UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HYDROGEOLOGIC CONDITIONS IN THE COASTAL PLAIN OF NEW JERSEY

By Eric F. Vowinkel and W. Kendall Foster

Open-File Report 81-405

Prepared in cooperation with the

U.S. ENVIRONMENTAL PROTECTION AGENCY

REGION II, WATER SUPPLY BRANCH

March 3, 1849

Trenton, New Jersey

April 1981

CONTENTS

Page

TABLES

GLOSSARY--Continued

Hydrologic cycle. The circulation of water from the sea, through the atmosphere, to the land; and thence, with many delays, back to the sea by overland and subterranean routes, and in part by way of the atmosphere; also the many short circuits of the water that is returned to the atmosphere without reaching the sea.

Hydraulic gradient. The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Infiltration. The flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradistinction to the word percolation, which connotes flow through a porous substance.

National Geodetic Vertical Datum of 1929 (NGVD of 1929). A geodetic datum derived from a general adjustment of first-order level nets of both the United States and Canada, formerly called "*mean sea level*."

Outcrop area. Regions where geologic units are exposed at or near the land surface.

Potentiometric surface. An imaginary surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Potential evapotranspiration. Water loss that will occur if at no time there is a deficiency of water in the soil for use of vegetation.

Precipitation. The discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface.

Reach. Generally, any length of a river.

Recharge area. The location where water enters the aquifer.

Runoff. The part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man in or on the stream channels.

Saltwater intrusion. Movement of saltwater so that it replaces fresh ground water.

FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC UNITS

For those readers who may prefer to use metric units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric units
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($(ft^3/s)/mi^2$)	0.01093	cubic meter per second per square kilometer ($(m^3/s)/km^2$)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch (in)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)

HYDROGEOLOGIC CONDITIONS IN THE COASTAL PLAIN OF NEW JERSEY

By
Eric F. Vowinkel and W. Kendall Foster

ABSTRACT

A wedge-shaped mass of unconsolidated sediments composed of alternating layers of clay, silt, sand, and gravel underlies the Coastal Plain of New Jersey. The hydrologic units of this mass vary in thickness, lateral extent, lithology, and water-bearing characteristics. Some of the units act as aquifers, whereas other units act as confining layers.

The entire sediment wedge is almost an independent and isolated hydrologic system. Components of the long-term hydrologic budget for the Coastal Plain are precipitation, streamflow, and water loss. Under natural conditions, average precipitation is about 44 inches per year; while streamflow and water loss are about 20 and 24 inches per year, respectively. More than 75 percent of the streamflow in the Coastal Plain is derived from ground-water runoff.

Some activities of man have modified the natural hydrologic cycle in the Coastal Plain. The primary activity affecting the system has been the withdrawal of ground water. Major changes in the flow patterns of water in several aquifers have been recognized during the past few decades partially as a result of increasing ground-water withdrawal. Where head gradients are large enough, water can be induced to flow from adjacent surface-water bodies or through confining beds. Induced recharge from the Delaware River to the Potomac-Raritan-Magothy aquifer system is occurring as a result of pumping stresses in the outcrop area of the aquifer. Recharge from the river to the aquifer from Salem to Burlington County was estimated to be about 113 cubic feet per second in 1978.

INTRODUCTION

Purpose and Scope

The U.S. Environmental Protection Agency (EPA) has been petitioned to designate the unconsolidated sediments underlying the counties of Monmouth, Burlington, Ocean, Camden, Gloucester, Atlantic, Salem, Cumberland, Cape May, and part of Mercer and Middlesex in New Jersey (fig. 1) as a sole or principal drinking water source for that area. This action is pursuant to Section 1424(e) of the Safe Drinking Water Act of 1974.

The U.S. Environmental Protection Agency, Region II, Water Supply Branch, has acted on this petition by requesting from the U.S. Geological Survey, Water Resources Division, New Jersey District, a hydrogeologic appraisal of the Coastal Plain of New Jersey. This report presents that appraisal and includes a description of the ground-water system, computation of an approximate hydrologic budget, and a summary of the effects of ground-water withdrawals on the natural hydrologic system of the Coastal Plain.

Method of Investigation

A base period from 1941 to 1978 was selected to determine from existing data, averages of stream discharge, precipitation, and water loss. Major ground-water withdrawal data from 1956 to 1978 are summarized by type of purveyor and aquifer. A digital simulation model of the Potomac-Raritan-Magothy aquifer system (Luzier, 1980) is utilized to estimate inflow and outflow from the aquifer and flow between the aquifer and the Delaware River.

Previous Studies

The hydrogeology of the Coastal Plain of New Jersey has been studied for a number of years. Recent aquifer simulation studies include reports on the Potomac-Raritan-Magothy aquifer system (Luzier, 1980), Farrington aquifer (Farlekas, 1979), Englishtown aquifer (Nichols, 1977), and the Wenonah-Mount Laurel aquifer (Nemickas, 1976). Prior to simulation studies county water-resources investigations were conducted. Significant county reports include Camden County (Farlekas and others, 1976), Ocean County (Anderson and Appel, 1969), Monmouth County (Jablonski, 1968), Atlantic County (Clark and others, 1968), Burlington County (Rush, 1968), Cumberland County (Rooney, 1971), Salem County (Rosenau and others, 1969), Gloucester County (Hart and Hilton, 1969), Middlesex County (Barksdale and others, 1943), Cape May County (Gill, 1962), and Mercer County (Vecchioli and Palmer, 1962). Parker and others (1964) investigated the water resources of the Delaware River basin. Rhodehamel (1973, 1970) investigated the geology and hydrology of the Mullica River basin and the Pine Barrens region in the Coastal Plain.

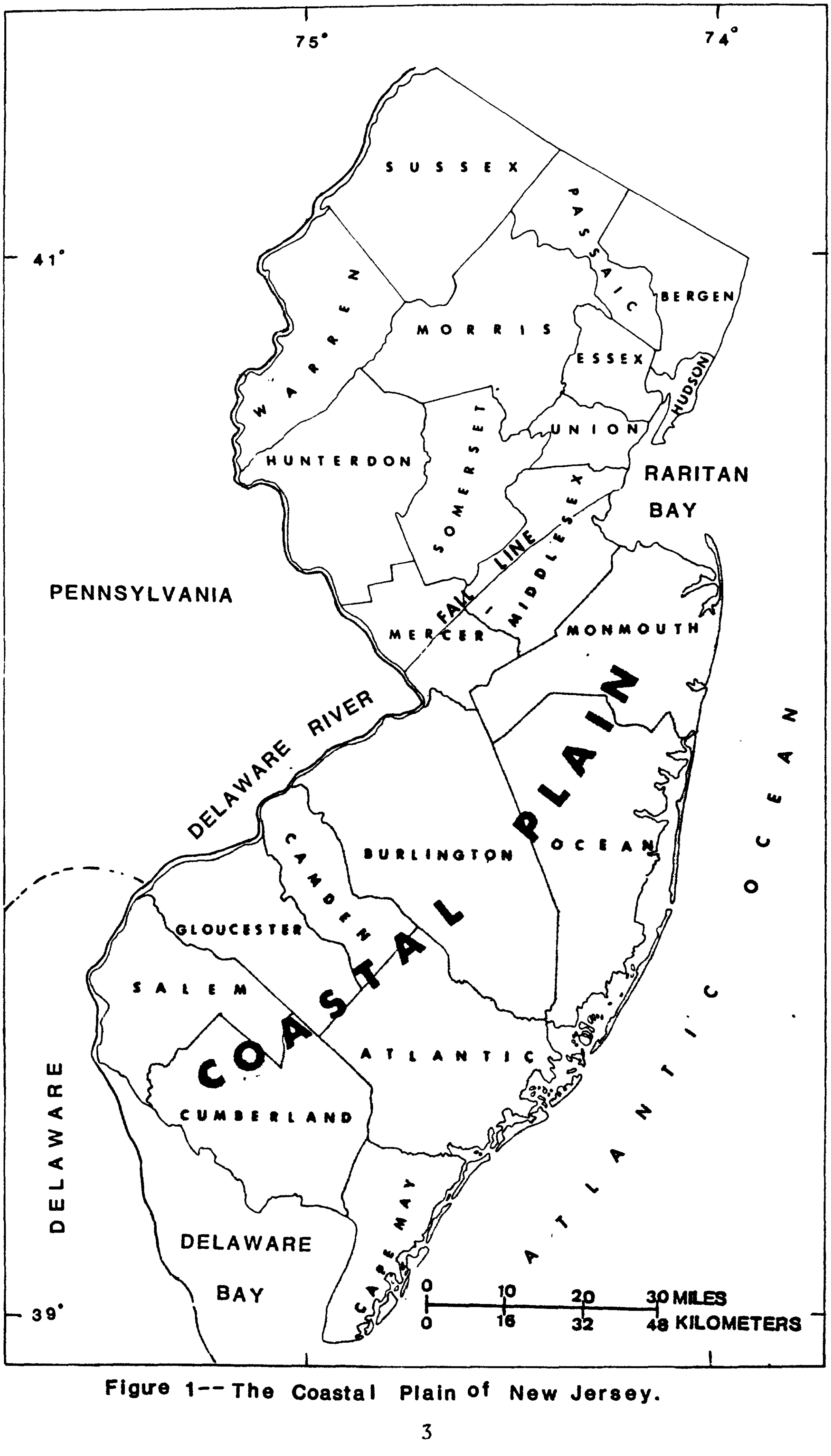


Figure 1--The Coastal Plain of New Jersey.

Acknowledgments

Special acknowledgments are extended to Anthony J. Velnich and George M. Farlekas who contributed drainage basin area information and the Potomac-Raritan-Magothy aquifer system model results, respectively.

DESCRIPTION OF THE AREA OF INVESTIGATION

Physiography

The Coastal Plain of New Jersey is part of the Atlantic Plain physiographic province. A Fall Line, extending northeast along the Delaware River and through Mercer and Middlesex counties, separates the Coastal Plain from the Appalachian Highlands. The Fall Line separates areas with major differences in topography, geology, and hydrology.

The Coastal Plain, lying southeast of the Fall Line, covers about 4,200 square miles. More than half of the land area is below an altitude of 50 feet above sea level (NGVD). The area is largely surrounded by salty or brackish water and is bounded by the Delaware River on the west, Delaware Bay on the south, the Atlantic Ocean on the east, and Raritan Bay on the north.

The land surface is divided into drainage basins (fig. 2). A drainage basin is an area that contributes runoff to a stream and its tributaries. A drainage divide marks the topographic boundary between adjacent drainage basins. A major stream divide in the Coastal Plain of New Jersey separates streams flowing to the Delaware River and the Atlantic Ocean.

Structural Setting

The New Jersey Coastal Plain is underlain by a wedge-shaped mass of unconsolidated sediments composed of clay, silt, sand and gravel. The wedge thins to a featheredge along the Fall Line and attains a thickness of over 6,000 feet at the tip of Cape May County, New Jersey (fig. 3). These sediments range in age from Cretaceous to Holocene and can be classified as continental, coastal, or marine deposits. The Cretaceous and Tertiary sediments generally strike on a northeast-southwest direction and dip gently to the southeast from 10 to 60 ft/mi. The overlying Quaternary deposits, where present, are basically flat lying. The unconsolidated Coastal Plain deposits are unconformably underlain by a pre-Cretaceous basement bedrock complex, which consists primarily of Precambrian (?) and lower Paleozoic rocks. Locally, along the Fall Line in Mercer and Middlesex Counties, Triassic rocks underlie the unconsolidated sediments. The geologic formations, their lithologies, and water-bearing characteristics are given in table 1.

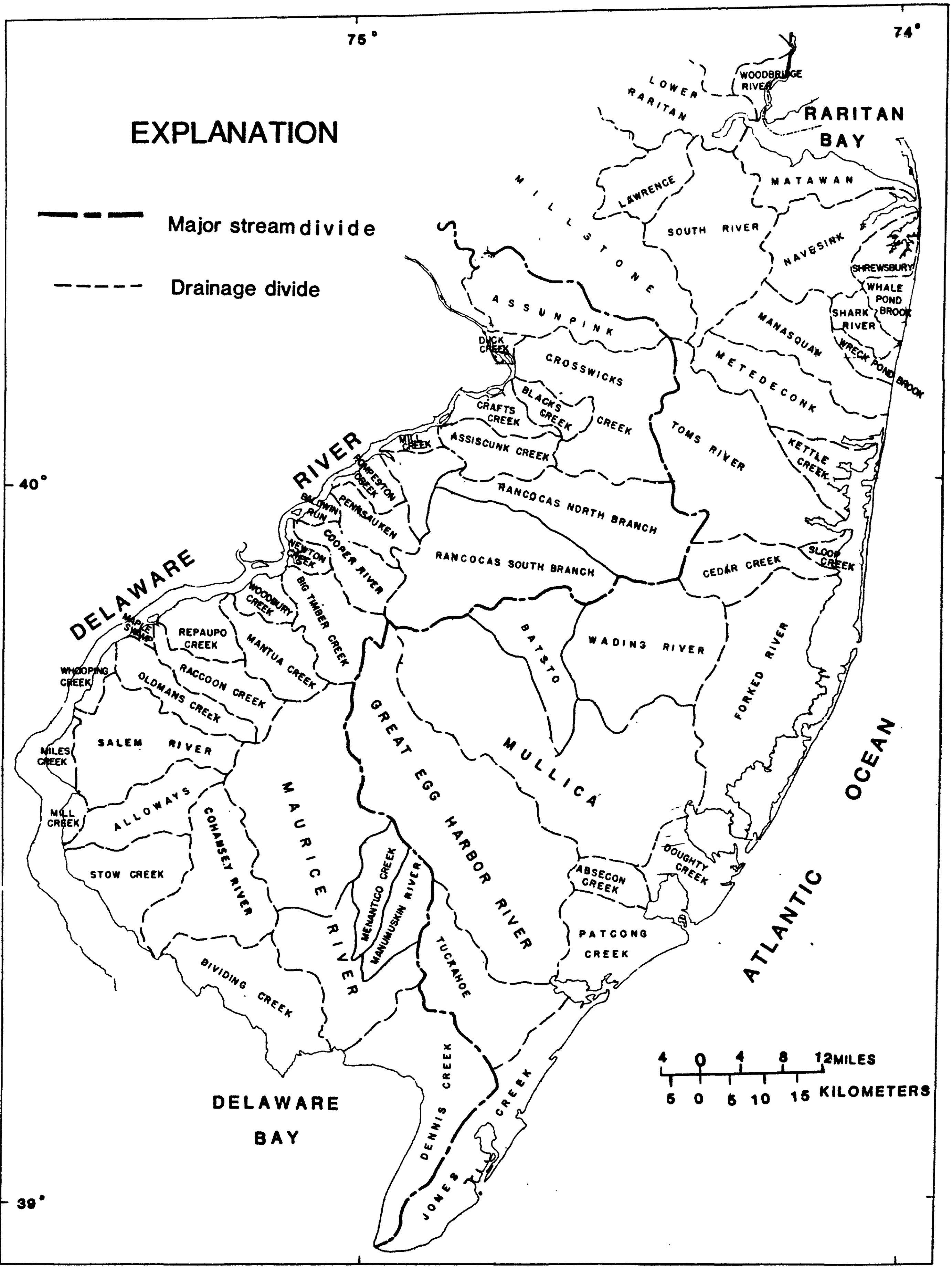


Figure 2-- Drainage basins in the Coastal Plain of New Jersey.

