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DEPARTMENT OF ENVIRONMENTAL PROTECTION

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SPECIAL REPORT NO. 36

GEOLOGY AND WATER RESOURCES OF THE WHARTON TRACT AND THE MULLICA RIVER BASIN IN SOUTHERN NEW JERSEY

PREPARED IN COOPERATION WITH
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

1973

GEOLOGY AND WATER RESOURCES OF THE WHARTON TRACT AND THE MULLICA RIVER BASIN IN SOUTHERN NEW JERSEY

By

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ABSTRACT

The Wharton Tract is an area of 150 square miles located in the Mullica River basin in southern New Jersey's Pine Barrens region. The tract is a relatively flat, low-lying, generally sandy area containing shallowly incised streams. The larger streams are commonly bordered by swamps. The tract was purchased by the State primarily as a water-supply preserve, but also for conservation and recreational purposes.

Mean streamflow at three continuous record gaging stations in the Wharton Tract is: Mullica River near Batsto (46.1-square mile drainage area), 66 mgd (million gallons per day); Batsto River at Batsto (70.5-square mile drainage area), 81 mgd; Oswego River at Harrisville (64.0-square mile drainage area), 55 mgd. Thus mean discharge from this 180.6-sq mi (square mile) area is 202 mgd or 1.12 mgd per sq mi.

Principal aquifers in the Wharton Tract and Mullica River basin are in the Kirkwood Formation of middle Miocene age, Cohansey Sand of Miocene(?) and Pliocene(?) age, and in overlying hydraulically connected deposits of Quaternary age.

The Kirkwood Formation is composed of sand, silt, and clay. Diverse lithologies represent deposition in different environments such as nearshore marine, barrier bar, lagoonal, estuarine, and tidal marsh. Hydraulic characteristics of the Kirkwood in the Mullica River basin are virtually unknown. Most Kirkwood aquifers in the basin are believed to be hydraulically connected with the overlying Cohansey Sand.

The Cohansey Sand is dominantly a quartz sand containing minor amounts of pebbly sand, silty sand, and interbedded clay. Almost all of the Wharton Tract and most of the Mullica River basin lie within the sandier area of the Cohansey, which contains approximately 75 percent sand beds and 25 percent silt and clay beds. Data from test drilling show that the upper 100 feet of sediments in the Wharton Tract contain about 93 percent sand beds, 3.5 percent clay beds, and 3.5 percent silt beds. The Cohansey in the Tract ranges in thickness from less than 50 feet to about 180 feet; the average thickness is about 125 feet.

The Cohansey Sand is believed to be, in overall aspect, a deltaic deposit. It contains materials that were deposited locally in nearshore-marine, fluvial, estuarine, lagoonal, and beach environments.

The hydraulic conductivity of Cohansey aquifer material ranges from about 90 to 250 feet per day (660 to 1,885 gallons per day per square foot) in southern New Jersey. One aquifer test in the Wharton Tract gives an average value of 130 feet per day (1,000 gallons per day per square foot). The transmissivity of the Cohansey Sand aquifer through most of the Wharton Tract is typically between 10,000 and 20,000 square feet per day (75,000 and 150,000 gallons per day per foot).

Deposits of Quaternary age form a discontinuous veneer lying unconformably above the Cohansey Sand. The most important hydrologic function of most of these deposits is to absorb precipitation and transmit the water to the underlying Cohansey Sand. Thicker deposits of estuarine sand and clay of the Cape May Formation fill a channel in the underlying Cohansey Sand along the lower reaches of the Mullica River. This channel deposit is 85 feet thick near Batsto.

Ground water and surface water in the Mullica River basin are low in dissolved solids, generally less than 50 mg/1 (milligrams per liter). Iron concentrations are generally high, up to 49,000 micrograms per liter (49 mg/1) in ground water and up to 7,100 micrograms per liter (7.1 mg/1) in the streams. The water is acidic as indicated by typical pH values of from 4.5 to 6.5. Color of the surface water is commonly high, ranging from 3 - 150 platinum-cobalt units. After appropriate treatment these waters are acceptable for most uses.

The Wharton Tract is well situated to support the growing water needs of nearby New

Jersey communities. Maximum development of water can be achieved by conjunctive use of ground and surface water. During most of the year, some water would be withdrawn either directly from streams or from adjacent wells. During periods of low flow during summer or fall water would be pumped from wells farther from the streams. From analysis of flow-duration curves it is estimated that 70 mgd of water could be developed with minimal effect upon low flows in the half of the tract above the gaging stations on the Mullica and Batsto Rivers. The quantity available in the entire tract is greater, possibly in the order of 150 mgd. With augmentation of streamflow by pumping from ground water, it is likely that considerably more water could be safely used on a perennial basis.

A possibility exists for multiple use of the water resources of the Mullica River through construction of an inexpensive tide barrier at the Garden State Parkway. This would create a fresh water lake in a State forest, park, and recreational area, which would also provide a flexible and economical water supply for much of the Atlantic coastal resort development.

INTRODUCTION

The Wharton Tract, situated in southern New Jersey's Pine Barrens region is an undeveloped, sparsely populated, and forested area of about 150-square miles (95,634 acres in 1970), which is drained by the Mullica River and its tributaries. The Mullica River system drains about 570 square miles of the Atlantic slope in the New Jersey coastal plain area. Most of the Wharton Tract lies in Burlington County but parts of it lie in Atlantic and Camden Counties. Location of the Wharton Tract is shown on figure 1.

The Wharton Tract was purchased by the State of New Jersey in 1954 for multiple-use conservation and development programs. Foremost among anticipated uses of the Wharton Tract was its potential as a source of water to meet future demands in southern New Jersey.

Unlike many land acquisitions for water-supply purposes, the Wharton Tract was purchased ahead of area needs. Population and industrial trends and estimates of the water-supply reserves within present service areas for Camden and Atlantic City suggest that near maximum utilization of Wharton Tract water-supply potential may not be needed before 2000 A.D. In the meantime, the tract is being extensively used for hunting, fishing, camping and other forms of outdoor recreation.

Purpose and Scope

In order for the water resources of the Wharton Tract to be developed wisely it is essential to evaluate the hydrology of the tract and the encompassing Mullica River basin. Such development should maximize value for water supply but at the same time minimize or avoid interference with existing private interests and with accepted multiple-uses such as recreation, hunting, fishing, natural-site preservation, wildlife conservation, forestry, and historic-site restoration.

The purpose of this study is to evaluate and report on the quantity, distribution, movement, and quality of water in the Wharton Tract and the Mullica River basin and to describe the geologic framework of these areas. The investigation was initiated under the direction of Henry Barksdale formerly District Engineer and continued under the direction of Allen Sinnott, formerly District Geologist, and his successor John E. McCall, District Chief.

Previous Investigations

Since the earliest days of the European settlers it was known that the interior region of southern New Jersey, could provide large quantities of water. During the eighteenth and early nineteenth century bog-iron furnaces, grist, lumber, and paper mills, as well as glassmaking factories were built on what is now the Wharton Tract. These were located and maintained there at least partly because of the dependable water supply and water power generated from the stable streamflows.

Joseph Wharton, after whom the tract is named, assembled the Wharton Tract holdings around 1876 (Boyer, 1931, p. 174) in order to obtain a water supply for Philadelphia, Pa. The New Jersey legislature quickly passed a law instituting the right of the State to restrain the exportation of natural resources, including water, out of the State. According to Vermeule (1894, p. 281) the earliest stream gaging in the Wharton Tract began about 1890 on the Batsto River, one of the main streams of the Mullica River system. Hence, it is not clear how Joseph Wharton in 1876 determined the amount of water available for sale to Philadelphia. Apparently, he realized the tract's water-supply potential from his knowledge of the character and quality of Mullica River streamflow, probably obtained through familiarity with the operations of lumber mills, grist mills, iron furnaces, and iron forges located along the Mullica River and its tributary streams.

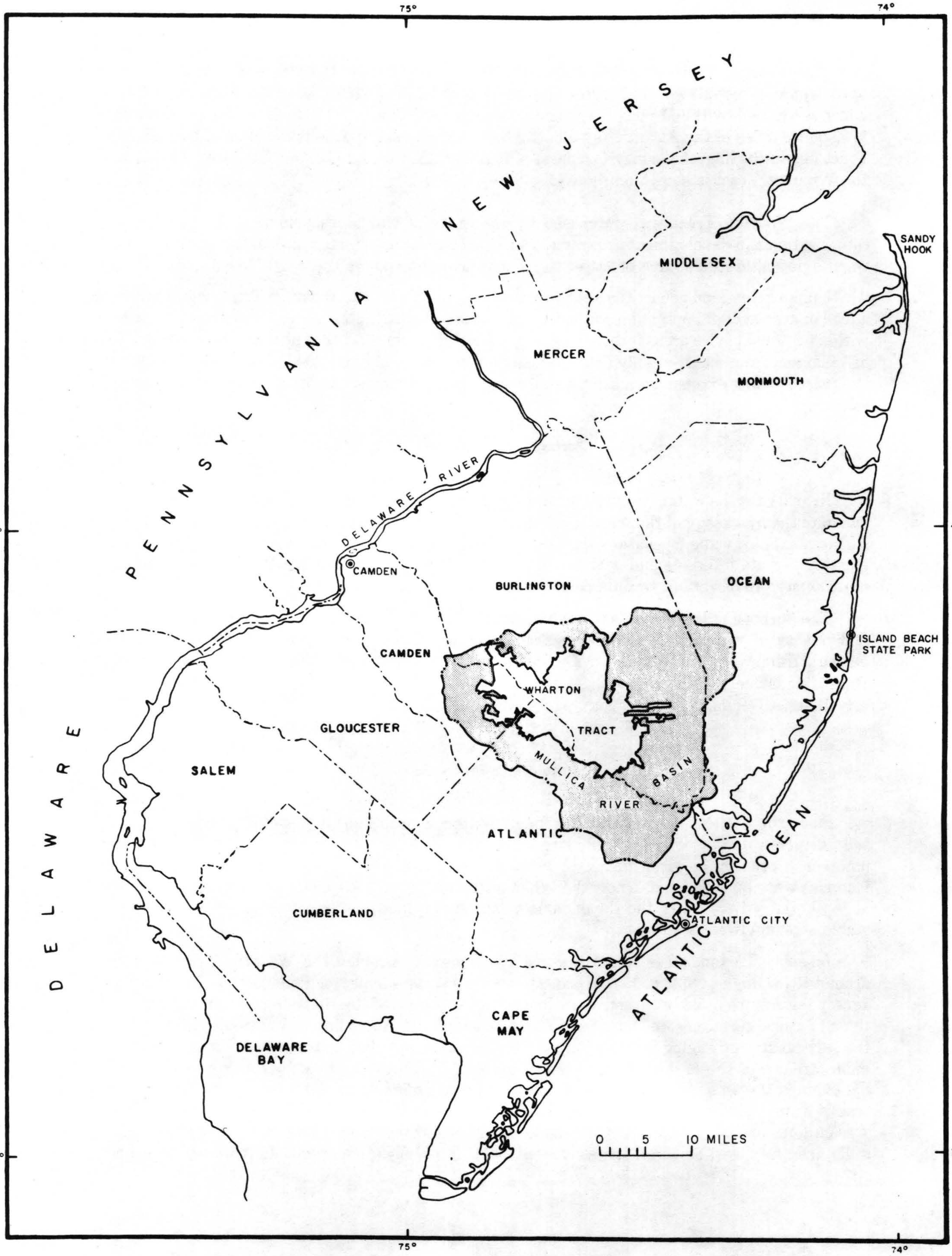

Figure 1. – Map of southern New Jersey showing location of the Wharton Tract and the Mullica River basin.

A brief discussion of the flow characteristics of the Mullica River was presented by C.W. Coman (1892, p. 115-116). Vermeule (1894) made estimates of flow in the Mullica River basin based upon short-period streamflow records of the Batsto River at Batsto. Nevertheless when the State of New Jersey attempted to purchase the Wharton Tract in 1911 and again in 1915 (Hill, 1926, p. 28), it was probably only little better informed than Joseph Wharton about the actual water-supply potential.

Hazen and others (1922, p. 45-48), at the request of the New Jersey Department of Conservation and Economic Development, submitted plans for the development of water supplies from surface reservoirs at the head of the tide on the Mullica and Wading Rivers. It was not until September 1927 that the State initiated the present-day continuous flow measurements on the Batsto River. Continuous streamflow records on the East Branch Wading River were begun in January 1931. The TAMS report (Tippets and others, 1955), utilizing streamflow records and U.S. Weather Bureau's climatic data recommended water withdrawals from the above-the-tide effective drainage area of the entire Mullica River system.

The U.S. Air Force conducted shallow subsurface explorations in the upland areas of the Wharton Tract during 1952. Eleven test holes were made. Engineering tests were made to obtain the foundation and bearing characteristics of the surficial materials for a proposed airport site.

Method of Investigation

Active field work by the author began in 1956. Geologic observations on the distribution of surficial gravel, sand, and clay were made in the tract. Subsurface exploration to depths of as much as 100 feet was conducted using power-auger equipment. Subsurface materials at a pumping test site along the Mullica River were explored in detail and an extensive well field was installed. A large-diameter pumping well was installed and a pumping test was conducted. A regional water-table contour map was prepared. Three continuous water-level recorders were used to determine the trend and range of ground-water fluctuations in the Wharton Tract. Data from these activities, including descriptive logs of test wells, grain size analysis, laboratory determinations of hydraulic conductivity, and water-level data from the pumping test along the Mullica River are available in the files of the Trenton, N.J. office of the U.S. Geological Survey.

Stream-discharge records at three continuous record gaging stations were analyzed. Chemical quality data of both the surface water (46 samples) and ground water (146 samples) of the Wharton Tract were collected.

GEOGRAPHY

Land and Water Use

Except for a few score people living at Batsto and Atsion villages, the 150 square miles of Wharton Tract is virtually uninhabited. Total population of the tract is about 100. In 1967 about 34,000 people were resident in the Mullica River basin in that part of the basin 10 feet or more above mean sea level. The population density of this 510 square-mile area is about 66 people per square mile. The area is predominantly forested and contains few villages and towns. The larger municipalities are Chatsworth and Jenkins (figure 9) at the headwaters of the Wading River in Burlington County, the northern part of the city of Hammonton in Atlantic County, and the sprawling but sparsely settled communities of Berlin, Atco, Waterford, Chesilhurst, Ancora, and Winslow Junction, which extend northwestward from Hammonton to the headwaters of the Mullica River in Camden County. Farm lands are located along the larger roads, principally in the western and southern parts of the basin. Farming, forestry, and recreation are the dominant income producing activities throughout much of the basin.

The major use of water in the Mullica River basin is for agriculture, particularly for strawberry, blueberry, and cranberry production. The following table gives the estimated values for 1967 of acreage, water use per acre, and the total water used for strawberries, blueberries and cranberries in the Mullica River basin.

Agricultural crop	Acres in production	Approximate water use (acre-ft per acre)	Million gallons per year (mgy)
Strawberries	510	1.5	166
Blueberries	3,850	1.5	1,900
Cranberries	2,515	3.0	2,500
Total			4,566

If allowance is made for the water requirements of other major corps, the agricultural water use in the Mullica basin is at least 5 bgy (billion gallons per year). Rural domestic use of water in the basin is estimated to total about 1 bgy based on a per capita use of 85 gpd (gallons per day). Consequently, the total water use for both agricultural and domestic purposes in the 510 square miles of Mullica River basin lying 10 feet or more above mean sea level is estimated to be on the order of 6 bgy or 16 mgd (million gallons per day).

Topography and Drainage

The Wharton Tract is drained by the Mullica River flowing southeastward to the Atlantic Ocean. Major tributaries of the Mullica River are the Batsto and Wading Rivers (fig. 9). Within the Wharton Tract, tributaries of these rivers include Nescocheague Creek, Sleeper Branch, Springers Brook, Tulpehocken Creek, West Branch Wading River, and Oswego River (sometimes called East Branch of Wading River).

The Wharton Tract has a relatively flat, low-lying surface with shallowly incised streams. Altitudes range from about 8 feet above mean sea level along the lower reaches of the Mullica River near the village of Lower Bank to about 130 feet above sea level on the western slope of Apple Pie Hill located about 3 miles west of Chatsworth. Most of the Wharton Tract lies below the altitude of 100 feet.

Upland areas, lying mainly between 50 and 100 feet above sea level, are flat or gently undulating and contain shallow streams in broad, and usually flat-bottomed valleys. Small hills, hillocks, and ridges commonly rise above the larger flat and undulating surfaces. Many of the smaller geomorphic features closely resemble those of shore, beach, and coastal environments. They are considered to be relicts of former high-level Pliocene-Pleistocene sea stands. Topographic slopes on the permeable soils in the Wharton Tract are gentle; surface gradients of 3 to 10 feet per mile are typical.

Ponds, small lakes, and stream channels occupy about 535 acres — less than 1 percent of the 95,634 acres of Wharton Tract. All these features are shallow and therefore the open-water storage is small. Wetland areas (swamps) form the riparian areas along many reaches of the streams and include isolated shallow depressions or bogs. Wetlands and open water areas occupy about 23 percent of the roughly 490 square miles of Mullica River drainage that lies above the head of salt-water tide near the village of Lower Bank. Distribution of wetlands is not uniform, varying from less than 4 percent of headwater areas to as much as 35 percent of downstream areas. Also the proportion of wetlands varies for different tributaries of the Mullica River. Table 1 presents data on the percentage of wetlands within the drainage area of tributary streams.

Soils

Soils in the Mullica River basin and Wharton Tract partly control the rate and amount of infiltration, the recharge to and discharge from the aquifer, and they largely establish the quality of the ground water. Wharton Tract soils are characteristic of the podzol and podzolic soil development in humid and temperate areas having mixed conifer and hardwood forests. Free drainage, characteristic of podzol soils, causes the upland soils to become droughty soon after rainfall.

Soils of the basin are variable despite the rather uniform appearance of the 4 to 12 inches of gray sand usually present at the surface. The dominant soil is sand, but soils range from fine to coarse, single-grained, free-draining sand and gravel through silt and clay. Clayey soils for the most part are restricted to the southwestern part of the Mullica River basin around Hammonton, Winslow Junction, Ancora, Waterford, and Chesilhurst. Clay and silt particles are transported downward from the A horizon (the horizon that lies immediately beneath the land surface) during soil development, and they commonly occur as coatings on larger particles or as an interstitial matrix in the B horizon, which lies immediately below the A horizon.

Upland soils of the Wharton Tract in general are coarse textured. Quartz is the predominant mineral of the silt, sand, and gravel fractions. Ilmenite ($FeTiO_3$) with its altered product leucoxene and Fe_2O_3 constitute about 1 or 2 percent of the soils. At places in upland areas clay may occupy as much as 30 percent of a soil horizon, but 10 percent clay is the more usual amount. The clay mineral is dominantly kaolinite although some illite occurs. Lime ($CaCO_3$) is practically nonexistent and when applied as a soil conditioner it is rapidly leached downward through the porous soil.

