SELECTED HYDROGEOLOGIC AND CHLORIDE-CONCENTRATION DATA FOR THE NORTHERN AND CENTRAL COASTAL AREA OF NEW CASTLE COUNTY, DELAWARE

By Martha A. Hayes, Scott W. Phillips, and Judith C. Wheeler

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Abbreviated water-quality units: Chemical concentrations are reported in milligrams per liter (mg/L).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

This report summarizes and presents existing hydrogeologic and chloride-concentration data from the northern and central coastal area of New Castle County, Delaware. The report was prepared as an initial stage to evaluate the effects that the proposed deepening of the main navigational channel of the Delaware River would have on ground-water resources in Delaware. The study area was defined on the basis of current and projected ground-water usage from aquifers known or thought to be in hydraulic contact with the Delaware River. The report includes maps that show the location of the study area and associated geologic and hydrologic characteristics. Tables listing hydrologic characteristics, water use, annual ground-water withdrawals, and chloride-concentration data for the study area also are included.

INTRODUCTION

The U.S. Army Corps of Engineers (COE), Philadelphia District, is evaluating the possibility of making improvements to the main navigational channel of the Delaware River. These improvements could include deepening the channel from the existing depth of about 40 ft below mean-low water (MLW) to about 45 ft below MLW, thereby extending navigable deep water from Delaware Bay to Philadelphia, Pa., and Camden, N.J. Many public and private ground-water supplies have been developed adjacent to the Delaware River in the reach where channel improvements are being considered. There are concerns that deepening the channel may adversely affect ground-water supplies developed in the adjacent Coastal Plain aquifers of Delaware. The Potomac aquifer system is of particular interest because it is the sole-source ground-water supply for northern New Castle County. A previous study (Phillips, 1987) has documented brackish-water intrusion from the Delaware River into aquifers of the Potomac Formation in northern New Castle County. The Magothy and Englishtown-Mount Laurel aquifers are sources of water in the southern part of the county below the Chesapeake and Delaware Canal (C&D Canal). Water quality in these aquifers and the Potomac aquifers could be affected if channel deepening causes salinity in the river and the C&D Canal to increase. Some of that water could infiltrate into adjacent aquifers, causing an increase in chloride and sodium concentrations.

The amount of water infiltrating from the Delaware River into the Potomac and other aquifers and the water's subsequent effect on ground-water quality is dependent on four factors: (1) the depth and distribution of the aquifers relative to the river channel, (2) the nature of the sediments overlying the aquifers where they extend under the river, (3) the direction and magnitude of the hydraulic gradient between the aquifers and the river, and (4) the salinity of the river water. Deepening the channel could affect factors 2 and 4 above. Dredging could breach confining layers of fine-grained relatively impermeable sediments under the river, which would provide a conduit for river water to flow into underlying aquifers. Removing 5 ft of bottom material from the river could cause higher salinity water to encroach farther upstream in the river and the C&D Canal. If this water migrates into the aquifers, it could eventually cause increased salinity in areas currently experiencing brackish-water intrusion. Even without deepening the channel, the hydraulic gradient between the river and aquifer (factor 3), which now is from the river into the aquifer in many places, is likely to increase because of higher rates of ground-water pumpage in New Castle County. Water-level data for the aquifers that are needed to evaluate the hydraulic gradient are presented in this report. Existing data related to factors 1 and 2 also have been compiled in this report and are presented along with chloride-concentration data (an indication of salinity) for the study area. This study was done in cooperation with the U.S. Army Corps of Engineers.

Purpose and Scope

This report presents available hydrogeologic and chloride-concentration data for the coastal area of northern and central New Castle County, Del. Data for the depth and distribution of aquifers and confining units, the aquifer and confining-unit sediments, water-level data within aquifers, and existing salinity distributions in ground water and river water are presented. Maps are provided to show the location of the study area and its associated geologic and hydrologic characteristics. Tables list information about the hydrogeologic characteristics, water use, annual ground-water withdrawals, and chloride-concentration data for the study area.

