STATE OF NEW JERSEY

STATE WATER POLICY COMMISSION

SPECIAL REPORT 7

WATER SUPPLIES FROM THE NO. 1 SAND IN THE VICINITY OF PARLIN, NEW JERSEY

1937

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STATE WATER POLICY COMMISSION

HOWARD T. CRITCHLOW, ENGINEER IN CHARGE

WATER SUPPLIES FROM THE NO. 1 SAND IN THE VICINITY OF PARLIN, NEW JERSEY

By Henry C. Barksdale

Prepared in cooperation with the United States Geological Survey

LETTER OF TRANSMITTAL

May 24, 1937

MR. GEORGE S. BURGESS, *Chairman*,
STATE WATER POLICY COMMISSION.

Dear Sir:

I am transmitting herewith a report on the water supplies from the No. 1 sand in the vicinity of Parlin, Middlesex County, New Jersey, by Mr. Henry C. Barksdale, Assistant Engineer. The report has been prepared in cooperation with the United States Geological Survey in connection with the cooperative work on ground waters which has been conducted since 1924 in various regions of the State. This report is one of a series which is being prepared on ground water conditions in the State.

The extensive use of the No. 1 sand in the vicinity of Parlin, on the southern side of the Raritan River, has been due to the location of a number of large industrial plants in that area. The report states that the draft of water from this sand is increasing and that its safe yield is being reached. Activities of these industries indicate that they will need additional waters to meet the future demands of their industrial processes. The conditions disclosed in the report indicate that additional water supplies for this area will have to be obtained from sources other than the No. 1 sand.

I therefore recommend that this report be published as a Special Report of the Commission in order that information contained therein may be made available to the people of the State.

Respectfully submitted,

H. T. CRITCHLOW,
Engineer in Charge.

NEW JERSEY STATE WATER POLICY COMMISSION

28 WEST STATE STREET, TRENTON, N. J.

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CONTENTS

ILLUSTRATIONS

WATER SUPPLIES FROM THE NO. 1 SAND IN THE VICINITY OF PARLIN, NEW JERSEY

By Henry C. Barksdale

INTRODUCTION

The cities of Perth Amboy and South Amboy and some of the neighboring municipalities derive their water supplies from the sands of the Raritan formation. In this area there are three sands in this formation known as the No. 1, No. 2, and No. 3 sands,* of which Nos. 1 and 3 are valuable water-bearing beds. The principal supplies of these municipalities are derived from the upper or No. 3 sand, but some water is also taken from the No. 1 sand, which is the lowest sand bed of the Raritan formation. The No. 1 sand also furnishes a part or all of the water supply for several large industrial plants located south of the Raritan River in the triangular area between South Amboy, Spotswood, and Sayreville, and along the north bank of the river from a point about opposite Sayreville to Perth Amboy. All these supplies are drawn from wells that lie within an area of about 30 square miles. In 1929 an average of about 8 million gallons daily was withdrawn from the No. 1 sand, and by 1935 the average daily consumption of water from this sand had increased to about 10 million gallons.

The pumping from this sand has lowered the head of the water in the sand about 110 feet in some places—from about 35 or 40 feet above sea level in 1897, when the first wells were drilled to this sand, to as much as 73 feet below sea level in the summer of 1935. This lowering of the water level in the wells tapping this sand has caused considerable anxiety about the permanency of the supply among the users of water from it and particularly among the operators of the chemical plants at Parlin, which are almost entirely dependent upon the sand for their

* The names of the sands and associated clay beds (see p. 3) are in part those used by Cook and Smock (Cook, G. H., and Smock, J. C., Report on the clay deposits of Woodbridge, South Amboy, and other places in New Jersey: New Jersey Geol. Survey, 1878) and subsequently more definitely by Ries, Kümmel and Knapp, (Ries, H., Kümmel, H. B., and Knapp, G. N., The clays and clay industry of New Jersey: New Jersey Geol. Survey, Final Rept., vol. 6, 1904).

water supply. This problem is indeed a matter for concern, especially as it might be difficult, or at least very expensive, to replace the water now being drawn from the No. 1 sand with water from other sources in the area.

Since 1923 certain phases of the ground-water supply in this area have been under investigation by the New Jersey Department of Conservation and Development, and in more recent years by the State Water Policy Commission, both in cooperation with the United States Geological Survey. Intermittent records of the water levels in wells that tap the No. 1 sand in Sayreville and at the Perth Amboy Water Works at Runyon have been collected throughout the course of this investigation, and very good records have been obtained since 1929. In addition to this material, excellent records of water levels and pumpage at Parlin since 1929 have been kept by the officials of the E. I. duPont de Nemours Co., and of the Hercules Powder Co. The present report has been prepared to make available a summary of the information collected about the No. 1 sand.

The section of this report that deals with the geology of the area was prepared in collaboration with Mr. Meredith E. Johnson, Assistant State Geologist. Mr. Johnson also gave valuable advice and criticism in the preparation of the remainder of the report. The writer gratefully acknowledges this assistance.

Many other persons have rendered aid of one kind or another in the course of the investigation that preceded this report and in the preparation of the report itself, and to them the writer expresses his appreciation. He is especially indebted to Mr. O. E. Meinzer and Mr. David G. Thompson for advice during the investigation and for criticism of the report and to Mr. R. W. Sundstrom, who assisted in collecting and assembling the data on which this report is based and who drew some of the illustrations for it. Mr. H. L. Dieker, Chief Engineer of the Perth Amboy Water Works, has furnished much valuable information about the development of the sand, and his son, Mr. E. V. Dieker, has assisted in collecting records of water levels and pumpage. Mention should also be made of the ready cooperation of the officials of the industries of the region, who furnished records of pumpage from their wells and of the water levels in them. Without this cooperation it would have been impossible to make a satisfactory study of the water-supply problems that relate to the No. 1 sand in this area.

GEOLOGY OF THE AREA

The No. 1 sand is a member of the Raritan formation, which is of Upper Cretaceous age. In the vicinity of Parlin the Raritan formation is underlain by sandstone and shale of Triassic age. A little farther to the southeast it is underlain by metamorphic rock. The No. 1 sand rests upon the Raritan fire clay, which is the lowest* member of the Raritan formation. The beds above the No. 1 sand are the Woodbridge clay, the No. 2 sand, the South Amboy fire clay, the No. 3 sand, and the Amboy Stoneware clay, in the order given. All these beds are members of the Raritan formation. In parts of the area under consideration the Raritan formation is overlain by the Magothy formation, which is composed principally of very fine sand with beds of clay in some places. These formations dip gently toward the southeast and tend to become thicker in that direction. They crop out in narrow beds that extend in a general northeasterly direction. The individual members and beds are, however, very irregular and locally some of them may dip in almost any direction. Throughout most of the area the surface is covered by Pleistocene or Recent sands and gravels, which obscure the older formations and make the mapping of their outcrops difficult. The outcrop of the No. 1 sand, which is almost everywhere covered by a thin layer of Pleistocene or Recent deposits, is shown in figure 1, and the vertical relations of the beds are shown in the geologic sections in figure 2.

Only two of the sands that occur in this area are notable water-bearing beds—the No. 1 sand, with which this report deals, and the No. 3 sand, which furnishes most of the public water supply for Perth Amboy and yields considerable quantities of water to other wells in the area. The No. 2 sand is irregular in occurrence (in some places entirely absent), low in permeability, and nowhere an important source of water supply. The Magothy sands are fine-grained and relatively impermeable. They almost invariably yield water of poor quality, although numerous domestic supplies have been obtained from them.

Some of the Pleistocene sands and gravels are highly permeable, but they are not usually thick enough to be of value as water-bearing beds. Their principal usefulness lies in the fact that they readily absorb the water that falls upon them as precipitation and transmit it to the beds beneath. One type of Pleistocene deposit, however,—the clayey phase

* The so-called Raritan potters clay is considered a part of the Raritan fire clay. Detailed observations in support of this usage will be presented in a later report.

