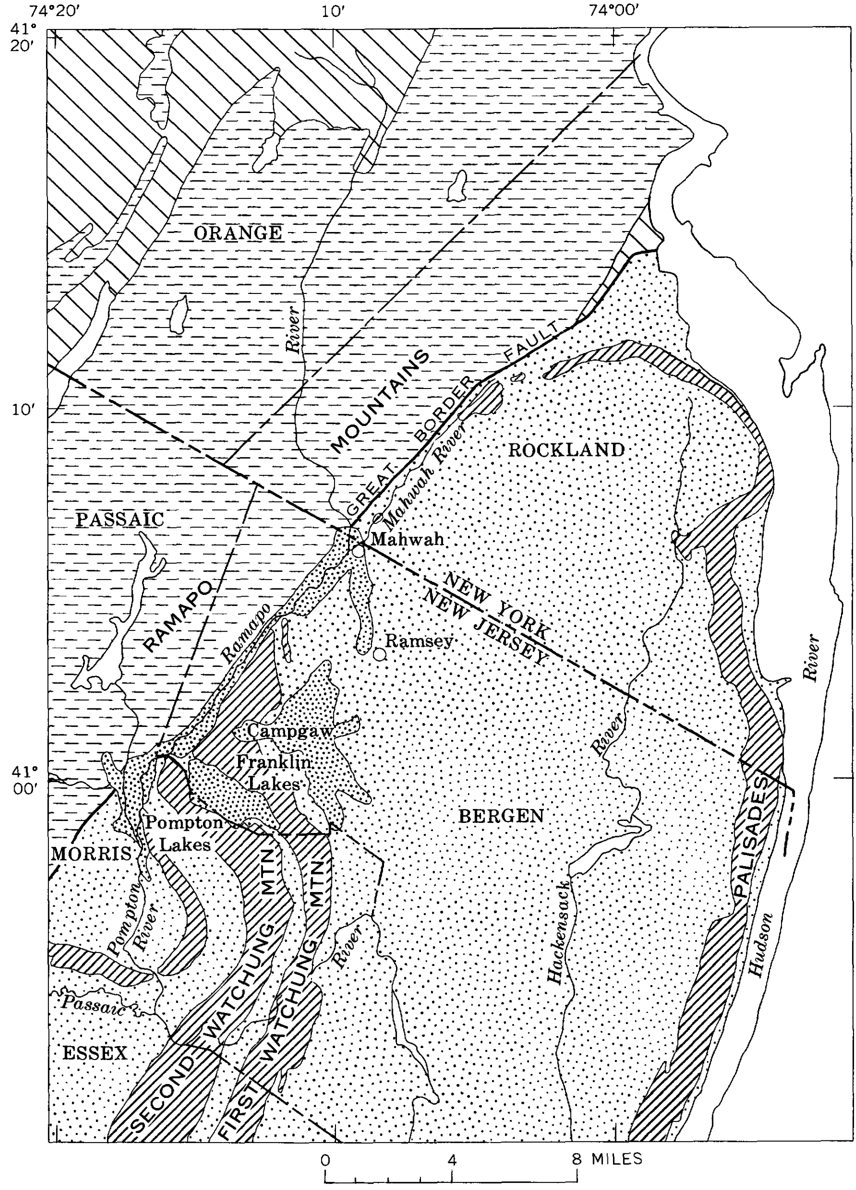


**Figure 2.** — General geology of northeastern New Jersey and the adjacent part of New York. Adapted from Johnson (1950) and New York [State publication] (1961).

EXPLANATION

|  |  |  |
|---|---|---|
| ▒ | Quaternary stratified drift<br>*(Shown only in the Ramapo River basin in New Jersey)* |  |
| ░ | Triassic sandstone, shale, and conglomerate | Newark Group |
| ▨ | Triassic diabase and basalt<br>*(trap rock)* |  |
| ▧ | Paleozoic shale, sandstone, and limestone |  |
| ▤ | Precambrian gneiss and other crystalline rocks |  |
| — | Contact |  |

to erosion than most sedimentary rocks, and they commonly form hills and ridges considerably above the general altitude of the sedimentary rocks. Examples are the Watchung Mountains, composed of basalt, and the Palisades, composed of diabase.

Regionally the dominant strike of the Newark Group is to the northeast, with the beds dipping gently to the northwest. However, locally in the basin, in Bergen and Rockland Counties, the strike differs markedly and is more nearly to the north to northwest (Kümmel, 1898, pl. III; 1899, p. 46).

### QUATERNARY ROCKS

Unconsolidated rocks of Quaternary age mantle the bedrock almost everywhere in the basin. These surficial deposits consist of unstratified and stratified drift deposited by the "Wisconsin" Glacier and its melt waters during the Pleistocene Epoch of the

Quaternary Period. To a much lesser extent, Holocene alluvial deposits, which are largely reworked Pleistocene sediments, occur along stream channels.

Unstratified drift, or till, which is commonly a mixture of particles ranging in size from clay to boulders, occurs over most of the area. The till cover on the gneiss is generally thin, a few feet to a few tens of feet thick, and bedrock exposures are numerous, particularly on steep slopes and summits. The till cover on the Triassic rocks is somewhat thicker—generally on the order of a few feet to many tens of feet thick, and, in some places, is more than 100 feet thick. The till cover on the Triassic rocks is commonly thinnest on the crests of the trap ridges and thickest on the lower lands.

In the New Jersey part of the basin, extensive deposits of stratified drift—chiefly sand and gravel—occur only over the Triassic rocks. Hydrologically, the most important deposits are the sand and gravel deposits in the Ramapo River valley. The River is bordered by terraces of stratified drift from the New York–New Jersey State line south to Pompton Lakes. The terraces range in width from less than a quarter of a mile to nearly 1 mile and average about half a mile (Salisbury, 1902, p. 575). These deposits are discussed in detail in the section "Induced River Infiltration."

Other extensive deposits of stratified drift occur in the areas of Franklin Lake (in the southern part of Franklin Lakes) and Campgaw, and in the lowland between Ramsey and Mahwah. Most of the stratified drift around Franklin Lake forms a plain between First and Second Watchung Mountains that extends from the Ramapo valley on the northwest to about 1 mile east of the lake. Kames occur near the east border of the plain and, also, north of the lake. The drift is commonly 100 feet thick in the Franklin Lake area, and drillers' records have reported it to be as much as 136 feet thick. In the Campgaw area the stratified drift occurs as kames, eskers, and irregular ice-contact deposits. There, the maximum thickness of the drift ranges from about 75 to 100 feet. The lowland from Ramsey to Mahwah is largely covered with stratified drift, some of which has formed eskers and kames. This very irregular shaped belt of stratified drift has an average width of about half a mile; however, little information is available on the thickness of these deposits. This belt connects with the belt of stratified drift along the Ramapo River near the New York–New Jersey State line.

The preceding description was abstracted from the report by Salisbury (1902), who discussed these deposits in detail.

# GEOHYDROLOGY

## HYDROLOGIC BUDGET

Virtually all water, both above and below the land surface, within the Ramapo River basin originates as precipitation on the basin. Average annual precipitation for the period 1921–50 ranged from 43 inches at Monroe, in the headwaters area, to 47 inches at Pompton Lakes, but most of the basin received an average of 44–45 inches (Parker and others, 1964, pl. 3). Practically all runoff from the basin is measured at Pompton Lakes gaging station with adjustment for diversion from Pompton Lake. The average annual discharge of the river at that gaging station for the period 1921–55 was 294 cfs (cubic feet per second). This flow is equivalent to 25 inches of runoff annually over the entire basin. The difference between the precipitation and the runoff can be attributed to losses due to evaporation and transpiration, as the net gains or losses to water stored within the system can be assumed to be negligible over a period of many years.

Hence, the hydrologic budget for the basin, in inches, can be stated as:

$$\text{Precipitation} = \text{Runoff} + \text{Evapotranspiration, or}$$

$$P_{45} = R_{25} + ET_{20}.$$

No difference exists between the long-term unit runoff in the basin above Mahwah and that for the entire basin above Pompton Lakes, as will be shown later in this report. Therefore, the slightly lower precipitation in the upper part of the basin is probably balanced by a slight reduction in the evapotranspiration losses, resulting in equal yield throughout the basin. The average annual runoff of 25 inches is equivalent to an average annual yield of 1.19 mgd (million gallons per day) per square mile. However, this average yield is not distributed uniformly with time. Typically, the runoff is many times higher in late winter and early spring than it is in late summer and early fall, even though precipitation is distributed fairly uniformly throughout the year. The difference in runoff rates is caused by evapotranspiration, which is at a minimum in the winter and a maximum in the summer. The availability and the variability of streamflow are discussed in greater detail later in this section.

## AVAILABILITY OF SURFACE WATER

### SOURCES

The sources of the surface water included in this study are indicated in plate 1, which shows streamflow in the Ramapo River basin as far downstream as Pompton Lakes, N.J., at a time of median streamflow at the gaging station at Ramapo River near

Mahwah, N.J. For the period 1931–60 the median streamflow (discharge) at this station was 134 cfs. The corresponding discharge at other points in the basin was determined by use of correlation curves based on streamflow measurements at various times.

The magnitude of the streamflow is represented by the width of the band (pl. 1), except for those tributaries in which discharge was too small (<2 cfs) to be distinguishable at the given scale. The seasonal variation in streamflow at the six stations along the main stem is indicated by the bar graphs shown on plate 1, which indicate the magnitude of discharge recorded on 5 selected days from September 1963 to September 1964. These particular days were selected because the streamflow, recorded on those dates, was measured at numerous locations along the main stem and its tributaries.

The discharge measurements illustrated by the bar graphs (pl. 1) were made during base-flow conditions (periods of no storm runoff) and, consequently, reflect the dry-weather flow at various dates during an abnormally dry year. Plate 1 thus serves as a convenient reference for the study of surface-water supply in the basin.

## PRINCIPAL STREAM

### THE RAMAPO RIVER

The Ramapo River rises near Monroe in Orange County, N.Y., at an altitude of 690 feet, and headwaters of some of the minor tributaries rise at altitudes of as much as 830 feet. The river flows through Monroe, Harriman, Arden, and Sloatsburg before it crosses the State line into New Jersey near Mahwah. One-half mile downstream from the State line, the Ramapo River is joined by the Mahwah River from the east. The Ramapo then flows in a generally southwesterly direction for about 12 miles to Pompton Lake, at the communities of Oakland and Pompton Lakes, the downstream boundary of the study. The drainage area increases from 60.9 square miles at Sloatsburg, N.Y., to 118 square miles near Mahwah, N.J., and to 160 square miles at Pompton Lakes, N.J.

After emerging from Pompton Lake, the Ramapo River flows south for about 1 mile and then joins the Pequannock River to form the Pompton River. The Pompton River flows into the Passaic River at Two Bridges (fig. 1).

## MAJOR TRIBUTARIES

In addition to the Mahwah River, principal streams joining the Ramapo River from the east in the study area are Darlington, Pond, and Haycock Brooks. Bear Swamp Brook is the principal stream from the west. The drainage area of each of these streams is less than 8 square miles, except that of the Mahwah River, which is about 26 square miles.

### STREAMFLOW CHARACTERISTICS

Discharge measurements, shown by number and given in the table on plate 1, were used to study the amount and variability of streamflow throughout the basin. The "stations" listed are of three types:

1. Continuous-record gaging stations, which provide a continuous record of river stage and discharge. These stations are suitable for all types of hydrologic studies.
2. Low-flow partial-record stations, at which discharge measurements are made on a systematic basis during periods of base flow to establish relations between discharge at these locations and some nearby continuous-record gaging stations (Buchanan and others, 1965). These stations are extremely useful in studying the low-flow hydrology of a region.
3. Miscellaneous sites, at which discharge measurements are made only for specific purposes. In this study, the miscellaneous measurements made to define streamflow throughout the basin on 5 selected days proved to be invaluable.

Flow of the Ramapo River at the north end of the reach used in this study has been measured at a gaging station near Mahwah, N.J., for a total of 48 years. From 1902 to 1906 there were once-daily readings of a chain gage, and from 1922 to 1966 there was a water-stage recorder. The average annual discharge during these 48 years of record was 221 cfs; the maximum yearly mean discharge, 461 cfs, occurred in 1903, and the minimum yearly mean discharge, 107 cfs, occurred in 1965. The daily streamflow ranged from a maximum discharge of about 12,400 cfs, on October 9, 1903, to a minimum of 7 cfs, on December 16, 1930, and again on September 12, 1932. Between these two extremes, there were many lesser floods, some periods of drought, and many periods in which discharge was very close to the seasonal normal.

Daily streamflow records are basic data for hydrologic studies, and one form of processed daily streamflow records—flow duration—is used in this report to present a record of past streamflow and, also, to provide estimates of anticipated future streamflow. (See fig. 3.)

If the streamflow for a period of record is representative of the long-term streamflow, the duration curve can be used to estimate the percentage of time that a given discharge will be equalled or exceeded in the future. This assumption is valid so long as there is no significant change in climate, in regulation or diversion of

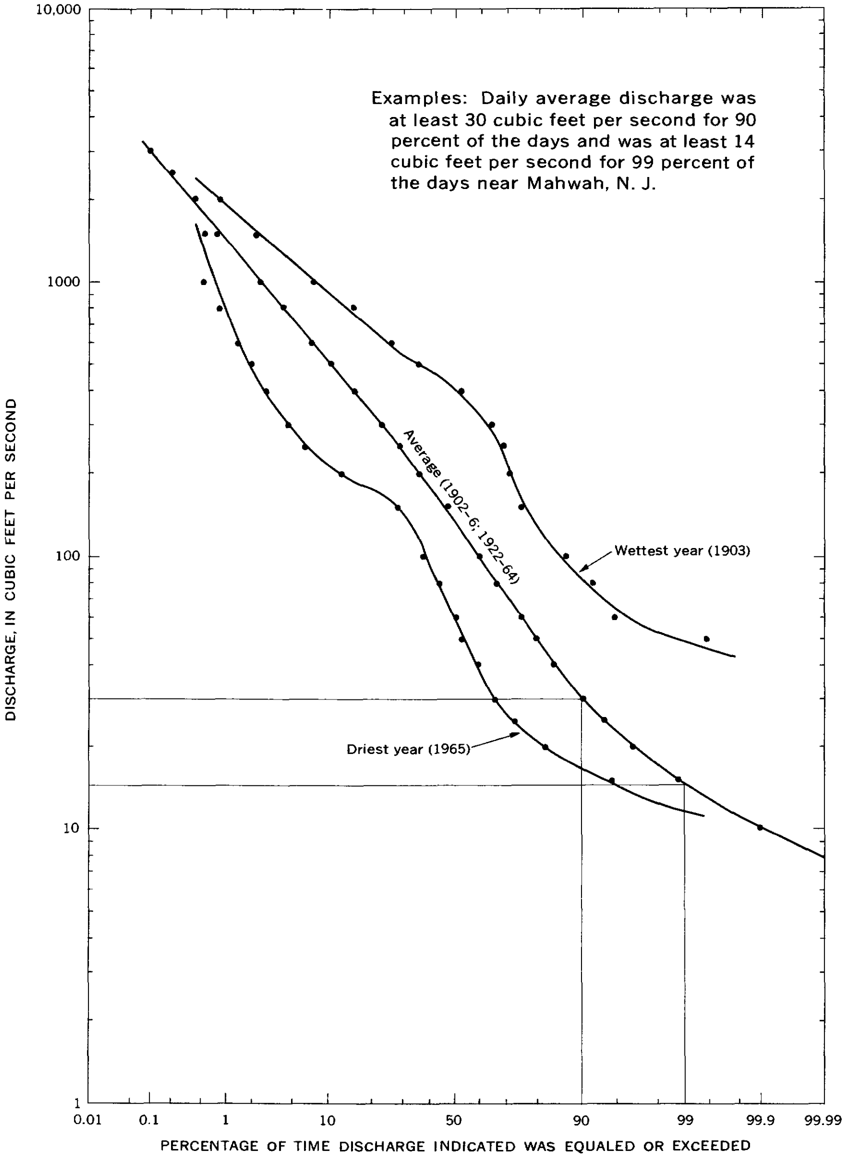
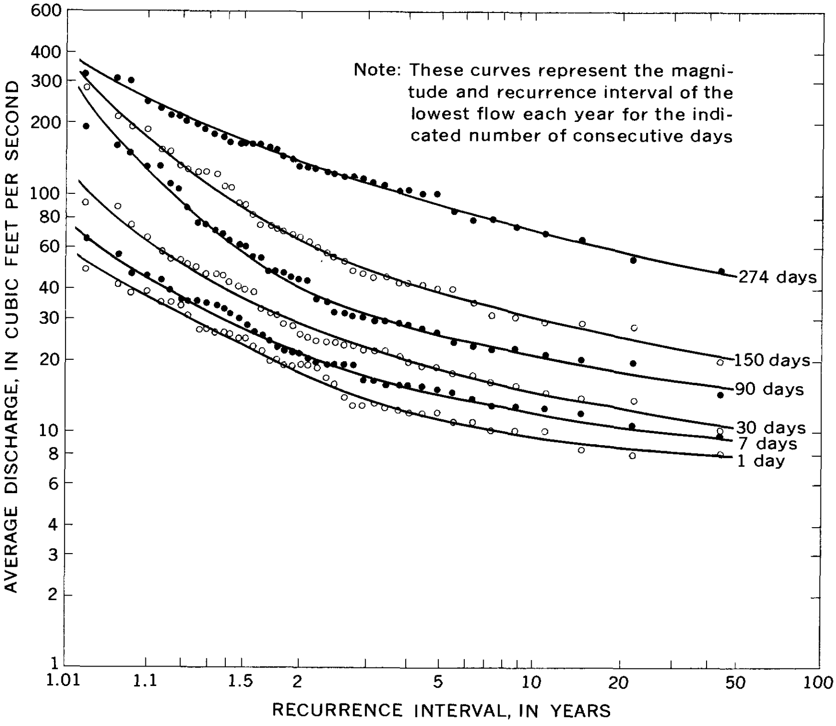


FIGURE 3. — Average duration curve of the daily flow at Ramapo River near Mahwah, N.J., for the years 1902-6 and 1922-64, and flow-duration curves for the wettest and driest years of record.

streamflow, or in land use, and the period of record includes a large number of whole years. Note, however, that the average flow-duration curve may not be applicable to any specific short period. The possible deviation of a curve for 1 year from the average flow-duration curve is demonstrated, in figure 3, by the curves for the wettest and driest individual years of record. The curves for all the other individual years of the record fall between the two extreme curves, and most of them actually fall much closer to the mean curve.

Low-flow characteristics recorded at Ramapo River near Mahwah, N.J., were analyzed by using the low-flow–frequency curves shown in figure 4. These curves represent the magnitude and frequency of the lowest flow each year for the indicated number of consecutive days. In addition to the curves in figure 4, information is available for the computation of curves showing the minimum mean discharge for durations of 3, 14, 60, 120, and 183 consecutive days (curves for these latter periods are not shown, as they would tend to clutter the illustration). Thus, for a particular water-supply problem, it may be desirable to draw more curves in one part of the family of curves and fewer in another. For example, the person requiring water at all times without the



Note: These curves represent the magnitude and recurrence interval of the lowest flow each year for the indicated number of consecutive days

FIGURE 4. — Low-flow–frequency curves for Ramapo River near Mahwah, N.J., 1923–66.

benefit of storage would be particularly interested in the minimum mean discharges for periods of 1, 3, and 7 consecutive days, but would have little interest in the minimum mean discharges for durations of 150, 183, and 274 consecutive days.

The estimated magnitude and frequency of future floods must be known for the proper design of any structures along a river. By use of flood-frequency information, the costs of alternate designs can be weighed against the estimated costs of occasional flood damage. Previous floods at Ramapo River near Mahwah, N.J., have been well documented by the discharge records at that gaging station, and figure 5 shows the flood-frequency curve for the period of record.

Flood-peak discharges for other locations in the New Jersey part of the basin can be estimated by using the method described by Thomas (1964). According to his analysis, the entire New Jersey part of the basin is hydrologically similar to the area above Mahwah and has the same flood characteristics. Therefore, the only significant variables to be considered in determining flood

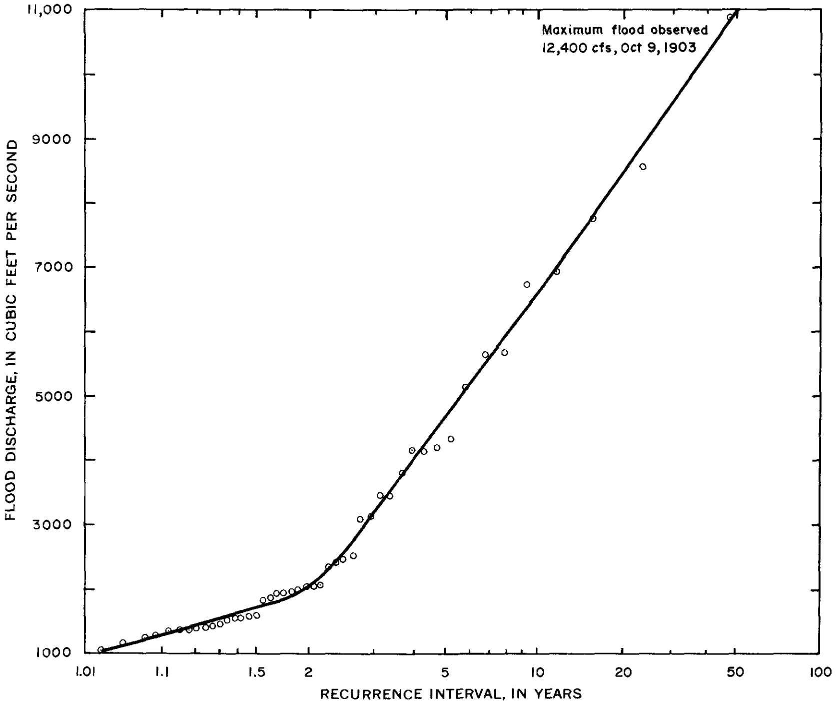


FIGURE 5. — Flood-frequency curve for Ramapo River near Mahwah, N.J., 1922–67.

magnitudes at other localities in the New Jersey part of the basin by the Thomas method are the size of drainage area and the percentage of that drainage area occupied by lakes and swamps.

Streamflow of the Ramapo River at the south end of the reach involved in this study has been measured at a continuous-record gaging station at Pompton Lakes, N.J., for a total of 45 years from 1921 to 1966. Because water has been diverted from the Ramapo River at Pompton Lakes to Wanaque Reservoir periodically since December 1953, it is not possible to compute meaningful flow-duration or low-flow frequency curves from processed daily streamflow records for the entire period. The published daily streamflow data during times of diversion reflect only the discharge remaining in the river after the diverted water has been pumped out. Consequently, these published discharge figures do not portray natural-runoff conditions and cannot be used in any arrays representing natural streamflow.

