Ground-Water Resources of Southern New Castle County Delaware

By D. R. RIMA, O. J. COSKERY, *and* P. W. ANDERSON

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By D. R. Rima, O. J. Coskery, and P. W. Anderson

ABSTRACT

Southern New Castle County has a land area of 190 square miles in north-central Delaware. It is predominantly a rural area with a population of about 9,500 people who are engaged chiefly in agriculture. By and large, the residents are dependent upon ground water as a source of potable water. This investigation was made to provide knowledge of the availability and quality of the ground-water supply to aid future development.

The climate, surface features, and geology of the area are favorable for the occurrence of ground water. Temperatures are generally mild and precipitation is normally abundant and fairly evenly distributed throughout the year. The topography of the area is relatively flat and, hence, the streams have low gradients. The surface is underlain to a considerable depth by highly permeable unconsolidated sediments that range in age from Early Cretaceous to Recent.

Nearly all the subsurface stratigraphic units yield some water to wells, but only four parts or combinations of these units are sufficiently permeable to yield large supplies. These are, from oldest to youngest, the nonmarine Cretaceous sediments and the Magothy Formation, the Monmouth Group, the Rancocas Formation, and the surficial terrace and valley-fill deposits. In the northern part of the area the nonmarine Cretaceous sediments and the Magothy Formation can be reached economically by wells. Yields in excess of 300 gpm (gallons per minute) have been obtained from wells screened in this aquifer, but the maximum productivity of the aquifer has not been tested. The Monmouth Group is used as a source of water in the central part of the area, where some wells yield as much as 125 gpm. The Rancocas Formation is the principal aquifer in the southern part of the area. Yields of 200–400 gpm can be expected from this aquifer, owing to its uniformly coarse texture, particularly in the upper part of the formation. The terrace deposits compose the shallow water-table aquifer throughout the area. In places the water-table aquifer is connected hydraulically to each of the other three aquifers. The yields of wells tapping this aquifer are generally small, because the saturated thickness of the aquifer is small. The aquifer does provide a convenient and economical source of water for domestic supplies, and the quality of the available water supply is generally satisfactory for most purposes.

The use of water in the area was estimated to be about 1.77 million gallons per day in 1959. Rural uses amounted to about 75 percent of the total, and municipal and industrial uses accounted for the remainder. Water for irrigation of crops constituted about half of the water pumped for rural use.

The total use of ground water in the area is a mere fraction of the supply available. Each of the four major aquifers is capable of vastly increased production. Future development, however, will be limited by the changes in the

quality of the water resulting from the future pumping regimen and the expanded pattern of development. Salt-water encroachment will become a problem in the eastern part of the area if steps are not taken to avoid it.

INTRODUCTION

This report summarizes the results of an investigation of the occurrence of ground water in southern New Castle County, Del. The investigation was made by the U.S. Geological Survey in cooperation with the Delaware Geological Survey as part of a Federal-State program of water-resources investigations.

LOCATION AND EXTENT OF THE AREA

As used in this report, southern New Castle County refers to the part of New Castle County, Del., lying south of the Chesapeake and Delaware Canal (fig. 1). It has a land area of about 190 square miles in the north-central part of Delaware. The area is bounded on the north by the Chesapeake and Delaware Canal and on the east by the Delaware River and Bay. The southern boundary is formed by the New Castle-Kent County line, and the western boundary coincides with the Delaware-Maryland State line. The area is bordered on three sides by bodies of surface water. Although the shorelines of these water bodies are irregular, the shape of the area conforms roughly to a rectangle with the longest dimension, about 16 miles, oriented in a north-south direction.

According to the 1960 census, southern New Castle County has a population of about 9,500 persons. About 60–70 percent of the people lives and works in rural areas. The remainder lives in small communities that serve mainly as trading centers for the rural population. A few light industries are located within the area, and recent zoning changes favoring heavier industries indicate that a considerable expansion of industrial activity can be expected in the future.

PURPOSE AND SCOPE OF THE INVESTIGATION

Residents of southern New Castle County are virtually dependent upon wells for their supply of fresh water. Although little difficulty has been experienced in meeting the modest requirements of individual domestic supplies, the growing demand for industrial, municipal, and irrigation water supplies and the accompanying increase in the cost of development have signaled the need for a systematic appraisal of the area's ground-water resources. The lack of such knowledge may severly handicap future attempts by large water users to locate and develop adequate supplies of fresh water. Without adequate water

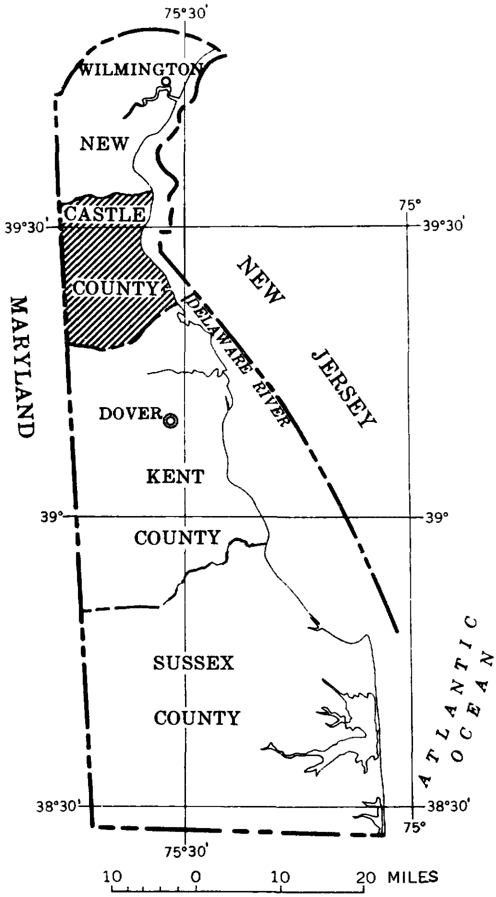

FIGURE 1.—Index map showing location of area described in this report.

supplies, economic growth and prosperity are virtually impossible. Thus, knowledge of the availability and quality of ground water is a critical factor in the future development of the area.

The purpose of the investigation described in this report was to obtain basic knowledge about the complexities of the occurrence of ground water in southern New Castle County. Attention was focused on the ground-water reservoirs capable of yielding enough water to satisfy the needs of industries, municipalities, and irrigation systems. During the initial phase of the investigation about 500 wells were inventoried to obtain pertinent geologic and hydrologic information. These data are the basis for most of the interpretations and for the conclusions presented in this report. In addition, three pumping tests were made to evaluate the hydraulic character of some of the reservoirs, and samples of water were collected from 23 selected wells and were analyzed to determine the chemical character of the water from each of the major ground-water reservoirs.

PREVIOUS INVESTIGATIONS

The earliest references to the occurrence of ground water in southern New Castle County is contained in the Annual Reports of the State Geologist of New Jersey for the years 1896, 1898, and 1901 (Woolman, 1897, 1899, and 1902). These reports contain records of the municipal wells that were drilled at Middletown, Del., near the turn of the century. A few years later, a brief discussion of the availability of ground water at Middletown appeared in the Dover folio of the Geologic Atlas of the United States (Miller, 1906, p. 10).

In 1955, a preliminary study of the ground-water resources of Delaware was made by Marine and Rasmussen (1955). Their report contains a brief account of the ground-water conditions in New Castle County and discusses the availability of ground water in the larger communities, including St. Georges, Middletown, and Odessa, which are located within the area discussed in this report.

In 1958, additional references to the occurrence of ground water in southern New Castle County were included in a report on the ground-water resources of the lower Delaware River Basin by Barksdale, Greenman, and others (1958). In the same year Rasmussen and others (1958) reported upon observations of chloride concentrations and water levels in the aquifers that cross the Chesapeake and Delaware Canal.

Several reports on the hydrology of areas adjacent to southern New Castle County also have been most helpful in the present study.

ACKNOWLEDGMENTS

The writers wish to express their sincere appreciation to the many well owners in the area for their assistance and cooperation in the assembly of the individual well records on which this report is based. Acknowledgment is due also to the water-well contractors who generously contributed much useful geologic and hydrologic information in the form of well logs and pumping data on the wells in the area. Special thanks are due to the cooperating agency, the Delaware Geological Survey, for making available copies of electrical and gamma-ray logs of several wells in the area and to the officials of Middletown, Del., including Mr. Toby Burris, waterworks superintendent, who permitted the use of the municipal wells for pumping tests.

WELL-NUMBERING SYSTEM

To facilitate the numbering of wells in Delaware, the State is divided into 5-minute quadrangles of latitude and longitude. As shown in figure 2, the quadrangles are lettered north to south with capital letters and west to east with lowercase letters. Each 5-minute quadrangle is further subdivided into twenty-five 1-minute blocks which are numbered from north to south in series of tens from 10 to 50 and from west to east in units from 1 to 5. (See fig. 2.) Wells within these 1-minute blocks are assigned serial numbers as they are scheduled. Thus, the identity of a well is established by prefixing the serial number with an upper- and lowercase letter followed by two numbers to designate the 5-minute and 1-minute blocks, respectively, in which the well is located. For example, well number Gd34-2, is the second well to be scheduled in the 1-minute block which has the coordinates "Gd34."

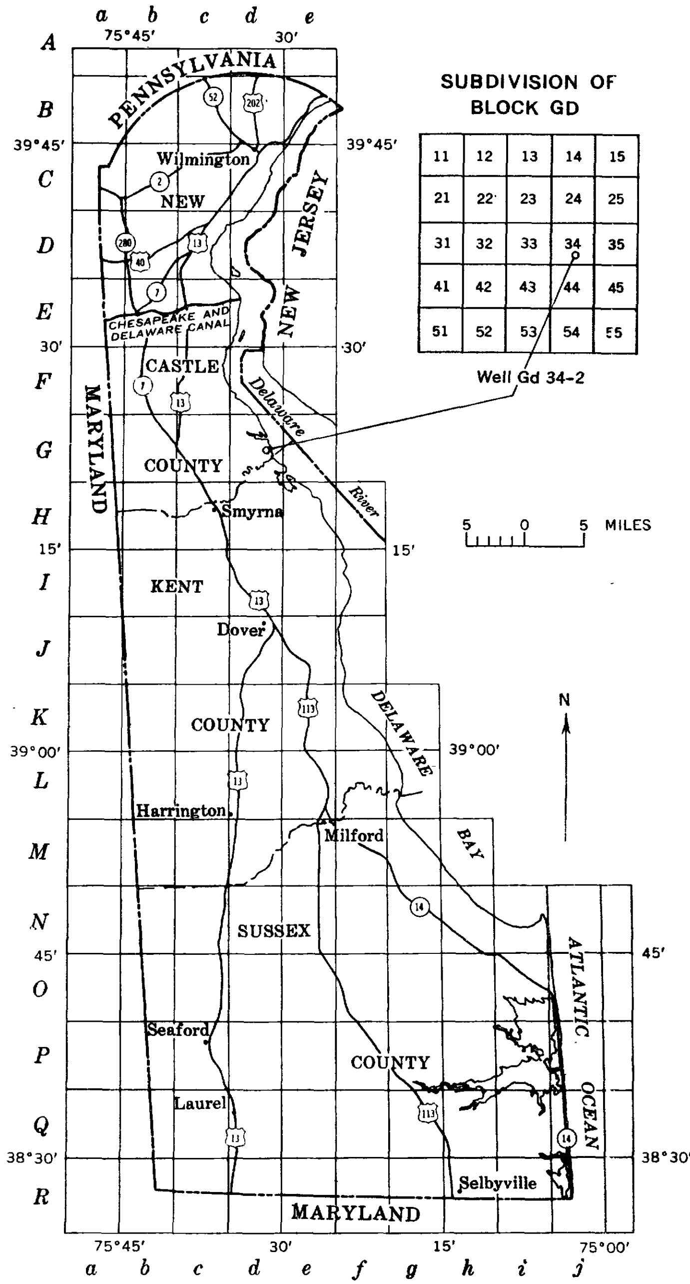

FIGURE 2.—Map showing the coordinates for the well-numbering system.

GENERAL FEATURES OF THE AREA

CLIMATE

The climate of southern New Castle County is relatively mild and humid owing to the proximity of the area to the Alantic Ocean. Winters are characteristically short and have abundant sunshine and a few light snowfalls; summers are warm and moist and precipitation is generally abundant and evenly distributed throughout the year. The growing season is exceptionally long in comparison with those of areas at similar latitudes.

The climate of southern New Castle County is described in detail in the published records of the U.S. Weather Bureau, which has maintained a network of weather stations in Delaware since 1895. The first weather station to be established in the area of this report, however, is the one at Middletown, Del., which was established in 1952. Therefore, much of the ensuing discussion is based on a comparison of the Middletown data with statewide averages.

In an average year, precipitation in appreciable amounts occurs on 7–10 days each month and 105 days during the year. The total amount of precipitation averages 46.2 inches per year for the State of Delaware as a whole, but at Middletown, Del., the average annual precipitation is only 40.9 inches. The statewide and the Middletown data show August to be the wettest month and January or February to be the driest. Precipitation, however, generally occurs more frequently from January through June than it does from July through December. This apparent discrepancy is explained by the fact that the intense storms of late summer and early fall actually deliver more water to the area than do the gentle winter and spring rains, but the latter are more frequent.

The mean annual temperature at Middletown, Del., is 55.0°F as compared with the statewide average of 55.5°F. The average monthly temperature at Middletown ranges from a low of 32.5°F in January to a high of 77.2°F in July. As a rule, temperatures in the vicinity of Middletown remain above freezing and, hence, are favorable for high rates of evaporation and for the growth of plants from mid-April to late October. Thus, the period of substantial water loss to the atmosphere by evaporation and transpiration is about 200 days each year, leaving about 165 days in which water losses to the atmosphere are minimal.

The secular cycles of precipitation and temperature are evident from the statewide data plotted in figure 3. The longest dry spell on record (9 years) began in 1908 and lasted until 1917. This drought period was offset by an 8-year period of above-average precipitation in the 1930's. Secular deviations of temperature appear to be shorter and less severe than those for precipitation.

TOPOGRAPHY AND DRAINAGE

Southern New Castle County is within the embayed section of the Atlantic Coastal Plain physiographic province (Fenneman, 1938, p. 13). As illustrated in figure 4, it occupies the northern part of the Delmarva[1] Peninsula, an elongated land mass that separates the Delaware River and Bay on the east from the Chesapeake Bay on the west. As is characteristic of areas in the Coastal Plain, the surface of southern New Castle County is relatively flat. For purposes of discussion, however, the area can be subdivided into two topographic units, or subareas—namely, a coastal lowland and an inland plain.

The coastal lowland forms a narrow belt, 2–5 miles wide, adjacent to the Delaware estuary. It is characterized by extensive tidal marshes which provide an excellent habitat for wildlife. The tidal marshes rarely rise more than 5 feet above sea level. They are separated by relatively narrow projections or "necks" of land that rise 10–20 feet above the level of the marshes. With few exceptions, the necks extend entirely across the lowland belt and form excellent beaches where they abut against the shore of the Delaware estuary.

