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GROUND-WATER GEOLOGY OF THE DELAWARE ATLANTIC SEASHORE

BY

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NEWARK, DELAWARE

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CONTENTS

ILLUSTRATIONS

TABLES

GROUND-WATER GEOLOGY OF THE DELAWARE ATLANTIC SEASHORE

ABSTRACT

The need for locating additional sources of ground water for the Delaware Atlantic seashore, a predominantly recreation-oriented area, is indicated by an expanding population in the belt between Philadelphia, Pennsylvania and Washington, D. C., combined with increasing leisure time. Present water use in the shore area is approximately 4 million gallons per day and will reach 9.3 million gallons per day by the year 2000.

A new geologic interpretation of the occurrence of deep aquifers in the Delaware Atlantic seashore area is presented. Recent data from deep wells has enabled the construction of a more accurate geologic framework upon which the hydrologic data are superimposed. Correlation of Miocene sands concludes that the Manokin aquifer lies at greater depths in southeastern Delaware than previously thought.

Moderately high transmissibility values (54,500 gpd/ft.) and specific capacities (average of 11.7 gpm/ft. of drawdown) for the Pocomoke aquifer indicate that further development is possible. The Manokin aquifer has a transmissibility of only 29,250 gpd, but greater drawdowns are available.

With proper well-spacing and development approximately 10 and 8 million gallons per day are available from the Pocomoke and Manokin aquifers, respectively. The Columbia (Pleistocene) aquifer will yield 5.2 million gallons per day from the headlands south of Lewes and 4.5 million gallons per day from the headlands to the southwest of Ocean View-Millville. Approximately one million gallons per day are available from small wells on the barrier island bars between Cape Henlopen and Fenwick Island, but this water is more vulnerable to salt-water contamination and pollution from septic tanks. The water from the Manokin and Pocomoke aquifers will need more treatment than water from the Pleistocene aquifer but is less vulnerable to salt-water encroachment.

Test holes to the Pocomoke aquifer are recommended in the Dewey Beach and southern Delaware Seashore State Park

areas. So little is known about the potential of the Manokin aquifer that test holes are needed along the entire seashore area, particularly at Dewey Beach, southern Delaware Seashore State Park, and Bethany Beach.

INTRODUCTION

Purpose and Scope

The evaluation of the ground-water resources of the Delaware Atlantic seashore is considered to be of utmost importance in light of the ever-increasing demand for outdoor recreation by a growing population that has more leisure time available than at any preceding time. Summer populations of beach communities and parklands along the Delaware Atlantic shoreline exceed 100,000 persons. Peak summer resident population in the Lewes-Rehoboth Beach area will almost double by 1990 and will treble in the Bethany Beach area during the same time interval (G. P. Rasmussen, 1969).

This report provides a new geologic interpretation of the occurrence of deep aquifers beneath the beach areas between Lewes and Fenwick Island. Recent drilling of deeper wells and the interpretation of driller's logs and electric logs has enabled the construction of a more accurate geologic framework upon which the hydrology can be superimposed. Chemical analyses of the ground water at different depths throughout the area are critical to the determination of ground-water quality. Attempts to obtain additional water-quality data for the deeper aquifers have met limited success, but enough control has been established to warrant test-drilling of these horizons.

The conclusions arrived at in this report are the result of a thorough inspection and evaluation of the basic water data in the files of the Delaware Geological Survey and a reconsideration of the work of previous investigators.

Location and General Features of the Area

The report area comprises approximately 50 square miles along a 25-mile strip of Atlantic shore from Cape Henlopen to Fenwick Island, Delaware (Figure 1).

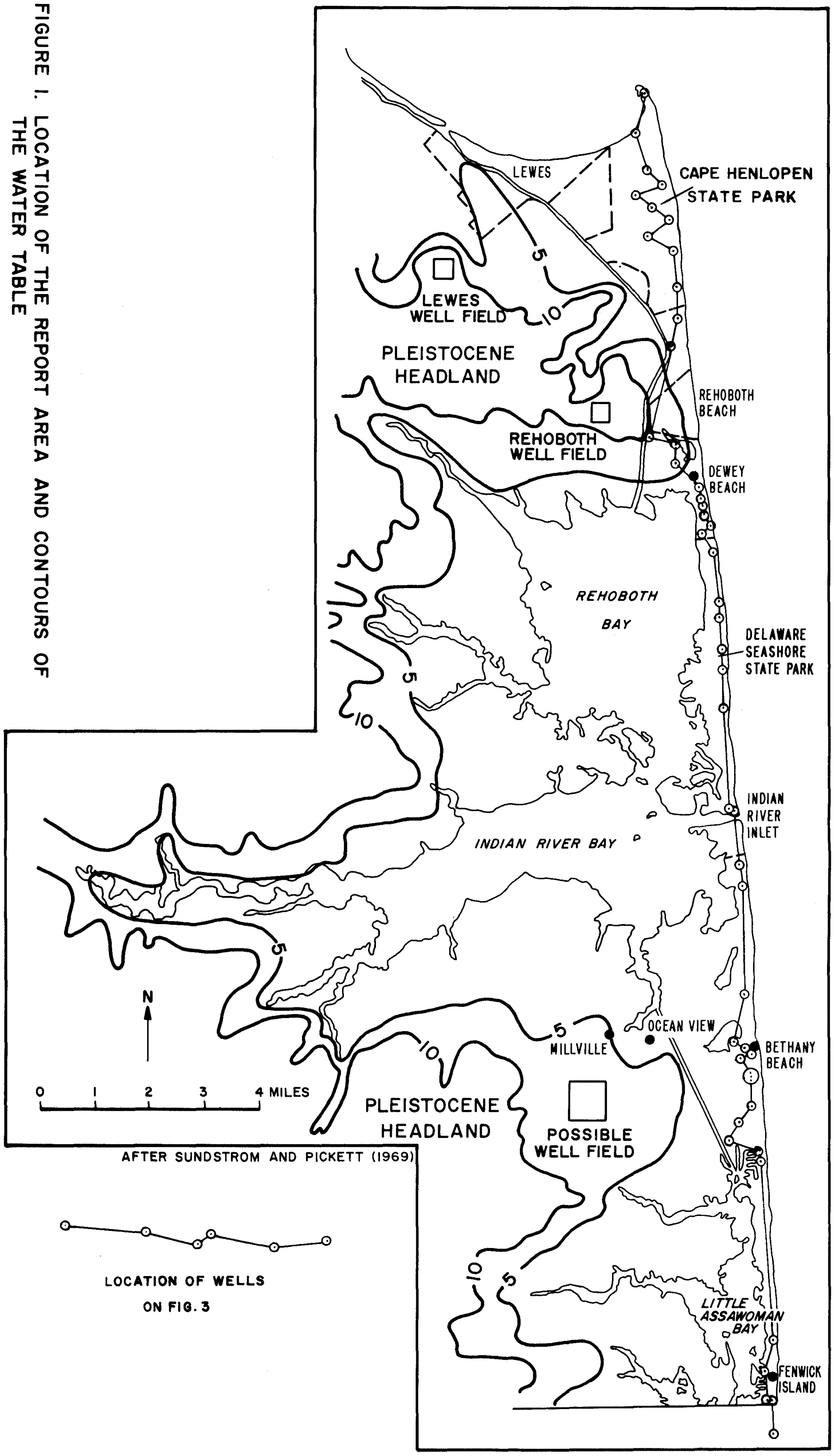

FIGURE 1. LOCATION OF THE REPORT AREA AND CONTOURS OF THE WATER TABLE

The predominant landforms along the Delaware Atlantic shoreline are baymouth bars, spits, and shoreline dunes. Land-tied sand bars form the shoreline along the Cape Henlopen-Fenwick Island strip and extend across Rehoboth Bay, Indian River Bay, and Little Assawoman Bay. The sand bar at Indian River Bay is cut by Indian River Inlet. Indian River, which has its source south of Georgetown, Delaware, flows eastward into Indian River Bay. The elevation of most of the 25-mile strip of shoreline is generally less than 15 feet. Greater elevations are found in the Rehoboth Beach area where Columbia Group (Pleistocene) sands rise to 20 feet above sea level and in the Cape Henlopen-Fort Miles area where Holocene dune sands rise to 81 feet. Much of the area on the landward side of the sand bars and dunes is only slightly above sea level and consists of tidal flats and marshes. Pleistocene headlands cut by canals containing brackish water are located west of these low areas.

