GEOLOGY AS A GUIDE TO REGIONAL ESTIMATES OF THE WATER RESOURCE

GEOLOGIC REPORT SERIES NO. 8

NEW JERSEY GEOLOGICAL SURVEY

DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT

GEOLOGY AS A GUIDE TO
REGIONAL ESTIMATES OF THE WATER RESOURCE

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Trenton, New Jersey

1968

FIRST INTERNATIONAL CONFERENCE

on

WATERS FOR PEACE

May 23-31. 1967

Washington, D. C.

This paper was presented to the conference at the morning expert session on Basic Data for Water Programs on 29 May, 1967 as a replacement for the paper by Ahmed A. Kamal, Under Secretary of State, Ministry of Irrigation, United Arab Republic.

This paper will appear in full in the Proceedings of the Conference to be published by the U. S. Department of the Interior for the ninety-six participating nations.

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26 Sept., 1967

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Abstract

Recent studies of ground water geology published by the New Jersey Geological Survey have been designed to provide information by which municipalities, counties, or regional planning groups can estimate the upper limits of the ground water resource in the area of interest. New Jersey is a water resource peninsula between the Delaware River and Bay on the west and the Hudson River and Atlantic Ocean on the east. Water development plans for New Jersey are limited to its own area and its share of any Delaware River development.

The geologic conditions within the State establish five ground water provinces with widely divergent potentials and problems. Three-fifths of New Jersey is a coastal plain whose low relief severely limits surface water development, while ground water is abundant and easily utilized. Estimates of the ground water potential should not only be based on the outcropping of a formation and the usual geologic and hydrologic factors, but also upon the area within which wells may be constructed to utilize the various sand formations.

The northern two-fifths of the State are underlaid by rock formations in three ground water provinces where fissure water conditions prevail. That part of northeastern New Jersey which has been glaciated forms a fifth ground water province. The presence or absence and the character of the Pleistocene cover noticeably changes the ground water potential of every underlying formation.

Careful examination of large numbers of well records from any geologic formation indicate the safe sustained yield in gallons per day per square mile. From these estimates of safe sustained yield the minimum lot size for suburban development or the maximum population densities or industrial water need per square mile can be determined for many areas of the state.

Introduction

Since its inception in 1865, the New Jersey Geological Survey, officially called the Bureau of Geology and Topography of the Department of Conservation and Economic Development, has been concerned with ground water problems. Since 1947 more than 67,000 well permits have been issued as a result of the enactment of a Well Drilling Law. About half of these permits have provided well records adequate for various ground water investigations. Thus it is only since the accumulation of well records resulting from enactment of the 1947 Well Drilling Law that we have had the large quantities of statistical data needed for regional studies of water resources with adequate treatment of the ground water potential. Seven areas, each in excess of 200 sq. miles, have been studied using a sample of between 1,000 and 2,000 of the better well records. In each of these studies, in addition to securing maximums, minimums, medians, averages and probabilities for both the depth and yield of wells drilled at a specific location, the data sample has been large enough to reveal not only the broad regional characteristics of each geologic formation but also significant local variations due to structure, lithologic or other changes in the geologic character of the formation.

Before examining these general relationships or some of the more significant detailed variations, it would seem advisable to point out that New Jersey's nearly seven million citizens live within an 8,204 square mile water resource peninsula. Only 7,500 sq. miles of this, the fifth smallest State of the United States, is land. The most urbanized of all the United States New Jersey is a State of contrasts. Over 67% of the population is found within the northeastern 23% of the State's area.[3] Three municipalities have permanent populations in excess of 37,000 people per square mile, but nearly 60% of the land area is in parks, in forests or in working farms. Nearly one quarter of the State, in that part of the Coastal Plain of southern New Jersey known as the Pine Barrens, has fifteen townships with a population density less than the national average of 50 people per square mile. The most densely populated of all of the States in the United States, with an average population density of 906 people per square mile, New Jersey has a 20 square mile Township in the northwestern corner of the State which has only 63 residents.[2]

New Jersey has a water problem because its major water users are concentrated in localities with very limited ground water resources which are usually adjacent to tidal waters. Topography and the shape of the drainage basins severely limit the development of surface water supplies near the most densely populated parts of the State. Legal restrictions on the transfer of water between basins and, amazingly, the very abundance of rainfall complicate all plans for future water resource development.

Rainfall

There are only a few places, and a very small percentage of the total area of our continental land masses, with an annual rainfall which exceeds that normal to New Jersey. New Jersey has about 43 inches of rainfall in the south, an average of 45 to 46 inches of rainfall in the north, and two areas in the Highlands which usually receive about 50 inches. This bountiful rainfall is evenly distributed throughout the year with almost 4 inches of precipitation each month.[7]

This abundance of precipitation and its distribution is a blessing which generates some unusual problems. It has not only made "a well" the most economical method of developing a water supply for all but the largest needs, but also has made certain that almost every well drilled anywhere in the State will give some water. Sub-surface conditions and the precipitation pattern during normal years assure a saturated ground water zone a few feet or a few tens of feet beneath the surface. Ground water recharge practices, recommended and considered in several areas of the State during the prolonged drought of the last five years, are normally either unnecessary or impractical because natural recharge is usually adequate and nearly continuous. Most important is the psychological factor that develops from easily secured water. The desirability and success of regional cooperation is stifled by the ever present possible alternative of wells. Adequately researched sound knowledge of ground water capability is extremely limited and continually in conflict with the water expertize of those who "know" of a well to an imaginary underground stream which will do the job. The greatest trouble is that for a short time or for sixty percent of the requirement they may be right.