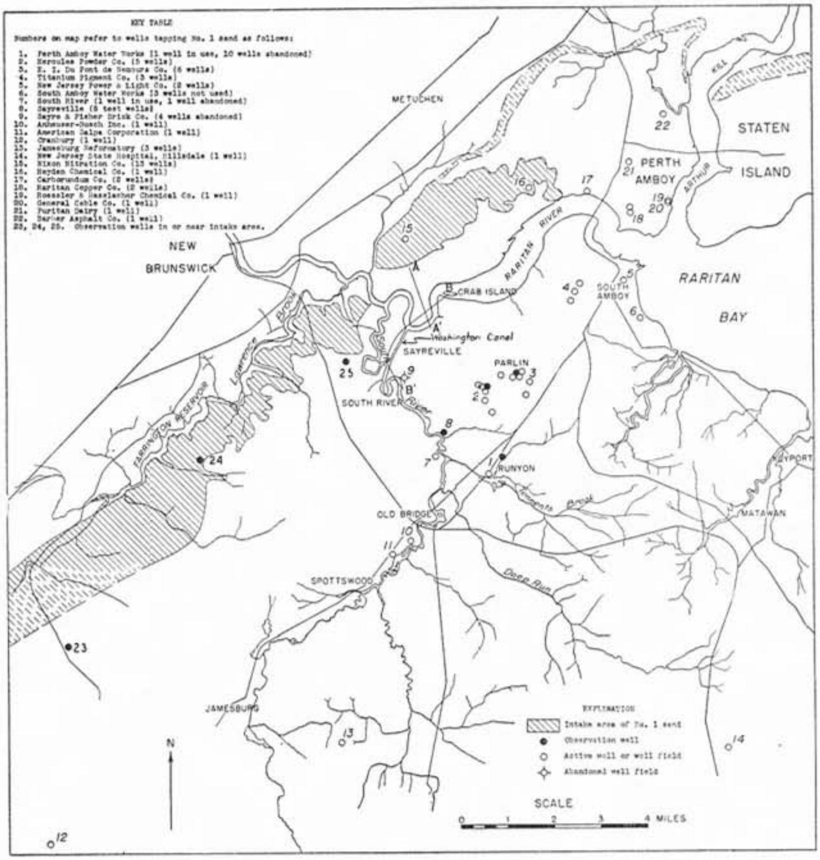


Figure 1. *Map of the Parlin area, New Jersey, showing intake area of No. 1 sand and principal wells tapping this sand. Geology by Meredith E. Johnson.*

of the Pensauken formation—is very dense and impermeable. Where it overlies a water-bearing sand it unquestionably prevents ready percolation of water into the underlying sand. On the other hand, where the older beds are overlain by considerable thicknesses of permeable Pleistocene deposits, the effective intake area of the underlying sand is probably larger than it would be if the Pleistocene deposits were absent, because water falling upon the sands and gravels at the surface may be conducted into the underlying sand in funnel-like fashion from an area of Pleistocene beds larger than that occupied by the older beds. South of the Raritan

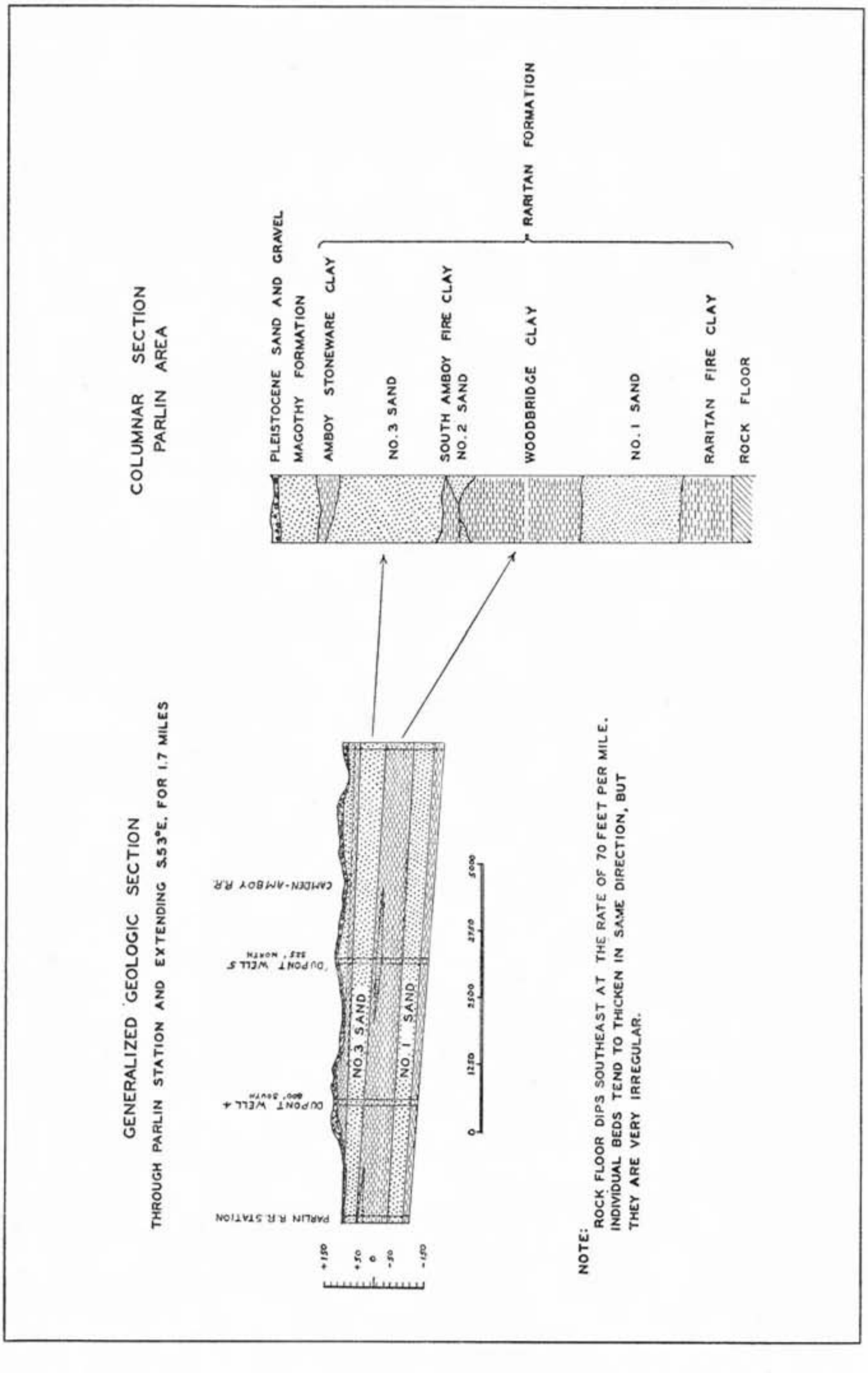


Figure 2. *Generalized columnar and geologic sections in the Parlin area. Geology by Meredith E. Johnson.*

River the blanketing effect of the clayey Pensauken may be counterbalanced by this funnel-like action of the permeable Pleistocene beds. North of the Raritan River the No. 1 sand is overlain in places by very considerable thicknesses of glacial deposits that probably increase the effective intake area of the sand.

The estuary of the Raritan River cuts across the outcrop area of the No. 1 sand and divides it into two parts. The level of the sea was formerly lower relative to the land of this area than at present, and the river cut a channel to bedrock or nearly to it from the mouth of Lawrence Brook to Perth Amboy. As the land and sea assumed their present levels this old channel was submerged, forming the present estuary, and its bottom was filled partly with sand and gravel but principally with river mud, which is relatively impermeable. This mud helps to protect the No. 1 sand from the brackish water that now fills the river where it crosses the outcrop, but it also restricts the connection between the part of the No. 1 sand north of the river and the part south of the river. In some localities a few feet of the No. 1 sand appear to have been left in place by the river, and in others the original sand appears to have been replaced by Pleistocene sand and gravel, so that some water probably can pass under the river from the intake area on the north side to the well fields on the south side.