Previous Work

Although there had been earlier work on the geology of southern Delaware, the first preliminary report on the geology and ground-water resources of Delaware was by Marine and Rasmussen (1955). The ground-water resources of the Delaware Atlantic seashore were treated in more detail by W. C. Rasmussen, et al. (1960) in a report on the water resources of Sussex County, Delaware, with a section on the problem of salt-water encroachment at Lewes. Slaughter (1962) discussed the beach-area water supplies between Ocean City, Maryland, and Rehoboth Beach, Delaware.

Baker, et al. (1966) evaluated the water resources of the State in a report prepared for the Delaware State Planning Office. A report on Delaware water was prepared by Rasmussen, Odell, and Beamer (1966) as a U. S. Geological Survey Water-Supply Paper.

A more definitive look at the quantitative aspects of the hydrogeology of eastern Sussex County was presented by Sundstrom and Pickett (1969). The conclusions arrived at in their report were very helpful in the preparation of the present report.

Regional water-quality patterns and salt-water encroachment were treated by Back (1966) and Upson (1966). Woodruff included the Atlantic shore area in his discussions of the occurrence of saline ground water in

Delaware aquifers (1969) and the general ground-water quality of the fresh-water aquifers of Delaware (1970).

The Columbia (Pleistocene) deposits of Delaware were discussed by Jordan (1964, 1967). The coastal sedimentary environments of the Lewes-Rehoboth Beach area have been outlined by Kraft (1968). A geologic cross-section of Delaware was prepared by Kraft and Maisano (1968) and includes wells at Dewey Beach and Bethany Beach as well as a map showing the depths to crystalline basement rocks.

A brief summary of the environmental geology of the Delaware Atlantic shore area was made by Pickett (1969) as part of a larger environmental study of the Rehoboth, Indian River, and Assawoman Bays submitted to the Governor of Delaware by the Delaware State Planning Office.

Acknowledgments

The author of this report extends his appreciation for all assistance and discussion in the preparation of the evaluation of the ground-water resources of the Delaware Atlantic seashore to Dr. Robert R. Jordan, State Geologist of Delaware, for his suggestion of the project and review of the results; to other members of the Delaware Geological Survey, Dr. Thomas E. Pickett, Dr. Nenad Spoljaric, and Mr. Kenneth D. Woodruff for enlightening discussions and review of the text; to Dr. John C. Kraft, Chairman, Department of Geology, University of Delaware, for assistance in interpreting the Holocene-Pleistocene boundaries in the sediments of the coastal area and for use of data and cross-sections accumulated by him; to Miss Marlene A. Carucci for typing the manuscript; to Mr. Elliott M. Cushing and Mr. Irwin H. Kantrowitz of the U. S. Geological Survey for their comments regarding the interpretation of the geologic framework; and to Delmarva Drilling Company and Paul E. White and Sons Drilling Company for supplying well logs and discussions of ground-water distribution in the shore area. Mr. Charles E. Dill, Jr., and Mr. Glenn K. Elliott, graduate students in the Department of Geology at the University of Delaware, provided data and comments on the Holocene sediments of the shore area. Mr. Rudolph F. Jass and Mr. Rea Wilkie of the Delaware State Planning Office provided population data and discussions related to proposed test-drilling at Delaware Seashore State Park.

Well Numbering System

To facilitate the numbering of wells in Delaware, the State is divided into 5-minute quadrangles of latitude and longitude. As is 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 25 one-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. Wells within these 1-minute blocks are assigned serial numbers as they are scheduled. 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 Qj42-5 is the fifth well to be scheduled in the 1-minute block that has the coordinates "Qj42."

POPULATION GROWTH AND WATER NEEDS

Delaware Atlantic Seashore Population Growth

Population projections by the Delaware State Planning Office indicate that present water supplies (as developed) are insufficient to satisfy the needs of the summer populations of the beach communities and parklands along Delaware's Atlantic shoreline. Summer weekend populations now exceed 100,000 persons and will greatly exceed that number as the population of the metropolitan areas that use Delaware's shore area continues to grow.

A 1967 household survey of the Bethany Beach area by the State Planning Office indicates that the majority of the summer residents come from the Washington-Baltimore metropolitan area: 39% from Washington, D. C., 22% from Maryland, 7% from Virginia, 13% from Sussex County, Delaware, and 7% from Pennsylvania. Summer day visitors to Rehoboth Beach in 1966 were predominantly from Maryland, Pennsylvania, and Virginia. It seems reasonable to conclude that as the Washington, Baltimore, and eastern Pennsylvania metropolitan areas continue to grow, there will be a substantial increase in the Delaware Atlantic seashore peak resident and day visitor populations over the next twenty years.

The best source of estimating the peak summer resident population comes from G. P. Rasmussen (1969) in a report on