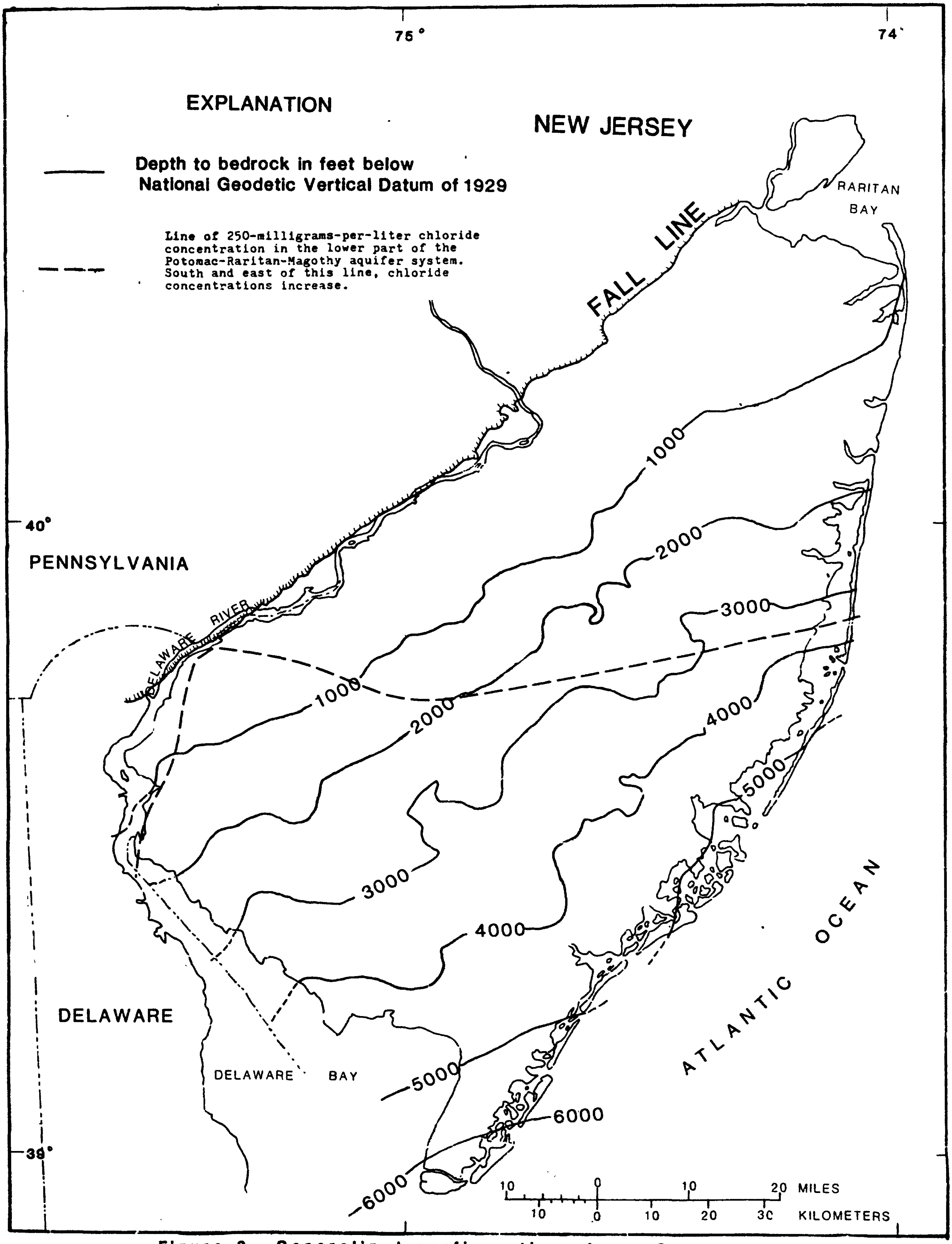


Figure 3--Generalized configuration of pre-Cretaceous bedrock surface below the Coastal Plain of New Jersey.
(Modified from Gill and Farlekas, 1976.)

Table 1--Maximum thickness, lithology, and water-bearing characteristics of geologic formations of the Coastal Plain of New Jersey.

SYSTEM	FORMATION	MAXIMUM REPORTED THICKNESS	LITHOLOGY	WATER-BEARING CHARACTERISTICS
Quaternary	Alluvial deposits	80	Sand, silt, and black mud.	Locally may yield small quantities of water to shallow wells.
	Beach sand and gravel		Sand, quartz, light-colored, medium grained, pebbly.	
	Cape May Formation	200	Sand, quartz, light-colored, heterogenous, clayey, pebbly, glauconitic.	Thicker sands are capable of yielding large quantities of water.
Tertiary	Pensauken Formation			
	Bridgeton Formation			
	Beacon Hill Formation	40	Gravel, quartz, light-colored, sandy.	No known wells tap this formation.
	Cohansey Sand	250	Sand, quartz, light-colored, medium to coarse-grained, pebbly; local clay beds.	A major aquifer. Ground-water occurs generally under water-table conditions. In Cape May, the aquifer is under artesian conditions. Inland from the coast and in the northern part of Ocean County, the upper part of the Kirkwood Formation is in hydraulic connection with the Cohansey Sand.
	Kirkwood Formation	780	Sand, quartz, gray to tan, very fine- to medium-grained, micaceous, and dark-colored diatomaceous clay.	Includes two aquifers. The principal artesian aquifer along the Atlantic Coast is the lower aquifer or the Atlantic City "800-foot" sand. The upper aquifer is artesian in Cape May. In the Atlantic City area it is also artesian but thin (10-20 feet) and not presently being used. Inland from the coast and in the northern part of the coast in Ocean County, the upper aquifer consists of the upper part of the Kirkwood Formation and the Cohansey Sand. Locally may be under semiartesian or artesian conditions.
	Piney Point Formation	220	Sand, quartz and glauconitic, fine- to coarse-grained.	Minor aquifer in New Jersey. Greatest thickness in Cumberland County.
	Shark River Marl	140?	Sand, quartz and glauconite, gray, brown, and green, fine- to coarse-grained, clayey, and green silty and sandy clay.	Locally may yield small quantities of water to wells.
	Manasquan Formation	180		Locally may yield small to moderate quantities of water to wells.
	Vincentown Formation	100	Sand, quartz, gray and green, fine- to coarse-grained, glauconitic, and brown clayey, very fossiliferous, glauconite and quartz calcarenite.	Locally may yield small to moderate quantities of water to wells.
	Hornerstown Sand	35	Sand, glauconite, green, medium- to coarse-grained, clayey.	Locally may yield small quantities of water to wells.
Cretaceous	Tinton Sand	25	Sand, quartz, and glauconite, brown and gray, fine- to coarse-grained, clayey, micaceous.	No known wells tap this sand.
	Red Bank Sand	150		Yields small quantities of water to wells in Monmouth County.
	Navesink Formation	50	Sand, glauconite, and quartz, green, black, and brown, medium- to coarse-grained, clayey.	Locally may yield small quantities of water to wells.
	Mount Laurel Sand	220	Sand, quartz, brown and gray, fine- to coarse-grained, glauconitic.	A major aquifer in the northern part of the Coastal Plain. A sand unit within the two formations forms a single aquifer.
	Wenonah Formation		Sand, quartz, gray and brown, very fine- to fine-grained, glauconitic, micaceous.	
	Marshalltown Formation	30	Sand, quartz and glauconite, gray and black, very fine to medium-grained, very clayey.	Leaky confining bed.
	Englishtown Formation	220	Sand, quartz, tan and gray, fine- to medium-grained; local clay beds.	A major aquifer in the northern part of the Coastal Plain. Two aquifer units in Ocean County.
	Woodbury Clay	325	Clay, gray and black, micaceous.	The two formations form a major confining unit throughout the New Jersey Coastal Plain. Locally the Merchantville may yield small quantities of water to wells.
	Merchantville Formation		Clay, gray and black, micaceous, glauconitic, silty; locally very fine-grained quartz and glauconitic sand.	
	Magothy Formation	4100	Sand, quartz, light-gray, fine-grained, and dark-gray lignitic clay.	Major aquifer system in New Jersey Coastal Plain. In the northern part of the Coastal Plain, two aquifers have been defined. They are the Farrington aquifer (mainly Raritan age) and the Old Bridge aquifer (Magothy age).
	Raritan Formation		Sand, quartz, light-gray, fine- to coarse-grained, pebbly, arkosic, red, white, and variegated clay.	
	Potomac Group		Alternating clay, silt, sand, and gravel.	
Pre-Cretaceous	Pre-Cretaceous Unconsolidated rocks and Wissahickon Formation	?	Precambrian and lower Paleozoic crystalline rocks, metamorphic schist and gneiss; locally Triassic basalt, sandstone, and shale.	Except along Fall Line, no wells obtain water from these consolidated rocks.

Major Aquifers and Confining Units

The wedge of sediment comprises one interrelated aquifer system that includes several aquifers and confining units. In general, aquifers and confining units in the Coastal Plain correspond to the geologic formations presented in table 1. However, the boundaries of the aquifers and confining beds may not be the same as the geologic formations for the following reasons: (1) the formations may change in physical character from place to place and may act as an aquifer in one area or a confining bed in another; (2) some formations are divided into several aquifers and confining beds; (3) adjacent formations may form a single aquifer or confining bed.

There are five major aquifers in the Coastal Plain. They are the Potomac-Raritan-Magothy aquifer system, Englishtown aquifer, Wenonah-Mount Laurel aquifer, lower "800-foot" sand aquifer of the Kirkwood Formation and the Kirkwood-Cohansey aquifer. The major aquifers and their respective confining units are described in ascending order from the bedrock surface.

Overlying the consolidated rocks of the bedrock is the Potomac-Raritan-Magothy aquifer system. This wedge-shaped mass of sediments of Cretaceous age is composed of alternating layers of clay, silt, sand, and gravel. These deposits range in thickness from a featheredge along the Fall Line to more than 4,100 feet beneath Cape May County. The Potomac-Raritan-Magothy aquifer system is exposed in a narrow outcrop along the Fall Line and the Delaware River. The aquifer is confined except in outcrop areas by the underlying crystalline rocks and the overlying Merchantville-Woodbury confining unit. In the northern part of the Coastal Plain, the Potomac-Raritan-Magothy aquifer system is divided into two aquifers. They are the Farrington aquifer (mainly Raritan age) and the Old Bridge aquifer (Magothy age).

A large part of the Potomac-Raritan-Magothy aquifer system in the southern Coastal Plain of New Jersey contains salty ground water with chloride concentrations ranging from less than 250 to as high as 27,000 mg/L (Luzier, 1980). The concentrations of chloride increase with depth as well as toward the ocean. The line of 250 mg/L chloride concentration in the lower part of the Potomac-Raritan-Magothy aquifer system is shown in figure 3.

The Merchantville Formation and Woodbury Clay form a major confining unit throughout most of the Coastal Plain of New Jersey. Although their permeability is very low, the Merchantville-Woodbury confining unit can transmit significant quantities of water when sizeable differences in potentiometric head exist between overlying and underlying aquifers.

The Englishtown aquifer overlies the Merchantville and Woodbury confining unit in the central and northern parts of the Coastal Plain. The aquifer is a significant source of water for Ocean and Monmouth Counties. In northern and eastern Ocean

County, the Englishtown aquifer can be subdivided into two water-bearing sands. Upper and lower units of quartz sand with thin interbeds of dark sandy silt are separated by a thick sequence of sandy and clayey lignitic silt (Nichols, 1977).

The Marshalltown Formation overlies the Englishtown sand in most of the Coastal Plain but overlies the Woodbury Clay in much of Salem County. The formation has a maximum thickness of 30 feet. Because the Marshalltown Formation is thin and contains some slightly to moderately permeable beds, it acts as a leaky confining bed.