Generally beneath the gray sand of the A soil horizon lies the B horizon which is a distinct yellowish-orange to yellowish-brown or yellowish-red zone of illuviated clay and organic matter mixed with the original mineral soil. Beneath this is the C horizon, a thick zone of mottled gray and yellow to uniformly yellow sand or sand and gravel representative of moderate to well-drained parent coastal plain sediments.

Forest litter on upland soils decomposes slowly and is often destroyed by frequent wildfires. These conditions, coupled with rapid leaching, maintain a low organic content in the soil. Accordingly, upland soils have low agricultural productivity and at present are most productive as forest land.

On the other hand, lowland soils (riparian and undrained depression wetlands) with shallow water table have accumulations of organic material and are somewhat more productive when formed. A thin, weakly developed, brown illuviated zone sometimes observed in upland soils is more strongly developed in these lowland soils; characteristically becoming a distinct chocolate brown zone frequently 4 to 6 or more inches thick. This zone is part of the B soil horizon and often lies at depths of between 12 and 18 inches. It is usually indurated to some degree and in places it is fragmented. It is generally a barrier to downward percolation. This chocolate-brown zone is a mixture of mineral soil and finely comminuted organic matter transported downward through the soil column. At places beneath this indurated zone of the B horizon, there is a strongly developed yellow silty and clayey sand in the lower part of the B horizon which lies above a thick yellow soil horizon called the C horizon. This yellow oxidized zone indicates a well-drained condition. More commonly, the B soil horizon is underlain by mottled gray and yellow or uniformly gray or gravelly sand indicative of reducing environments typical of moderate to poorly drained soils, where the water table may range from 0 to 5 feet below land surface throughout the year.

Original bedding structures of the parent alluvial and near-shore-marine sediments are clearly preserved in the B and especially in the C soil horizons. At places, impervious iron oxide cemented layers develop in the B horizon and may extend to the surface at prominent ground water seepage areas along riparian borders. Iron oxide cemented layers also occur in upland areas.

Bulk density, the mass or weight of a dry soil, including air, for the sandy upland soils ranges between 1.3 and 1.8 grams per cubic centimeter. For a material such as quartz sand this indicates that considerable porosity exists. Porosity, of the B and C soil horizons of these upland soils is about 35 percent. Specific retention is the percentage of water per unit volume of material that is retained in the pores against the pull of gravity after saturation. Specific retention of Wharton Tract upland soils averages about 12 or 13 percent.

The percent of water per unit volume of saturated material yielded by gravity drainage is the specific yield. Stated another way porosity minus specific retention equals specific yield. Sandy upland soils of the Wharton Tract have specific yields of about 22 percent. Such specific yields are rather typical of sandy materials and indicate that large volumes of water can be stored in the soil. Infiltration rates of water moving downward through the soil can be as much as 15 inches per hour. Rates in the dominantly mineral soil horizons generally range between 0.63 and 9.0 inches per hour. However, the water storage capacity in the soil column above the less permeable horizons generally is great enough to permit infiltration of all the rainfall that is normally experienced. This characteristic couples with very gentle surface slopes eliminates most of the opportunity for overland runoff except when the ground surface is frozen.

The chemical character of precipitation modified by its percolation through the forest litter and soil column establishes the fundamental nature of ground-water chemistry in the Wharton Tract. Markley (1962, p. 77) lists 48 determinations of cation-exchange capacity for several common soils under forest and cultivated conditions. These data indicate that the cation-exchange capacity of much of the Wharton Tract soil is probably small, averages about 4.0 milliequivalents per 100 grams of soil at neutrality, and is probably rarely above 10.0. Such low exchange capacity probably results from the rapid free drainage, the single-grained soil structure, as well as the chemically stable minerals of the parent material. Podzol soils are acidic and the pH of the various soil horizons usually ranges from 3.7 to 6.5. The more common pH range appears to be 4.0-5.0. Ion-exchange capacity generally decreases with increased hydrogen ion mobility so that these acid soils can be expected to have minimum ion-exchange capacity.

Abundant additional information on the soils of the Mullica River basin is available on agricultural and engineering soils maps (Lee and others, 1923; McCormack, Holman, and Jumikis, 1955a, 1955b, and 1955c; and Minard, Holman, and Jumikis, 1955), and in the soils studies of Markley and Krohn (1966).

Vegetation

About 85 to 90 percent of the Wharton Tract is forested. The tract is covered by oak-pine and pine-oak upland tree communities, well adapted to the droughty soils. Beneath these forest covers there are woody-shrub communities of huckleberry, lowbush blueberry, wintergreen, and sheep laurel. Scrub oak and mountain laurel thickets are also widespread. The upland forest is decidedly an open type in which the tree crowns infrequently form a solid canopy.

Low-lying riparian areas are occupied either by communities of white cedar, generally as a rather pure species stand, or by mixtures of cedar and hardwood swamp tree species such as red maple, gray birch, blackgum, and sweetbay (swamp magnolia). High bush blueberry, dangleberry, bayberry, swamp azalea, and clethra form the dominant woody understory.

Climate

The Wharton Tract experiences a temperate, humid, and dominantly continental climate, modified by intrusion of oceanic air masses, particularly during the summer and early fall. Table 2 shows the U.S. Weather Bureau 1931-60 monthly and annual precipitation and temperature normals for the Indian Mills and Hammonton weather stations, just outside the tract.

GENERAL HYDROLOGY

The initial source of all water in the Mullica River basin is precipitation. Much of the precipitation is transpired by plants or is evaporated from the vegetal, litter, soil, and water surfaces on which it falls and thus is returned to the atmosphere as water vapor. These phenomena are termed collectively "evapotranspiration." Except during unusually intense rainfall, when there is some overland flow, most of the precipitation on upland areas that is not evaporated or transpired infiltrates the permeable sandy soil of the basin and eventually percolates to the ground-water reservoir. As ground water it gravitates more or less laterally to nearby streams or continues to move to deeper horizons from which it eventually is discharged to major streams at greater distances.

Surface Water

Streamflow records are available from three continuous-record gaging stations in the Mullica River basin. The gaging stations are on the Mullica River 2.5 miles north of Batsto, the Batsto River at Batsto, and the Oswego River at Harrisville. A summary of the mean annual discharge and the maximum and minimum annual mean discharge at these gaging stations is given in table 3.

Mean monthly flow of these streams for the period of record is presented in figure 2. Highest mean monthly streamflow occurred in March and the lowest mean monthly streamflow occurred in September or October. Figure 2 shows that streamflow per square mile of drainage area differed greatly in the three gaged basins; Oswego River had the lowest unit stream discharge and the Mullica River had the highest unit stream discharge.

The record of past streamflow at the three gaging stations is presented in flow-duration curves in figure 3. These are cumulative-frequency curves that show the percentage of time during which specified discharges were equaled or exceeded in a given period. For example, during the period October 1927 to September 1967, the mean daily discharge of the Batsto River at Batsto was at least 38 mgd for 90 percent of the days. According to Searcy (1959) "If streamflow during the period on which the flow-duration curve is based represents the long-term flow of the stream, the curve may be considered a probability curve and used to estimate the percent of time that a specified discharge will be equaled or exceeded in the future."

The low-flow characteristics of the Mullica, Batsto, and Oswego Rivers at the gaging stations were analyzed by the low-flow frequency curves shown in figures 4, 5, and 6. These curves developed from a Log Pearson Type II analysis, represent the magnitude and frequency of the lowest flow each year for the indicated number of consecutive days. For example, the minimum average flow of the Mullica River for 30 consecutive days to be expected once in an average time interval of 5 years is 15 mgd.

The average discharge of the 180.6 square miles of drainage area above the stream gages on the Mullica, Batsto, and Oswego Rivers is 202 mgd, an average of 1.12 mgd per sq mi or about 23.5 inches. Inasmuch as the average annual yield from the gaged parts of the Mullica River basin is 1.12 mgd per sq mi, the 150-square-mile Wharton Tract can be expected to yield, on the average, from the area within the tract, about 170 mgd. However, the drainage from an additional 195 square miles of the upper Mullica River basin passes southeastward through the tract and hence the average total yield of the upper Mullica at the Wharton Tract is about 390 mgd.

Ground Water

The water table is that surface in an unconfined water body at which the pressure is atmospheric. It fluctuates with recharge and discharge of ground water. Figure 7 shows the manner and magnitude of average monthly water-table fluctuations during 1956-68. Figure 8 depicts a

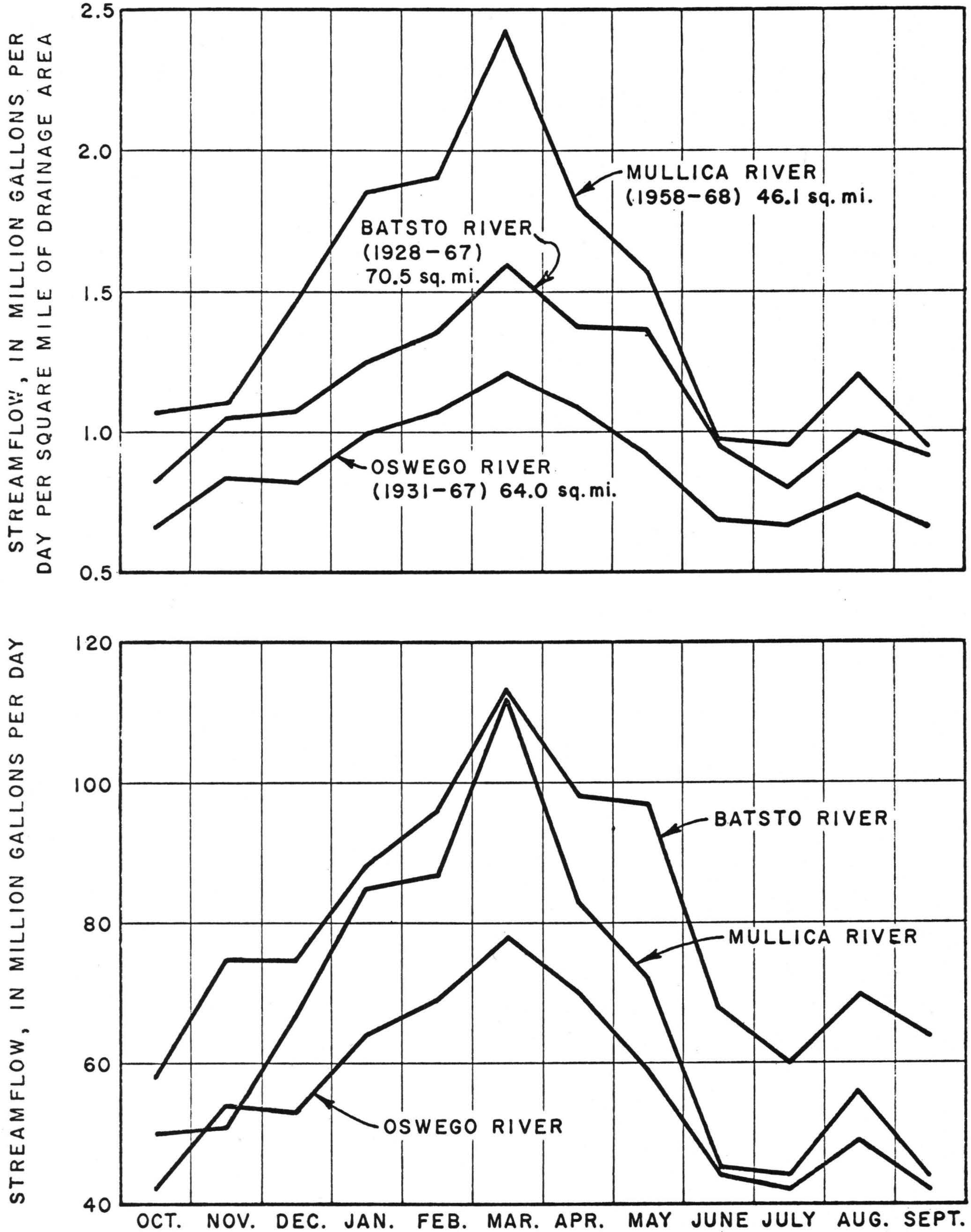

Figure 2 – Mean monthly stream flow for three streams in the Mullica River basin.

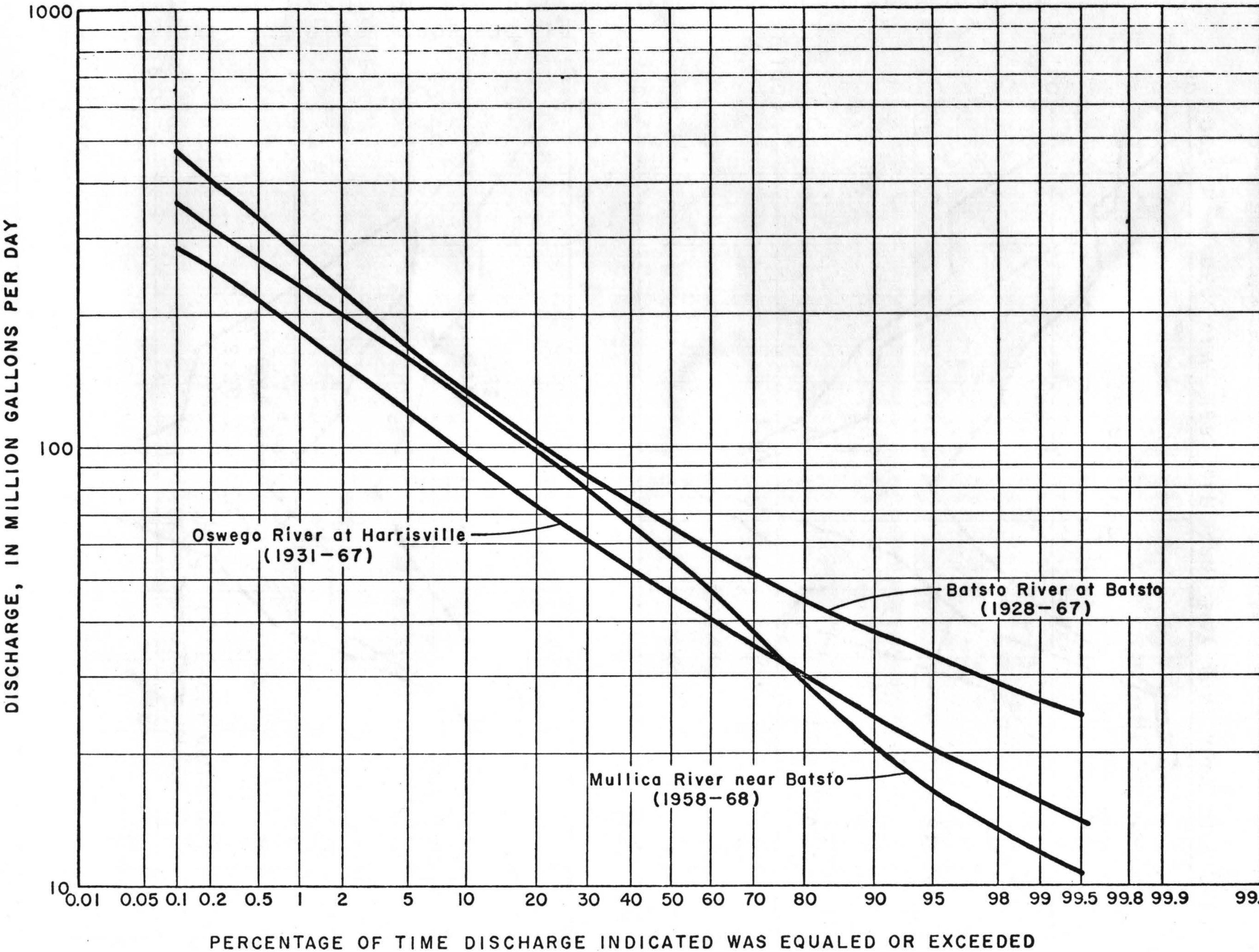

Figure 3. – Duration of daily flows for three streams in the Mullica River basin.

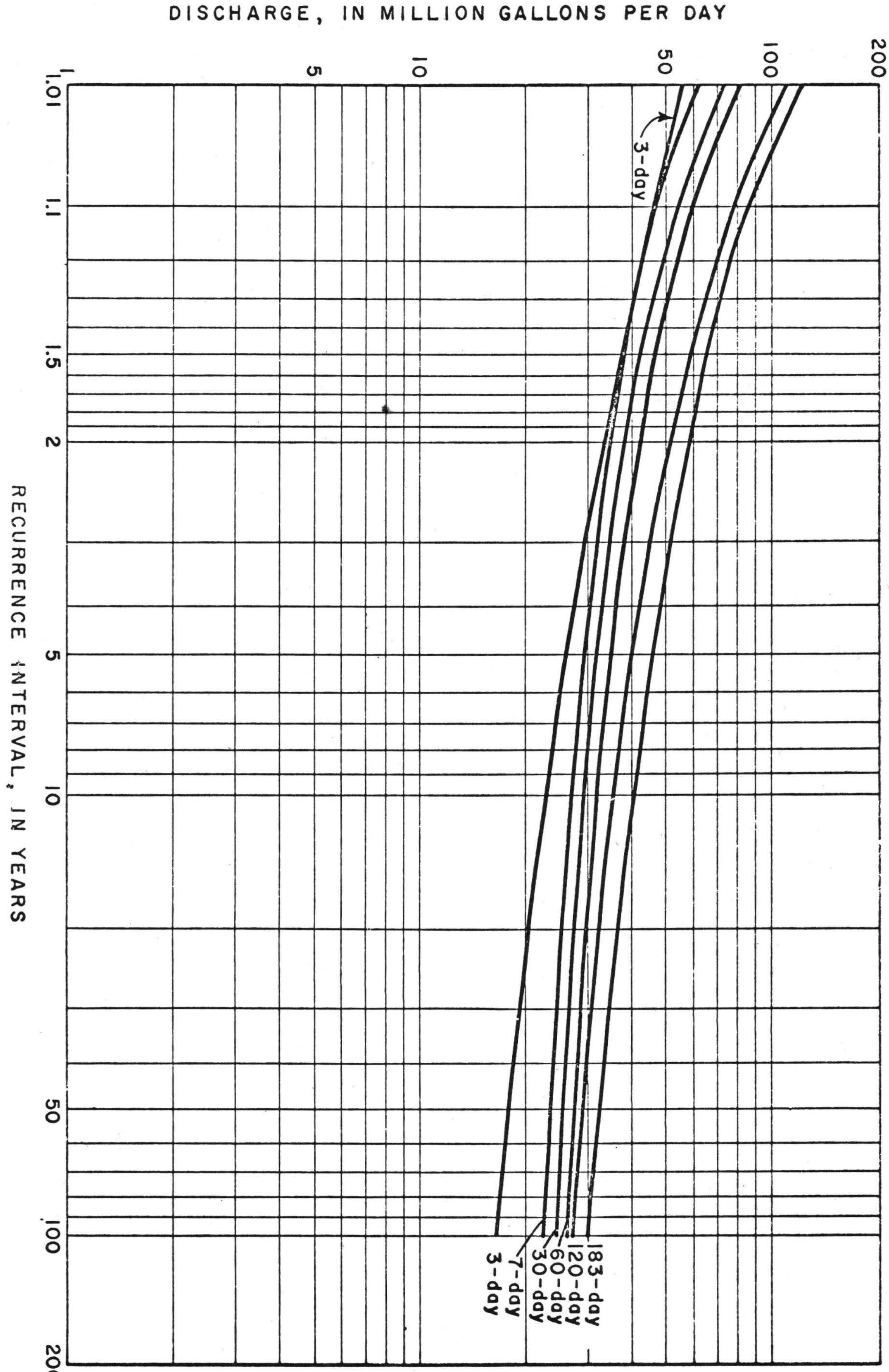

Figure 4. – Magnitude and frequency of minimum annual discharge of the Batsto River at Batsto, N.J. for the indicated number of consecutive days, based on climatic years, 1928-66.