Reported monthly discharges since December 1953 have been adjusted for the amount of water diverted from the river, and those adjusted figures are comparable to the discharge figures prior to December 1953. Figure 6 shows a double-mass curve comparing the discharge of the Ramapo River near Mahwah, N.J., with that at Pompton Lakes, N.J., from October 1922 to September 1966. The solid line in figure 6 represents the observed streamflow (water actually flowing in the stream). The relationship from 1922 to 1953 is almost a straight line, indicating a constant ratio for the discharge at one location to the other. The line for this period also approximates an equal-yield (per square mile) relationship at the two locations. After 1953, however, the solid line bends away from the Pompton Lakes axis, reflecting the diversion from the river at that location. The dashed line from 1953 to 1966 is based on the streamflow at Pompton Lakes, adjusted for the water diverted from the river, compared with the concurrent natural discharge at the gaging station near Mahwah. The dashed lined extension of the almost straight line representing the 1922 to 1953 relationship indicates that the relationship between the natural runoff at the two locations remained constant for the entire period. Furthermore, the dashed line continues the approximate equal-yield relationship at the two locations, which means that, during the period 1922–53, the intervening drainage area of 42 square miles between Mahwah and Pompton Lakes yielded as much per square mile as did the 118-square-mile area upstream from Mahwah. This is also true for the period 1953–66, even though the published daily stream discharge records for the Pompton Lakes station were affected by the amount of flow diverted from the river.

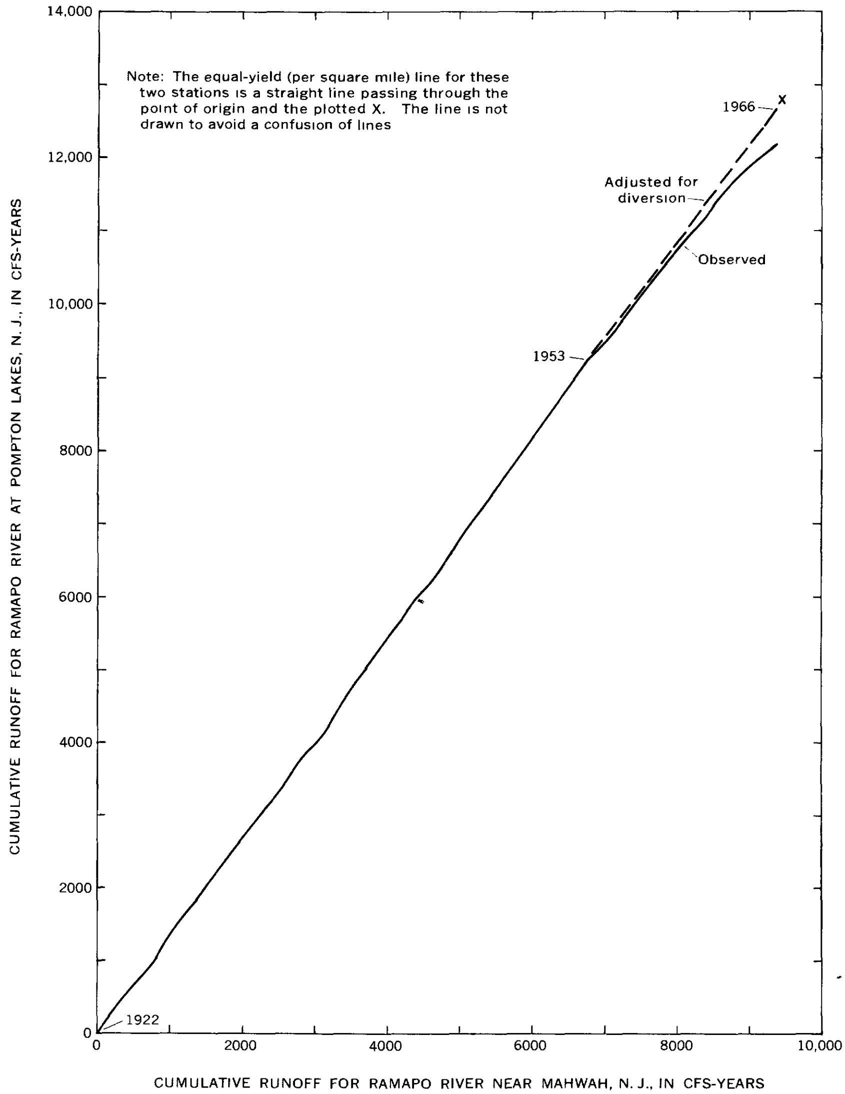


FIGURE 6. — Double-mass curve of runoff at Ramapo River near Mahwah and Ramapo River at Pompton Lakes, N.J., 1922–66.

Systematic measurements at partial-record stations during periods of base flow permit a study of the relationships between streamflow at the low-flow partial-record stations and that at nearby continuous-record gaging stations. Curves of relation are drawn where indicated by the measurements.

Figure 7 shows two such curves, one for Darlington Brook at

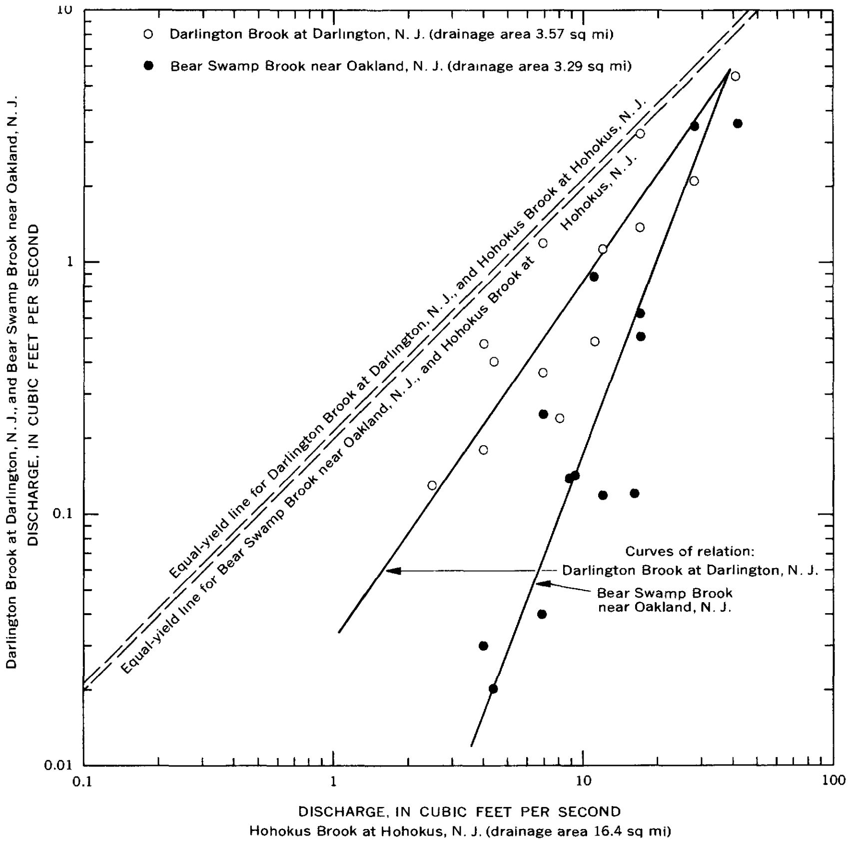


FIGURE 7. — Base-flow relations for Darlington Brook at Darlington, N.J., and Bear Swamp Brook near Oakland, N.J., compared with those for Hohokus Brook at Hohokus, N.J., 1963–67.

Darlington, N.J.—typical of the streams within New Jersey joining the Ramapo River from the east and draining the drift-covered Triassic rocks—and the other for Bear Swamp Brook near Oakland, N.J.—typical of streams joining the Ramapo River from the west and draining the Precambrian rocks. Discharge at both stations is compared with that at Hohokus Brook at Hohokus, N.J., a continuous-record gaging station in the Passaic River basin, about 7 miles to the southeast. This station was selected for the comparisons because it has a small drainage area, it is nearby, and its data gave the best correlation of those attempted. The equal-yield lines indicate where the curves of relation would be positioned if the two smaller streams yielded the same amount per square mile as Hohokus Brook at Hohokus, N.J. Note that the streamflow during dry periods is not nearly so well sustained in

Bear Swamp Brook as it is in Darlington Brook and in Hohokus Brook. In fact, many of the small tributary streams from the west go dry as early as June in a dry year. However, this low "dry-weather" discharge is commonly offset by a high rate of runoff during storms.

As indicated earlier and shown on plate 1, stream discharge was measured at many locations along the main stem and on the major tributaries on 5 selected days during the present study. The days on which measurements were made were all during periods of base flow, when the magnitude of the streamflow at Ramapo River near Mahwah, N.J., ranged from the 99.8 to the 23 percent points on the flow-duration curve (fig. 3). These measurements gave insight to the source of the water in all parts of the basin and showed the areas of water diminution or unusual accretion.

## AVAILABILITY OF GROUND WATER

Some ground water can be obtained nearly everywhere in the basin. However, both the occurrence and the availability of ground water vary considerably according to the geologic materials underlying the different parts of the study area. In the consolidated rocks, fractures and solution cavities (secondary porosity) provide the principal means of storing and transmitting water, but, because these openings constitute only a very small part of the total volume of the rocks, the capacity of these rocks to store and transmit water is low. In the areas of unconsolidated rocks—principally in the Ramapo River valley, where sand and gravel occur—ground water occurs in interstitial openings (primary porosity) between the individual grains of these unconsolidated sediments. These openings constitute a relatively high percentage of the total volume of the sediments, and this, together with the high permeability of the sand and gravel, makes their capacity to store and transmit water much greater than that of the consolidated rocks. Although the clay and silt also have high porosity, they generally have very low permeability; hence, despite their great capacity to store water, their ability to transmit water is generally very low.

Ground water generally occurs under water-table (unconfined) conditions throughout the basin. Although partial confinement results from discontinuities in permeability, and artesian conditions may prevail locally, no regional artesian aquifers are known to occur anywhere in the basin. Virtually all the ground water in the basin originates within the basin as local precipitation. After moving through the aquifers, the ground water eventually discharges into the tributary streams or directly into the Ramapo River, or it is intercepted by wells.

Construction features and yield characteristics of the wells selected for this study are given in table 1, and their locations are shown in figure 8.

## WATER-BEARING PROPERTIES OF THE ROCKS

### GNEISS

Unweathered gneiss has a low primary porosity and, therefore, is relatively impermeable. Fracturing and weathering, however, develop secondary porosity and permeability. Thus, nearly all the ground water in the gneiss is in the weathered zone near the land surface. Fault fractures and joints in the weathered zone have been enlarged by frost action, by plant roots, and by the dissolving action of circulating ground water. The water-bearing fractures decrease in size and number with depth, and it is generally not economically worthwhile to drill wells any more than 200–300 feet deep.

Within the Ramapo River basin the depth to which water-bearing fractures occur in the gneiss may be even shallower. The gneiss constitutes the rugged topography of Ramapo Mountains, which indicates that the rock is resistant to erosion and is not easily weathered. In addition, because of the geologically recent glaciation, most of the severely weathered gneiss has been scoured away, and all that remains is fresh or only slightly weathered rock. Hence, in most of this area perhaps only the upper 200 feet is water bearing.

The yield of a well that taps the gneiss depends largely on the size and number of fractures penetrated by the well, a factor which varies considerably from place to place. The area underlain by gneiss is very sparsely settled, and little information is available on well yields. However, the data available indicate that at least a few gallons per minute are obtainable, even near the crest of the mountain. Large yields are not to be expected from the gneiss. When locating wells in the gneiss, the chances of drilling a well having a satisfactory yield would be greatest in the valleys or draws, as the valleys commonly are formed along fault zones or where the rock is more extensively jointed.

For maximum well yields, wells tapping the gneiss should be thoroughly developed by such techniques as surging and (or) wire brushing to remove drill cuttings that may have sealed off the water-bearing fractures during the drilling. Use of a chemical aid, such as sodium hexametaphosphate, may also expedite the development process. The yield of a poor well is more apt to be improved from development of the well than from deepening the well much beyond 200 feet because of the diminution in size and number of water-bearing fractures with depth.

TABLE 1. — *Construction features and*

[Well locations shown in figure 8. Symbols: sd, stratified drift; b, Brunswick Formation; bs, per minute per

| Well No. | Owner | Driller | Date drilled | Altitude above mean sea level (ft) | Total depth drilled below land surface (ft) | Depth to bedrock below land surface (ft) | Diameter of well (in.) | Depth to which well is cased (ft) |
|---|---|---|---|---|---|---|---|---|
| **Borough of Franklin Lakes** | | | | | | | | |
| 1 | Hackensack Water Co. | Artesian Well & Equipment Co., Inc. | 1957 | 360 | 56 | | 22 | 40 |
| 2 | do | do | 1957 | 360 | 92 | 92 | 8 | 30 |
| 3 | do | do | 1966 | | 330 | 55 | 8 | 112 |
| **Township of Mahwah** | | | | | | | | |
| 1 | Mahwah Water Dept. | | | 555 | 300 | 24 | 10 | |
| 2 | do | | | 555 | 303 | 28 | 8 | |
| 3 | do | | | 555 | 306 | 30 | 8 | |
| 4 | do | | | 555 | 82 | 28 | 10 | |
| 5 | do | | | 555 | 222 | 26 | 10 | |
| 6 | do | | | 555 | 300 | 33 | 10 | |
| 7 | do | | | 555 | 390 | 21 | 10 | |
| 8 | do | | | 550 | 655 | 42 | 10 | |
| 9 | do | | | 550 | 36 | 30 | 8 | |
| 10 | do | | | 550 | 300 | 31 | 10 | |
| 11 | do | | | 545 | 297 | 35 | 8 | |
| 12 | do | | | 545 | 227 | 27 | 8 | |
| 13 | do | | | 545 | 300 | 37 | 8 | |
| 14 | do | | | 545 | 288 | 30 | 8 | |
| 15 | do | | | 545 | 383 | 33 | 10 | |
| 16 | do | Rinbrand Well Drilling Co., Inc. | 1961 | 415 | 320 | 12 | 10 | 33 |
| 17 | do | do | 1953 | 256 | 95 | | 18 | 65 |
| 18 | do | do | 1953 | 254 | 95 | | 18 | 70 |
| 19 | do | do | 1953 | 254 | 103 | | 18 | 83 |
| 20 | do | do | 1953 | 270 | 140 | | 12 | 110 |
| 21 | do | do | 1959 | 260 | 116 | 115 | 8 | |
| 22 | do | do | 1960 | 260 | 123 | 120 | 8 | 110 |
| 23 | do | do | 1965 | 450 | 320 | 75 | 8 | 85 |
| 24 | Immaculate Conception Seminary | do | 1949 | 340 | 415 | | 8 | 38 |
| 25 | do | do | 1948 | 360 | 435 | | 8 | 61 |
| 26 | Ramsey Water Dept. | | 1935 | 300 | 450 | | | |
| 27 | do | | 1935 | 300 | 310 | | | |
| 28 | American Brake Shoe Co. | Wm. Stothoff Co., Inc. | 1953 | 290 | 203 | 83 | 10 | 91 |
| 29 | do | do | 1953 | 290 | 301 | 71 | 10 | 84 |
| 30 | do | do | 1953 | 290 | 42 | 39 | 10 | 29 |
| 31 | Camp Yaw Paw, Boy Scouts of America. | Rinbrand Well Drilling Co., Inc. | 1936 | 800 | 152 | <5 | 4/6 | 60 |
| 32 | do | Burrows Well Drilling Co., Inc. | 1960 | 850 | 120 | <5 | 6 | 20 |
| 33 | do | do | 1962 | 800 | 86 | <5 | 6 | 20 |
| 34 | Camp Glen Gray, Boy Scouts of America. | Henry A. Kieffer | 1953 | 600 | 100 | 0 | 6 | 21 |
| 35 | do | do | 1959 | 640 | 125 | 3 | 6 | 21 |

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See footnotes at end of table.

*yield characteristics of selected wells*

Watchung Basalt; gn, gneiss. Abbreviations: gpm, gallons per minute; gpm per foot, gallons foot of drawdown]

| Screen setting below land surface (ft) | Type of aquifer | Static water level below land surface at time of drilling (ft) | Yield (gpm) | Drawdown (ft) | Specific capacity (gpm per ft) | Length of test (hr) | Remarks |
|---|---|---|---|---|---|---|---|
| | | | **Borough of Franklin Lakes** | | | | |
| 40– 56 | sd | 7 | 200 | 24 | 8.3 | 24 | Shadow Lake production well. |
| 30– 40 | sd | 4 | 188 | 17 | 11 | | Shadow Lake test well. |
| None | b & bs | 48 | 222 | 27 | 8.3 | 11 | Hilltop terrace well. |
| | | | **Township of Mahwah** | | | | |
| None | b | | 240 | <25 | | | Owner's well 14.[1] |
| do | b | | 225 | <80 | | | Owner's well 5.[1] |
| do | b | | 150 | <80 | | | Owner's well 6.[1] |
| do | b | | 200 | | | | Owner's well 12.[1] |
| do | b | | 125 | <80 | | | Owner's well 13.[1] |
| do | b | | 125 | <114 | | | Owner's well 11.[1] |
| do | b | | 60 | <80 | | | Owner's well 10.[1] |
| do | b | | 100 | <114 | | | Owner's well 7.[1] |
| do | b | | Flow 15 | | | | Owner's well 7½.[1] |
| do | b | | 165 | <80 | | | Owner's well 9.[1] |
| do | b | | 105 | <80 | | | Owner's well 4.[1] |
| do | b | | 125 | <80 | | | Owner's well 2.[1] |
| do | b | | 48 | <80 | | | Owner's well 1.[1] |
| do | b | | 100 | <80 | | | Owner's well 3.[1] |
| do | b | | 60 | <80 | | | Owner's well 8.[1] |
| do | b | 30 | 175 | 160 | 1.1 | 8 | Fardale No. 1. |
| 65– 95 | sd | 8 | 420 | 50 | 8.4 | 72 | Ford No. 3. Data at time well drilled. Some details have changed. |
| 70– 95 | sd | 5 | 1,230 | 9 | 137 | 72 | Ford No. 4. Data at time well drilled. Some details have changed. Chemical analysis available. |
| 83–103 | sd | 10 | 700 | 60 | 11.7 | 72 | Ford No. 1. Data at time well drilled. Some details have changed. Chemical analysis available. After redevelopment well produced 800 gpm with 16 ft of drawdown. |
| 110–140 | sd | 16 | 688 | 80 | 8.6 | 72 | Ford No. 2. Data at time well drilled. Some details have changed. |
| | sd | 16 | 310 | 56 | 5.5 | 8 | Test well 1. Screen removed; nearest river. |
| 110–120 | sd | 18 | 516 | 36 | 14.3 | 2 | Test well 2. Observation well; farthest from river. |
| None | b | 50 | 155 | 64 | 2.4 | 24 | Campgaw well. |
| do | b | 21 | 150 | 129 | 1.2 | 8 | Owner's well 1. Combined pumpage averaged 40,000 gpd from wells 1 and 2. Chemical analysis available. |
| None | b | 30 | 110 | 120 | .9 | 8 | Owner's well 2. Average pumpage of 40,000 gpd from wells 1 and 2. |
| do | b | | | | | | North Central Ave. well 1. Chemical analysis available. |
| do | b | | | | | | North Central Ave. well 2. |
| do | b | | 18 | | | | Owner's well 1. Not used. |
| do | b | 11 | 5 | | | | Owner's well 2.[2] |
| 29– 39 | sd | 11 | 170 | 19 | 9 | 8 | Owner's well 3.[2] |
| None | gn | 4 | 8 | 116 | .07 | | Owner's well 1. Main supply well. Chemical analysis available. |
| do | gn | 20 | 3 | | | | Owner's well 2. |
| do | gn | 9 | 11 | | | | Owner's well 3. |
| do | gn | 6 | 12 | 19 | .63 | 11 | Owner's well 2. East end of Lake Vreeland. |
| do | gn | Flowing | 14 | 50+ | <.28 | 5 | Owner's well 3. West end of Lake Vreeland. Chemical analysis available. |

TABLE 1. — *Construction features and yield*

| Well No. | Owner | Driller | Date drilled | Altitude above mean sea level (ft) | Total depth drilled below land surface (ft) | Depth to bedrock below land surface (ft) | Diameter of well (in.) | Depth to which well is cased (ft) |
|---|---|---|---|---|---|---|---|---|
| **Borough of Oakland** | | | | | | | | |
| 1 | Oakland Water Dept. | Rinbrand Well Drilling Co., Inc. | 1931 | 420 | 98 | 98 | 8 | 75 |
| 2 | do | do | 1931 | 265 | 190 | | 8 | 175 |
| 3 | do | Artesian Well & Equipment Co., Inc. | 1940 | 265 | 98 | | 8 | 82 |
| 4 | do | Rinbrand Well Drilling Co., Inc. | 1946 | 265 | 107 | | 10 | 71 |
| 5 | do | do | 1950 | 220 | 126 | | 6 | 112 |
| 6 | do | do | 1954 | 220 | 130 | 128 | 12 | 108 |
| 7 | do | do | 1956 | 240 | 96 | 93 | 12 | 85 |
| 8 | do | do | 1957 | 240 | 100 | 76 | 12 | 56 |
| 9 | do | do | 1959 | 240 | 112 | 110(?) | 12 | 85 |
| 10 | do | do | 1958 | 240 | 88 | 84 | 12 | 72 |
| 11 | do | do | 1967 | 300 | 150 | 91 | 12 | 90 |
| 12 | do | do | 1967 | 205 | | | 12 | 65 |
| 13 | Raritan Plastics, Inc. | do | 1962 | 290 | 333 | <31 | 8 | 31 |
| 14 | Camp Tamarack, Boy Scouts of America. | Parkhurst Well Drilling Co. | About 1940 | 680 | 190 | | 6 | |
| 15 | Charles J. Klein | Frank K. Jennings | | 220 | 62 | | 6 | |
| 16 | The Hansen House | Burrows Well Drilling Co., Inc. | 1955 | 230 | 115 | 51 | 6 | 51 |
| **Borough of Pompton Lakes** | | | | | | | | |
| 1 | Borough of Pompton Lakes. | Artesian Well & Equipment Co., Inc. | 1964 | 200 | 250 | 31 | 8 | 31 |
| **Borough of Ramsey** | | | | | | | | |
| 1 | Ramsey Water Dept. | Artesian Well & Equipment Co., Inc. | 1945 | 335 | 316 | 20 | 12 | 44 |
| 2 | do | do | 1945 | 335 | 303 | 20 | 12 | 49 |
| 3 | do | do | 1946 | 330 | 303 | | | |
| 4 | do | Rinbrand Well Drilling Co., Inc. | 1953 | 350 | 300 | <47 | 10 | 47 |
| 5 | do | do | 1953 | 350 | 501 | | 8 | 124 |
| 6 | do | M. W. Ives & Sons | 1956 | 350 | 400 | 52 | 10 | 77 |
| 7 | do | do | 1956 | 465 | 400 | 20 | 10 | 37 |
| 8 | do | do | 1956 | 355 | 400 | 21 | 10 | 61 |
| 9 | do | Rinbrand Well Drilling Co., Inc. | 1963 | 450 | 500 | 100 | 10 | 120 |
| 10 | do | do | 1964 | 480 | 440 | 14 | 10 | 37 |
| 11 | do | Burrows Well Drilling Co., Inc. | 1965 | 380 | 400 | 105 | 12/10 | 111 |
| 12 | do | do | 1965 | 350 | 400 | 82 | 10 | 104 |
| **Township of Wayne** | | | | | | | | |
| 1 | Wayne Township Water Dept. | Rinbrand Well Drilling Co., Inc. | 1940 | 400 | 252 | 40 | 8 | 40 |
| 2 | do | do | 1940 | 410 | 272 | 60 | 6 | 68 |
| 3 | do | do | 1954 | 340 | 200 | 25 | 8 | 25 |
| 4 | do | | 1942 | 280 | 160 | | 8 | |
| 5 | do | | 1949 | 260 | 203 | | 12 | |
| 6 | do | | Before 1940. | 260 | 206 | | 8 | |