Another barrier to the movement of water from the area north of the river to the well fields south of it is a ridge of trap rock that rises from the general level of the rock floor on which the Raritan formation was deposited and appears to have been high enough to thin the No. 1 sand and in some places prevent its deposition entirely. This ridge underlies the river from Perth Amboy to Sayreville. Toward the southwest it lies beneath the base of the No. 1 sand. The available data do not justify an estimate of the quantity of water that moves from the intake area north of the river to the well fields south of it, but it is certainly a much smaller quantity than would be derived from an intake area of the same size south of the river.

A considerable number of test borings have been made at different times along the estuary of the Raritan River for the purpose of determining the nature of the materials beneath the surface. These borings are not spaced closely enough to permit a definite correlation of all the materials beneath the river, but they give a reasonably good idea of the nature of the materials that fill the old river channel and they serve to emphasize the irregularity of the deposition of those materials. The results of the test borings for the Liberty Bridge at Perth Amboy and of some of those for the proposed New Jersey Ship Canal are particularly useful in the study of the water supply from the No. 1 sand in the Parlin area and are discussed in the following paragraphs.

The test borings for the foundations of the Liberty Bridge between Perth Amboy and South Amboy are distributed across the river along a line that is approximately parallel to the strike of the No. 1 sand. Except at the extreme ends of the line they reached the trap ridge, which underlies the river at this locality. They show two facts that are significant in the present study: first, that the old river channel was cut down to bedrock at this point, and second, that on the south side of the river the trap ridge lies either directly below the river fill or directly beneath the Woodbridge clay. In most of the region the No. 1 sand lies directly beneath the Woodbridge clay, but in this locality the sand is absent, because the trap ridge stood higher than the level at which the No. 1 sand was deposited nearby. Accordingly, along the line of these test holes the Woodbridge clay provides a seal that prevents any connection between the No. 1 sand south of the river and the river deposits and thus protects this part of the sand from salt-water contamination. A single boring south of the river near Crab Island also encountered the trap rock directly beneath the Woodbridge clay, but unfortunately there are no test borings between these two localities to indicate whether or not the seal is continuous.

Another significant group of wells are the test borings that were drilled near Sayreville by the Corps of Engineers, United States Army, in connection with the study of the proposed New Jersey Ship Canal. Two groups of these wells are here discussed: those along a line (A-A′, fig. 1) that crosses the estuary of the Raritan River about a mile below the mouth of the South River and those along a curved line (B-B′, fig. 1) that extends from a point on Crab Island southwestward to a point near the northeast end of Washington Canal, thence approximately parallel to the canal to its southern end, and thence southeastward to a point near the town of South River. Graphic logs of both groups of wells are shown in figure 3.

The logs of the first-mentioned group of wells show that at this location the old river channel was eroded to bedrock (diabase and shale of Triassic age) and that it was filled principally with sand of the Cape May formation of Pleistocene age. At this point, as at the Liberty

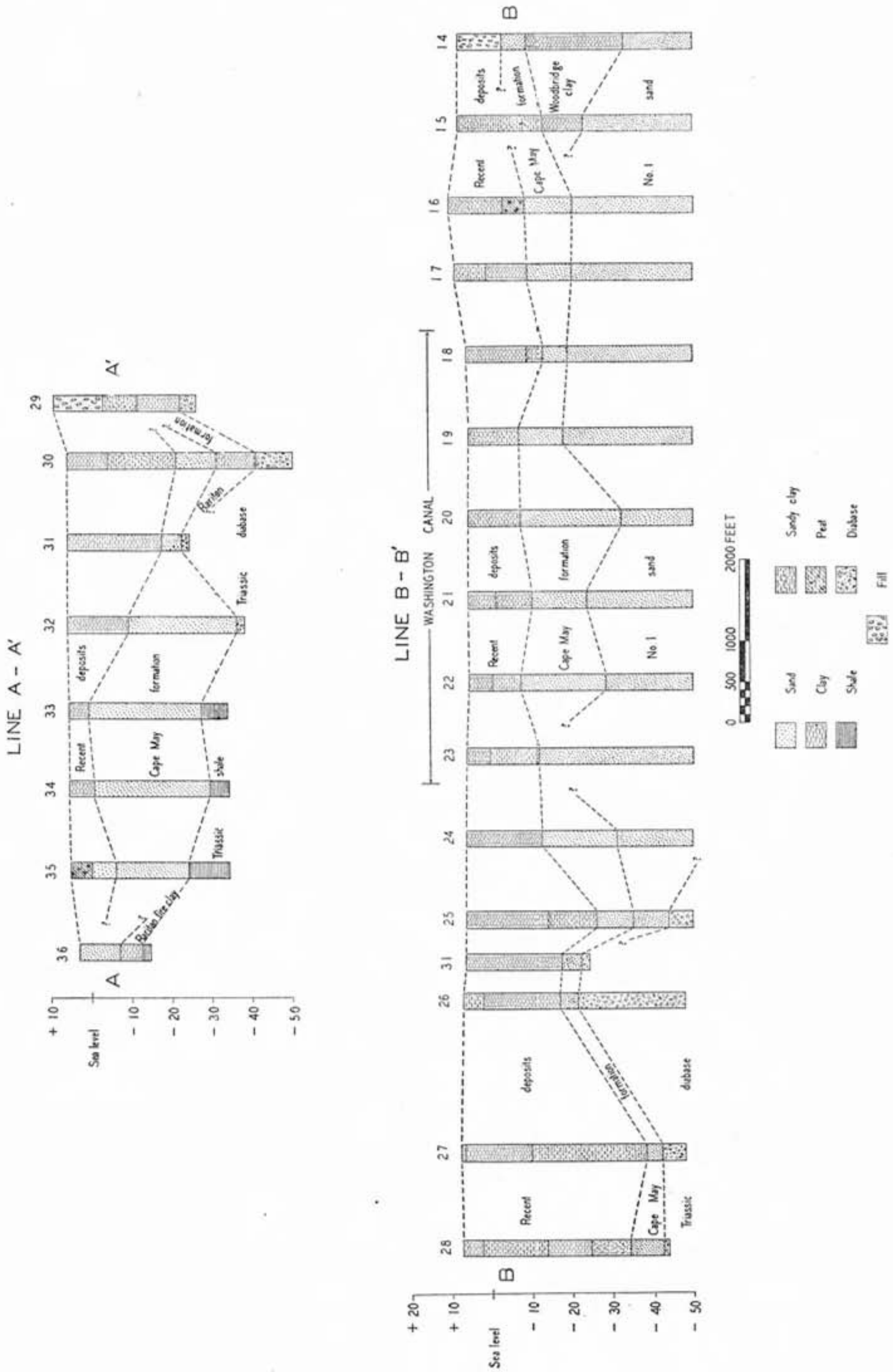


Figure 3. *Graphic logs of test borings made by Corps of Engineers, U. S. Army, along lines A-A' and B-B' in Figure 1. Geology by Meredith E. Johnson.*

Bridge, there appears to be no connection between the river fill and the No. 1 sand, but the materials in the old channel beneath the Recent deposits of river mud are highly permeable and would readily conduct salt water into the sand if there were a connection.

A much more serious situation is indicated by the logs of the wells in the second group. Along line B-B′ the Cape May formation appears to lie directly upon the No. 1 sand for a distance of several thousand feet. The Washington Canal, which parallels this line from well 18 to well 23, was dredged down through the relatively impermeable Recent deposits and into the sand of the Cape May formation for a considerable part of its length. It therefore appears probable that the brackish water in the canal can now reach the No. 1 sand through the permeable sand of the Cape May at the bottom of the canal. It is possible, of course, that equally dangerous conditions may exist in other parts of the area where test borings have not been made, but from the data available it seems that the most serious danger of salt-water contamination of the No. 1 sand lies in this canal.