A Water Resource Peninsula

Geologically, geographically, topographically, and politically New Jersey is a water resource peninsula divided into four northeast-southwest cross compartments. The major streams and rivers of the State are short and quickly carry the runoff component of any precipitation to the natural water bodies which form all but 48 of New Jersey's 487 mile long perimeter. Except for the Delaware watershed and the Delaware main stem, the major drainage systems are chiefly within a single cross compartment.[8]

A straight 48 mile surveyed boundary line with New York nearly bisects an S-shaped drainage divide (See Figure 1). In return for not developing the head waters of New York's Wallkill River (210 sq. mi.) which are found in New Jersey along the western half of this boundary, New Jersey is allowed to develop and utilize much of the water from the head waters in New York State of the Passaic and Hackensack Rivers (212 sq. mi.) which flow into New Jersey across the eastern part of the boundary line.[8]

To the east and parallel to the Hackensack, on the other side of the non-water bearing Palisades basalt sill, of which more later, is the Hudson River which here is tidal, salty and polluted. The waters of New York Harbor and the lower Hudson form 60 miles of the eastern boundary of New Jersey. South of New York Harbor and Raritan Bay for 137 miles to Cape May at the entrance to Delaware Bay, the eastern boundary is the Atlantic Ocean. Delaware Bay forms the southern and part of the western boundary of the State. From Cape May the water of the first sixty miles of the estuary, sometimes more, is too salty to permit its use for industrial or public water supplies either directly or indirectly from wells. The lower Delaware River is tidal to Trenton, 131 miles up river from Cape May. Above Trenton the usually potable waters of the Delaware River form the western boundary of New Jersey for 111 miles to the first-mentioned New York State line. A major multiple-use water reservoir, Tocks Island, is planned for the upstream 37 miles of this portion of the river.

The utilization and allocation of all water resources, both ground and surface, in the Delaware River Basin is now under the control of the Delaware River Basin Commission, a cooperative partnership between the Federal government and the four States having territory within the river basin. Some 2,866 sq. mi., 34% of New Jersey's total area, and about 40% of the total runoff, along the western and southern sides of the state are part of the Delaware River drainage basin.[5]

In the northeast corner of the State the Hackensack and Passaic (this includes the Rahway and Elizabeth) Rivers drain about 1,500 sq. miles of the most densely populated part of the State, the northern part of the Piedmont Physiographic Province.[8] Surface water development within these urbanized watersheds is nearly complete with all practical reservoir sites now utilized. The 1,100 square mile watershed of the Raritan River drains the central part of the State into Raritan Bay. The Raritan Basin includes a small part of the Highlands, nearly all the southern half of the Piedmont and a small segment of the Coastal Plain. Until recently undeveloped, the utilization of this surface water resource has begun with the construction of two large reservoirs and the investigation of other available sites. A third drainage system is composed of a number of short Coastal Plain streams which drain about 1,653 square miles of southeastern New Jersey directly into the Atlantic Ocean.

The peninsula characteristic of New Jersey's water resource is further emphasized when it is pointed out that the reservoirs of the New York City Catskill