Description of Study Area

The study area was defined on the basis of current and projected ground-water usage from aquifers known or thought to be the uppermost aquifer underlying the Delaware River. The study area lies in northern and central New Castle County, Del., and is bounded approximately on the west by U.S. Route 13, on the east by the Delaware River, on the north by the Christina River, and on the south by the Appoquinimink River (fig. 1). These boundaries were chosen to include the parts of aquifers where most of the pumpage in this area of the State occurs. Topography is relatively flat to gently rolling, with land-surface elevations ranging from sea level to about 80 ft above sea level. The area is underlain by unconsolidated sediments of the Atlantic Coastal Plain Physiographic Province that form a wedge-shaped deposit of highly variable permeability (Cushing and others, 1973). The Coastal Plain sediments range in thickness from a few feet at the Christina River to approximately 1,600 ft at the Appoquinimink River (Sundstrom and Pickett, 1971).

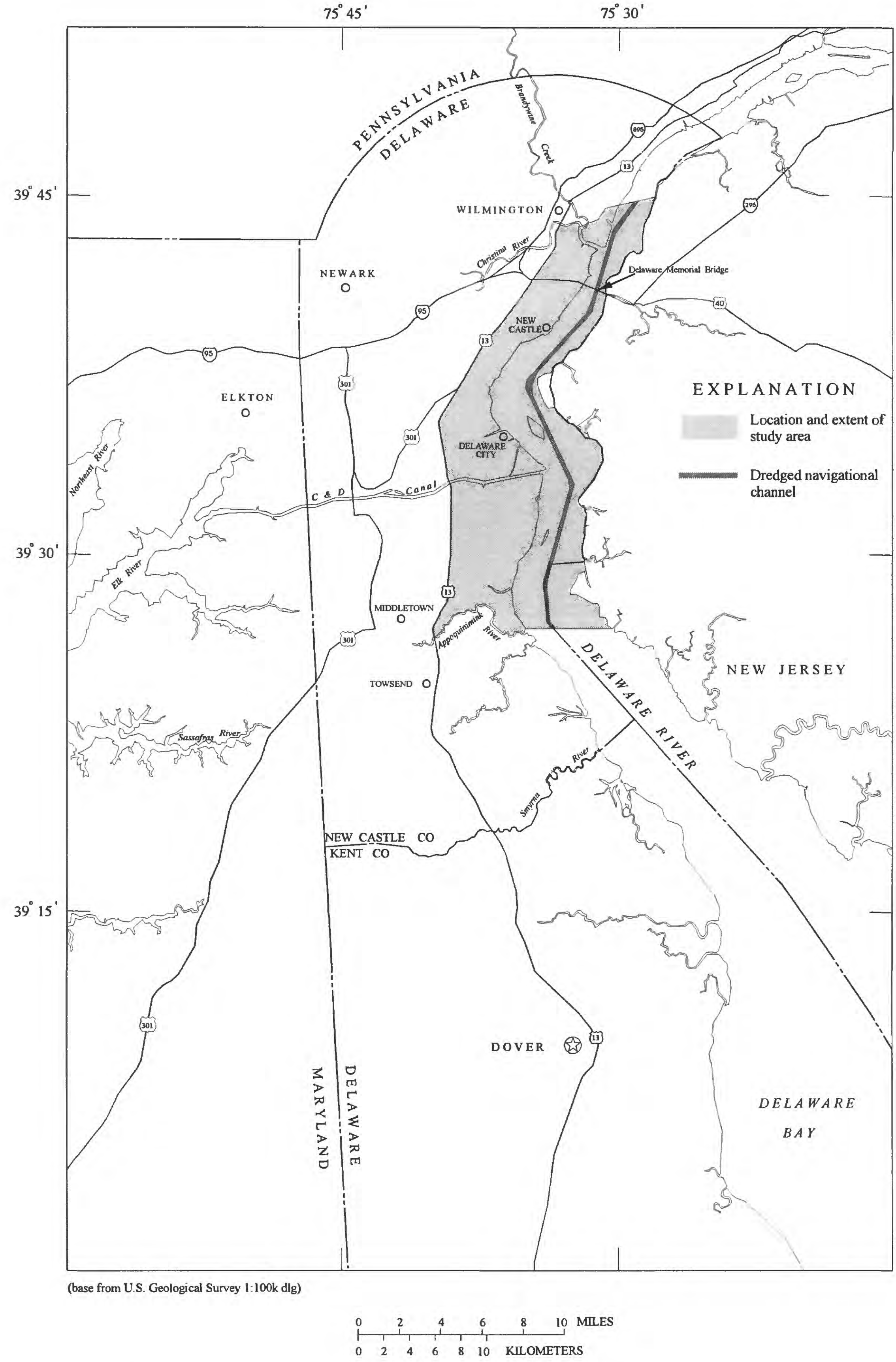

Figure 1. Location of study area.

Conceptual Models of Saltwater Intrusion

Brackish water, which is water with salinity and corresponding chloride concentrations between that of normal seawater and that of normal freshwater (Bates and Jackson, 1987), is found in the aquifers adjacent to the Delaware River under three conditions: Infiltration from the river (Phillips, 1987); leakage from landfills; and at depth, as naturally occuring brines in the southernmost part of the study area (Sundstrom and Pickett, 1971; Groot, 1983). The focus of this report is on conditions related to potential brackish-water infiltration from the Delaware River. Elevated chloride concentrations caused by landfills and the formation of brines at depth are not related to conditions in the Delaware River and are not presented in this report.