NO. 1 SAND

PHYSICAL PROPERTIES

The capacity of a sand to store and transmit water is determined by its physical properties. Seven volumetric samples of the No. 1 sand were collected at its outcrop and examined in the hydrologic laboratory of the United States Geological Survey. The results of the analyses of these samples are shown in the accompanying table. The method of making analyses and the interpretation of the results are discussed in detail by Mrs. Stearns* in a paper published in 1927. It will suffice here to define briefly the features shown in the table of analyses.

The apparent specific gravity is the specific gravity of an oven-dried sample of the sand including the pore spaces. It must not be confused with the specific gravity of the mineral grains composing the sand.

The mechanical analysis is largely self-explanatory. It shows the proportion of grains of various sizes found in the sample expressed in percentages of the total weight of the sample.

* Stearns, Norah Dowell, Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596-F, 1927.

PHYSICAL PROPERTIES OF SAMPLES OF MATERIALS FROM NO. 1 SAND IN PARLIN AREA, NEW JERSEY

Laboratory No.	Apparent specific gravity	Mechanical analysis (percent by weight)							Porosity (percent)	Moisture equivalent (percent by volume)	Coefficient of permeability
		Larger than 1.0 mm.	1.0-0.50 mm.	0.50-0.25 mm.	0.25-0.125 mm.	0.125-0.062 mm.	Silt	Clay			
2160	1.70	1.4	29.9	37.2	26.9	1.9	1.7	1.1	34.7	2.1	325
2161	1.70	21.8	57.4	15.1	3.5	.8	.8	.5	35.2	1.7	1,700
2162	1.94	59.0	21.7	14.4	3.1	.5	.3	.3	26.5	. .	3,500
2163	1.73	.4	51.7	44.3	1.8	.3	.3	1.1	34.6	3.7	2,250
2164	1.75	4.2	57.1	34.4	3.1	.3	.3	.4	33.7	1.8	2,250
2165	1.71	7.3	75.0	10.6	.4	.9	2.2	3.2	35.6	5.7	1,300
2166	1.62	1.0	5.1	28.5	56.0	6.7	1.9	.9	39.5	2.5	210

2160. South River; abandoned sand pit about 1½ miles north of town, 20 feet above Raritan fire clay.
2161. Same pit as 2160, 25 feet above Raritan fire clay.
2162. Same pit as 2160, 35 feet above Raritan fire clay.
2163. South River; about 1 mile northwest of town, 2½ feet below Woodbridge clay.
2164. Same locality as 2163, 3½ feet below Woodbridge clay (represents locally coarse streak).
2165. Milltown; from highway cut about 1 mile east of town, 1 foot above Raritan fire clay.
2166. Milltown; Marcus Wright's pit, 13½ feet above Raritan fire clay.

The porosity of a sample is the percentage of pore space in its total volume; that is, the percentage of space not occupied by solid mineral matter.

The moisture equivalent is the volume of water that a saturated sample of the material will hold against a centrifugal force 1,000 times as great as the force of gravity expressed as a percentage of the total volume of the sample. It is a measure of the specific retention of the formation from which the sample was taken. The term "specific retention" is used to express the quantity of water that a soil will retain against the pull of gravity if it is drained after having been saturated. The ratio of the volume of this retained water to the total volume of the sample, expressed as a percentage, is the specific retention. It is impossible to determine the specific retention of a formation from a small sample because capillary attraction holds a greater proportion of the water in a short column of a material than in a long column of the same material. For a material such as the No. 1 sand the moisture equivalent as determined in the laboratory is probably about the same as the specific retention of the formation. The porosity less the moisture equivalent is therefore an approximate measure of the quantity of water that can be drained out of the formation under the influence of gravity.

The coefficient of permeability is a measure of the capacity of the sand to transmit water. It is based upon Darcy's law that the rate of flow in capillary tubes varies in direct proportion to the hydraulic gradient. As used by the United States Geological Survey and expressed in field terms, the coefficient of permeability is the number of gallons of water a day at 60° F., that would flow through a section of the sand 1 mile in length and 1 foot thick (measured at right angles to the direction of flow) under a hydraulic gradient of 1 foot per mile. The coefficients of permeability of the samples from the No. 1 sand indicate that its capacity to transmit water is moderately high. The average permeability of this sand is probably about the same as that of the Atlantic City 800-foot sand but less than that of the Raritan sands at Camden, N. J.

QUALITY OF THE WATER

The water from the No. 1 sand usually contains an objectionable quantity of iron. When this constituent is removed it is a highly satisfactory water for both industrial and domestic uses.

Three representative samples of water from this sand were collected in 1933 and analyzed in the Water Resources Laboratory of the United States Geological Survey. The results of these analyses are shown in the accompanying table. In each sample the total dissolved solids were less than 40 parts per million, which is unusually low for ground water. The iron content of the water varies considerably from place to place, which is characteristic of waters from the Raritan formation. Most of the iron had been precipitated out of the water when the samples reached the laboratory, which indicates that the iron is in a form in which it can be easily removed from the water.

Analyses of water from wells tapping the No. 1 sand in the Parlin area
[Analyzed by K. T. Williams, U. S. Geological Survey. (Parts per million)]

	1	2	3
Silica (SiO_2)	8.7	..	..
Iron (Fe)	6.0	3.5	1.9
Manganese (Mn)	.0	.1	.1
Calcium (Ca)	3.8	..	..
Magnesium (Mg)	.9	..	..
Sodium (Na)	2.1	* 4.3	* 4.1
Potassium (K)	.4		
Bicarbonate (HCO_3)	5.0	7.0	18
Sulphate (SO_4)	10	9	9
Chloride (Cl)	3.0	3.0	4.0
Nitrate (NO_3)	.10	.10	.10
Total dissolved solids	37	23	34
Total hardness as $CaCO_3$	13	10	21

* Calculated.

1. Perth Amboy Water Works, Runyon, N. J., deep well. Sample collected April 15, 1933.
2. E. I. Du Pont de Nemours Co., Parlin, N. J., well No. 5. Sample collected April 14, 1933.
3. Anheuser-Busch Inc., Old Bridge, N. J., deep well. Sample collected April 14, 1933.

The chloride content of these samples was only 3.0 and 4.0 parts per million. This small amount suggests that an increase of a few parts per million in the chloride content might be significant in indicating salt-water encroachment. The chloride content varies slightly from place to place. A study of the relation between the location of each well that taps the No. 1 sand in the area and the chloride content of the water might yield information in regard to the danger of salt-water contamination. It is recommended that such a study be included in the future investigations of the supply from this sand.

Samples of water from wells that tap the No. 1 sand and that seem to be most exposed to contamination by salt water should be collected at regular intervals and analyzed for their chloride content. This is especially true of wells between the Washington Canal and the well fields at Parlin. If no wells exist in this area, it would probably be worth while to drill two or three test wells at selected points for the sole purpose of procuring samples.

HISTORY OF DEVELOPMENT

The first water supply developed from the No. 1 sand south of the Raritan River was at the Perth Amboy Water Works at Runyon, where a well was drilled to it in 1897. About the same time wells were drilled to this sand in the city of Perth Amboy. For several years after 1897 the No. 1 sand at Runyon was the principal source of water supply for the city of Perth Amboy. At first the water was delivered to the surface entirely by natural flow. Later this supply was augmented by pumping from the No. 3 sand, and water from both sands was used. In 1930 a new well with a capacity of about 2 million gallons daily was drilled to the No. 1 sand at Runyon, and the older wells tapping this sand, which had not been used much for several years, were definitely abandoned. The wells drawing from this sand at the South Amboy Water Works were drilled in 1918-19 and those at the South River Water Works were drilled in 1912.