The inland plain lies west of the coastal lowland belt and extends throughout the remainder of the report area. The boundary between these two physiographic units is marked by a fairly abrupt rise in the general level of the land surface from 25 feet or less above sea level to over 50 feet above sea level. Generally, the zone of transition from one level to the other occurs within a distance of less than 1,000 feet, but it broadens to almost half a mile in a few places.

The inland plain constitutes the heartland, or core, of the Delmarva Peninsula. In many respects, it resembles a fluvial terrace. The characteristic surface features of this section include the following: Relatively broad, flat interstream areas that appear to be the remnants of a former terrace or upland surface; narrow, deeply incised valleys formed by the headward erosion of the major streams draining the area; and many small, undrained depressions in the upland areas that are called "Carolina Bays" (Cooke, 1940, 1943). In the report area the surfaces of the broad interstream areas slope gently to the east from an average altitude of about 75 feet above sea level near the western margin of the area to about 50 feet above sea level along the eastern edge of the inland plain adjacent to the coastal lowland.

[1] Name derived from the three States—Delaware, Maryland, and Virginia—among which the peninsula is divided.

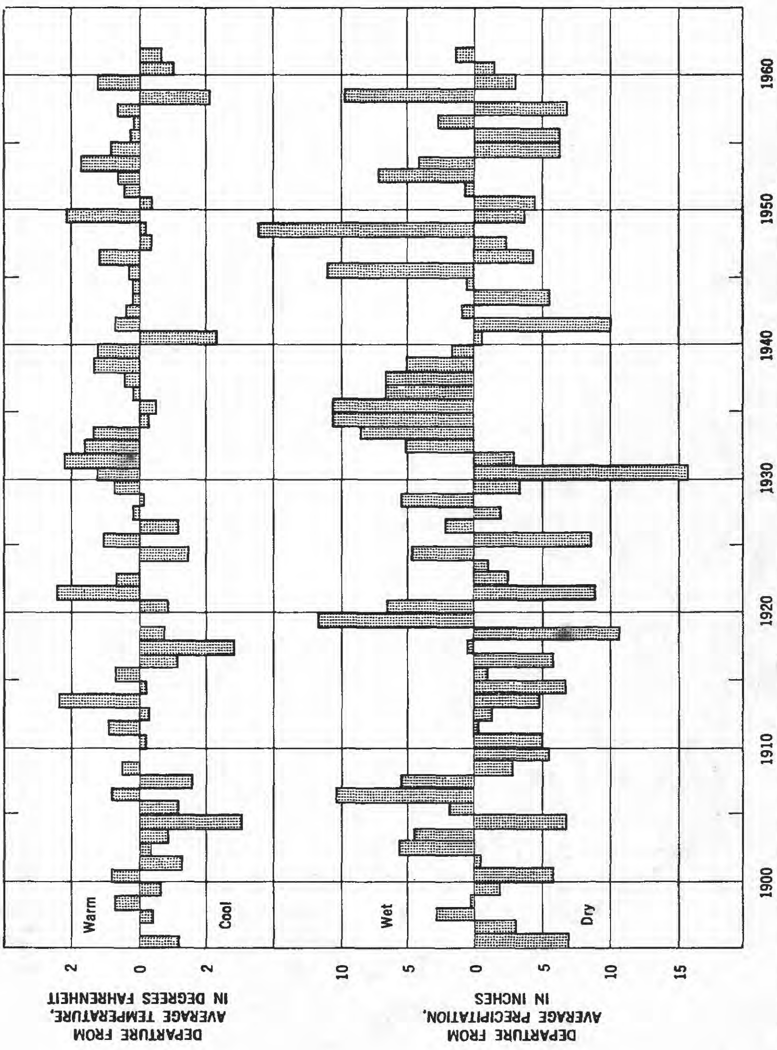

FIGURE 3.—Graph showing the annual departures of precipitation and temperature from the long-term average for the State of Delaware.

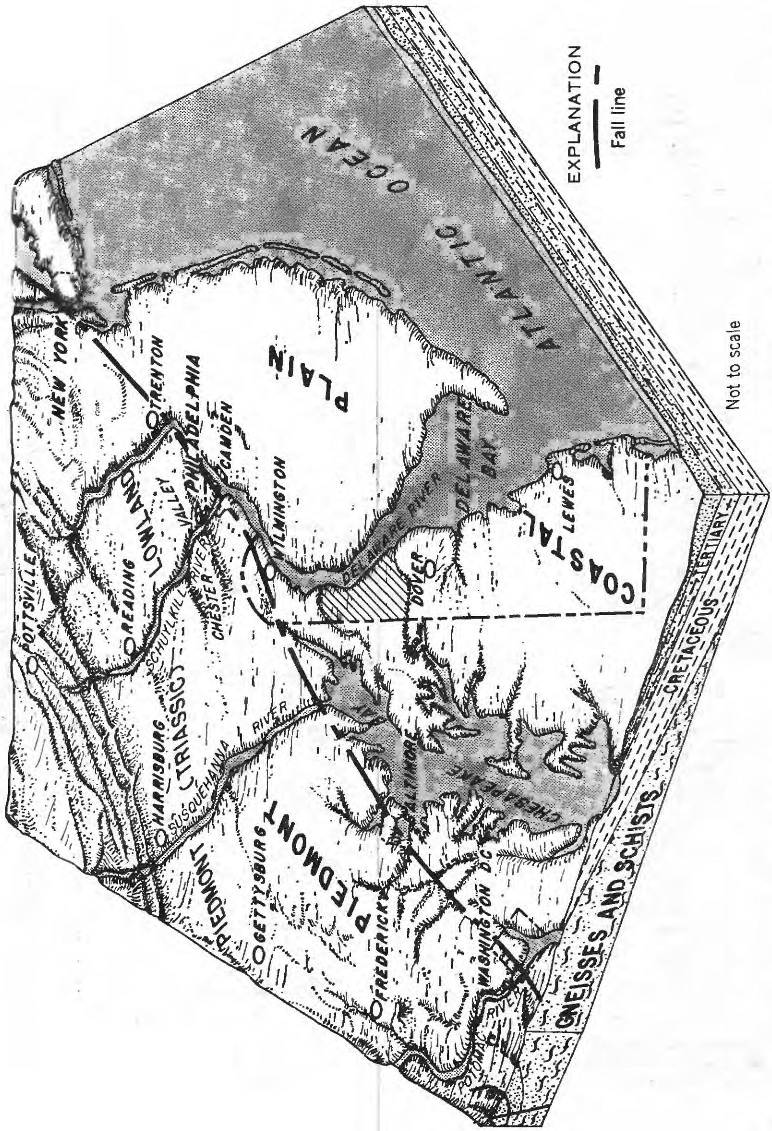

FIGURE 4.—Block diagram showing the physiographic environment of the area described in this report. Adapted after Johnson, Bascom, and Sharp (1933); Rasmussen (1957); and Raisz (1939). Not to scale.

Surface drainage in southern New Castle County is divided into two major components, as follows: (1) A system of eastward flowing tributaries to the Delaware estuary and (2) a system of westward flowing tributaries to Chesapeake Bay. Most of the area is drained by the system of tributaries to the Delaware River. The principal streams in this system from north to south are Drawyers Creek, Appoquinimink Creek, Blackbird Creek, and the Smyrna River. These streams rise in the western part of the report area and are joined by many small branches that form a dendritic pattern. The major streams have relatively steep gradients (20–30 feet per mile) and little or no flood plains near their headwaters. Downstream, the gradients decrease to less than 10 feet per mile, and the streams meander across an ever-widening flood plain. Where the streams enter the coastal lowland, their flood plains merge with the broad coastal marshes.

A narrow belt, generally less than 3 miles wide, along the western margin of the report area is drained by the system of westward-flowing tributaries to Chesapeake Bay. The named headwater streams in this system include (from north to south) Back Creek, Great Bohemia Creek, and the Cypress Branch Chester River. As these streams constitute the headwaters of the Chesapeake drainage system, their features are similar to those of the headwater streams in the Delaware system.

GEOLOGY

Southern New Castle County is underlain by a thick sequence of unconsolidated sediments, which rest unconformably upon a basement complex of ancient crystalline rocks. Little is known about the basement rocks in southern New Castle County, except that they are continuous with and, thus, closely related to the rocks of the neighboring Piedmont province. Studies made in that area reveal that these rocks consist of highly metamorphosed sedimentary and igneous rocks that range in age from Precambrian to early Paleozoic. A number of rock types have been recognized—including gneiss, schist, marble, gabbro, diorite, and granodiorite. Although these rocks differ greatly in their origin and mineralogic character, all are dense, hard, massive, and—in their unaltered state—impervious. Therefore, the upper surface of the basement complex represents, for all practical purposes, the lower limit of occurrence of water-bearing zones in southern New Castle County.

The unconsolidated sediments consist of alternating beds or sheetlike deposits of clay, silt, sand, and gravel that were laid down during the Cretaceous, Tertiary, and Quaternary periods of geologic time. In general, the beds dip gently toward the southeast. The oldest; or lowermost, beds have the greatest slope (about 100 feet per mile), and the youngest have the least (less than 10 feet per mile). Regionally, the unconsolidated sediments compose a wedge-shaped mass that thickens in the direction of the Atlantic Ocean. This characteristic structure is shown schematically along the southwestern margin of the block diagram in figure 4.

Within the report area the sequence and character of the unconsolidated sediments are fairly well known from many well logs and a few scattered surface exposures. The total thickness of these sediments ranges from about 400 feet in the northwestern corner of the area to about 2,500 feet along the southeastern margin. Over half of the total thickness of the unconsolidated sediments in the area is made up of nonmarine sediments of Early and Late Cretaceous age. These sediments represent a series of overlapping and coalescing deltas or alluvial fans that were deposited in a near-shore environment by rivers laden with sediment from the erosion of the nearby Piedmont province. Coarse-grained sediments (sand and gravel) were deposited in the river channels, while fine-grained materials (clay and silt) accumulated on the flood plains and in swampy backwater areas. Doubtless, the migration, or shifting of the position, of the river channels account for the abrupt changes in the character of the sediments both vertically and horizontally.

The nonmarine sediments are overlain by marine sediments of Late Cretaceous, Paleocene, Eocene, and Miocene age. The marine sediments are characterized by a series of thin sheetlike deposits of sand, silt, and clay that are fairly uniform over wide areas. The thickness of the marine sediments increases from about 10 feet in the extreme northeastern corner of the area to nearly 800 feet beneath the Smyrna River, which forms the southeastern margin of the area. The lowermost marine sediments are well exposed in the banks of the Chesapeake and Delaware Canal, and the younger formations are exposed successively in the major stream valleys to the south.

The youngest sediments in the area, those of the Quaternary System, constitute a small but significant part of the total thickness of the unconsolidated sediments. They include stream-terrace and valley-fill deposits of Pleistocene age and eolian and alluvial deposits of Recent age. In general, these deposits occur as a thin veneer covering the older sediments.

The age, thickness, and lithology of each of the stratigraphic units that have been recognized in the subsurface of southern New Castle County are summarized in table 1. The nonmenclature differs slightly from that used in some previous reports in that the Matawan and Monmouth Groups of Late Cretaceous age are not differentiated into formations and the lowermost unit of the Tertiary System is designated the Rancocas Formation instead of Aquia Greensand. The correlation of these units with equivalent subdivisions in Maryland and New Jersey, however, is shown on plate 1, a geologic section from Woodstown, N.J., to Fredericktown, Md. The stratigraphic interpretation of the well in Maryland was taken from a report by Overbeck and Slaughter (1958, p. 368) and the interpretation for the wells in New Jersey was obtained from J. C. Rosenau (U.S. Geol. Survey, written communication).

TABLE 1.—*Subsurface stratigraphic table for southern New Castle County, Del.*

Era	Time-rock units: System	Time-rock units: Series	Rocks units	Thickness (feet)	Lithologic character
Cenozoic	Quaternary	Recent	Alluvial and eolian(?) deposits (undifferentiated)	0–50	Dark-gray carbonaceous silt and fine white sand in proximity to tidal marshes and estuaries.
		Pleistocene	Terrace and velley-fill deposits (undifferentiated)	?	Pale- to dark-yellowish-orange poorly to well-sorted gravel, sand, silt, and clay on broad alluvial terraces and in filled valleys.
			Unconformity		
	Tertiary	Miocene	Calvert Formation	0–125	Gray, blue, green, and brown silt and clay containing a few thin interbeds of yellow- to orange-colored fine- to medium-grained sand.
			Unconformity		
		Eocene	Nanjemoy Formation	0–90	Greenish-gray to black silty sand and clayey silt. Very glauconitic and moderately fossiliferous. Grades downward into underlying greensand.
		Eocene and Paleocene	Rancocas Formation	0–165	Chiefly fine- to coarse-grained, green and white sand with varying amounts of glauconite. Slightly fossiliferous. Lower part consists of a limy highly fossiliferous sand with numerous indurated beds and light-gray to dark-green glauconitic sand, silt, and clay.
			Unconformity		
Mesozoic	Cretaceous	Upper	Monmouth Group (undifferentiated)	0–120	Gray to black clayey silt and silty sand, grading downward into greenish-gray to yellowish-brown medium- to coarse-grained glauconitic and quartzose sand. Numerous beds of partially cemented sandstone. Highly fossiliferous near the top.
			Matawan Group (undifferentiated)	0–185	Upper part consists of dark-gray to black micaceous sandy and clayey silt. Middle part consists of greenish-gray fine-grained micaceous silty sand. Lower part consists of dark-gray to green micaceous glauconitic silt and clay with minor beds of sand. Fossiliferous and, in places, lignitic.
			Magothy Formation	10–80	White fine- to coarse-grained sugary sand and very dark-gray carbonaceous silty clay.
			Unconformity		
		Upper and Lower	Nonmarine Cretaceous sediments (undifferentiated)	400–1,700	Chiefly red and gray variegated tough silt and clay containing lenses and stringers of light-gray to yellowish-brown fine- to very coarse-grained quartz sand and gravel.

GROUND-WATER HYDROLOGY

Ground-water hydrology is the science that deals with the occurrence of water beneath the earth's crust. More specifically, it is concerned with the occurrence of ground water, or water beneath the land surface, that is free to move by gravity toward wells and springs. Considerable research has been done to establish and verify the physical laws and principles that govern the occurrence and movement of ground water. These basic concepts are described in detail by Meinzer (1923, 1949), Tolman (1937), and Todd (1959). A brief summary of the principles and concepts are repeated here to explain the technical terms used in subsequent sections of this report.