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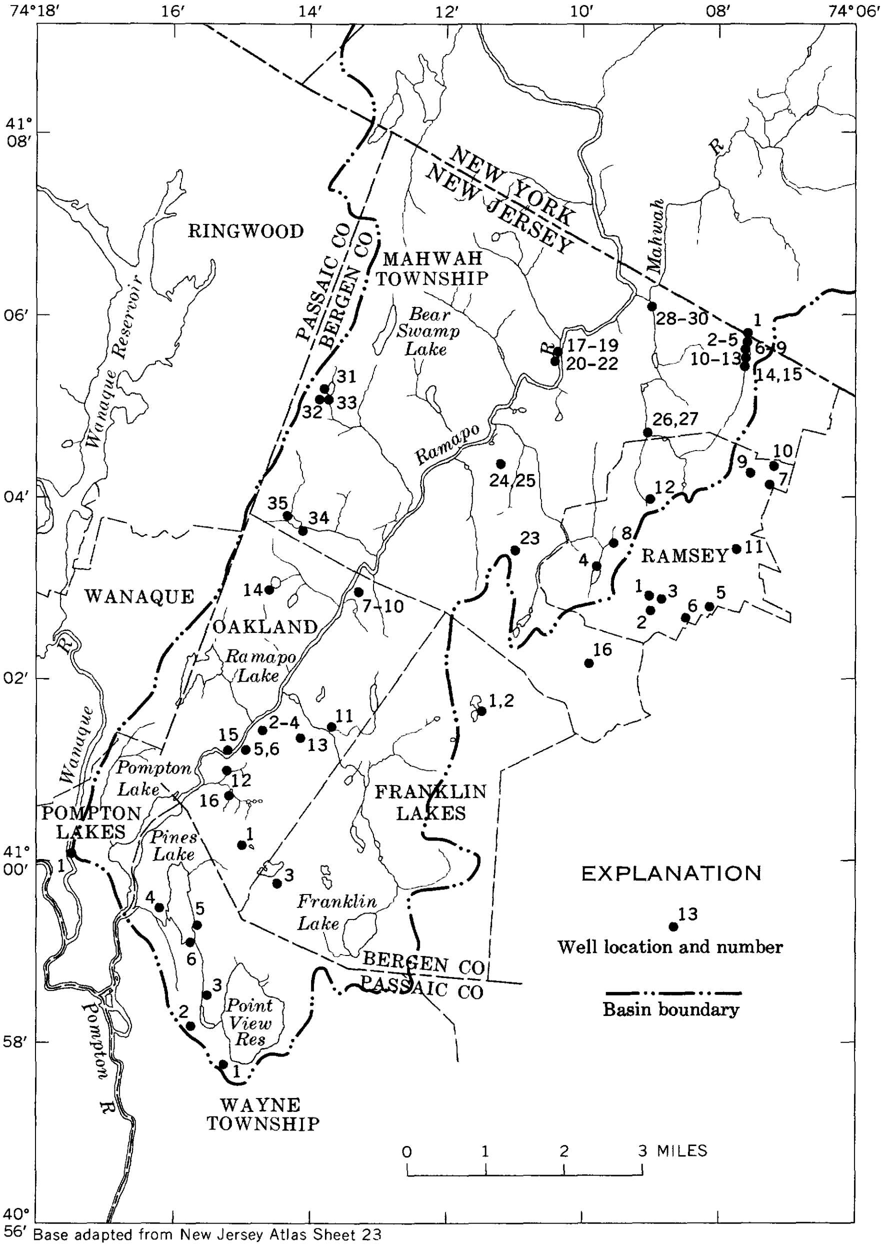
[1] Composite chemical analysis available from this field.
[2] Uses 50,000 gpd from wells 2 and 3.
[3] Static water level above land surface.

Although the storage capacity of the gneiss is very low, moderate and even high well yields can be obtained under very favorable recharge conditions as indicated by well 1 in Pompton Lakes (table 1). This well, located in the valley of the Wanaque River, just beyond the Ramapo River basin limits, is reported to yield *characteristics of selected wells*—Continued

| Screen setting below land surface (ft) | Type of aquifer | Static water level below land surface at time of drilling (ft) | Yield (gpm) | Drawdown (ft) | Specific capacity (gpm per ft) | Length of test (hr) | Remarks |
|---|---|---|---|---|---|---|---|
| **Borough of Oakland** | | | | | | | |
| 75– 98 | sd | 45 | 75 | 15 | 5.0 | 24 | Lake Avenue well. Abandoned in 1936. |
| 175–190 | sd | 60 | 125 | 70 | 1.8 | 24 | Valley View No. 1. Not used. |
| 82– 98 | sd | | 100 | | | | Valley View No. 2. Not used; observation well. |
| 71– 91 | sd | 57 | 168 | 18 | 9.3 | 24 | Valley View No. 3. Not used. |
| 112–126 | sd | 5 | 200 | 45 | 4.4 | 16 | Bush No. 4 |
| 108–128 | sd | 17 | 1,160 | 58 | 20 | 50 | Bush No. 5. Chemical analysis available. |
| 85– 93 | sd | 14 | 308 | 64 | 4.8 | | "Soons" No. 6. |
| 56– 76 | sd | 10 | 419 | 49 | 8.6 | 12 | "Soons" No. 7. Chemical analysis available. |
| 85–110 | sd | 7 | 970 | 7 | 139 | 16 | "Soons" No. 8. Chemical analysis available. |
| 72– 84 | sd | 14 | 171 | 46 | 3.7 | 14 | "Soons" No. 9. Not used; observation well. |
| 80– 90 | sd & b | [3]>25 | 582 | >150 | <3.9 | 72 | Route 208 well. |
| 65– 91 | sd | 6 | 1,016 | 12 | 85 | 72 | Spruce Street well. |
| None | bs | 8 | 42 | 182 | .23 | 8 | Uses maximum of 30,000 gpd. |
| do | gn | | | | | | Yield poor. Chemical analysis available. |
| | sd | | | | | | Abandoned. |
| None | b | 27 | 60 | 35 | 1.7 | 3 | Used for air conditioning. |
| **Borough of Pompton Lakes** | | | | | | | |
| None | gn | 6 | 140 | 25 | 5.6 | 4 | |
| **Borough of Ramsey** | | | | | | | |
| do | b | 1.5 | 100 | 188 | .53 | 12 | East Oak Street Well 1. Abandoned. |
| do | b | 1 | 134 | 189 | .71 | 12 | East Oak Street well 2. |
| do | b | Flowing | 174 | >105 | <1.6 | 24 | East Oak Street well 3. |
| do | b | 2 | 200 | 155 | 1.5 | 24 | Woodland Avenue well. Chemical analysis available. |
| do | b | 11 | 57 | 179 | .32 | 8 | No. 6 test well. |
| do | b | 16 | 200 | 174 | 1.2 | 24 | Martis Avenue well. |
| do | b | 54 | 126 | 126 | 1.7 | 36 | East Crescent Avenue well 1. |
| do | b | 1.5 | 220 | 168 | 1.3 | 34 | Darlington Avenue well. Chemical analysis available. |
| do | b | 50 | 105 | 195 | .54 | 72 | Airmont Avenue well. |
| do | b | 37 | 110 | 213 | .52 | 72 | East Crescent Avenue well 2. |
| do | b | 3 | 151 | 86 | 1.7 | 3½ | Dixon Street well. |
| do | b | 2 | 151 | 269 | .56 | 72 | Elbert Street well. |
| **Township of Wayne** | | | | | | | |
| do | bs & b | 15 | 50 | 50 | 1.0 | 8 | Point View well. |
| do | b | 65 | 50 | 15 | 3.3 | 12 | Lionhead Lake well 1. |
| do | b | 10 | 115 | 140 | .82 | 24 | Lionhead Lake well 2. Chemical analysis available. |
| do | b | | 75 | | | | Pines Lake well. |
| do | b | | 160 | | | | Pines Lake well 2. Chemical analysis available. |
| do | b | | 100 | | | | Pines Lake well 3. |

140 gpm with only 25 feet of drawdown. The gneiss there is overlain by 31 feet of sand and gravel and is in hydraulic continuity with the river. The high yield of this well is a result of induced recharge from the river through the sand and gravel. A similar instance of recharge in the Ramapo River basin was reported by Perlmutter (1959, p. 14) for a well in Hillburn, N.Y.



Base adapted from New Jersey Atlas Sheet 23

FIGURE 8. — Locations of wells selected for study in the New Jersey part of the Ramapo River basin. Note that separate sets of consecutive well numbers are used in each borough or township. Wells are described in table 1.

### BRUNSWICK FORMATION

Virtually all ground water in the Brunswick Formation, especially in the shale beds, occurs in interconnecting fractures that have resulted mainly from jointing. There is some additional void space in the sandstone and conglomerate beds where cementing material is lacking—either because it was never deposited or because it has been dissolved and removed by circulating ground water. Perlmutter (1959, p. 19) presented data which substantiates the conclusion that practically all the movement of ground water through these rocks takes place in fractures. In his samples, where the primary porosity of the rock was as high as 20.9 percent, the permeability was only 28 gpd per sq ft (gallons per day per square foot) ; and where the porosity was 15.5 and 10 percent, the permeability was zero in each.

The most important fractures with respect to transmitting ground water are generally vertical joints (Knapp, 1904, p. 79). Observations made by many observers at numerous places throughout the outcrop area of the Brunswick in New Jersey indicate that one set of vertical joints roughly parallels the strike of the rocks, and a second set is generally perpendicular to the strike. In places, the steeply dipping joints have different orientations. In addition, open bedding-plane joints are common in surface exposures, but they are thought to be of little water-bearing importance below the surface (Knapp, 1904, p. 79; Herpers and Barksdale, 1951, p. 24). Major and minor faults also occur in some places, and, locally, the fractures resulting from faulting may be the most important water bearers. In places, the water in these rocks occurs in only a few preferentially fractured zones, whereas in other places the ground water is more uniformly distributed throughout the upper few hundred feet of rock.

Typically, ground water in sufficient quantities for domestic purposes (10 gpm) can be obtained nearly everywhere in the Brunswick Formation from wells that are 6 inches in diameter and 100–200 feet deep. However, wells drilled in the Brunswick for maximum yield, such as for public supply or industrial use, are generally 8 or 10 inches in diameter and 300–400 feet deep. Reported yields of 30 large-diameter (greater than 6 inches) wells tested for maximum yield within and adjacent to the Ramapo River basin range from 48 to 240 gpm and average 137 gpm with the median yield being 125 gpm. The distribution of the yields is as follows:

| *Yield (gpm)* | *Number of wells* |
|---|---|
| Less than 101 | 7 |
| 101–200 | 20 |
| More than 200 | 3 |

The relation between yield and depth of the wells is shown in figure 9, and all but one of these higher yielding wells were 300–400 feet deep. The paucity of data for depths less than 300 feet suggests that the large-yield wells were drilled deeper because sufficient water was not present at the shallow depths.

Specific capacity is the discharge of a well, expressed as the rate of yield per unit of drawdown—generally gallons per minute per foot (gpm per ft). Specific capacities for 15 of these wells ranged from 0.32 to 2.4 and averaged 1.1 gpm per ft. The median specific capacity was also 1.1 gpm per ft. These specific capacities were computed from yield and drawdown data reported by the driller, and they are for pumping tests of 8 to 72 hours duration. The distribution of the specific capacities is as follows:

| *Specific capacity (gpm per ft)* | *Number of wells* |
|---|---|
| Less than 0.51 | 1 |
| 0.51–1 | 6 |
| 1.1 –1.5 | 6 |
| 1.6 –2 | 1 |
| Greater than 2 | 1 |

Like the relation of yield to depth, the higher specific capacities are for wells 300–400 feet deep (fig. 9).

The foregoing discussions suggest the following conclusions: (1) The yield to be expected from a large-diameter well drilled into the Brunswick Formation in this area is on the order of 100 to 200 gpm. (2) The probable well depth necessary to obtain this yield is somewhere between 300 and 400 feet. (3) The probable specific capacity of such a well will be between 0.5 and 1.5 gpm per ft.

In addition, it can be deduced from figure 9 that little if any additional yield will be realized by drilling deeper than about 400 feet; in other words, if the quantity of water desired is not found within the first 400 feet of drilling, it is better to drill a second well at another location rather than to drill the first well deeper than 400 feet. Elsewhere in New Jersey, large quantities of water have been developed from wells tapping the Brunswick at depths greater than 400 feet, but these occurrences are the exception, not the rule. Generally, very deep wells in the Brunswick notably yield little water, and the reason they have been drilled to such depths is that sufficient water was not found nearer the surface. Hence, the aquifer in the Brunswick Formation can be considered to extend about 400 feet below land surface.

Because of the generally low specific capacity of Brunswick wells, extreme care must be exercised in locating new wells near existing wells so that well interference will be at a minimum. Although not documented within the Ramapo River basin, the Brunswick Formation elsewhere has exhibited directional hydrau-

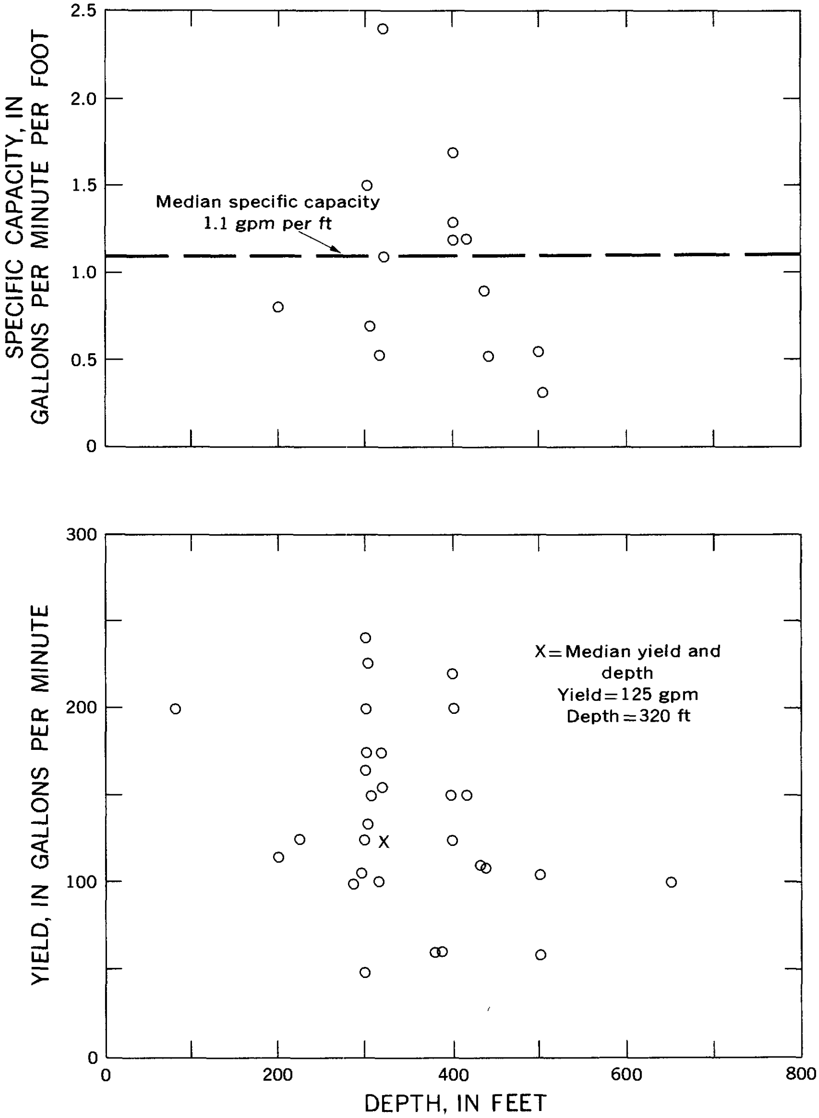


FIGURE 9. — Relation of depth to yield and specific capacity of wells tapping the Brunswick Formation.

lic behavior, or anisotropy, under pumping conditions (Vecchioli, 1967).Water levels in wells alined along the strike of the formation show greater interference than those in wells alined in transverse directions. Hence, well interference can be minimized by alining wells in directions other than parallel to the strike. Within the Ramapo basin, the Brunswick Formation has a generally northerly strike, varying from north-northwest to north-northeast; therefore, interference should be minimal in wells alined roughly east-west. However, the local strike could be more precisely determined by an examination of outcrops in the vicinity of the site to be drilled.

Moreover, knowledge of the hydraulic anisotropy is of importance when attempting to locate a well with respect to a potential source of pollution. If the well and the pollution source are alined parallel to the strike of the Brunswick, the chances of the well becoming polluted are greater than if the alinement is transverse to the strike.

### WATCHUNG BASALT

Ground water in the Watchung Basalt occurs mainly in fractures, but some occurs in vesicular zones. In describing the basalt sheets in the area just to the south of the Ramapo River basin, Darton, Bayley, Salisbury, and Kümmel (1908, p. 9, 10) reported that vesicular zones are usually present at the bases of the sheets and that the upper parts of the sheets are vesicular to considerable depth. There is also evidence that the individual sheets are composed of multiple flows, and, hence, intrasheet vesicular zones may also be common. However, the most highly water bearing parts of the basalt are probably the uppermost and lowermost parts at or near the contact with the sandstone and shale of the Brunswick Formation. Ground-water movement commonly is concentrated in these contact zones. Weathering associated with this ground-water movement could enlarge fracture openings or increase interconnection of vesicles.

Little information is available regarding the ability of the basalt to yield water to wells in the Ramapo River basin, although numerous domestic wells furnish small supplies of ground water from the basalt. In nearby Morris County, yields of five public-supply wells tapping basalt were reported to range from 30 to 54 gpm (Gill and Vecchioli, 1965). Nichols (1968) reported a range in yield from 146 to 400 gpm for 7 public-supply wells tapping basalt sheets in Essex County. The median yield of these wells is 250 gpm. However, these high yields pertain only to successful wells that are presently in use, and the many unsuccessful wells are not considered. These rocks probably should not be considered as sources of large ground-water supplies. Locally, it may be possible to develop high-capacity wells in them, but, in general, they seem capable of yielding only small to moderate supplies.

### QUATERNARY DEPOSITS

Quarternary deposits mantle the bedrock practically everywhere in the basin. Because of their widespread surface occurrence, one of their chief hydrologic characteristics is to absorb precipitation and subsequently transmit the water downward to the underlying rock aquifer and laterally to streams. Where the saturated thickness of these deposits and their permeability are sufficiently great, they serve as aquifers. Indeed, the stratified drift in the Ramapo valley forms the most productive aquifer in the basin. The upland stratified drift deposits that occur in the vicinity of Franklin Lake and in the Campgaw–Crystal Lake area are of minor importance as aquifers.

Wells that commonly yield several hundred gallons per minute and as much as 1,200 gpm with only 5 feet of drawdown have been developed in the valley stratified drift (valley fill). These wells are the main source of supply for the Township of Mahwah and the only source of supply for the Borough of Oakland. Because the valley fill is the most important aquifer in the basin, with respect to both present development and future potential, it is treated at length in a later section.

The upland stratified drift constitutes aquifers of local importance wherever its saturated thickness is on the order of several tens of feet, as at Franklin Lake and in the Campgaw–Crystal Lake area. The saturated thickness of the upland drift varies considerably from place to place, and, hence, it is difficult to predict the yield from a well completed in it. Well 1 in Oakland (table 1) is reported to yield 75 gpm from a saturated thickness of 50 feet. Well 1 in Franklin Lakes (table 1) is reported to yield 200 gpm, also from a saturated thickness of 50 feet; however, pumping of this well induces recharge from Shadow Lake, and its yield may therefore be atypical. The Borough of Oakland has recently completed a well (No. 11, table 1) which is reported to produce 582 gpm from drift and the underlying Brunswick Formation. The drift there has a saturated thickness of 90 feet.

Data are not available to define the saturated thickness of the upland stratified drift everywhere. The most favorable thickness and, hence, the best places for well development in these deposits appear to be near Franklin Lake and in the Campgaw–Crystal Lake area. Elsewhere, the deposits are generally thin or lacking.

Till, because of its great heterogeneity in particle size, is generally poorly permeable and does not yield water readily to wells; hence, it is not considered to be an aquifer. However, till may have a porosity many times greater than that of the underlying rock, and its unit storage capacity would be correspondingly greater. The water stored in the till serves to replenish storage in the rock aquifer as the storage becomes depleted by wells.

### SUSTAINED GROUND-WATER YIELD IN UPLAND AREAS

In the humid northeast, ground water is a replenishable resource, and so long as withdrawals do not exceed the recharge, there should be no long-term decline in water in storage. An estimate of the magnitude of recharge to the various aquifers can be made by separating the streamflow hydrograph into components of overland runoff and ground-water runoff. Unfortunately, continuous streamflow records in the Ramapo River basin in New Jersey are available only for the main stream, and estimates of recharge based on these records are of little use for investigating specific aquifers because the main stream integrates the diverse geology and hydrology of the basin.

Base-flow measurements were made on all the significant tributary streams on four occasions during the spring-summer recession of 1964 and once in September of 1963. On the basis of these measurements, two streams were selected as representative of the two halves of the basin—Bear Swamp Brook for the streams draining the rugged gneiss terrain to the west, and Darlington Brook for the streams draining the gentler terrain underlain largely by the drift-covered Brunswick Formation to the east. These discharge data are as follows:

| | Drainage area (sq mi) | Discharge (cfs) | | | | |
|---|---|---|---|---|---|---|
| | | 9–25–63 | 4–27–64 | 6–3–64 | 7–1–64 | 9–3–64 |
| Bear Swamp Brook.......... | 3.29 | 0.02 | 3.46 | 0.12 | 0.04 | 0.03 |
| Darlington Brook.............. | 3.57 | .40 | 2.11 | [1]1.4 | 1.20 | .47 |

[1] Estimated.

From these data it can be deduced that ground-water discharge to either stream during the summer is low, particularly for Bear Swamp Brook, indicating that the storage and recharge potential of the rocks drained by these streams is low. To obtain some idea of the magnitude of the ground-water part of streamflow, the above measurements and subsequent ones were correlated with the stream discharge records for Hohokus Brook at Hohokus, N.J. (fig. 7), the nearest continuous-record station satisfying correlation criteria. Thus, a more complete picture of base flow during the 1964 recession was developed. Synthetic hydrographs were constructed on the bases of the correlations for the April through September 1964 period.

The amount of ground-water discharge during this particular 6-month period was then obtained by summing the values below the base-flow–recession curve. Ground-water discharge is generally at a maximum in April and at a minimum in September; hence, although not rigorously correct, one can estimate the annual ground-water discharge reasonably well by doubling this 6-month discharge. This premise was tested by analyzing the ground-water discharge part of the streamflow at Ramapo River near Mahwah for the entire 1964 water year (Oct. 1, 1963–Sept.