Although the Wenonah Formation and Mount Laurel Sand are distinct lithologic units, they are hydraulically connected and together form the Wenonah-Mount Laurel aquifer. The Mount Laurel Sand, a coarser sand unit than the Wenonah Formation, is the major component of the aquifer. The combined thickness of the Wenonah Formation and Mount Laurel Sand in outcrop is as much as 100 feet. In the subsurface they range in thickness from 40 feet to slightly more than 200 feet (Nemickas, 1976). The Wenonah-Mount Laurel aquifer is an important water producing aquifer in the northern and western parts of the Coastal Plain.

Overlying the Wenonah-Mount Laurel aquifer is a confining unit that comprises several geologic units. The confining unit consists of the Navesink Formation, Red Bank Sand, Tinton Sand, Hornerstown Sand, Vincentown Formation, Manasquan Formation, Shark River Marl, Piney Point Formation and the basal clay of the Kirkwood Formation. Some of these geologic units may act as aquifers on a local basis.

The Kirkwood Formation includes several water-bearing units. The major Kirkwood aquifer is the principal artesian aquifer within the Kirkwood Formation, also known as the Atlantic City "800-foot" sand (Barksdale and others, 1936). The Kirkwood "800-foot" sand aquifer extends along the Atlantic Coast from Cape May to Barnegat Light and some distance inland. In Cape May and Cumberland Counties, the upper artesian aquifer of the Kirkwood Formation is defined as the Rio Grande water-bearing zone (Gill, 1962). This aquifer is productive only locally in Cape May County. Along the coast north of Barnegat Light and inland from the coast in Ocean, Burlington, Atlantic, and the western part of Cumberland Counties, the sands of the upper part of the Kirkwood Formation are hydraulically connected to the overlying Cohansey Sand.

The Cohansey Sand is typically a light-colored quartzose sand with lenses of silt and clay. The Cohansey Sand is exposed throughout most of the outer part of the Coastal Plain and attains a maximum thickness of about 250 feet. Ground water in the Cohansey aquifer occurs generally under water-table conditions except Cape May County, where the aquifer is confined. Inland from the coast and in the northern part of Ocean County, the upper part of the Kirkwood Formation is in hydraulic connection with the Cohansey Sand and they act as a single aquifer.

NATURAL HYDROLOGIC BUDGET OF THE COASTAL PLAIN OF NEW JERSEY

Figure 4 is a simplified representation of the hydrologic cycle of the Coastal Plain. The diagram shows the general paths of water movement and their interrelationships. The ultimate source and sink of water is the ocean. All freshwater in the Coastal Plain is derived from the ocean by the processes of evaporation and precipitation. Precipitation may return directly to the atmosphere by evapotranspiration, discharge into surface-water bodies, or recharge the ground-water reservoir through the land surface. Shallow ground water generally discharges into streams. Streams and rivers discharge water to the ocean to complete the cycle. The water cycle is a dynamic system and can be influenced by natural stresses of drought or storms. The flow of water responds to the stress and adjusts to maintain equilibrium.

The long-term water budget for an area can be expressed as:

$$P = R + WL + GWD + \Delta S \qquad \text{Equation 1}$$

where P = precipitation
R = runoff
WL = water loss (evapotranspiration)
GWD = ground-water discharge directly to saltwater
ΔS = change in water storage

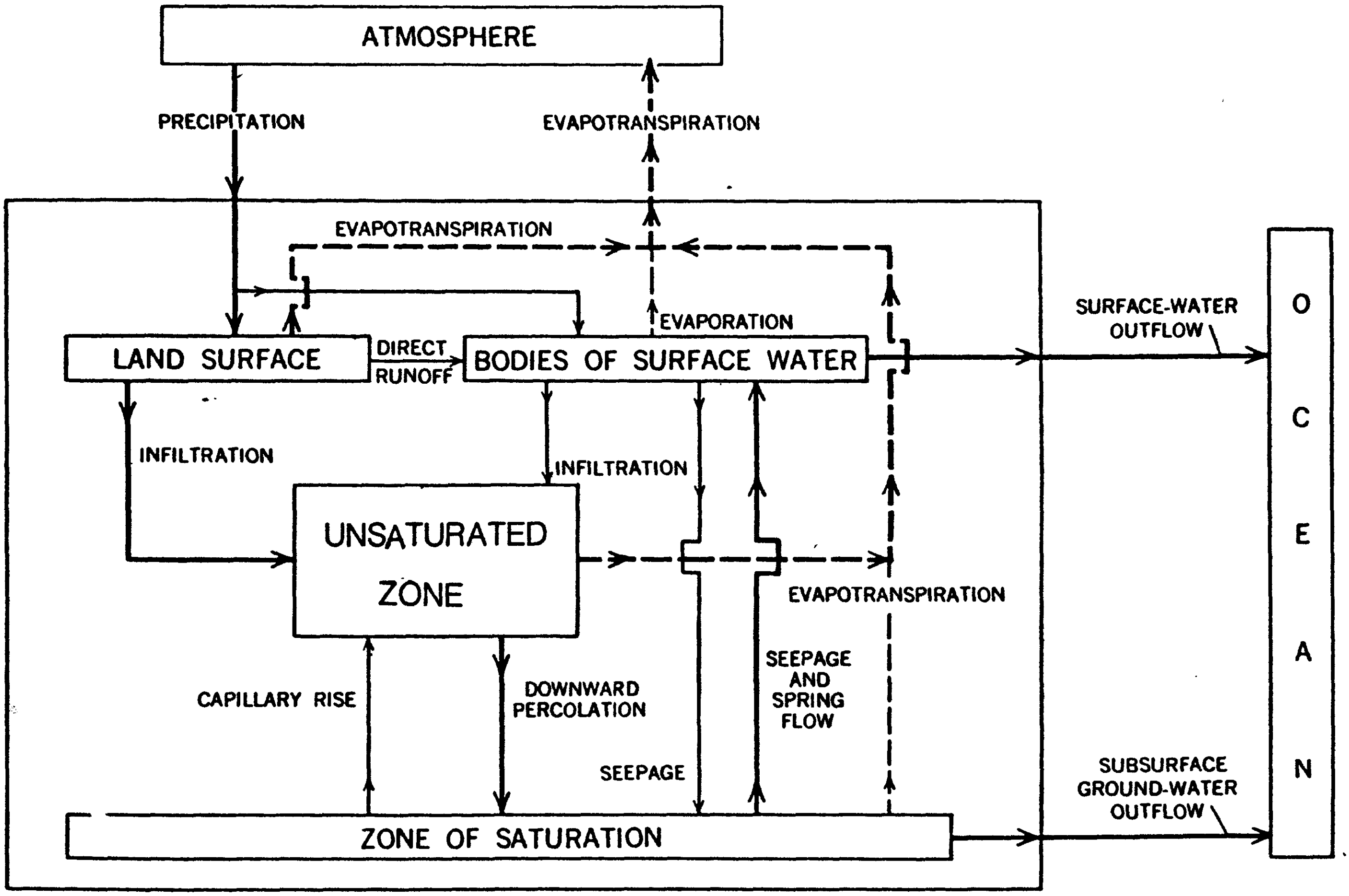
For a particular area and interval of time, inflow of water is equal to outflow plus or minus the change in storage. If the time interval is sufficiently long, the net change in storage is negligible in comparison with inflow and outflow. Under natural conditions, the quantity of ground water discharged directly to saltwater is a small portion of total outflow. The relation for a long period then reduces to:

$$\text{Inflow} = \text{Outflow}$$

$$P = R + WL \qquad \text{Equation 2}$$

Precipitation

The source of all freshwater inflow to the Coastal Plain is precipitation. Rain and snow are the primary types of precipitation and are caused by the ascent and cooling of moist air. This process causes the formation of clouds and condensation of water.



EXPLANATION

Heavy lines represent major flow paths; thin lines, minor flow paths; solid lines, flow of liquid water; dashed lines. flow of gaseous water

Figure 4--The hydrologic system under natural conditions.

(Modified from Franke and McClymonds, 1972.)

Average values of precipitation may be misleading unless information on the distribution of values is available. The U.S. Department of Commerce, National Oceanic and Atmospheric Administration, provided monthly precipitation data from 1941 to 1978. These data were used to determine average annual precipitation for selected sites in New Jersey, Pennsylvania, and Delaware (table 2). Locations of these sites appear in figure 5. Average precipitation in the Coastal Plain varies little from month to month although precipitation is greater in the spring and fall.

Areal variations of precipitation are not large due to the consistent low lying topography of the Coastal Plain. Generally, averages were lower in the southern Coastal Plain and along the shoreline. Averages within the Coastal Plain of New Jersey ranged from a low of 41 in/yr in Shiloh, Cumberland County, to a high of 47 in/yr in Toms River, Ocean County. Overall, the Coastal Plain receives an average of approximately 44 in/yr of precipitation.

Table 2.--Summary of average annual precipitation for selected weather stations in New Jersey, Pennsylvania, and Delaware, 1941-78.

Map number*	Station name	Precipitation (in/yr)
1	Atlantic City WSO	44.8
2	Atlantic City Marina	40.6
3	Audubon	43.8
4	Belleplain State Forest	45.5
5	Burlington	43.4
6	Freehold	46.0
7	Glassboro	44.4
8	Hammonton 2 NNE	45.2
9	Hightstown 1 N	43.9
10	Indian Mills 2 W	44.2
11	Long Branch 2 S	46.6
12	Millville FAA Airport	42.3
13	Moorestown	43.4
14	New Brunswick	44.9
15	Pemberton 3 E	44.6
16	Shiloh	41.2
17	Toms River	47.1
18	Trenton WSO	41.5
19	George School	44.0
20	Marcus Hook	41.4
21	Philadelphia WSO	39.9
22	Dover	42.1
23	Newark University Farm	41.1
24	Wilmington Porter Res	40.5
25	Wilmington Ncastle WSO	43.0
	Average	44

* Stations located in figure 5.

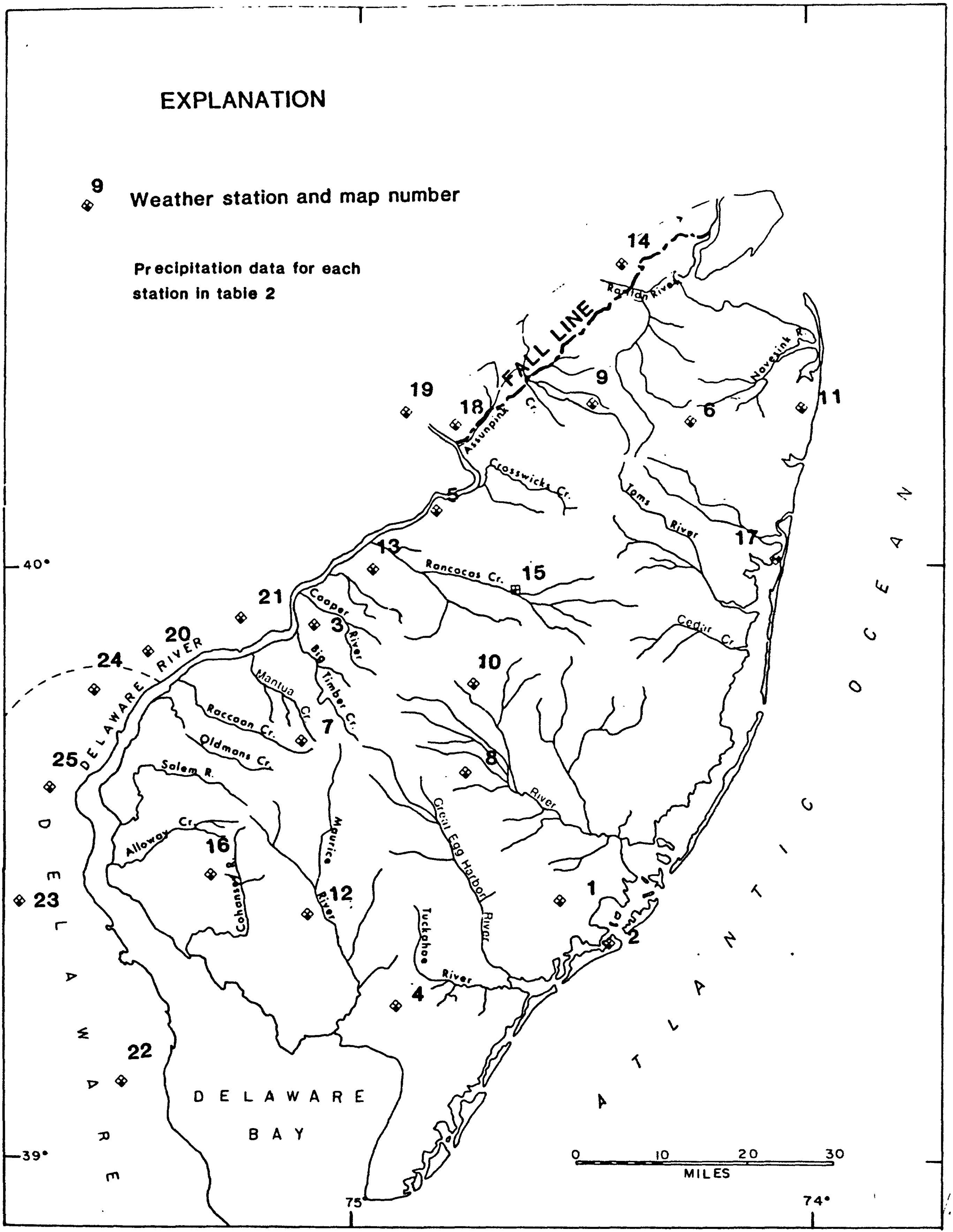


Figure 5--Selected weather stations in New Jersey, Pennsylvania, and Delaware.