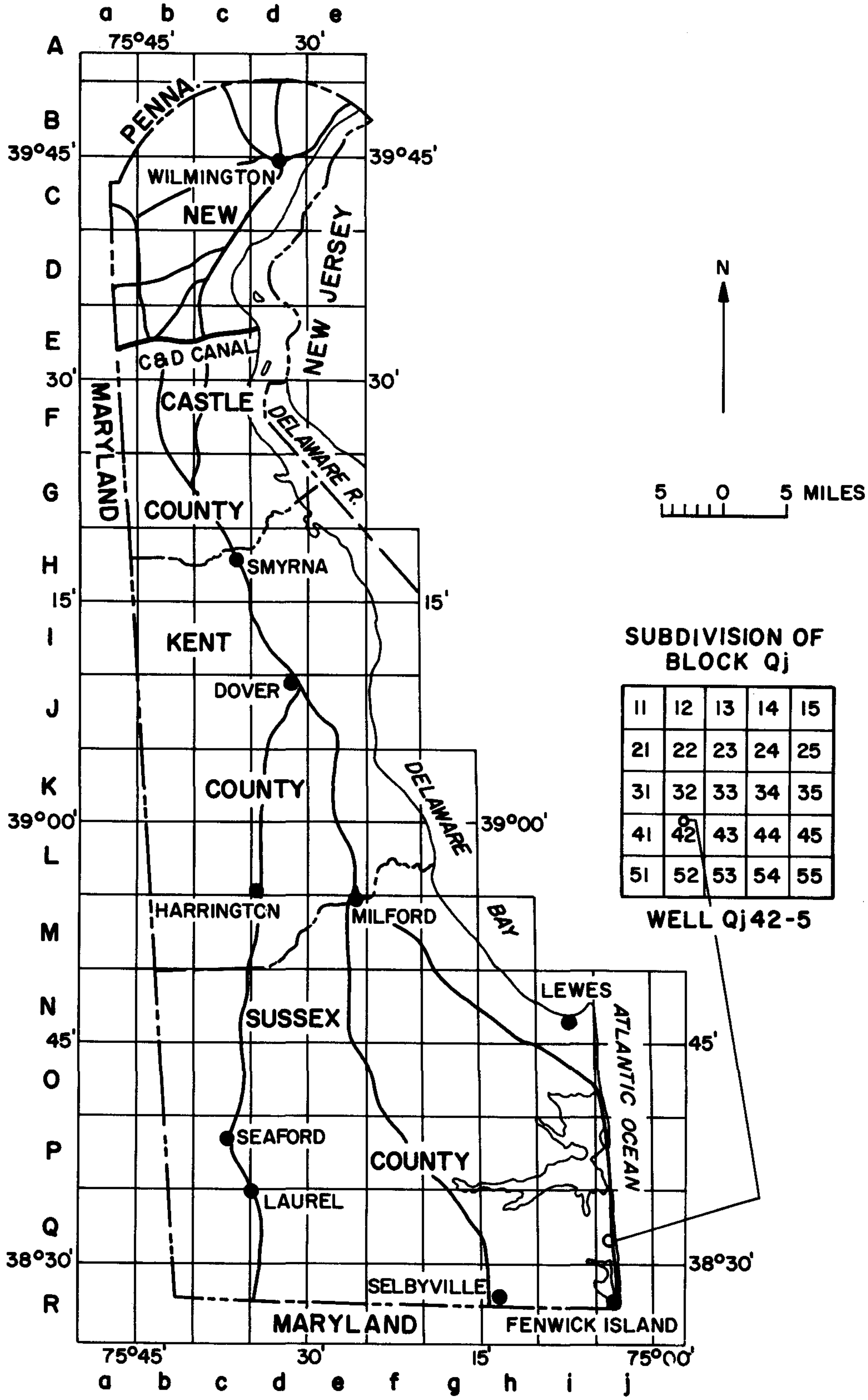

FIGURE 2. MAP SHOWING THE COORDINATES FOR THE WELL-NUMBERING SYSTEM.

the long range water pollution control plan for Sussex County, Delaware. Current population estimates and projections of permanent population were provided by the Delaware State Planning Office. Table 1 reports population in terms of sanitary sewer districts. These same districts were used to discuss present and projected water use along the shore area and are referred to in that portion of this report as water districts.

Present and Projected Water Use

Previous ground-water reports for the Delaware Atlantic seashore area have reported water use by each political entity. However, in light of the rapid growth of these beach communities and the fact that they have found it necessary to be grouped together into more efficient sanitary sewer districts, it seems logical that these same communities be grouped into water districts with the same boundaries as the sewer districts. Table 2 reports water use by sewer district. Figures for the years 1957 and 1966 are taken from previous reports and represent both metered and estimated use for all of the communities within the sewer district. Figures for the years 1970, 1990, and 2000 were arrived at from population projections given by Rasmussen. It was assumed that the average water use per day per person for these years would be 100 gallons. The projected populations are figures for peak summer resident population and do not include day visitors or trailer camps.

In addition to water use by the resident population within the sewer districts there is also a demand for potable water at the two state parks (Figure 1) along the Delaware Atlantic seashore. A report by the Delaware State Planning Office (1970) states that the instant capacity of Delaware Seashore State Park is now 41,000 and that an instant capacity of 66,000 is needed by 1980. Assuming a 20-gallon/day/person water use for visitors to these state parks the following amounts of water are needed: 0.82 mgd (1971) and 1.32 mgd (1980). At Cape Henlopen the projected instant capacity is 23,500 persons, requiring 0.47 mgd. The demand for water at these state parks is, however, peak demand during the tourist season.

Table 1. Delaware Atlantic seashore area sanitary sewer district population projections (G. P. Rasmussen, 1969).

	1970	1990	2000
1. Lewes-Rehoboth Beach			
a. City of Lewes	5,900	9,200	10,900
b. City of Rehoboth Beach	10,200	15,850	18,750
c. Dewey Beach Area	7,750	12,950	15,650
d. North Shores-Henlopen Acres	1,350	2,000	2,350
e. West Rehoboth Bay Vista	1,400	2,100	2,450
f. Midway Area	1,100	1,700	2,050
g. Murrays Corner-Five Points	1,000	1.250	1,400
Lewes-Rehoboth Total*	28,700	45,050	53,550
2. Greater Bethany Beach			
a. City of Bethany Beach-Sussex Shores	3,800	7,650	9,600
b. Ocean View and Millville	700	900	950
c. Middlesex Beach and South Bethany	1,150	3,700	5,000
d. North Bethany Beach Shoreline	100	6,000	9,000
Greater Bethany Beach Total*	5,750	18,250	33,550
3. Fenwick Island*+	2,900	4,950	6,000
Total sewered population	37,350	68,250	93,100

*Population represents peak summer resident population.
+Population includes unincorporated as well as incorporated areas within the proposed sanitary sewer district boundaries (see Rasmussen, 1969).
Population of trailer parks has not been included.

Table 2. Water use for the Delaware seashore area in million gallons per day (mgd).

Sewer District	1957*	1966**	1970	1990	2000
Lewes-Rehoboth Beach	1.135+	2.115	2.870	4.505	5.355
Greater Bethany Beach	0.040+	0.159	0.575	1.825	3.355
Fenwick Island	0.005	0.040	0.290	0.495	0.600
Total	1.175	2.278	3.735	6.825	9.310

*Data from W. C. Rasmussen, *et al.* (1960).
**Inventory of the use of water in Delaware by Stuart W. McKenzie, Hydrologist, Water Resources Center, University of Delaware.

GEOLOGY OF THE DELAWARE ATLANTIC SEASHORE

General Geologic Setting

The Delaware Atlantic seashore is part of the larger Atlantic Coastal Plain Province. Sediments of the Coastal Plain in Delaware strike approximately N45°E and dip to the southeast at 10 to 30 feet per mile with older units dipping more steeply. Geologic and hydrologic rock units tend to thicken downdip. The sequence of unconsolidated clays, silts, sands, and gravels overlying the crystalline basement is approximately 6,500 feet thick at Cape Henlopen and approximately 7,700 feet thick at Fenwick Island (Spangler and Peterson, 1950). The "basement complex" of probable Precambrian and Paleozoic age is overlain by strata of probable Triassic age, and by other sediments of known Cretaceous, Tertiary, and Quaternary ages (see Figure 3 for geologic cross-section of the Delaware Atlantic seashore area).

Most ground-water exploration along the Delaware Atlantic shoreline has been limited to depths of less than 200 feet. However, from this meager accumulation of descriptive logs and electric logs it is considered that enough knowledge has been gained to indicate the favorability of test wells to certain depths that have not yet been used as ground-water sources. Sands containing salt water are found at some horizons (500 feet at Cape Henlopen and 400 feet at Fenwick Island). Table 3 describes the