Ground-water-flow directions under steady-state (prepumping) and pumping conditions are shown in figures 2a and 2b, respectively. These simplified flow models show the primary hydrogeologic factors that influence the movement of brackish water from the Delaware River into the underlying aquifers. These factors include (1) water levels in the aquifers relative to sea level, (2) the distribution of aquifer outcrop and subcrop areas and overlying confining units, (3) the nature of bottom sediments in the bay, and (4) the distribution of and sedimentary sequence in paleochannels and dredged channels.

Water levels in the aquifers exert the major control on river-water intrusion and are strongly related to pumping. A typical flow regime under steady-state (prepumping) conditions is shown in figure 2a. As fresh ground water is withdrawn from the aquifers, water levels decline, often to below sea level. As this happens, directions of flow change until a new equilibrium between hydraulic heads in the aquifers and the bay is established. A typical flow regime under pumping conditions is shown in figure 2b.

The distribution of aquifer outcrop and subcrop areas and overlying confining units plays an important role in determining the degree to which brackish-water intrusion is likely to occur. Where aquifers crop out or subcrop in Delaware Bay and chloride concentrations in the river are higher than in the ambient ground water, brackish water (which is denser than freshwater) can flow downward into the aquifer. If the hydraulic head in the aquifer is sufficiently high, or low permeable silt and clay confining units crop out or subcrop in the bay above the aquifer, brackish-water intrusion is retarded.

Sediments are deposited in the bottom of the bay by fluvial and tidal action. The nature of these sediments affects the ease with which brackish water is able to intrude into the aquifers. If the bottom sediments consist of silt, clay, or organic ooze, hydraulic conductivity is apt to be low, and brackish-water intrusion is inhibited. Conversely, if the bottom sediments consist of sand and gravel or are relatively thin, brackish-water intrusion is apt to be facilitated.

The distribution of paleo- or dredged channels affects the brackish-water intrusion because the creation of channels can remove confining units.