Before the beginning of the World War, in 1914, only a few industrial plants in Perth Amboy, South Amboy, and Sayreville, were using water from the No. 1 sand. The total industrial consumption probably was not much over 1 million gallons daily. The favorable location of the region for export trade produced a sudden increase in industrial activity during the war and a corresponding increase in the industrial use of water from the No. 1 sand. Unfortunately there are practically no records of pumpage during these years, but from the information available about the capacity of the wells then in use it seems probable that the total rate of pumpage from the sand did not exceed 5 or 6 million gallons daily in the area under consideration.

Many of the industrial plants established in this area during the war have been adapted to peace-time operations and have continued or increased their use of water. In recent years new industries have been attracted to the area and the pumpage has increased. The total capacity of the wells that now tap the No. 1 sand in this area is probably more than 20 million gallons daily. The average daily consumption of water from the sand, from both municipal and industrial wells, from 1929 to 1935 is shown in the accompanying table. The figures given are necessarily partly estimated, but they are believed to be reasonably accurate.

Average consumption (partly estimated) of water from the No. 1 sand between Perth Amboy and Jamesburg by geographic divisions, 1929-35.

(Million gallons daily)

Year	1929	1930	1931	1932	1933	1934	1935
At Parlin	6.202	5.964	5.053	4.353	5.441	6.570	7.640
South of Raritan River except at Parlin	.233	1.124	1.471	1.545	.516	.449	1.426
North of Raritan River	1.681	1.571	1.383	1.040	1.021	1.115	1.131
Total	8.116	8.659	7.907	6.938	6.978	8.134	10.197

CONDITIONS AFFECTING SAFE YIELD

METHOD OF STUDY

The safe yield of a water-bearing sand is the maximum rate at which it will yield water indefinitely without impairing the quantity or quality of the supply. Quantitatively a water-bearing sand may be considered either as a reservoir in which water is stored or as a conduit through which it is transmitted. Usually the conception of a reservoir is most useful in studying sands in which water-table conditions exist, and that of a conduit is most useful in studying artesian sands. Except where there is danger of salt-water contamination, the safe yield of a water-bearing sand that acts primarily as a reservoir is the difference between its rate of intake and the rate of unavoidable natural discharge. The safe yield of a water-bearing sand that acts as a conduit may be limited by its intake capacity, by the rate at which water can be transmitted through the sand to the wells without lowering the water to a depth from which it can not be withdrawn economically, or by the danger of impairing the quality of the water in the sand. It seems probable that the capacity of the No. 1 sand in this area may be limited either by its intake capacity or by the danger of salt-water intrusion rather than by the capacity of the sand to transmit water to the well fields. In this report the quantitative factors that may limit the safe yield of the No. 1 sand will be considered first, after which consideration will be given to the limitations that are due to the danger of salt-water intrusion.

INTAKE CAPACITY

The intake capacity of a sand depends on the area through which water may enter it, on the amount of water available for absorption in this area, and on the rate at which the sand absorbs water. The intake area of the No. 1 sand has been mapped (see fig. 1) but it is uncertain how much of it may be tributary to the wells at Parlin. The sand will probably absorb much of the water that falls upon its intake area as precipitation if it is not removed by evaporation, transpiration or stream-flow. There is unquestionably enough storage capacity in the No. 1 sand to care for seasonal peaks of consumption and probably enough to take care of any deficiencies in intake that might occur in a dry year or even in several dry years. A study of the intake area necessary to supply the demand from this sand can therefore be based on the average daily rate of pumping. For the same reason the average yearly rate of precipitation rather than the lowest rate may be used as a basis for estimating the amount of intake.

The average annual precipitation on the outcrop area of the No. 1 sand is about 46 inches. Of this amount about 20 inches is probably returned to the air by evaporation from the soil and by the transpiration of plants. The remainder is disposed of by stream flow and by groundwater intake. Measurements of stream flow by the U. S. Geological

Survey in cooperation with the New Jersey State Water Policy Commission indicate that the average run-off from drainage areas in this part of New Jersey is 18 to 22 inches a year. This would leave only 4 to 8 inches of the normal precipitation available for ground-water intake.

It seems probable, however, that the No. 1 sand absorbs considerably more of the annual precipitation than the figures just quoted would indicate. South of Raritan River the intake area of the No. 1 sand lies within the drainage area of Lawrence Brook. The measurements of the flow of this stream show that its yearly run-off is from 3 to 6 inches less than that of neighboring streams. Although there may be other factors that account for some of this deficiency, some of it is doubtless due to the absorption of water by the No. 1 sand. The intake area of the No. 1 sand covers about one-third of the drainage area of Lawrence Brook, so that if the deficiency in the yield of this stream were due entirely to absorption of water by the No. 1 sand, the deficiency in run-off from the intake area of the sand would be three times as great as that for the stream as a whole, or from 9 to 18 inches a year. If the water table in the intake area is lowered by the pumping from the sand, the amount of precipitation that could be absorbed by the sand would probably be increased, because the water entering the sand would pass out of reach of the plant roots more quickly and the flow from the sand into streams would be decreased or even reversed. Several small tributaries of Lawrence Brook flow across the intake area of the No. 1 sand and may yield additional water to the sand, especially if the water table has been lowered along their courses.

In the light of the preceding discussion and because the estimate of evaporation and transpiration is necessarily approximate, it may be assumed with some degree of reasonableness that the amount of water absorbed by the No. 1 sand is nearer 20 inches per year than 4 or 8 inches. On this basis an intake area of about 9.5 square miles would be required to supply 9 million gallons daily, which was the average rate of pumpage from the sand south of the Raritan River in 1935, or about 10.7 square miles to supply the total pumpage on both sides of the river in that year. Obviously if the absorption on the intake area is less than 20 inches the intake areas required would be greater.

If the deposits and the trap ridge beneath the Raritan River prevent the wells south of the river from drawing an appreciable quantity of water from the intake area north of it, practically all the water pumped from these wells must come from the intake area south of the river, and in 1935 the cone of depression of these wells must have extended far enough to intercept all the intake from the area between the river and a point northwest of Jamesburg unless water was taken from storage in the sand. If no water was taken from storage in the sand, the cone of depression extended at least 10 miles from the area of heaviest pumping at Parlin. The wells south of the river possibly draw some water from the intake area north of it, but even if there were an unrestricted connection between the two areas of the sand, it would be necessary for the cone of depression to extend about 8 miles along the strike of the formation in each direction from Parlin in order to include an intake area large enough to provide an annual intake equal to the quantity of water pumped in the whole area in 1935.

In 1927, when no water was being pumped from this sand at the Perth Amboy Water Works at Runyon, the head in the wells to it at this plant had been lowered 25 or 30 feet below the original static level by the pumpage at Parlin and elsewhere in the region. The observation wells at Runyon are about 1-1/2 miles from the wells at Parlin, where most of the water was being taken from the sand. The fact that the head had been lowered this much at a distance of 1-1/2 miles from the center of pumping suggests that the cone of depression may indeed have extended 8 or 10 miles at that time because a cone of depression normally flattens out as the distance from the pumping wells increases. It probably extends farther today.

About three-quarters of the area of Farrington Reservoir on Lawrence Brook lies on the outcrop of the No. 1 sand. If the water level in the sand is lowered enough, the intake from this underwater part of the outcrop will almost certainly be much greater than that from a similar land area. After the bottom of the reservoir has been covered with silt, the intake from it will be decreased but it will probably be an important potential source of water for the No. 1 sand for many years to come. If the cone of influence extends as much as 8 miles from Parlin, it includes practically all of the reservoir that lies on the outcrop of the No. 1 sand, but the head may not be lowered enough to cause flow from the reservoir into the sand.