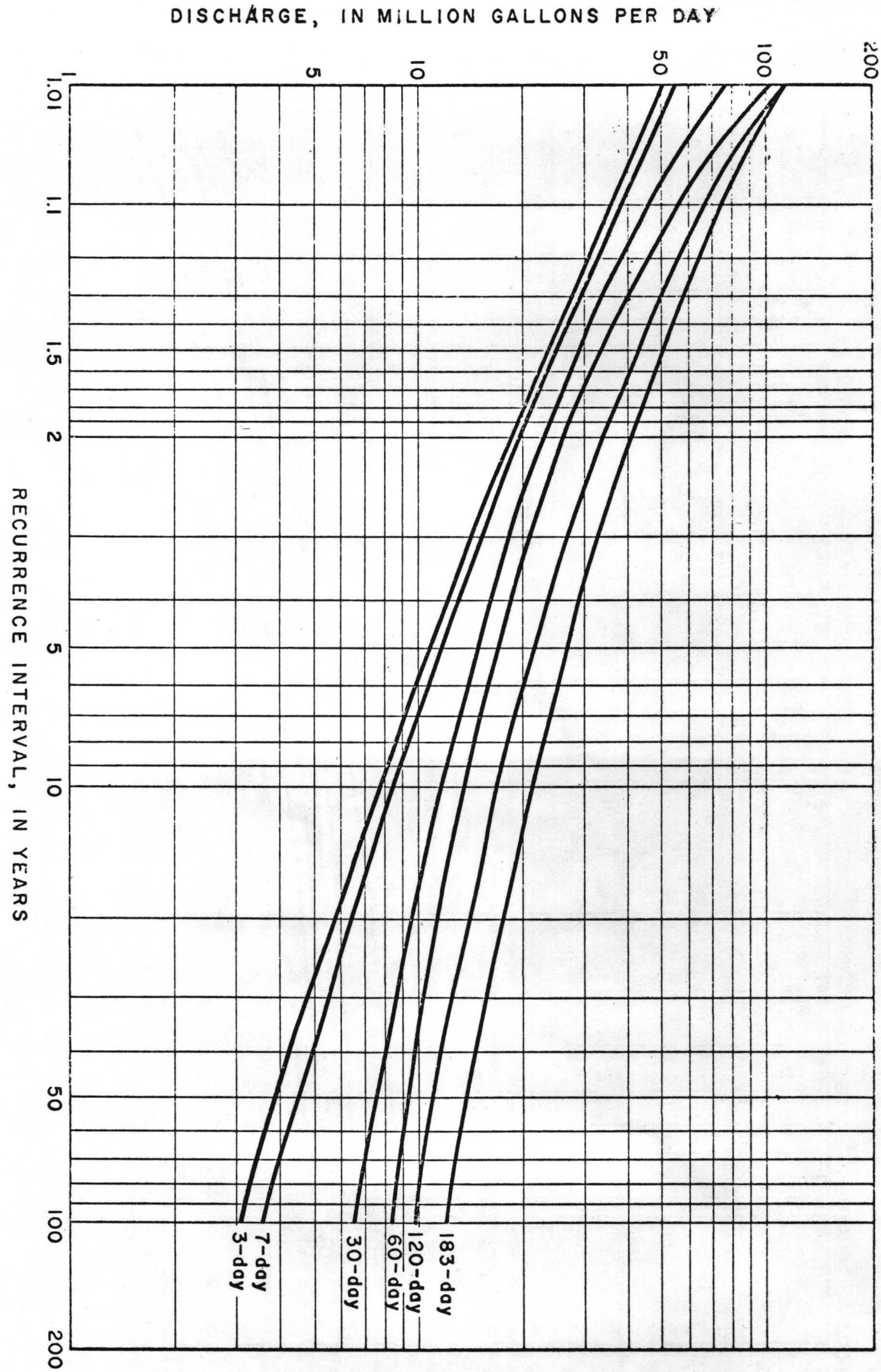

Figure 5. – Magnitude and frequency of minimum annual discharge of the Mullica River near Batsto, N.J. for the indicated number of consecutive days, based on climatic years, 1958-67.

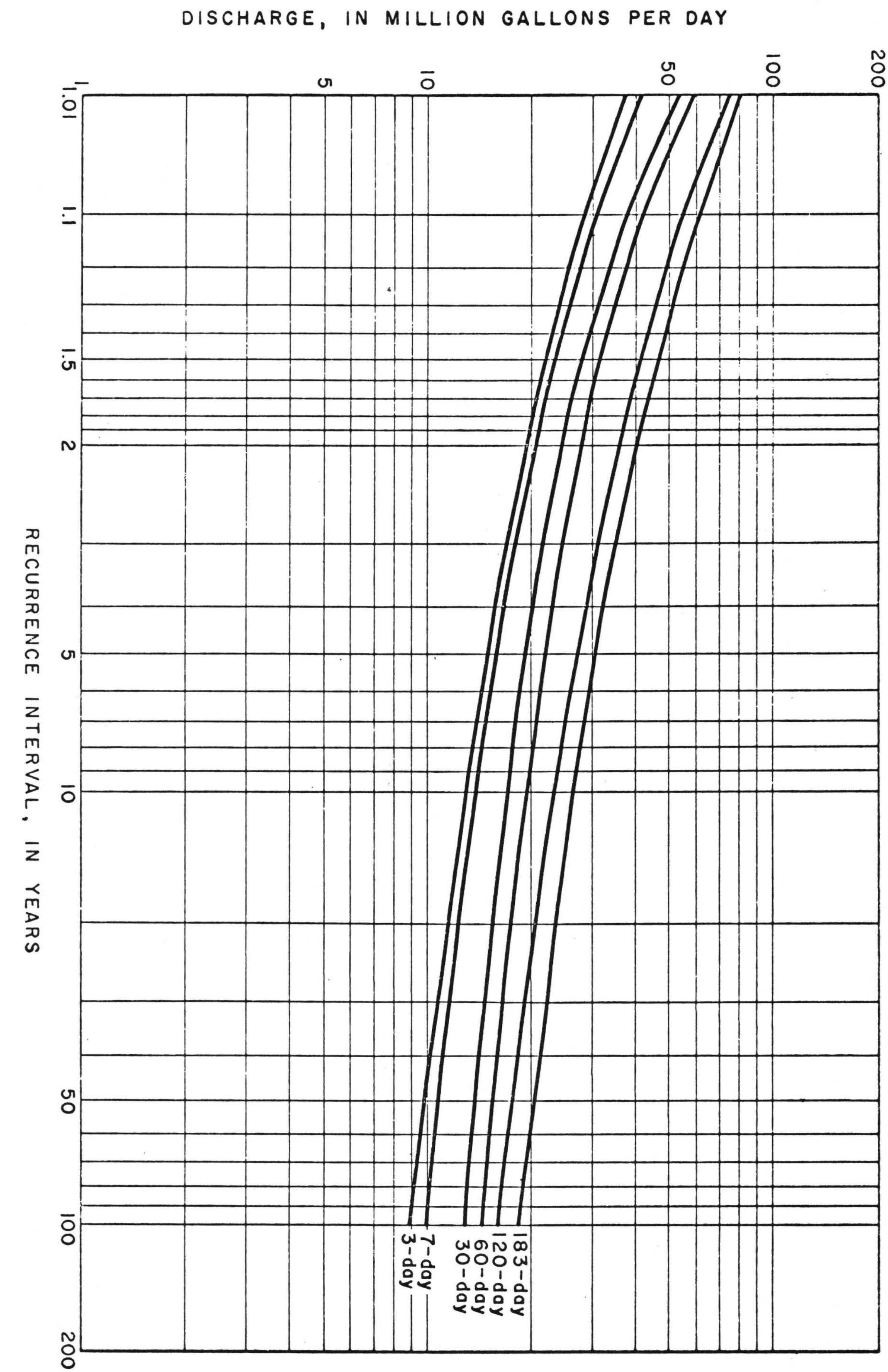

Figure 6 – Magnitude and frequency of minimum annual discharge of the Oswego River at Harrisville, N.J. for the indicated number of consecutive days, based on climatic years, 1931-66.

series of typical day-by-day water table fluctuations in the Mount well situated in an upland area of the Wharton Tract.

Water-level fluctuations are as much as 13 feet between extreme recorded wet and dry periods, and as much as 10 feet from spring to fall in one year. However, an average annual fluctuation of about 5 or 7 feet may be considered normal for upland areas.

Ground water is constantly moving under the force of gravity from positions of high head to those of lower head. In unconsolidated coastal-plain material this movement is through connected pores, or interstices in the reservoir materials. Because of friction and various other impeding forces along the irregular walls of the interstices, ground-water flow is slow — often measured in several tens to hundreds of feet per year. The average velocity of movement in the more permeable parts of the aquifer (hydraulic conductivity = 100 to 130 ft per day) (750 to 1,000 gpd per ft^2) in the northwestern part of the Wharton Tract is calculated to range from 120 to 160 feet per year based upon an average gradient of 7 feet per mile and an average effective porosity of 40 percent.

The terms hydraulic conductivity and transmissivity used in this report replace the older terms field coefficient of permeability and coefficient of transmissibility. A porous isotropic medium containing a homogeneous fluid has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path. Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. Values for the new terms are given in this report in units of days and feet and are followed in parenthesis by values for the older terms in units of days, gallons, and feet. Hence, a hydraulic conductivity of 130 feet per day is equivalent to a coefficient of permeability of 1,000 gpd per sq ft.

Figure 9 shows the general configuration of the water table in the Mullica River basin. The configuration is inferred from surface topography and altitudes of streams, swamps, and lakes, as shown on U.S. Geological Survey 7½-minute topographic quadrangle maps. Estimates of depths to the water table in interfluvial areas are from scattered data on ground-water levels and the author's general experience in the basin and elsewhere in the Pine Barrens region. Highest water levels (140 feet above mean sea level) are found in the northeastern part, just 2 miles east of Woodmansie. The lowest water levels approach sea level along the lower reaches of the Mullica River. The water table slopes generally toward the major rivers and streams such as the Mullica, Batsto, Tulpehocken, Oswego, Wading, and Bass Rivers.

All coastal-plain formations in the Mullica River basin contain water. However, not all are important aquifers; some strata are above the permanent zone of saturation and do not yield water to vertical wells. Others, for example clayey strata below the water table, contain water in subcapillary pores that transmit water very slowly. In both cases water does not flow through the interstices toward a well in sufficient abundance for the material to be considered an aquifer.

The clayey strata may form part of the boundary of an aquifer and establish whether the aquifer is confined or unconfined. If the ground-water reservoir is unconfined it is classified as a water-table aquifer. However, if the ground water reservoir is bounded by overlying and underlying clayey strata and it possesses a hydrostatic pressure head by virtue of its being full, the aquifer is classified as an artesian aquifer. Under such conditions a well penetrating the aquifer will permit the confined water to rise in the well tube to its natural hydrostatic level at some distance above the top of the aquifer. Such a well is an artesian well. When the water in the well rises above the land surface at the well site the well is classified as a flowing artesian well. An aquifer may be under an artesian regime between two confining beds but continue into an area where an unconfined free surface exists. Hence an aquifer may be confined in one area and unconfined in an adjacent area.

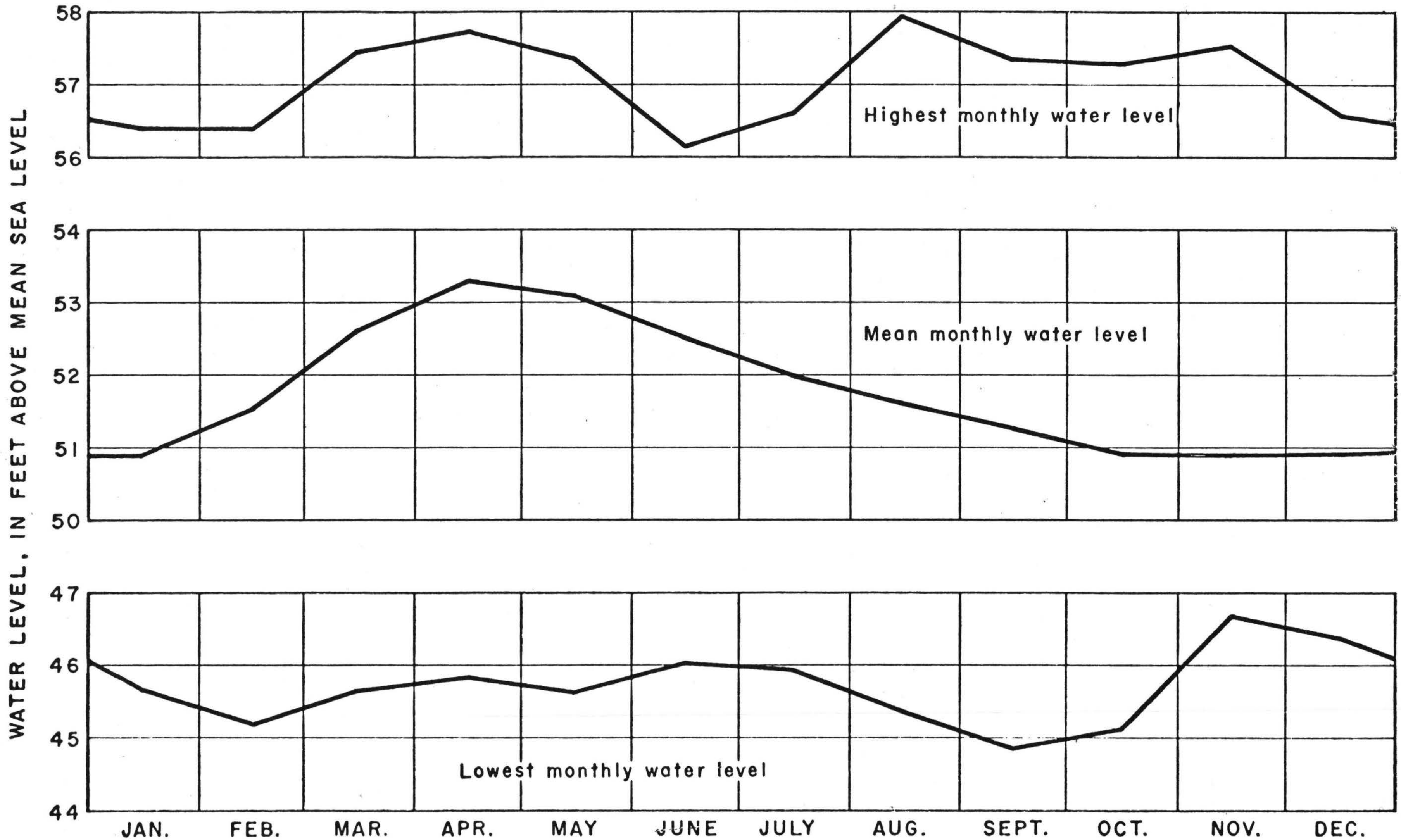

Figure 7 – Monthly ground-water level in the Mount well, 1956-68.

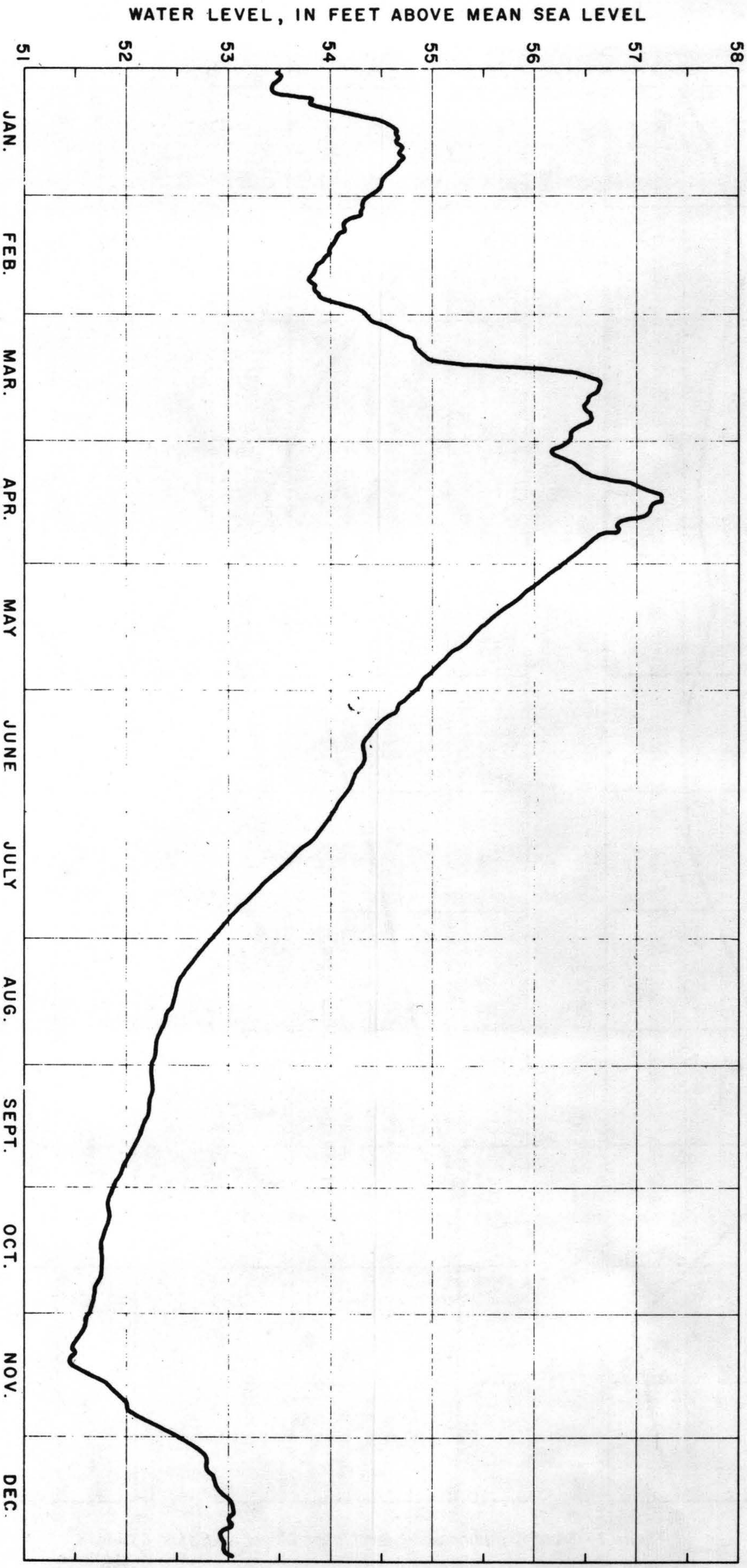

Figure 8 – Daily ground-water hydrograph of the Mount well, 1960.