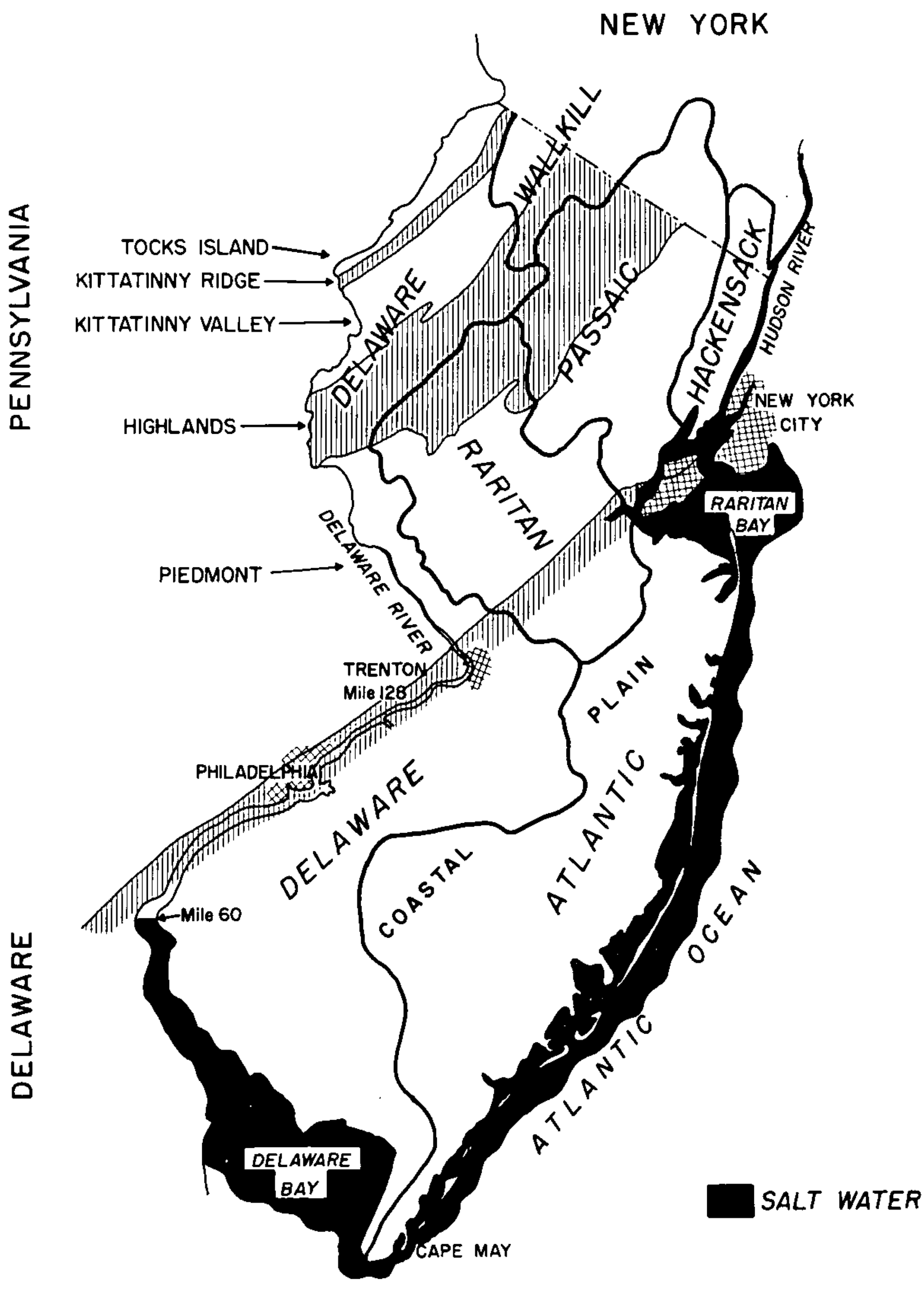

NEW YORK
PENNSYLVANIA
DELAWARE
TOCKS ISLAND
KITTATINNY RIDGE
KITTATINNY VALLEY
HIGHLANDS
PIEDMONT
WALLKILL
DELAWARE
PASSAIC
HACKENSACK
HUDSON RIVER
NEW YORK CITY
RARITAN
RARITAN BAY
DELAWARE RIVER
TRENTON
Mile 128
PHILADELPHIA
Mile 60
PLAIN
ATLANTIC
COASTAL
DELAWARE
ATLANTIC OCEAN
ATLANTIC
DELAWARE BAY
CAPE MAY
SALT WATER

FIG.1

Water System are just to the north of New Jersey. To the west are the various municipal water systems in Pennsylvania. The authority of the Delaware River Basin Commission, and still binding earlier legal controls, limit the amount of water (100,000,000 gallons per day) which New Jersey may take out of the Delaware River Basin. These water systems have pre-empted the utilization of nearly all potential water resources outside of New Jersey's boundaries.[9] In planning the utilization of its water resources New Jersey must work almost entirely within the capabilities of its own area.

The total amount of rainfall and the total amount lost to evaporation and transpiration is determined by the climate. It is geology, however, that determines the ratio of runoff to recharge and whether or not, there is also some aspect of how, these increments of the water resource can be increased. For New Jersey as a whole, the total normal precipitation works out to a little more than two million gallons per day per square mile.[7] About half of this total precipitation is lost through evaporation and transpiration. Therefore, for all of New Jersey's 7,500 square miles of land, the maximum water resource is no more than one million gallons per day per square mile. This is only available if all of the runoff and all of the recharge can be utilized.

Geologic Concepts

There are a host of terms and measurements applied to the geological conditions immediately adjacent to the well. As the area of consideration is broadened, we get such terms as aquifer and aquiclude, which define or measure general conditions of ground water confined to a geologic formation. There are many theoretical conclusions about ground water which particularly apply to the sediments and sedimentary formations. Much of this experience has come from studies of oil and natural gas which are not found in igneous and crystalline rocks. This may explain in part the lack of studies as to how fluids move through these relatively impermeable geologic bodies. In Oil Geology, also, while there has been a great deal of concern for geologic structures and geologic history because of their influence upon the location of favorable oil pools, there has been a more restricted use of geology in investigation than that which is needed for the more ubiquitous occurrence of ground water.

In fact, the three most general of geologic relationships in water resource planning are so obvious that more often than not they are improperly weighted. The improper weighting may be in part due to the lack of detailed knowledge of what actually happens to water beneath the surface. Rainfall and runoff can be measured, slopes may be computed, but the actual quantity of ground water available generally must be secured by inference. Efforts to reduce these inferences to a minimum, lead to a desire to secure precise measurements. Since much of the information available must be obtained from wells or test borings, a tendency develops to measure a set of values whose distribution is not yet well known. This in turn leads to other inferences. The large number of well records available to the New Jersey Geologic Survey while usually neither complete nor precise tend to eliminate this basic difficulty because their very volume smoothes the curve and compensates for some errors, particularly when changes in well records are keyed to changes in geology. In many studies only part of the geology factor is used in water resource planning.