30, 1964) and the April–September part of the discharge was found to be only slightly less than half the total for the year.

Accordingly, by doubling the 6-month totals, the computed ground-water discharge to Darlington Brook during the 1964 water year averaged 0.165 mgd per square mile, and that to Bear Swamp Brook averaged 0.117 mgd per square mile. Total runoff for the 1964 water year for the Ramapo River near Mahwah was only 73 percent of the long-term mean. Hence, if the respective ground-water discharges are adjusted to reflect the long-term mean, one obtains values of 0.208 mgd per square mile for Darlington Brook and 0.160 mgd per square mile for Bear Swamp Brook.

These figures of ground-water discharge are minimal values. Of course, not all the ground-water discharged in and near a stream is measureable at the mouth of the stream because of the water losses due to evapotranspiration along the stream's course. Moreover, not all ground water within each tributary basin necessarily discharges to the tributary—some may bypass the local system and discharge directly to the Ramapo River, possibly as underflow in the drift-filled valleys. However, measurements of the main stream at several points suggest that little gain occurs in this way. Nonetheless, these low ground-water discharge values are thought to be on the right order of magnitude, on the basis of the following considerations:

1. The flow-duration curve for Ramapo River near Mahwah has a steep slope, which, according to Searcy (1959, p. 22) denotes a highly variable discharge, made up largely from direct runoff. Further, he stated that a flat slope at the lower end of the curve indicates a large amount of storage, and a steep slope indicates a negligible amount. The curve for the Ramapo is steep throughout, thus implying that ground-water discharge constitutes only a small part of the total discharge. Although the Ramapo River above Mahwah does not drain the area under discussion, it does drain similar rocks.
2. The rugged topography of the gneissic terrain of Bear Swamp Brook basin and the general absence of thick drift cover greatly facilitate overland runoff and, conversely, greatly impede infiltration. Relief in Darlington Brook basin is moderate, but much of the drift overlying the Brunswick Formation has low permeability, and the capacity of the basin for overland runoff far exceeds its infiltration capacity. Thus, although the ground-water discharge to Darlington Brook is greater than that to Bear Swamp Brook, it nonetheless constitutes only a small part of the total runoff.

3. Barksdale and others (1943, p. 149) estimated the "safe yield" of the Brunswick Formation—where the rock is well fractured and overlain by thick layers of permeable sand—to be on the order of half a million gallons per day per square mile. This estimate was made for the formation in Middlesex County, N.J., where the topography is relatively flat and glaciation has done little to modify the aquifer in the Brunswick. But in the Ramapo River basin, the local relief is considerably greater, and much of the Brunswick is mantled with poorly permeable drift. Furthermore, the weathered upper part of the Brunswick aquifer is thinner because of glacial scour, which results in less storage capacity, as the storage capacity of the weathered part is probably much greater than that of the unweathered rock. Consequently, even though the amount of annual precipitation in each of the two areas is similar, the sustained yield of the Brunswick in the Ramapo basin is believed to be considerably less than that in Middlesex County.

On the basis of the analysis of base-flow measurements and the foregoing arguments, it appears reasonable to expect the sustained ground-water yield of the gneiss to be on the order of 100,000–200,000 gpd per sq mi, or about 1/10–2/10 of the total runoff. The average sustained yield of the Brunswick Formation probably ranges from 200,000–300,000 gpd per sq mi, or about 2/10–3/10 of the total runoff. The sustained yield of the basalt is believed to be similar to that of the gneiss.

These estimates of sustained yield should be considered as only an approximate order of magnitude of the yield that can be developed, on the average, from the respective rocks. In places, the yields realized may be more or less than the figures given, but, in general, much larger yields should not be expected. Development of more precise yield estimates would require considerable instrumentation such as continuous-recording observation wells and streamflow gaging sites. However, such refinements of the yield estimates are probably not justifiable economically, as the yields from wells tapping these rocks are generally poor compared with those tapping the much higher yielding sand and gravel deposits along the Ramapo River. The sand and gravel deposits presently supply most of the ground-water demands in the basin, and they most probably will continue to do so.

## GROUND-WATER DEMAND

Less than 5 mgd of ground water was pumped during 1966 from all the aquifers within the Ramapo River basin. Of this amount, 4.3 mgd was supplied to the public-supply systems of

Mahwah, Oakland, Ramsey, and Wayne. Industrial and institutional pumpage from private wells equaled 0.1–0.2 mgd, and pumpage from private domestic wells probably amounted to another 0.1–0.2 mgd.

By far the greatest part of the ground water withdrawn in the basin was from the Quaternary stratified drift along the Ramapo River. Of the public-supply pumpage of 4.3 mgd, about 75 percent of this amount (or 3.2 mgd) was obtained from the Quaternary stratified drift, whereas the remaining 25 percent (or 1.1 mgd) was obtained from the Late Triassic Brunswick Formation. (See fig. 10.) Very little water is pumped from either the Late Triassic basalt or the Precambrian gneiss, partly because of the poor yield of these rocks and partly because the areas underlain by these deposits are largely uninhabited.

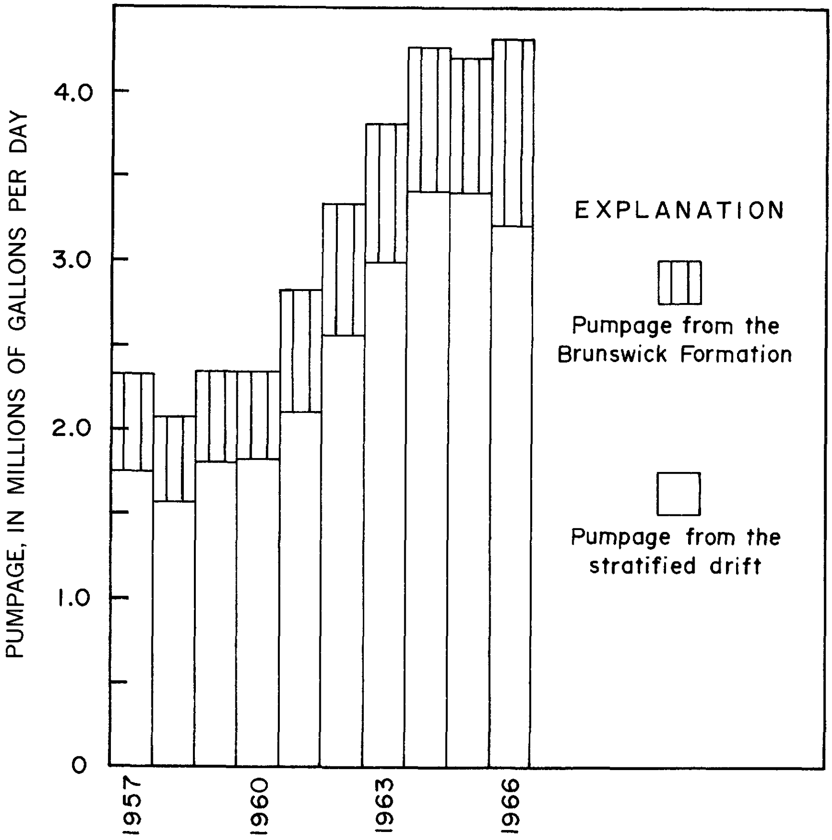


FIGURE 10. — Ground-water pumpage for public supply in the New Jersey part of the Ramapo River basin, 1957–66.

The public-supply pump sites in the basin and the withdrawal from each are shown in figure 11.

Use of ground water increased sharply during the period 1957–66, as shown in figure 10. For example, in 1957 the total public-supply pumpage at Mahwah, Oakland, and Ramsey (including some from wells outside the basin limits) was 2.6 mgd, whereas in 1966 the total public-supply pumpage for these areas was 4.6 mgd, an increase of 80 percent. All public water supply for these towns is from wells. Neglia, Elam, and Rothenburg (1967, p. 28) estimated that the future demands, in millions of gallons per day, will be as follows:

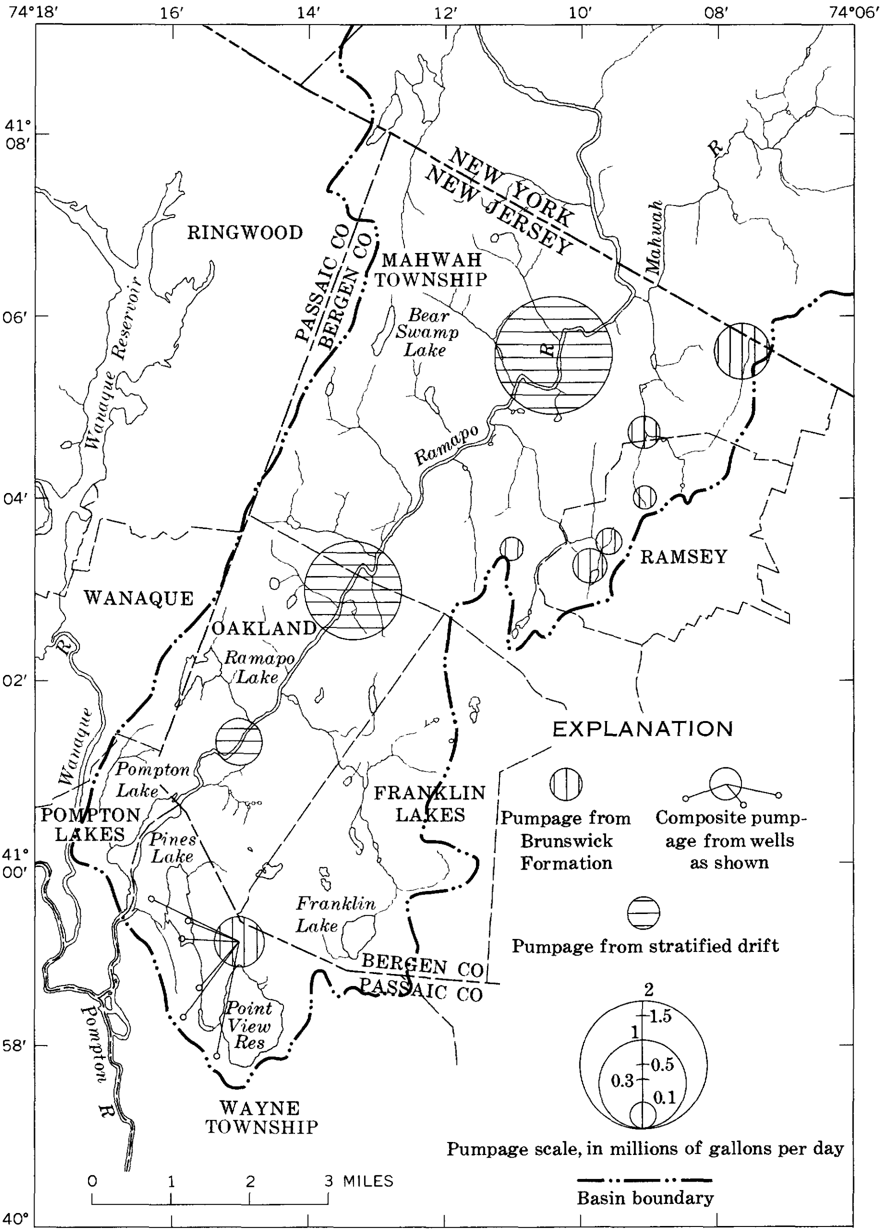
| | Year | | | |
|---|---|---|---|---|
| | 1970 | 1980 | 1990 | 2000 |
| Mahwah | 3.25 | 4.00 | 4.71 | 5.47 |
| Oakland | 2.55 | 3.36 | 4.46 | 5.18 |
| Ramsey | 1.19 | 1.80 | 2.44 | 3.96 |
| Total | 6.99 | 9.16 | 11.61 | 14.61 |

Hence, it is estimated that the demand in the year 2000 will be more than three times the demand in 1966 (4.6 mgd).

## WATER QUALITY

Water is commonly thought of as the "universal solvent" because of its ability to dissolve more substances than any other liquid. On its way through the hydrologic cycle, water takes on impurities, either as dissolved constituents or as suspended particles. Precipitation absorbs gases, such as carbon dioxide and oxygen, as it falls through the atmosphere, and in industrial areas it can absorb such atmospheric contaminants as sulfur dioxide, ammonia, and carbon monoxide. Particulate matter, such as dust, bacteria, and spores, are also "flushed" from the atmosphere by precipitation. Generally, however, the amounts of dissolved and suspended contaminants carried to the earth's surface by precipitation are very small.

Once on the earth's surface or in the ground, the water dissolves various amounts of mineral matter from the soil and rocks over, or through, which it flows. The water can also absorb contaminants from fertilizers, herbicides, pesticides, salts (used for snow and ice removal), and industrial and municipal solid and liquid wastes. Generally, the longer water remains in contact with the soil and rock—or in contact with the manmade source of contamination—the more mineralized it becomes. Suspended matter picked up by the water consists largely of sediment derived from erosion of the land surface, but many of man's additions to the environment also significantly affect the physical quality and usability of the water.



Base adapted from New Jersey Atlas Sheet 23

FIGURE 11. — Distribution of the ground-water pumpage for public supply in the New Jersey part of the Ramapo River basin.

Standards of water quality vary considerably, according to the intended use of the water. Water suitable for one use may be

TABLE 2. — *Chemical analyses of water from the principal water-bearing*

[Symbols for water-bearing formations: sd, stratified drift; b, Brunswick Formation; gn, gneiss. and

| Well No. (fig. 8) | Location | Water-bearing formation | Date of collection | Temperature (°C) | Silica ($SiO_2$) | Iron (Fe) | Manganese (Mn) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| New Jersey State Dept. of Health, potable-water standards[1] | | | | | .... | 0.30 | 0.05 | ...... | .... | .... | .... |
| 18 | Mahwah Township | sd | 8–25–64 | 11.1 | 13 | 0.00 | 0.00 | 22.0 | 5.4 | 7.1 | 1.0 |
| 19 | do | sd | 8–25–64 | 10.6 | 13 | .11 | .00 | 21 | 5.4 | 5.6 | .9 |
| 9 | Oakland | sd | 5–21–64 | 10.6 | 16 | .06 | .00 | 23 | 5.1 | 5.1 | .0 |
| 8 | do | sd | 5–21–64 | 9.4 | 18 | .16 | .00 | 29 | 8.0 | 6.3 | .0 |
| 6 | do | sd | 5–21–64 | 10.6 | 18 | .02 | .00 | 44 | 11 | 9 | .0 |
| 24 | Mahwah Township | b | 3–18–64 | 10.6 | 21 | .03 | .00 | 34 | 16 | 15 | .2 |
| 26 | do | b | 5–19–64 | ..... | 21 | .05 | .00 | 26 | 11 | 16 | .0 |
| 4 | Ramsey | b | 5–19–64 | 11.1 | 18 | .05 | .11 | 36 | 9.7 | 6.0 | .0 |
| 8 | do | b | 5–19–64 | 10.6 | 19 | .04 | .00 | 24 | 9.2 | 12 | .0 |
| 3 | Wayne Township | b | 6– 4–64 | ..... | 24 | .09 | .00 | 21 | 8.8 | 5.4 | .2 |
| 5 | do | b | 6– 4–64 | 11.1 | 23 | .08 | .00 | 47 | 17 | 13 | .5 |
| 1 | do | b | 4–29–59 | 10.6 | ... | ...... | .... | .... | .... | 20 | .... |
| 1–15 | Mahwah Township | b | 4–29–59 | 9.4 | 18 | .05 | .06 | 30 | 16 | 4.5 | .5 |
| 31 | do | gn | 5–28–64 | 10.0 | 12 | 3.4 | .00 | 32 | 3.2 | 4.9 | .2 |
| 35 | do | gn | 7– 8–64 | 10.0 | 14 | .28 | .00 | 13 | 2.9 | 3.7 | 1.0 |
| 14 | Oakland | gn | 7–17–64 | ...... | 13 | .32 | .00 | 7.6 | 2.7 | 3.4 | 1.0 |

[1] Maximum limits advised for drinking water.

wholly unsuitable for another. For example, water used for public supply must be free from objectionable tastes and odors and must meet sanitary specifications, whereas water for an industrial use might not be required to be odorless and potable, but rather to have a certain temperature or be lacking a particular chemical constituent, such as iron.

The New Jersey Department of Health has established standards for maximum concentrations of many constituents in water used for potable purposes; these standards are given in table 2. In general, all the major aquifers in the Ramapo River basin contain water of satisfactory chemical quality for potable use without treatment (table 2). Very rarely is untreated surface water potable, and that in the Ramapo River is no exception. Another major difference in the chemical quality of ground water and surface water is that ground water is generally constant in both quality and temperature, whereas both quality and temperature of surface water vary seasonally and with the amount of stream discharge. The changing quality of surface water will be discussed in detail later in this section.

Results from analyses of 16 ground-water samples are given in table 2. Analyses of water samples from the Ramapo River and its tributaries have been published in the annual water-quality *formations in the New Jersey part of the Ramapo River basin*

Data are in milligrams per liter, except those values for temperature, specific conductance, pH, color]

| Bicarbonate ($HCO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Dissolved solids (residue at 180°C) | Hardness as $CaCO_3$ |  | Specific conductance (micromhos at 25°C) | pH | Color | Owner and owner's well No. |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Calcium, magnesium | Noncarbonate |  |  |  |  |
| ...... | 250 | 250 | 1.5 | 20.0 | 500 | 170 | .... | ...... | .... | 15 |  |
| 62 | 20 | 16 | 0.0 | 1.7 | 118 | 77 | 26 | 202 | 6.8 | 5 | Mahwah W. D. Ford No. 4. |
| 66 | 22 | 8.1 | .0 | 1.6 | 113 | 75 | 21 | 181 | 6.9 | 5 | Mahwah W. D. Ford No. 1. |
| 73 | 20 | 8.3 | .0 | 1.0 | 123 | 79 | 19 | 184 | 7.1 | 3 | Oakland W. D. Soons No. 8. |
| 88 | 21 | 14 | .1 | 4.3 | 155 | 106 | 34 | 235 | 7.0 | 2 | Oakland W. D. Soons No. 7. |
| 144 | 25 | 16 | .0 | 8.6 | 215 | 155 | 37 | 338 | 7.7 | 3 | Oakland W. D. Bush No. 5. |
| 128 | 24 | 25 | .1 | 12 | 227 | 151 | 46 | 346 | 7.6 | 2 | Immaculate Conception Seminary No. 1 |
| 107 | 39 | 9.4 | .1 | 7.9 | 183 | 110 | 23 | 288 | 7.6 | 2 | Ramsey W. D. Central Ave. No. 1. |
| 136 | 23 | 6.9 | .0 | 4.2 | 177 | 130 | 19 | 278 | 7.7 | 1 | Ramsey W. D. Woodland Ave. well. |
| 92 | 29 | 7.9 | .0 | 9.0 | 155 | 98 | 23 | 243 | 8.1 | 2 | Ramsey W. D. Darlington Ave. well. |
| 86 | 21 | 3.7 | .1 | 1.2 | 129 | 89 | 18 | 194 | 7.2 | 3 | Wayne Township Lionhead Lake No. 2. |
| 127 | 76 | 14 | .1 | 5.2 | 278 | 188 | 84 | 404 | 7.8 | 4 | Wayne Township Pines Lake No. 2. |
| 171 | 52 | 9.8 | ... | 12 | ...... | 175 | 35 | 372 | 7.9 | 3 | Wayne Township Point View well. |
| 132 | 27 | 7.6 | .0 | 10 | 168 | 141 | 33 | 295 | 7.1 | 3 | Mahwah W. D. old field. |
| 100 | 18 | 2.5 | 1.0 | .2 | 124 | 94 | 11 | 203 | 7.2 | 3 | Camp Yaw Paw well 1. |
| 45 | 15 | 1.9 | .5 | .2 | 79 | 45 | 8 | 120 | 6.7 | 5 | Camp Glen Gray well 3. |
| 19 | 19 | 3.3 | .1 | .4 | 56 | 30 | 15 | 88 | 6.2 | 3 | Camp Tamarack. |

reports; hence, they are not duplicated herein. Rather, these surface-water analyses are shown in graphical or summary form in this section of the report.

### GROUND-WATER QUALITY

Ground water contains mineral matter dissolved mainly from the soil and rock through which it has percolated. Accordingly, the water quality can differ considerably from one aquifer to another, as well as from place to place within the same aquifer. The major aquifers in the Ramapo River basin yield water of somewhat differing chemical character although water from each contains calcium as the predominant cation and bicarbonate as the predominant anion (fig. 12).

Based on the analyses presented in table 2, water from the Precambrian gneiss is characteristically low in dissolved-solids content (56–124 mg/l), is soft to moderately hard (30–94 mg/l) (milligrams per liter), and is acidic to neutral, with the pH ranging from 5.2 to 7.2. (See fig. 13.) In comparison, water from the Brunswick Formation contains moderate amounts of dissolved solids (129–278 mg/l), is moderately hard to very hard (89–188 mg/l), is neutral to slightly alkaline, with the pH ranging from 7.1 to 8.1. Water from the Quaternary sand and gravel deposits

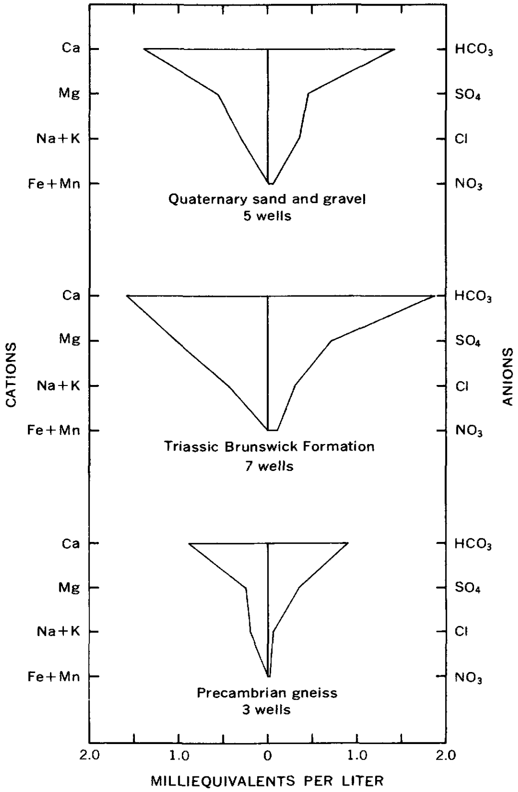


FIGURE 12. — Comparison of the mean chemical quality of water from the three major aquifers in the New Jersey part of the Ramapo River basin.

contains moderate amounts of dissolved solids (113–215 mg/l), is generally moderately hard (75–155 mg/l), and is neutral to slightly alkaline, with the pH ranging from 6.8 to 7.7.