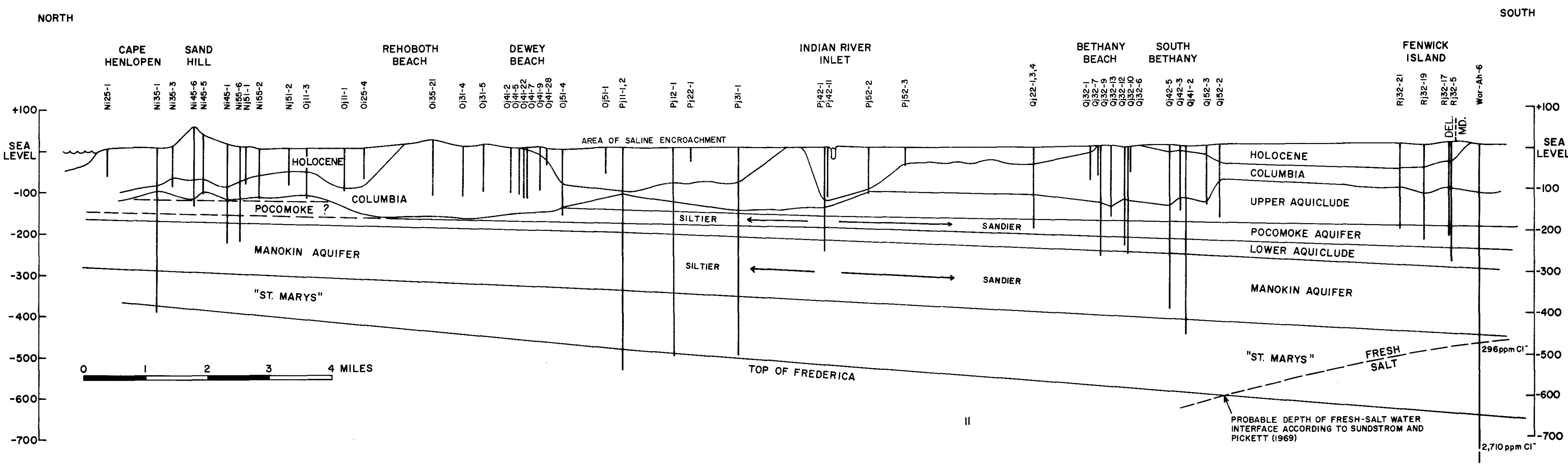

FIGURE 3. GEOLOGIC CROSS-SECTION OF THE DELAWARE-ATLANTIC SEASHORE AREA.

general nature, depths, and thicknesses of the stratigraphic and hydrologic units underlying the Delaware Atlantic seashore from the surface down to the salt-water horizons.

Table 3. Geologic units in the Delaware Atlantic shore area.

Series	Unit	Subunit	Thickness (ft)	Lithology
Holocene			0-130	clay, silt sand
Pleistocene	Columbia Group		10-180	sands and gravels
Miocene	Chesapeake Group	Upper aquiclude	10-100	silt and clay
		Pocomoke aquifer	35-55	fine to medium sand
		Lower aquiclude	20-50	silt and clay
		Manokin aquifer	120-160	fine to medium sand w/gravel
		St. Marys Fm. (?)	100-180	clay and silt
		Frederica aquifer	20 (?)	sand and silt

Miocene Series

In Delaware, Miocene sediments are correlated with the Chesapeake Group but are not subdivided into formations because available data do not conclusively indicate lithologic similarity and continuity with formations in New Jersey and Maryland. The Chesapeake Group unconformably overlies the glauconitic Piney Point Formation (Eocene) in the report area. Jordan (1962) describes the

Chesapeake Group as a gray and bluish-gray silt containing beds of gray, fine to medium sand and some shell beds. The major sand horizons are the principal Miocene aquifers in Delaware and are known as: Cheswold (lowermost), Frederica, Manokin, and Pocomoke (uppermost). In addition there are thin, probably discontinuous, water-bearing sandy zones referred to by Sundstrom and Pickett (1968) as "minor Miocene aquifers."

In this report, the term Chesapeake Group is adhered to except to note that the thick (100-180 feet) silt beneath the Manokin aquifer is probably in part the St. Marys (?) Formation (W. C. Rasmussen, et al., 1960; Sundstrom and Pickett, 1970).

As a result of a lack of detailed stratigraphic control, it seems more practical to consider the various units encountered in the subsurface to be hydrogeologic units (essentially, some units are aquifers and others are aquicludes) rather than formal geologic units.

Cheswold Aquifer

In eastern Sussex County the Cheswold is a 10-foot thick sandy zone consisting of medium to coarse silty sand and shells, often containing much silt. It tends to lose its identity as an aquifer to the southeast of Georgetown, Delaware, and probably pinches out just to the south of Rehoboth Beach (Sundstrom and Pickett, 1968, 1969). As the fresh-salt water interface in the Cheswold aquifer probably occurs at 700 feet below sea level (coinciding with the pinch-out point south of Rehoboth Beach) and as the permeability of the aquifer is low because of the increased silt content, making deep wells uneconomical, the Cheswold aquifer will not be considered as a source of ground water for the Delaware Atlantic seashore.

Frederica Aquifer

The Frederica aquifer is separated from the Cheswold aquifer by gray sandy silts. Lithologically the Frederica is very similar to the Cheswold, consisting of generally medium to coarse sand with some gravel and locally abundant shells (Marine and Rasmussen, 1955). It is likely that the Frederica aquifer pinches out just to the southeast of Lewes at a depth of 400 feet below sea level (Sundstrom and Pickett, 1969), although well Ni35-1 (well locations are shown in Figures 1 and 3) at Cape Henlopen derived fresh water from a depth of 385 feet (apparently the Frederica aquifer). Two additional wells, Pj11-1, south of Dewey Beach, and Wor-Ah-6, south of Fenwick Island in Maryland, have sandy horizons at 480 feet and 656 feet, respectively. These water-yielding or sandy horizons coincide with a downdip extension of contours on the top of the Frederica aquifer as prepared by Sundstrom and Pickett (1969), assuming a constant dip for the aquifer to the south of Lewes, Delaware. However, as it appears that the Frederica aquifer, like the Cheswold aquifer, becomes less permeable downdip and is most probably saline at a point south of Indian River Inlet, this aquifer is not considered as a source of ground water for the Delaware Atlantic seashore.

St. Marys Formation (?)

The sandy horizons previously mentioned as being the Frederica aquifer are separated from the Manokin aquifer by a thick (100-180 feet) aquiclude composed of gray silt and clay with fine sand. This aquiclude is probably, in large part, the St. Marys Formation (?) and is so considered for the purpose of this report. Some water may be derived from sandy lenses but, in general, the St. Marys Formation (?) will not be a source of ground water for the report area.

Manokin Aquifer

The Manokin aquifer is a gray fine- to medium-grained sand. The upper portion is generally finer-grained with silt and some layers of sticky gray clay. The lower portion is coarser, often containing coarse sands and pea-sized gravels. The entire sequence of sands seems to lack microfossils, but some horizons contain shell fragments. The Manokin subcrops beneath the Columbia Formation in a northeast-southwest trend across Delaware from north of Lewes, through Georgetown and Laurel, and into Maryland to the west of Delmar. The subcrop distribution of the Manokin in Delaware as reported by Slaughter (1962) and Sundstrom and Pickett (1969, 1970) is essentially the same: a belt from 6 to 10 miles in width (see Figure 4). The thickness of the aquifer in the Delaware Atlantic shore area ranges from 120 to 160 feet, with the greater thicknesses near Fenwick Island. Recent drilling at Delaware Seashore State Park and older well logs indicate that the Manokin aquifer to the north of Indian River Inlet is much siltier than to the south.