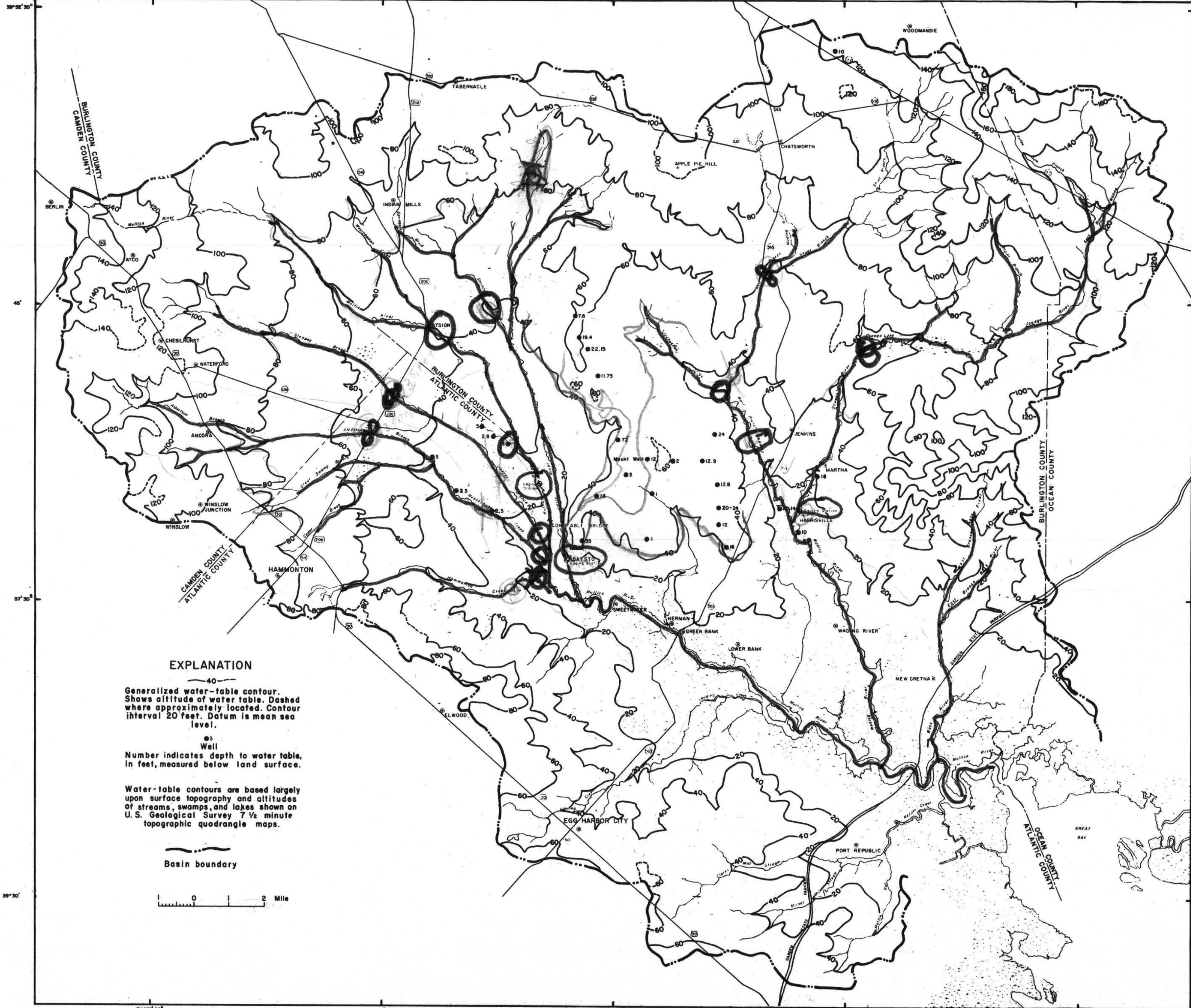

Figure 9 – Water-table map, Mullica River basin.

For the large water-table aquifer underlying the Mullica River basin the amount of water recoverable by pumping wells ranges from about 10 to 23 percent of the sediment volume. When a well tapping the water table is pumped, water is removed from storage and the influence of the pumping well extends slowly outward until the volume of water removed from storage is balanced by the amount of water that is diverted from natural discharge or is obtained from recharge.

When a well in an artesian aquifer is pumped the rock pores are not dewatered as is true for water-table aquifers. However, there is a release of hydrostatic pressure, the effect of which, travels rapidly away from the well for a considerable distance. This widespread release of pressure slightly compresses the granular framework of the aquifer as well as also causing an almost insignificant expansion of the water itself. The combined effect of these two phenomena releases water from storage. The volume of water released per unit volume of aquifer is commonly several orders of magnitude smaller for artesian aquifers than for water-table aquifers.

A comparison of figure 9, the water-table map and figure 11, the regional head distribution map of the deeper aquifer (Kirkwood Formation) indicates the general existence of hydraulic continuity throughout the upper 100 to 200 feet of permeable section. In ground-water discharging areas in the downstream reaches of the basin, the head in the lower aquifer is usually a few feet higher than the water-table altitudes directly above.

In the southeastern part of the Mullica River basin (in area 2 shown on figure 12) a thick and areally continuous sequence of clay and silt strata in the Cohansey Sand and the overlying Pleistocene and Holocene deposits decreases the vertical hydraulic continuity of the aquifer system. Consequently much of the ground water in this area moves laterally along the permeable beds that are largely confined between clay layers. Wells in riparian areas tapping the permeable beds intercalated between these clays have static water levels 10 to 15 feet above the water table and are flowing artesian wells. This artesian condition can be noted by comparing the water levels of figures 9 and 11 in the vicinity of Sweetwater, Green Bank, Lower Bank, and Harrisville.

HYDROGEOLOGY

The Atlantic Coastal Plain in New Jersey is composed of a sequence of essentially unconsolidated quartz gravel, sand, silt, and clay that dips and thickens southeastward toward the Atlantic Ocean. Dips range from about 11 to 100 feet per mile. Lowest beds have the steepest dips, and upper beds have the gentlest dips. The Coastal Plain sediments range in thickness from a feather edge along the fall line near the Delaware River to as much as 6,000 feet in Cape May County. In the Wharton Tract they range from about 1,800 to 2,500 feet thick. The lowest beds are dominantly continental deposits; the overlying beds are dominantly marine deposits. An overlying discontinuous veneer of Quaternary deposits is composed of fluvial and nearshore marine sand, gravel, silt, and clay. Unconformably below the coastal plain sediments are dense, relatively nonwaterbearing Precambrian to lower Paleozoic(?) metamorphic rocks.

Aquifers studied during this investigation are in the Kirkwood Formation, Cohansey Sand, and in the overlying deposits of Quaternary age. The lithology and water bearing properties of these units are summarized in the stratigraphic section in table 4.

TERTIARY DEPOSITS

Kirkwood Formation

Geology

The Kirkwood Formation of middle Miocene Ages is the lowest Miocene formation exposed at the surface in New Jersey. This formation, composed chiefly of sand, silt, clay, and some gravel, was first named by Knapp (1904, p. 81-82) for its exposure near the village of Kirkwood in Camden County, N.J. However, at least part of the formation (the highly fossiliferous "Shiloh Marl" of Cumberland County) was recognized as a Miocene unit by Cook (1868, p. 288-290, 294-299). At its type locality the Kirkwood Formation is a feldspathic, fine-grained, gray to white-colored, yellow- and red-banded, and thin- to thick-bedded quartz sand.

The Kirkwood, according to Minard and Owens (1962), contains several distinct and mappable lithologic units. Lithologies include diatomaceous clay; carbonaceous (lignitic) and micaceous dark silty sand; red, yellow, and gray feldspathic sand; and clean fine to medium grained gravel and sand. Sandstone, cemented by an opal and chalcedony matrix and iron oxide is also present especially along the coast. These diverse lithologies are lumped together because of their unconformable stratigraphic position between the underlying early Tertiary formations and the overlying Cohansey Sand.

Two wells in the Wharton Tract, one at Atsion, another at Harrisville, penetrate the entire thickness of the Kirkwood Formation. At Atsion the Kirkwood is about 100 feet thick. Downdip at Harrisville it is about 285 feet thick. At Island Beach State Park the Kirkwood is 250 feet thick and at the Oswego Lake observation well, about 4 miles southeast of Oswego Lake, it is 295 feet thick. At Atlantic City the Kirkwood is reported to be more than 700 feet thick (Richards, 1945, p. 896). Downdip thickening results from an increase in the number of beds as well as from a general thickening of individual beds.

The Kirkwood Formation unconformably overlies several formations in New Jersey. In the subsurface it overlies the Piney Point(?) Formation of late Eocene age (Gill, 1962, p. 15). In the outcrop area a few miles west of the Wharton Tract it overlies the Hornerstown, Vincentown, and Manasquan Formations. Farther north, the Kirkwood apparently extended a short distance onto the Red Bank Sand. The unconformity at the base of the Kirkwood Formation has small relief, perhaps no more than several tens of feet locally.

The Kirkwood Formation lies unconformably below the Cohansey Sand. Figure 10 shows the general configuration of the identifiable upper surface of the Kirkwood Formation in southern New Jersey.

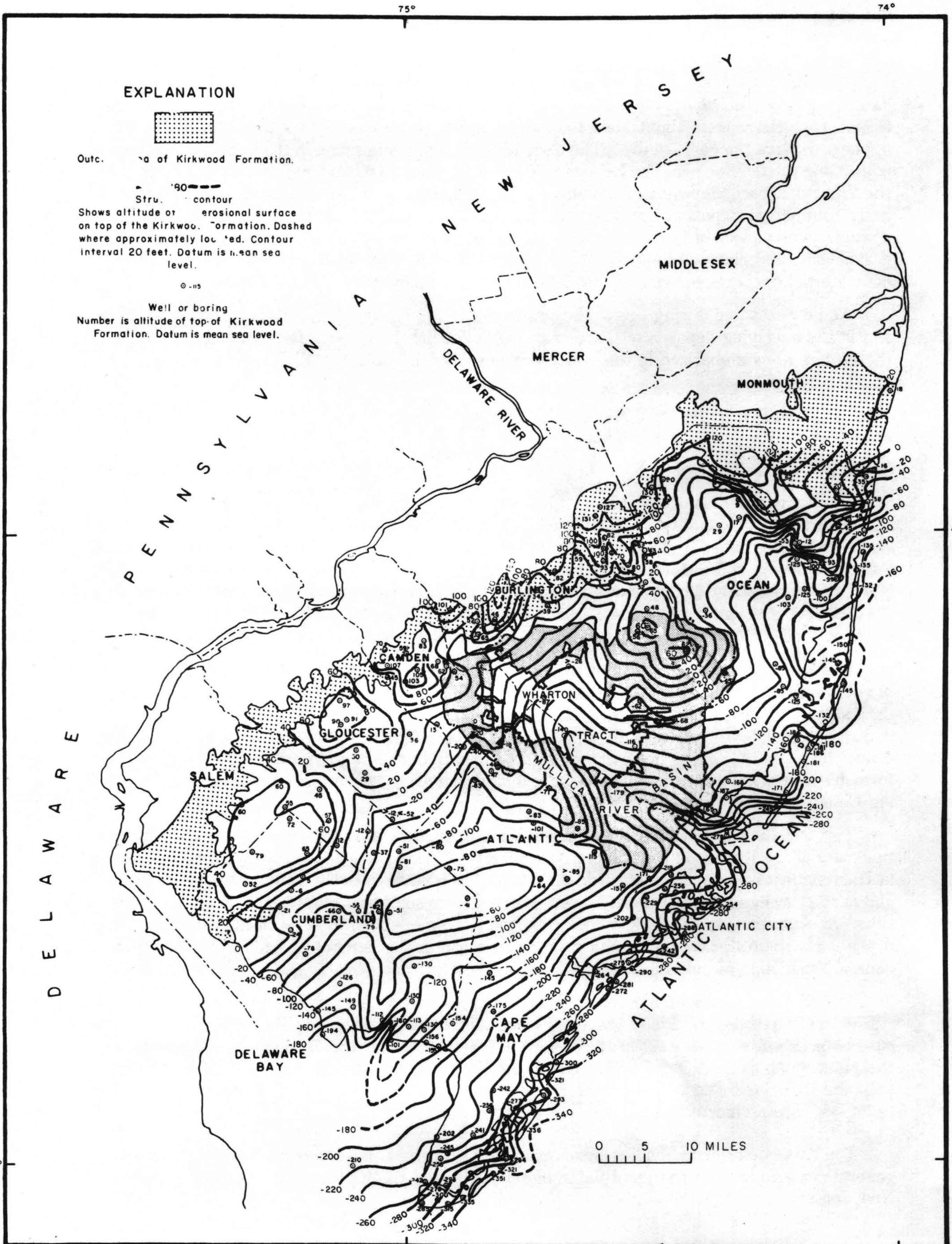

Figure 10. – Structure-contour map of the top of the Kirkwood Formation in southern New Jersey.

The different lithologies in the formation represent different depositional environments including nearshore marine, neritic, barrier bar, lagoon, estuarine, and tidal marsh. In response to marine transgression and regression barrier beaches migrated back and forth across a region now occupied by the coast. At times the beach may have moved westward perhaps a dozen or more miles west of the present coast where coarse sand and gravel interpreted as beach deposites have been encountered in well drilling. These deposits are intercalated with nearshore marine and lagoonal deposits. Inland from the coast, beach deposits are less common and thinner and lagoonal deposits are thicker and more common. Local coarse sand and gravel penetrated by inland wells may be representative of lag deposits in swift tidal inlets. Some of these deposits seem to be alined with modern drainage ways.

Diatom beds in the Kirkwood represent shallow-water sediments, as indicated by the presence of many neritic, lagoonal, and estuarine fossil animals and terrestial plant remains. According to Dunbar and Rodgers (1957, p. 58), "the diatomite beds in the Miocene deposits of the Chesapeake Bay area are associated with very shallow-water deposits." Several of the upper diatomaceous clays and their associated water-bearing sands have been noted by Woolman (1891, p. 271-273; 1892, p. 223-226) in wells and outcrops southeast of an irregular line trending northeast from Shiloh through Bridgeton, Vineland, Hammonton, Herman, and Barnegat (see figure 11). Lower diatomaceous clay beds generally persist for about 5 miles northwest of this line. Relatively extensive water-bearing beds can be found, southeast of this boundary.

Lack of shell material in places in the formation may be attributed to the dissolving of shells by lagoonal water that was characteristically low in pH and oxygen content. Further solution of shell material by acid ground water may explain the absence of fossils in the Kirkwood.

Toward the end of Kirkwood time moderate uplift of the land occurred to the west and northwest with accompanying regression of the sea. Channels cut into the Kirkwood are filled with yellow limonitic sand which at most places includes both the upper part of the Kirkwood and the Cohansey Sand. An especially large deep channel beneath the Mullica River basin trending toward Atlantic City is shown in figure 10. Rejuvenated streams introduced considerable thicknesses of fine sand and silt to the lagoons. These dark-colored, massive-bedded sands buried the older diatomaceous sediments which were, in part, truncated. Inland, the late Kirkwood sediments probably were subjected to intensive subaerial weathering before being covered by deposits of the Cohansey Sand. Weathering is indicated by the thick and highly oxidized state of Kirkwood beds lying beneath the unoxidized Cohansey Sand. At such places variegated colors of bright orange-yellow and light gray are common to the Kirkwood.

Hydrology

Several aquifers have been identified in the Kirkwood Formation along the coast. However, probably only a small part of the Mullica River basin above present-day tidal action is underlain by Kirkwood aquifers that extend updip from the coast. The correlation of the aquifers, lying at depths generally from 200 to 400 feet in the Mullica River basin, with the higher yielding aquifers along the coast is, in general, poorly understood. Updip, from the coast the Kirkwood Formation thins, water-bearing sands become attenuated and in many locations the materials change from clean medium-to-coarse-grained sand to clayey and silty fine grained sand. Accordingly, in the interior areas the Kirkwood Formation contains fewer and less permeable water-bearing sands. Above the head of tide in the Mullica River basin the number of identifiable and areally extensive Kirkwood water-bearing horizons is probably no more than two or three.

Most of the Kirkwood aquifers in the Wharton Tract are probably those lying stratigraphically above the diatomaceous clays. These aquifers are, in general, less permeable and considerably less extensive than the aquifers along the coast. Most of the water-bearing strata are hydraulically connected to the overlying Cohansey Sand, and consequently are a part of a large upper Kirkwood-Cohansey aquifer system underlying all the Mullica River basin.

The generalized potentiometric surface of the Kirkwood Formation, depicted for 1963-65, is shown on figure 11. It shows that ground water is moving toward the major surface drainage ways, such as the Mullica, Great Egg Harbor, and Maurice Rivers. Locations of the areas of high head beneath present topographic highs, coupled with discharge to major surface streams, suggest hydraulic connection between the upper Kirkwood strata and the Cohansey Sand over wide areas.

Because there has been no significant change in quantity or location of pumpage throughout the Mullica River basin, the configuration of the potentiometric surface in the basin has not changed significantly in recent years. Actually, there never has been large-scale pumping in the Mullica River basin and the best historic record of head decline of 4 feet in nearly 85 years (to 1957). This decline seems due mainly to the constant losses of pressure by artesian flow of many wells in and around the Sweetwater area. Head decline in the flowing Harrisville well has been about 3 to 5 feet in 103 years.

Hydraulic characteristics of the Kirkwood Formation in the Mullica River basin are virtually unknown. A single laboratory determination of hydraulic conductivity for a fine silty Kirkwood sand in the Wharton Tract 2.5 miles northwest of Batsto, gave a value of 2.4 feet per day (18 gpd per sq ft). Although this fine-grained sand is fairly characteristic of some of the sandy Kirkwood materials underlying the Wharton Tract its hydraulic conductivity is believed to be lower than that of the more permeable aquifer materials.

Cohansey Sand

Geology

The name Cohansey was first applied by Knapp (1904, p. 81) and by Kummel and Knapp (1904, p. 137-138) to the thick (up to 250 ft) and areally extensive wedge of sandy strata lying above deposits of recognized Kirkwood age. The type locality at Cohansey Creek, in Cumberland County, N.J., was cited later by Bascom and others, (1909, p. 114). Knapp at first considered the Cohansey Sand to be of Pleistocene(?) age but later reported it to be of Pliocene or Miocene age. The formation may be any age between middle Miocene and late Pleistocene, but is classified presently as Miocene(?) and Pliocene(?), based upon its stratigraphic position, extremely rare but well-preserved plant fossils (Hollick, 1892, p. 330, and 1900, p. 197-199), and its compatible orientation with other Tertiary deposits in New Jersey.