Runoff

Runoff is streamflow unaffected by artificial diversion, storage, or other works of man in or on the stream channel. All runoff is derived from precipitation. Runoff is composed of two major components. Direct runoff reaches stream channels by overland flow of rainfall or snowmelt. Ground-water runoff reaches stream channels by ground-water discharge from water-table aquifers. Direct runoff is the principal contributor to storm and flood flows and ground-water runoff maintains the base flow of streams.

Streamflow data from 35 gaging stations (fig. 6) and 64 low-flow partial-record stations were used to determine average annual runoff from the Coastal Plain of New Jersey from 1941 to 1978. Where data were available, streamflow records were adjusted for the effects of storage and/or diversion.

The 35 gaging station records represent flow from 1,280 mi^2, or approximately 30 percent of the Coastal Plain. Table 3 is a list of selected gaging stations and corresponding period of record. Twelve gaging stations, covering 890 mi^2 of the Coastal Plain, have streamflow records for the entire base period. Gaging stations with less than five years of record were not used. Low-flow partial-record stations represent flow from 800 mi^2, or 19 percent of the Coastal Plain. Low-flow partial-record stations are sites where limited streamflow data are collected during base flow conditions. Average annual streamflow at low-flow partial-record stations is estimated by least-normal squares regression equations and comparison with concurrent daily discharges at nearby long-term continuous gaging stations (B. D. Gillespie, written communication, 1981). Average annual streamflow in ungaged areas is estimated by comparison of flow at nearby gaged stations with similar basin characteristics.

Drainage areas were grouped by direction of flow and reaches of major streams (fig. 7). The streams within the Coastal Plain flow into four major bodies of water (Atlantic Ocean, Raritan Bay, Delaware River, and Delaware Bay). These drainage areas are divided into 17 segments.

Average annual streamflow for the 17 segments is presented in table 4. The average annual streamflow from the Coastal Plain from 1941-78 is about 20 in/yr. Approximately 55 percent of the streamflow drains in an easterly direction into the Raritan Bay and the Atlantic Ocean, and the remaining 45 percent flows toward the Delaware River and Delaware Bay.

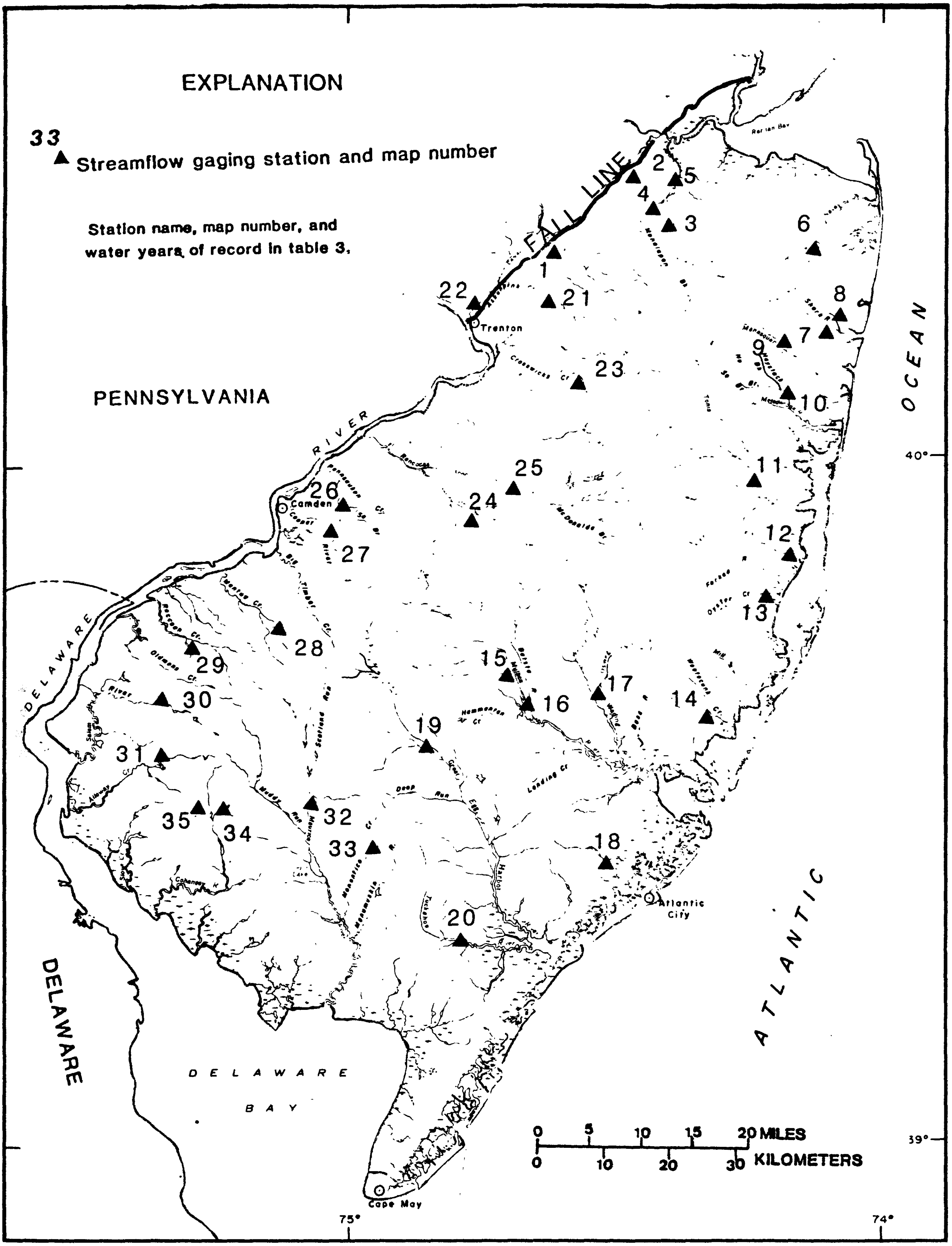
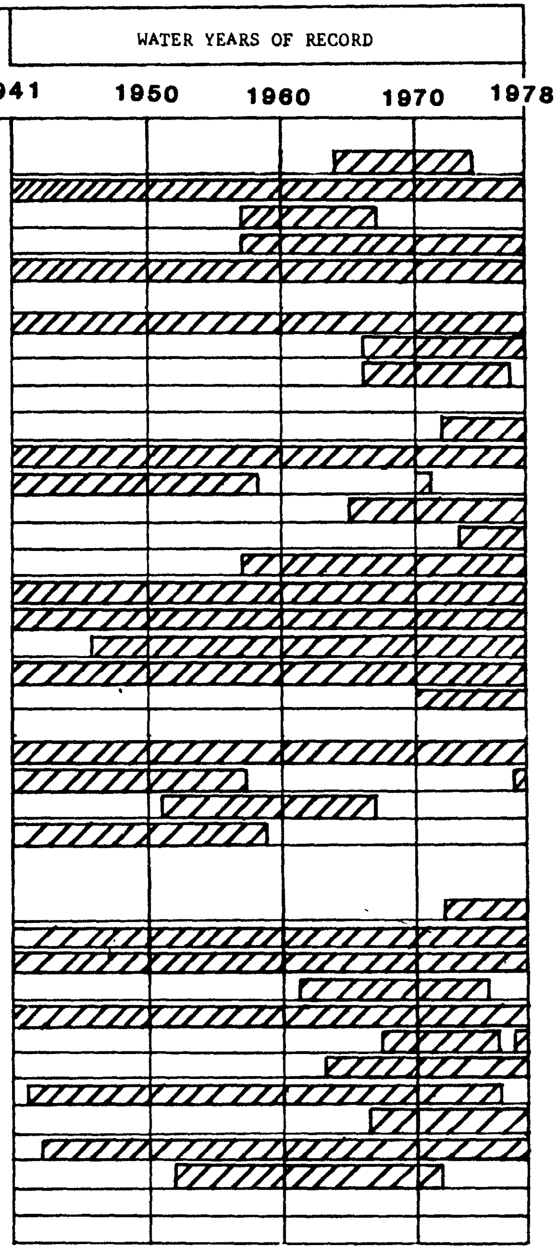


Figure 6 --Selected streamflow gaging stations in the Coastal Plain of New Jersey.

Table 3.--Selected streamflow stations in the Coastal Plain of New Jersey, 1941-78.

MAP NUMBER*	STATION NUMBER	STATION NAME
		RARITAN RIVER BASIN
1	01400730	MILLSTONE RIVER AT PLAINSBORO
2	01405000	LAWRENCE BROOK AT FARRINGTON DAM (30% NON-COASTAL)
3	01405300	MATCHAPONIX BROOK AT SPOTSWOOD
4	01405400	MANALAPAN BROOK AT SPOTSWOOD
5	01405500	SOUTH RIVER AT OLD BRIDGE
		ATLANTIC COASTAL BASIN
6	01407500	SWIMMING RIVER NEAR RED BANK
7	01407705	SHARK RIVER NEAR NEPTUNE CITY
8	01407760	JUMPING BROOK NEAR NEPTUNE CITY
9	01408000	MANASQUAN RIVER AT SQUANKUM
10	01408120	NORTH BRANCH METEDECONK RIVER NEAR LAKEWOOD
11	01408500	TOMS RIVER NEAR TOMS RIVER
12	01409000	CEDAR CREEK AT LANOKA HARBOR
13	01409095	OYSTER CREEK NEAR BROOKVILLE
14	01409280	WESTECUNK CREEK AT STAFFORD FORGE
15	01409400	MULLICA RIVER NEAR BATSTO
16	01409500	BATSTO RIVER AT BATSTO
17	01410000	OSWEGO RIVER AT HARRISVILLE
18	01410500	ABSECON CREEK AT ABSECON
19	01411000	GREAT EGG HARBOR AT FOLSOM
20	01411300	TUCKAHOE RIVER AT HEAD OF RIVER
		DELAWARE BAY BASIN
32	01411500	MAURICE RIVER AT NORMA
33	01412000	MENANTICO CREEK NEAR MILLVILLE
34	01412500	WEST BRANCH COHANSEY RIVER AT SEELEY
35	01413000	LOPER RUN NEAR BRIDGETON
		DELAWARE RIVER BASIN
21	01463620	ASSUNPINK CREEK NEAR CLARKSVILLE
22	01464000	ASSUNPINK CREEK AT TRENTON (30% NON-COASTAL)
23	01464500	CROSSWICKS CREEK AT EXTONVILLE
24	01465850	SOUTH BRANCH RANCOCAS CREEK AT VINCENTOWN
25	01467000	NORTH BRANCH RANCOCAS CREEK AT PEMBERTON
26	01467081	SOUTH BRANCH PENNSAUKEN CREEK AT CHERRY HILL
27	01467150	COOPER RIVER AT HADDONFIELD
28	01475000	MANTUA CREEK AT PITMAN
29	01477120	RACCOON CREEK NEAR SWEDESBORO
30	01482500	SALEM RIVER AT WOODSTOWN
31	01483000	ALLOWAY CREEK AT ALLOWAY



*Location shown in figure 6.

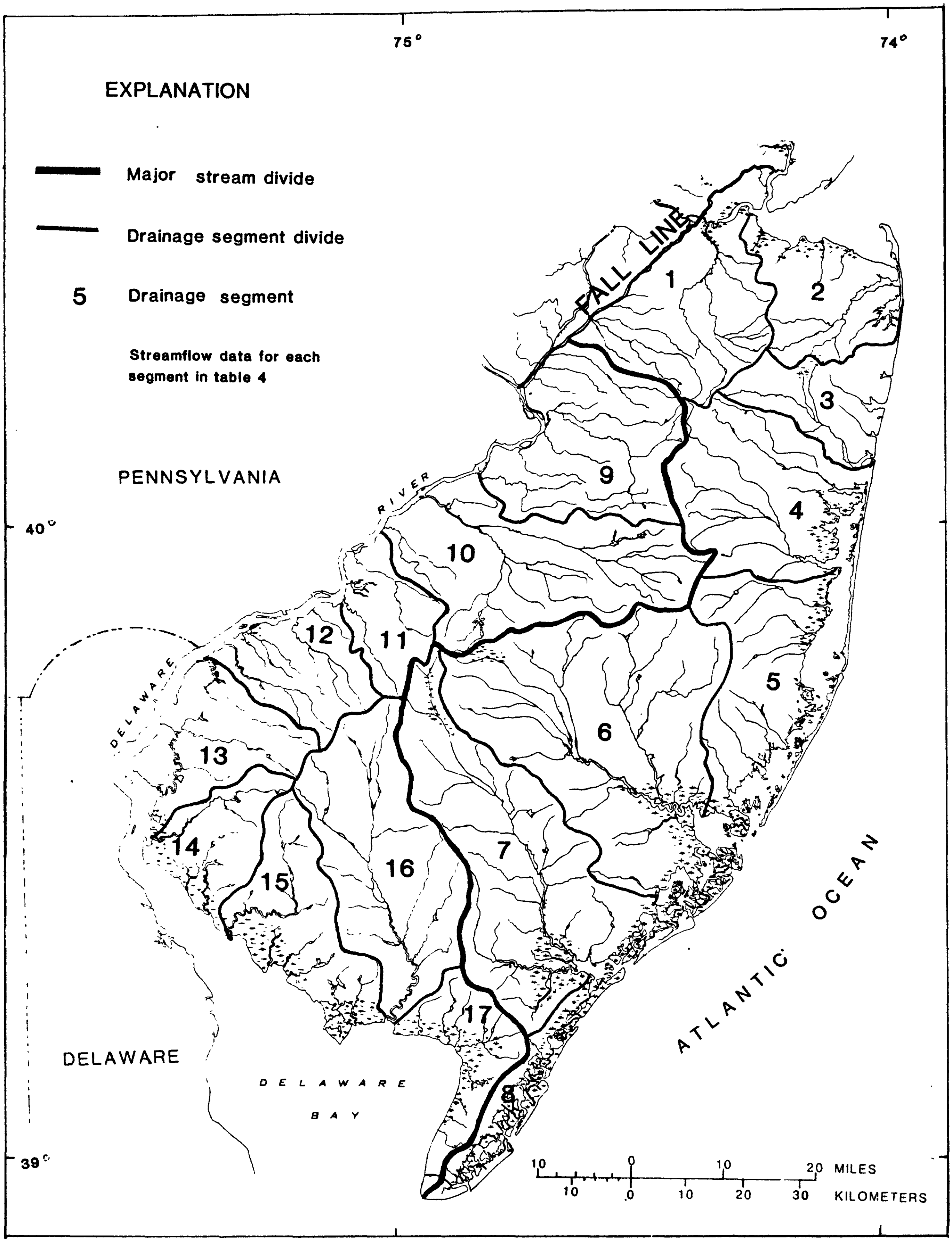


Figure 7--Drainage segments in the Coastal Plain of New Jersey.