The New Jersey Geological Survey, when examining many well records, has found it necessary to continually reexamine the geological variations which may affect ground water conditions. Examples of this approach will be cited later in the paper. It would seem worthwhile, at this point, to examine briefly the three major areas in which geology should always be applied to water resource studies. The past geologic events have first determined the rock or sediments which occurred. Subsequent events, geologic history, and this is the part of the concept most often ignored, cause the development of the geologic structure and a host of minor conditions such as jointing, faulting, lithification or solution in the geologic body. Finally, the most recent events of the geologic history act upon the rock body with all its modifications from the past and develop the topography, the thickness and character of the overburden, the soil and the response to weather and climate. The total of events in the geologic past establish for each ground water province a distinct set of geologic formations and geologic conditions which influence the amount of runoff, the rate of ground water recharge and the capacity for ground water storage. Even minor variations in the geology or topography may be sufficient, particularly if they reinforce the effectiveness of a geologic or water resource process to cause widely divergent water resource potentials and problems.

New Jersey's Ground Water Provinces

Three of New Jersey's five ground water provinces are in northern New Jersey; (1) the Piedmont of Triassic shales, sandstones and lava flows which has most of New Jersey's population, (2) the Highlands with sparsely settled ridges and valleys of Precambrian granites and gneisses with infolded Paleozoic slates and quartzites and (3) the Valley and Ridge Province of Paleozoic limestones and shales of agricultural northwestern New Jersey. Differing in detail with each geologic formation, all are in what may be called "rock well country" where ground water is governed by the conditions found in the occurrence of "fissure water" or, in the few limestone formations, by "cavern water." The remaining two ground water provinces are "sand well country." The fourth province and most important of the two, the Coastal Plain, is underlain by Cretaceous and Tertiary sands, clays and marls. The fifth ground water province, the Pleistocene sands and gravels, is most important in the northeastern and northern glaciated portion of the State, the drainage basins of the Passaic, Hackensack, and that part of the Delaware watershed north of the Highlands (Fig. 1). However, Pleistocene deposits are thick enough as terraces along the Delaware over the whole Cape May point and in many other small areas to warrant their consideration as a potential source of water for local needs.

The Coastal Plain Sand Wells

The Coastal Plain is that three-fifths of New Jersey south of Raritan Bay, and east or north of the Delaware River estuary. Just south of Raritan Bay, high ground, the Highlands of the Navesink, in the northern part of the Coastal Plain almost reaches an elevation of four hundred feet. Over half of the Coastal Plain, however, is less than one hundred feet above sea level.[7] The generally low relief and a sandy soil are so favorable to ground water recharge, that even minor surface streams are usually at least four miles apart. Floods are unknown except when a heavy rain falls during a period when the ground has been frozen.

There is still a great deal to be learned about the ground water resources of the Coastal Plain. Most of the concern at present is with the local areas threatened by salt water intrusion because wells have been overpumped. The very extent of the area, its very low population density, its abundant rainfall and its highly permeable geologic formations make the entire Coastal Plain, and particularly that area underlain by the Cohansey formation, almost impossible to evaluate in detail. The economics of New Jersey's water situation at present is such that large well fields in the Coastal Plain with a potential of billions of gallons of water per day, cannot yet compete with some of the nearer and still available surface water resources required to meet the needs of the northern metropolitan areas.[6] The sources of water for future needs of the seashore communities and of industrial development in the southernmost counties are jealously guarded by the local citizens. Thus, while it is apparent that the Coastal Plain will some day be important in ground water development, there are several good geological and non-geological reasons for considering it as a separate part of New Jersey.

Geologically, as indicated above, the Coastal Plain is New Jersey's most distinctive ground water province. Since it is composed of those geological formations in which there has been the greatest amount of the investigation of the movement of fluids through rocks, the detailed ground water problems are relatively easy to solve. The regional problems are more difficult because the population is found chiefly around the borders which, except for the 28 miles northeast from Trenton, are usually not only tidal, but for all but about 71 of the 310 mile shore, salty enough to be a threat to ground water supplies.

The Geology of the Coastal Plain

The geology of the Coastal Plain may be compared to a super-sandwich in which there are five layers or geologic formations which are sand aquifers, the Cohansey formation on top and the Raritan formation on the bottom, separated by other layers which are predominately clays or marls. The clay and marl formations, while not completely impermeable, are thick enough to effectively retard ground water movement into or out of the water-bearing sands of the adjacent aquifers. Each aquifer may be considered for the solution of local problems as a separate water-bearing formation. Each of the Coastal Plain formations is tilted toward the southeast and also thickens in the same direction. Our sandwich is in effect a pile of wedges consisting of various unconsolidated sediments deposited on a tilted floor of crystalline rocks. This basement of crystalline rocks is at the surface along the line of the Delaware River estuary and some 2,000 to 7,000 feet below the surface along the Atlantic shore.