The Cohansey Sand underlies an area of approximately 2,350 square miles southeast of the Kirkwood outcrop area in the coastal plain. The occurrence of outliers within the Kirkwood outcrop area indicates that the Cohansey was more extensive at one time. At many places in the Wharton Tract this sand is exposed at the surface; at other places it is overlain by thin deposits of Quaternary age.

Lithology of the Cohansey Sand is variable. It is dominantly a yellow (limonitic) quartz sand containing minor amounts of pebbly sand, fine-coarse sand, silty and clayey sand, and interbedded clay. It contains small amounts of weathered feldspar; chert, vein quartz, and notable amounts of rounded ironstone pebbles; and lenses or fragments of carbonaceous materials within beds of kaolinitic clay. Fine- to medium-sized muscovite flakes are found only in trace amounts in some areas. Some beds in the northern part of the outcrop contain detrital lignitic particles, and may contain as much as 2 to 10 percent dark heavy minerals, mainly ilmenite. Markewicz and others (1958, p. 10) report that the opaque mineral ilmenite and its alteration product leucoxene average 85 percent of the entire suite of accessory minerals.

Sand beds range from thick beds to thin seams intercalated with clay units. Both parallel bedding and cross-stratification occur. Cross stratification can be used to distinguish the Cohansey from the Kirkwood. Gravel beds may be several feet thick but are generally less than 1 foot thick. The coarser materials range from very fine grained sand to well-rounded pebbles of quartz and quartzite up to 5 inches in diameter. Pebbles ranging from subangular to well rounded are dominantly of the milky vein-quartz types; however, clear, pink, and smoky-quartz varieties and

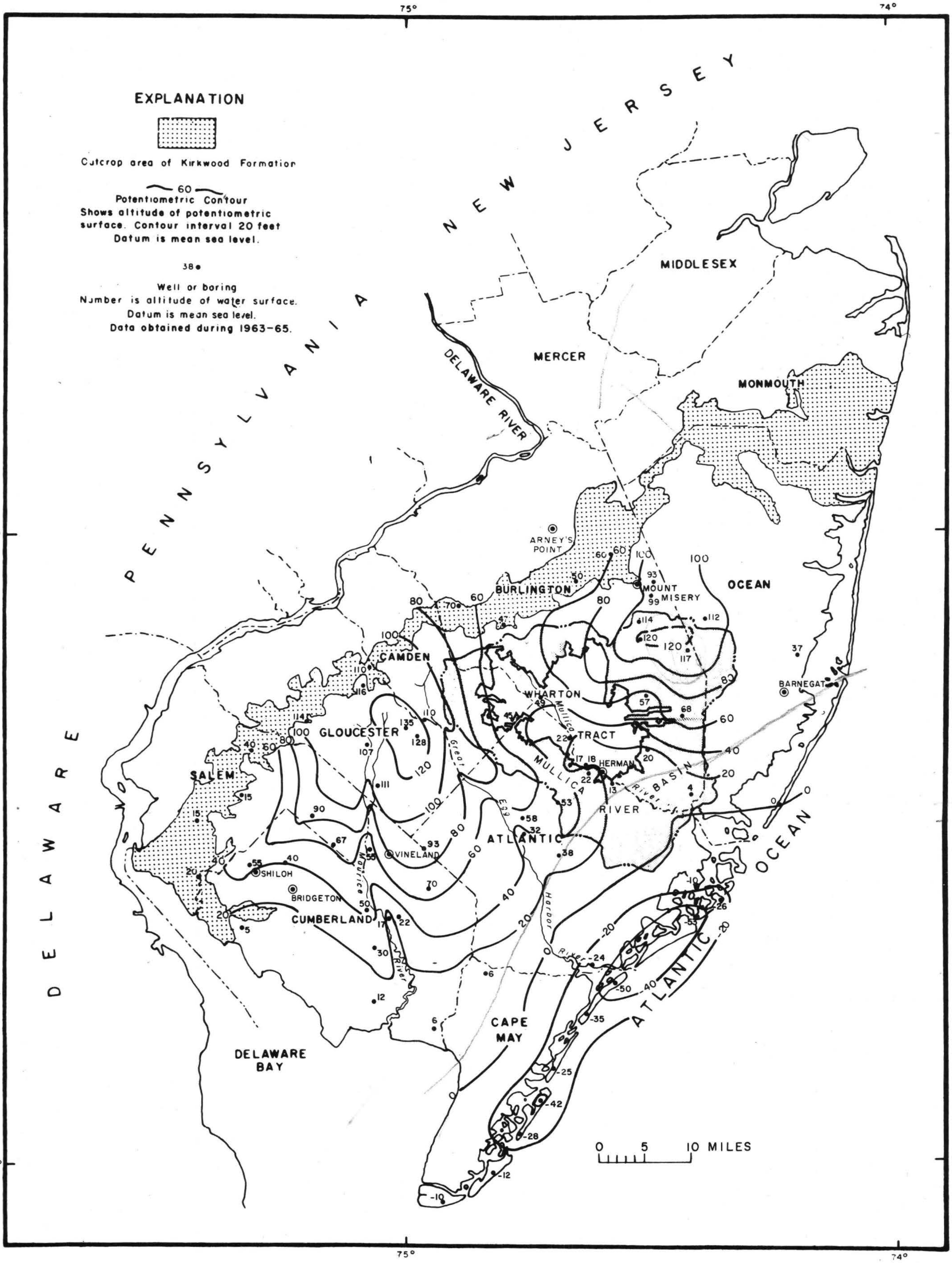

Figure 11. – Map showing the generalized potentiometric surface of the Kirkwood Formation in southern New Jersey.

chert pebbles are common. The quartz sand grains are generally of the clear or the slightly opaque smoky varieties. Characteristically they have a limonitic or, less frequently, a hematitic stain on their surfaces. Some sands however, have no iron-oxide staining and are light gray to white. Frosted surfaces are common, suggesting that some of the sand has suffered considerable eolian action. Sand grains having solution-pitted surfaces are less common.

The Cohansey contains massive to laminated white, yellow, red, and light-gray carbonaceous clay in beds ranging in thickness from thin stringers to as much as 24 feet. Individual large clay beds may extend over an area of several hundred acres. Clay and clayey-sand zones, composed of a number of beds, form thick sections and may be preponderant in the Cohansey throughout several square miles. Combined thicknesses are as much as 40 feet locally. Examples of such areas are located at Winslow in Camden County and east of Woodmansie in Burlington and Ocean Counties. Well drilling records show that some clay beds occur within 20 feet of the land surface throughout a considerable part of the formation's areal extent.

Areal variations in clay, silt, and sand content of the Cohansey are shown in figure 12. Area 1 contains thick sand beds, which are interpreted as fluvial and delta front deposits containing relatively thin discontinuous sections of laminated clay. Where determined, the clay and silt beds in the upper 100 ft average 11.3 and 13.3 percent, respectively, of the section. A thicker sequence of more massive-bedded clays generally occurs in area 2. Clay and silt beds comprise about 24 and 16 percent, respectively, of the upper 100 feet of the Cohansey in area 2. The more massive-bedded clays are generally gray, blue, and, less frequently, cream in color and contain disseminated vegetal matter. They have a less oxidized appearance than the multicolored laminated clays occurring in area 1. Organic material, including large logs and limbs, occurs in distinct beds or layers. Other forms of fossil material are rare. The relative quantities of sand, silt, and clay are not well known along the coast in area 3 (fig. 12). However, logs of wells in Cape May (Gill, 1962) and Atlantic (Clark and others, 1968) counties indicate that the proporation of sand is greater there than in area 2.

Almost all the Wharton Tract and most of the Mullica River basin lie in the sandier and therefore more permeable area 1. Data from 2,643 feet of drilled material at 33 well sites, mainly in the upper 100 feet of sediments, indicate that the Cohansey in the Wharton Tract contains 3.5 percent clay beds, 3.5 percent silt beds, and 93 percent sand beds. Multicolored thin (0.1 to 3 feet thick) laminated clays and silts are widely distributed and are common throughout the upper 100 feet of Cohansey Sand in the Tract. These clays and silts are intercalated with a thick sequence of sand beds which lies above a prominent black, dark-gray, to olive-gray colored carbonaceous clay. This clay zone lies between 30 and 90 feet below sea level.

The Cohansey Sand unconformably overlaps the Kirkwood Formation at a number of places. The Kirkwood is, except perhaps in the Sandy Hook area (Minard, 1969, p. 27-28), the only formation that directly underlies the Cohansey. Bascom and others (1909, p. 110-111) and Minard and Owens (1963) report an unconformity between these two formations. Isphording (1970a, p. 336, and 1970b, p. 996) on the other hand, believes the contact is mainly conformable but that local disconformities exist. However, the sharp boundary observed in well samples between the yellowish-orange colored oxidized Cohansey strata and the light- to dark-gray oxidized Kirkwood strata suggests widespread unconformable relations. Other indicators of an unconformity include an indurated and sometimes blocky iron-oxide zone observed at a number of locations at the Kirkwood-Cohansey contact, the almost total absence of Feldspar in the Cohansey relative to the Kirkwood, and a small but apparent difference in the dip and strike of the two units. In the Mullica River basin unconformable discontinuous veneers of modified Beacon Hill Gravel and Quaternary age sediments overlie the Cohansey.

The average strike of the Cohansey Sand, according to Owens and Minard (1960, p. B184), is N. 73°E. and its average dip is about 10 feet per mile to the southeast. It ranges in thickness from a featheredge to more than 250 feet along the southern coastal part of the State where, according to Richards (1945, p. 896, 934), its base may extend nearly 400 feet below sea level. The thickness

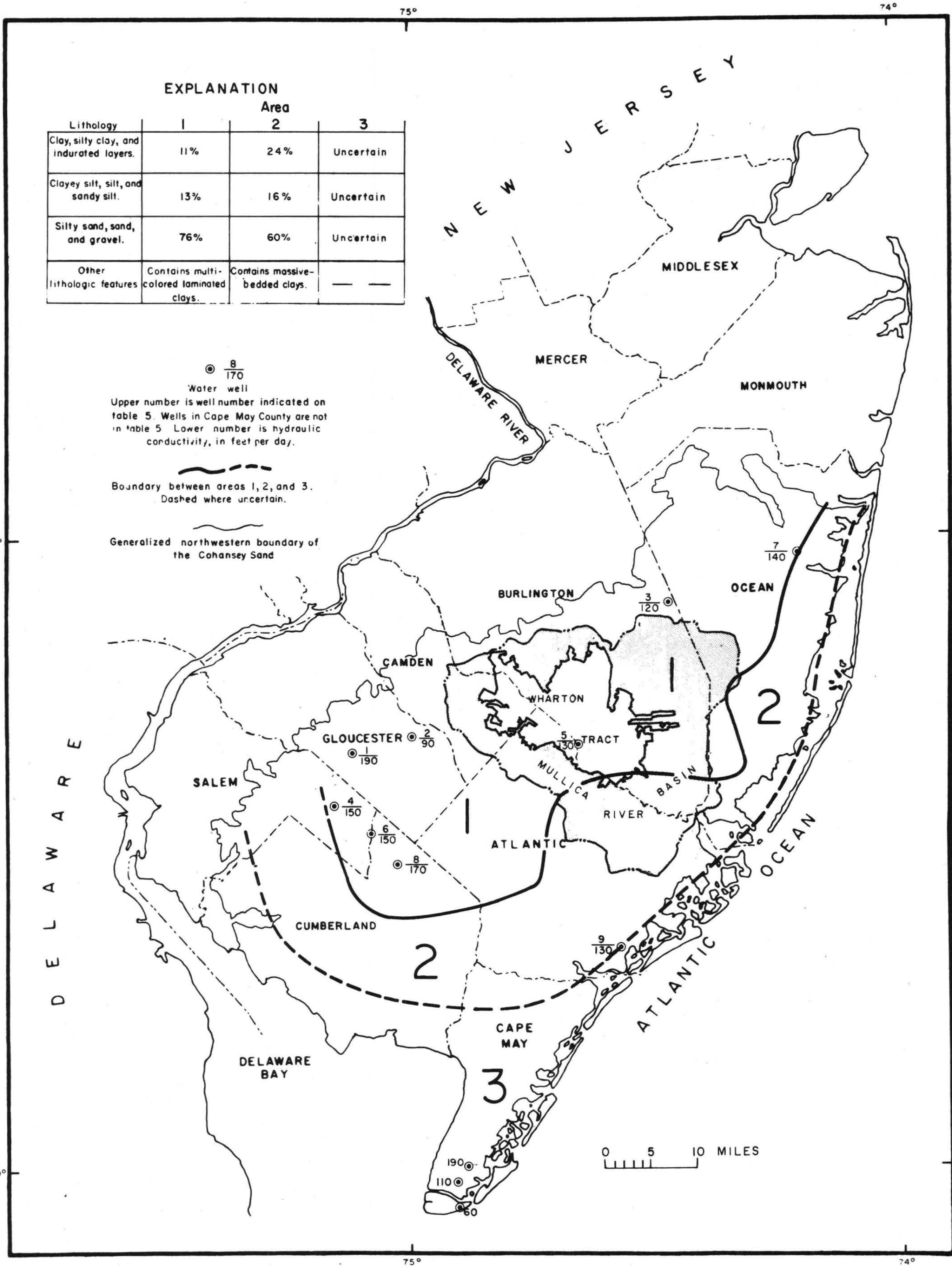

Figure 12. – Map of southern New Jersey showing selected lithologic and hydrologic parameters of the Cohansey Sand.

in the Mullica River basin ranges from about 25 feet in the Tabernacle-Indian Mills area to more than 200 ft in the Port Republic area. The average thickness in the Mullica River basin is about 140 feet. In the Wharton Tract the thickness ranges from less than 50 feet in the area immediately west of Indian Mills to about 180 feet near Green Bank. The average thickness in the Tract is about 125 feet. The thickness of the Cohansey Sand and overlying sediments of Quaternary age in New Jersey Coastal Plain are shown in figure 13.

The Cohansey Sand has been identified as stream, fluvial plain, deltaic, estuarine, lagoonal, beach, and other nearshore-marine deposits. Gill (1962, p. 19-20) has interpreted subsurface Cohansey deposits in Cape May County as estuarine in origin. On the other hand, Cohansey materials in an outlier near Arneys Mount in Burlington County are clean and contain cross laminations and swash-concentrated opaque-mineral laminae indicating a beach environment. At Mount Misery in Burlington County, relatively thick sections of long sweeping steeply dipping foreset beds suggest a marine-delta environment. A few miles east of Woodmansie in Burlington County and at Winslow in Camden County a thick sequence of carbonaceous, irregular-shaped, lenticular-shaped, and laminated tabular clay layers are interpreted to be abandoned fluvial-channel slack-water fill, and interchannel deposits characteristic of fluvial environments and alluvial plains. Associated silty sand and less prominent sand and gravel beds are interpreted as being river channel deposits. In this report the Cohansey is thus considered to have deposits of all these environments, and therefore is interpreted to be a mixed- or transitional-environment deposit that, in overall aspect, is a partly dissected ancient subdelta plain.

Shepard (1959, p. 144-145) has suggested the use of laminated clay as valuable criteria for recognizing certain deltaic environments. The occurrence of bluish colored clay laminae containing fine carbonaceous particles is considered to indicate a delta-front environment where topset beds of marine deltas are formed. The limited areal extent of these clay bodies which occur in area 1 in the Cohansey Sand, their large number, and their wide distribution suggest a series of coalescent deltas from small distributary streams.

The boundary line between Areas 1 and 2 (figure 12) marks the seaward extent of these laminated clays and thus marks roughly the position of delta-front sedimentation. Northwest of the boundary line (Area 1 on fig. 12) are thick deposits of fluvial and delta-front sand. Southeastward (area 2 on fig. 12), are sequences of massive bedded clays whose marginal areas position with respect to the laminated clays of area 1 and lenticular shape suggest distal bar to prodelta environments of deposition. Elongated circular-shaped lenses having small thicknesses suggest an interdistributary bay environment. The massive clays persist southeastward towards the coast where in area 3 more sand is present and apparently marine conditions were dominant throughout much of Cohansey time.

As the fluvial Cohansey materials are composed primarily of kaolinitic clay, quartz sand, and chert, which are typical end-products of multicycled erosion and redeposition, the Cohansey is thought to be partly the product of subaerial erosion of older coastal plain deposits. Trace amounts of euhedral-shaped grains, as well as a somewhat larger number of angular-shaped grains, however, suggest that some streams were eroding areas of weathered crystalline rocks. The cleaner, well-rounded, and well-sorted quartz sands, which contrast sharply with the more angular materials, seem to be reworked from older sediments exposed on the shallow submerged shelf. This mixing apparently was done by increased wave and current energies resulting from cycles of marine transgression.

Waves and currents ultimately removed silt and clay from the beach sand and gravel and deposited the finer sand, silt, and clay of the Cohansey Sand in sheltered lagoon and bay environments. During periods of marine transgression and regression quartzose materials were spread out and transported southwestwardly along the advancing and retreating beaches and in the nearshore neritic environments along the delta periphery. Hence, widespread sheet sands are intercalated with other types of Cohansey deposits. At the end of Cohansey time the sea withdrew leaving a white sheet-sand as the Cohansey's youngest marine bed.

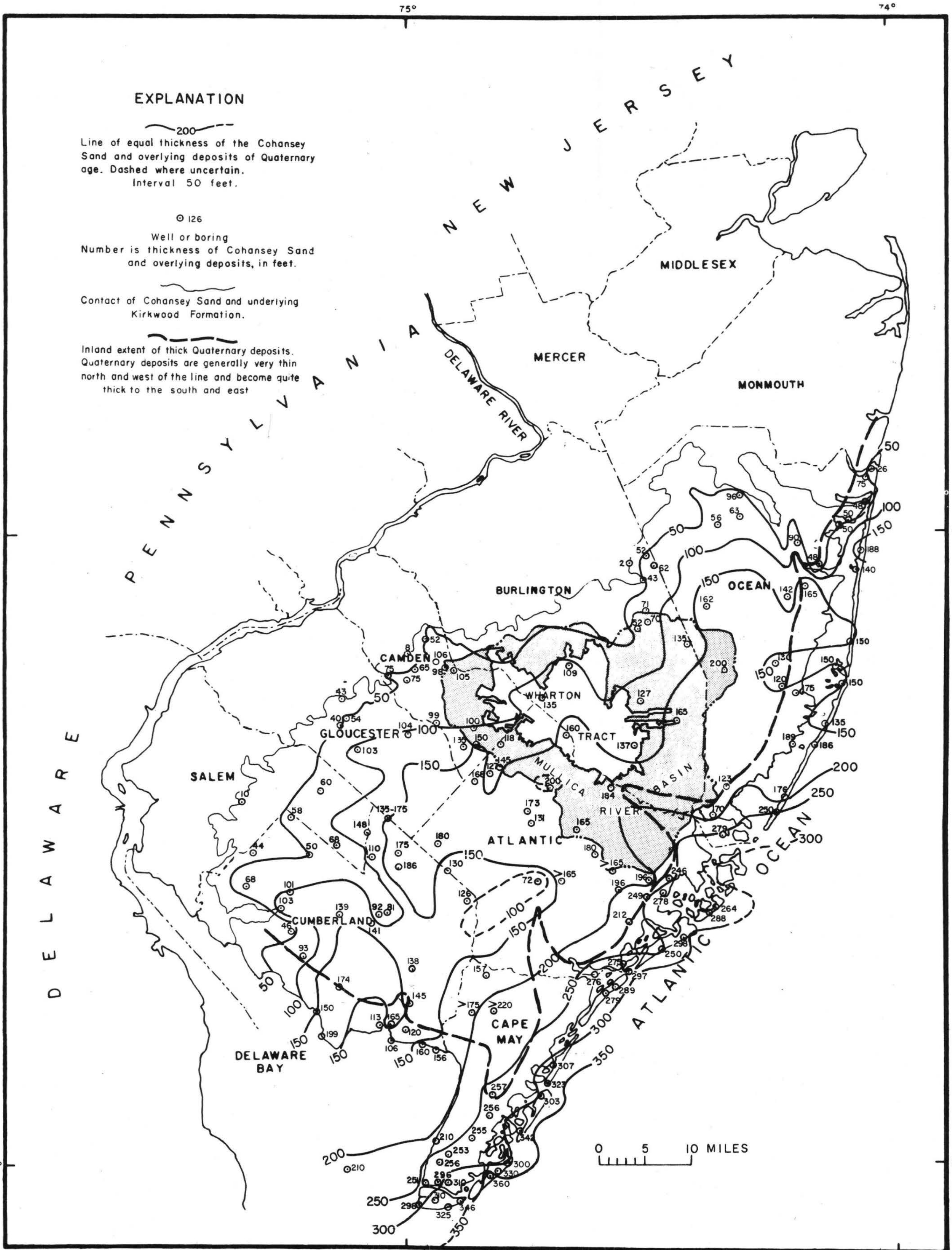

Figure 13. – Thickness map of the Cohansey Sand and overlying deposits of Quaternary age.