PRINCIPLES AND DEFINITIONS

The rock materials composing the earth's crust are generally not completely solid, as they contain numerous openings or voids, called **pores** or **interstices,** in which fluids and gases such as water or air can be stored. Where the openings are sufficiently large and interconnected, the fluids or gases that occupy the rock void can move readily from one opening to another; thus, the rocks of the earth's crust are said to be **porous** if they contain voids and **permeable** if the voids are sufficiently large and interconnected so that fluids or gases can move through them.

Water that falls on the land surface and filters through the surficial soil zone percolates downward through the underlying permeable rock materials until it reaches the **zone of saturation,** a zone in which all the interconnected pores are completely filled with water under hydrostatic pressure. The upper surface of the zone of saturation, where that surface is formed by permeable rocks, is called the **water table.** Immediately above the water table is the **capillary fringe,** a zone in which some or all the rock openings are filled with water that is continuous with the water in the zone of saturation but is held against the downward force of gravity by capillary attraction. Although the capillary fringe may be completely saturated with water, it is excluded from the zone of saturation because the water in the capillary fringe is not under hydrostatic pressure.

The water table has a configuration similar to, but with less relief than the land surface beneath which it occurs. The position of the water table in the subsurface is marked by the height to which water will rise in a well tapping the uppermost part of the zone of saturation where the surface of that zone is exposed to atmospheric pressure. Generally, the water table does not remain in a fixed position but fluctuates up and down in response to changes in the amount of water in storage in the zone of saturation. **Recharge,** or the addition of water to the zone of saturation, causes the water table to rise; conversely, **discharge,** or the removal of water from the zone of saturation, causes the water table to decline. Thus, fluctuations of the water table are indicative of the relative differences in the rates of recharge and discharge from place to place and from time to time.

The rock materials within the zone of saturation differ greatly in their physical character and, hence, in their capacity to store and transmit water. The capacity of a rock material to store water is determined by its **porosity,** the ratio of the aggregate volume of void space to the total volume of the rock expressed as a percentage. The capacity of a rock material to transmit water is controlled by its **permeability.** This capacity can be quantitatively defined as the rate of discharge of water through a unit cross-sectional area of the rock material at right angles to the direction of flow if the hydraulic gradient is unity. Porosity and permeability are not directly related properties. For example, clays and silts tend to have relatively high porosities (more than 40 percent) but very low permeabilities owing to the minute size of their interstices. In contrast, sands and gravels usually have modest porosities (about 20–40 percent), but they are many times more permeable than deposits of clay and silt.

Specific yield is the ratio of the amount of water that will drain from a saturated rock under the force of gravity to the total volume of the rock. It is expressed as a percentage and is always less than the rock porosity, because some water is always retained in the interstices of a rock against against the force of gravity. The volume of water that is retained, expressed as a percentage of the total rock volume, is called **specific retention.** Thus, the sum of the specific yield and the specific retention of a rock is equal to its porosity.

An **aquifer** or **ground-water reservoir** is a formation, a group of formations, or a part of a formation, within the zone of saturation, that is sufficiently permeable to transmit or yield usable quantities of water to wells. Formations or zones that are less permeable than adjacent aquifers are called **confining beds** because they tend to prevent or retard the movement of ground water. An aquifer in which the upper surface of the water is exposed to atmospheric pressure and is, thus, free to rise and fall in response to changes in the volume of water in storage is called a **water-table aquifer.** In contrast, the term **artesian** is applied to an aquifer in which the water is confined under a sufficient pressure to rise above the top of the aquifer but not necessarily above the land surface. The height to which water in an artesian aquifer will rise in tightly cased wells that tap the aquifer is called the **piezometric surface** of the aquifer.

HYDRAULIC PROPERTIES OF AQUIFERS

The hydraulic properities of an aquifer are expressed quantitatively by two coefficients, the coefficient of storage and the coefficient of transmissibility. The **coefficient of storage** of an aquifer is the volume of water that the aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to the surface. In water-table aquifers the coefficient of storage is virtually equal to the specific yield— that is, the drainable interconnected pore space. In artesian aquifers the coefficient of storage is related to the elastic properties of the aquifer skeleton and of the water itself and is much smaller than under water-table conditions. The **coefficient of transmissibility** is the number of gallons of water per day that will pass through a cross section of an aquifer 1 foot wide, extending the full saturated height of the aquifer, under a hydraulic gradient of 100 percent. It is equal to the coefficient of permeability (expressed in similar units) multiplied by the thickness of the aquifer. If the coefficient of storage and transmissibility are known, it is possible to determine the most desirable spacing of wells and the optimum pumping rate and to predict the effects of pumping on water levels.

Coefficients of transmissibility and storage are determined for an aquifer by measuring the effect of withdrawal of water from a well upon water levels in other wells tapping the same aquifer at known distances from the pumped well. Mathematical formulas by which these effects are analyzed were derived from the fundamental heat equations (Theis, 1935). Application of the formulas is based upon the following assumptions: (1) the aquifer is homogeneous, isotropic, and has infinite areal extent; (2) the discharge or recharge well penetrates and receives water from the entire thickness of the aquifer and has an infinitesimal diameter; (3) the coefficient of transmissibility is constant at all times and at all places; and (4) water removed from storage is discharged instantaneously with decline in head. If the aquifer being tested deviates substantially from these basic assumptions, the determinations of the coefficients of transmissibility and storage are invalid unless corrections for the deviations can be made.

QUALITY OF WATER

Adequate knowledge of the quality of water is of nearly equal importance to information on quantity and availability. Although most waters can be treated by specific methods to produce a water of desired quality, cost dictates the extent to which treatment is practicable. Thus, investigations on quality of water are often useful in evaluating the suitability of the water for domestic, industrial, and agricultural use and in determining the extent and effect of saline-water encroachment.

CHEMICAL AND PHYSICAL PROPERTIES

Water dissolves more substances than any other liquid. It is for this reason that ground water in its passage through the rocks of the earth's crust does not remain entirely pure. Generally, temperature, pressure, and duration of contact with the various rock types and soils determine the kind and amount of mineral constituents present in ground waters. Ground water, which is in intimate contact with the host rocks for long periods of time, is not only usually more concentrated but also more uniform in mineral content than surface water.

The following chemical and physical determinations were made on at least one water sample collected from each of the 23 wells sampled during this investigation: Silica, iron, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, carbonate and noncarbonate hardness, dissolved solids, specific conductance, pH, color, and temperature.

RELATION TO USE

Excessive concentrations of various constituents make ground water unusable for certain purposes. The following paragraphs contain descriptions of six selected constituents or properties of water and a brief discussion of their significance to water users.

HYDROGEN-ION CONCENTRATION (pH)

The term "pH" is used as a measure of the intensity, or degree, of acidity or alkalinity of water. Water having a pH of 7.0 is defined as neutral (above 7.0 as alkaline and below 7.0 as acidic). In general, shallow ground waters are slightly acidic (pH 5.5–6.5), owing to the presence of weak acids, principally carbonic acid, formed by solution of carbon dioxide in the atmosphere and soil.

DISSOLVED-SOLIDS CONTENT

Dissolved solids are a measure of the amount of dissolved mineral matter in the water. The maximum concentration, prior to treatment, recommended for most domestic uses is 500 ppm (parts per million). Industrial tolerances differ widely, but few industrial processes permit a maximum concentration of more than 1,000 ppm.

Dissolved-solids content is also an important consideration in the use of waters for irrigation. The water-uptake relations of plants are controlled by the osmotic-pressure differential between the soil solution and plant solution. A plant cannot draw as much water from a concentrated soil solution as it can from a dilute soil solution. For most waters that could be considered for irrigation, the following general relation is applicable:

$$\text{Dissolved solids} = \text{Specific conductance} \times 0.65 \pm 0.1$$

For ground water in southern New Castle County, the multiplication factor is usually 0.70 ± 0.02. The dissolved-solids hazard of irrigation waters has been classified by the U.S. Salinity Laboratory Staff, in terms of specific conductance, as:

	Micromhos		*Micromhos*
Low	<250	High	750–2,250
Medium	250–750	Very high	>2,250

IRON

Iron is dissolved from many soils and rocks, but it is usually found in greater concentrations in ground water than in surface water. When exposed to air, ferrous iron is oxidized to ferric iron and is precipitated as a reddish-yellow oxide. Ground waters that contain carbon dioxide will readily dissolve iron from rocks, sands, and soils to form a soluble ferrous carbonate.

Iron content does not usually make a water unsuitable for irrigation. In the washing and cleaning processes, however, water with more than a few tenths of a part per million of iron can cause a reddish-colored stain. Excessive iron in water is also troublesome to industrial users, because iron scale, or deposits formed by iron-reducing bacteria, may result in clogging of well screens, pipes, and industrial equipment.

Iron is usually removed by aeration and filtration, treatment with lime, passage through ion-exchange filters, or held in solution through the use of sequestering agents such as polyphosphates.

CHLORIDE

The chloride content of waters is attributed to natural mineral origin or to contamination by industrial and domestic wastes and sewage. When used for irrigation, water containing excessive amounts (as low as 100 ppm) is toxic to most plants. Chlorides catalyze corrosion of boilers, pipes, and fittings. Concentrations as low as 20 ppm have been reported to be corrosive.

The U.S. Public Health Service Drinking Water Standards (1962) recommends that the chloride content of water used for public supplies should not exceed 250 ppm.

NITRATE

In water, nitrogen may occur in several forms, depending on the level of oxidation. Nitrate, the completely oxidized state of nitrogen, is the principal form in most natural water. Soluble nitrogen compounds in plant debris, animal excrement, and inorganic nitrate fertilizers probably constitutes the major source of nitrate in ground water in the southern New Castle County area. Small but additional amounts of nitrate may be added to the ground water by seepage of industrial or domestic wastes. The U.S. Public Health Service (1962) recommends that nitrate concentration in excess of 45 ppm in water should not be consumed by infants. High nitrate content seems definitely to be associated with methemoglobinemia, a disease characterized by certain specific blood changes, and cyanosis, a condition in which the surface of the body becomes blue. (California Water Pollution Control Board 1952, p. 301).

HARDNESS

The term "hardness" refers to the ability of water to form an insoluble curd with soap. The curd is seen on fabric as a gray color. Hard water is also responsible for scale in boilers, pipes, fittings, and hot-water heaters.

"Carbonate," or "temporary," hardness in water is primarily due to calcium and magnesium bicarbonate. This type of hardness can be removed either by boiling or by treatment with lime. "Noncarbonate," or "permanent," hardness—primarily caused by other calcium and magnesium salts—cannot be removed by either boiling or by lime. It can be reduced, however, by treatment with lime and soda ash or by the use of cation-exchange resins. There is no difference between these two types of hardness in relation to the amount of soap required to form a lather, although a water containing noncarbonate hardness generally forms a harder scale in boilers than the carbonate type.

In the most frequently used classification, water that has a hardness of 60 ppm or less is considered "soft," 61–120 ppm is "moderately hard," 121–180 ppm is "hard," and more than 180 ppm is "very hard."

HYDROLOGIC CHARACTER OF THE PRINCIPAL AQUIFERS

The occurrence of ground water in any area is, in large measure, dependent upon the character and distribution of the underlying rock materials. In southern New Castle County the rock materials within economic reach of water wells consist of unconsolidated deposits of clay, silt, sand, or gravel. All of these materials are porous, owing to their detrital nature, but only the deposits of sand and gravel

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are sufficiently permeable to transmit usable quantities of water to wells.

Nearly all the stratigraphic units listed in table 1 will yield some water to wells because they contain some permeable zones, but only those that are composed predominantly of sand or gravel are capable of supporting the large yields of municipal, industrial, or irrigation wells. There are four such principal aquifers or reservoirs in the report area (pl. 2). These are, from oldest to youngest in geologic age, (1) the nonmarine Cretaceous sediments and the Magothy Formation, (2) the Monmouth Group, (3) the Rancocas Formation, and (4) the terrace and valley-fill deposits.

NONMARINE CRETACEOUS SEDIMENTS AND THE MAGOTHY FORMATION

Although the nonmarine Cretaceous sediments and the Magothy Formation are different lithologically, the permeable zones in these two stratigraphic units are not separated by a continuous confining bed. The absence of a continuous confining bed allows the free interchange of water through points or areas of mutual hydraulic connection, and, therefore, the combined interval has a common hydrostatic head and will yield eventually, if not immediately, a comparable quality of water to wells that are screened in either or both units. For this reason the combined stratigraphic interval is here considered as a single aquifer or ground-water reservoir. A similar interpretation has been applied to the equivalent stratigraphic interval in New Jersey (Barksdale, and others, 1958, p. 91).

In this report, the term "nonmarine Cretaceous sediments" is applied to the thick sequence of fluvial deposits that compose the oldest and largest part of the Cretaceous System of Delaware. (See table 1.) These deposits consist of tough variegated clays and silts that are interbedded with lenses and stringers of sand and gravel. They are continuous with and equivalent to the Potomac Group and the Raritan Formation of Maryland and New Jersey (Marine and Rasmussen, 1955, p. 42). They are not differentiated in Delaware, however, owing to the similarity of the lithology of the various formations (Spangler and Peterson, 1950, p. 21; Groot, 1955, p. 25–26). The Magothy Formation was named by Darton (1893, p. 407–419) for exposures of distinctive sands and clays along the Magothy River in Maryland. The name has since been applied to equivalent sediments in New Jersey and Delaware.