Table 4.--Summary of average annual streamflow, precipitation, and water loss for drainage segments in the Coastal Plain of New Jersey, 1941-78.

Basin	Drainage segments *	Area (mi²)	(ft³/s)	**Streamflow (ft³/s/mi²)	(in/yr)	Precipitation (in/yr)	Water loss (in/yr)
Atlantic	1	280	386	1.38	18.7	44.6	25.9
	2	174	280	1.61	21.9	46.2	24.3
	3	136	201	1.48	20.1	45.6	25.5
	4	298	523	1.76	23.9	46.4	22.5
	5	202	427	2.11	28.6	44.9	16.3
	6	604	1047	1.73	23.5	45.3	21.8
	7	478	641	1.34	18.2	44.6	26.4
	8	29	30	1.03	14.0	41.4	27.4
Subtotal		2201	3535	1.61	21.8	45.2	23.4
Delaware	9	301	365	1.21	16.4	44.0	27.6
	10	396	548	1.38	18.7	44.4	25.7
	11	122	224	1.84	24.9	43.7	18.8
	12	149	229	1.54	20.9	43.4	22.5
	13	187	201	1.08	14.7	42.2	27.5
	14	129	157	1.22	16.6	41.2	24.6
	15	211	296	1.40	19.0	41.4	22.4
	16	382	558	1.46	19.8	43.3	23.5
	17	130	134	1.03	14.0	43.2	29.2
Subtotal		2007	2712	1.35	18.3	43.2	24.9
Total		4208	6247	1.48	20.2	44.2	24.0

* Locations of drainage areas in fig. 7

** Adjusted for diversions

Areal variations in runoff within the Coastal Plain are similar to rainfall variations. Unexpected differences are the result of inadequate data to describe the physical characteristics of each of the segments. Ground-water divides sometimes differ significantly from surface divides and considerable quantities of ground water may leave the drainage segment by subsurface flow bypassing the surface channel.

In the Coastal Plain, a large percentage of streamflow is derived from ground-water discharge into stream channels. This is due to climatic, physiographic, geologic, and hydrologic conditions within the environment. The most important condition is the ability of upper geologic units to transmit large quantities of water downward to the ground-water body. Ground-water runoff within the Pine Barrens region of the Coastal Plain constitutes about 90 percent of the total annual stream discharge (Rhodehamel, 1970). Because the ground-water reservoir has the capacity to temporarily store precipitation from individual storm events, ground-water discharge to streams is uniform compared to streamflow resulting from direct runoff.

Based primarily on estimates of ground water contributing to streamflow and base runoff, several estimates of ground-water recharge in the Coastal Plain have been made. In the outcrop areas of the Potomac-Raritan-Magothy aquifer system where it is unconfined, recharge to the aquifer is about 12 in/yr (Barksdale, 1943). In the outcrop area of the Farrington aquifer, the recharge to ground water is 12 in/yr (Farlekas, 1979). Recharge ranges from 12 to 20 in/yr in the outcrop of the Old Bridge aquifer (Barksdale, 1943).

In contrast, natural recharge to deep, confined aquifers is primarily by vertical leakage from the upper layers. Only a small percentage of the water within the unconfined ground-water system leaks to the confined aquifers; but over a large area and a long period of time, the amount of water transmitted can be significant.

In summary, average recharge to the Coastal Plain in outcrop areas ranges from about 12 to 20 in/yr. Small areal variations in ground-water recharge are primarily a result of the slope of the land surface, permeability of the sediments, and the degree of urbanization.

Water Loss

Water loss in the Coastal Plain occurs primarily by evapotranspiration. Evapotranspiration is water withdrawn from a land area by evaporation from water surfaces, moist soil, and transpiration from plants. Estimates of water loss may be obtained by finding the difference between precipitation and runoff for an area. Average annual water loss is computed for each segment in the Coastal Plain using Equation 2 and is equivalent to about 24 inches (table 4). Average water loss is greater in the southern part of the Coastal Plain where temperatures are higher.

Water Storage

Water storage is the quantity of water stored in surface-water and ground-water reservoirs. Natural surface-storage capacity of an area includes the capacity of its lakes, ponds, swamps, and stream channels. Underground storage includes the capacity of the sediments to hold water. Aquifers serve as natural reserviors and conduits of ground water. The Coastal Plain is a ground-water dominated hydrologic system. The amount of water stored in surface-water reservoirs is small compared to the quantity stored in the ground.

The quantity of water stored fluctuates in response to changing rates of inflow and outflow. Surface-water changes occur quickly. An example is flooding after storms. Ground-water storage fluctuations occur with a considerable lag time. Over a sufficient period of time (several years) the change in storage is negligible in comparison to inflow and outflow. Therefore, in the long term water budget the change in storage (ΔS) is equivalent to zero.

HOW MAN HAS MODIFIED THE NATURAL HYDROLOGIC CYCLE

Some activities of man tend to alter the natural hydrologic cycle. The natural flow system (fig. 4) in the Coastal Plain has been modified by the addition of flow paths (fig. 8) that increase the rate of outflow from the Coastal Plain to the ocean. Some of the major modifications to the hydrologic cycle are: (1) disposal of direct runoff into storm sewers; (2) ground-water withdrawals; and (3) disposal of used water to sanitary sewers.

Disposal of Direct Runoff

Under natural conditions, precipitation runs off directly into surface-water bodies or infiltrates into the ground-water reservoir. The large scale construction of streets, parking lots, buildings, and other impervious surfaces reduces the amount of infiltration and increases the quantity of direct runoff.

The increased direct runoff has necessitated the construction of storm-drainage facilities to prevent flooding. Little information is available on storm sewers, but the amount of water discharged through these pipes is significant. Areas where storm sewers are used extensively include urban areas adjacent to the Delaware River, Raritan Bay, and the Atlantic coastline.

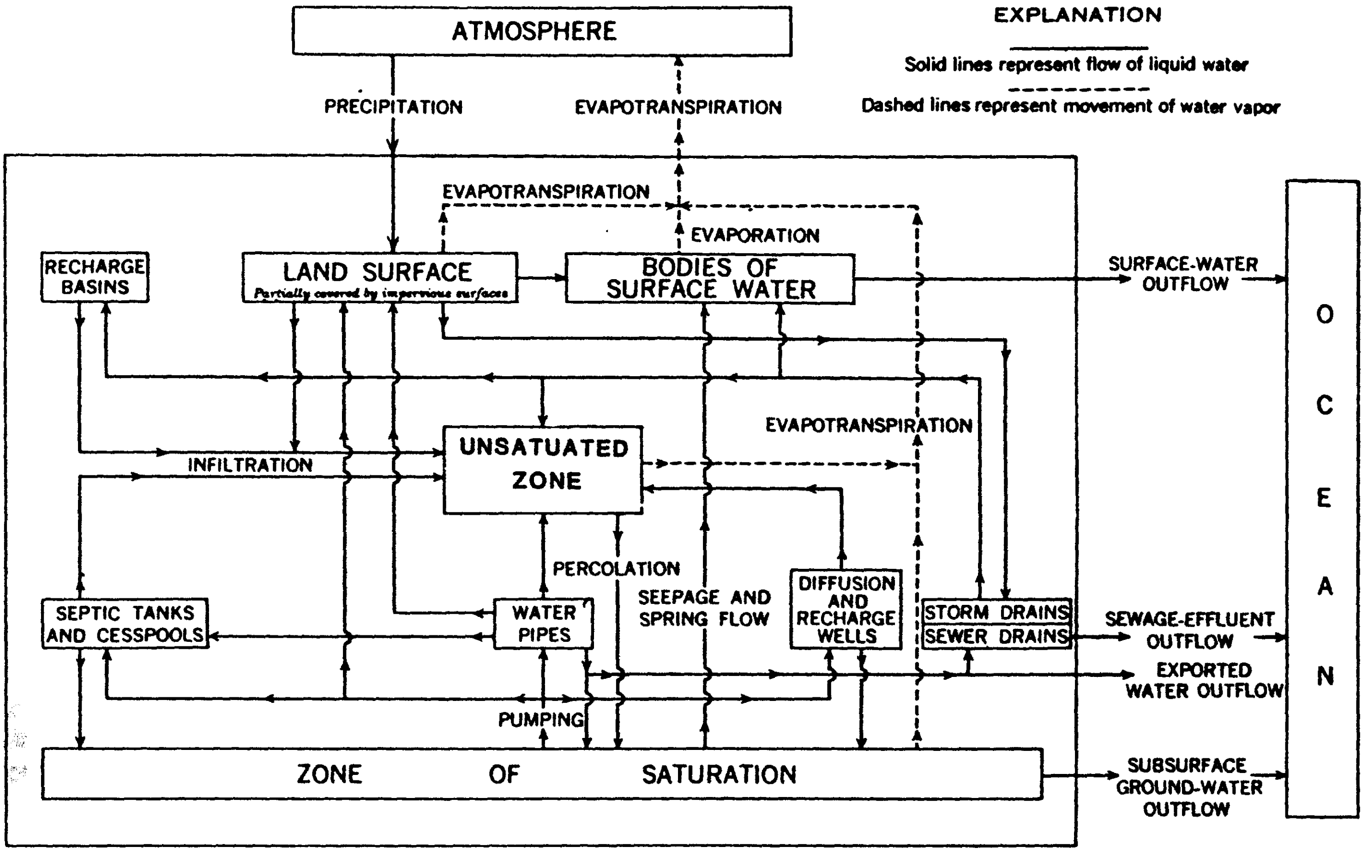


Figure 8--The hydrologic system showing modifications by man's activities.
(Modified from Franke and McClymonds, 1972.)

In general, these water-distribution systems reduce the amount of ground-water recharge and transmit runoff directly to nearby streams. The streams transmit the direct runoff to the ocean. This transfer of runoff from the land surface to streams occurs much faster than if precipitation recharged to the ground-water reservoir.

Ground-Water Withdrawals

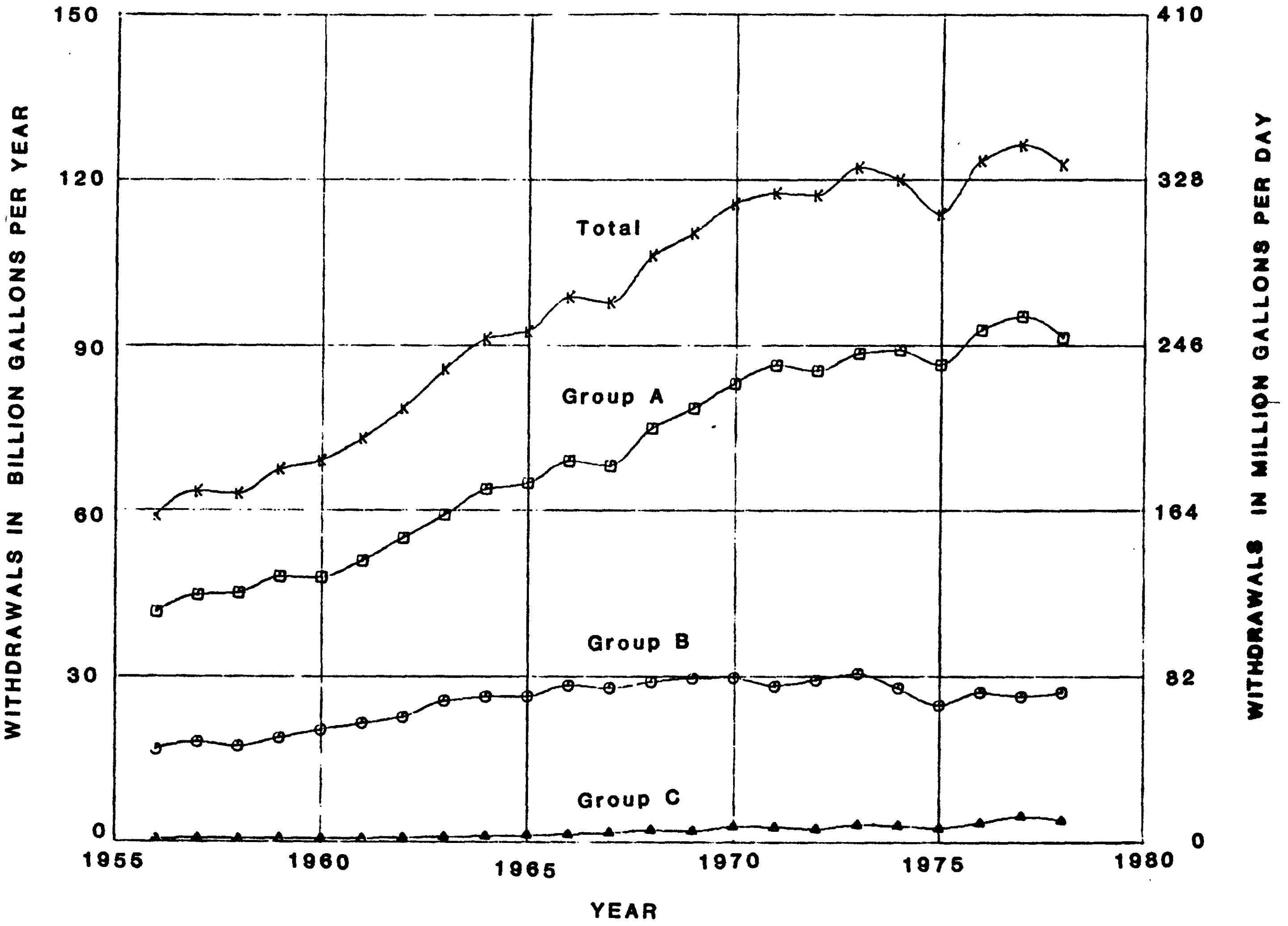
Ground water is the primary source of water supply in the Coastal Plain of New Jersey. Records of ground-water withdrawals indicate a significant increase from 1956 to 1978. Major ground-water withdrawals have more than doubled from 160 Mgal/d in 1956 to 335 Mgal/d in 1978.