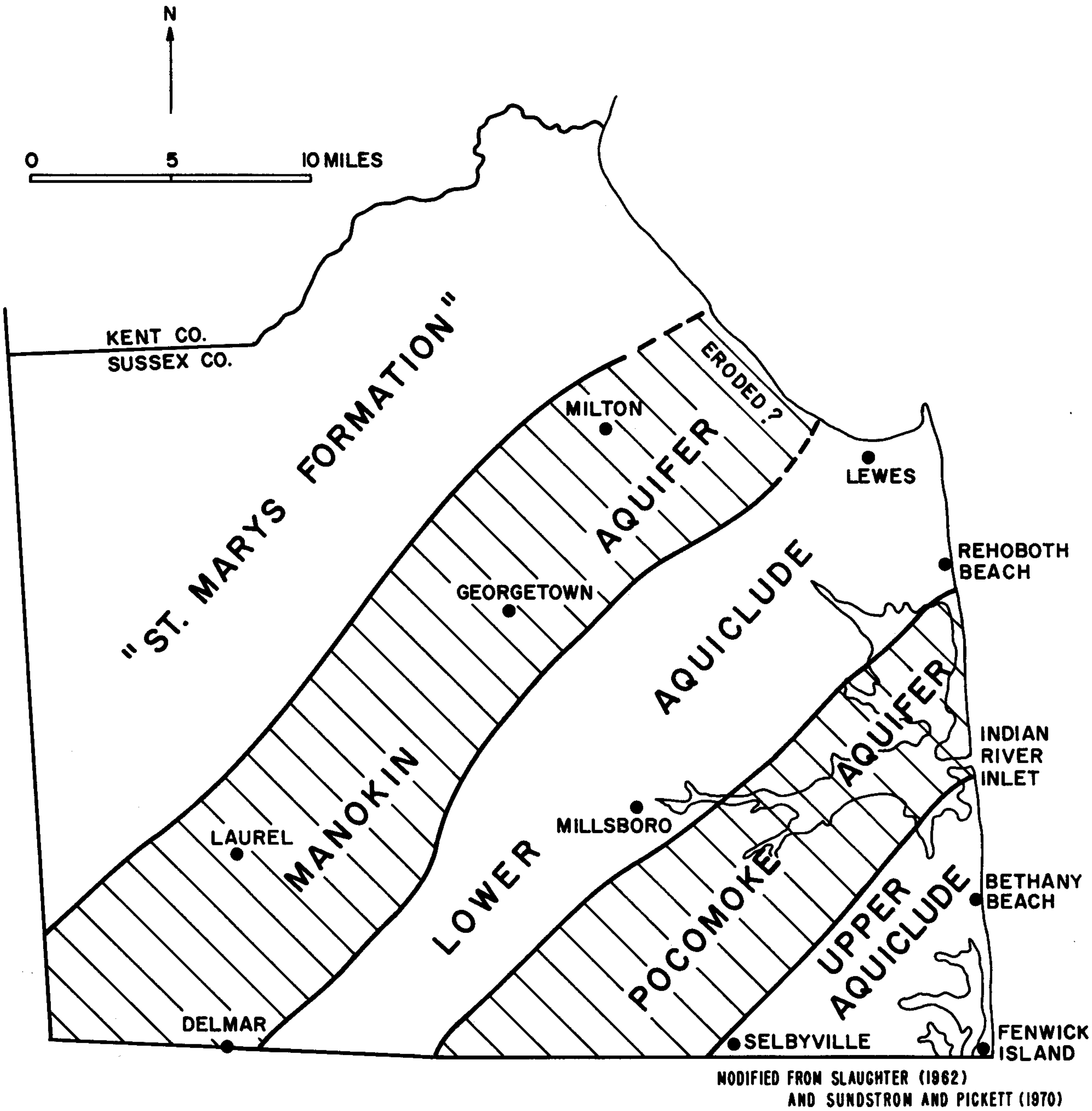

FIGURE 4. SUBCROP DISTRIBUTION OF THE MANOKIN AND POCOMOKE AQUIFERS.

Lower Aquiclude

The Manokin aquifer is separated from the Pocomoke aquifer by a sequence of clays, silts, and fine sands that act an an aquiclude. Some of the sands may yield small quantities of water for individual domestic wells. The thickness of the aquiclude ranges from 20 to 50 feet. The small thicknesses are in the Cape Henlopen-Rehoboth Beach area.

Pocomoke Aquifer

The Pocomoke aquifer is a gray fine- to medium-grained sand with some silty horizons and lenses of sticky gray clay. The Pocomoke is siltier to the north of Indian River Inlet. In the Delaware Atlantic shore area thicknesses range from 35 to 55 feet, with the greater thicknesses to the south. The aquifer subcrops beneath sands of the Columbia Group (Pleistocene) as an 8-mile wide belt extending to the southwest from just south of Rehoboth Beach to just east of Delmar (see Figure 4). Slaughter (1962) and Sundstrom and Pickett (1969, 1970) show the subcrop area of the Pocomoke aquifer in Delaware, and these patterns are reasonably accurate considering the well-data available. However, it seems likely that the northern edge of the Pocomoke subcrop should be shifted some two miles farther north than Slaughter indicated. Also, the Pocomoke has not been removed by Pleistocene erosion in the southeastern part of Sussex County as is indicated by Sundstrom and Pickett (1969).

Upper Aquiclude

In the southern part of the Delaware Atlantic seashore the Pocomoke aquifer is separated from the Pleistocene sands by a gray clay and silt sequence that protects against salt-water contamination from above. The thickness of the aquiclude ranges from 10 to 100 feet. The greater thickness in the southern portion of the area is attributable to the gain of a downdip sandy horizon in the Bethany Beach-Fenwick Island section.

Note on Miocene Aquifer Correlation

Previous interpretations of the Miocene aquifers along the Delaware Atlantic shore have considered that the first Miocene aquifer encountered below the

Pleistocene sands at the 170 to 200-foot depth in the Bethany Beach-Fenwick Island area was the Manokin aquifer (Rasmussen, _et al._, 1960; Baker, _et al._, 1966; Sundstrom and Pickett, 1969). The present report differs from these earlier studies in that it concludes that the aquifer encountered at this depth is actually the Pocomoke aquifer. This conclusion was arrived at after inspection of descriptive logs and electric logs for wells drilled in this area, particularly wells Qj42-5 and Wor-Ah-6. The Manokin aquifer is not encountered in wells at Bethany Beach until a depth of approximately 280 feet and at Fenwick Island at approximately 295 feet.

Pleistocene Series

In the Delaware Atlantic shore area the Pleistocene sediments consist of mostly coarse, moderately sorted, quartz sand with gravel and some thin silts. The Pleistocene Series has been subdivided in the report area into the Columbia, Omar, and Beaverdam Formations, or collectively, the Columbia Group (Jordan, 1962). The sediments are generally yellow- to reddish-brown, but also various tones of gray. The sands and gravels are similar in appearance to sands and gravels of the Chesapeake Group in some areas. The thickness of the Columbia Group sediments along the shore varies from 10 to 180 feet. The thickest sequences of Columbia sediments are beneath the Rehoboth Beach-Dewey Beach area, the area just to the north of Indian River Inlet, the Bethany Beach area, and at the Delaware-Maryland border near Fenwick Island. The Columbia sediments have almost been removed by post-Pleistocene erosion at Rehoboth Bay, Indian River Bay (south of the inlet), and to a lesser degree at Little Assawoman Bay.

Holocene Series

These sediments are predominantly estuarine deposits (silts, clays, and fine sands), lagoonal deposits (sandy silts and clays, rich in organic matter), and barrier bar deposits (medium to coarse, well-sorted sands), and dune sands. The thickest Holocene deposits are found in the areas of Cape Henlopen, Rehoboth Bay, Indian River Bay, and Little Assawoman Bay. Thicknesses of the sediments range from 0 to 180 feet. The upper surfaces and outer edges of these deposits are often in direct contact with brackish water or seawater, therefore they seldom serve as aquifers except on the barrier island bars where sufficient head is maintained to keep the salt water below the pumping level in wells.

GROUND-WATER HYDROLOGY OF THE AQUIFERS

As the fresh-salt water interface in certain aquifers occurs within the Delaware Atlantic seashore area or as the permeability of the aquifer is too low to economically warrant pumping from deep wells, geologic horizons such as the Cheswold aquifer and the Frederica aquifer, even though they might be water-bearing, are not considered as a source of ground water for the area. Only those aquifers that yield water of dependable quantity and reasonable quality are discussed below.