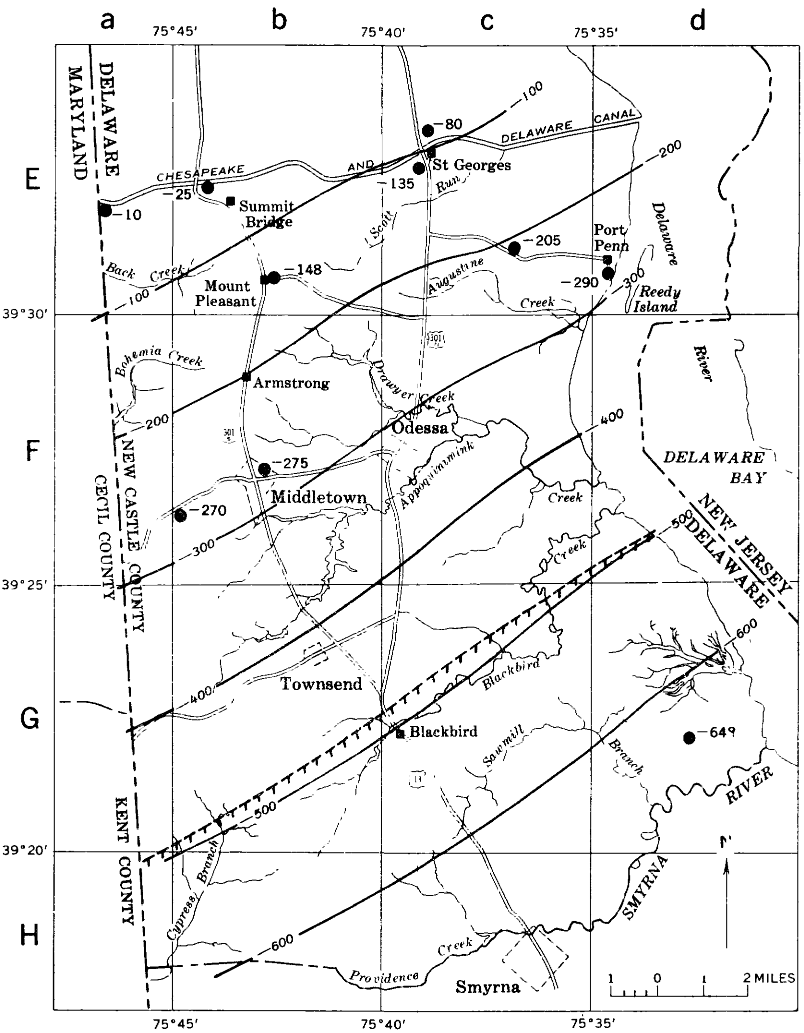
DISTRIBUTION AND THICKNESS

Both the nonmarine Cretaceous sediments and the Magothy Formation are exposed in their normal sequence in the banks of the Chesapeake and Delaware Canal beginning at a point about 2½ miles east of the Maryland-Delaware State line and continuing westward into Maryland. The nonmarine sediments are exposed also at many places along the major stream valleys north of the canal in northern New Castle County. South of the canal both stratigraphic units occur in the subsurface beneath younger sediments. The depth to the top of the nonmarine Cretaceous sediments is shown by means of contours in figure 5. A similar map of the Magothy Formation is given in figure 6. As the reference datum for the contour lines is sea level, the depth to which a well must be drilled to reach the top of either stratigraphic unit can be calculated easily by adding the altitude of the well site above sea level to the depth below sea level as indicated by the contours in figures 5 and 6. For example, to reach the top of the Magothy Formation (fig. 6) a well at Townsend (altitude 65 feet) would need to be drilled to a depth of 465 feet.

The combined thickness of the nonmarine sediments and the Magothy Formation increases from about 430 feet in the northwestern corner of the area to about 1,800 feet in the subsurface beneath the Smyrna River. Although both stratigraphic units thicken downdip, the Magothy Formation accounts for the least amount of the total increase in thickness. Along the canal, the thickness of the Magothy Formation ranges from about 10 to 30 feet. Downdip, the formation thickens gradually to about 35 feet in a well at Middletown and to 80 feet in a well near Smyrna. The remaining increase in thickness of about 1,300 feet is attributed to the nonmarine sediments. It is unlikely that mere enlargement of the beds present in the outcrop area could account for such a large increase in vertical thickness. A more tenable hypothesis is the addition of beds to the nonmarine sequence, either younger or older than those in the outcrop area.

LITHOLOGIC CHARACTER

The nonmarine sediments consist chiefly of light-gray, brown, or pink-tinted beds of clay, silt, and intermingled masses of white to yellow sand and gravel. The fine-grained materials are generally plastic and are rarely uniform in either texture or color. They generally contain admixtures of sand and, in places, lignitic material. The coarse-grained materials are poorly to well-sorted, crossbedded, and angular to subrounded. Locally, they are cemented by iron oxide, which forms hard crusts and pipelike concretions. In surface exposures, the texture of the sediments changes abruptly both horizontally and vertically. For example, within a few feet a bed of light-gray clay may grade laterally into a pink or brown clay or sandy silt or into a gravelly sand. The abrupt changes in lithology make it difficult to trace a single bed more than a few tens of feet.



EXPLANATION

Structure contour
Drawn on top of nonmarine Cretaceous sediments. Datum is mean sea level. Contour interval is 100 feet

Approximate position of interface between fresh and salt water

Well
Number indicates altitude of top of formation, in feet. Datum is mean sea level

FIGURE 5.—Map of lower New Castle County showing structure contours on top of the nonmarine Cretaceous sediments.

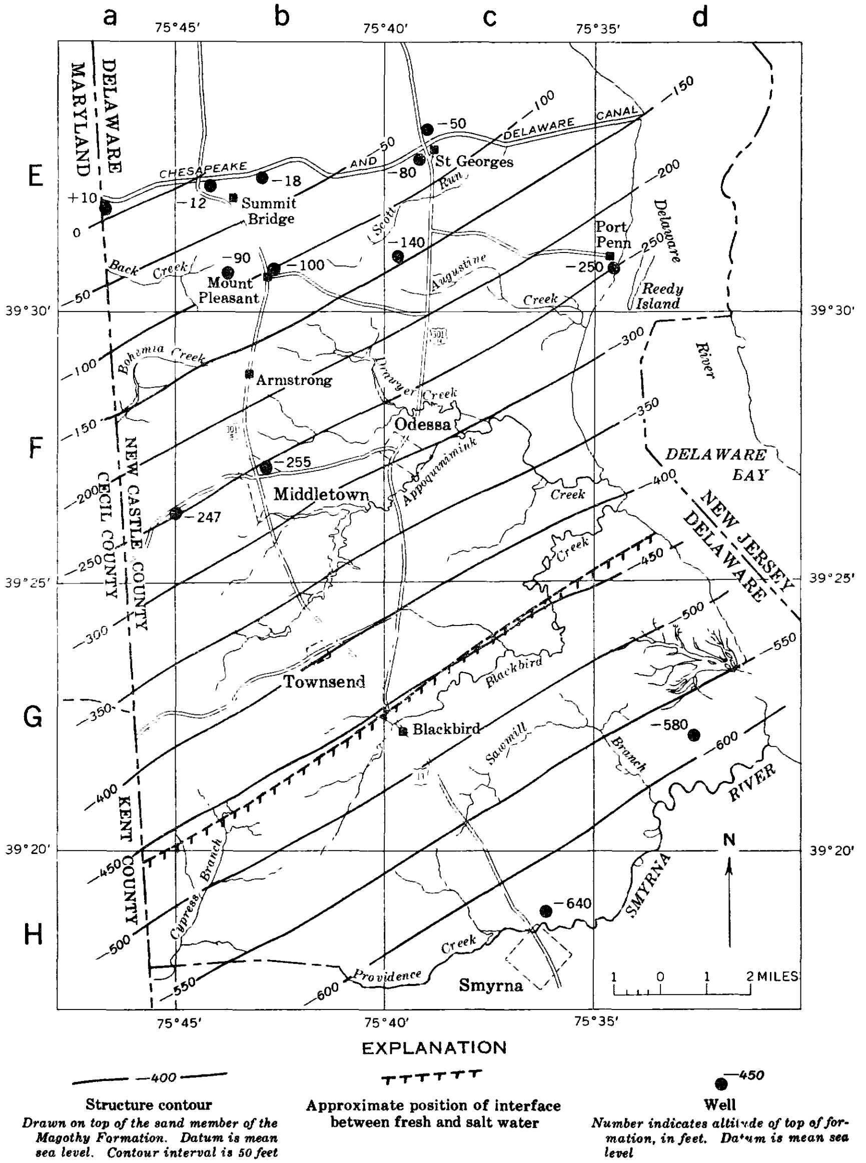


Figure 6.—Map of lower New Castle County showing structure contours on top of the sand member of the Magothy Formation.

The irregular nature of the sediments is evident in well logs such as those shown on plate 1. Throughout the nonmarine sequence, the logs of closely spaced wells show virtually no recognizable points of correlation, whereas the overlying sequence of predominantly marine sediments can be traced easily from one well to the next.

The Magothy Formation is composed of light-colored fine to coarse sands and dark-colored carbonaceous clays. In exposures along the Chesapeake and Delaware Canal, Carter (1937, p. 248–249) recognized three distinct members which he described as follows:

> The first and lowermost member is a fine, yellow, iron-stained to buff, micaceous, compact sand containing variable proportions of clay of the same color, plus additional small patches or lenses of black sticky clay up to 1 foot in length and 1 inch in thickness. This sand makes up an average of more than half the thickness of the Magothy formation throughout its extent of 3¼ miles along the canal. The second or middle member consists of white sand and clay. The bedding is very irregular for the sand may rapidly grade into clay within less than 3 inches of vertical thickness; it may gradually grade into the clay giving all proportions of admixed clay and sand; or it may be distinctly laminated and sharply interbedded with the clay. The sand of this member is most unique and differs so widely from all the other sands seen along the canal that it is recognizable at sight. It is coarse, sharp and "sugary" grained, and is composed largely of pure quartz with a small content of mica. The third or upper member is black clay also possessing characteristics that permit of its immediate recognition. It is dark blue to black, massive clay of sticky, slippery character, containing much lignitized plant material and some grains of amber. Near its top are to be found many very hard rounded and variously shaped masses of gray siderite up to 15 inches in length.

Downdip, the Magothy Formation is composed predominantly of fine- to medium-grained white "sugary" sand. The distinctive character and relative thinness of the Magothy Formation make it an excellent marker bed for subsurface correlation.

WATER-BEARING PROPERTIES

The difference between the lithologic character of the nonmarine sediments and the Magothy Formation are reflected in their water-bearing properties. The coarse-grained materials of the nonmarine sediments constitute an intricate network of highly permeable zones that are embedded in less permeable masses of clay or silt. Although the deposits of sand and gravel may appear to be disconnected or isolated when viewed in any two dimensions, their continuity in the third dimension is virtually certain owing to the continuous nature of their deposition as part of a widespread deltaic complex. For, as the individual deltas enlarged and the position of the river channels meandered or shifted from time to time across the front of the delta, abrupt changes might result in the type sediment being deposited locally, but the channels themselves would, of necessity, continue to exist and thereby continue to be the site of deposition of the coarsest sediments. In such an environment it would be a rare coincidence indeed if the new channel positions were not in some way connected to the old.

In contrast to the nonmarine sediments, the Magothy Formation contains a nearly continuous sheetlike deposit of permeable sand near the base of the formation. The sand member is interbedded locally with less permeable beds of dark-gray clay which become more extensive and more continuous toward the top of the formation. The texture of the sand ranges from fine to coarse, but it is generally uniform over fairly wide areas. This texture implies a rather uniform coefficient of permeability for the formation and, therefore, a relatively constant water-bearing capacity.

Additional insight into the water-bearing character of the nonmarine sediments and the Magothy Formation can be gained from available well data. The recorded yields of wells screened in the nonmarine sediments in the report area range from 15 to 300 gpm (gallons per minute), and those in the Magothy Formation range from 10 to 320 gpm. These data give the misleading impression that the productivity or water-bearing capacity of the sands in the two stratigraphic units are equal or nearly so. Actually, the yields of individual wells usually depend more upon the details of well construction than upon the productivity of the aquifer. A more reliable index to the relative productivity of an aquifer, however, is the specific capacity of a well, or the number of gallons of water produced for each foot of drawdown (lowering of the water level) in the well.

The relative specific capacities of eight wells screened in the nonmarine sediments and three wells screened in the Magothy Formation are shown in figure 7, a graph that shows the relation between yield and drawdown for each of the wells. The specific capacities of the wells are indicated by the slope of an imaginary line through the point representing the well and the origin of the graph—the steeper the slope of the imaginary line, the higher the specific capacity of the well. In general, the slopes of the imaginary lines through the points representing the wells screened in the Magothy Formation are less than those through the points representing the wells screened in the nonmarine sediments. Thus, the sands of the nonmarine sediments seem to be much more productive than those of the Magothy Formation.

During this investigation no pumping tests were made on wells screened in the nonmarine sediments, but a pumping test was made at Middletown, Del., to determine the hydraulic coefficients of the Magothy Formation. The wells used in this test are owned by the town of Middletown and are at the water plant on Lake Street. The results of the test showed the coefficient of storage (S) of the Magothy Formation to be 6×10^{-5}, well within the range of values for artesian aquifers, and the coefficient of transmissibility (T) to be 4,000 gpd (gallons per day) per ft. As the thickness of the water-bearing part of the Magothy Formation at Middletown is about 20 feet, the field coefficient of permeability (P) can be calculated by dividing the transmissibility of the aquifer by the thcikness of the water-yielding zone. The permeability so obtained is 200 gpd per sq ft.

From the calculated values of T and S, it is possible to prepare the time- and distance-drawdown graphs in figures 8 and 9. The time-drawdown graph (fig. 8) is used to determine the amount of drawdown that will occur in a well screened in an ideal aquifer having the hydraulic characteristics determined for the Magothy Formation after pumping the well at a specified rate for a given period of time. In turn, this information can be used to determine the maximum capacity of such a well and to design the most suitable pumping equipment for use on the well. The distance-drawdown graph (fig. 9) shows the effect of pumping with distance from the pumped well. This information is useful in determining the amount of interference between wells and, hence, the desirable spacing of production wells.

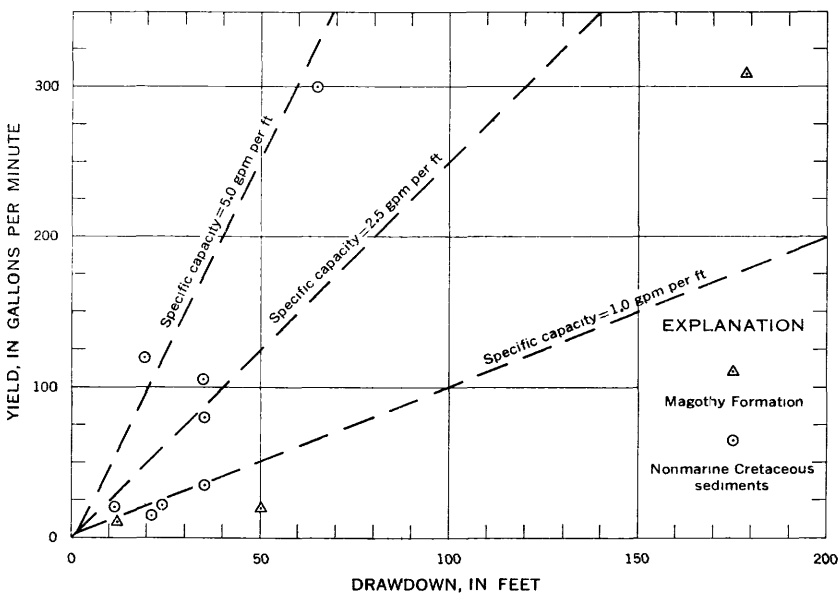


FIGURE 7.—Graph showing relation between yield and drawdown of wells screened in the Magothy Formation and the nonmarine Cretaceous sediments.