## SURFACE-WATER QUALITY

The chemical and physical quality of surface water varies with the discharge of the stream, as well as with the geology of the drainage area. Anderson and George (1966, p. G6) stated that:

> During and for several days after moderate-to-heavy precipitation, the major part of water flowing in a stream is the result of direct overland runoff. This stream water has had little contact time with soluble materials, and its dissolved-solids concentration generally approaches that of precipitation. The concentration of dissolved solids in a stream during high-flow conditions, therefore, usually is at a minimum (fig. 1) [of Anderson and George, 1966].
>
> During sustained periods of fair weather, the flow in a stream is maintained largely by ground-water inflow. Consequently, the dissolved-solids

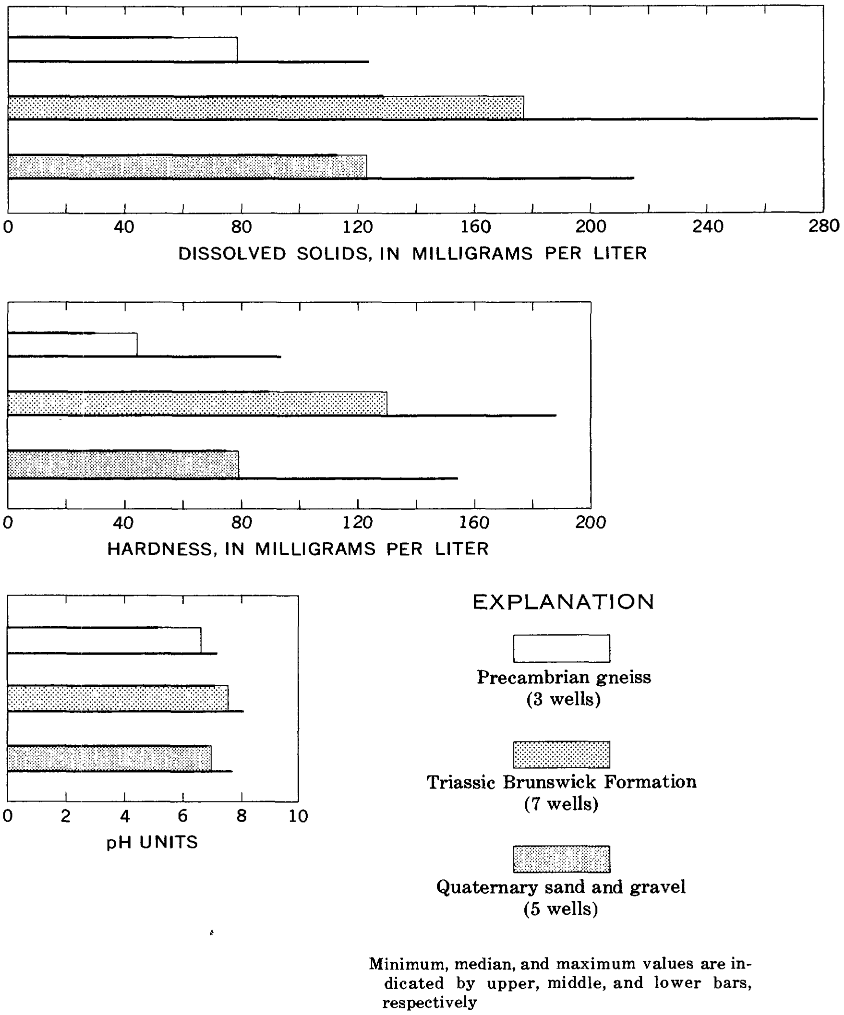


FIGURE 13. — Minimum, median, and maximum quality characteristics of water from the three major aquifers in the New Jersey part of the Ramapo River basin.

concentration during low-flow conditions reflects that of the ground-water inflow. Because this ground water usually contains more dissolved solids than the surface runoff, owing to the longer duration of its contact with soluble materials, the dissolved-solids concentration in most streams is at a maximum during periods of low flow (fig. 1) [of Anderson and George, 1966].

The relation of discharge to dissolved-solids concentration in the Ramapo River near Mahwah and at Pompton Lakes is shown in figure 14. At both places the concentration of dissolved-solids increases as the discharge decreases. However, the change is less

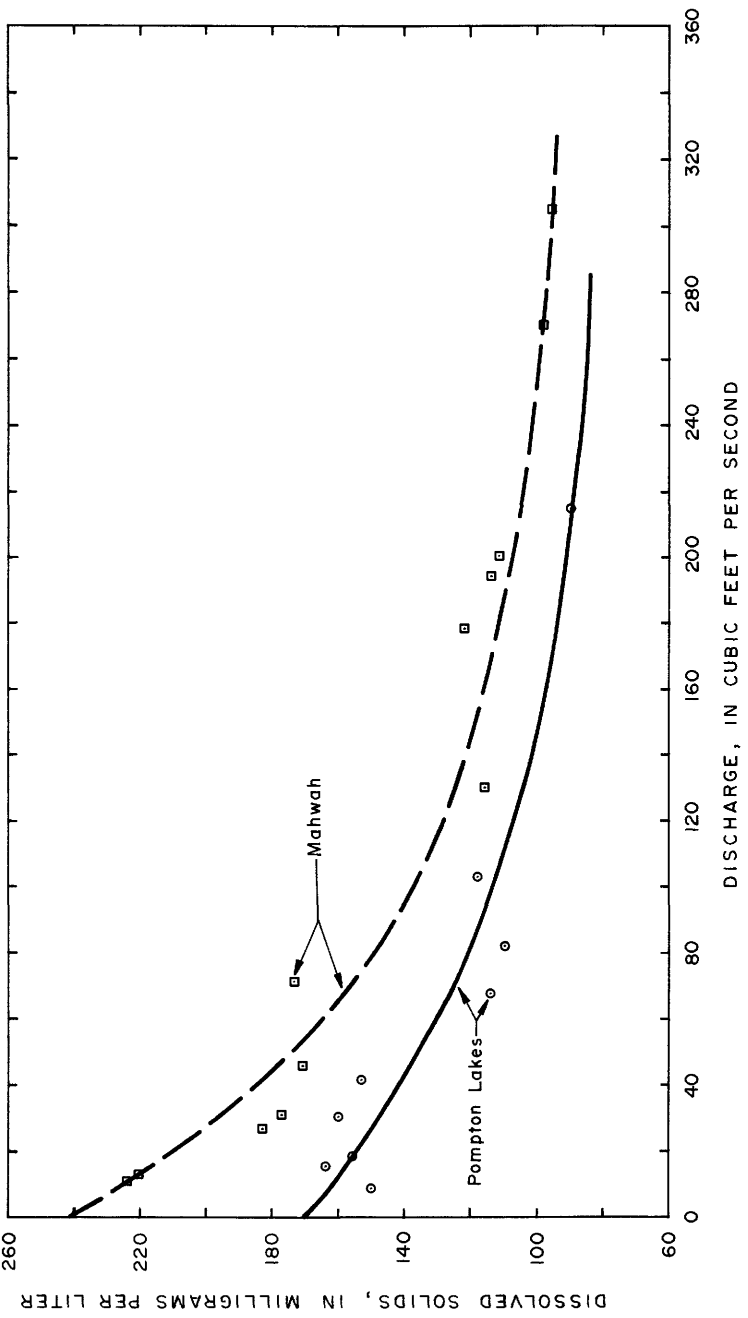


FIGURE 14. — Relation between dissolved-solids concentration and discharge of Ramapo River near Mahwah and Ramapo River at Pompton Lakes, N.J.

sharp at the outlet of Pompton Lake, probably because the lake acts as a dampening agent, thus tending to average the extremes in quality. Water flowing from Pompton Lake contains less dissolved solids throughout the range in discharge, indicating that the lake influences the chemical quality of the Ramapo River water, for it will be shown that little change in quality occurs between Mahwah and Oakland, at the head of Pompton Lake.

The difference in the dissolved-solids concentration in the water entering and that leaving Pompton Lake is slight during periods of high flow and is more pronounced during periods of low flow. At times of high flow, water stored in the lake mixes with the inflow in a smaller proportion than it does at times of low flow. In late summer and early fall, following a long period of low flow, the water flowing from the lake during and just after a rainstorm might be higher in dissolved-solids content than the inflow.

Hardness of water also increases with decreasing discharge, as shown in figure 15, and it, like the dissolved-solids concentrations, is less for all observed stream discharges at Pompton Lakes than it is near Mahwah.

The relation of surface-water quality to geology and ground water can be demonstrated by comparing the quality characteristics of the tributary streams with those of the various aquifers. In figure 16 a comparison is made between the hardness, dissolved solids, and pH of water at high and low base flow from the tributary streams draining Precambrian rocks and from those draining Triassic rocks and Quaternary deposits. The surface water from the area underlain by Precambrian rocks is low in dissolved-solids concentration (42–50 mg/l), is very soft (20–23 mg/l), and is slightly acid to neutral (pH 6.3–6.8). In contrast, the water of streams draining Triassic and Quaternary rocks is higher in dissolved-solids concentration (105–128 mg/l), is moderately hard (66–90 mg/l), and is neutral (pH 6.7–7.4). This comparison is very similar to the comparison made of the ground water from these rocks. Tables 3 and 4 summarize the water-quality data for the tributary streams.

The similarity in the chemical quality of ground water and of surface water during low base flow can be seen by comparing figure 17 with figure 12. Darlington Brook drains Triassic and Quaternary rocks, whereas Bear Swamp Brook drains Precambrian rocks. The graphic representations of the chemistry of these surface waters are similar to those of the chemistry of ground water from Precambrian rocks and from Triassic and Quaternary rocks (fig. 12) particularly in regard to the overall mineralization of the water.

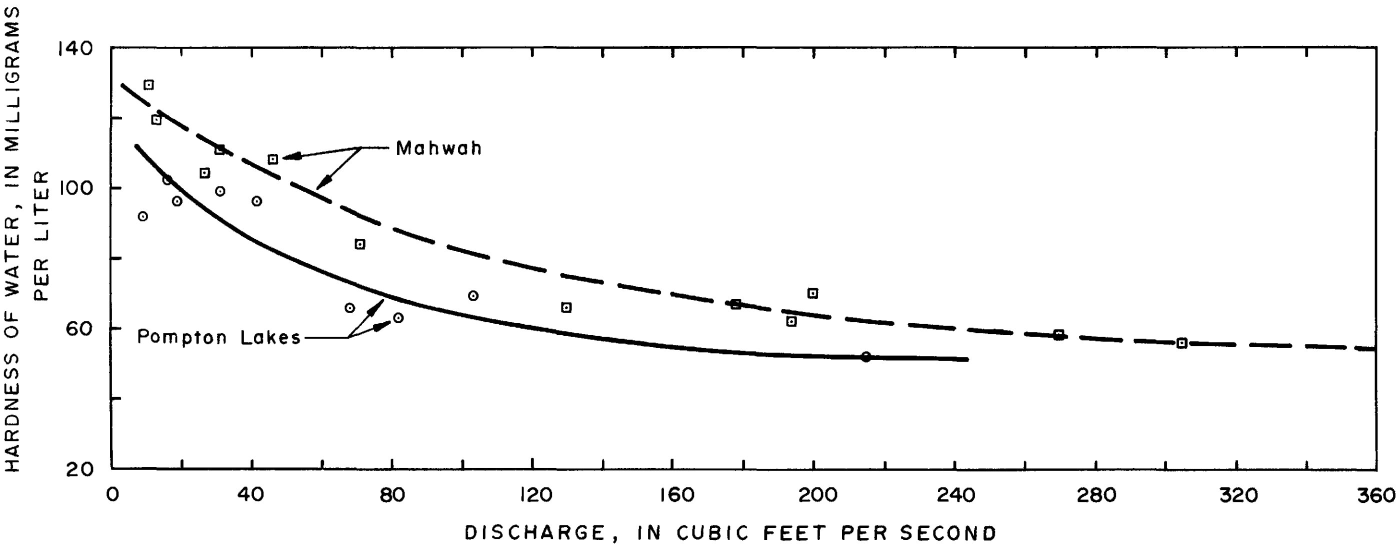


FIGURE 15. — Relation between hardness of water and discharge of Ramapo River near Mahwah and Ramapo River at Pompton Lakes, N.J.

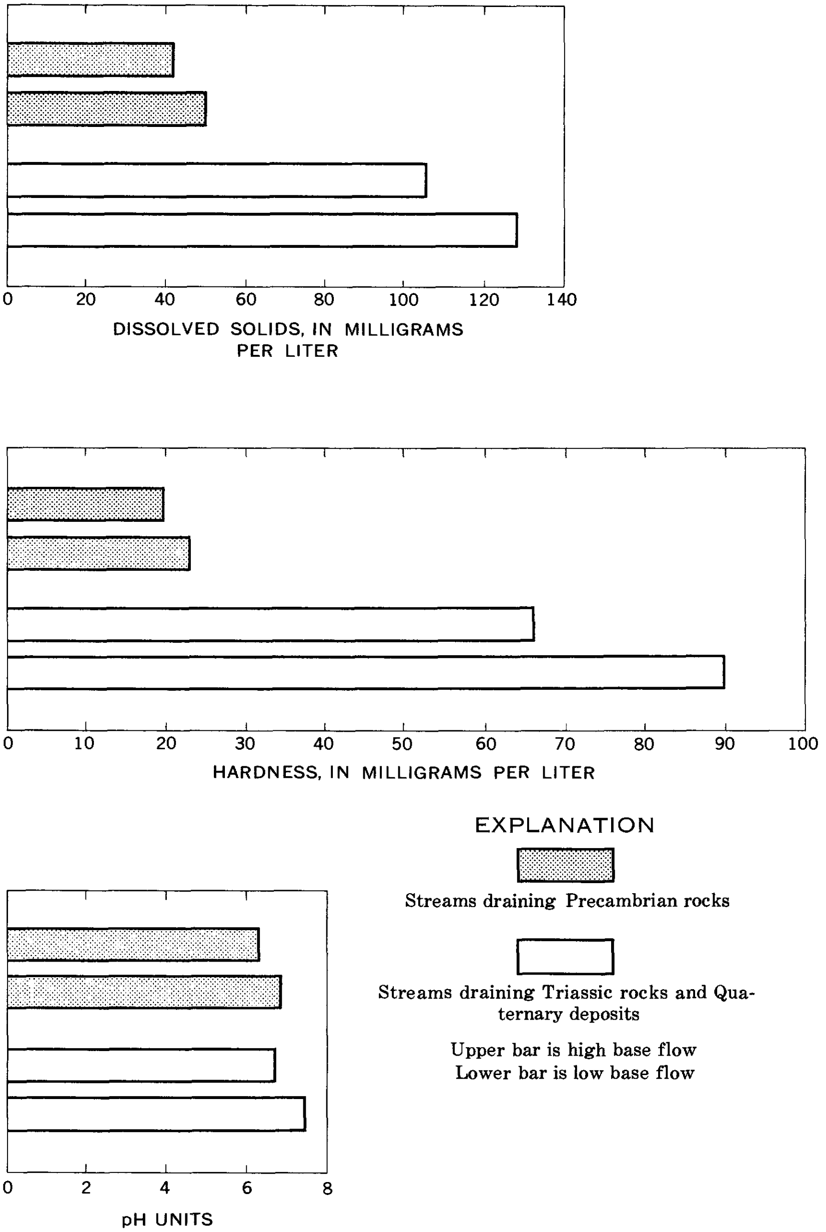


FIGURE 16. — Comparison of median quality characteristics at high and low base flow of streams draining Precambrian rocks with those draining Triassic and Quaternary rocks.

TABLE 3. — *Water-quality characteristics of tributary streams draining Precambrian rocks in the New Jersey part of the Ramapo River basin*

[All values, except those for pH, are in milligrams per liter]

| Base-flow stage | High | | | Intermediate | | | Low | | |
|---|---|---|---|---|---|---|---|---|---|
| Date(s) | 4–27–64,<br>4–21–65 | | | 6–3–64 | | | 9–25–63,<br>7–1–64 | | |
| Number of samples | 11 | | | 5 | | | 9 | | |
| | Minimum | Maximum | Median | Minimum | Maximum | Median | Minimum | Maximum | Median |
| Sodium (Na) and potassium (K) | 1.6 | 26 | 2.8 | 2.8 | 25 | 4.1 | 2.3 | 22 | 3.9 |
| Bicarbonate ($HCO_3$) | 4 | 18 | 7 | 8 | 270 | 22 | 8 | 46 | 14 |
| Sulfate ($SO_4$) | 14 | 36 | 17 | 15 | 45 | 17 | 12 | 18 | 13 |
| Chloride (Cl) | 1.5 | 22 | 2.5 | 2.0 | 36 | 3.0 | 1.0 | 15 | 3.0 |
| Nitrate ($NO_3$) | .0 | 25 | .2 | .4 | 9.8 | .5 | .2 | 17 | .6 |
| Hardness as $CaCO_3$: | | | | | | | | | |
| Calcium, magnesium | 18 | 46 | 20 | 19 | 246 | 31 | 17 | 42 | 23 |
| Noncarbonate | 12 | 31 | 15 | 13 | 31 | 15 | 5 | 15 | 8 |
| Dissolved solids | 36 | 137 | 42 | 42 | 300 | 57 | 41 | 127 | 50 |
| pH | 5.7 | 7.1 | 6.3 | 6.2 | 7.6 | 6.4 | 6.4 | 7.2 | 6.8 |

TABLE 4. — *Water-quality characteristics of tributary streams draining Quaternary and Triassic rocks in the New Jersey part of the Ramapo River basin.*

[All values, except those for pH, are in milligrams per liter]

| Base-flow stage | High | | | Intermediate[1] | | Low | | |
|---|---|---|---|---|---|---|---|---|
| Date(s) | 4–27–64,<br>4–21–65 | | | 6–3–64 | | 9–25–63,<br>7–1–64 | | |
| Number of samples | 9 | | | 2 | | 12 | | |
| | Minimum | Maximum | Median | Minimum | Maximum | Minimum | Maximum | Median |
| Sodium (Na) and potassium (K) | 3.0 | 12 | 6.2 | 6.9 | 9.4 | 5.8 | 22 | 7.7 |
| Bicarbonate ($HCO_3$) | 14 | 80 | 44 | 84 | 86 | 75 | 167 | 90 |
| Sulfate ($SO_4$) | 18 | 29 | 24 | 19 | 20 | 15 | 30 | 19 |
| Chloride (Cl) | 2 | 24 | 7 | 7.5 | 10 | 4.5 | 30 | 8.3 |
| Nitrate ($NO_3$) | .6 | 7.2 | 2.2 | 1.4 | 3.0 | 1 | 13 | 3 |
| Hardness as $CaCO_3$: | | | | | | | | |
| Calcium, magnesium | 27 | 93 | 66 | 86 | 87 | 67 | 164 | 90 |
| Noncarbonate | 16 | 36 | 24 | 17 | 17 | 0 | 38 | 19 |
| Dissolved solids | 55 | 144 | 105 | 124 | 127 | 105 | 219 | 128 |
| pH | 6.2 | 7.8 | 6.7 | 7.4 | 7.1 | 7.2 | 8.1 | 7.4 |

[1] Median values for intermediate base-flow stage were not determined.

Downstream changes in the chemical quality of the Ramapo River are demonstrated on plate 2 for high and low base-flow conditions. Upper reaches of the Ramapo River drain a limestone area (fig. 2) ; the water is fairly highly mineralized (calcium and bicarbonate concentrations are particularly high), as shown by the graphic representation of the water quality at the Newburgh Junction (N.Y.) site. (See pl. 2.) Downstream from Newburgh Junction, the Ramapo drains Precambrian rocks which yield water having a low dissolved-solids content. Hence, the highly mineralized streamflow from the area above Newburgh Junction has been considerably diluted by the time it reaches Sloatsburg. From Sloatsburg downstream to Oakland, the chemical quality of the streamflow remains relatively constant. Simultaneous data are not available at Pompton Lakes; however, pairs of samples taken at other times at the Mahwah site and the Pompton Lakes site (fig. 18) indicate that the streamflow from the lake is less

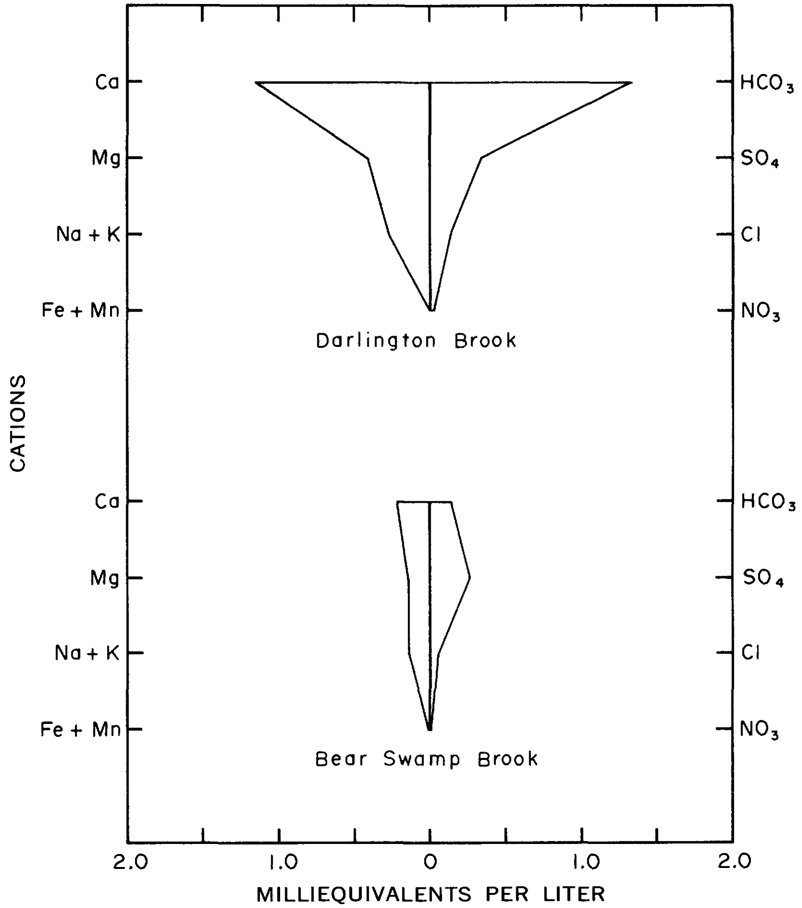


FIGURE 17. — Comparison of chemical quality of water from Darlington Brook with that from Bear Swamp Brook at low base flow, July 1, 1964.

mineralized than that entering the lake, if the chemical quality of the stream is assumed to have been uniform between Mahwah and Oakland at these times, too. Figure 18 also shows the seasonal variations in water quality as the streamflow recedes from the high spring-runoff stage to the low stage at summer's end. As the flow decreases, the ground-water contribution to the stream becomes an increasingly dominant part of the stream discharge, to the point that eventually the total flow is derived from ground-water discharge. Accordingly, the streamflow becomes more and more mineralized. (See fig. 18.)