Hydrology

Based upon its storage capacity, hydraulic conductivity, and availability for direct recharge, the Cohansey Sand is the most important fresh-water aquifer in the New Jersey coastal plain. The Cohansey is essentially a water-table aquifer but low-pressure confined conditions exist over relatively large areas, especially in the lower parts of the aquifer. The contained water, with modest treatment, is well suited for a wide variety of industrial, agricultural, and domestic uses. The Mullica River basin, and more specifically the central parts of the Wharton Tract, contain some of the more permeable water-bearing materials in the Cohansey Sand.

Values of hydraulic conductivity derived from aquifer tests at nine sites in southern New Jersey are shown in table 5 and figure 12. Calculated values for hydraulic conductivity range from 90 to 250 feet per day (660 to 1,885 gpd per sq ft). More common values throughout much of the aquifer range between 130 and 150 feet per day (1,000 and 1,200 gpd per sq ft). This widespread uniformity probably reflects the widespread and generally uniform character of the marine sheet-sand deposits of the Cohansey Sand.

The transmissivity of the more permeable section of the Cohansey Sand aquifer may be roughly estimated as follows: the thickness at any point on the thickness map (fig. 13) is multiplied by the appropriate average percentage of permeable section shown on figure 12, and this result is then multiplied by an appropriate hydraulic conductivity value from figure 12. The general range of transmissivity in the Mullica River basin is from about 4,700 to 20,000 ft^2 per day (35,000 to 150,000 gpd per ft). Within the Wharton Tract typical values range between 10,000 and 20,000 ft^2 per day (75,000 and 150,000 gpd per ft). Transmissivity values increase to the southeast as the aquifer thickens to the southeast. Also the greater thickness within the buried drainage ways initially established in post-Kirkwood times results in greater values of transmissivity.

Water in the Cohansey Sand in area 1 is unconfined near the top of the saturated zone but exists under low- to moderate-pressure confined conditions in the deeper parts of the aquifer. When wells in area 1 tapping the deeper parts of the aquifer are pumped, this pressure is generally soon dissipated and the aquifer then essentially acts as a water-table aquifer. During aquifer tests, calculated coefficients of storage which initially are representative of moderately confined artesian aquifers (for example 1.0×10^{-3} to 1.0×10^{-2}) may change, with continued pumping, to coefficients of unconfined conditions ranging from about 1.0×10^{-1} to as much as 2.6×10^{-1}. Table 5 lists the storage coefficients determined from available aquifer tests in southern New Jersey. Low values at tests 1, 4, and 9 are indicative of confined conditions, whereas higher values such as test 5 are indicative of unconfined conditions.

An aquifer test was conducted in June 1960 on a 15-acre area adjacent to the Mullica River, 2.5 miles northwest of Batsto. The purpose of the test was to determine the hydraulic characteristics of the water bearing materials along the lower reaches of the major streams and to determine the degree of hydraulic continuity between the Mullica River and the bounding aquifer. Descriptions of the observation well network, geologic conditions, and movement of ground water in the test area are presented in Lang (1961), Lang and Rhodehamel (1962), and Rhodehamel and Lang (1962).

The pumped well was screened from 61 to 81 feet below the land surface and pumped at 1,000 gpm for 12 days. Drawdown data from observation wells located near the pumped well, when analyzed by the Theis (1935) non-equilibrium formula, provided values of transmissivity of 33,000-40,000 ft^2 per day (250,000 - 300,000 gpd per ft). However, because drawdown was affected by recharge boundaries, these values are considered too great.

Drawdown data were analyzed also using an equilibrium formula. Although true equilibrium had not been reached at the end of 12 days of pumping, the cone of depression had assumed a nonvarying shape during the latter part of the test period and the use of an equilibrium equation was considered applicable. The average transmissivity calculated by this method is 20,000 ft^2 per day (150,000 gpd per ft) and is probably indicative of the transmissivity of the full thickness of the water-bearing sands beneath the test site. The coefficient of storage using an equilibrium formula developed by Ramsahoye and Lang (1961) was computed to be 0.16.

During the test, ground water that normally would move down-gradient toward the stream was diverted toward the pumping well. Poor hydraulic connection between aquifer and the Mullica River was shown by the water-level contour map which indicated that little water moved from the river into the aquifer under pumping conditions. This poor connection is probably caused by a thin deposit of relatively impermeable bog iron in the bed of the Mullica River. Good hydraulic connection of the aquifer and water in the swamps is indicated by the drying up of the swamps on both sides of the river after about 6 days of pumping.

Values of hydraulic conductivity of the more permeable Cohansey materials are reported by Monroe and Pentz (written commun., 1936). Values of 41 samples range from 9 to 388 ft per day (68 to 2,903 gpd per sq ft), and the average is about 83 ft per day (620 gpd per sq ft). This average is about 40 percent smaller than the average of about 130 ft per day (1,000 gpd per sq ft) for the available Cohansey Sand-upper Kirkwood values obtained from aquifer tests.

Core samples from well 4-H in the Wharton Tract (see table 6) have been evaluated, and characteristics of their grain-size distribution have been correlated with laboratory-determined values of hydraulic conductivity. Grain-size evaluation was made on single-bed materials to prevent errors resulting from the addition of very fine grained material from thin silt and clay layers or material from layers indurated with iron oxide. In figure 14 the laboratory-determined values of hydraulic conductivity are plotted against a grain-size parameter that is obtained by multiplying the median grain size (in millimeters) by 100 and dividing the product by the square of the percentage of the combined silt and clay fraction in the sample. The grain-size parameter used in the correlation is based upon a volumetric grain size frequency distribution. Laboratory-determined grain-size data, which were recorded on a percent-by-weight basis, were converted mathematically to a percent-by-volume basis. The grain-size parameter and its relationship to hydraulic conductivity as indicated in figure 14 are similar to those of Morrow, and others (1969, p. 312-321), Masch and Denny (1966, p. 665-677), Griffith (1955, p. 15-31), and Preuss and Todd (1963, p. 12-18).

Specific capacities of wells tapping the Cohansey Sand are high, ranging from 5 to 121 gallons per minute per foot of drawdown. Table 7 presents a range of yields and specific capacities observed for wells tapping the Cohansey-upper Kirkwood aquifer in southern New Jersey.

Beacon Hill Gravel

Unconformably and stratigraphically above the Cohansey Sand is the Beacon Hill Gravel of Pliocene(?) age. The Beacon Hill Gravel contains coarse-grained quartz sand, pebbles of vein quartz, quartzite, and fossiliferous chert derived from the Helderberg Group. The formation is about 20 feet thick at its type locality, Beacon Hill in Monmouth County, New Jersey. Prolonged erosion during and since Pliocene time has thinned it in places and has probably removed the formation from wide areas. Identifiable Beacon Hill deposits are now restricted to small scattered remnants at the highest altitudes in the New Jersey Coastal Plain.

Clearly recognizable outcrops of Beacon Hill Gravel do not occur in the Wharton Tract. Within the Mullica River basin it forms the summit of Apple Pie Hill southwest of Chatsworth and the summits of two lines of prominent hills along the boundary of the Mullica River basin east and southeast of Woodmansie in Burlington County.

Many lesser prominences in the Wharton Tract possess gravelly cappings, some containing materials somewhat characteristic of the Beacon Hill Gravel. These are probably modified Beacon Hill deposits which have been altered by mass wasting and fluvial transport since Beacon Hill time. They are generally less than 4 feet in thickness, and occupy a total of about 1 percent of the area.

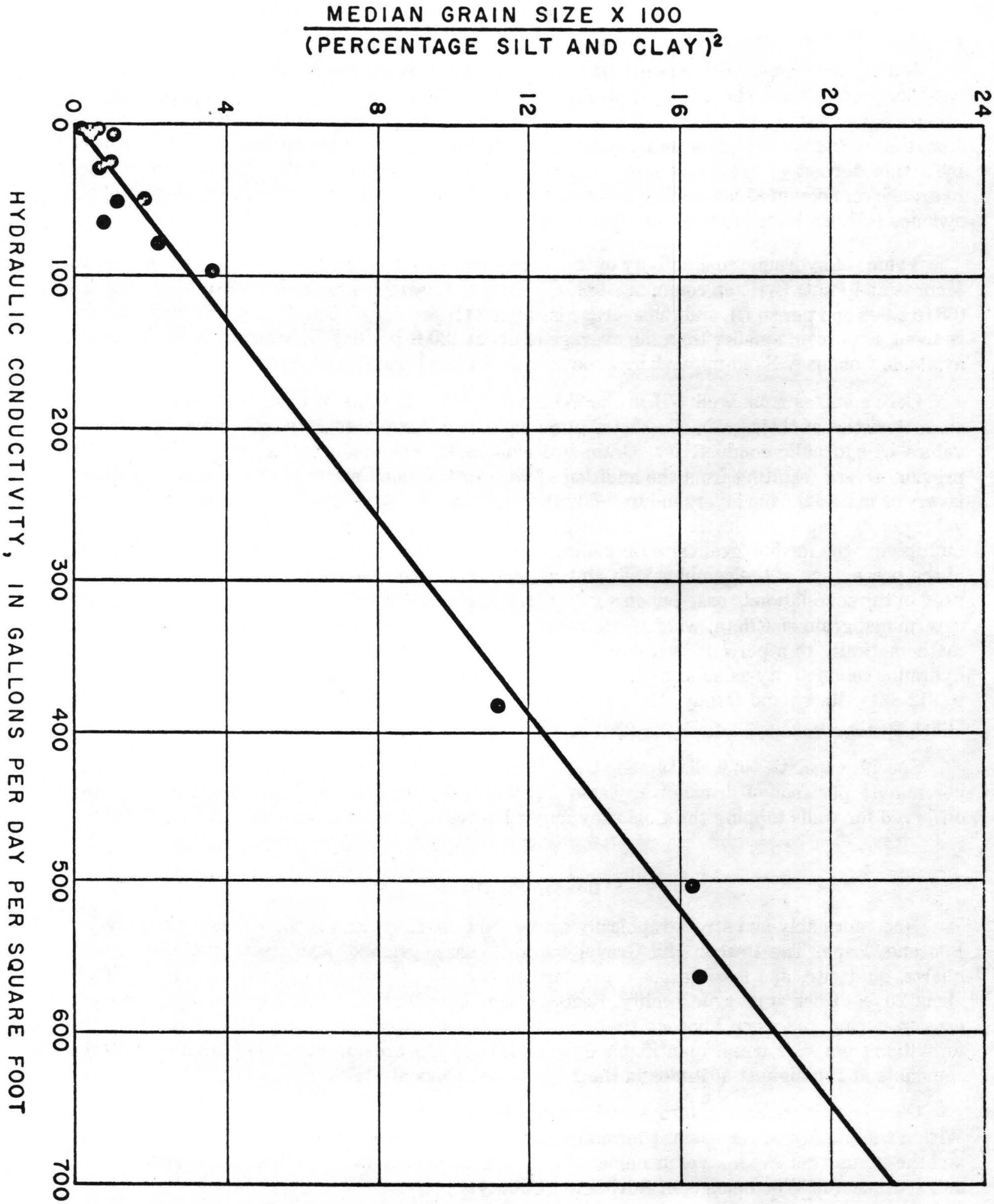

Figure 14. – Relation of hydraulic conductivity to grain size of core samples from well 4-H in the Wharton Tract.

Because Beacon Hill Gravel deposits occur only at the higher altitudes, are of small areal extent, and generally are only a few feet thick they do not constitute an important aquifer. Furthermore, weathering associated with soil formation has reduced the hydraulic conductivity by deposition of clay and iron-oxide coatings around the particles thus creating a notable amount of induration. In places, as much as 20 feet of impermeable ironstone conglomerate cappings exist. The formation's major hydrologic function within the Mullica River basin is to transmit precipitation downward to recharge the aquifer in the Cohansey Sand.

The chert and quartzose gravel lithology and the occurrence of ilmenite in both the Cohansey and Beacon Hill Gravel suggest a similar provenance for the two formations. However, differences in the coarseness of material and in the structure of the two formations suggest a change in the mechanism and site of deposition. A longer dominantly marine transport to a nearshore environment took place during Cohansey time and a shorter dominantly stream transport to a fluvial environment took place during Beacon Hill time.

Quaternary Deposits

Deposits of Quaternary age form a discontinuous veneer lying unconformably above the Cohansey Sand throughout much of the Mullica River basin. The three major Quaternary formations of the New Jersey coastal plain are represented. From the oldest to the youngest these are the Bridgeton, Pensauken, and Cape May Formations.

Bridgeton and Pensauken Formations

The Bridgeton and Pensauken Formations, as described by Salisbury and Knapp (1917), are considered by MacClintock and Richards (1936) to form a "complex" of deposits resulting from the various episodes of deposition and erosion characteristic of the early Pleistocene in southern New Jersey. The deposits have characteristics of fluvial deposition; they are cross stratified in many places, occupy channels, and show rapid vertical and horizontal changes of texture. They are as much as 20 feet thick. These formations are composed chiefly of a highly weathered mixture of unconsolidated materials to fully indurated (iron-oxide cemented) beds of red to yellow quartz sand containing large amounts of vein quartz. Pebbles of shale, sandstone, quartzite, and chert, and kaolinitic clay are also present. The clay is either in pods and nodular masses or in thin lenses and beds.

Bridgeton and Pensauken deposits, commonly containing lag gravel at the surface, cap the tops and mantle the upper slopes of most of the pronounced hills and narrow ridges that range in altitude from 50 to 190 feet. The higher deposits in any one locale in the Wharton Tract generally are less quartzose, coarser, less rounded, more weathered, and more indurated than those deposits lying below and along the flanks of the higher deposits.

The Bridgeton and Pensauken in the Mullica River basin are derived from sources similar to those of the Cohansey Sand and Beacon Hill Gravel and derived from erosion of these formations. Hence it is difficult to distinguish these deposits accurately. They are probably more widely distributed than shown by Salisbury (1899, pl. 1), Lewis and Kummel (1910-1912), and Parker and others (1964, pl. 7).

Cape May Formation

The Cape May Formation was originally named by Salisbury (1898, p. 20) for its excellent development in Cape May County. The name was applied to coastal-terrace deposits, considered to be of marine origin, extending from sea level to 30 to 50 feet above sea level. Salisbury believed these deposits to be of Wisconsin age because the coastal terrace extends up the Delaware River and eventually blends into Wisconsin outwash deposits. Salisbury and Knapp (1917, p. 162-164) redefined the Cape May Formation to include valley terrace deposits along many streams of southern New Jersey. These are observed at altitudes as high as 150 feet and slope down the valley to merge with the marine terrace deposits bordering the present coast. MacClintock and Richards (1936) demonstrated that the Cape May Formation is of pre-Wisconsin age — most probably reaching its present state of deposition and erosional development largely during the Sangamon Interglaciation. Their definition and Kummel's (1940, p. 158) definition of the Cape May includes the stream terrace deposits described by Salisbury and Knapp (1917, p. 162-164).

The Cape May Formation in the Mullica River basin is derived primarily from eroded materials of the Bridgeton, Pensauken, and Cohansey Formations. It is difficult to distinguish the Cape May from its parent materials except on the basis of its lesser degree of weathering, smaller particle size, and lesser degree of soil development.

Cape May fluvial-terrace deposits form a widespread sheet of sand and pebble alluvium. They underlie broad flats largely within present valley walls and are the most extensive Cape May deposits in the Wharton Tract and Mullica River basin. They occur at altitudes as high as 190 feet above sea level in the Mullica River basin. The deposits are seldom more than 15 feet thick and more usually 1 to 8 feet thick, except in the tidal reaches of streams where Cape May fluvial-terrace deposits and overlying alluvium of Holocene age are as much as 20 to 40 feet thick.

In Cape May County, Gill (1962, p. 21-31) has shown that the Cape May Formation contains four lithologic facies deposited in three depositional environments — estuarine, marine, and deltaic. In the Mullica River basin estuarine sand and the overlying estuarine clay facies of the formation appear to be present in the reaches of the old drainage way below Constables Bridge (located about 1 mile northwest of Batsto). This conclusion is based upon the channel-like nature of these deposits; their lithologic nature, stratigraphic position, and Quaternary age. The estuarine sand facies and the overlying estuarine clay facies fill an almost totally buried Quaternary channel cut into the underlying Cohansey Sand in the vicinity of the Mullica River.

At an aquifer-test site, located about 2.5 miles northwest of Batsto, the thickness of Cape May estuarine deposits is about 85 feet. The ancient channel is at least 112 feet deep at Sweetwater and reaches a depth of at least 229 feet at Atlantic City. The slope of the channel base is about 7 or 8 feet per mile southeastward to the Atlantic Ocean.

The most important hydrologic function of the Cape May fluvial-terrace deposits is their ability to absorb precipitation and transmit water to underlying aquifers. Because hydraulic continuity with the underlying Cohansey is excellent, they can be considered a part of the Cohansey Sand-upper Kirkwood aquifer system.

Post-Cape May alluvial deposits are closely associated with the Cape May fluvial terraces. This association is also true of the silt, sand, clay, bog iron ore, and marshland deposits of Holocene age bordering and accumulating in the stream channels, estuaries, and back bays of the Mullica River basin. Most of these deposits are fine-grained, carbonaceous sand, silt, and clay having low hydraulic conductivities. Their infiltration capacities are generally less than those of the underlying Cape May fluvial terrace deposits. Along the Mullica River below Constables Bridge and along the Wading River at least below Harrisville the clays of Holocene age probably act as confining units to the underlying aquifers of the Cape May Formation and the Cohansey Sand-Upper Kirkwood aquifer.