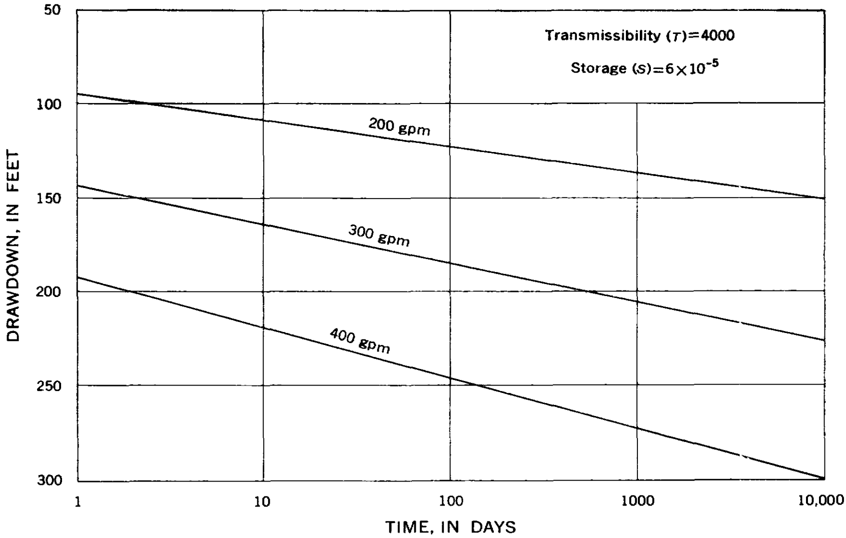


FIGURE 8.—Theoretical time-drawdown relation for a pumping well screened in an ideal aquifer having the hydraulic characteristics determined for the Magothy Formation.

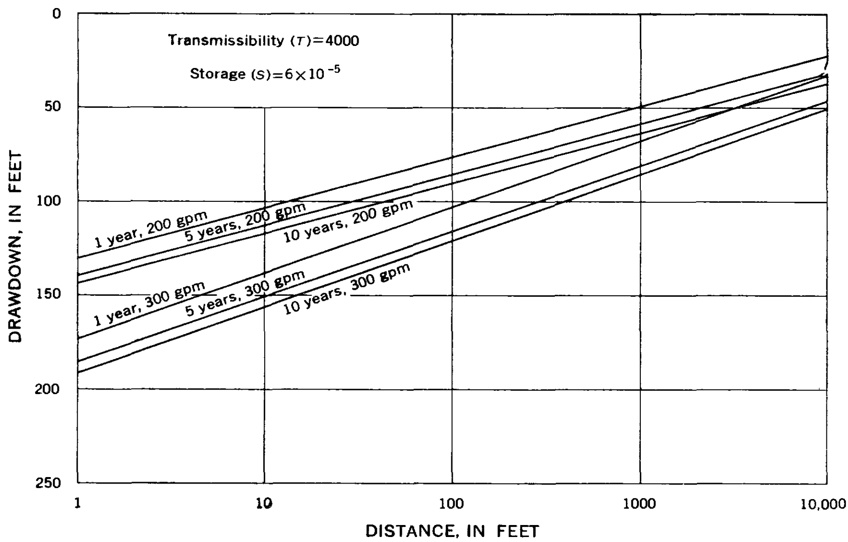


FIGURE 9.—Theoretical distance-drawdown relation for an ideal aquifer having the hydraulic characteristics determined for the Magothy Formation.

QUALITY OF WATER

Chemical analyses were made of water samples from five wells that produce water from the nonmarine Cretaceous sediments and the Magothy Formation. Three of the wells that were sampled are located along the Chesapeake and Delaware Canal near the Delaware-Maryland State line. The other two wells are in the town of Middletown. Thus, the wells are within a 4-mile radius of each other and may not be representative of water from wells screened in the same aquifer in other sections of the report area.

All the analyses from the nonmarine Cretaceous sediments and the Magothy Formation indicate water of a similar chemical character. Maximum, average, and minimum observed concentrations and maximum and minimum pH values are presented in table 2. The average chemical analysis is shown graphically in figure 10. The water is generally low in dissolved-solids content (48–140 ppm) and varies in pH from slightly acidic to slightly alkaline (5.9–7.6). It usually contains undesirable concentrations of iron (0.90–6.3 ppm) and is fairly soft (18–62 ppm hardness). Calcium, sodium, and bicarbonate are the predominant ions in waters sampled from the nonmarine Cretaceous sediments and the Magothy Formation.

TABLE 2.—*Summary of chemical analyses of ground water from the nonmarine Cretaceous sediments and the Magothy Formation*

[Chemical analyses in parts per million]

	Maximum	Average	Minimum
Iron (Fe)	6.3	3.9	0.9
Calcium (Ca)	17	10	4.5
Magnesium (Mg)	4.7	3.1	1.6
Sodium and Potassium (Na+K)	26	13	2.4
Bicarbonate (HCO_3)	133	65	8
Sulfate (SO_4)	16	9.2	1.6
Chloride (Cl)	5.0	2.2	.5
Fluoride (F)	.2	.1	0
Nitrate (NO_3)	2.5	.6	0
Dissolved solids (residue on evaporation at 180° C.)	140	81	48
Hardness, as $CaCO_3$:			
Calcium, magnesium	62	38	18
Noncarbonate	15	2	0
pH	7.6	--------	5.9

N. H. Beamer (in Rasmussen and others, 1958), reported that the analysis of water from well Eb31–1, which is screened in the Magothy Formation, showed a slight increase in sulfate content (from 6.3 ppm on May 17, 1956, to 23 ppm on Oct. 4, 1956) and a corresponding decrease in pH (from 7.0 to 5.9, respectively). The Magothy Forma-

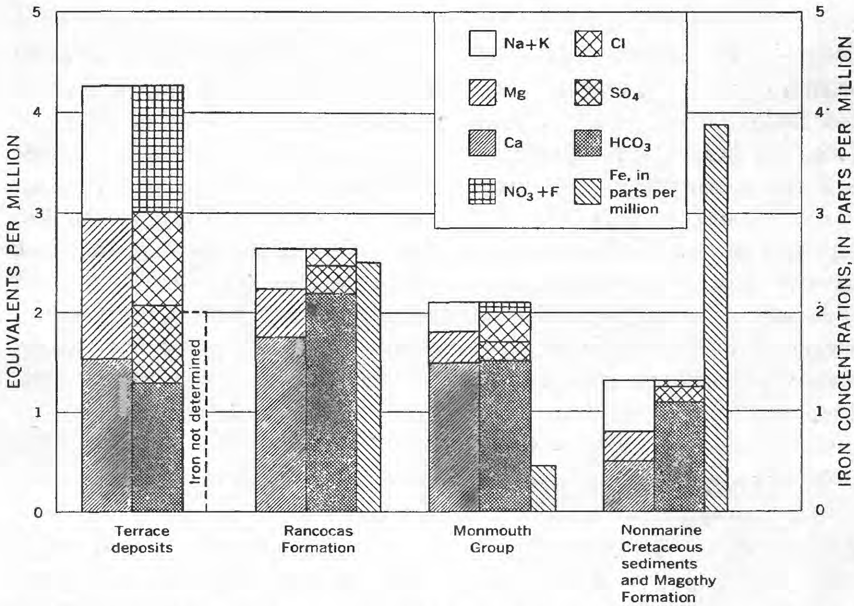


FIGURE 10.—Graph showing average chemical analyses of water from four hydrologic units in southern New Castle County, Del.

tion, from which this well produces water, has appreciable concentrations of the minerals pyrite and marcasite, both consisting of iron disulfides. Beamer concluded that exposure of these minerals to oxidizing conditions at low ground-water stages may result in formation of sulfuric acid and, thus, add sulfate to the ground water. The decrease in pH tends to support this observation.

Chemical analyses of water from 10 wells in adjacent Cecil County, Md., tapping the Patuxent, Patapsco, Raritan, and Magothy Formations were reported by Overbeck and Slaughter (1958, p. 130). Analyses of these wells are similar to those in the Middletown-Canal area. The water is usually low in dissolved-solids content (22–167 ppm), varies in pH (5.0–7.5), and is usually soft (5–106 ppm hardness). The iron content is often high (0.05–21 ppm). A public supply well at Chesapeake City is reported (Overbeck and Slaughter, 1958, p. 110) to contain at times as much as 40 ppm of iron.

Downdip, the water in the nonmarine Cretaceous sediments and the Magothy Formation is believed by the authors to be salty or at least brackish. This belief stems from field observations that confirm the theoretical pattern of water movement within the aquifer as deduced by Barksdale and others (1958, p. 109–112). The inferred position of the interface between fresh and salty water in the Delaware part of the aquifer is shown on figures 5 and 6. It appears to be a valid interpretation for the following reasons: (1) An analysis of water from the Magothy Formation at Middletown, Del., shows the water to be fresh with a low specific conductance (226 micromhos) and a negligible concentration of chloride (1.4 ppm); (2) a sample of water obtained from the Magothy Formation during the drilling of a test well about 5 miles northeast of Smyrna, Del., contained as much as 300 ppm chloride; and (3) an electric log of the test well about 5 miles northeast of Smyrna shows evidence of the presence of saline or brackish water in the sands of the Magothy Formation and the nonmarine Cretaceous sediments. Thus, fresh water is known to occur in the nonmarine Cretaceous-Magothy aquifer at Middletown, Del., and salty or brackish water is presumed to occur in the aquifer in the vicinity of Smyrna, Del.

MONMOUTH GROUP

The Monmouth Group was named by Clark (1897, p. 331–336) for typical exposures of the upper part of the Cretaceous System in Monmouth County, N.J. The name has since been applied to equivalent strata in Delaware and Maryland. In New Jersey, the Monmouth Group is subdivided, in ascending order, into three formations: the Mount Laurel Sand, the Navesink Formation, and the Red Bank Sand. Attempts to trace these subdivisions southwestward along the strike into Delaware have not been entirely successful. Carter (1937, p. 262) recognized the Mount Laurel Sand in the eastern part of the Chesapeake and Delaware Canal, but Groot, Organist, and Richards 1954, p. 21) identified the same unit as the Red Bank Sand. The former interpretation appears to be more in agreement with the subsurface correlations that are shown on plate 1, but additional study will be required to resolve the controversy. No subdivisions have been recognized in Maryland where the Monmouth is considered to be a formation.

DISTRIBUTION AND THICKNESS

The Monmouth Group crops out in the northern part of the project area in a narrow southwestward-trending belt that includes the eastern end of the Chesapeake and Delaware Canal. Good exposures can usually be found in the banks of the canal and in the stream valleys within the belt of outcrop where the surficial mantle of Quaternary deposits has been removed by erosion. Southeast of the outcrop belt, the Monmouth Group descends into the subsurface where it has been recognized in many wells (pl. 2). The depth to the base of the Monmouth Group is shown in figure 11, and the depth to the top of the first permeable sand in the group is shown in figure 12. These maps can be used to predict the depth to which wells must be drilled to obtain water from this aquifer.

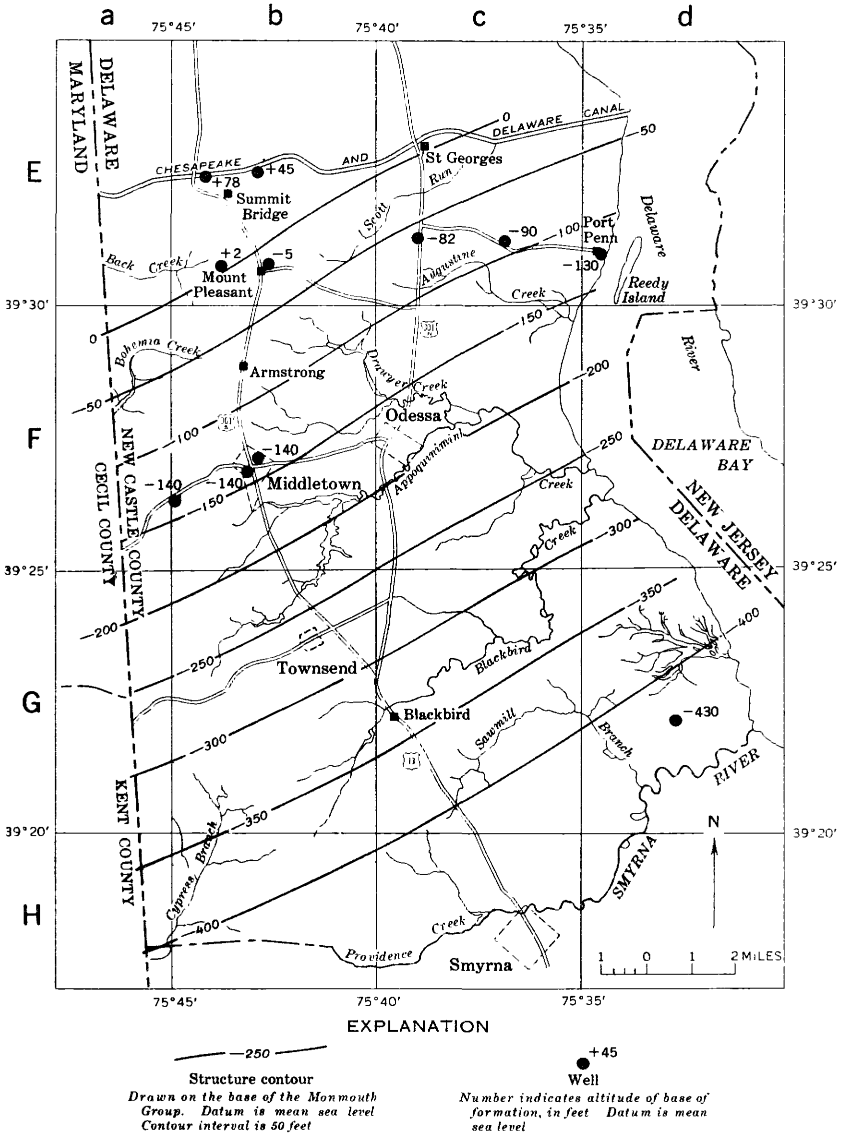


FIGURE 11.—Map of lower New Castle County showing structure contours of the base of the Monmouth Group.