Major ground-water withdrawals are those from wells that have been permitted by the State of New Jersey to withdraw 100,000 gallons per day or more. The figures presented on ground-water withdrawals do not include all major withdrawals because data from some ground-water users holding "grandfather rights" are unavailable. These users are not required to report withdrawals to the state, and it is not possible to know what "grandfather rights" are actually being used. Few "grandfather rights" still exist, and most of these wells are located in the southern part of the Coastal Plain and are used for irrigation. It is estimated that the data presented is within 15 percent of the total major ground-water withdrawals in the Coastal Plain.

Ground-water withdrawals are aggregated by county, type of purveyor, and aquifer to indicate where demand for ground water is greatest. The type of purveyor is determined by the primary use of the water. Figure 9 is a graph of major ground-water withdrawals from the Coastal Plain by type of purveyor.

Group A represents purveyors that provide potable water. Included in this category are municipal and private water companies and self-supplied institutions such as hospitals, schools, or correctional facilities. Some water companies sell part of their water supply to industry and other private concerns for uses other than drinking water.

Group A well sites are shown in figure 10. The sites are concentrated around the perimeter of the Coastal Plain along the Delaware River, Raritan Bay, and the Atlantic coastline. Population density is greater around the perimeter of the Coastal Plain than in the interior. Figure 9 shows the steady increase of ground-water withdrawals in Group A from 1956 to 1978.



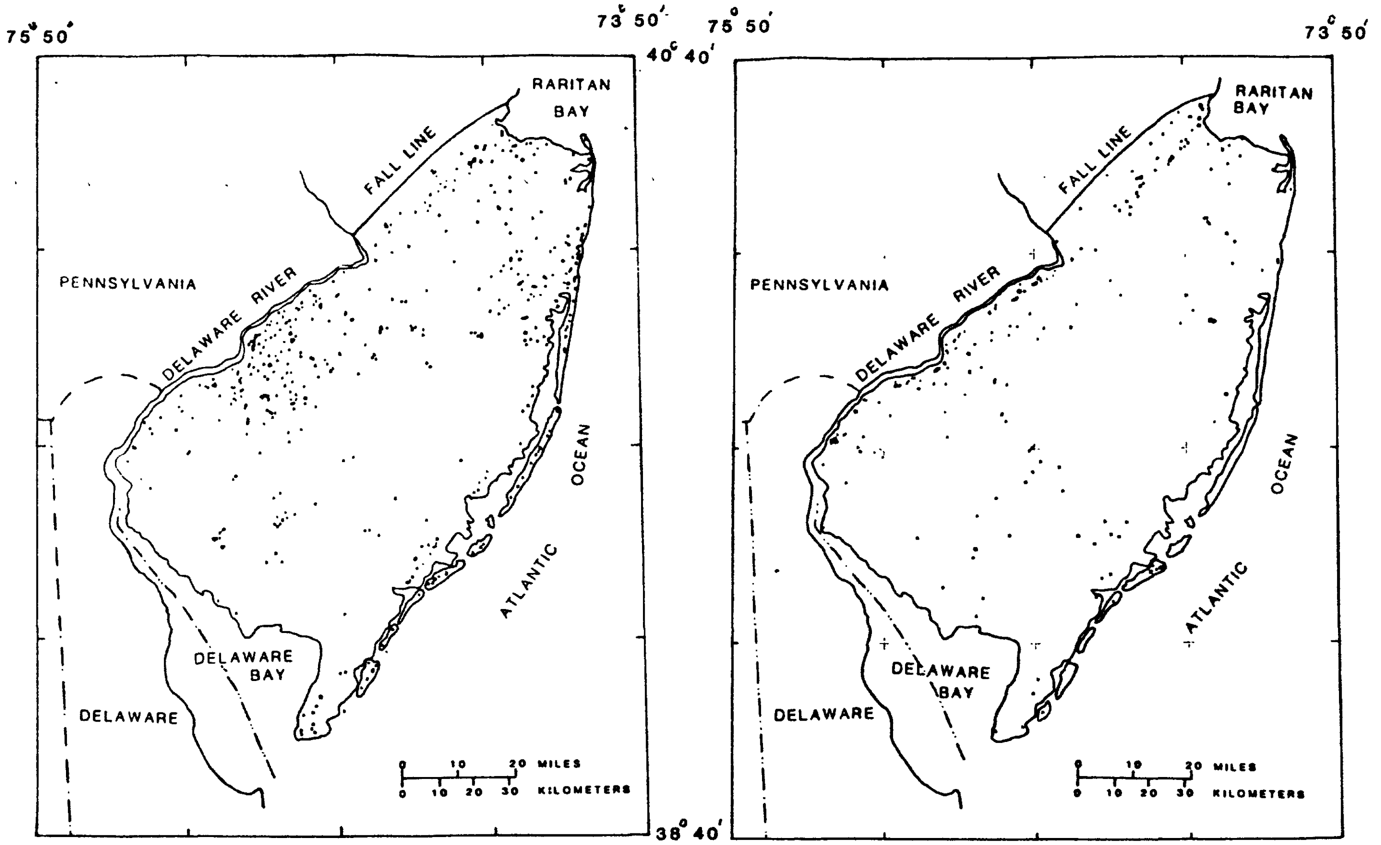
EXPLANATION

Group A = Public supply, institutional

Group B = Industrial, commercial

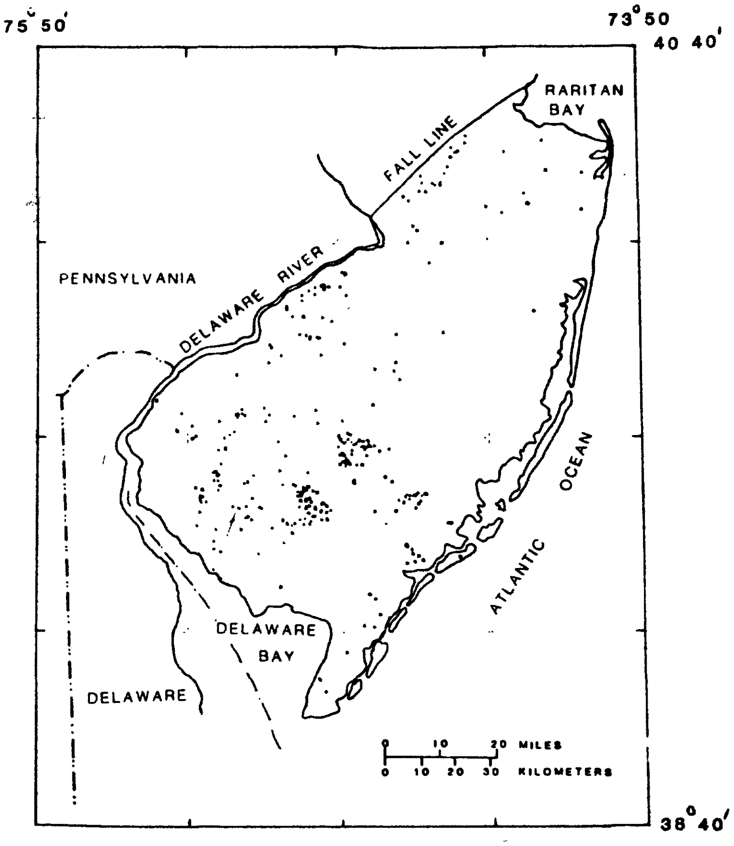
Group C = Agriculture, irrigation, stock

Figure 9--Major ground-water withdrawals from the Coastal Plain of New Jersey by type of purveyor, 1956-78.



Group A

Group B



Group C

EXPLANATION

• Ground-water withdrawal site

Group A = Public supply, institutional

Group B = Industrial, commercial

Group C = Agriculture, irrigation, stock

Figure 10--Major ground-water withdrawal sites in the Coastal Plain of New Jersey by type of purveyor, 1956-78.

Group B includes private purveyors of ground water for use in industry and commercial businesses. The largest demand for ground water from privately owned industrial wells is along a corridor adjacent to the Delaware River and Raritan Bay (fig. 10). Middlesex County withdraws the largest amount of ground water in this category, followed by Gloucester, Burlington, Salem, and Cumberland Counties (table 5).

Table 5.--Major ground-water withdrawals from the Coastal Plain of New Jersey by county and type of purveyor, 1978*
[Million gallons per day]

County	Group A	Group B	Group C	Total
Atlantic	20.66	1.94	3.58	26.18
Burlington	30.51	9.21	1.23	40.95
Camden	67.49	4.61	0.13	72.23
Cape May	10.93	1.14	.23	12.30
Cumberland	14.23	4.96	2.18	21.37
Gloucester	16.57	10.18	.22	26.97
Mercer	7.18	.83	.11	8.12
Middlesex	24.74	24.18	.46	49.38
Monmouth	25.97	3.31	1.33	30.61
Ocean	29.56	8.15	<.10	37.71
Salem	2.76	6.09	1.25	10.10
Total	250.60	74.60	10.72	335.92

* Withdrawal data does not include domestic users or unavailable "grandfather rights" withdrawals.

Group A = Public supply, institutional
Group B = Industrial, commercial
Group C = Agriculture, irrigation, stock

Purveyors in Group C include users of ground water for agricultural purposes. In this category, more than 90 percent of the ground water is used for irrigation of crops. Irrigation of crops with ground water is extensive in Atlantic, Cumberland, and Salem Counties. Other uses include water for stock and watering of golf courses.

The relative location and concentration of Group C well sites appear in figure 10. These sites do not constitute all agricultural withdrawals owing to a lack of available data. A large proportion of "grandfather rights" are for irrigation purposes.

Not all gross withdrawals represent a loss of water from the hydrologic system of the Coastal Plain. The proportion that is lost (net withdrawal) depends on the type of water use and the method of disposal of used water. Purveyors in Groups A and B usually transport ground water from the withdrawal site to a water treatment plant. After the water is treated and distributed for use, the used water is transported through pipes to a sewage treatment plant or directly to a stream without treatment. Often, the ground water is transported considerable distances from the original point of withdrawal.

Although data is not available, it is known that a large proportion of the ground-water withdrawals by purveyors in Groups A and B (325 Mgal/d) is removed from a point in the ground-water reservoir and discharged to a point in a stream. Some leakage from the distribution systems to the water-table aquifer occurs, but the amount is usually less than 15 percent.

Group C purveyors do not move ground water far from its original source. Water for irrigation of crops generally comes from water-table aquifers. Some water is removed from the ground-water system through evapotranspiration. The water that is not used by crops or evaporated from land surfaces recharges the water table.

Aquifers vary in lithology, thickness, lateral extent, water-bearing characteristics, and saltwater content. The demand for ground water also varies due to changes in population, industrialization, and agriculture. For these reasons, different aquifers are utilized in different areas as the primary source of ground water.

There are five regional aquifers capable of yielding large quantities of water in the Coastal Plain. They are the Potomac-Raritan-Magothy aquifer system, Englishtown aquifer, Wenonah-Mount Laurel aquifer, lower "800-foot" sand aquifer of the Kirkwood Formation and the Kirkwood-Cohansey aquifer. Other aquifers including the Vincentown-Manasquan, Piney Point, and Red Bank are used locally. The importance of the five major aquifers as sources of ground water is shown in figure 11.

The Potomac-Raritan-Magothy aquifer system is the most widely used aquifer in the Coastal Plain, but it is not the primary source of ground water for every county (table 6). The Cohansey and Kirkwood aquifers are the primary sources of ground water in Atlantic, Cape May, and Cumberland County. In these counties the Potomac-Raritan-Magothy aquifer system contains salty water. The Englishtown and Wenonah-Mount Laurel aquifers are productive mainly in the northern and central counties of the Coastal Plain.