The suspended-sediment load of the Ramapo River near Mahwah was measured during the period February 27, 1964, to June

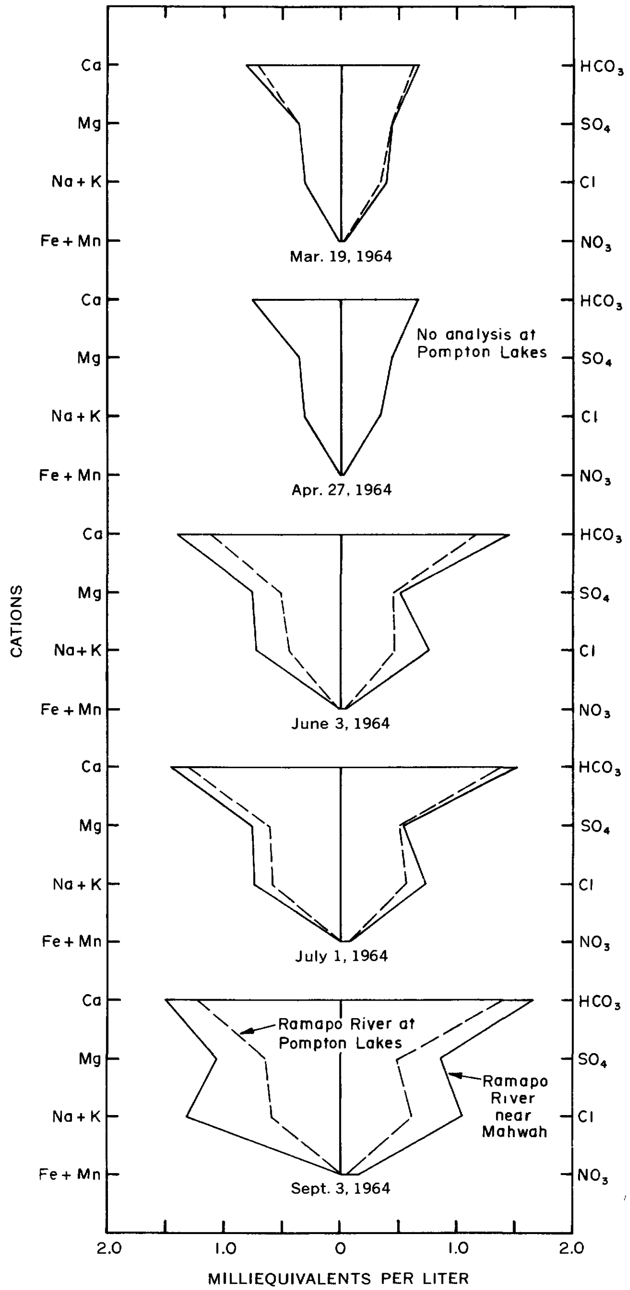


FIGURE 18. — Comparison of changes in chemical quality of streamflow at Ramapo River near Mahwah with those at Ramapo River at Pompton Lakes during the spring and summer period of 1964.

19, 1965, and these data have been published by the U.S. Geological Survey (1964, 1965). The highest sediment load observed, 950 tons per day, occurred on February 8, 1965, when the stream discharge was 1,630 cfs. The lowest sediment load, 0.1 tons per day, occurred on September 17, November 23, and November 24, 1964, on which days the respective stream discharges were 8.4, 18, and 17 cfs.

A plot (fig. 19) of these data versus stream discharge reveals that in general the greater the streamflow, the greater the sediment load. However, the relationship between sediment load and discharge of the Ramapo River is not simple. Maximum stream-sediment load occurs during storm-runoff periods, and, the greater the storm intensity and resulting runoff, the greater the sediment load. However, sediment load decreases sharply after the storm at a faster rate than the rate of decrease in stream discharge.

Temperature curves, plotted for the flow at Ramapo River near Mahwah and Ramapo River at Pompton Lakes are shown in figure 20. The curves are very similar except for the summer months, when the temperatures are somewhat lower at the Pompton Lakes site. Pompton Lake accounts for the lower temperature, for large bodies of water change temperature slowly. Annual range in temperature at Pompton Lakes is from a low of 1.9°C in January to a high of 22.5°C in July. For the river at Mahwah, the annual range in temperature is from a January low of 1.6°C to a July high of 24.9°C. The air temperature is also lowest in January and highest in July.

## INDUCED RIVER INFILTRATION

### WATER-BEARING CHARACTER OF THE STRATIFIED DRIFT IN THE RAMAPO RIVER VALLEY

Terraces of Quaternary stratified drift border the Ramapo River from the New York State line to Pompton Lakes (fig. 2). The width of these valley-fill deposits is very irregular and ranges from less than 500 feet just below Darlington to more than 4,000 feet in the southern part of Oakland. Generally, the width is on the order of 2,000 feet.

The drift consists mostly of well-sorted to poorly sorted sand and gravel. Locally, there are discontinuous lenses of silt or clay, but these are, by far, subordinate to the sand and gravel. Owing to the scour-and-fill nature of the stream-channel deposition, individual beds change abruptly, both laterally and vertically.

The thickness of the valley fill varies considerably from place to place because of the irregular land surface at some places and, also, because of the irregularity of the underlying bedrock surface

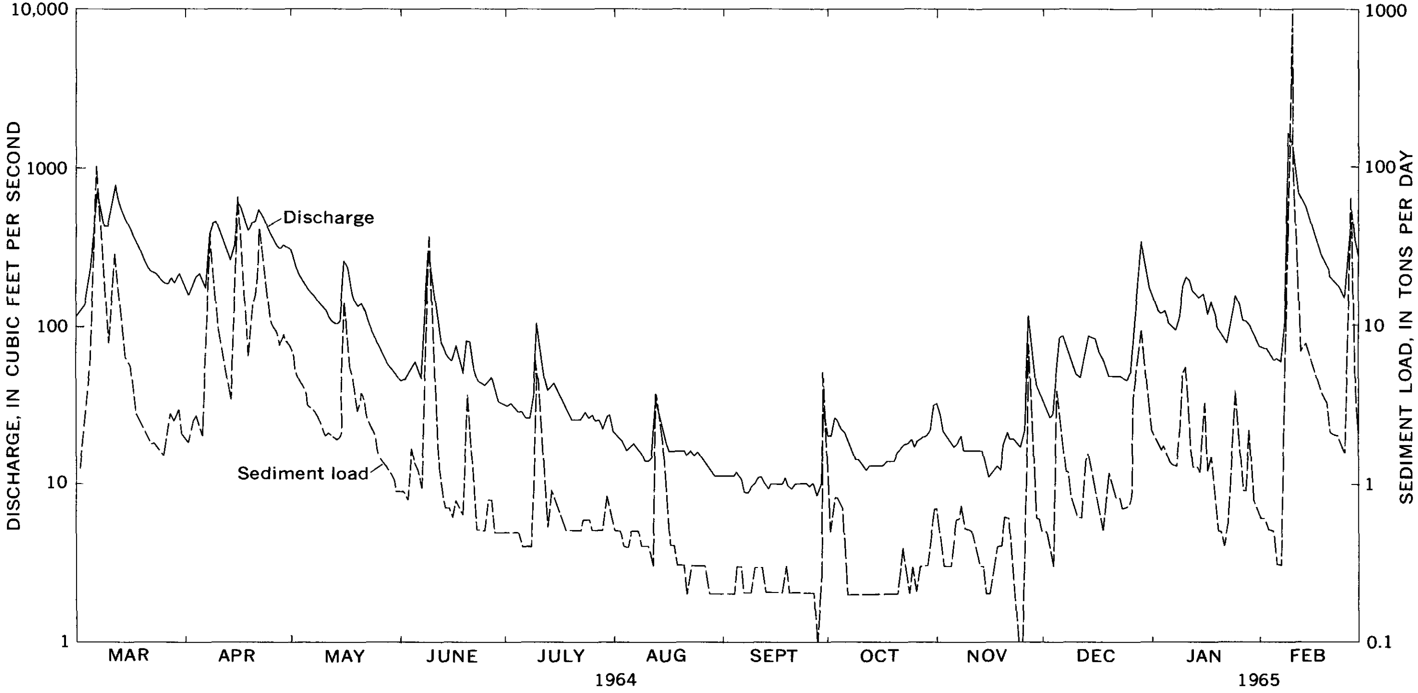


FIGURE 19.—Relation between stream discharge and sediment load at Ramapo River near Mahwah, N.J., March 1964 to February 1965.

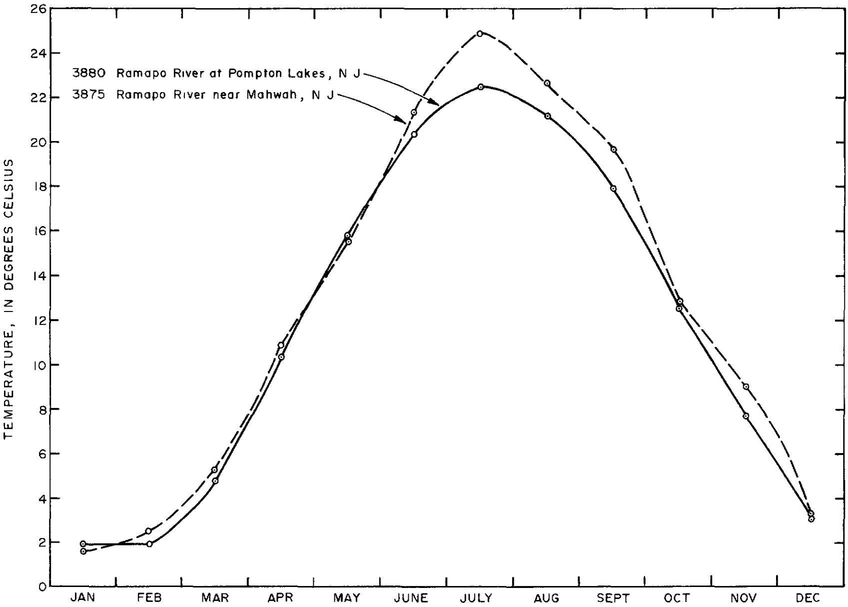


FIGURE 20. — Mean monthly water temperatures of discharge at Ramapo River near Mahwah and Ramapo River at Pompton Lakes, based on random sampling from 1930 to 1967.

everywhere. The maximum known thickness of these deposits is at Oakland, where the valley fill is 212 feet thick. (See pl. 3, section *C–C′*.) However, only the lower 160 feet is saturated there. Throughout the rest of the river valley, the maximum saturated thickness of the valley-fill deposits is on the order of 100 feet.

The magnitude of the quantity of water contained in the valley fill can be estimated if the following assumptions are made: (1) The volume of the saturated valley fill is assumed to be approximately that of an inverted triangular prism having a width of 2,000 feet, a height of 100 feet, and a length of 46,000 feet (distance from the State line to the head of Pompton Lake). The volume of this prism is 4.6 billion cubic feet. (2) The average porosity of these materials is assumed to be about 25 percent, based on a comparison of the porosities reported for similar materials elsewhere. Hence, if 25 percent of the 4.6 billion cubic feet of material is water, then an estimated 1.15 billion cubic feet of water is stored in the valley fill. This amount is equal to 8.6 billion gallons, or about 7½ times the amount of water pumped from these deposits in 1966. However, not all of this amount is recoverable from the porous ground-water reservoir because some of it adheres to the surfaces of the granular materials. The recoverable amount of water in storage in the valley fill is probably on the order of 5–7 billion gallons.

High-yielding wells can be developed in these deposits, as demonstrated by the large-diameter municipal wells at Mahwah and Oakland (table 1). Each of these wells was reported to have a tested yield of at least several hundred gallons per minute when drilled. Four of these wells, each in a different area, have reported tested yields ranging from 970 to 1,230 gpm (gallons per minute). Specific capacities of these wells vary widely but are reported to be as much as 139 gpm per foot of drawdown. The variations in well yields and specific capacities from place to place, and even within the same well field are believed to result partly from the variability of the aquifer and largely from the differences in well design and construction—particularly the degree of well development. For example, redevelopment of one of the Mahwah wells increased its specific capacity five-fold.

The high specific capacity of these wells indicates that the permeability of the valley-fill deposits is also high, as specific capacity is directly related to permeability. Laboratory permeability data for three samples collected at Oakland (Weston and Sampson, 1924, p. 70) support this. The three permeability determinations ranged from 2,600 gpd per sq ft for well-sorted medium sand to 25,000 gpd per sq ft for well-sorted coarse sand, with the permeability of the more poorly sorted gravel sample falling in between. According to Todd (1959, p. 53) such values represent permeabilities of good aquifers. Although most of the valley fill probably has a relatively high permeability, considerable difference in permeability is to be expected from place to place, as well as vertically at any one place, because of the variations in both grain size and sorting of the sand and gravel.

### WELL-FIELD HISTORY

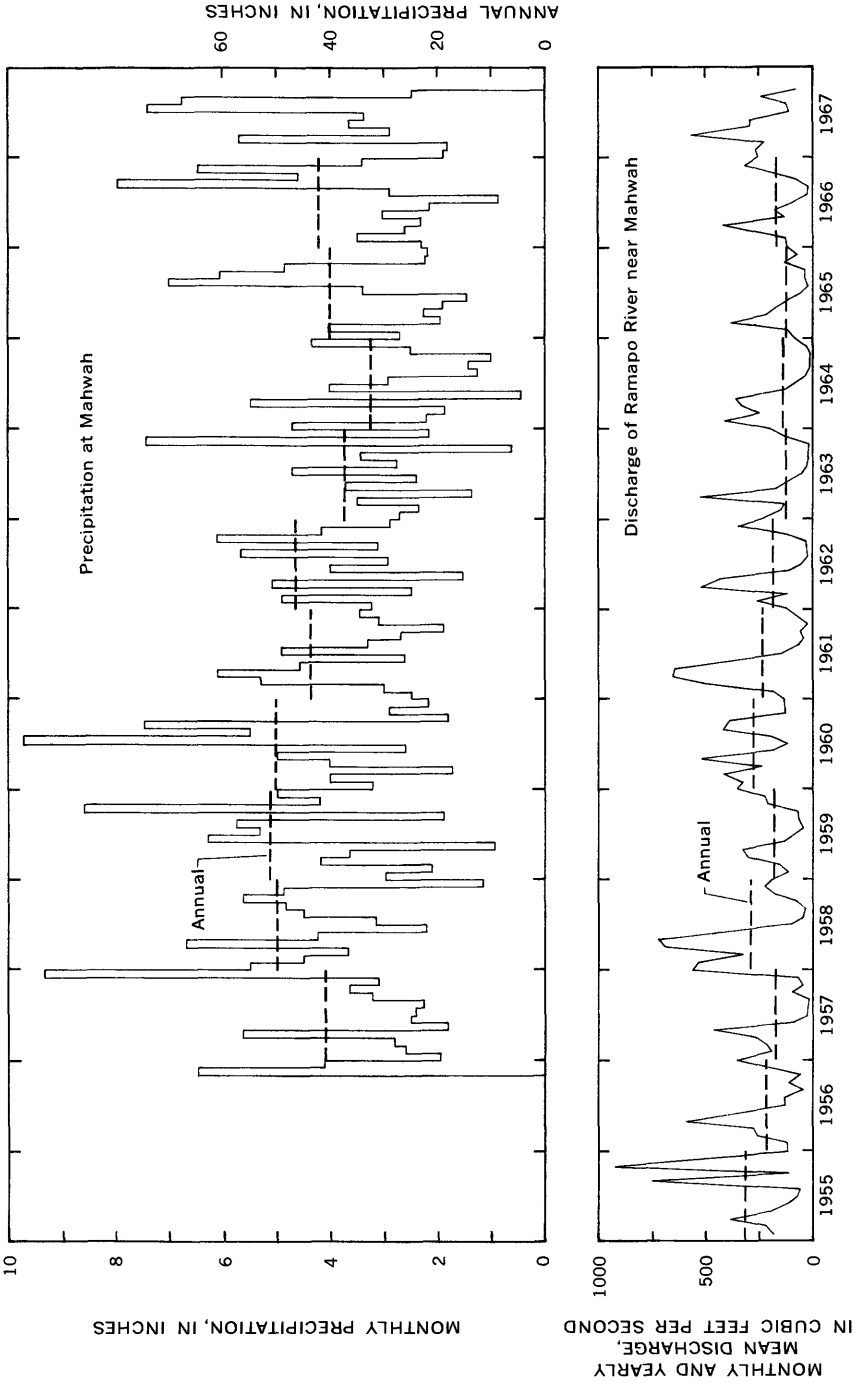
A 12-year record of water levels and pumpage from the Mahwah "Ford" well field permits an evaluation of the long-term yield of the field. These data, together with streamflow and precipitation data, are shown in figure 21.

Originally, the ground-water level in the well field was about the same as the stream level. Pumpage from this field over the years has caused a cone of depression to develop, and the ground-water level is now some 10–15 feet below the stream stage. The ground-water level in the well field varies according to discharge (or stage) of the Ramapo River and with the pumpage rate, as shown by the hydrographs in figure 21.

Figure 21 shows that through 1961 the pumpage rate remained fairly stable, at slightly more than 1.0 mgd. Concomitantly, the nonpumping, static ground-water level in the field fluctuated generally between about 250 and 240 feet above mean sea level. During this time the annual mean stream discharge varied little each year from the long-term mean. From 1962 to 1966 the pumpage rate increased, reaching a high of 1.71 mgd in 1966. The increased pumpage rate during 1962–66, coupled with an extended period of below-normal precipitation and streamflow, resulted in a decline in the nonpumping, static ground-water level, so that its range of fluctuation was from about 240 to 230 feet above mean sea level—a range 10 feet lower than that for 1955–61. Near stabilization of the pumping rate during 1964–66 resulted in the near stabilization of the water level, suggesting that a new equilibrium condition was achieved—that is, a new gradient was established that induced sufficient infiltration from the stream to balance the ground-water withdrawal. Finally, reduction in the annual pumpage rate in 1967, together with an increase in stream discharge, resulted in a rise in ground-water levels.

An estimate of the maximum yield obtainable from this well field can be made by plotting the lowest monthly water level for each of the years 1960–66 against the annual average pumpage for each year and extending this trend to a critical water-level value. (See fig. 22.) The critical water level is defined as the lowest point to which the nonpumping water level can be allowed to decline, so that the pumping level in the wells remains above the well screens. To simplify the estimate for the Mahwah "Ford" well field, only wells 1 and 4 are considered, as these are the most efficient wells (those having the highest specific capacities) in the field. The top of the screen in well 4 (the higher of the two well screens) is at an altitude of about 185 feet. Presently, wells 1 and 4 are pumped together at a combined rate of 2,000 gpm, during which well 4 has a drawdown of about 5 feet, and well 1 a drawdown of 16 feet. This pumping rate is equal to slightly less than 3 mgd. If an allowance of 20 feet is made for drawdown, and this 20 feet added to the 185-foot altitude for the top of the screen, then the altitude of the critical water level is 205 feet. In figure 22, note that the extension of the curve intersects the 3 mgd pumpage line at a lowest projected average monthly water level of 208 feet, just 3 feet above the critical water level of 205 feet. Under present recharge conditions, therefore, the maximum sustained yield that can be developed from this field is about 3 mgd.

The above estimate is based on a considerable extrapolation of the observed trend, and, at higher rates of pumpage, a steeper


Precipitation at Mahwah
Annual
ANNUAL PRECIPITATION, IN INCHES
0
20
40
60
MONTHLY PRECIPITATION, IN INCHES
0
2
4
6
8
10
Discharge of Ramapo River near Mahwah
Annual
MONTHLY AND YEARLY MEAN DISCHARGE, IN CUBIC FEET PER SECOND
0
500
1000
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967

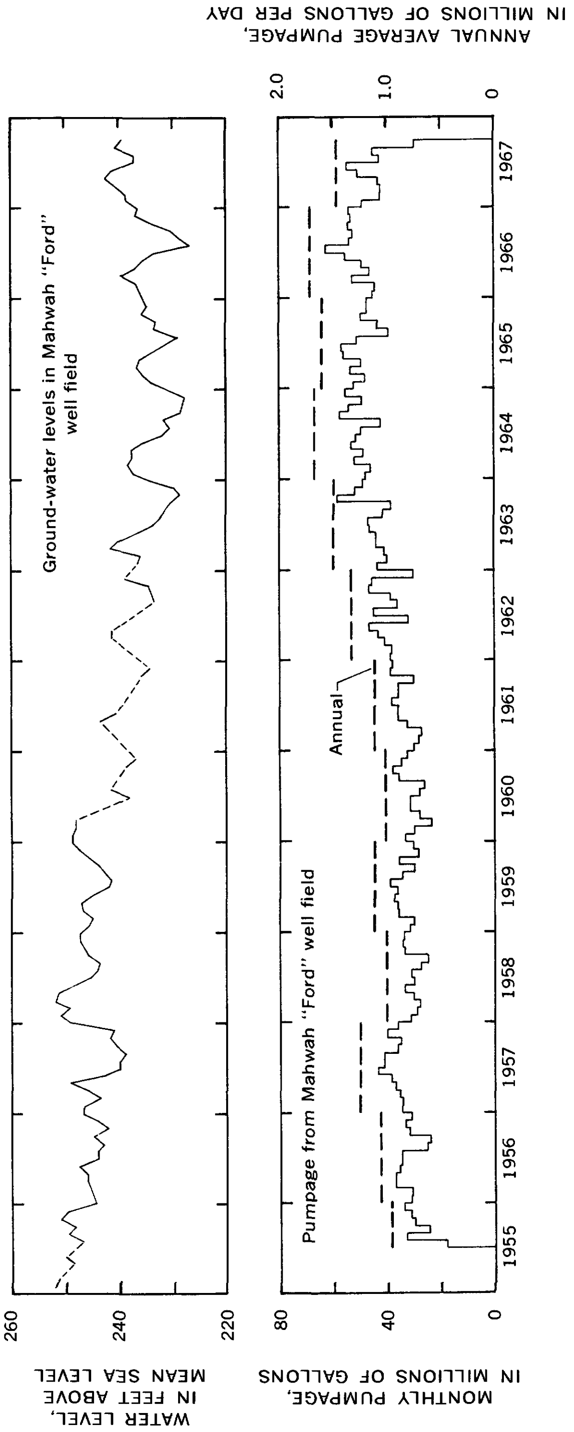


FIGURE 21. — Monthly pumpage from the Mahwah "Ford" well field, average monthly static water level in wells 1 and 4, Ramapo River discharge at gage near Mahwah, and precipitation at Mahwah, 1955–67.

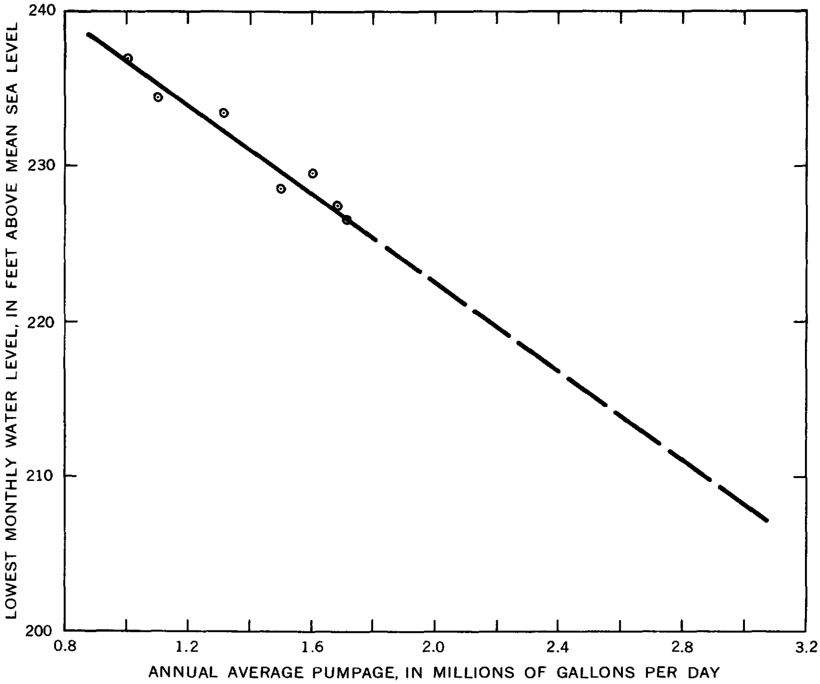


FIGURE 22. — Evaluation of yield from the Mahwah Water Department "Ford" well field, 1960–66.

drawdown relationship might apply. Conversely, the regression curve shown in figure 22 is based on the 1960–66 record—a time of prolonged drought. Streamflow available for induced infiltration during most of that period was well below normal, whereas during periods of normal precipitation, the streamflow is consistently higher, and the ground-water level is correspondingly higher. Accordingly, the estimate of 3 mgd as the maximum possible sustained yield from this well field very probably is conservatively low. It follows, then, that the availability of streamflow and the rate of stream infiltration are the major limitations affecting the ground-water supply from the drift.