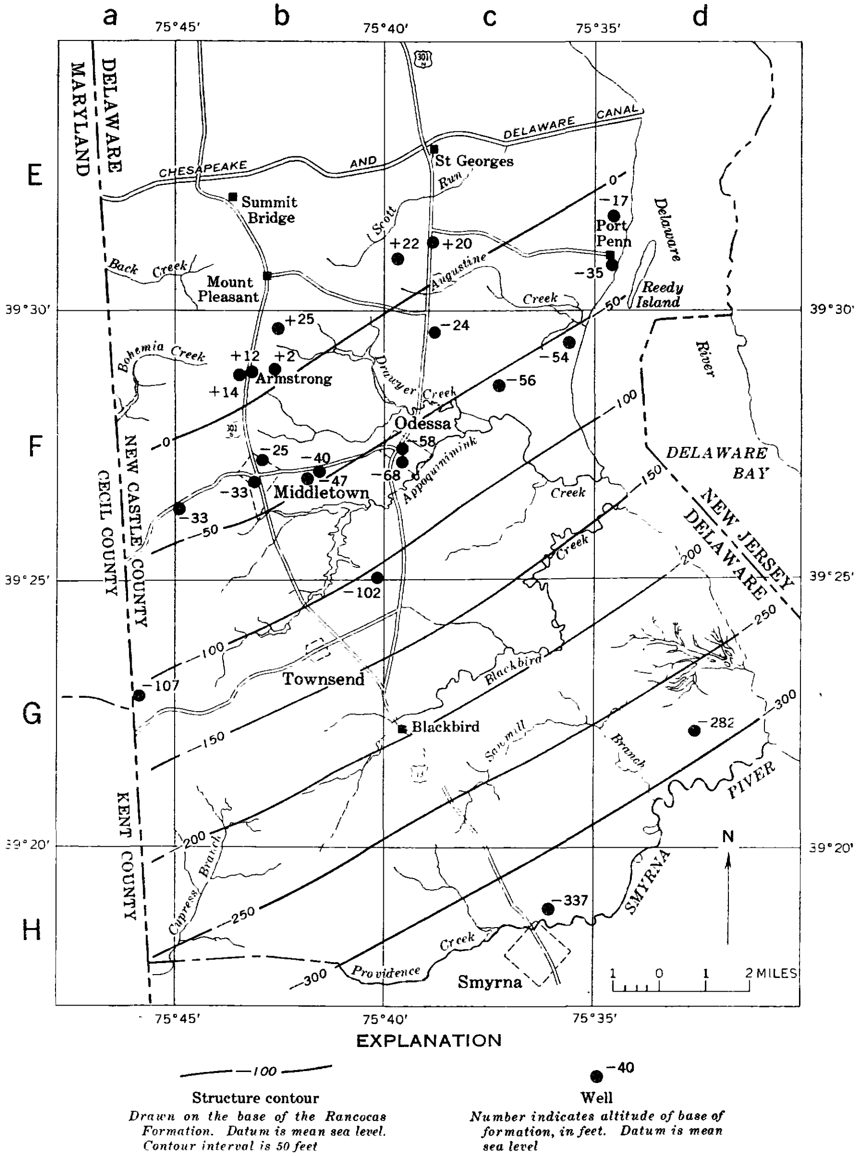


FIGURE 12.—Map of lower New Castle County showing structure contours on top of the sand in the Monmouth Group.

The thickness of the Monmouth Group in the outcrop area increases from less than a foot along its northernmost point of outcrop to about 80 feet before it disappears into the subsurface. The increase in thickness in the outcrop area represents primarily the beveling of the edge of the group by post-depositional erosion. In the subsurface, the thickness of the group increases more gradually to about 120 feet in a well near Smyrna.

LITHOLOGIC CHARACTER

The Monmouth Group is composed chiefly of medium to coarse quartzose sand containing glauconite and fossils. In surface exposures, the color of the sand is light reddish brown mottled with white; but in the subsurface, the characteristic color is a mixture of medium to dark green and light gray. This feature has prompted well-drillers to refer to the sand as a "salt-and-pepper sand." In general, the texture of the sand is fairly uniform, but the mean grain size appears to increase from the bottom of the sand towards the top and also in the direction of dip. In places the sand is partially cemented either by ferruginous material from the weathering of glauconite or by calcareous material from the solution of the contained fossils.

The uppermost few tens of feet of the Monmouth Group is composed of a bed of dark-greenish-gray sandy and clayey silt which contains an abundance of marine fossils and glauconite. The silt is very sandy near the base and becomes more clayey towards the top. It is included in the Monmouth in this report because most of the fossils that have been reported from it are of Late Cretaceous age. Nevertheless, as shown by the correlations of well logs on plate 1, the silt appears to be equivalent to the combined stratigraphic interval represented in western New Jersey by the Navesink Formation of Cretaceous age and the Hornerstown Sand of early Tertiary age. A core taken from the upper few feet of this silt in a well northeast of Smyrna has yielded a microfauna which Mr. R. R. Jordan (Delaware Geol. Survey, written communication) has identified as early Tertiary in age.

WATER-BEARING PROPERTIES

The sand part of the Monmouth Group is an extensive aquifer in southern New Castle County (pl. 2). Its capacity to store and transmit water is not as great as either the nonmarine Cretaceous sediments or the Magothy Formation, but it is tapped by many wells in the central part of the project area. The relation between the reported yields and drawdowns of the wells screened in the Monmouth Group is shown in figure 13. The highest yields shown in the graph are those reported for a group of wells in the vicinity of Armstrong, a small community about 2 miles north of Middletown. The specific capacities of the 27

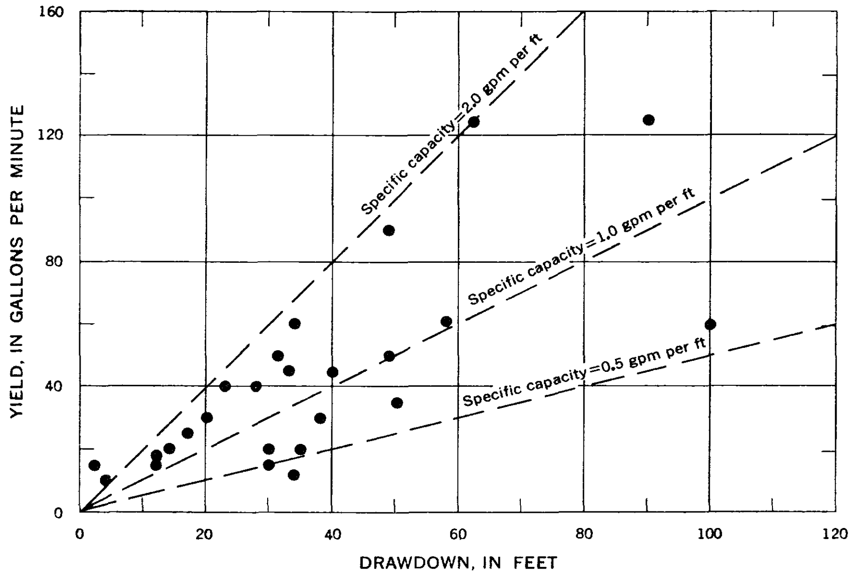


FIGURE 13.—Graph showing relation between yield and drawdown of wells screened in the Monmouth Group.

wells for which data are plotted in figure 13 range from 0.4 to 2.5 gpm per ft. of drawdown and average 1.2 gpm per ft. The wells that have above-average specific capacities are concentrated in and near the belt of outcrop of the Monmouth Group where the aquifer is overlain by a thin mantle of highly permeable terrace deposits. Downdip, the specific capacities of wells screened in the Monmouth Group tend to taper off.

The hydraulic coefficients of the aquifer in the Monmouth Group were determined from a pumping test which was made at Middletown in April, 1961. Analysis of the test data indicates that the coefficient of storage (S) of the aquifer is 2.5×10^{-4} and the coefficient of transmissibility (T) is about 1,800 gpd per ft. As the thickness of the aquifer at Middletown is about 85 feet, the field coefficient of permeability is about 20 gpd per sq. ft., or about one-tenth that of the Magothy Formation.

QUALITY OF WATER

Water samples were collected and analyzed from a total of six wells that tap the sand of the Monmouth Group. Two of the wells sampled are near St. Georges, two others are in Odessa, and the remaining two are in Middletown. The analyses of the samples are summarized in table 3.

Water from the Monmouth Group has a variable dissolved-solids content (74–187 ppm). The predominant ions are calcium and bicarbonate. Iron is generally present in small concentrations (0.21–0.57 ppm). In the St. Georges area, the water is high in nitrate (13–22 ppm). Average concentrations observed in water from the Monmouth Group are shown graphically in figure 10.

In general, the concentration of dissolved solids is low in the area of outcrop of the aquifer, but it increases abruptly downdip. The hardness of the water ranges from soft (less than 60 ppm) in the outcrop area to hard (140 ppm) in a well in Middletown about 3 miles downdip from the outcrop area. The pH also ranges from acidic in the outcrop area to alkaline in the downdip parts of the aquifer. The low concentrations and pH values near the outcrop probably reflect recharge water from the intake area or from hydrologically connected aquifers (terrace and valley-fill deposits). The higher concentrations of dissolved solids and hardness and pH values found downdip are more representative of the lithologic character in the group.

TABLE 3.—*Summary of chemical analyses of ground water from the Monmouth Group*

[Chemical analyses in parts per million]

	Maximum	Average	Minimum
Iron (Fe)	0. 57	0. 44	0. 21
Calcium (Ca)	44	30	4. 5
Magnesium (Mg)	7. 3	3. 9	1. 4
Sodium and Potassium (Na+K)	10	6. 8	4. 1
Bicarbonate (HCO_3)	157	92	11
Sulfate (SO_4)	18	9. 3	. 8
Chloride (Cl)	28	9. 8	2. 0
Fluoride (F)	. 3	. 2	. 1
Nitrate (NO_3)	22	6. 1	0
Dissolved solids (residue on evaporation at 180° C)	187	140	74
Hardness, as $CaCO_3$:			
Calcium, magnesium	140	93	19
Noncarbonate	40	17	0
pH	8. 1	--------	5. 9

RANCOCAS FORMATION

The Rancocas Formation was named by Clark (1894, p. 161–177) for exposures along Rancocas Creek in Burlington County, N.J. Later, equivalent strata were recognized in Delaware by Clark, Bagg, and Shattuck (1897) and mapped by Miller (1906). The Pancocas Formation was considered to be Late Cretaceous in age until Cooke and Stephenson (1928) proved the deposits to be lowermost Tertiary in age. The type section in New Jersey has been subdivided into two formations, the Hornerstown Sand below and the Vincentown Formation above and expanded to include the Manasquan as the top formation, but these units have not been recognized in Delaware.

DISTRIBUTION AND THICKNESS

The Rancocas Formation crops out beneath a surficial mantle of Quaternary sediments in a belt that trends southwestwardly through the central part of the project area and includes the towns of Middletown and Odessa, Del. It is exposed chiefly in the valleys of Appoquinimink and Drawyer Creeks and their tributaries. Southeast of the belt of outcrop, the Rancocas Formation occurs in the subsurface as shown on the fence diagram (pl. 2). The depth to the top and bottom of the formation in the project area is shown by means of contours on figures 14 and 15.

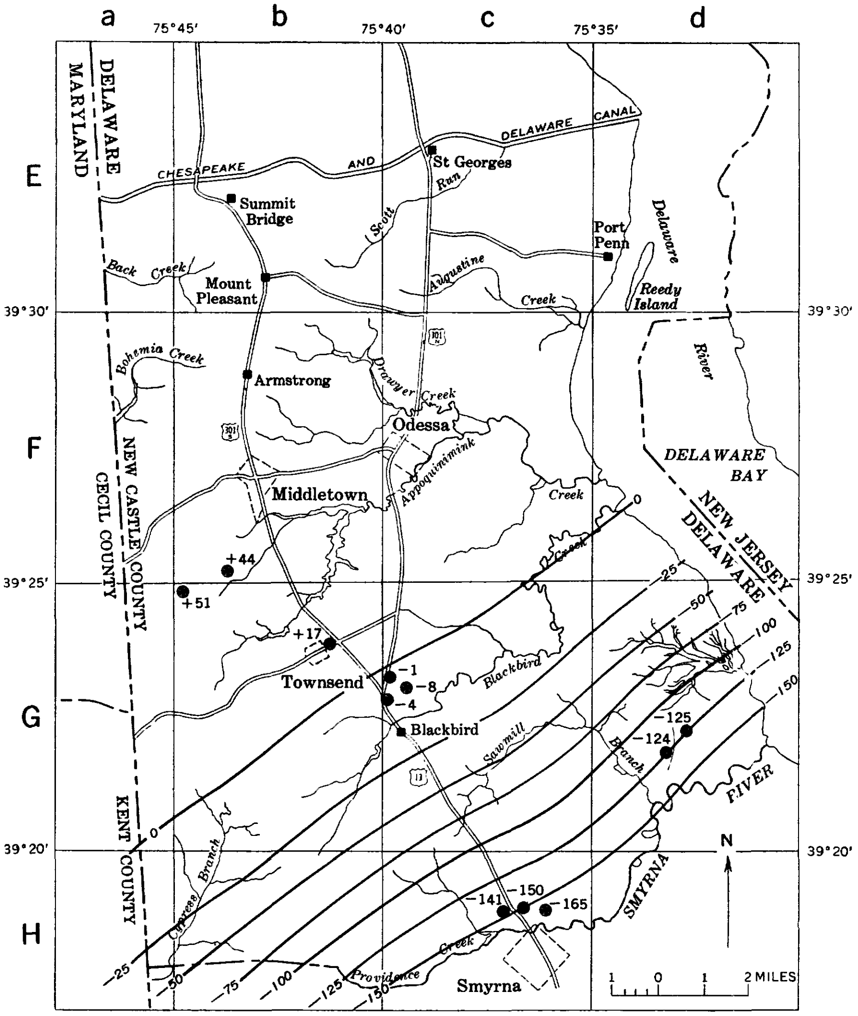
The thickness of the Rancocas Formation increases from slightly less than 100 feet in the outcrop area to 165 feet at Smyrna. Most of the increase in thickness is the result of a transgressive overlap by the Calvert Formation of Miocene age.

LITHOLOGIC CHARACTER

The Rancocas Formation is characterized by three lithologic facies: a coarse-grained greensand containing as much as 90 percent glauconite, a calcareous or limy sandstone containing glauconite and numerous marine fossils, and a quartzose sand containing minor amounts of glauconite. The first two facies occur chiefly in the lower part of the formation. In general, the greensand is the predominant material, and the calcareous sandstone forms a series of discontinuous interbeds. This sequence of bedding is evident from electrical logs of wells that penetrate the formation such as the one shown in figure 16. The narrow high-resistivity "kicks" shown on the log indicate the presence of thin indurated beds interspersed in a matrix of less resistive sediments; presumably the greensands. The third facies, the quartzose sand, is characteristic of the upper part of the formation. The sand is generally coarse to very coarse grained and moderately well sorted, and the predominant shape of the grains is subangular to subrounded. Glauconite and fossils are generally present in the upper part of the formation, but they are far less abundant than in the lower part.