The geological investigations in the Coastal Plain, so far concluded, indicate that the curve of well yields is similar to the curve developed for the rock formations to the north which will be examined in detail later in the paper. Well records indicate that the sedimentary layers or formations change their water characteristics in all directions, thus, any particular aquifer is far from uniform in its water resource potential.[1] While it is generally true that the Cohansey is an excellent aquifer, there are some small areas where wells are very poor and others where clay is mined from this formation at the surface. Similarly, while the Raritan is an excellent aquifer from Raritan Bay as far south as Philadelphia, wells in the Philadelphia area are not completed in the same part of the formation utilized by wells further north. Down river towards Delaware Bay, it becomes a poor aquifer for water development, not only because there is the danger of increasing salt water intrusion but also because there is a greater possibility that more adequate supplies of water of better quality can be developed from the stratigraphically higher formations inland.

There is rarely any difficulty in solving local ground water problems in the Coastal Plain. The need for regional solutions has only recently arisen as industrial development and growing towns have required more water than can be produced by their own wells. Two examples of the need to use all aspects of geology illustrate the importance of this concept to regional planning. In a twenty-five square mile area near Trenton the crystalline basement is so close to the present surface that the Raritan aquifers were never deposited. Obviously this area can never be used for industrial, irrigation or public water supply. Yet, several unsuccessful attempts to secure large capacity wells were made because the Raritan formation is present and the crystalline basement was supposed to be a very flat plain. The second example is a gravel filled Pleistocene channel, over 100 feet thick and at most a quarter of a mile wide which cuts across the Raritan formation for several miles. Wells completed in these gravels have capacities in the 1,000 gallons per minute range, which is two or three times greater than that of the nearby Raritan wells.[10]

Coastal Plain Regional Estimates

A general analysis of the Coastal Plain water resources should consider three different problems in three areas: (1) the sparsely populated central area with the Pine Barrens (2) the seashore resorts with many people for four months out of the year and (3) the urban, suburban and industrial belt bordering the Delaware River from Trenton to Salem (Mile 60). For most of the Coastal Plain, and the Pine Barrens, regional estimates of the available ground water should be slightly less than half the total precipitation in the area. Along the Atlantic Coast the practice of drilling wells on the offshore bar, or close to the bay shore, and the large influx of summer visitors complicate the estimates. However, we are still dealing with a single hydrologic unit, three sand formations whose capacity is directly related to precipitation, demand, and the area of supply. Tide marshes, bays and the principles of the fresh water bubble must be considered for accurate estimates.

Methods for estimating the water resource potential of the urban, suburban and industrial belt bordering the south side of the Delaware River have not yet been developed. Enough work has been done to show that a "use area" must be applied in preparing regional estimates. This western border of the Coastal Plain extends about fifteen miles inland and is not quite coincident with the area of the northwesterly flowing Coastal Plain tributaries of the Delaware River (Fig. 1). Most of the streams have their headwaters in the western part of the outcrop area of the Cohansey formation.

Each tributary flows successively across stratigraphically lower and lower Coastal Plain formations until within five miles of the Delaware River they are flowing across the Raritan formation. Each of the five major aquifers from the Cohansey down to the Raritan, depending on the local demands for ground water, may be discharging water to the stream or recharging the aquifer. At several places between Camden, opposite Philadelphia, and Trenton, heavy pumping has lowered the ground water level in the Raritan so that 80-90% of the water pumped is from the Delaware River.[6]

Within this belt of successive surface exposures of the Coastal Plain formations it is possible to complete wells in one aquifer, the Raritan, then two, and finally if necessary, in five different aquifers as one moves southeast or up the Delaware River tributaries. With this choice of either one deep well to the Raritan or one or two shallow wells to the stratigraphically higher formations nearer the surface, it is possible for one or more aquifers to be locally overpumped. When an aquifer is depleted, vertical leakage from adjacent aquifers will start to compensate for the loss in hydraulic head.

Regional estimates must, therefore, be equated to the total area of all aquifers which are being used by wells in the region. Particular attention needs to be given to all uses and aquifers up-dip from the area being studied. This "use area" has been found in a study of Coastal Plain wells to be about five times the width of the outcrop of each aquifer. The per square mile safe sustained yield of any part of this area would be only one fifth that of the rest of the Coastal Plain, about 200,000 gallons per day per square mile, for all withdrawals by wells to any and all aquifers. Such an estimate is known to be too low because, as withdrawals empty the aquifers, recharge from the Delaware or its tributaries, or from the over-lying formations will be induced, thus increasing the available total supply of ground water.

Enough work has been done in the Coastal Plain to indicate that the present regional demands are about half of the most pessimistic estimates of the maximum available ground water.