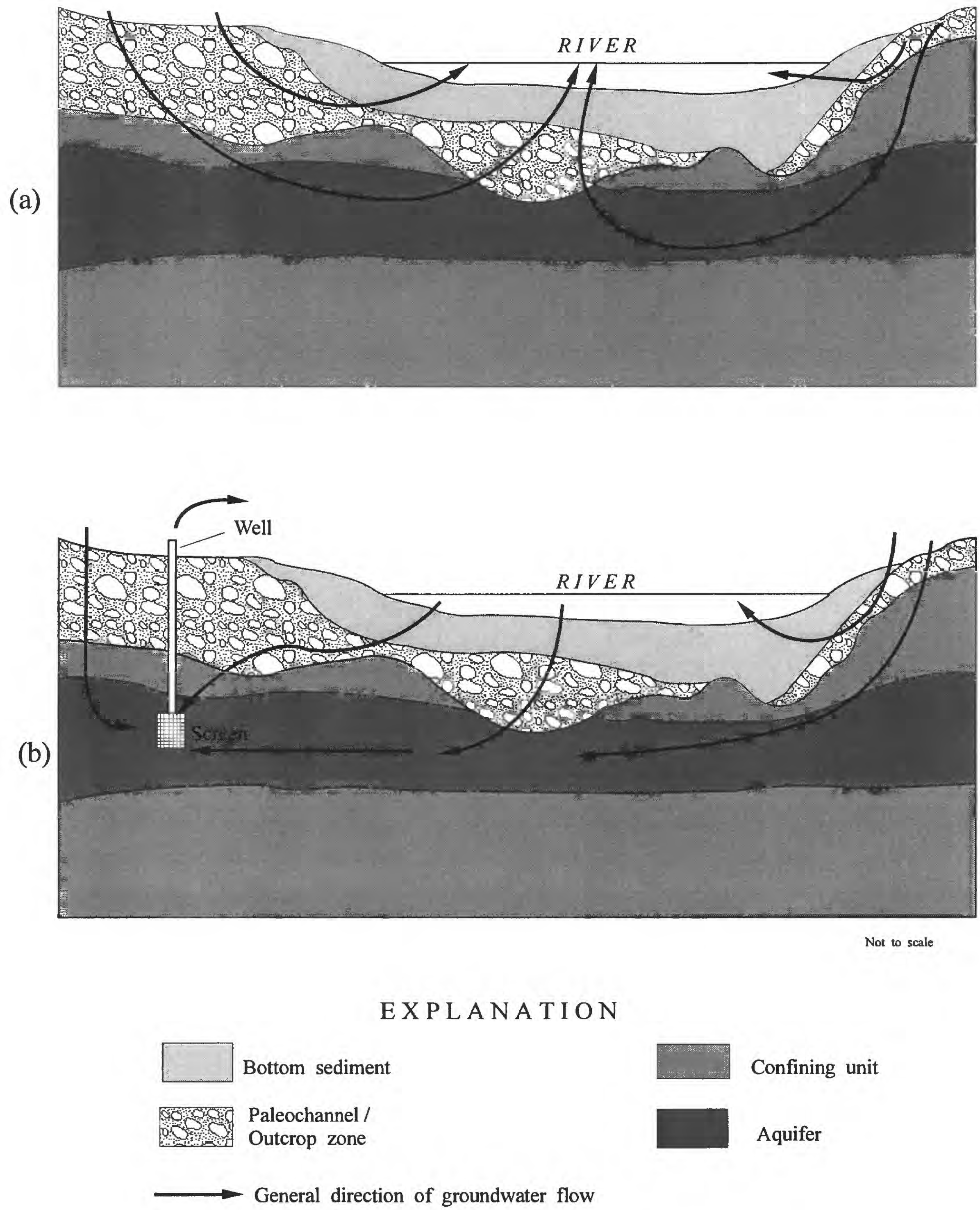

Figure 2. Schematic diagrams showing ground-water-flow directions under (a) steady-state and (b) pumping conditions. (from Phillips and Ryan, 1989)

This changes the distribution of aquifer outcrop at these locations and can expose areas of high permeability and relatively low hydraulic head to the river and facilitate the flow of brackish water into the aquifer.