## RECHARGE TO THE STRATIFIED DRIFT

Natural recharge to the stratified drift results from (1) precipitation directly on the drift, (2) infiltration of overland flow from adjacent uplands, (3) seepage from streams emerging from the uplands and flowing across the stratified drift before discharging into the Ramapo River, and (4) seepage from the Ramapo River during flood stages.

Within the river valley, the stratified drift underlies an area of about 4½ square miles. The 45 inches of average annual precipitation on this area equals 2.14 mgd per square mile, or a total of 9.6 mgd for the entire area. Not all of this amount reaches the water table, however, because of overland runoff and evapotranspiration. If the evapotranspiration (based on the annual basin yield cited earlier) were subtracted, the remaining precipitation represents a maximum recharge potential of only 1.2 mgd per square mile, or a total of 5.4 mgd for the 4½-square-mile area. Accordingly, the aquifer must depend on other sources of recharge to support monthly well yields greater than several millions of gallons per day without depleting ground-water storage excessively.

The amount of upland runoff that recharges the stratified drift, either from overland runoff or from tributary stream seepage, is difficult to estimate; however, the amount probably is not very large. In fact, upland runoff is believed to be the least significant source of recharge to the stratified drift. Seepage from the Ramapo River during flood stages is considered to be a major source of recharge, as shown by the stage-hydrograph comparisons made in the next section, but this amount, too, is difficult to estimate.

Even more important than the naturally occurring seepage during flood stages is the amount of recharge that could be continuously induced from the Ramapo River by the withdrawal of water from wells tapping the drift. The amount of induced seepage is important because it constitutes a major limitation to the amount of water that can be developed from the aquifer. As will be demonstrated, ground-water level is closely related to stream discharge (or stage), and a high stream discharge results in a high ground-water level. Moreover, the higher the stream discharge, the greater the area through which infiltration can occur.

### HYDRAULIC CONTINUITY BETWEEN THE STRATIFIED DRIFT AND THE RIVER

For the sand and gravel deposits to supply high sustained well yields, the deposits must be hydraulically connected with the river in order to receive induced seepage (recharge) from the river. Several approaches may be employed to demonstrate the existence (or, conversely, the lack) of interconnection. Those used in this study are as follows:

1. Intersection of natural ground-water-level profiles with the stream.
2. Correlation of fluctuations in both the stream stage and the ground-water level.

3. Comparison of the seasonal variations in temperature of ground water and of surface water.
4. Evaluation of pumping-test data.
5. Comparison of chemical quality of water from the stream with water from the stratified drift.
6. Seepage losses.

Appraisals of each of these approaches are given below.

### GROUND-WATER-LEVEL PROFILES

If ground water in a stream valley is hydraulically connected to the surface water, a profile showing the ground-water level across the valley should intersect the stream. If such a profile shows the ground-water level to be considerably above or below the stream level, there probably is an impermeable barrier between the two water bodies that prevents direct hydraulic connection.

Information sufficient for constructing a ground-water-level profile is available for only one place in the valley. (See pl. 3, section *A–A′*.) At that locality the profile intersects the stream. Other static water-level data from wells and borings, both adjacent to and away from the stream, indicate that the ground-water level in all these holes is about the same as the river stage opposite them. Geologic data indicate that confining materials are sparse. Hence, it is concluded that the ground-water-level profile everywhere would intersect the stream under nonpumping, static conditions, which, in turn, suggests that good hydraulic continuity exists throughout the river valley.

### FLUCTUATIONS IN STREAM STAGE AND GROUND-WATER LEVEL

During the course of the investigation, fluctuations of ground-water level in the stratified drift were observed at three places in the valley. These places were (1) in the Mahwah Water Department "Ford" well field (well 22, table 1), on the west side of the Ramapo River in Mahwah; (2) in the Oakland Water Department "Soons" well field (well 10, table 1), on the east side of the river, just below the Oakland-Mahwah boundary; and (3) in an unused well field of the Oakland Water Department (well 3, table 1), on the east side of the river, near the center of Oakland. (Well numbers cited above are those used in fig. 8 and in the first column of table 1 of the present report.)

A part of the record at each of the three well sites, correlated with the fluctuations of surface-water stage opposite each well site, is presented in figures 23, 24, and 25. The surface-water hydrograph was synthesized by correlating a few stream-stage measurements obtained at each site with the continuous stream-

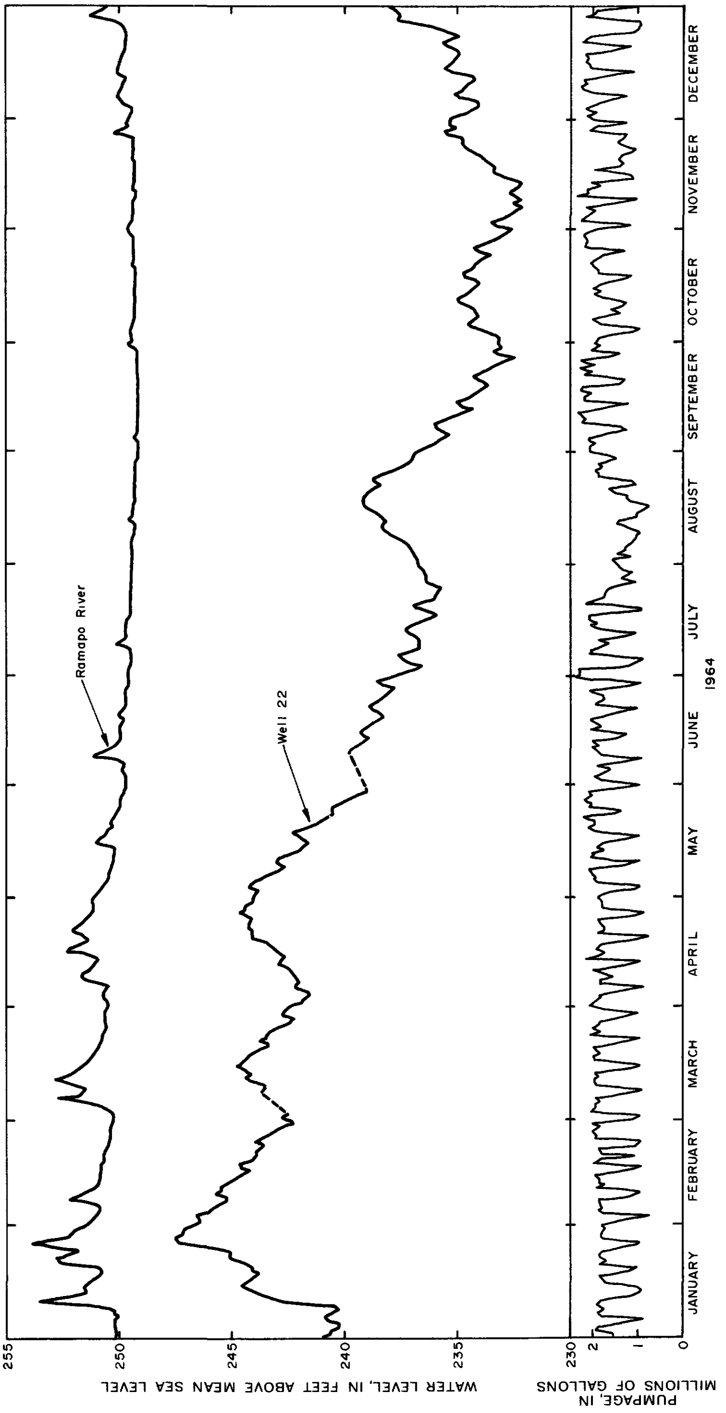


FIGURE 23. — Daily pumpage from the Mahwah "Ford" well field, highest daily water level in observation well (No. 22), and synthesized mean daily stage of the Ramapo River opposite the well field, 1964.

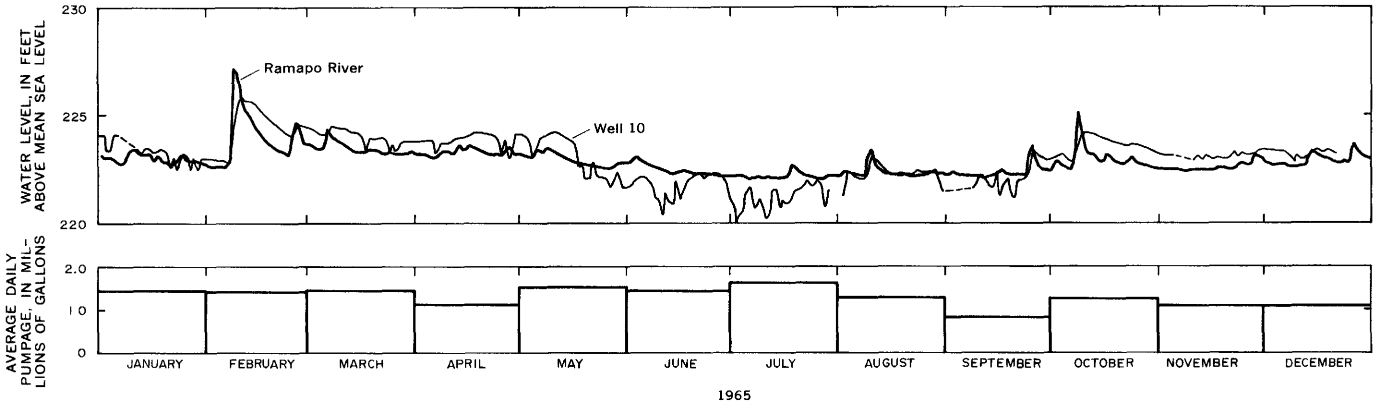


FIGURE 24. — Average daily pumpage from the Oakland "Soons" well field, highest daily water level in observation well (No. 10), and synthesized mean daily stage of the Ramapo River opposite the well field, 1965.

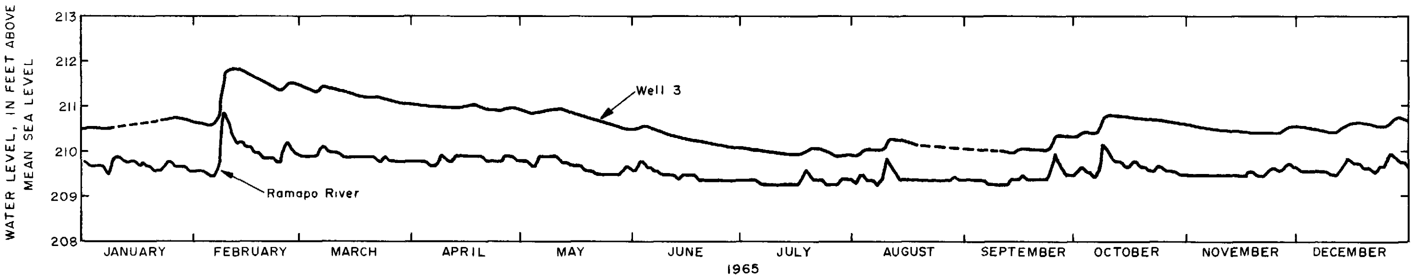


FIGURE 25. — Highest daily water level in observation well (No. 3) near Oakland Center and synthesized mean daily stage of the Ramapo River adjacent to the well, 1965.

flow record obtained at the stream gage near Mahwah. Although the daily stream-stage values so obtained are not precise, they do show the similarity between the fluctuations in stream stage (discharge) and those in ground-water levels in the wells.

The hydrographs for the Oakland Center site (fig. 25) show close agreement between the fluctuations in stream stage and those in ground-water level, particularly during the periods of rising stream discharge. Declines in ground-water level are more gradual than the declines in stream stage, partly because water drains more slowly from the stratified drift. Thus, the stratified drift acts as a storage reservoir, not only for the water infiltrated directly from precipitation, but also for a large amount of bank storage.

Hydrographs of ground-water levels obtained at the Oakland "Soons" well field (fig. 24) and the Mahwah "Ford" well field (fig. 23) also show a similarity in fluctuations with those of the stream hydrographs opposite those sites. However, the ground-water level is affected by pumping in these well fields, and, at times, the fluctuations caused by pumping mask those which are in response to stream-stage fluctuations. Pumpage from the two well fields is plotted on these hydrographs, and the influence of pumping changes on ground-water levels is readily apparent.

Flood-stage data obtained for two floods in 1955 provide additional evidence in support of hydraulic continuity between the river and the stratified drift (fig. 26). The ground-water level was observed at the Mahwah "Ford" field well 4, which is about 50 feet west of the Ramapo River, and the river stage was measured at the gage about 5,000 feet upstream. Similarity of the graphs within each set is readily apparent, although the peak ground-water level occurred several hours after the maximum river stage. Undoubtedly, precipitation directly on the drift during the storm contributed to the rise in ground-water level, but the similarity between the rise in stream stage and that in ground-water level strongly suggests direct hydraulic continuity between the two water bodies.

### SEASONAL TEMPERATURE VARIATIONS OF GROUND WATER AND SURFACE WATER

Ground water in the basin, occurring at depths of several tens of feet to a few hundred feet, generally has a nearly constant year-round temperature that approaches the average annual air temperature of the areas. Perlmutter (1959, p. 6) reported the average annual air temperature at Suffern, N.Y., to be about 51°F (10.6°C).

Temperature of ground water in the Mahwah "Ford" well field

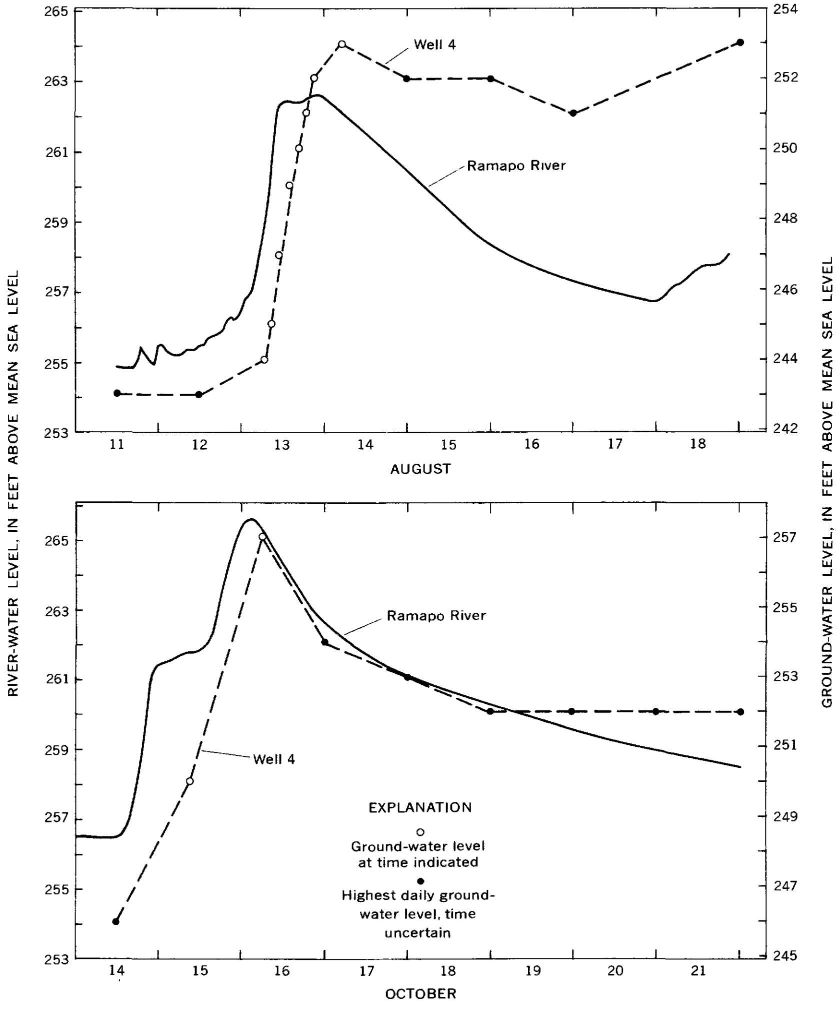


FIGURE 26. — Ramapo River stage at gage near Mahwah and water level in well 4 at the Mahwah "Ford" well field during two major floods in 1955.

was measured periodically during 1964, 1965, and part of 1966. These temperatures ranged from a low of about 8°C in early April to a high of about 13.5°C in late September, as shown in figure 27. The variation in ground-water temperature is not nearly so great as the variation in river-water temperature, but it is significantly more than one would expect for normal ground-water conditions. The average river-water–temperature cycle ranges from a low of about 3°C in January to a high of about 25°C in July. The exact timelag of ground-water maximum and minimum temperatures with those of surface water cannot be obtained from figure 27

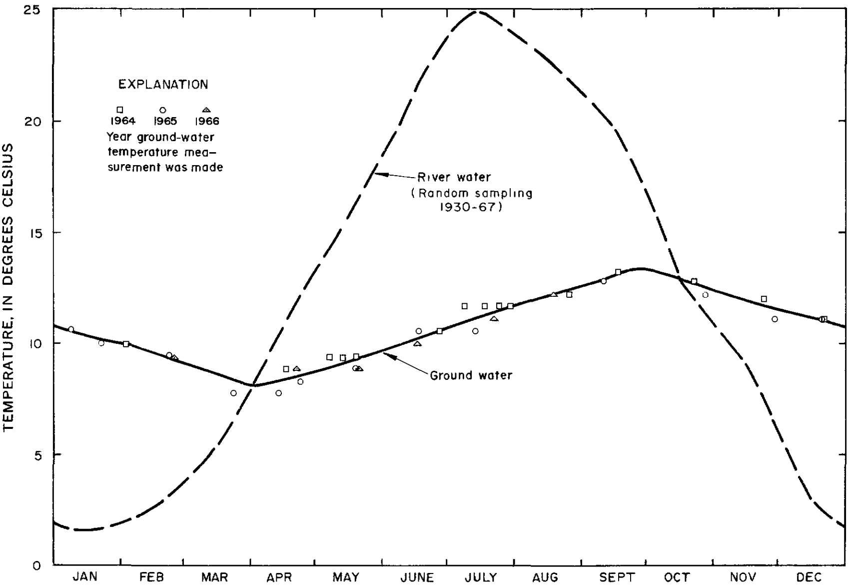


FIGURE 27. — Water temperatures of the Ramapo River at gage near Mahwah and ground-water temperatures at the Mahwah Water Department "Ford" well field.

because the surface-water data represent monthly average figures which are here plotted in midmonth. However, the timelag deduced from these curves is at least 2 months. The 2-month timelag for ground-water temperatures applies to this particular well field, whereas water temperatures in wells that are closer to the stream or that are screened at shallower depths would have proportionally shorter timelags.

The fact that the range in ground-water temperatures is relatively wide may be indicative of induced river recharge. However, the range is much less than the range in surface-water temperatures partly because the water pumped from the wells at any one time is a composite of the water which has entered the aquifer at various times—that is, because of various distances between points of infiltration and point of withdrawal. For example, if cold water that has traveled a long distance reaches a well at the same time as warm water transmitted from a shorter distance (or the reverse), the temperature extremes would be subdued by the mixing of these waters. Also the heat-exchange properties of the aquifer would tend to regulate the water-temperature extremes. The timelag in ground-water maximum and minimum temperatures, compared with maximum and minimum stream-water temperatures, reflects only in a general way the time it

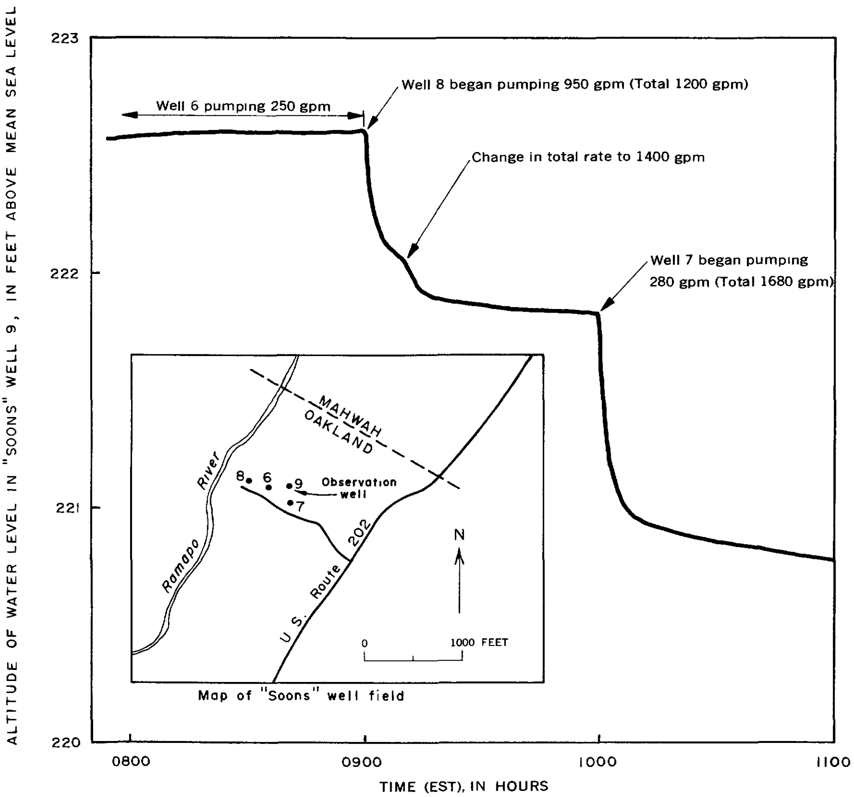


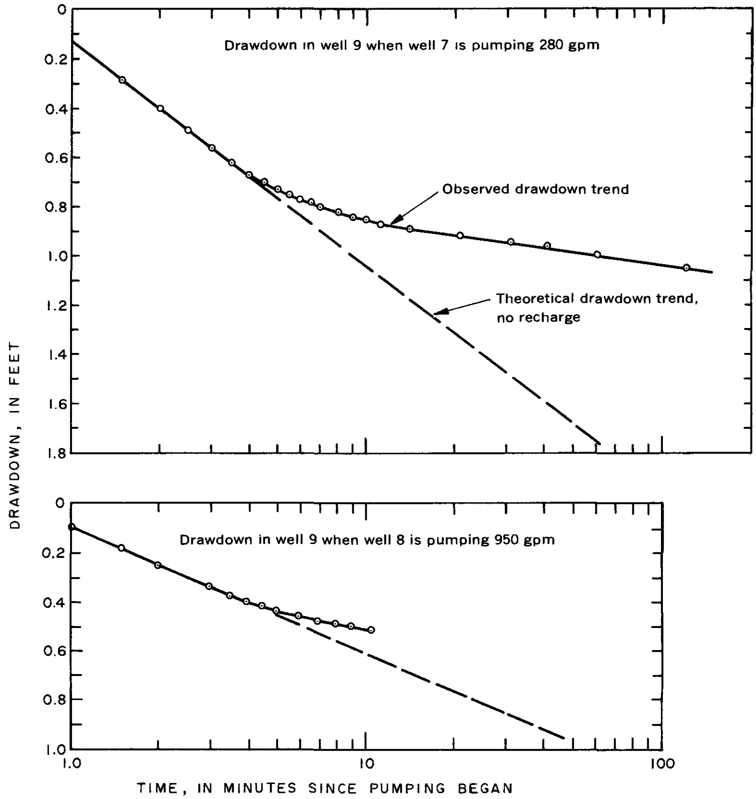
FIGURE 28. — Record of Oakland "Soons"

takes for the water to move from the streambed to the aquifer and, thence, into the well.