Pleistocene Wells in the Northeast

Before considering the "rock well" area an examination of the other "sand well" provinces would seem advisable. The relative success in completing large capacity wells in the thick glacial sand and gravels in some of the valleys of northeastern New Jersey illustrates both the importance of the "inadequacy" factor, which will be discussed shortly, and attention to the details of historical geology mentioned earlier. Thick Pleistocene sands and gravels in three areas of northeastern New Jersey have been intensively explored by water companies, industry, and ground water experts as a source of water. In the Hackensack Valley about half of the wells have been completed with very large capacities in the 500 gpm to 1,000 gpm range. The other half of the wells have been either dry or have given less than 100 gpm. An exploratory program seeking old river channels beneath the clays of the Glacial Lake Passaic section of the upper Passaic Valley, has been no more successful. To the south and to the east, in the Passaic Basin, the probabilities of success are even less. Each of ten exploratory programs have had only one Pleistocene well out of five completed with usable capacities. In one such program a successful well was later completed in the underlying Brunswick shale. It had less capacity than a good Pleistocene well, but had double the yield of the best of the six unsuccessful glacial wells. In the northern part of the Passaic Basin near the New York line and around the northern edges of the Glacial Lake Passaic sector highly successful Pleistocene wells have been completed about 80% of the time. Why this may be so is under study. Northern New Jersey had a second advance of the ice sheet after the earliest Wisconsin maximum (the last and most recent of the great Pleistocene ice sheets). Could it be that the silt-laden water from the melting ice of the second advance plugged the gravels laid down by the streams of the Wisconsin maximum? That this is the case, is a reasonable hypothesis upon which to base regional ground water resource estimates for the glacial deposits of northeastern New Jersey.

Geologic Factors in "Rock Country"

The six guiding principles in the application of geology to rock country wells are: (1) there is no correlation between depth and yield, (2) each drainage basin, no matter how minor, is a surface and ground water entity, (3) water is usable only from fractures, fissures and solution openings, (4) successful industrial wells are completed in the first 200 to 500 feet of rock, (5) porous and permeable Pleistocene or deep weathered rock regolith zones above the rock will usually act as a built-in reservoir to increase well capacity and (6) glacial till, heavy clay soil, or bedrock close to the surface will decrease well yields.

The northern two-fifths of New Jersey, "the rock country," where fissure water conditions prevail, is divided into the previously mentioned compartments of the Piedmont, the Highlands and the Valley and Ridge. It is in the Piedmont, which has the greatest concentration of people and which is undergoing some of the more rapid urbanization, that there is the greatest demand for the solution for both individual and regional ground water problems. The methods used in estimating the ground water potential of the rock formations of the Piedmont apply equally well to all the rock formations in the other two ground water provinces. The presence and nature of thick Pleistocene sediments must be considered in the manner discussed above.

Most of the Piedmont, and a very large portion of the Raritan Drainage Basin, is underlaid by the Triassic Brunswick shales and the Stockton sandstones. These two formations are equally productive, although a large sample of industrial wells will show that the sandstone gives perhaps 20% more water when compared to the shale. Domestic and small capacity industrial wells are always successful. Industrial wells will average about 150 gallons per minute.

In contrast to these two "aquifers"(?), they have no usable porosity, the diabase of the Palisades, the basalt lava flows of the Watchung Mountains and the Lockatong argillite of the southwestern Piedmont are hopeless as sources of ground water. In these rocks a 30 gpm well for industrial, public supply or other large water use may be considered excellent and one out of every five household wells will probably be inadequate, if not dry, when the drilling is stopped.

Wells and the Geological Formations of the Piedmont

The diabase of the Palisades sill, which borders the New Jersey side of the Hudson for some 30 miles, is a natural ground water dam or wall nearly devoid of fractures big enough and open enough to provide water for wells. A ten gallon per minute well is excellent. The underlying sandstone is in direct contact with the Hudson. Early in the century some small industrial wells were drilled and then overpumped so that for many years the sandstone wells have given only salt water. In the valley of the Hackensack on the west side of the Hudson, in spite of the thick clays beneath the Hackensack meadows, a number of wells in basalt, in the sandstone, and in the "clays" were found to be good. To explain this contradiction, for the Hackensack meadows are tidal, a large number of well records were examined and a bedrock map of the meadows was completed.

Among other things, this illustrated the need to apply all facets of geological thinking to ground water problems. The top of the Diabase sill and the overlying sandstone were more frequently fractured than the bottom of the sill, probably because of the post-Triassic folding in the region. The importance of the faults was emphasized because these were the only good well sites in the Palisades. The "clays" were found to have sand lenses either in the pre-glacial river valleys or in deltas formed in an earlier glacial lake which are now buried under clays of the most recent glacial lake, whose clay bottom now forms the meadows. The deltas under Newark and elsewhere are apparently connected hydrologically to the present-day uplands outside the tide marsh area. It was this careful examination of all available well and test boring data which emphasized the need for a large data sample for the proper evaluation of the regional occurrence of ground water.

A regional study of Mercer County around Trenton was begun at this time. There were at least six false starts until the nature of the curve showing the reported capacities of wells was understood. We have all read reports which give the maximum and minimum well capacities for a formation. In Mercer County because there are two formations, the Brunswick shale and the Lockatong argillite, which look alike but have very different ground water conditions, it was necessary to find out the difference between the formations, the odds so to speak, for getting any given quantity of water. This study also made it possible to compare other types of formations since there was an area of Precambrian gneisses which also contained a Paleozoic quartzite, and was thus like the Highlands, a diabase which is an extension of the Palisades sill found on New Jersey's northeastern border, the previously mentioned Pleistocene river channel gravels and a sizable area of the Coastal Plain with an excellent exposure of the Raritan formation.