Manokin Aquifer

Although previous reports such as those prepared by Rasmussen and Slaughter (1955), Rasmussen, et al. (1960), and Sundstrom and Pickett (1969) present hydrologic data (specific capacities, storage coefficients, and transmissibility values) for the Manokin aquifer, the data was actually obtained from pump tests of what is now known to be the Pocomoke aquifer. As was explained in the previous note on Miocene aquifer correlation, the Manokin in the southern portion of the Delaware Atlantic shore area was not encountered until recently by deep drilling.

A recent pumping test at well Qj41-2, south of Bethany Beach, provides the only transmissibility value for the Manokin aquifer in this part of Delaware. Recovery data obtained after 25 hours of pumping at 205 gallons per minute gave a transmissibility of 29,250 gpd/ft. (gallons per day per foot). A specific capacity of 3.97 gallons per minute per foot of drawdown was also obtained. However, it is felt that the well was not completely developed and that a specific capacity of 10 gallons per minute per foot of drawdown is more representative. Table 4 shows examples of drawdowns caused by pumping 12 hypothetical wells 5,000 feet apart on a line from Indian River Inlet to Fenwick Island assuming a storage coefficient of 0.0005, a transmissibility of 29,250 gpd/ft., and a pumping period of 10,000 days from a 12-inch well. The volume of water available (8 million

Table 4. Examples of drawdowns in the Manokin aquifer caused by pumping 12 hypothetical wells 5,000 feet apart on a line from Indian River Inlet to Fenwick Island.

Well	1	2	3	4	5	6	7	8	9	10	11	12
Rate of pumping GPM	400	400	400	400	450	450	450	450	500	500	500	500
Drawdown of well 1 (ft)	43	14	12	10	9	9	8	8	7	7	7	6
" " " 2 "	14	43	14	12	10	9	9	8	8	7	7	7
" " " 3 "	12	14	43	14	12	10	9	9	8	8	7	7
" " " 4 "	10	12	14	43	14	12	10	9	9	8	8	7
" " " 5 "	11	12	13	16	48	16	13	12	11	10	9	9
" " " 6 "	10	11	12	13	16	48	16	13	12	11	10	9
" " " 7 "	9	10	11	12	13	16	48	16	13	12	11	10
" " " 8 "	9	9	10	11	12	13	16	48	16	13	12	11
" " " 9 "	9	10	10	11	12	13	15	17	53	17	15	13
" " " 10 "	9	9	10	10	11	12	13	15	17	53	17	15
" " " 11 "	8	9	9	10	10	11	12	13	15	17	53	17
" " " 12 "	8	8	9	9	10	10	11	12	13	15	17	53
Pumping Level (10,000 days)	152	161	167	171	177	179	180	180	182	178	173	164

Allowable drawdown	200 to 260 feet
Distance between wells	5,000 feet
Time of pumping	10,000 days
Transmissibility	29,250 gallons per foot
Coefficient of storage (assumed)	0.0005
Well diameter	12 inches
Well efficiency (assumed)	100 per cent

gallons per day) from the aquifer in the shore area is to be considered a maximum and assumes 100 percent well efficiency.

Pocomoke Aquifer

It has been stated by Sundstrom and Pickett (1969) that in the Bethany Beach area the artesian pressure of the Pocomoke (called Manokin by them) has not been seriously affected by pumping. Numerous wells drilled at Fenwick Island into this aquifer flow under artesian pressure, as does one well at Indian River Inlet. Sundstrom and Pickett report specific capacity data for five wells in the artesian portion of the aquifer range from 3.0 to 18.7 with an average of 11.7 gpm per foot of drawdown. It is their opinion that a specific capacity of 25 gpm per foot of drawdown will result if development of the wells is excellent. This is based on a transmissibility of 60,000 gallons per day per foot and a storage coefficient of 0.0005 (no S was reported in the study area but they concluded that this was a likely value). A transmissibility value of 26,500 gallons per day per foot reported at Ocean City, Maryland (six miles south of Fenwick Island), for the Manokin (possibly the Pocomoke) is also indicative of the potential of this aquifer. Table 5 shows examples of drawdowns caused by pumping 12 hypothetical wells 5,000 feet apart on a line from just north of Indian River Inlet to Fenwick Island assuming a transmissibility of 54,500 gpd/ft., a storage coefficient of 0.0005, and a pumping period of 10,000 days from a 12-inch diameter well. The volume of water available (10 million gallons per day) from the aquifer in the shore area is to be considered a maximum and should be used with some caution as the transmissibility value was obtained from a very short (two hours) pumping test on well Qj32-12 at Bethany Beach (the only data available).

Columbia Group (Pleistocene) Aquifer

Pumping tests at Lewes and at Rehoboth Beach have resulted in the determination of transmissibilities that range from 45,000 to 135,000 gpd/ft., with an average of 88,000 gpd/ft. Sundstrom and Pickett (1969) assumed that 100,000 gpd/ft. was representative of the aquifer. Specific capacities (gallons per minute per foot of drawdown) in the shore area range from 0.6 to 16.0, with the average for 22 wells being 6.9 gpm/ft. of drawdown. The higher specific capacities are in

Table 5. Examples of drawdowns in the Pocomoke aquifer caused by pumping 12 hypothetical wells 5,000 feet apart on a line from Indian River Inlet to Fenwick Island.

Well	1	2	3	4	5	6	7	8	9	10	11	12
Rate of pumping GPM	500	500	500	550	550	550	600	600	600	650	650	650
Drawdown of well 1 (ft)	29	10	9	8	7	7	6	6	6	5	5	5
" " " 2 "	10	29	10	9	8	7	7	6	6	6	5	5
" " " 3 "	9	10	29	10	9	8	7	7	6	6	6	5
" " " 4 "	8	9	11	32	11	9	8	8	7	7	6	6
" " " 5 "	8	8	9	11	32	11	9	8	8	7	7	6
" " " 6 "	7	8	8	9	11	32	11	9	8	8	7	7
" " " 7 "	7	8	8	9	10	12	35	12	10	9	8	8
" " " 8 "	7	7	8	8	9	10	12	35	12	10	9	8
" " " 9 "	7	7	7	8	8	9	10	12	35	12	10	9
" " " 10 "	7	7	8	8	8	9	10	11	13	38	13	11
" " " 11 "	7	7	7	8	8	8	9	10	11	13	38	13
" " " 12 "	6	7	7	7	8	8	8	9	10	11	13	38
Pumping Level (10,000 days)	112	117	121	127	129	130	132	133	132	132	127	121

Allowable drawdown	150 to 200 feet
Distance between wells	5,000 feet
Time of pumping	10,000 days
Transmissibility	54,500 gallons per foot
Coefficient of storage (assumed)	0.0005
Well diameter	12 inches
Well efficiency	100 per cent

the Lewes-Rehoboth Beach area and the lowest values in the Bethany Beach-Fenwick Island area. Sundstrom and Pickett also state that although coefficients of storage of the Pleistocene aquifer have been determined, they are too low and probably the true value approaches the effective specific yield (0.15) of the aquifer.

As was determined by Baker, et al. (1966), the amount of water available from the water-table aquifer (Columbia Group) in the Lewes area is 0.5 mgd/sq.mi. This amounts to 5.2 mgd (million gallons per day) in the area of Pleistocene headland within the 5-foot contour line shown in Figure 1 for the Lewes-Rehoboth Beach area. Assuming that the amount of water available in the Pleistocene headland west of Bethany Beach is the same (0.5 mgd/sq.mi.), an additional 4.5 mgd may be pumped from the area within the 5-foot contour shown in Figure 1.