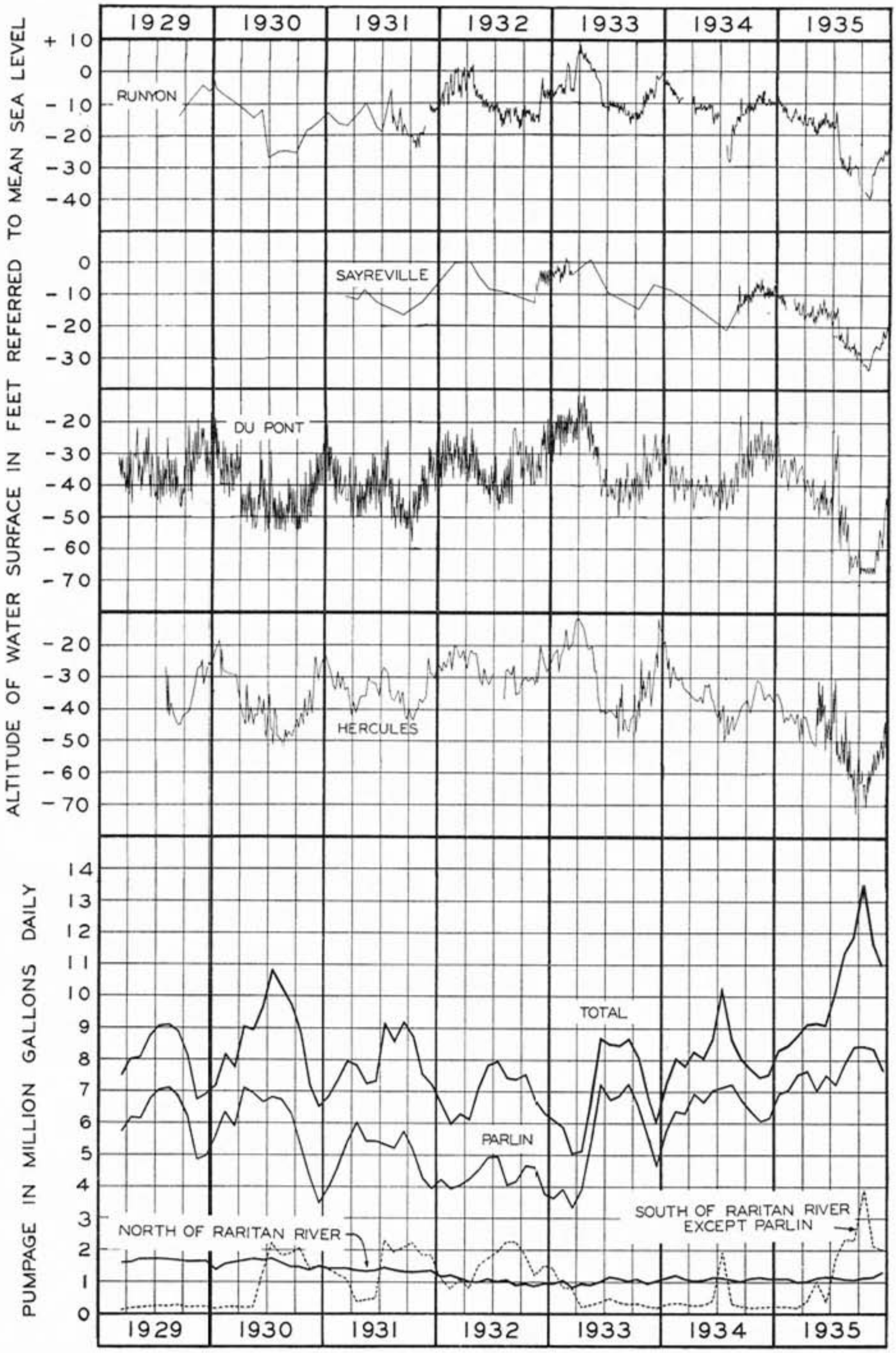


Figure 4. *Fluctuations of water levels in observation wells at Runyon, Sayreville, and Parlin, and the average rate of pumping in the whole area and in parts of it, March 1929 to December 1935.*

RELATION BETWEEN PUMPAGE AND WATER LEVELS

GENERAL FEATURES

Periodical or continuous records of water levels in the old deep well No. 8 at Runyon have been obtained since 1929 and a similar record of the water levels in an abandoned test well at the site of the proposed Sayreville Water Works has been obtained since 1931. The officials of the E. I. duPont de Nemours Co., and of the Hercules Powder Co., have kept records of the water levels in two observation wells at Parlin since 1929. They have also kept accurate records of the water pumped from the No. 1 sand at their plants. A few of the other users of this water have kept records of pumpage, and it has been possible to estimate with reasonable accuracy the total amount of water pumped from this sand each month since early in 1929. The fluctuations of the water level in the four observation wells and the average daily rate of pumpage each month from March 1929 to December 1935 are shown in figure 4. For convenience in analysis the pumpage is shown for certain geographic units as well as for the whole area. The water levels are referred to mean sea level, which is about 35 feet below the original static level. This diagram shows a positive relation between the pumpage from the sand and the water levels in the observation wells. It also shows that the greater part of the pumpage in the area is concentrated at Parlin; that the pumpage north of the river has decreased from 1929 to 1935; and that the pumpage south of Raritan River, exclusive of Parlin, has been very irregular but has increased more rapidly than in other parts of the area during the last year. The increased pumpage at Parlin and elsewhere south of the Raritan is undoubtedly responsible for the exceptionally low water levels in the observation wells in 1935.

REGIONAL SPECIFIC CAPACITY

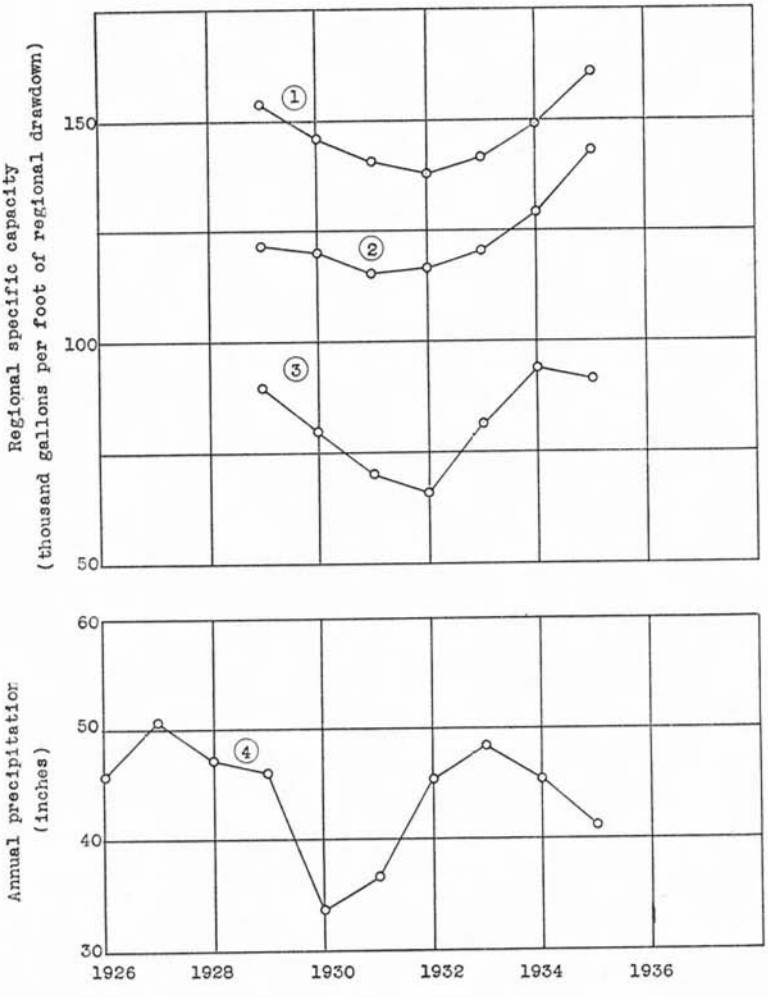
It is difficult to determine directly from a diagram like that of figure 4 whether or not there is a definite mathematical relation between the rate of pumping from the sand and the lowering of the water level in wells that tap the sand. Some lowering of the water level must be expected as the rate of pumping is increased, because a steeper gradient is required to overcome the resistance of the sand to the more rapid flow of water from the intake area to the point of withdrawal. Obviously the lower water level will increase the cost of pumping, but it does not indicate that the capacity of the sand to yield water has been impaired unless the lowering of the head is out of proportion to the increase in pumpage.