The Well Capacity Curves

The well records from 215 wells in the shale formation, which underlies much of the most densely populated part of New Jersey and in which wells are nearly always successful, were compared with the well records from 225 wells in the Lockatong argillite, a formation common to the southwestern Piedmont with the water characteristics of the Palisades diabase and basalt lava flows, in which one out of every five wells is usually unsuccessful. The results of this comparison are shown in Figure 2. The number of wells (each block represents a single well) was plotted against a base using the reported yield, in gallons per minute, at one gallon intervals. No matter how the two formations are compared, whether by maximums, averages, medians or total yield, wells in the argillite are at best only half as good as wells completed in the shale. This holds true for both the numbers of wells in any particular range of yields, except the poorest, and for a comparison of yields at any part of the curve, such as for industrial wells.

More important than the comparison of probable yields from two different geologic formations is the shape of the curve itself. If the right-hand side of Figure 2 were continued at the same scale as the main part of the diagram, where each bar represents an increase in reported yield of one gallon per minute, the best well would be to the right of the diagram at a distance equal to 16 times the length of the horizontal base. It is this extremely long tail of the curve with a very few wells which gives rise to the erroneous concept of wells "tapping underground rivers."

When the geologic formations are compared in such a way it is possible to estimate in a rough way their comparative regional capability. For the argillite, diabase or other formations with a low potential there must be a modifying factor for the unsuccessful wells that give some but not enough water. For example, if 5 gpm is assumed to be the minimum acceptable yield, 30% of the argillite wells are unsuccessful as compared to 5% of the shale wells. An argillite well is therefore less than half as good as a shale well. To take care of the probability that a portion of the wells will be inadequate, an "inadequacy factor" should be applied.

Some of the information provided in Figure 2 is also shown in Table 1 in a different form. The Table compares the shale and the argillite yields with other types of geologic formations including the Coastal Plain and Pleistocene "sands."

Lot Size and Population Density

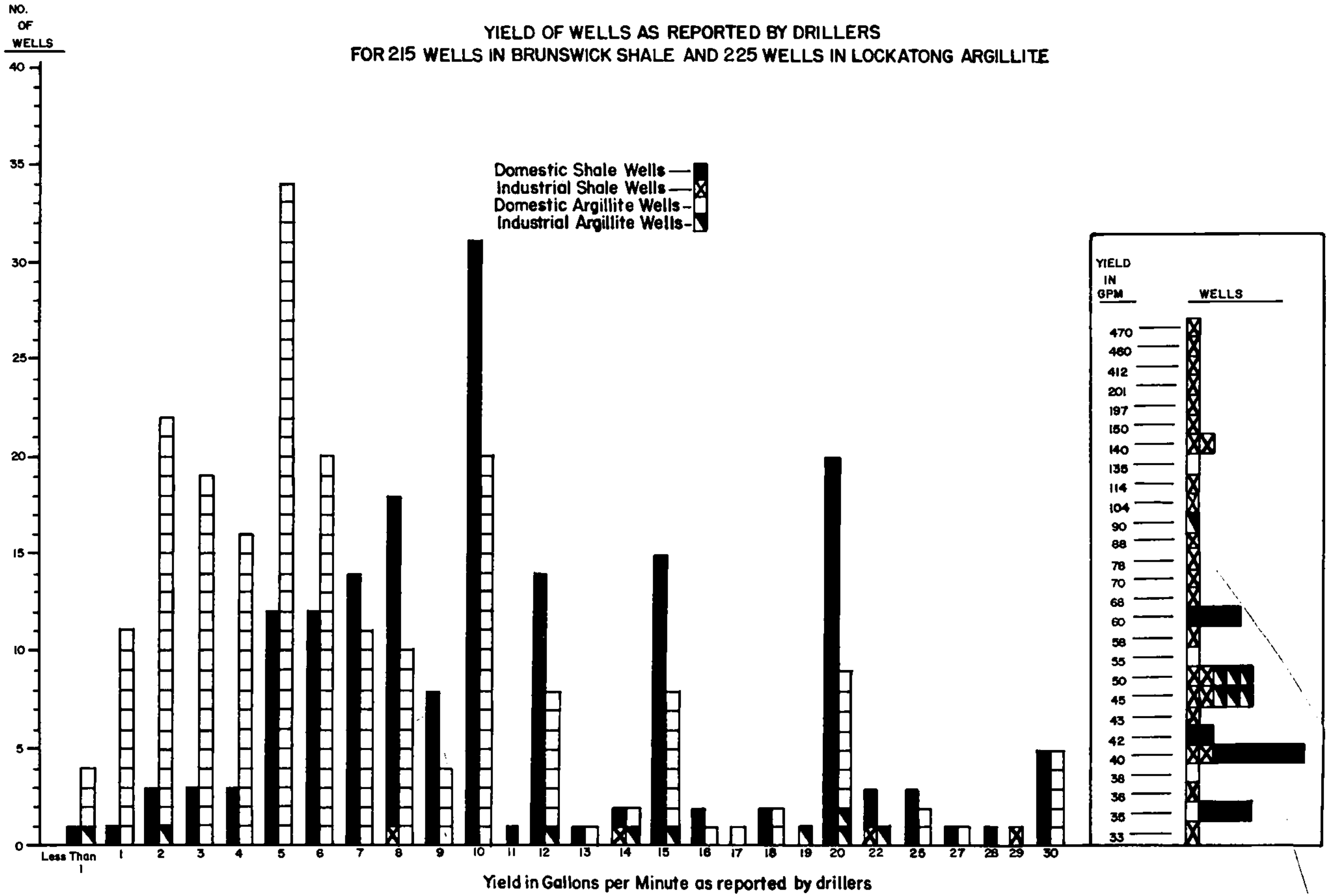
A safe sustained ground water yield of 500,000 gallons per day per square mile has been used by the New Jersey Geological Survey for the Brunswick shale and the Stockton sandstone for many years. It may be computed in a variety of ways, as a function of rainfall or runoff. If this safe sustained yield is correct, a household of five, a little higher than average, using 100 gallons per person per day, a little lower than average, would use 500 gallons per day. A thousand households on 640 acres, a square mile, would use the safe sustained yield and each house would be on a lot of two-thirds of an acre. This is about the minimum size lot on which a well, a house, and a septic tank can be fitted without violating health laws.