## PUMPING-TEST ANALYSIS

When a well is pumped, a cone of depression—or a drawdown of the water level—is created around the well, and the cone continues to expand and deepen until it captures sufficient water to equal the water being discharged from the well. This equilibrium can be reached through either an increase in the rate of recharge to the aquifer or a decrease in the rate of natural discharge from the aquifer. If a stream intersects the aquifer, water can be provided to the aquifer by the stream when the cone of depression expands to the stream. Once this occurs, the drawdown cone either ceases to expand or continues to expand at a much lower rate.

A controlled pumping test was conducted at the Oakland "Soons" well field to determine the presence or absence of a recharge boundary resulting from intersection of the drawdown



well-field test, May 18, 1965.

cone with the nearby Ramapo River. The test consisted of monitoring the water level in an unused well in the field while other wells in the field were pumped. The water-level record, together with a summary of the pumping-rate changes, is presented in figure 28. The water-level trends show that the drawdown rate is very high immediately after a pumping-rate increase. However, the rate of drawdown decreases rather abruptly within minutes after the rate of pumping is increased, indicating the presence of a recharge boundary close to the well field. The most likely nearby source of recharge is the Ramapo River; hence, it can be concluded that the river is the recharging boundary and that it is hydraulically continuous with the aquifer.

## WATER-QUALITY COMPARISONS

Comparison of chemical analysis of water from the Ramapo River with water from wells tapping the valley-fill deposits shows that the two waters are similar. No unusual correlative or discrepant value of a chemical constituent was observed in either of the waters. Thus, available water-quality data do not provide evidence of favorable hydraulic connection, nor do the data constitute evidence against the existence of the connection.

### SEEPAGE LOSSES

Perhaps the most convincing evidence of intimate hydraulic connection of the Ramapo River and the valley-fill aquifer is the seepage losses noted throughout the valley from Mahwah (station 3875) to Oakland (station 3879.1). Streamflow measurements were made on five occasions on both the tributary streams and the main stream at several places. Similar measurements were made in the reach between Mahwah and Darlington (station 3876.1) on one other occasion. Analysis of these data has shown the Ramapo River to be a losing stream along various reaches at different times of the year. A graphic summary of these data is given on plate 4.

If the contribution of tributary streams is excluded, for each of the days of measurement, the Ramapo was a losing stream from Mahwah to below Darlington (station 3876.7). Considering the measurements made in 1964, the net loss in streamflow is seen to extend farther downstream from Mahwah as the summer progresses. The graphs (pl. 4) also show that some of the water which is lost in the upper reaches of the channel perhaps reappears downstream. However, much of the seepage losses probably results from the ground-water pumpage along the channel, which induces river recharge. Centers of pumping are shown on plate 4.

The extension downstream of the losing reach of the stream through the summer of 1964 may be partly the result of increased pumpage from the well fields, particularly in relation to the smaller seasonal magnitude of the streamflow, as suggested by the hydrograph of the observation well (No. 3) near Oakland Center (fig. 29). As demonstrated previously, the water level in this well fluctuates with the stream stage; this is also indicated on the hydrograph (fig. 29) from April to late August 1964. In late August and September, the ground-water-level decline in well 3 near Oakland Center (fig. 29) is sharply accentuated, whereas the surface-water stage shows almost no change. The sharp decline in ground-water level is the result of the marked increase in pumpage from the nearby Oakland "Bush" well field during August and September. The pumpage increase at this well field, some 2,000 feet downstream from the observation well, expanded the drawdown cone to the vicinity of the observation well. Thus, the enlarged drawdown cone probably induced greater infiltration of river water at a time when stream stage was very

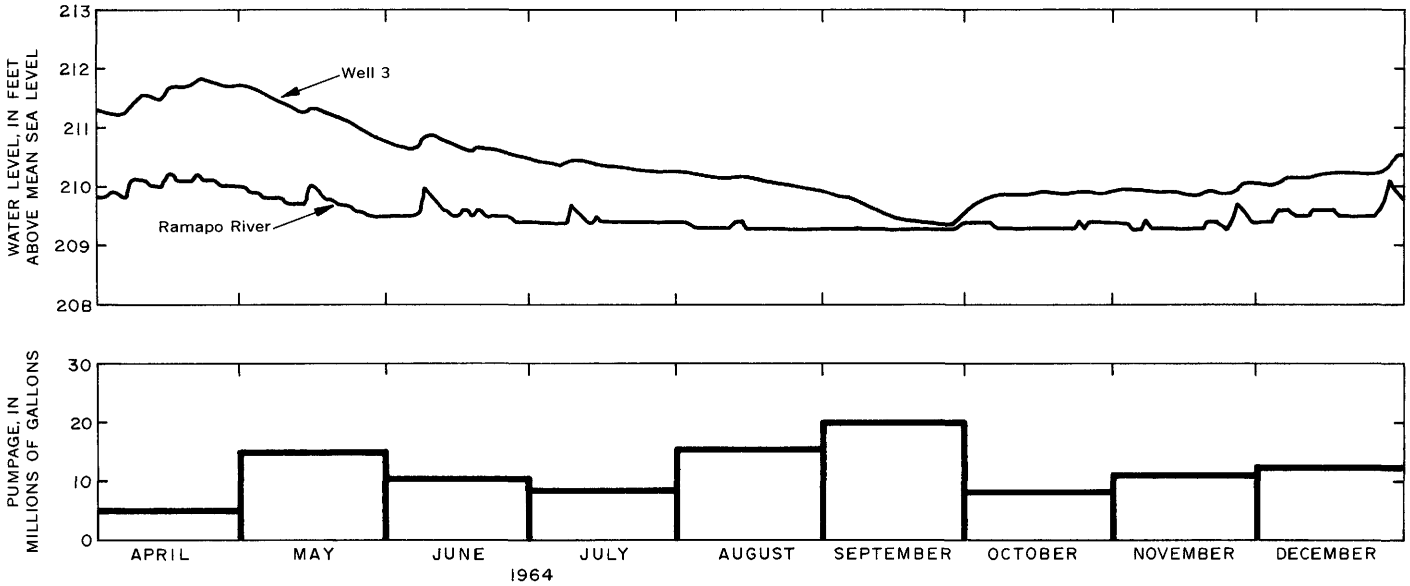


FIGURE 29.— Monthly pumpage from Oakland "Bush" well field, highest daily water level in observation well (No. 3) near Oakland Center, and synthesized mean daily stage of the Ramapo River adjacent to the well, April–December, 1964.

low, resulting in the farthest downstream extension of the "losing" reach of the stream. Undoubtedly, the high rate of evapotranspiration also caused some reduction in streamflow, but the amount is unknown.

### LIMITATIONS TO THE SUPPLY

The stratified drift can yield water to wells at a high rate, owing to its high permeability. However, despite its unit storage also being high, its overall storage capacity is small because of its limited volume. The storage has been shown to be on the order of 7½ times the volume of water pumped in 1966. Hence, for the drift to function as a high-capacity aquifer, it must depend on fairly continuous recharge.

Direct rainfall can be expected to supply only a few million gallons per day of recharge. The Ramapo River is a source of continuous recharge, but because of its highly variable discharge, its ground-water recharge potential is also highly variable. Moreover, the existing water-diversion rights to the Ramapo streamflow at Pompton Lake and downstream preclude any appreciable reduction in streamflow, particularly during low-flow periods.

The low-flow frequency curves in figure 4 show that near Mahwah a flow of 41 cfs (26 mgd) for 90 consecutive days has a recurrence interval of 2 years — or a 50 percent probability of such a low flow occurring each year. For 30 consecutive days the 2-year recurrence-interval flow is 30 cfs (19 mgd), and for 7 consecutive days it is about 22 cfs (14 mgd). These discharges near Mahwah represent about 75 percent of the corresponding flows to be expected at Pompton Lakes, based on the equal-yield relationship developed earlier. Therefore, large withdrawals of ground water without return of the used water to the stream could reduce these stream discharges to the extent that the stream might go completely dry for several days under extended dry conditions.

Low-flow augmentation of Ramapo River flow would provide for a more constant rate of recharge and, also, for sufficient streamflow to prevent dry streambed conditions from occurring. The many lakes, some of which are already controlled, offer abundant possibilities for storing the excess winter and spring runoff. Among favorable sites in New Jersey which could be considered are Havemeyer Reservoir, MacMillan Reservoir, and Bear Swamp Lake. Combined capacity of these reservoirs after construction of higher dams would be 4.4 billion gallons (Neglia and others, 1967). Owing to the small catchment area at each of these sites, water would have to be pumped up from the Ramapo River in order to utilize the maximum practical storage available at these sites. A benefit-cost analysis for such low-flow augmentation would require a detailed engineering study, which is beyond the scope of the present study.

With or without low-flow augmentation, better use can be made of excess runoff by improving the hydraulic interconnection between the river and the aquifer. At present, the area through which infiltration can occur is limited to the relatively narrow stream channel. The use of wing dams, recharge pits, spreading areas, and canals would increase the infiltration area and, thus, allow for a higher rate of ground-water recharge. Existing gravel pits could be utilized as recharge pits, once the gravel deposits have been worked to capacity. Moreover, the gravel deposits in other areas could be worked, and, in so doing, additional recharge pits would be created as a by-product. These artificial recharge works could be used during times of high discharge to accelerate replenishment of aquifer storage which was depleted during times of inadequate recharge. Although such recharge works are certainly feasible physically, a detailed cost-benefit analysis would have to be made to determine the economic feasibility of the various plans.

An onstream reservoir has been proposed for construction at Oakland to develop the water resources of the Ramapo basin. Neglia, Elam, and Rothenberg (1967, p. 18) cited a study by the U.S. Army Corps of Engineers for a reservoir which would have a dependable yield of about 72 mgd. However, because of existing downstream water-diversion rights of the North Jersey District Water Supply Commission at Pompton Lake, and of the Passaic Valley Water Commission on the Pompton and Passaic Rivers, and because of the State requirement for a minimum bypass flow, the dependable reservoir yield is reduced to 6 mgd (Neglia and others, 1967, p. 19).

The maximum yield that can be developed from the stratified drift under natural conditions—that is, with no low-flow augmentation or artificial recharge—is somewhat meaningless, inasmuch as present diversions already result in a significant depletion of streamflow during times of low streamflow. It has been shown, however, that development of a sustained yield of 3 mgd at a site from two properly constructed wells is feasible under the existing conditions. The valley contains numerous other sites favorable for the construction of high-yielding wells, but it would not take many more of these installations pumping out of the valley to nearly dry up the stream at times. Much of the water might, however, be returned to the stream after it is used and, hence, become available for reuse. The treated water might be returned directly to the stream, or it could be discharged into a worked-out gravel pit.

Based on the streamflow losses cited earlier, rates of streamflow infiltration can be computed for the reach of the Ramapo River in the vicinity of the Mahwah well field, where the channel bed consists mainly of sand and gravel. The seepage losses and the calculated infiltration rates are as follows:

| Date of measurement | Seepage loss (cfs) | Stream gaging-station No. (below gage near Mahwah) | Channel length (ft) | Infiltration rate (cfs per 1,000 ft of channel length) |
|---|---|---|---|---|
| 9-25-63 | 2.5 | 3876.7 | 22,000 | 0.11 |
| 10-23-63 | 5.5 | 3876.1 | 15,000 | .37 |
| 4-27-64 | 6.5 | 3876.7 | 22,000 | .30 |
| 6- 3-64 | 7 | 3876.7 | 22,000 | .32 |
| 7- 1-64 | 7.5 | 3876.7 | 22,000 | .34 |
| 9- 3-64 | 5.5 | 3876.7 | 22,000 | .25 |

Converting from cubic feet per second to gallons per day, the maximum rate observed equals 240,000 gpd per 1,000 feet of channel length. Within this reach of the stream the channel is about 100 feet wide. The seepage rate per unit area equals 2.4 gpd per square foot of streambed. The temperature of the stream water affects the infiltration rate considerably, as water is more viscous at colder temperatures. However, the estimated seepage rate of 2.4 gpd per square foot of streambed was determined for river water at about the mean annual temperature; hence, this value should be representative of average conditions.

On the basis of an average natural-seepage rate of 2.4 gpd per square foot of streambed, a channel length of 46,000 feet from the State line to the head of Pompton Lake, and an average channel width of 100 feet, it should be possible to develop a supply of at least 11 mgd from pumping wells tapping the stratified drift without the aid of any artificial recharge facilities. Because the infiltration rate is directly related to the gradient induced between the stream and the aquifer, an increase in gradient, owing to an increase in pumpage, would result in a greater infiltration rate and, consequently, a larger quantity of water that could be developed from the stratified drift—provided that the necessary streamflow is available for infiltration.

The Ramapo River at Pompton Lakes has a 46-year average annual discharge of 289 cfs, or about 187 mgd. However, the lowest mean discharge of record for a water year was only 138 cfs, or 89 mgd. This occurred in the 1965 water year, and it represents a discharge adjusted for the diversion from Pompton Lake. Present (1968) average daily demand on flow from the Ramapo River amounts to 65 mgd, with 25 mgd representing the diversion to the Wanaque Reservoir by the North Jersey District Water

Supply Commission and 40 mgd representing the minimum-flow requirement below Pompton Lake. Diversion from Pompton Lake, when the flow is greater than 40 mgd, is allowed to the extent of an annual average draft of 25 mgd, with the exception that no pumping is allowed during the June through September period. If the present demand is subtracted from the lowest annual discharge, the water remaining totals 24 mgd. However, because part of this flow may have occurred as flood flow over and above the rate at which the streamflow can be pumped and stored, this method of analysis provides only a crude approximation of the streamflow remaining for development in the dryest year of record. A more detailed engineering analysis follows.

The amount of Ramapo River water available for development by recharge to the stratified drift for the drought period October 1964 to September 1967 was studied by Asghar Hasan (written commun., Aug. 25, 1969) of the New Jersey Division of Water Policy and Supply. Hasan calculated the daily quantities of river water available after diversion to Wanaque Reservoir by the North Jersey District Water Supply Commission (legal diversion limit, 9.125 billion gallons per year) and legal minimum-flow requirements (40 mgd, if available) below Pompton Lake.

The precise quantity of water available for development is based not only on daily flows in the Ramapo River, but also on the facilities for recharging the water to the stratified drift and on the storage capacity of the stratified drift. If 5.5 billion gallons (approximately two-thirds) of the 8.5 billion gallons in the stratified drift can be temporarily withdrawn from storage, a sustained yield of 20 mgd from the stratified drift can be achieved by inducing recharge from available river water, up to a maximum of 43 mgd. By increasing the maximum aquifer recharge to 75 mgd, the sustained yield is increased only by 5 mgd because of the limited number of days flows of that rate are available. Such high recharge rates are possible only through the use of extensive facilities, such as pumping stations, recharge pits, and spreading areas.

According to Hasan's analysis, water would be diverted from the river for recharge to the stratified drift only on days when the stream discharge exceeds 40 mgd after diversion to Wanaque Reservoir. However, because considerable natural recharge will occur by seepage from the river, sustained withdrawals of 20–25 mgd from the drift would result in a dry stream during periods of normally very low flow, and, in such event, low-flow augmentation from surface reservoirs would be desirable. Indeed, the conjunctive use of the stratified drift and the surface reservoirs previously cited could permit a sustained yield greater than 25 mgd from the Ramapo River basin.

Furthermore, if the water pumped from the drift were returned to the drift, after use and satisfactory treatment, by such techniques as gravel-pit recharge, seepage basins, or spreading grounds, water losses from the Ramapo River could be minimized. Because household use involves little consumption of water and because that will probably be the major use of water within the basin, it may be possible to reclaim for reuse most of the water pumped from the stratified drift. Again, an economic study would be needed to compare the cost of such a plan against other alternatives.

The technical feasibility of recharging the drift with treated sewage can be tested by employing existing facilities near Mahwah, with perhaps some modifications. Effluent from the sewage-treatment plant on the Ramapo River near the New York State line could be piped to the gravel pits adjacent to the Mahwah "Ford" well field about 1 mile downstream. Acceptance of the effluent by the stratified drift could be determined and also the effects of the recharge on the cone of depression created by the well field could be studied.

## SUMMARY

This study of the water resources of the Ramapo River basin attempted to define the hydrology of the basin and evaluate the feasibility of developing large ground-water supplies from the stratified drift in the Ramapo River valley by inducing recharge from the river. Also considered briefly is the possibility of recharging the stratified drift with treated sewage effluent. The waters of the basin must be recognized as a single resource, as the development of either the ground water or the surface water affects the development of the other.

The Ramapo River is a major tributary of the Pompton River and, thence, the Passaic River. The Ramapo's headwaters and 70 percent of its drainage area are in New York; therefore, the amount of water available for development in the New Jersey part of the basin depends to a great extent on the control of an out-of-State source.

In New Jersey, the Ramapo River basin drains parts of Bergen and Passaic Counties. The New Jersey part of the basin is rather sparsely populated, and most of the development is east of the river. The area west of the river, which is mountainous and wooded, is underlain by Precambrian gneiss and is sparsely mantled with Pleistocene glacial deposits. In the area east of the river, however, glacial deposits occur nearly everywhere, and the underlying bedrock is made up of shale, sandstone, and conglomerate of the Brunswick Formation and the Watchung Basalt, both of Triassic age. Deposits of stratified drift more than 100 feet thick occur throughout the river valley.

The basin receives an average annual precipitation of about 45 inches. The average annual runoff at Pompton Lakes is 25 inches, and the remaining 20 inches is lost to evapotranspiration. Discharge of the Ramapo River is highly variable, as demonstrated by the flow-duration curve and by the flood-frequency and low-flow-frequency curves. Tributary discharge is also highly irregular, particularly in the area underlain by the gneiss because of the low-storage capacity of the rocks and the rough topography. Many of the small tributaries go dry during extended periods of no precipitation.

Some ground water can be obtained from wells practically everywhere in the basin. The Brunswick Formation is the most productive consolidated-rock aquifer. Large-diameter public-supply wells tapping the Brunswick commonly yield 100–200 gpm. Most of these wells have specific capacities of 0.5–1.5 gpm per foot of drawdown. Little information is available on the yields of wells tapping the gneiss and the basalt, but, in general, they are capable of yielding at least small amounts of water for domestic use, and large yields from these aquifers are not to be expected. The stratified drift in the Ramapo valley constitutes the most productive aquifer in the basin. Yields of more than 1,000 gpm and specific capacities of more than 100 gpm per foot of drawdown have been obtained from wells developed in the stratified drift. In the uplands, around Franklin Lake and in the Campgaw–Crystal Lake area, the stratified-drift deposits are thick enough to constitute minor aquifers. Based on base-flow measurements made during the spring and summer of 1964, the sustained ground-water yield in upland areas is estimated to be about 200,000–300,000 gpd per square mile for the drift-covered Brunswick Formation and about 100,000–200,000 gpd per square mile for the gneiss and basalt.

Ground water is utilized for water supply throughout the basin. Major users are the public-supply systems of Mahwah, Oakland, and Ramsey, and, to a lesser extent, Wayne Township. Pumpage from all aquifers for all uses in 1966 was less than 5 mgd. The stratified drift supplied about 75 percent of the ground water withdrawn by the public-supply systems; the remaining 25 percent was obtained from the Brunswick Formation. Continued population growth within the basin will place greater demands on the ground water.

Ground-water quality varies from aquifer to aquifer. Water from the gneiss has a low dissolved-solids content, is soft to moderately hard, and has a pH that is acidic to neutral. Water from the Brunswick Formation contains moderate amounts of dissolved solids, is moderately hard to very hard, and it has a pH that is neutral to slightly alkaline. The stratified drift generally yields water that is intermediate in chemical quality between that of the gneiss and that of the Brunswick Formation.

Surface-water quality varies greatly during the year, depending in part upon the percentage of streamflow derived from ground-water discharge. At times of low flow, the chemical quality of water from the tributary streams is substantially the same as that of ground water from the rocks drained by the streams. At higher flows, the stream water is less mineralized. The Ramapo River changes very little chemically between Mahwah and Oakland, but its dissolved solids and hardness are somewhat reduced in Pompton Lake. The Ramapo, like its tributaries, is more highly mineralized during periods of low flow.

The water supply of the basin can be best developed through the pumping of wells constructed in the stratified drift in the Ramapo River valley. Induced river infiltration would result. The stratified drift is an aquifer of high permeability, but its storage capacity is small, owing to its limited areal extent. Maximum saturated thickness of the drift throughout the valley is about 100 feet, and ground-water storage is estimated to be 8.5 billion gallons. The Ramapo River is a major source of recharge to the drift. Hydraulic connection exists between the river and the aquifer, as demonstrated by water-level profiles, correlation of stream-stage and ground-water-level fluctuations, comparison of seasonal temperature variations of ground water with those of surface water, pumping-test data, and seepage losses.

Downstream requirements limit reduction in the minimum flow of the Ramapo River at Pompton Lakes when it is 40 mgd (61.9 cfs) or less. Low-flow-frequency curves show that flows of less than 40 mgd for 90-day periods have a recurrence interval of 1.5 years. When the flow is greater than 40 mgd, diversion from Pompton Lake of an annual average draft of 25 mgd is allowed; however, no pumpage is allowed for the June through September period. Large-scale pumpage from the stratified drift would induce infiltration from the river and thereby affect these downstream rights. In fact, the stream might go completely dry at times because of such development.

Low-flow augmentation and recharge-storage structures would increase the amount of water that can be developed from the drift. Reservoir sites for storing excess winter and spring runoff could be developed in the western part of the basin, and the pits that have been worked for sand and gravel along the river could be used as recharge pits.

Infiltration rates, calculated from seepage losses in the reach of the stream near Mahwah and applied to the entire reach from the New York State line to Pompton Lake, indicate that at least 11 mgd could be developed from induced river infiltration. Based on the storage capacity of the stratified drift and an analysis of daily flows in the Ramapo River during the drought period of October 1964 to September 1967, an estimated 20–25 mgd of Ramapo River water is available for development from the stratified drift. However, without low-flow augmentation or return of treated sewage effluent to the drift, pumpage of this magnitude might result in a dry stream during periods of no precipitation and very low flow.

Losses from the Ramapo River could be minimized by returning treated sewage effluent directly to the stream or by recharging the stratified drift with treated-sewage effluent. Recycling of water is possible because of the generally nonconsumptive uses within the basin. Worked-out gravel pits could be utilized as recharge installations.

Detailed engineering studies are necessary to determine the economic feasibility of the various alternatives for producing artificial recharge.

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