For a single well there is a definite relation between the lowering of the head and the yield, which is determined by the nature of the sand and the construction of the well. Within certain limits, the yield per unit of drawdown, which is called the specific capacity of the well, is constant. If the well is pumped too heavily its specific capacity will decrease.

If the pumpage from the No. 1 sand were concentrated in a single well, or if a truly representative figure could be obtained for the average lowering of the head in the sand in the area over which the active wells are scattered, a similar relation between pumpage and drawdown should exist. This relation has been called the regional specific capacity. It is the regional yield per unit of regional drawdown. A tendency of the regional specific capacity to decrease with increased pumping, or even with long-continued pumping at the same rate, would suggest that the safe yield of the sand was probably being exceeded.

The principal difficulty in computing the regional specific capacity for any area lies in satisfactorily determining the regional drawdown, because the water level in every well in the area is affected to some extent by the pumping of every other well in it. The pumping of the wells nearest an observation well affects the water level in the observation well the most, so that the lowering of the water level in any one well may not safely be considered representative of the regional drawdown. Furthermore, the distribution of pumpage in the area varies from time to time, so that each observation well may be differently affected at different times by the same total rate of pumping in the entire region. The best that can be done is to compute an average lowering of the water levels in all observation wells, or preferably an average weighted on the basis of the distance from each observation well to each important center of pumping and of the distribution of total pumpage between these centers.

For each year from 1929 to 1935 the regional specific capacity of the No. 1 sand in the area under consideration has been determined by using the average daily rate of pumpage and the regional drawdown computed by several different methods of weighting the lowering of the water levels in the four observation wells shown in figure 4. The results of three typical sets of computations are shown in the upper part of figure 5. They show that the regional capacity has varied from year to



1. Average daily rate of pumping in whole area divided by regional drawdown below original static level based on the weighted average of the water levels in four observation wells.

2. Average daily rate of pumping south of Raritan River divided by regional drawdown below original static level based on the weighted average of the water levels in four observation wells.

3. Average daily rate of pumping at Parlin divided by average drawdown below original static level in two test wells at Parlin.

4. Annual precipitation (average of precipitation at New Brunswick and at Runyon).

Figure 5. *Regional specific capacity of the No. 1 sand computed on the basis of three different assumptions for each year, 1929-35, and the annual precipitation on the intake area, 1926-35.*

year, but none of the methods of computing the regional specific capacity gave results that indicated a consistent decline in the yield of the sand per foot of regional drawdown. This result suggests that the pumpage from the sand has not exceeded the capacity of the sand to transmit water from the outcrop area. Many of the variations shown from year to year are probably caused by changes in the distribution of pumpage that were not compensated by the weighting of the water levels in the observation wells. For example, the rise from 1934 to 1935 in the first two curves is probably caused by increased pumpage north of Parlin, where there are no observation wells. The observation wells at Parlin and southward were not much affected by this increase in pumpage and the yield per foot of drawdown appeared to increase. If possible, at least one observation well should be established in the area between Parlin and South Amboy in order that a more representative figure for the regional lowering of head may be obtained.

RELATION BETWEEN REGIONAL SPECIFIC CAPACITY AND INTAKE

The shape of the third curve of regional specific capacity suggests a relation between regional specific capacity and precipitation. The annual precipitation is shown at the bottom of figure 5 for comparison. There appears to be a lag of a year or two between the curve for precipitation and that for regional specific capacity. Part of this similarity may be due to the distribution of pumpage in the well fields at Parlin. The pumpage there was low in 1931, 1932, and in the early part of 1933. During this time certain wells that are nearest the observation wells probably furnished a larger proportion of the water pumped than they did in years when the pumpage was higher. Nevertheless the similarity between the two curves seems too great to be entirely accidental.

The yield per foot of drawdown appears to decline during dry periods, probably because the water table in the intake area is lowered appreciably and thus the head at the wells is lowered without actually increasing the slope between them and the intake area. At such times the cone of depression must extend farther in order to include enough intake area to yield the amount of water being pumped from the wells unless water is taken from storage in the sand. Unfortunately no measurements of water levels in the outcrop area of the No. 1 sand are available to check this assumption.

Whether or not the explanation just given is correct, there would probably be a considerable amount of intake even in the dryest year of record for this region. In the part of the intake area nearest the wells all the water that can enter the sand, even in wet years, is probably withdrawn promptly. Here the losses to the atmosphere and to stream flow are probably already at a minimum, and any decrease in precipitation would necessarily cause a decrease in intake and a lowering of the water table. In the more remote parts of the intake area a dry season would probably produce a smaller lowering of the water table because the losses would be reduced as the head was lowered.

The apparent lag of a year or more between precipitation and regional specific capacity is difficult to understand. A rather detailed study of the effect of precipitation on the water levels at Parlin, made by Mr. G. E. Linn, of the E. I. duPont de Nemours Co., indicates that fluctuations in precipitation are reflected as fluctuations of water level in that vicinity in about six months. Probably the longer apparent lag shown in figure 5 is due, in part at least, to the method of computing the regional specific capacity. It is conceivable that if the regional specific capacity were computed for shorter periods the lag might not appear so great.

Presumably the sand is filled with water at all times from the well field to the intake area, or nearly to it. The fluctuations of water level in the observation wells where the sand is under artesian pressure represent changes in pressure at these wells and not any considerable change in the quantity of water stored in the sand near them. It is true that the sand and its confining beds are slightly elastic and compressible, but this would not account for a lag of more than a few days at most. The well fields that draw from the No. 1 sand are so close to the intake area that fluctuations of the water table in the intake area are probably translated rather promptly into fluctuations of pressure at the wells. Perhaps the most logical explanation of the longer lag is that in the intake area, where changes in the altitude of the water table represent actual changes in the quantity of water in storage, the cone of depression expands and contracts rather slowly and considerable time elapses before the changes in head are large enough to affect the regional specific capacity.

In the absence of actual measurements of water level in the intake area it may be worth while to estimate the magnitude of the change in the quantity of water stored in the No. 1 sand when the water table in the intake area rises or falls. As already stated, the specific yield of a sand cannot be determined from a small sample in the laboratory, but the difference between the porosity of the sample and its moisture equivalent is an approximate measure of the specific yield. The average difference between the porosity and the moisture equivalent of the six samples from the No. 1 sand for which the moisture equivalent was determined (see table p. 10) is 32.6 percent. If this figure is assumed to represent the specific yield of the No. 1 sand, then about 68 million gallons of water is stored in a saturated body of this sand 1 square mile in area and 1 foot thick. Obviously this quantity of water would have to be removed in order to lower the water level 1 foot over an area of 1 square mile. The widest and most rapid fluctuations of water level would, of course, occur in the area nearest the well field, but if all intake were stopped completely and 9 million gallons of water were removed from 10 square miles of this sand every day for one year, the average level of the water in it would be lowered only about 4.8 feet. These figures suggest that the changes in the water level in the intake area through the removal of water by pumping would be slow.

The direct absorption of water by the sand from an average storm is probably less than 1 inch. If the specific yield of the sand is 32.6 per cent, 1 inch of water absorbed by the sand would raise the water level in it a little more than 3 inches. This rise would not occur immediately after the water fell on the surface as precipitation, because some time would be required for it to move down to the water table. It seems probable, therefore, that fluctuations of the water table in the intake area due to precipitation are also slow.