WATER-BEARING PROPERTIES

The Rancocas Formation is the principal aquifer in the southern part of the project area. Owing to its uniformly coarse texture, it is capable of yielding moderate to large supplies of water (200–500 gpm) to properly constructed wells. This conclusion is not evident from the reported yields of individual wells screened in the formation, which range from 15 to 330 gpm, but it is strongly suggested by the data plotted in figure 17 showing the relation between yield and drawdown. The specific capacity of the wells for which data

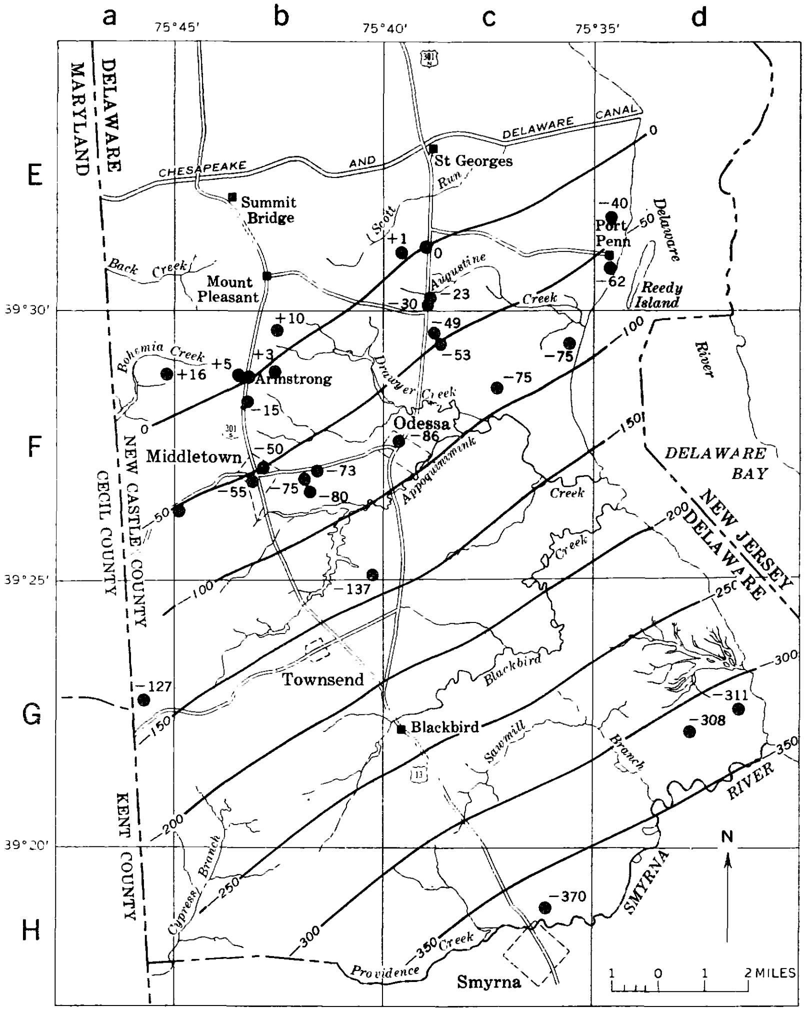


EXPLANATION

—25—
Structure contour
Drawn on top of the Rancocas Formation. Datum is mean sea level. Contour interval is 25 feet

●-4
Well
Number indicates altitude of top of formation, in feet. Datum is mean sea level

FIGURE 14.—Map of lower New Castle County showing structure contours on top of the Rancocas Formation.



EXPLANATION

—— 100 ——

Structure contour

Drawn on top of the sand in the Monmouth Group. Datum is mean sea level Contour interval is 50 feet

● −75

Well

Number indicates altitude of top of formation, in feet. Datum is mean sea level

FIGURE 15.—Map of lower New Castle County showing structure contours of the base of the Rancocas Formation.

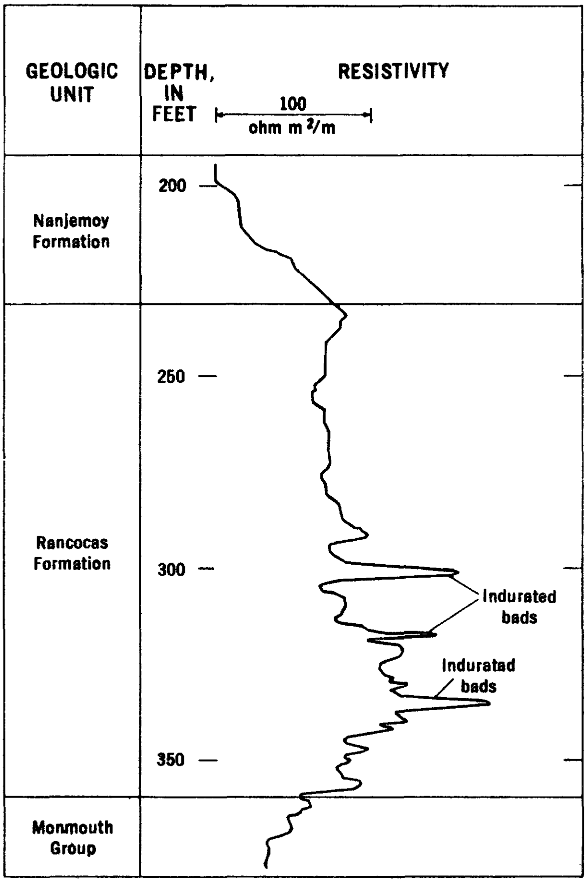


FIGURE 16.—A part of the resistivity log of well Hc24-4, located northeast of Symrna, Del.

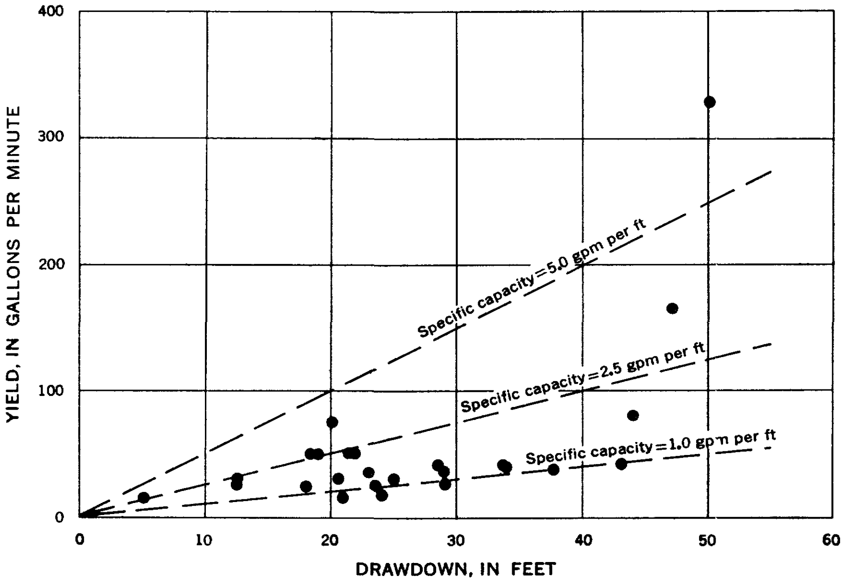


FIGURE 17.—Graph showing relation between yield and drawdown of wells screened in the Rancocas Formation.

are plotted averages 2.3 gpm per ft, and the maximum is 6.5 gpm per ft. It is significant to note that the two wells with reported yields in excess of 100 gpm have specific capacities (3.5 and 6.5) considerably above the average. These values are probably more indicative of the true productivity of the aquifer, because the wells, unlike many of the others, were drilled to obtain the maximum available supply.

During this investigation the hydraulic coefficients of the Rancocas Formation were not determined because no facilities could be found that were suitable for making pumping tests.

QUALITY OF WATER

Samples of water from seven wells screened in the Rancocas Formation have been analyzed for chemical quality. One well is in Middletown. The remaining six wells are divided equally among the towns of Odessa, Townsend, and Clayton, which is less than 1 mile west of Smyrna and just south of the New Castle County line. The maximum, average, and minimum observed concentrations and the maximum and minimum pH values are presented in table 4. The average chemical analysis of water from the Rancocas Formation is shown in figure 10 in comparison with similar data on water for the other three principal aquifers.

The water from the Rancocas Formation is moderately mineralized (79–236 ppm) with calcium and bicarbonate as the predominant ions. In general, the concentrations of most of the chemical constituents are higher downdip than they are in the outcrop area. In the outcrop area the water is acidic (pH 5.8), high in iron (8.1 ppm), and soft to hard (32–142 ppm). Downdip, the water is slightly alkaline (pH 7.0–7.9), low in iron (0.25–0.57 ppm), and moderately hard to hard (117–156 ppm). The high iron content in the outcrop area is attributed to the abundance of glauconite in the lower part of the Rancocas Formation. The hardness is mostly of the "temporary," or carbonate type.

TABLE 4.—*Summary of chemical analyses of ground water from the Rancocas Formation*

[Chemical analyses in parts per million]

	Maximum	Average	Minimum
Iron (Fe)	10	2.5	0.25
Calcium (Ca)	47	35	7.3
Magnesium (Mg)	11	6.3	2.5
Sodium and Potassium (Na+K)	20	9.9	4.6
Bicarbonate (HCO_3)	229	134	18
Sulfate (SO_4)	39	13	1.9
Chloride (Cl)	14	4.9	.5
Fluoride (F)	.5	.2	.1
Nitrate (NO_3)	2.2	.7	0
Dissolved solids (residue on evaporation at 180° C)	236	171	79
Hardness, as $CaCO_3$:			
Calcium, magnesium	156	120	32
Noncarbonate	51	18	0
pH	7.9	--------	5.8

TERRACE AND VALLEY-FILL DEPOSITS

The terrace and valley-fill deposits are the main constituents of the water-table aquifer in southern New Castle County. They represent the accumulation of sediments in the project area during the Pleistocene Epoch, when the region to the north was covered by continental glaciers. Thus, the terrace and valley-fill deposits are composed chiefly of outwash that was carried southward from the ice front by meltwater streams. The terrace deposits have been subdivided into the Wicomico and Talbot Formations on the geologic map of the Dover folio (Miller, 1906) and the Elkton-Wilmington folio (Bascom and Miller, 1920). These subdivisions, however, are based on topographic position of the deposits and not on differences in the lithologic character of the materials.

DISTRIBUTION AND THICKNESS

The terrace and valley-fill deposits constitute the surficial materials nearly everywhere in southern New Castle County. The exceptions are the flood plain and tidal-marsh areas and the narrow belts along the upper reaches of the major streams. The thickness of these deposits differ from place to place as a function of the difference between the pre-Pleistocene erosional surface and the present one. Although evidence of the pre-Pleistocene erosional surface is obscure, a general concept of the surface can be gained from the exposures along the major stream valleys and from the interpretation of well logs. These data suggest that the pre-Pleistocene surface is a subdued replica of the present-day topography—that is, the highest recorded levels of the pre-Pleistocene surface are beneath the present-day uplands and the lowest levels are beneath the lowlands. This feature is visible on the fence diagram (pl. 2) by the overall decrease in the thickness of the terrace deposits from west to east.

The irregularities of the pre-Pleistocene surface, particularly the depressions, which are the sites occupied by the valley-fill deposits, are less well-known or predictable. In fact, the location of only two such sites have been found. One of the sites is visible in the banks of the Chesapeake and Delaware Canal, a short distance west of St. Georges. The other site is known from logs of wells in Smyrna, Del. It is almost certain that other sites, now unknown, exist, and can be discovered by test drilling.

LITHOLOGIC CHARACTER

The terrace and valley-fill deposits are composed chiefly of sand and gravel containing some local beds or lenses of soft plastic silt or clay. The predominant colors of the sand and gravel are tan, orange, brown, and yellow, owing to the abundance of iron oxide. The deposits are generally crossbedded, poorly sorted, and coarse to very coarse textured, individual grains are well-rounded. The coarsest materials are usually near the base of the deposits.

WATER-BEARING PROPERTIES

As mentioned previously, the terrace and valley-fill deposits compose the bulk of the shallow water-table aquifer in southern New Castle County. Owing to their coarse texture, these deposits are among the most permeable materials in the project area. Their productivity, however, is limited by the amount of saturated thickness that occurs below the water table. This is not a serious limitation to the productivity of the valley-fill deposits, which extend as much as 100 feet below the water table. The terrace deposits, on the other hand, rarely extend more than 20 feet below the water table, and—in many places—only the lowermost few feet of the materials are saturated. For this reason, the terrace deposits are not considered to be an important source of other than small domestic water supplies.

Nevertheless, the terrace deposits are important to the overall availability of ground water in the project area. In the northern half of the project area, the terrace deposits rest directly upon and, thus, are hydraulically connected to the aquifers in the Monmouth Group and the Rancocas Formation. Consequently, the highly permeable and porous terrace deposits constitute an important source of recharge to the underlying aquifers. This recharge, in effect, increases the quantity of water that can be obtained from the underlying aquifers.

In contrast, the valley-fill deposits are among the most permeable materials to be found in the project area. In Smyrna, where these materials are tapped by wells, yields in excess of 1,000 gpm are common, and specific capacities are correspondingly high.

QUALITY OF WATER

Five wells, identified as drawing water from the terrace deposits, have been sampled and analyzed for chemical quality. The wells are all within a 2-mile radius of St. Georges on the Chesapeake and Delaware Canal. Therefore, these wells are not necessarily representative of water from the water-table aquifer in other sections of the area under study. Overbeck and Slaughter (1958, p. 130) reported chemical analyses of two wells in adjacent Cecil County, Md., which are identified as drawing from the Wicomico Formation of Pleistocene age. Water from these two wells contains a lower dissolved-solids content (42–46 ppm) than that from wells near St. Georges (92–556 ppm) but the water from both areas has the same relative chemical character. Maximum, average, and minimum concentrations and maximum and minimum pH values observed in water from this hydrologic unit are presented in table 5. The average chemical analysis is graphically shown on figure 10.

Chemical analysis of water samples indicate that the ground water from the terrace deposits is generally higher in dissolved-solids content than that from the other water-bearing units (fig. 10). The dissolved-solids content in the water from the terrace deposits varies from 92 to 556 ppm, whereas the dissolved-solids content of water from the other major aquifers in the project area ranges from 48 to 236 ppm. The water in the terrace deposits is slightly acidic (pH 6.2–6.9) and usually hard (34–245 ppm). The hardness is mostly of the "permanent," or noncarbonate type. Calcium, magnesium, and nitrate are usually the predominant ions, although some of the analyses showed higher concentrations of sulfate and chloride than were observed in the samples from other hydrologic units in the area.

TABLE 5.—*Summary of chemical analyses of ground water from terrace deposits of Quaternary age*

[Chemical analyses in parts per million]

	Maximum	Average	Minimum
Calcium (Ca)	57	31	5.3
Magnesium (Mg)	25	17	5.1
Sodium and Potassium (Na+K)	58	32	8.7
Bicarbonate (HCO_3)	281	78	16
Sulfate (SO_4)	99	37	4.4
Chloride (Cl)	44	23	7.0
Fluoride (F)	0	0	0
Nitrate (NO_3)	138	80	28
Dissolved solids (residue on evaporation at 180° C)	556	385	92
Hardness, as $CaCO_3$:			
Calcium, magnesium	245	147	34
Noncarbonate	162	84	15
pH	6.9		6.2

Water withdrawn from the water-table aquifer is especially subject to contamination from surface sources. Possible contamination of the wells near St. Georges is indicated by high nitrate concentrations in wells Ec21-1 (53 ppm), Ec22-1 (102 ppm), Ec22-2 (138 ppm), Ec22-7 (28 ppm), and Ec34-1 (81 ppm). These high nitrate concentrations may be due to industrial and municipal wastes from St. Georges, irrigation water from nearby farms, or swamp water along the Canal and Delaware River, or a combination of all these.