If we compare argillite to shale in Figure 2 we find it is only half as good by any standard. With a 30% "inadequacy factor" if we consider it only one third as good, the lot must be three times as big as the shale lot to provide the water needed for the individual household well. This would require a two acre minimum lot size.

This approach which compares the yield curve of a large statistical sample of wells completed under the same geologic conditions, to a similar sized sample and area where the ground water potential of the geologic formations is known may not be perfect but it seems to work.

A housing development on red shale with half acre lots has been observed for ten years. As more and more houses, and wells were built, the well yields declined and the wells were completed at greater depth. During the recent drought every house except those on the perimeter of the development had to deepen their well.

In another development built on argillite, it has been observed that one acre lots have problems of inadequate wells and/or pollution. To a lesser degree this also was found to hold true for lots of one and one-half acres. The two acre lots, on the other hand, have as yet, had no difficulties with wells.



NOTE: Due to a lack of space, the yield in gallons per minute of the better wells is continued in the vertical column to the right.

FIG. 2

Table 1

Yield in Gallons per Minute for Domestic Wells

Rock Formation	No. of Domestic Wells in Sample	Best Well	4th Best Well	Aver. Well	Ratio 1st-4th*	Ratio 4th-Aver.*
Pre-Triassic (Precambrian and Hardyston)	26	50	20	10	2½/1	2/1
Stockton sandstone	148	60	50	20	1½/1	2½/1
Argillite	208	135	30	9	4½/1	3½/1
Brunswick shale	186	60	45	15	1½/1	3/1
Diabase	100	100	25	9	4/1	3/1
Raritan (Magothy-Raritan)	120	80	60	19	1½/1	3½/1
Pleistocene	20	80	20	13	4/1	1½/1

Yield in Gallons per Minute for Industrial Wells

Rock Formation	No. of Industrial Wells in Sample	Best Well	4th Best Well	Aver. Well	Ratio 1st-4th*	Ratio 4th-Aver.*
Pre-Triassic (Precambrian and Hardyston)	41	266	100	41	2½/1	2/1
Stockton sandstone	80	905	600	147	1½/1	4/1
Argillite	16	90	50	32	1½/1	1½/1
Brunswick shale	29	470	201	110	2/1	2/1
Diabase	none	—	—	—	—	—
Raritan (Magothy-Raritan)	69	1500	1040	327	1½/1	3/1
Pleistocene	27	340	200	112	1½/1	2/1

**Numerators rounded to nearest one-half.*

Conclusions

A method of determining a minimum lot size, a maximum population density, or a maximum industrial water use based on individual on-site wells and estimated safe sustained ground water yields expressed as gallons per day per square mile has been developed for a number of geologic formations. Constant revision to correct for the many geological variables affecting the ground water occurrences is required. A five year drought confirms that the estimates are workable and zoning laws based on the method have not yet been successfully challenged in the courts.

From the work of the New Jersey Geological Survey, as indicated above, the author concludes that many studies of regional ground water resource capabilities have not been made with a sufficiently large data network, nor do they usually consider all of the geologic factors which add to or decrease the regional capabilities. There would seem to be a tendency to over-generalize the geologic conditions as the region studied becomes larger. The studies being carried out in New Jersey suggest that by using a large sample of well records a general curve of ground water yields for each geologic formation may be established. This curve will permit the comparison of one geologic formation with another. As soon as this becomes possible, experience with respect to ground water conditions in one area may be modified to predict conditions in other areas with nearly similar geology.

Bibliography

The material presented in this paper is chiefly from the files of the New Jersey Bureau of Geology and Topography and from the various reports and publications prepared within the Division of which it is a part. The items listed below are for the convenience of those who wish more details. Information about any one topic may be found in one or more of the references below.

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