Rates of change in flow direction are determined by the relative elevations of the water level in the river and the aquifer, the orientation and physical characteristics of the aquifer, the distance to a pumped well from the zone of hydraulic contact, and the rate of recharge to and discharge from the aquifer. Ground water generally moves very slowly. Years, decades, or centuries may pass before brackish water reaches a well.

Previous Investigations

Numerous investigations related to ground water have been conducted in the study area. The investigations can be organized into five categories: (1) General geology and hydrology; (2) ground-water resource information; (3) investigations and compilations of ground-water quality; (4) investigations and compilations of water quality in the river; and (5) quantitative investigations of ground-water flow, including intrusion of river water into the Potomac aquifer.

(1) Results of studies of the general geology and hydrology of the study area have been reported by Jordan and Groot (1962), Bonini (1967), Spoljaric (1967), Spoljaric and Woodruff (1970), Owens and others (1970), Pickett (1970), Pickett and Spoljaric (1971), Cushing and others (1973), Woodruff (1981 and 1986), Duran (1986), Trapp (1992), and Vroblesky and Fleck (1991).

(2) General ground-water resource information has been reported by Marine and Rasmussen (1955), Rasmussen and others (1957), Rima and others (1964), Sundstrom and others (1967), Sundstrom and Pickett (1971), Groot and others (1983), Knobel (1985), Talley (1978 and 1988), Frick and Shaffer (1977), and Metcalf & Eddy (1991a and 1991b).

(3) Investigations and compilations of ground-water quality have been reported by Groot and Beamer (1958), Woodruff (1969 and 1970), Apgar (1979), Groot (1983), Talley (1985), Avery and others (1993), and Bachman and Ferrari (1995).

(4) Investigations and compilations of water quality in the river have been reported by Cohen (1957), Martin and Denver (1982), Hull and Titus (1986), Phillips (1987), Delaware River Basin Commission (1989), DiLorenzo and others (1993), and White (1993).

(5) Quantitative investigations of ground-water flow have been reported by Ambrose and others (1980), Apgar and Panigrahi (1982), Martin and Denver (1982), Martin (1984), Phillips (1987), and Avery and others (1994), who evaluated the area along the reach of the Chesapeake and Delaware Canal.

The results of these investigations as they relate to the current project are presented in this report.

Acknowledgments

Data for this report were provided by Gerald Kauffman (Regional Planning and Management, New Castle County) and by officials of the Delaware Department of Public Health, the Delaware Department of Natural Resources and Environmental Control (DNREC), and the U.S. Army Corps of Engineers, Philadelphia District (COE). Publications and other information were provided by Scott Andres of the Delaware Geological Survey (DGS), Blair Venables and Stuart Lovell of DNREC, John Sharpe of the Delaware Estuarine Program, Richard Tortoriello of the Delaware River Basin Commission, and the COE.

HYDROGEOLOGIC DATA

Relatively impermeable crystalline basement rocks in the study area slope seaward and are overlain by a wedge-shaped deposit of unconsolidated sediments of highly variable permeability (Cushing and others, 1973). This deposit ranges in thickness from a few feet at the Christina River to approximately 1,600 ft at the Appoquinimink River (Sundstrom and Pickett, 1971). The sediments consist of a system of unconsolidated sand and silty clay that represent cycles of marine transgression and regression interrupted by erosional and depositional unconformities. In the study area, a series of aquifers and confining units can be defined in these sediments on the basis of their mineralogic, structural, physical, and chemical properties. Many of these properties were determined by the depositional environments of the aquifers. These depositional environments ranged from fluvial (Potomac Formation) through marginal-marine (Magothy Formation), to marine (Matawan, Monmouth, and Rancocas Groups) (Spoljaric and Jordan, 1966). These sediments are overlain unconformably by the fluvial deposits of the Columbia Formation.