Holocene Aquifer

At certain localities shallow drive-point wells obtain small quantities of water suitable for individual homes: Cape Henlopen to north of Rehoboth Beach; from south of Dewey Beach to north of Indian River Inlet; from south of Indian River Inlet to north of Bethany Beach; from south of Bethany Beach to just north of Fenwick Island. These areas are all located on the barrier island bars, and fresh water is available where the head is sufficient to keep the salt-water interface from reaching pumping wells. As an approximation, perhaps one million gallons per day are available from this aquifer without deterioration of water quality by saline intrusion. Wells should not be closely spaced because of the danger of salt-water contamination. Pollution potential from overflowing septic tanks also exists. Storm washover can also cause contamination of the aquifer.

GROUND-WATER CHEMICAL QUALITY

The U. S. Public Health Service (1962) has set up drinking water standards for public water supplies. They state that "drinking water shall not contain impurities in concentrations which may be hazardous to the health of consumers; that it should not be excessively corrosive to the water supply system, and that substances used in its treatment shall not remain in the water in concentrations greater than is required by good practice."

Ground-water quality analyses of waters from the Delaware Atlantic seashore aquifers do not include all of the constituents recommended by the U. S. Public Health Service. The following, for which the maximum recommended concentration is given, are generally reported: chloride (250 mg/l), iron (0.3 mg/l), and total dissolved solids (500 mg/l). One milligram per liter (mg/l) is approximately equivalent to one part per million (ppm) and the terms are used interchangeably in this report. Waters of less than pH 7.0 are acid and contribute to corrosion of water supply systems. Hardness is also reported in many of the analyses and may be classed (Durfor and Becker, 1964) as soft (0-60 mg/l of $CaCO_3$), medium hard (61-120), hard (121-180), and very hard (more than 180).

Manokin Aquifer

Chemical quality data of waters derived from the Manokin aquifer are quite meager because so few wells have penetrated the unit. Four wells supply the following:

Well No.	Chloride (ppm)	Iron (ppm)	Total Dissolved Solids (ppm)	Hardness (ppm as $CaCO_3$	pH
Qj42-5 (340-360 ft)	60	4	---	170	7.3
Wor Ah-6 (363-373 ft)	35	12	191	84	6.4
Ni55-6	---	5	---	---	6.3
Qj41-2 (341-366 ft)	65	7.7	---	103	6.9

Pocomoke Aquifer

Few data are available for the water quality of this aquifer. However, it is in use at Bethany Beach, Sussex Shores, and Fenwick Island. One well at Indian River Inlet penetrated to the horizon of the Pocomoke aquifer (170-180 feet) and reported irony water. Well Pj12-1 at Delaware Seashore State Park contains 220 ppm chloride due to salt-water encroachment. The Pocomoke in Maryland, south of the Delaware state line, has the following average chemical characteristics (Rasmussen and Slaughter, 1955): iron (4.5 ppm), bicarbonate (150 ppm), chloride (19 ppm), medium hard (105 ppm), total dissolved solids (187 ppm), and pH (7.0).

Pleistocene (Columbia) Aquifer

The iron content for 18 wells averages 2.6 ppm (range 0.04 to 7.5 ppm). The pH for 19 wells averages 6.5 (range 6.0 to 8.1). The hardness for 17 wells averages 46 ppm (range 17 to 84 ppm). Chlorides for 19 wells average 29.6 ppm (range 7 to 86 ppm). The aquifer is also vulnerable to pollution from septic tanks.

Holocene Aquifer

As in some parts of the Pleistocene aquifer where permeable sediments are in intimate contact with salt water, there are often problems of high chloride content in water derived from the Holocene sediments. Other factors which make development of the Holocene aquifer risky are high iron content, odor, taste, and vulnerability to pollution from septic tanks. In areas where there is sufficient fresh-water head established to hold back salt-water intrusion the water quality is similar to that of the Pleistocene aquifer.

SALT-WATER ENCROACHMENT

In coastal areas where permeable geologic materials such as sand are in intimate contact with saline bodies of water (the ocean, bays, lagoons, and marshes) there is an ever-present danger that over-pumping of unconfined or partially confined aquifers may result in salt-water contamination of the wells if the fresh-water head is not sufficient to hold back intrusion by the denser salt water. Over-pumping of confined aquifers can also result in contamination of the aquifer as salt water moves updip toward the pumping wells. In the case of confined aquifers the salt water present in the lower portions of the aquifer may be the result of higher stands of the sea or sea water entrapped in the sediments when they were originally deposited and which has not yet been flushed out by fresh water.

The position of the fresh-salt water interface can be reasonably predicted by a knowledge of the amount of fresh-water head in the aquifer. The Ghyben-Herzberg Principle states that the fresh-salt water interface is to be found 40 feet below sea level for every foot of fresh water above sea level. The relationship is expressed as:

$$h = (g-1)H$$

where:

h = height of fresh water above sea level
g = specific gravity of sea water
H = total depth of fresh water below sea level

If it is assumed that the average specific gravity of sea water is 1.025 and that the fresh water head is 1 foot above sea level then:

$$H = \frac{h}{g - 1} = \frac{1}{1.025 - 1}$$

$$H = 40 \text{ feet}$$

History of Salt-Water Encroachment in the Report Area

The towns of Lewes and Rehoboth Beach have had to abandon earlier wellfields because of salt-water encroachment of the Columbia (Pleistocene) aquifer by nearby bodies of salt water. As the demand for potable water increased in Lewes, salt water moved toward the city wellfield from the deepened Lewes and Rehoboth Canal (1943-44) and the location of a new wellfield was necessitated. The problem was resolved by the location of the wellfield on the Pleistocene headland to the southwest of the old wellfield (Marine and Rasmussen, 1955). The location is shown in Figure 1.

A similar situation existed at Rehoboth Beach (1943-44) where increased pumping resulted in salt-water contamination of the old wellfield located on the barrier island bar. Location of a new wellfield (Figure 1) to the west of the Lewes and Rehoboth Canal on the same Pleistocene headland as the new Lewes wellfield resolved the problem (Marine and Rasmussen, 1955).

The area of Cape Henlopen and Fort Miles has experienced water quality problems from salt-water contamination of Holocene and Pleistocene aquifers. This was resolved by locating the Fort Miles wellfield farther inland.

Dewey Beach, supplied by private wells, reports brackish water, high iron content, and marshy odor. These problems result from movement of water from the Holocene sediments into the Pleistocene aquifer due to pumpage.

Salt-water contamination has also been a problem at Indian River Inlet because the area is bounded on three sides by salt water and also because of the movement of salt water from the Holocene sediments of the bays and inlet into the Columbia (Pleistocene) aquifer.

Bethany Beach has not faced problems of salt-water intrusion. The shallow Columbia (Pleistocene) aquifer, which is vulnerable to salt-water intrusion, is not used extensively during the summer season in order to preserve its quality for year-round use. During the summer a well in the Pocomoke aquifer is used.

Shallow wells in Fenwick Island have been plagued by salt-water contamination due to the presence of bodies of salt water on two sides. A very thin veneer of Holocene sediments is not sufficient to prevent movement of the salt water into the Pleistocene aquifer. The upper Miocene aquiclude at Fenwick Island contains small sands that may also be contaminated by salt water in the Pleistocene aquifer.

Salt-Water Encroachment Potential of the Major Aquifers

The following summarizes the salt-water encroachment potential for the Delaware Atlantic seashore aquifers:

Manokin Aquifer

Ground-water in the Manokin aquifer of the southern portion of the seashore area is not salty at the present time. Water from 340-360 feet depth in well Qj42-5 contains 60 ppm chloride, and water from 363-373 feet depth in well Wor-Ah-6 (in Maryland, just south of Fenwick Island) contains 35 ppm chloride. However, there is some indication of a salt-water front in what this report considers to be the St. Marys Formation(?) as is illustrated in Figure 3. Control points for construction of the salt-water front are: fresh-salt water interface in 600 feet below sea level in the Frederica aquifer (Sundstrom and Pickett, 1969), and at 464-474 feet in the St. Marys

Formation(?) where 296 ppm chloride is reported (Kantrowitz, 1969). It would be advisable to monitor the water quality of Manokin wells in the southern portion of the shore area.