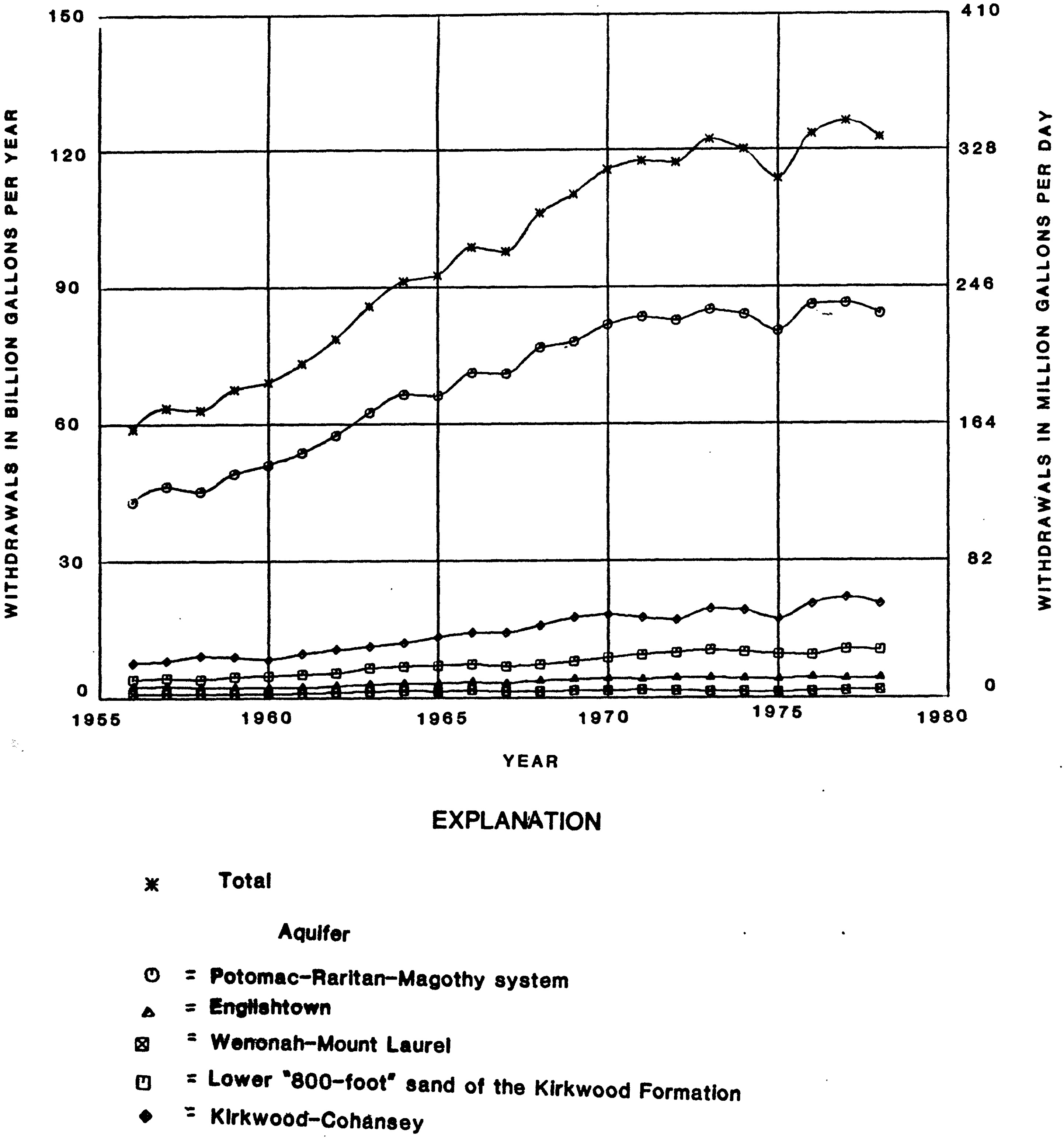


Figure 11-Major ground-water withdrawals from the Coastal Plain of New Jersey by aquifer, 1956-78.

Table 6.--Major ground-water withdrawals from the Coastal Plain of New Jersey by county and aquifer, 1978.*
[Millon gallons per day]

County	Potomac-Raritan-Magothy	Englishtown	Wenonah-Mt. Laurel	Kirkwood (where confined)	Kirkwood-Cohansey	Other
Atlantic	-	-	-	9.12	16.75	.30
Burlington	38.96	.49	1.14	-	.36	-
Camden	69.57	.76	.88	-	1.00	.98
Cape May	-	-	-	5.36	6.38	.56
Cumberland	-	-	-	.80	20.12	.45
Gloucester	25.19	-	.02	-	1.76	
Mercer	8.12	-	-	-	-	-
Middlesex	49.38	-	-	-	-	-
Monmouth	21.60	6.25	1.31	-	1.14	.31
Ocean	11.53	4.59	.03	4.22	12.50	4.84
Salem	6.10	-	1.32	-	1.86	.82
Total	230.45	12.09	4.70	19.50	61.98	8.26

* Withdrawal data does not include domestic users or unavailable "grandfather rights" withdrawals.

Disposal of Used Water to Sanitary Sewers

Sanitary sewers, cesspools, septic tanks, and recharge wells are used to dispose of sewage. Recharge wells are not common in the Coastal Plain. Cesspools and septic tanks are gradually being replaced by local and regional sewerage authorities. Sanitary sewers affect the hydrologic system differently than cesspools and septic tanks.

Before the development of water companies and sewerage authorities, water was usually pumped from water-table aquifers and discharged into shallow cesspools and septic tanks. This exchange of water may cause a change in the quality of the water, but does not significantly affect the quantitative balance in the ground-water reservoir.

The introduction of sewer systems to replace septic tanks and cesspools short circuits the hydrologic cycle by removing the water from a point within the ground-water reservoir to a point of discharge in a stream. The stream carries this discharge into salty water outside the boundary of the system. Data on the amount of water transferred from sewer systems into streams and then to saltwater are not available.

EFFECTS OF MAN'S ACTIVITIES ON THE HYDROLOGIC CYCLE

Man has modified the natural hydrologic cycle in the Coastal Plain by increasing the rate of outflow from the system to the ocean. One major effect of the increased outflow of water is a regional decline in ground-water levels. The hydrologic budget is balanced by a decrease in storage and an increase in inflow. Ground-water storage decreases, but the change in storage is usually very small in comparison to the total amount of water stored. The declines in potentiometric head in the aquifers may change the direction of flow of water in the aquifer in order to increase inflow. Induced recharge and saltwater encroachment are a result of the changes in direction of flow.

Regional Ground-Water Declines

Significant regional water-level declines have occurred in the Potomac-Raritan-Magothy aquifer system, Englishtown aquifer, Wenonah-Mount Laurel aquifer, and the "800-foot" sand aquifer of the Kirkwood Formation. No apparent regional cones of depression have developed in the Cohansey aquifer. These sediments are very permeable and largely unconfined. These conditions are not as conducive to the creation of regional cones of depression as are confined aquifers.

Water-level declines result in the lowering of potentiometric head. Water flows from high to low head. Where head gradients are large enough, water can be induced to flow from adjacent surface-water bodies or through confining beds. The saltwater-freshwater interface may also move in response to the water-level declines. Documented examples of induced recharge and saltwater encroachment show the effects of man's activities on the natural hydrologic cycle.

Induced Recharge

In the Coastal Plain, ground-water withdrawals may induce recharge (inflow) to aquifers by: (1) inducing inflow of water from streams, lakes, and swamps by reversing the normal hydraulic gradient towards those discharge areas, and (2) inducing inflow of water from adjacent aquifers or confining beds by increasing hydraulic gradients.

Ground-water withdrawals in the Potomac-Raritan-Magothy aquifer system have been shown by computer model simulation to cause water to be induced from the Delaware River and overlying aquifers. In New Jersey, the Potomac-Raritan-Magothy aquifer system outcrops along the Delaware River for about 65 miles from Mercer to Salem Counties. Before the Coastal Plain along the Delaware River became heavily populated and industrialized, ground water flowed from the Potomac-Raritan-Magothy aquifer system to the Delaware River. Ground-water withdrawals from the Potomac-Raritan-Magothy aquifer system have resulted in ground-water level declines of 1.5 to 2.5 ft/yr from 1966 to 1976 (Luzier, 1980).

A reversal in the direction of ground-water flow near pumping centers is occurring in response to the decline in head. To determine the extent of the head decline, the U.S. Geological Survey developed a digital ground-water flow model of the Potomac-Raritan-Magothy aquifer system (Luzier, 1980). The model can simulate flow between the Potomac-Raritan-Magothy aquifer system and the Delaware River.

Figure 12 shows part of the modeled area from Burlington to Salem Counties. Model simulations were made using actual ground-water withdrawals from 1956 to 1973 and projected withdrawals after 1973. Within the boundary of Area 1, a 1 percent compounded annual growth rate in ground-water withdrawals is used to project post-1973 ground-water withdrawals. Outside of Area 1, a 2 percent compounded annual increase in ground-water demand is used.

Table 7 shows modeled inflow from the Delaware River to the aquifer system in 1973 and 1978 (G. M. Farlekas, written communication, 1980). The Delaware River in the modeled area is divided into 14 reaches of variable length. Induced recharge for the modeled area in 1973 is about 103 ft^3/s. About 43 percent of the total inflow to the Potomac-Raritan-Magothy aquifer system in 1973 was induced recharge from the Delaware River (Luzier, 1980, p. 66).

The greatest inflow to the aquifer system is between reaches 6 and 7 where inflow is 7.9 and 6.8 $(ft^3/s)/mi$,

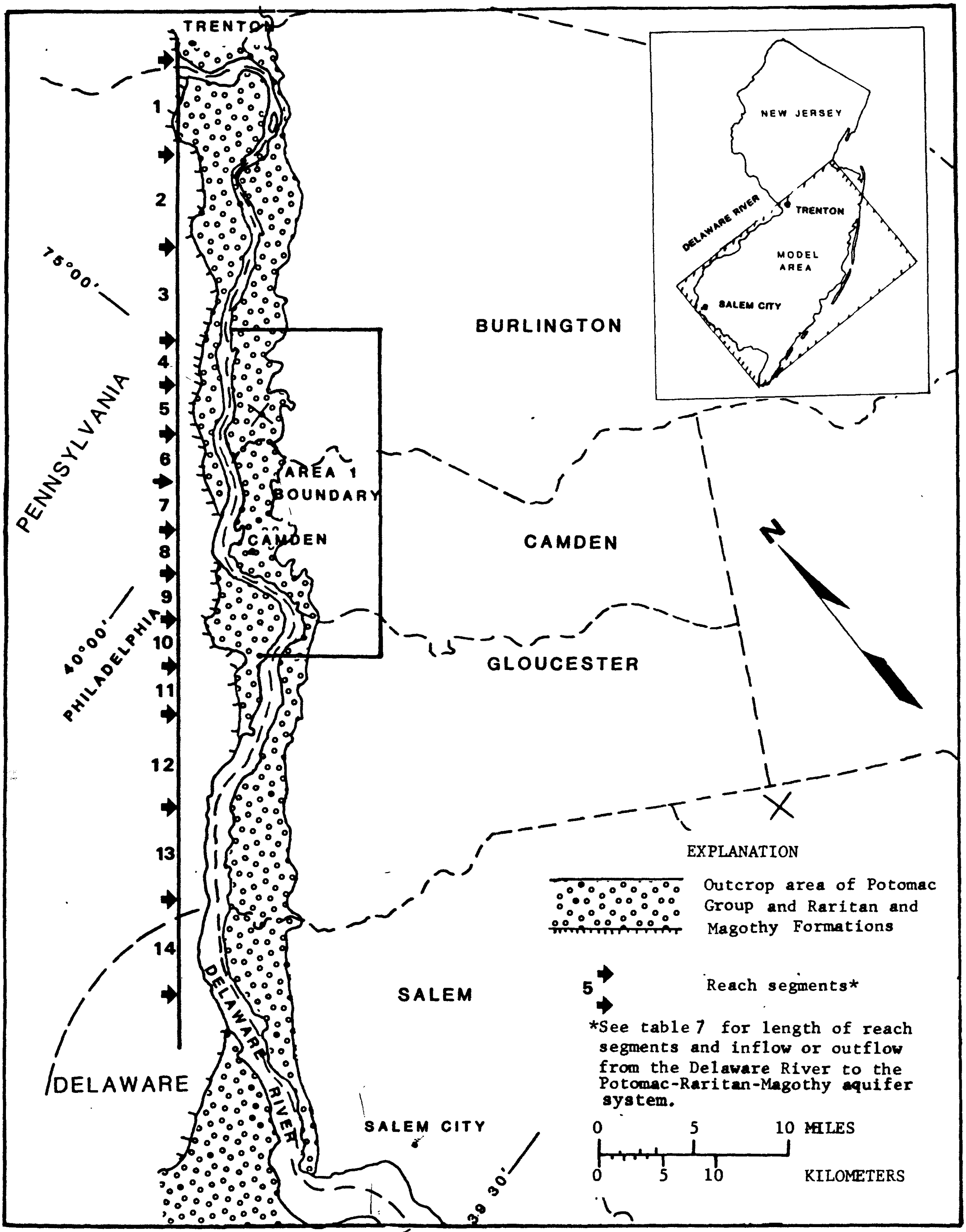


Figure 12 --Modeled area showing outcrop area and river reaches for the digital simulation model of the Potomac-Raritan-Magothy aquifer system.

respectively. Reaches 6 and 7 are located adjacent to Camden City where the ground-water demand from the Potomac-Raritan-Magothy aquifer system is great. The only reach that shows a net discharge from the aquifer to the Delaware River is reach 1. This reach shows a loss of 0.1 (ft^3/s)/mi of ground water from the aquifer to the river.