Surficial deposits of the Columbia Formation blanket most of the study area. The thickness of these deposits is highly variable, reflecting the occurrence of the sediments as fillings of former stream valleys (paleochannels) (Jordan, 1964). Several paleochannels were exposed by the construction of the C&D Canal (fig. 1). The channels range up to more than half a mile in apparent width and cut into the underlying formations from elevations of 40 to 70 ft above sea level down to tens of feet below sea level. Paleochannels are found in many locations all over the study area and form a locally productive water-table (unconfined) aquifer that provides recharge to underlying confined aquifers where they subcrop.

Ground water in the study area flows in water-table and confined aquifers. Several confined aquifers crop out or subcrop beneath the Columbia Formation in the study area. The geologic units that contain these aquifers include the Potomac Formation, Magothy Formation, Matawan Group (Englishtown Formation), Monmouth Group (Mount Laurel Formation) and Rancocas Group (Vincentown Formation). The distribution of these units (with the Columbia Formation removed) is shown in figure 3. The relation between the stratigraphy and the water-bearing properties of the aquifers in New Castle County is summarized in table 1. Each of the aquifers in the study area is

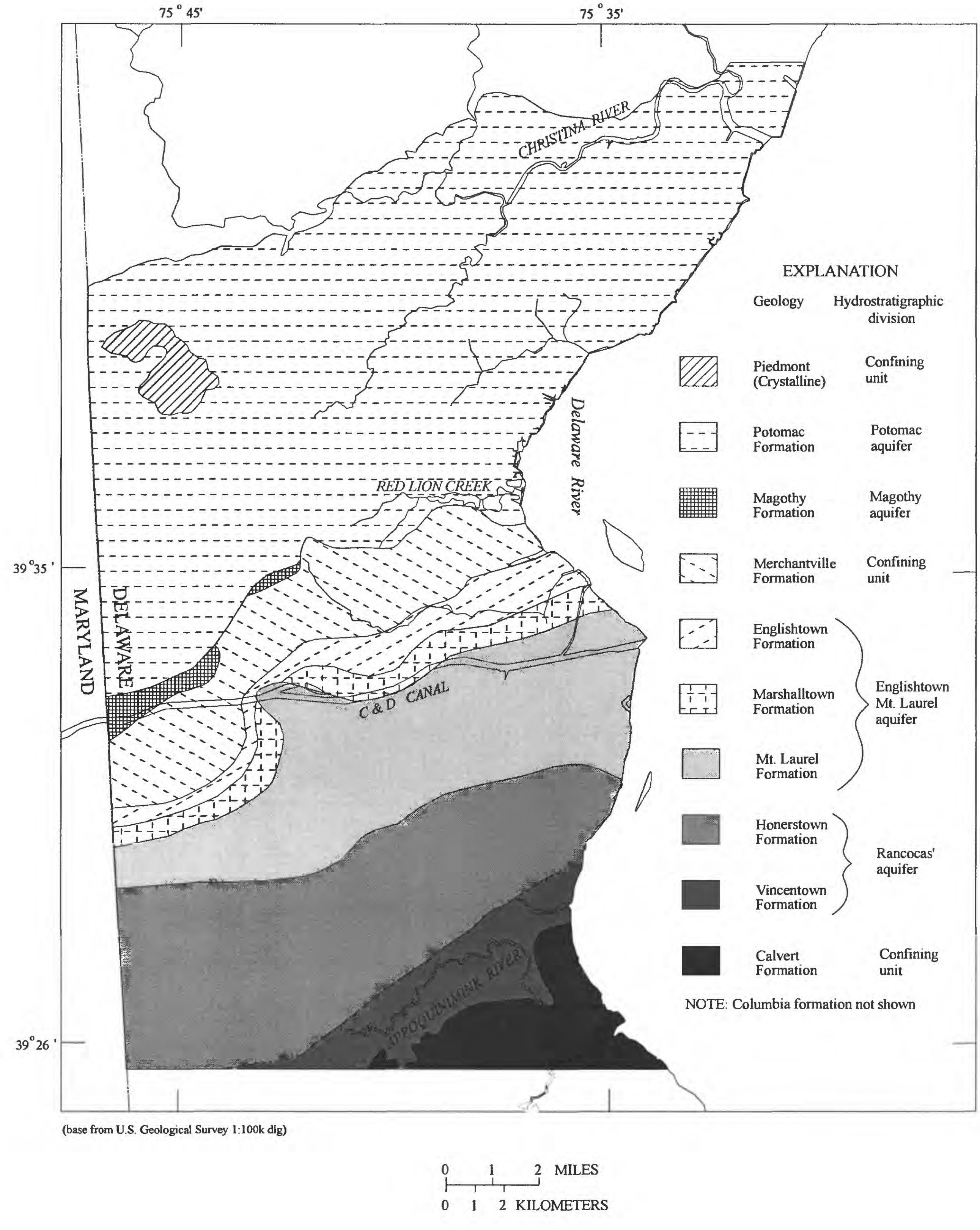

Figure 3. Geology of Delaware within the northern and southern boundaries of the study area. (modified from Sundstrom and Pickett, 1971; and Bachman and Ferrari, 1995).

Table 1. Hydrostratigraphy of central New Castle County, Delaware

System	Series	Stratigraphic unit	Hydrostratigraphic division Delaware (New Jersey)	Lithology	Water-bearing properties
Quaternary	Holocene and	Holocene sediments		Silt, sandy silt, silty sand, some gravel, abundant organics, some peat	Leaky confining unit
	Pleistocene	Columbia Group	Columbia aquifer (Holly Beach aquifer)	Sand, gravel, some clay, dominantly quartz; fluvial	Water table aquifer, usually surficial, often in hydraulic connection with an underlying unit, large quantity of water where thickness is greater than 40 ft