Well Pj12-1, recently drilled at Delaware Seashore State Park, contained 220 ppm chloride in the Pocomoke aquifer and resistivity curves of the electric log indicate that the Manokin aquifer is saltier. The higher chloride content of the ground water in this area is attributable to salt-water encroachment from Rehoboth Bay and the Atlantic Ocean as a result of the absence of sufficient fresh water head (originally maintained by the presence of a Pleistocene headland containing fresh water).

Pocomoke Aquifer

Wells at Ocean City, Maryland, some 8 miles south of Fenwick Island and 5.5 miles downdip, pump water from the Pocomoke and have never had trouble with salt water. The chloride content of these wells is about 30 ppm. Salt-water encroachment from the south is not a problem in the seashore area. However, as is mentioned above, the chloride level is approaching the limit (250 ppm) in the area to the east of Rehoboth Bay due to salt-water encroachment.

Columbia (Pleistocene) Aquifer

The sands of this aquifer, because of their unconfined nature and the presence of nearby bodies of salt water, are vulnerable to salt-water contamination due to excessive pumping or drainage practices which lower the fresh-water head and permit the salt water to move forward and upward. Figure 1 (contours from Sundstrom and Pickett, 1969) shows the five- and ten-foot contour lines on the water table in the Delaware Atlantic seashore area. The area between the five-foot contour and the Atlantic Ocean or other bodies of salt water (bays, inlets, canals, and marshes) is considered to be a danger zone because of the definite possibility of salt-water encroachment if pumping rates are excessive. Municipal wells and industrial wells that are to be pumped at high rates for long periods of time should be placed on the landward side of the ten-foot contour. Caution should be used by shore communities if heavy pumping is contemplated for wells placed between the five- and ten-foot contours. It would be advisable to maintain a line of forward monitor wells between the pumping wells and the salt-water front if very high pumping rates on a continuous basis are being considered.

It should also be pointed out that any deepening of the Assawoman Canal to the west of Bethany Beach could result in salt-water intrusion of the Columbia (Pleistocene) aquifer in a manner and degree comparable to what happened to the Lewes and Rehoboth wellfields when the Lewes and Rehoboth Canal was deepened. A wellfield located in this area should be positioned far enough away from the present Assawoman Canal to avoid this problem.

Holocene Aquifer

The problems mentioned for the Columbia (Pleistocene) aquifer are the same for the Holocene aquifer. This aquifer should be used only for individual domestic wells because the aquifers are usually thin and the proximity of the fresh-salt water interface is often quite close.

AREAL SUMMARY OF GROUND-WATER RESOURCES

A new interpretation of the geologic framework upon which the hydrologic data has been superimposed concludes that sufficient ground water is available to meet the needs of the Delaware Atlantic seashore area to at least the year 2000.

Correlation of two Miocene aquifers, the Manokin and the Pocomoke, by means of electric logs and descriptive logs results in a revision of the subsurface geology of southeastern Delaware and the discovery of a deeper aquifer that is the true downdip extension of the Manokin aquifer.

The Manokin and Pocomoke aquifers will yield a maximum of 8 and 10 million gallons per day, respectively, in the shore area. The Columbia (Pleistocene) aquifer will yield 5.2 million gallons per day from the headland to the south of Lewes and 4.5 million gallons per day from the headland to the southwest of Ocean View-Millville. Approximately one million gallons per day is available from small wells along the barrier island bars, but this water is more vulnerable to salt-water contamination and pollution from septic tanks. The water from the Manokin and Pocomoke aquifers will need more treatment than water from the Pleistocene aquifer but they are less vulnerable to salt-water encroachment.

The following is a summary of the ground-water resources by area along the Delaware Atlantic seashore in terms of sewer districts. Some recommendations are made for test drilling.

Lewes-Rehoboth Beach

Additional quantities of water for this area can be obtained from more wells on the Pleistocene headland where the present wellfields are located. The community of Dewey Beach, which does not have a central water supply, should consider exploratory holes to the Manokin aquifer (200-250 feet deep) or obtaining water from Rehoboth Beach.

Cape Henlopen State Park

Some water can be obtained from the old wellfield used by Ft. Miles. Water can also be obtained in small quantities from the Pleistocene and Holocene aquifers in the area. Drilling wells near the Lewes and Rehoboth Canal is not recommended because of past problems of salt-water encroachment toward wellfields near the Canal.

Delaware Seashore State Park

Expansion of recreational facilities will require additional water supplies. Well Pj12-1, drilled in July, 1971, indicates that salt-water encroachment has taken place in both the Pocomoke and Manokin aquifers in the northern part of the park. Further test-drilling is recommended at Indian River Inlet to test these two aquifers. Although the water from the Pocomoke is irony, it is considered that the chloride content will be lower and the yield greater.

Greater Bethany Beach

This area has four alternatives for ground water: 1) maintaining the present wells in the Pleistocene aquifer; 2) drilling additional wells in the Pocomoke aquifer; 3) drilling new wells to the Manokin aquifer; 4) construction of a wellfield on the Pleistocene headland to the south of Millville and southwest of Ocean View where the water table contours indicate a fresh water head in excess of 10 feet.

Fenwick Island

At present the greater number of wells in Fenwick Island are drilled into the Pocomoke aquifer. A number of small wells obtain water from the Pleistocene aquifer but there seems to be a threat of salt-water encroachment. Deeper wells to the Manokin may be warranted in the future.

CAUTIONS AND RECOMMENDATIONS

The proper utilization of the ground-water resources of the Delaware Atlantic seashore depends on an awareness of the interaction of the various components of the hydrologic cycle. This is the complete cycle through which water passes, commencing as water vapor in the atmosphere, changing to rain, snow or ice, then moving along or into the ground, and finally returning to the atmosphere by means of evaporation and transpiration. A decrease in precipitation can result in lowering of water tables, permitting salt-water intrusion, drying-up of shallow wells, and increased pumping costs. Deepening, widening, or addition of canals and drainage ditches can lower the water table or permit the entrance of salt water into the aquifer, as has occurred along the Lewes and Rehoboth Canal. Improper well-spacing can result in well interference and excessive drawdown. High water table and the presence of septic tanks might result in contamination of the aquifer by overflow from the septic tanks. The elimination of the recharge areas due to overdevelopment and covering with impermeable surfaces can lower the water table.

Well construction standards as established by the Delaware Water and Air Resources Commission should be strictly adhered to in order to avoid aquifer contamination by surface waters.

Development of the inland ground-water resources, those on the Pleistocene headlands and farther west, may be more economical than the deeper aquifers because of treatment costs. The waters from the Pocomoke and Manokin aquifers generally are more acid, harder, and very irony as compared to the Columbia (Pleistocene) aquifer. However, the cost of water lines from the headlands to the shore areas may be more expensive than treatment of the water from the deeper aquifers. A much greater amount of water is available to the west of the seashore area and if needed can be brought to the centers of population along the shore.

The possibility and desirability of recharge of treated waters to the water-table (Columbia) aquifer should be considered. Treatment to remove nitrates would be necessary. The benefits of recharge are quite obvious, but certain problems might arise. If recharge took place in areas of high water table, this might result in flooded basements and swampy properties. The consideration of recharge should include a knowledge of what might happen to the area when the water is spread over the surface of the ground or pumped down recharge wells. At present it appears that recharge will not be needed because of the low population density, but this might change in the future. In addition, recharge on the seaward side of wellfields in the Columbia (Pleistocene) aquifer might prevent salt-water intrusion.

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