Three observation wells equipped with water-stage recorders were established in or near the intake area of the No. 1 sand in the summer of 1936. One is south of the Raritan River and near it. Another is about 10 miles southwest of the river, and an intermediate well is near the Farrington reservoir. These three wells should make possible a more thorough study of the problems relating to the behavior of the water table in this sand. The observation of water levels in them should be continued until the behavior of the water table in this area is well understood.

DANGER OF SALT-WATER CONTAMINATION

The danger of salt-water contamination of the No. 1 sand in the area under consideration depends on two factors, neither of which is susceptible to very definite analysis. The study of this problem must therefore be based largely on assumptions. Salt water cannot be drawn into the wells and contaminate the water taken from them unless it is already in the sand or unless there is a connection between the sand and some body of salt water. Furthermore, the salt water cannot be drawn into the wells in the area under consideration unless the cone of depression extends far enough to draw it in, even if it is present in the sand, or has access to it.

The sands of the Raritan formation are believed to have been laid down under brackish water. The fact that they now contain fresh water is evidence that fresh water from their outcrops on the land has flowed through the sands and flushed the brackish water from them. At the time that this flushing occurred, there was necessarily an opening through which the brackish water escaped from the sand, probably beneath the bed of the ocean. It is conceivable that salt water might be drawn back into the sand along the same channels through which it was forced out if those channels are still open and exposed to salt water. However, Raritan sands that are probably connected with the No. 1 sand yield fresh water at Asbury Park and at intermediate points. The sand may therefore be presumed to contain fresh water at least 25 miles down the dip from the wells at Parlin, and it is extremely improbable that the cone of depression of the wells in the area now under consideration will ever extend that far. Therefore, danger of salt-water contamination by upward percolation along the dip from the east is so remote that it merits no further consideration.

The water of the Raritan River, which cuts directly across the area under consideration, has a chloride content that ranges from about 2,000 parts per million near Sayreville to about 15,000 parts per million near Perth Amboy. This water is believed to be the most serious menace to the fresh-water supply from the No. 1 sand. It has already been pointed out that the river once cut its channel almost to the bottom of the No. 1 sand at least as far down the dip as Perth Amboy and that this channel was subsequently filled with river mud, sand, and gravel. It has also been pointed out (see fig. 3) that the Cape May sands are in contact with the No. 1 sand near the Washington Canal, and it is entirely possible that a similar condition may exist somewhere beneath the river. If the Cape May sands beneath the river are exposed to the salt water in it, this salt water could enter them and pass from them into the No. 1 sand. On the basis of the present knowledge of the structure of the area, the conditions along the Washington Canal seem to constitute the gravest danger of salt-water contamination of the No. 1 sand, but it is by no means certain that equally serious conditions do not exist elsewhere. Already one of the wells at the plant of the Sayre & Fisher Brick Co. has yielded salt water. This well was drilled about 1905 and may have developed a leak in the upper part of its casing, where it may pass through shallow water-bearing sands that are not protected by a clay cover and contain salt water. On the other hand, it is probably significant that the water of this well was contaminated some time after the Washington Canal was dredged. Unfortunately the Sayre & Fisher wells have been abandoned and filled and are no longer available for sampling. Samples of water should be collected periodically from wells located between the plants at Parlin and the canal and analyzed for chloride content, even though it may be necessary to drive test wells for this purpose. This water sampling program should give warning if the salt water is approaching the well fields, so that other arrangements for water supply can be made with a minimum of haste and expense.

A few wells that reach the No. 1 sand at or near Perth Amboy have been contaminated with salt water. This fact strongly suggests that there is a connection between the salt water in the river and the part of the No. 1 sand that lies north of the river. If the sand were continuous beneath the river, the cone of depression caused by the pumping south of it would unquestionably extend far enough to draw in salt water from this vicinity. Possibly, however, if there is a connection between the two parts of the sand, it is so restricted or so devious that this cone of depression does not extend to the area in which salt-water contamination has been observed.

If the salt water should gain access to the sand south of the river from some point in the river bottom, it is impossible to predict where the contamination might first appear, because of the irregularity of the formations beneath the river. However, it would seem that the wells of the New Jersey Power & Light Co. and of the Titanium Pigment Co. are perhaps most exposed to contamination in this way, unless the trap ridge protects the sand for a considerable distance along the river as it does at the Liberty Bridge. Samples of water should be collected monthly or quarterly from these wells for chloride determination in order that any possible advance of salt water from this direction may be detected as soon as possible.

In most places the Cape May sands beneath the river are covered by a layer of river mud that is relatively impervious and perhaps protects them from the salt water in the river. Dredging in the river channel may already have opened a passage through which salt water can enter the No. 1 sand. Of course, any future dredging will increase the danger. However, as shown by the test borings for the Liberty Bridge, the No. 1 sand near South Amboy appears to be cut off from the sands in the river bottom by the trap ridge and the Woodbridge clay, which lies directly upon the trap rock. It is not certain, however, that the trap ridge rises high enough to protect the No. 1 sand for any great distance or that the river mud, where it overlies the sands, is entirely effective as a seal. It is recommended that any further deepening of the river channel be preceded by enough test borings to make certain that the No. 1 sand is adequately protected.

SUMMARY AND CONCLUSIONS

The pumping in the vicinity of Parlin has lowered the head of the water in the No. 1 sand in that area as much as 110 feet below its original static level. This fact has naturally raised the question as to whether or not the safe yield of the sand is being exceeded. The results of the studies made to the present time indicate that the lowering of head has not been out of proportion to the increase in pumpage and that the safe yield probably has not thus far been exceeded unless salt water has access to the sand at some point within the cone of depression of the wells in the area. It seems likely, however, that the safe yield of the sand is being approached, and any large increase in pumpage may exceed it.

The safe yield of the No. 1 sand in this area may be limited by the intrusion of salt water rather than by the quantity of water that can be withdrawn from the sand continually. There appears to be danger of contamination of the sand by salt water from the estuary of the Raritan River. The disposition of the materials below the river channel is so irregular that no definite predictions can be made. Dredging operations in the bed of the river unquestionably increase the danger of salt-water contamination.

The intake area of the No. 1 sand in this area, and to a large extent the whole sand, is divided into two parts by the estuary of the Raritan River and the ancient trap ridge that underlies it. If the wells south of the Raritan River must rely on the intake area south of the river for their supply, the cone of depression of these wells must extend approximately 10 miles from Parlin in order to include enough intake area to supply the quantity of water pumped from these wells in 1935. Even if there were an unrestricted connection between the two parts of the sand, the cone of depression would have to extend about 8 miles in both directions from Parlin. No information is available about the fluctuations of the water table in the intake area, but water-level observations in wells farther down the dip indicate that the cone of depression may indeed extend 8 or 10 miles from Parlin. The yield of the intake area may be increased by infiltration from the Farrington Reservoir, which lies upon it, and also from several small streams with flat swampy valleys that cross it from the southeast.

There appears to be good evidence that the water level in the wells at Parlin is affected by fluctuations of precipitation. This relation suggests that at least a part of the intake area is now yielding all the water that can enter the sand, so that the cone of depression must be extended in dry years in order to include enough of the intake area to supply the wells.

Although much has been learned about the water supply from the No. 1 sand, there remain many problems that need to be better understood. The collection and study of records of the pumpage from the sand and of the water levels in wells tapping it should be continued and intensified. Especially valuable information may be obtained from a study of the fluctuations of the water levels in the new observation wells in the intake area. At least one observation well should be established in the area between Parlin and South Amboy. Additional test wells should be drilled as suggested in the preceding pages. These test wells are needed to obtain samples of water to detect the possible advance of salt water, particularly in the vicinity of the Washington Canal, and to obtain additional information about the geology of the area with special reference to the location of the trap ridge and its effectiveness in protecting the sand from salt-water encroachment. Water samples should be collected periodically from every available well that taps the No. 1 sand in the area, and these samples should be analyzed for chloride content. In general, the observations now being made should be continued and extended in order that the problems relating to the water supply from this sand may be better understood.

INDEX

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INDEX

INDEX

INDEX