None of the samples analyzed were from wells tapping the valley-fill deposits. Nonetheless, the water from the valley-fill deposits is satisfactory for most uses, but—locally—it is treated for objectionable concentrations of iron.

UTILIZATION OF GROUND WATER

The use of ground water in lower New Castle County averaged about 1.77 mgd (million gallons per day) in 1959, the latest year for which pumpage data have been compiled. About 75 percent of water pumped was used for rural purposes, including about 670,000 gpd used for irrigation. Pumpage for municipal supplies accounted for 14 percent of the total water use, or about 240,000 gpd, and that for industrial and commercial uses amounted to about 11 percent, or 200,000 gpd. The types of use and source of supplies are given in table 6, and the location of the principal centers of pumping and the relative amount of water withdrawn from each source are shown in figure 18.

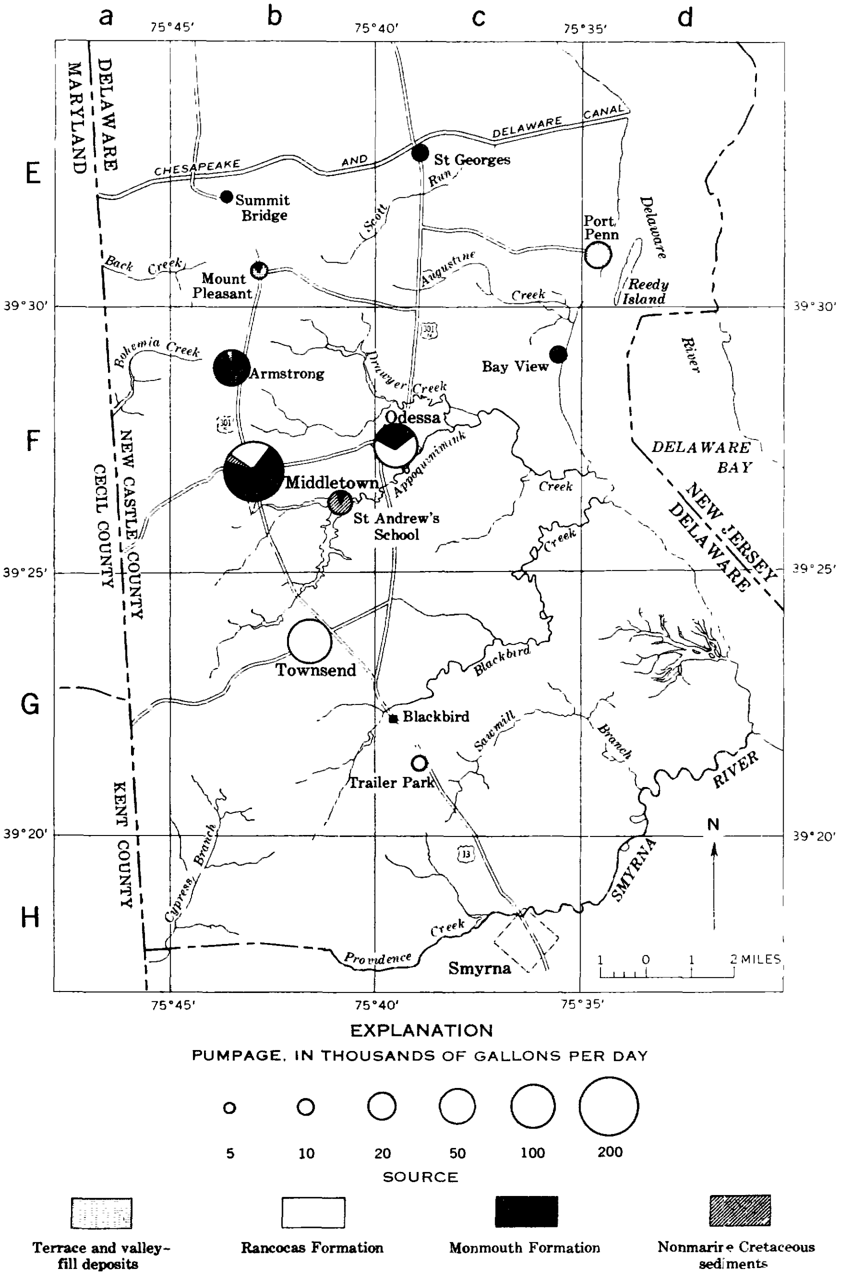


FIGURE 18.—Map of southern New Castle County, Del., showing use of ground water in 1959 and geologic source of supply.

TABLE 6.—*Average daily pumpage, in thousand gallons per day, of ground water by geologic source in lower New Castle County in 1959*

Supplies	Nonmarine Cretaceous	Monmouth Formation	Rancocas Formation	Terrace and valley-fill deposits	All other sources	Total
Public:						
Middletown	10	120	60	0	0	190
Townsend	0	0	30	0	0	30
St. Andrews School	20	0	0	0	0	20
Industrial and Commercial	0	50	150	0	0	200
Rural [1]	50	290	210	770	10	1,330
Total	80	460	450	770	10	1,770

[1]Includes 670,000 gpd used for irrigation.

PUBLIC SUPPLIES

Ground-water supplies have been developed for public use in southern New Castle County by two municipalities, Middletown and Townsend. These systems serve 26 percent of the population of the report area and furnish water for nearly all residential and commercial needs and a part of the industrial requirements within their service areas. The amount of water pumped at Middletown averages about 0.2 mgd, most of which is withdrawn from the Rancocas Formation and the Monmouth Group. In 1962 a new well was drilled and screened in the Magothy Formation. The yield of this well (more than 300 gpm) has more than doubled the supply of water available to the municipal system.

The municipal system at Townsend is supplied by a single well which is screened in the Rancocas Formation. This well has a yield of 60–70 gpm, somewhat more than is now being used.

INDUSTRIAL AND COMMERCIAL SUPPLIES

Industrial and commercial establishments operating in southern New Castle County use about 200,000 gpd of ground water. Most of the industry within this area is concerned with the processing of vegetables and poultry. Table 6 lists these supplies collectively and shows the amount of ground water pumped and the geologic source, or aquifer from which the water is withdrawn.

RURAL WATER SUPPLIES

Rural water supplies are, as interpreted herein, all small individual systems providing water for homes and farms outside those areas supplied by municipal water systems. The primary use of these supplies is for domestic and farm purposes, the latter including water used by livestock and for irrigation. In 1960 an average of 1.3 mgd was pumped from ground-water sources in lower New Castle County for these purposes.

DOMESTIC

Domestic use is herein interpreted as water used for drinking, cooking, washing, sanitation, and lawn and garden care. Collectively, such use over an area such as that of southern New Castle County assumes significant proportions, although the amount used by each household or each person is relatively small. Of the total population of lower New Castle County in 1960, about 7,000 people were dependent upon water from individual wells and small cooperative systems. According to Boggess (1960, p. 99) the per capita use of water in rural areas of Delaware is 60 gpd for those who have running water and 10 gpd for those who do not. By multiplying the per capita use by the populations in each category, the domestic use of water in southern New Castle County is estimated to be 400,000 gpd.

FARM AND STOCK

An estimated 250,000 gpd was used in 1960 for general farm purposes, such as cleaning, spraying, and stock watering. Approximately half of the total amount was used by dairy herds, and the remainder was used by beef cattle, horses, mules, hogs, chickens, and turkeys. The overall estimate of use is based on the per capita requirements for livestock as reported by MacKichan (1957), and the data obtained from the 1959 census of Agriculture (U.S. Dept. of Commerce, 1961).

IRRIGATION

Irrigation of crops in lower New Castle County is dependent upon climatic factors. It is usually done after a period of little or no precipitation or as a supplement to inadequate precipitation over the critical period of crop growth. At such times streams are reduced to base flow and are wholly dependent upon discharge from ground-water reservoirs. This is also true of other "surface-water" sources of irrigation water such as impounded lakes and excavated ponds. Consequently, it would seem that water used for irrigation purposes is, in the main, obtained from the ground water storage. It may also be concluded that the amount of water used will vary considerably from year to year depending upon the amount of precipitation occurring in the months immediately preceding and during the growing season. Precipitation data presented in figure 3 indicate a deficiency in precipitation during the 1959 calendar year, the year for which data are compiled in this report. Thus, the figures given herein represent more or less extensive use of water for irrigation to offset the lack of rainfall.

Irrigated land in lower New Castle County has over a period of 11 years increased from 9 acres in 1949 to 1,785 acres in 1959. Data supplied by the Department of Agricultural Economics, University of Delaware, indicate that 244 million gallons of water were used for irrigation of crops in New Castle County in 1959. This amount represents a use of about 2 mgd during the 1959 growing season, but only about 0.7 mgd when averaged over the year.

CONCLUSION

The four major aquifers underlying southern New Castle County are capable of producing many times more than the 2 mgd currently being used. The present use does not exceed the local capacity of any of the major aquifers. Only one aquifer at one locality—the Monmouth Group at Middletown—appears to be producing near its maximum capacity. Even at Middletown, there is no shortage of water because two other aquifers can be tapped by wells, namely: (1) The lowermost aquifer, comprised of the highly productive nonmarine sediments and the Magothy Formation; and (2) the uppermost aquifer, which includes the Rancocas Formation and the terrace deposits. Elsewhere, any of the major aquifers or ground water reservoirs can be used on a vastly increased scale.

In the northern part of the project area, the water-table aquifer is the most readily available source for supplying additional water needs. If this source proves to be inadequate for a particular need, wells can be drilled to tap the underlying reservoir formed by the nonmarine Cretaceous sediments and the Magothy Formation. The depths to be drilled to tap this supply are easily calculated from the structure contour maps (figs. 5 and 6).

In the southern part of the project area, large-supply wells can be drilled to tap the highly productive Rancocas Formation. The uniform character of this aquifer makes it a dependable source of supply. The upper, or younger, part of the Rancocas is capable of higher sustained yields than the lower, or older, part. Because the upper, or younger, part of the formation does not crop out, the farther downdip the formation is tapped, the higher will be the yields of wells.

Future test drilling will probably reveal additional sites where the valley-fill deposits can be tapped by wells. These sites will offer excellent opportunities for the development of additional water supplies. Although considerable effort may be required, the discovery of additional valley-fill deposits may prove to be most important to the future water supply of the project area.

Although large quantities of water can be developed in the project area, the suitability of the water to meet future needs will depend in large measure upon the chemical character of the water. At the present time the quality of water from the major aquifers is satisfactory for most purposes, but there is no guarantee that it will remain so.

Changes in hydraulic head due to heavy pumping, may affect the quantity and sources of influent water and, ultimately, the quality of the water in the aquifer. Consider an aquifer that is normally replenished by precipitation. When heavily pumped, recharge can be induced from surface-water sources or other hydraulically connected aquifers. The result would be a change in chemical quality dependent upon the source of recharge. In the extreme northeastern part of the project area near St. Georges, the terrace deposits rest directly upon and are hydraulically connected with the Monmouth Group. Possible mixing of water from the upper hydrologic unit, which contains high nitrate concentrations (28–138 ppm), and water from the underlying aquifer is indicated by relatively high nitrate concentrations in wells in that area.

The quality of water at the intake region also is important. Water percolating through soils rich in organic materials may gain carbon dioxide, which increases its solvent power. Carbon dioxide concentrations in water from wells tapping the water-table aquifer are high (5.2–56 ppm) in relation to the concentrations in other hydrologic units. Rainfall or snowmelt contain low dissolved-solids content and, therefore, will have a diluting effect on the water-bearing formation. Swamp water may be acidic and high in nitrate concentration. Irrigation water percolating into an aquifer may contain high concentrations of potassium, sulfate, phosphate, and nitrate. Water withdrawn from the water-table aquifer contains high nitrate concentrations, ranging from 28 to 138 ppm. This indicates contamination of the aquifer by either industrial or municipal wastes or possibly irrigation water.

The intake to an aquifer intercepted by a tidal estuary may contain high chloride concentrations and dissolved solids due to saline-water encroachment. Each of the four hydrologic units in the southern New Castle County area are exposed to possible saline-water encroachment, either from the Chesapeake and Delaware Canal or the Delaware River and Bay. Rasmussen and others (1958) observed chloride concentrations and water levels in aquifers that cross the tidal Chesapeake and Delaware Canal. They reported that

> fluctuations in water levels in the wells near the canal follow the tidal ebb and flow of the brackish water in the canal, but this is believed to be primarily a pressure response. No correlation was detected between the quality of water in the wells and that of water in the canal.

Although information on the nature and extent of saline-water encroachment along the Delaware estuary in Delaware, is scant, the U.S. Geological Survey has 15 observation wells in nearby Salem and Cumberland Counties, N.J., to monitor the movement of saline waters in that area. Some of the wells, because of increased industrial pumping and the proximity of saline surface water, show increased chloride concentrations.

At the time of this investigation in 1962, no evidence was found of the encroachment of brackish water into fresh-water acquifers in southern New Castle County from either the Delaware estuary or the Chesapeake and Delaware Canal. Nonetheless, the presence of bodies of brackish water along the northern and eastern borders of the area should be considered as potential threats to the future development of acquifers in southern New Castle County.

The most likely places for encroachment to occur are near the suboutcrops of the principal acquifers beneath the Delaware estuary and the Chesapeake and Delaware Canal. At these sites, the major aquifers are exposed to the brackish water in the estuary and the canal. The suboutcrops beneath the canal are covered by not more than a few feet of silt of low permeability. The suboutcrops beneath the estuary, however, are somewhat better insulated from the brackish water by the presence of thick alluvial muds, which line the channel of the estuary. As these muds are considerably less permeable than the aquifers, some protection from encroachment is afforded the adjacent aquifers. Nevertheless, movement of water from the estuary into the fresh-water aquifers will occur if the natural hydraulic gradient is reversed by pumping from the aquifer. Consequently, much care should be exercised in developing large ground-water supplies close to the estuary.

Should it become necessary to develop large supplies adjacent to the estuary, consideration should be given to protecting the producing acquifer from encroachment. Such protection would be afforded by any arrangement that prevents the natural hydraulic gradient from being entirely reversed in the area between the producing wells and the shoreline of the estuary. For example, a line of injection wells could be placed parallel to the shoreline and interposed between the shoreline and the point or area of withdrawal. By injecting water into the producing acquifer at a rate sufficient to offset the loss in head at the shoreline caused by pumping, a ground-water divide could be maintained to prevent the encroachment of brackish water from the estuary into the fresh-water aquifer.

In short, the quantity of ground water available will not be as serious a limitation upon the future development of water supplies in southern New Castle County as will be the present and future chemical quality of the water.

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