Table 7.--Model-simulated inflow from the Delaware River to the Potomac-Raritan-Magothy aquifer system

River reach*	Length of reach (mi)	Recharge to aquifer system (ft^3/s) 1973	Recharge to aquifer system (ft^3/s) 1978	Recharge to aquifer system (ft^3/s)/mi 1973	Recharge to aquifer system (ft^3/s)/mi 1978
1	8.04	-1.4	-0.8	-0.17	-0.18
2	6.24	1.3	2.1	.21	.34
3	5.02	5.6	6.6	1.12	1.31
4	2.50	1.0	1.3	.40	.53
5	2.71	3.6	4.0	1.33	1.48
6	2.91	21.8	23.0	7.49	7.90
7	2.81	18.0	19.1	6.41	6.80
8	2.81	8.9	9.4	3.17	3.34
9	2.81	4.6	4.9	1.64	1.74
10	4.52	12.2	13.1	2.70	2.90
11	2.50	11.0	11.9	4.40	4.76
12	6.49	10.6	11.8	1.63	1.82
13	5.41	.9	1.4	.17	.26
14	5.41	4.4	5.1	.81	.94
Totals	60.18	102.5	112.9	31.31	34.01

* Location of reaches shown in figure 12.

Negative values represent flow from the aquifer system to the river.

Model projections to the year 2000 suggest that if withdrawals were kept constant (zero growth), further head reduction in the aquifer system would cease within two years over large parts of the study area. If withdrawals increased at a compounded annual rate of 3 percent, a cone of depression already encompassing most of the Coastal Plain would broaden and deepen with heads ranging from 60 to 160 ft below NGVD by the year 2000. Induced recharge from the Delaware River would increase to about 300 ft^3/s or about 60 percent of total recharge to the aquifer system (Luzier, 1980, p. 69).

The reductions in head in the Potomac-Raritan-Magothy aquifer system have also increased leakage from the overlying Englishtown and Wenonah-Mount Laurel aquifers through the Merchantville Formation-Woodbury Clay confining unit. In the model simulation, approxmately 30 percent of the recharge to the Potomac-Raritan-Magothy aquifer system in 1973 was due to leakage from overlying aquifers (Luzier, 1980, p. 66).

Withdrawal of water from the Englishtown aquifer has had a marked effect on the water level in the overlying Wenonah-Mount Laurel aquifer. Decline in head in the Englishtown aquifer from 1959 to 1970 was 8 to 12 ft/yr over a large area. As a consequence of this change in head, increased quantities of water apparently leak from the Wenonah-Mount Laurel aquifer and through the confining layers into the Englishtown aquifer (Nichols, 1977).

Saltwater Encroachment

If the recharge from precipitation and induced infiltration is insufficient to replace ground water from heavily pumped areas close to the saltwater-freshwater interface, the interface may advance toward pumping centers. The inland extent of the saltwater interface is not accurately known for most of the Coastal Plain aquifers. However, saltwater intrusion into freshwater aquifers in the Coastal Plain of New Jersey has occurred at several locations and poses a threat to the potable ground-water supply in these localities.

A large part of the Potomac-Raritan-Magothy aquifer system in the southern Coastal Plain of New Jersey contains salty ground water. The concentrations of chloride increase with depth as well as toward the ocean. According to Luzier (1980) head reductions caused by withdrawal of ground water near the saltwater interface are more than sufficient to cause the slow migration of the salty water toward pumping centers.

Lateral saltwater intrusion is occurring in a part of the Old Bridge aquifer in the vicinity of Keyport and Union Beach Boroughs in Monmouth County, N.J. The reduction in water levels has caused a reversal in the direction of ground-water flow in the Old Bridge aquifer. Prior to development, water in the aquifer flowed into Raritan Bay. However, saltwater is flowing inland from the submerged (exposed) outcrop of the aquifer beneath Raritan Bay (Schaefer and Walker, 1981).

Water-level declines in the Farrington aquifer in certain areas adjacent to the Raritan River were sufficient to allow saltwater to move into the aquifer. Saltwater intrusion in the Farrington aquifer has caused numerous wells to be abandoned (Appel, 1962, and Barksdale, 1943).

Extensive ground-water withdrawals in the lower peninsula of Cape May County have decreased potentiometric head in the Kirkwood and Cohansey aquifers. This has caused the landward migration of the saltwater interface in the aquifers (Gill, 1962a).

The final assessment in the study by Luzier (1980) confirms the conclusion made by Barksdale and others (1958, p. 126).

> "The great value of ground-water supplies from the Raritan and Magothy Formations justifies all reasonable measures to prevent or delay the serious and long lasting effects of saltwater encroachment. The maintenance of freshwater in the Delaware River is probably the most important preventive measure that can be taken. Next in importance would be the careful and intelligent areal distribution of pumpage in such a way as to take maximum advantage of induced freshwater recharge and to avoid concentrated reductions of freshwater head near the margin of the saltwater in the aquifers."

This evaluation can be applied to all Coastal Plain aquifers to insure that ground-water supplies are protected from saltwater encroachment.

SUMMARY

The Coastal Plain of New Jersey is an interrelated hydrologic system which responds to natural and man-made stresses. The wedge of unconsolidated sediments underlying the Coastal Plain of New Jersey is comprised of a series of hydrologic units that have varying thickness, lateral extent, and water-bearing characteristics. Some of the units act as aquifers, while others act as confining beds. Previous to development by wells, the ground-water system was in a state of dynamic equilibrium.

Withdrawal of ground-water by wells is a stress superimposed on a previously balanced ground-water system. The response of an aquifer to pumping stresses may result in an increase in recharge to the aquifer, a decrease in the natural discharge, a loss of storage within the aquifer, or a combination of these effects. Also, the response of an aquifer to stress may extend beyond the limits of the aquifer being evaluated.

Changes in the natural flow system have been recognized within the Coastal Plain as a result of ground-water withdrawals from Coastal Plain aquifers. Steady declines in ground-water levels have been recognized within the Potomac-Raritan-Magothy aquifer system (including the Farrington and Old Bridge aqufiers), and the Englishtown, Wenonah-Mount Laurel, and Kirkwood aquifers. As a result, large differences in hydraulic head have caused induced recharge from both surface-water bodies and adjacent aquifers. Significant quantities of water are recharged to the Potomac-Raritan-Magothy aquifer system from the Delaware River near pumping centers. Induced leakage of ground water through the confining bed from the Englishtown and Wenonah-Mount Laurel aquifers to the Potomac-Raritan-Magothy aquifer system has occurred. Also the saltwater-freshwater interface has advanced further inland in some aquifers.

In conclusion, by careful planning and coordination of ground-water and surface-water resources within the Coastal Plain, a maximum beneficial use can be achieved. Since most of the water supply developed on the Coastal Plain is derived from ground water, an intelligent areal distribution of ground-water withdrawals is important in order to maintain an environmentally sound equilibrium within the Coastal Plain aquifer system.

SELECTED REFERENCES

Anderson, H. R., and Appel, C. A., 1969, Geology and ground-water resources of Ocean County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 29, 13 p.

Appel, C. A., 1962, Salt-water encroachment into aquifers of the Raritan Formation in the Sayreville Area, Middlesex County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 17, 47 p.

Barksdale, H. C., Greenman, D. W., Lang, S. M., Hilton, G. S., and Outlaw, D. E., 1958, Ground-water resources in the tri-state region adjacent to the lower Delaware River: New Jersey Department of Conservation and Economic Development Special Report 13, 190 p.

Barksdale, H. C., Johnson, M. E., Baker, R. C., Schaefer, E. J., and DeBuchananne, G. D., 1943, The ground-water supplies of Middlesex County, New Jersey: New Jersey Water Policy Commission Special Report 8, 160 p.

Barksdale, H. C., Sundstrom, R. W., and Brunstein, M. S., 1936, Supplementary report on the ground-water supplies of the Atlantic City region: New Jersey Water Policy Commission Special Report 6, 139 p.

Clark, Glenn, and others, 1968, Summary of ground-water resources of Atlantic County with special reference to public water supplies: New Jersey Department of Conservation and Economic Development Water Resources Circular 18, 53 p.

Donsky, Ellis, 1963, Record of wells and ground-water quality in Camden County, New Jersey: New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply Water Resources Circular 10, 70 p.

Farlekas, G. M., 1979, Geohydrology and digital-simulation model of the Farrington aquifer in the northern Coastal Plain of New Jersey: U.S. Geological Survey Water-Resources Investigations 79-106, 55 p.

Farlekas, G. M., Nemickas, Bronius, and Gill, H.E., 1976, Geology and ground-water resources of Camden County, New Jersey: U.S. Geological Survey Water-Resources Investigations 76-76, 146 p.

Federal Register, 1979, Environmental Protection Agency Region II: Ground water system of the New Jersey Coastal Plain: Volume 44, No. 56.

Forman, R. T., 1979, Pine Barrens: Ecosystem and Landscape, Adademic Press, New York, 601 p.

Franke, O. L. and McClymonds, N. E., 1972, Summary of hydrologic situation on Long Island, New York, as a guide to water-management alternatives: U.S. Geological Survey Professional Paper 627-F, 58 p.

Geraghty and Miller, Inc., 1979, The Statewide Water Supply Master Plan Task 7C. Groundwater management interim output: Port Washington, New Jersey.

Gill, H. E., 1959, Geology and ground-water resources of the Cape May Peninsula, Lower Cape May County, New Jersey: New Jersey Department of Conservation and Economic Development Water Resources Circular 1, 19 p.

__________, 1962a, Ground-water resources of Cape May County, New Jersey, salt-water invasion of principal aquifers: New Jersey Department of Conservation and Economic Development Special Report 18, 171 p.

__________, 1962b, Records of wells, well logs, and summary of stratigraphy of Cape May County, New Jersey: New Jersey Department of Conservation and Economic Development Water Resources Circular 8, 54 p.

Gill, H. E., and Farlekas, G. M., 1976, Geohydrologic maps of the Potomac-Raritan-Magothy aquifer system in the New Jersey Coastal Plain: U.S. Geological Survey Hydrologic Investigations Atlas, HA-557.

Hardt, W. F., 1963, Public water supplies in Gloucester County, New Jersey: New Jersey Department of Conservation and Economic Development Water-Resources Circular 9, 55 p.

Hardt, W. F., and Hilton, G. S., 1969, Water resources and geology of Gloucester County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 30, 130 p.

Jablonski, L. A., 1968, Ground-water resources of Monmouth County, New Jersey: New Jersey Department of Conservation and Economic Development Water Resources Circular 4, 28 p.

Langbein, W. B. and Iseri, K. T., 1960, General introduction and hydrologic definitions: U.S. Geological Survey Water-Supply Paper 1541-A.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms - revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Luzier, J. E., 1980, Digital-simulation and projection of head changes in the Potomac-Raritan-Magothy aquifer system, Coastal Plain, New Jersey: U.S. Geological Survey Water-Resources Investigations No. 80-11, 72 p.

Nemickas, Bronius, 1976, Digital-simulation model of the Wenonah-Mount Laurel aquifer in the Coastal Plain of New Jersey: U.S. Geological Survey Open-File Report 75-672, 42 p.

Nichols, W. D., 1977, Geohydrology of the Englishtown Formation in the Northern Coastal Plain of New Jersey: U.S. Geological Survey Water-Resources Investigations 76-123, 62 p.

Olsson, R. K., 1975, Upper Cretaceous and Lower Tertiary stratigraphy New Jersey Coastal Plain: 2nd annual field guide, Petroleum Exploration Society of New York, New York, N.Y.

Parker, G. G., and others, 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.

Rhodehamel, E. C., 1970, A hydrologic analysis of the New Jersey Pine Barrens region: New Jersey Department of Environmental Protection, Division of Water Resources, Water Resources Circular No. 22, 35 p.

__________, 1973, Geology and water resources of the Wharton Tract and Mullica River basin in southern New Jersey: New Jersey Department of Environmental Protection, Division of Water Resources Special Report No. 36, 58 p.

Richards, H. G., and others, 1962, Generalized structural contour maps of the New Jersey Coastal Plain: New Jersey Department of Conservation and Economic Development Geologic Report Series 4, 38 p.

Rooney, J. G., 1971, Ground-water resources Cumberland County, New Jersey: New Jersey Department of Environmental Protection, Division of Water Resources Special Report 34, 83 p.

Rosenau, J. C., and others, 1969, Geology and ground-water Resources of Salem County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 33, 142 p.

Rush, F. E., 1962, Records of wells and ground-water quality in Burlington County, New Jersey: New Jersey Department of Conservation and Economic Development Water Resources Circular 7, 104 p.

__________, 1968, Geology and ground-water resources of Burlington County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 26, 65 p.

Schaefer, F. L., and Walker, R. L., 1981, Saltwater intrusion into the Old Bridge aquifer in the Keyport-Union Beach Area of Monmouth County, New Jersey: U.S. Geological Survey Water-Supply Paper 2184.

Thornthwaite, C. W., 1952, An approach toward a rational classification of climate: Readings in the Geography of North America; American Geographical Society, New York.

Vecchioli, John, and Palmer, Mark, 1962, Ground-water resources of Mercer County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 19, 71 p.

Widmer, Kemble, 1965, Geology of the ground-water resources of Mercer County, New Jersey: New Jersey Department of Conservation and Economic Development Geologic Report Series 7, 115 p.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Monthly normals of temperature, precipitation, and heating and cooling degree days 1941-1978: Climatography of the United States No. 81 (By State), National Climatic Center, Asheville, N.C.