WATER QUALITY

Water from the principal aquifers in the Mullica River basin can be broadly classified as a sodium bicarbonate-chloride-sulfate type. With common treatment procedures it is suitable for a wide variety of uses. Representative analyses are presented in table 9. Only high concentrations of iron and manganese (greater than 0.3 milligrams per liter) and low pH (less than 7.0) are objectionable for most uses without pretreatment.

Ground water in the basin comes from precipitation that percolates through forest litter, and enters a porous ground-water reservoir that is remarkably inert to chemical solution. When not polluted by man's activities, the water is low in dissolved solids, ranging from 25 to 50 mg/l (milligrams per liter). Hardness, mainly noncarbonate, is low, generally less than 40 mg/l. Because of the low dissolved solids, the ground water is only weakly buffered against large changes in its hydrogen-ion concentration. The water has a rather uniform temperature that approximates southern New Jersey's mean annual air temperature of about 54°F. The water is high in dissolved carbon dioxide which is obtained partly from the air, but largely from the biological decomposition of forest litter and soil microorganisms. Carbon dioxide reacts with the water to provide small amounts of carbonic acid which, in turn, dissociates (ionizes) and thereby contributes hydrogren ions. The presence of carbonic acid gives ground-water recharge in the basin an acidic character; pH values of 4.5-5.0 are commonly reported in the ground water.

Because of its acidic character and low buffering capacity, the water is corrosive and readily dissolves iron from the iron-bearing organic compounds in the decaying forest litter and attacks iron minerals in the soil and underlying sediments. This dissolved iron is generally in the ferrous state, but is rapidly altered to ferric hydroxide, probably by an oxidation that uses oxygen, which is also carried downward by the percolating water.

As the ground water moves through the aquifer, it is eventually cut off from its sources of carbon dioxide and oxygen. The water, through oxidizing reactions, loses its dissolved oxygen. Hydrogen ions in the water react in the absence of oxygen with the abundant ferric hydroxide to produce soluble ferrous ions which are transported away by the ground water. Ultimately, much of the free carbon dioxide is consumed in supplying the carbonic acid that continues, by dissociation, to produce the hydrogen ions. As significant amounts of the carbon dioxide are expended, the carbon dioxide-bicarbonate buffering system is altered, and the pH of the water is shifted to a slightly alkaline state.

When a well is pumped, ground water is brought to the surface and aerated. Any remaining gas (there is usually some) is quickly liberated, partly from the bicarbonate present, and oxygen is provided to rapidly oxidize the dissolved ferrous iron. The oxidation process provides increased hydrogen-ion concentrations in water which gives the water an acid nature. Furthermore, an iron oxide is formed and precipitated as a red-colored floc. Release of small amounts of carbon dioxide from the ground water significantly alters the hydrogen-ion concentration and raises the pH of the water, because this water has very low dissolved solids and a weak alkaline buffering system.

Iron-oxide precipitate formed upon aeration of discharging ground water is the source of bog-iron deposits common to the riparian areas of the basin. The phosphate mineral, vivianite, occurs in the bog iron deposits and boron is found in ground water of the Cohansey Sand, especially in areas of ground-water discharge. Sources of phosphate and boron, however, are practically nonexistent in the Cohansey Sand and the Kirkwood Formation (Wilkerson and Comeforo, 1948, p. 143). This suggests that some ground water in the Cohansey probably moves up from a glauconite-bearing formation underlying the Kirkwood Formation — either the Piney Point Formation or the Manasquan Formation.

Chemical and spectrographic analyses of stream samples collected at non-tidal sampling stations in the basin are published in annual water quality basic-data releases (U.S. Geological Survey, 1964-66). The predominant ions are sodium, chloride, and sulfate. However, the amount of these and other dissolved substances is quite low. Dissolved-solids content is generally below

50 mg/l; the pH ranges from 4.3-6.6 indicating acidic conditions; color is high, ranging from 3-150 Pt-Co units; iron is high, ranging from 160-7,100 micrograms per liter (0.16-7.1 mg/l); and the water is soft, 1-40 mg/l hardness as calcium carbonate. Usually after appropriate treatment these waters are acceptable for most uses. Higher nitrates in Springers Brook (ranging from 3.6-4.4 mg/l) than observed at other sampling stations (less than 2.0 mg/l) suggest contamination, possibly from agricultural sources.

Color is one of the more variable surface water quality parameters. The water is clear throughout most of the nongrowing season. During the growing season the color is formed by the complexing of iron compounds with organic exudates such as tannins. The more complete the oxidation, the more intense is the brownish color.

Iron concentrations in the Mullica River appear to increase with stream flow. This relation may be caused by a temporary entrapment of iron compounds in the large swamplands bordering the streams. Most of the entrapment occurs when ground water that contains dissolved iron compounds is evaporated and transpired during warm fair-weather periods. Some iron is released continuously by decay of vegetal detritis and stored in the riparian zone. The longer the fair-weather period, the larger the quantity of iron compounds trapped in the swamps. When precipitation occurs, iron is flushed out of the swamps and concentrations increase in the stream. Concentrations for a given flow are larger in the summer than in the winter. Apparently, the entrapped iron builds up over longer periods during the summer. The reduction of evapotranspiration during the cooler months keeps the swamps wetter and the flushing more frequent. Also, the reduced vegetal decay in the cooler period does not favor a large storage of iron compounds between periods of flushing. As a result the iron content for any given winter-time streamflow, though increasing with increased discharge, is relatively small.

Surface-water temperatures reach 25.6°C (78°F) during summer low-flow periods. In winter months, the influx of ground water having a temperature of about 12.2°C (54°F) generally prevents the streams from freezing bank to bank, even though winter air temperatures drop well below freezing.

The salt water-fresh water interface in the Mullica River, as defined by a sharp change in chloride concentrations, generally lies within the 2.8-mile reach of the Mullica River between the bridge at Lower Bank and the Green Bank-Weekstown Road bridge at Green Bank as indicated by data presented in table 8.

The lower reaches of the Mullica River system (the Bass, Batsto, Wading, and the Mullica itself) are influenced by tides. Work by Coonley and others (1971), carried out on August 21, 1968 when flows in the Wading and Bass Rivers were about one-half that of their long-term averages, shows that chloride concentrations were 350 mg/l during high-tide conditions at the community of Wading River, and as much as 2,040 mg/l during low-tide conditions about 0.25-mile above the village of New Gretna. Saline water probably reaches as far up stream as the junction of the East and West Branches of Bass River.

As streamflow increases, saline water from the ocean is flushed farther downstream. This relationship is indicated by the plot of salinity in the Mullica River at French Point, located 0.5 mile downstream from the Garden State Parkway, (Durant, Rutgers Univ., written commun., 1970) against stream flow in the Batsto River at Batsto (figure 15). Data for the maximum salinity plot were collected at high tide and those for the minimum salinity plot, at low tide.

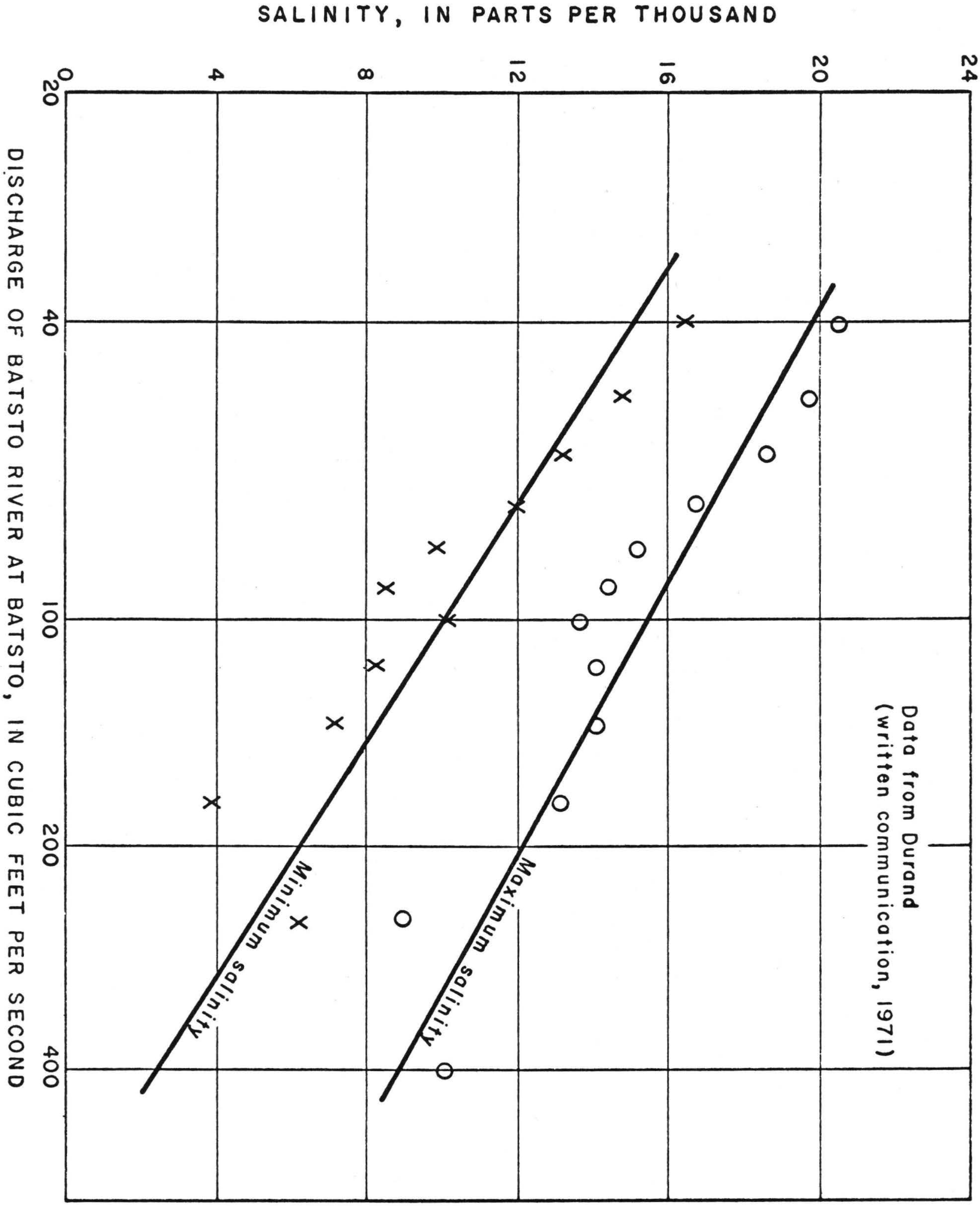

Figure 15. – Relation of salinity in the Mullica River at French Point to stream flow in the Batsto River at Batsto.

WATER-RESOURCES DEVELOPMENT OF THE WHARTON TRACT

The Wharton Tract is well situated to support the growing water needs of nearby southern New Jersey communities, including the industrialized communities along the Delaware River and the resort communities along the New Jersey coast (Tippetts and others, 1955, p. V1-V13). Wharton Tract water can be used to augment or replace any of these local supplies that become depleted or polluted and can be used to minimize salt-water intrusion dangers that may be created by overdrafts on water supplies at Atlantic Ocean resort communities. Because the Wharton Tract has an elevated inland location, there is little danger of sea-water encroachment except locally along the tidal parts of some streams. Even along tidal reaches, aquifers are protected by a relatively thick sequence of overlying Pleistocene estuarine clays. Small tidal barrier dams, similar to those presently in use in Cape May County and elsewhere, could rectify salt-water encroachment if it becomes a problem.

Substantial quantities of water can be developed from the Wharton Tract by conjunctive use of ground water and surface water. The Cohansey Sand is capable of yielding 700 gpm or more to individual wells. Furthermore, the average total yield of the upper Mullica River at the Wharton Tract is about 390 mgd. Nevertheless, limitations on development of water from the tract are imposed by the need to maintain streamflow at or above certain minimum amounts. Inadequately planned withdrawls of ground water or surface water from the tract could cause streamflow to periodically fall below acceptable minimum flows.

One way to regulate streamflow and thus assure flows above prescribed minimums is by use of surface reservoirs. In the relatively flat Mullica River basin, however, surface-reservoir waters would cover large areas to shallow depths. Thus, large evaporation losses would accompany this type of development. Annual evaporation losses may be expected to range between 29 and 34 inches of water depth from any reservoir in southern New Jersey (Hely and others, 1961; Kohler and others, 1959, Pl.2; and Carter, 1958, p. 261). Such losses would exceed half a billion gallons of water per year per square mile of water surface. Hence the 54-square mile surface-reservoir impoundment for the Mullica-Wading River systems proposed in 1922 (Hazen and others, 1922, p. 45-48) would permit a water loss of 27 billion gallons per year or approximately 75 million gallons per day. This water loss could be avoided, as discussed later, by use of a smaller reservoir confined entirely within the normal channel of the tidal part of the Mullica River and its tidal tributaries.

Optimum development of Wharton Tract water probably entails withdrawal of water from the major streams such as the Batsto and Mullica Rivers during periods of relatively high flow. This water can be obtained either directly from the streams or from wells near the streams.

Wells for an induced-river-recharge development need be only 12 to 15 inches in diameter, 100 to 150 feet deep, have 20- to 30-foot well screens installed in either natural or artificial gravel packing, and be placed between 100 and 150 feet from the stream. The streambeds, however, are commonly clogged by iron-oxide (bog iron) deposits, and may require dredging or scarification to provide good hydraulic connection between the streams and the aquifer. When pumped at rates of about 700 gpm, wells spaced, for example, about 1,000 feet apart along the streams in the Wharton Tract will produce about 4 feet of water-level decline midway between well sites. After equilibrium conditions are reached only a small amount of the pumped water will be coming from ground-water storage, the rest being stream water filtered through more than 150 feet of sand.

During periods of low streamflow, water should be withdrawn from wells located much greater distances, up to several miles, from the major streams. Withdrawal of ground water from such areas would not immediately affect discharge of the major streams. Ultimately, streamflow would be reduced as ground water discharge to the streams decreases. The development of maximum quantities of water from the Wharton Tract, then, depends largely upon locating and operating well fields in such manner that streamflow reduction caused by ground water pumpage from upland wells is minimal during periods of low streamflow. Direct diversion of surface water or pumping of wells adjacent to the stream should, of course, occur during periods when streamflow is greater than the prescribed minimum discharge.

From an analysis of flow-duration curves of the Batsto River at Batsto and the Mullica River near Batsto, Harold Meisler (written commun., 1971) has estimated the quantity of water that is available for development from these basins. For this estimate, prescribed minimum flows at the gaging stations were set at amounts equal to the historical mean annual seven day consecutive low flow; 21.5 mgd in the Mullica River and 35.5 mgd in the Batsto River. In addition, an assumption is made that ground-water pumpage from wells a few miles from the major streams can be managed so that streamflow will not be significantly reduced during the dryest periods of the year even during extended drought. On this basis, an estimated 70 mgd of water could be developed from the 116.6 square mile drainage area above the two gages. Although only about two-thirds (roughly 75 square miles) of this drainage area is within the Wharton Tract, most, perhaps all, of the 70 mgd of water from these two basins could be obtained within the Wharton Tract.

As only about 75 square miles of the Wharton Tract lies within this drainage area, the quantity of water available for development from the entire 150 square mile tract is certainly greater than the estimated 70 mgd. It is suggested that the quantity of water available for development from the entire Wharton Tract and upper Mullica River is of the order of 150 mgd if developed as a ground water-surface water system that provides no additional surface water storage facilities (Harold Meisler, written commun., 1971).

Obtaining these estimated quantities of water depends upon not reducing streamflow during periods having the lowest streamflow. One way to ensure that streamflow during the lowest flow periods is not reduced below acceptable limits is to augment streamflow by pumping ground water from near the basin divides into the streams during such periods. Augmentation by pumping from ground-water reserves makes it feasible to develop conjunctive use up to the design limit and probably to exceed the estimated 150 mgd even during droughts.

The combining of downstream surface-water reservoirs with a tidal dam has been suggested by J.E. McCall (written commun., 1969). The suggestion incorporates development of ground and surface waters in the Mullica River basin with impoundment of fresh water behind a tide barrier at or near the Garden State Parkway. The dam would create a 13-mile long fresh-water lake extending upstream to the existing dams on Batsto and Mullica Rivers at the Batsto State Park and Historical Site. This lake also would extend up the Oswego River about 6 miles, well into the Wharton Tract. The total surface area is practically equal to that which is now covered by normal high tides, so evaporation would be about the same as from the existing streams and tidal marshes.

The barrier plan, in its simplest form, would include a fixed dam across the opening under the Garden State Parkway bridge over the Mullica Estuary at an altitude 2 or 3 feet above normal high tide. The reservoir level would be about 1 foot higher than now reached by the spring tides during a summertime full moon or new moon. The lake would occupy the same area now covered by high tides and existing bridges, docks and shore facilities would not be disturbed. Such a dam would be overtopped, on the average, several hours each year by abnormally high tides, allowing a small slug of brackish water to invade the reservoir. The high sustained flow of the Mullica River would tend to restrict the upstream movement of this brackish water and flush it seaward.

Other alternatives are:

1. A fixed dam 5 or 6 feet higher than normal tide that would effectively prevent brackish water entering the reservoir but would both deepen and increase the area of the impoundment. This alternative would require acquisition of additional riparian land.

2. A movable-gate or inflatable barrier that could be operated to control salt-water invasion and lake levels for maximum benefits and minimum damages. The plan would reduce the need to buy riparian lands, because lake levels could be stabilized and maintained at or near the desired

altitude. Raising of the barrier for 3 hours, spanning the period of any abnormally high tide would cause less than a 5-inch rise in lake level, even if the Mullica and its tributaries were filling the lake at the rate of the maximum flood of record.

3. Location of a tide barrier at or near the Burlington-Ocean-Atlantic Counties boundary line some 2.5 miles farther downstream could back fresh-water up two more large creeks and one smaller stream. This would add about 10 miles to the length of the main lake and tributary arms and would shorten the length of pipelines for water supply to Atlantic City and other shore communities. This alternative, however, would require about 5 miles of low earth dike across marshlands and would place a barrier downstream of several large marinas harboring vessels that operate in Great Bay and the Atlantic Ocean. This alternative would probably not be practical unless incorporated with a relocation of U.S. Highway 9. If U.S. Highway 9 is ever separated from the Garden State Parkway crossing of the Mullica River, the new roadway embankment would serve as a dike in the same manner as the Garden State Parkway would for the suggested primary barrier site.

Probably the greatest value from a tide barrier on the lower Mullica would be attached to the multiple-use features — specifically the recreational potential of the resulting large freshwater lake with stable level and reduction of the modest danger of salt-water invasion of ground-water aquifers. However, substantial water-supply benefits might also be expected owing to the nearness to places of greatest need. Atlantic City, for example, could pump from the lake to Doughty Pond and Kuehnle Reservoir, with only 8 miles of pipeline, to use existing storage and treatment works. Such off-stream pumped storage near the coast would enable beneficial use of nearly all of the runoff of the Mullica not needed for quality control to preserve the established shellfish industry. If use of the natural runoff is ever temporarily exceeded, the lake could be replenished from wells in the Wharton Tract by pumping directly into the stream channels, eliminating many miles of pipeline construction. Otherwise, the Wharton Tract wells could be reserved for water supply in surrounding local areas and the rapidly developing corridor paralleling the Delaware River.

The principal disadvantage of the proposed tide barrier is the cutting off of navigation between the bay and ocean and the Mullica River estuary above the barrier. This could be avoided by construction of a suitable lock and the cost thereof might be justified by the increased recreational potential. If the State chose to restrict the size of boats permitted on the Mullica Reservoir to a size that is trailer-transportable, then simple launching ramps on both sides of the barrier would suffice. Few large boats navigate upstream of the Garden State Parkway even at present, as the channel is winding and shallow, especially at low tide.

SUMMARY

The Wharton Tract is an undeveloped, sparsely populated, and forested area of 150 square miles located in the Mullica River basin in southern New Jersey's Pine Barrens region. The tract was purchased by the State of New Jersey in 1954 primarily as a water supply preserve, but also for multiple conservation and recreational purposes.

Mean streamflow at three continuous record gaging stations in the Mullica River basin are: Mullica River near Batsto (46.1 sq mi drainage area), 66 mgd; Batsto River at Batsto (70.5 sq mi drainage area), 81 mgd; Oswego River at Harrisville (64.0 sq mi drainage area), 55 mgd. Thus the mean streamflow from this 180.6 sq mi area is 202 mgd, an average of 1.12 mgd/sq mi or about 23.5 inches. As the drainage area at the most downstream points in the Wharton Tract includes 195 sq mi in addition to the 150 sq mi of the tract itself, the total average streamflow at these points can be expected to be (on the basis of 1.12 mgd per sq mi) about 390 mgd.

The Wharton Tract is underlain by from 1800 to 2500 feet of unconsolidated coastal plain sediments consisting of gravel, sand, silt, and clay that dip and thicken southeastward toward the Atlantic Ocean. Principal aquifers in the Wharton Tract and Mullica River basin are in the Kirkwood Formation of middle Miocene age, Cohansey Sand of Miocene(?) and Pliocene(?) age, and in overlying hydraulically connected deposits of Quaternary age.

The Kirkwood Formation is composed of gravel, sand, silt, and clay. Diverse lithologies represent deposition in different environments such as nearshore marine, barrier bar, lagoonal, estuarine, and tidal marsh. The formation ranges in thickness from 50 to 450 feet in the Mullica River basin. High-yielding Kirkwood aquifers that occur along the Coast probably do not extend very far into the Mullica River basin. In the Wharton Tract there are probably no more than two or three areally extensive Kirkwood aquifers and most of these are probably hydraulically connected with the overlying Cohansey Sand. Hydraulic characteristics of the Kirkwood in the Mullica River basin are virtually unknown.

The Cohansey Sand which unconformably overlies the Kirkwood Formation is dominantly a quartz sand containing minor amounts of pebbly sand, silty sand, and interbedded clays. Almost all of the Wharton Tract and most of the Mullica River basin lie within the sandier area (area 1 on figure 12) of the Cohansey which contains approximately 75 percent sand beds and 25 percent silt and clay beds. Clay in this area generally is laminated and occurs in discontinuous sections. Data from test drilling show that the upper 100 feet of sediments in the Wharton Tract contain about 92 percent sand beds, 3.5 percent clay beds, and 3.5 percent silt beds. The Cohansey in the Tract ranges in thickness from less than 50 feet to about 180 feet and its average thickness is about 125 feet. The southern one quarter of the Mullica River basin occurs in the less sandy area (area 2 on figure 12). In this area the Cohansey contains approximately 60 percent sand beds and 40 percent silt and clay beds and the clay is generally more massive bedded.

The Cohansey Sand is believed to be, in overall aspect, a deltaic deposit. It contains materials that were deposited locally in nearshore marine, fluvial, estuarine, lagoonal, and beach environments. The occurrence of bluish colored clay laminae containing fine carbonaceous particles and the wide distribution, large number, and limited areal extent of these clay bodies suggest a series of coalescent deltas from small distributary streams entering an active marine environment.

Based upon its storage capacity and hydraulic conductivity and on the availability for direct recharge, the Cohansey Sand is the most important fresh-water aquifer in the New Jersey coastal plain. It is essentially a water-table aquifer although low pressure confined conditions exist, especially in the lower horizons of the aquifer.

The hydraulic conductivity of Cohansey aquifer material determined from pumping tests at nine sites in southern New Jersey ranges from about 90 to 250 ft per day (660 to 1,885 gpd per sq ft). One pumping test in the Wharton Tract gives an average value of 130 ft per day (1,000 gpd sq

ft). The transmissivity of the Cohansey Sand aquifer through most of the Wharton Tract is typically between 10,000 and 20,000 ft^2 per day (75,000 and 150,000 gpd per ft). Transmissivity generally increases to the southeast as the aquifer thickens in that direction.

Deposits of Quaternary age form a discontinuous veneer lying unconformably above the Cohansey Sand. The three major Quaternary Formations of the New Jersey Coastal Plain are represented. These are the Bridgeton, Pensauken, and Cape May Formations. The Bridgeton and Pensauken are generally fluvial deposits composed of gravel, sand, and clay and are as much as 20 feet thick. The Cape May Formation is derived primarily from erosion of sand and pebble alluvium generally not greater than 15 feet thick. Thicker deposits (85 feet thick near Batsto) of estuarine sand and clay of the Cape May Formation fill a channel in the underlying Cohansey Sand along the lower reaches of the Mullica River. The most important hydrologic function of most of the Quaternary deposits is to absorb and transmit precipitation to the underlying Cohansey Sand with which they are hydraulically connected.

Ground water and surface water in the Mullica River basin are low in dissolved solids, generally less than 50 mg/l. Hardness, mainly noncarbonate, is also low, generally less than 40 mg/l. Ground-water temperature is approximately 12.2°C (54°F). Surface-water temperatures reach 25.6°C (78°F) during the summer. Iron concentrations are generally high, up to 49,000 micrograms per liter (49 mg/l) in ground water and up to 7,100 micrograms per liter (7.1 mg/l) in the streams. Iron-oxide precipitate formed upon aeration of ground water discharging into surface-water bodies is the source of bog-iron deposits common to the riparian areas of the basin. Both ground water and surface water are acidic as indicated by typical pH values of from 4.5 to 6.5. Color of the surface water is commonly high, ranging from 3 - 150 Pt-Co (platinum-cobalt) units. During the growing season, the color is formed by the complexing of iron compounds with organic exudates such as tannins. The water is clear during most of the nongrowing season. After appropriate treatment the ground water and surface water of the Mullica River basin are suitable for most uses.

The Wharton Tract is well situated to support the growing water needs of nearby New Jersey communities. Optimum development of water can be achieved by conjunctive use of ground and surface water. During most of the year some water would be withdrawn either directly from the major streams or from adjacent wells. Wells for induced river recharge development need be only 12 to 15 inches in diameter, 100 to 150 feet deep, and between 100 and 150 feet from the stream. Yields of 700 gpm or more from individual wells spaced about 1,000 feet apart are feasible. During periods of low summer or fall flows water would be pumped from wells located further from the streams. Limitations on development of water from the Tract result from the need to maintain streamflow at or above acceptable minimum amounts. Even withdrawals of water from wells located several miles from the major streams will ultimately reduce streamflow. Consequently, the development of maximum quantities of water from the Wharton Tract depends upon locating and operating well fields in such manner that stream flow reduction caused by ground-water withdrawals is minimal during periods of low streamflow.

From analysis of flow duration curves it is estimated that 70 mgd of water could be developed in the half of the Tract above the gaging stations on the Mullica and Batsto Rivers while permitting minimum flows at the gaging stations equal to the historical mean annual 7-day consecutive low flow (21.5 mgd in the Mullica River and 35.5 mgd in the Batsto River). The quantity of water available from the entire Tract is tentatively estimated to be 150 mgd, if developed as a ground water-surface water system that contains no additional surface-water storage facilities. More water could be safely developed by augmentation of low streamflow from ground-water pumpage.

Greater development of the water resources of the Mullica River basin can probably be achieved through construction of a tide barrier at or near the Garden State Parkway. The barrier would create a fresh-water lake which would cover an area practically equal to that now covered by normal high tide. The Fresh-water lake would also have recreational value.

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TABLES

TABLE 1.—Percentage of wetland and open-water areas in parts of the Mullica River Basin

Drainage basin	*Drainage area (sq mi)*	*Wetland and open-water areas (sq mi)*	*Wetland and open-water areas (percent)*	*Data source*
Batsto River above Batsto, N.J.	70.5	12.9	18.3	Thomas (1964, p.8)
Oswego River at Harrisville, N.J.	64.0	9.5	14.8	Thomas (1964, p.8)
Mullica River above gaging station about 2 mi NW of Batsto	46.1	12.9	28.0	This report
Nescocheague Creek	41.5	8.4	20.2	This report
Sleeper Branch	36.2	8.9	24.6	This report
Total	258.3	52.6	20.4	
Mullica River above salt-water tide at Lower Bank, N.J.[1]/	489.8	112.3	22.9	This report

[1]/Includes all basins listed in table.

TABLE 2.—Average monthly and annual precipitation and temperature at Indian Mills and Hammonton, N.J., (1931-60).

Data from U.S. Weather Bureau

U.S. Weather Bureau Station or Division	*Precipitation, in inches*												
	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Annual*
Indian Mills	3.62	3.11	4.28	3.42	3.88	3.90	4.27	5.46	3.60	3.41	3.71	3.23	45.89
Hammonton	3.57	3.25	4.26	3.60	3.92	3.95	4.56	5.64	3.77	3.69	3.74	3.73	47.68
Average	3.60	3.18	4.27	3.51	3.90	3.92	4.42	5.55	3.68	3.55	3.72	3.48	46.78

	Temperature, in degrees Fahrenheit												
	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Annual*
Indian Mills	33.3	33.8	40.7	51.4	62.0	70.2	74.7	72.9	66.3	55.9	45.2	34.8	53.4
Hammonton	34.2	34.5	41.9	52.3	62.7	71.6	76.1	74.2	67.7	57.2	46.7	37.1	54.7
Average	33.8	34.2	41.3	51.8	62.4	70.9	75.4	73.6	67.0	56.6	46.0	36.0	54.1

TABLE 3.—Streamflow data for three gaging stations in the Mullica River basin

Stream	*Location*	*Period of Record Analyzed*	*Drainage Area (sq mi)*	*Minimum Annual Mean Discharge (mgd)*	*Minimum Annual Mean Discharge (inches)*	*Maximum Annual Mean Discharge (mgd)*	*Maximum Annual Mean Discharge (inches)*	*Mean Annual Discharge (mgd)*	*Mean Annual Discharge (inches)*
Mullica River near Batsto	Lat 39° 40′28″ Long. 74° 39′55″	October 1957 to September 1968	46.1	33 (1966)	14.8	108 (1958)	49.1	66	30.0
Batsto River at Batsto	Lat 39° 38′33″ Long 74° 39′00″	October 1927 to September 1967	70.5	43 (1966)	12.7	125 (1958)	37.1	81	24.2
Oswego River at Harrisville	Lat 39° 39′47″ Long 74° 31′26″	October 1930 to September 1967	64.0	27 (1966)	8.8	82 (1939)	26.9	55	18.2

TABLE 4.—Uppermost part of the stratigraphic section of the Coastal Plain in the Mullica River basin.

System	*Series*	*Formation*	*Lithology*	*Thickness (in feet)*	*Water-bearing properties*
Quaternary	Holocene	Undifferentiated deposits in stream channels, marshes, estuaries, and bays.	Clay, silt, sand, bog iron, and peat	0-10	Not suitable for water Supply. Generally low hydraulic conductivities and infiltration capacities.
		Unconformity			
	Pleistocene	Cape May Formation	Clay, silt, sand, and gravel	0-120	Highly permeable; Transmits water to underlying Cohansey Sand. Forms part of the Cohansey aquifer where it is below the water table.
		Unconformity			
		Pensauken Formation Unconformity Bridgeton Formation	Gravel, sand, and silt; some sand beds are indurated with iron oxide.	0-20	Transmit water to underlying Cohansey Sand; Not suitable for water supply.
		Unconformity			
Tertiary	Pliocene(?)	Beacon Hill Gravel	Sand and gravel	0-20	Transmits water to underlying Cohansey Sand; not suitable for water supply.
		Unconformity			
	Pliocene(?) and Miocene(?)	Cohansey Sand	Sand with gravel, silt, and clay.	25-200	Major aquifer. Transmissivity typically 10,000-20,000 sq ft per day (75,000-150,000 gpd per ft). Capable of yielding 1,000 gpm to individual wells.
		Unconformity			
	Miocene	Kirkwood Formation	Clay, silt, sand, and gravel.	50-450	In general, hydraulically connected to overlying Cohansey aquifer. Hydrologic properties unknown in the Mullica River basin but is a major aquifer along the coast.
		Unconformity			

TABLE 5.—Hydraulic characteristics of the Cohansey-upper Kirkwood aquifer system in New Jersey

Well No. (Figure 12)	Aquifer Test Location	County	Date of Test	Method of Evaluation	Hydraulic Conductivity (ft per day)	Hydraulic Conductivity (gpd per sq ft)	Transmissivity (ft^2 per day)	Transmissivity (gpd per ft)	Storage Coefficient
1	Clayton City well	Gloucester	11/9/56	Jacob semilog[1] This is a PRMWF	130	1,000	4,000	30,000	estimated initially at about 1.0 x 10^{-3}
1	Clayton City well	do.	8/7/57	do. THIS WELL IS DISTROYED	250	1,885	7,500	56,500	not determined
2	Williamstown Well No. 4	do.	11/12/51	do.	90	660	8,300	62,000	not determined
3	Well 18-V-Lebanon State Forest, N.J.	Burlington	8/4/58	Theim equilibrium[2]	120 (average of 20 values)	880	12,000 (average of 20 values)	88,000	not determined unconfined
4	Paulaitis Farm	Salem	Nov. 1959	Theis non-equilibrium[3] Hantush and Jacob non steady leaky[4]	150	1,100	4,300	32,000	3 x 10^{-4}(initial value)
5	Wharton Tract 2.5 mi nw of Batsto	Atlantic Burlington	June 1961	Theis equilibrium[3]	130	1,000	20,000	150,000	0.16[5]
6	1 mi N of Brotmanville	Salem	1966	Theis non-equilibrium[3]	150	1,130	20,000	150,000	4.4 x 10^{-2}
7	Toms River Chem. Co., Toms River	Ocean	Jan. 1956	do.	140	1,050	3,800	28,400	not determined unconfined
8	Vineland	Cumberland	1963-1964	Thiem equilibrium[2]	170	1,300	10,000	77,000	not determined
9	Linwood Country Club, Linwood	Atlantic	4/22/53	Theis non-equilibrium[3] and Jacob Semilog[1]	130 (average value)	1,000	16,000 (average value)	122,000	4.2 x 10^{-4} (average value)
	Vineland Chemical	Cumberland	1986	Theis Cooper Jacob			9050 10500		4.0 x 10^{-4} 3.4 x 10^{-4}

[1]/Jacob, C.E., (1950)
[2]/Thiem (1906)
[3]/Theis (1935)
[4]/Hantush and Jacob (1955)
[5]/Ramsahoye and Lang (1961)

TABLE 6.—Data for Cohansey Sand core samples from Test Well 4-H in the Wharton Tract

Sample depth interval (feet)	*Hydraulic conductivity (ft/day)*	*(gpd/ft²)*	*Lithologic Description*
82.0 - 82.3	13	97	Sandy clay, yellow color
83.3 - 83.6	6.4	48	Sandy clay, yellow color
84.25- 84.75	.05	0.4	Cohansey clay, plastic
85.64- 86.0	3.3	25	Very fine clayey sand, pale yellowish orange color
86.0 - 86.3	.4	3	Very fine sand, clayey, pale yellowish orange color
86.4 - 86.7	8.7	65	Fine to medium clayey sand, pale yellowish orange color
87.5 - 88.0	6.8	51	Very fine to medium sand, pale grayish yellow color
88.35- 88.68	51	380	Medium sand, light yellowish gray color
89.5 - 89.8	.7	5	Gray plastic clay laminae and sand stringers
90.8 - 91.0	3.9	29	Poorly sorted, clayey medium sand, light yellowish gray color
95.25- 95.5	1.1	8	Very fine sand, very silty and clayey, pale yellowish orange
96.4 - 96.6	.3	2	Sandy clay layer, light gray color
97.7 - 98.0	.5	4	Sandy clay layer, light gray color
100.25-100.55	11	79	Medium sand, somewhat silty, dark grayish brown color
102.3 -102.8	75	560	Well sorted, fine to medium, beach sand, pale grayish yellow color
103.25-103.75	67	500	Well sorted fine to medium beach sand, pale grayish yellow color

TABLE 7.— Selected data from wells tapping the Cohansey Sand — upper Kirkwood Aquifer in New Jersey

Well diameter (inches)	*Well yield (gpm)*	*Specific Capacity (gpm per ft of drawdown)*	*Length of screen (in feet)*	*Location*
6	50	5	10	Lebanon State Forest Saw Mill Site, Burlington County
6	150	6.7	10	Middle Branch Basin in Lebanon State Forest, Burlington County.
8-6	240	3.2	20	Amatol Tract, near Elwood[1], Atlantic County.
10	770	48.1	30	Seabrook Farms Well, Cumberland County.
12	1,025	46.6	24.0	Seabrook Farms Well, Cumberland County.
12	920	57.5	24.5	Seabrook Farms Well, Cumberland County.
12	960	18.1	21	Seabrook Farms Well, Cumberland County.
12	1,070	18.8	25	Seabrook Farms Well, Cumberland County.
12	1,190	21.6	25	Seabrook Farms Well, Cumberland County.
12	1,130	14.7	26	Seabrook Farms Well, Cumberland County.
12	1,009	21.8	20	Wharton Tract Pumping
	1,400	21.5		Test Site, near Batsto
12	2,000	41.7	132	Whitesbog, N.J., Burlington County
17	1,089	121.0	120	Hog Wallow near Chatsworth, N.J.

[1]/This is a very old well; though screen is not plugged it is probably less efficient than modern well screens.

TABLE 8.– Chloride concentrations in the Mullica River at high tide, December 20, 1957.

Mean Daily Discharge (cfs)	*Sample Location*	*Chloride (mg/l)*	*Remarks*
Batsto River at Batsto 648	Bridge at Lower Bank, New Jersey	1,520	Composite sample in 12-ft channel depth
		1,580	Bottom sample indicating no salt-water wedge, but tidal mixing
	Bridge at Green Bank, New Jersey (2.8 miles upstream from Bridge at Lower Bank)	66	Composite sample through depth of channel water
		74	Bottom sample indicating no salt-water wedge but tidal mixing