Tertiary	Miocene	Calvert Formation	Confining unit south of Appoquinimink River	Silty clay; marine	Confining unit
	Paleocene	Rancocas Group	Rancocas aquifer (Vincentown aquifer)	Quartz; silty, glauconitic sand; marine	Sandy zones function as aquifers
Cretaceous	Upper	Monmouth Group and Matawan Group	Englishtown-Mt. Laurel aquifer system (Wenone-Mt.Laurel aquifer and Englishtown aquifer system)	Medium-coarse sand with glauconite, fossils, some silt; marine Fine sand and silt, micaceous and glauconitic; marine	Sandy zones function as aquifers interbedded with leaky confining units
	Lower	Magothy Formation	Magothy aquifer (Upper Potomac-Raritan-Magothy [PRM] aquifer system)	Silty clay with interbedded sand, predominantly quartz and kaolinite; marginal marine	Hydraulically connected to upper Potomac aquifer
		Potomac Formation	Upper, middle, and lower Potomac aquifers (Middle and lower PRM aquifer system)	Quartz sand with some gravel, variegated silt and clay, some beds of gray clay; fluvial	Sandy zones function as aquifers in lower, middle, and upper parts of Potomac Formation
Paleozoic and Precambrian		Crystalline rocks (basement)	Confining unit (basement)	Complex assemblage of igneous and metamorphic rocks	Not an important aquifer in the Coastal Plain

described in more detail in the following sections, from north to south in order of subcropping. Particular emphasis is placed on the uppermost aquifer directly underlying the Delaware River and its river-channel deposits.

The geology of the study area (fig. 3) and the available cross sections of the river indicate that the Delaware River might cross outcrops of the Potomac, Englishtown-Mt. Laurel, and Rancocas aquifers (Sundstrom and Pickett, 1971; Frick and Shaffer, 1977; Phillips, 1987; Bachman and Ferrari, 1995). As shown in table 1, Holocene sediments of various thickness overlie most of these geologic formations. The Potomac aquifers underlie the river from about 3 mi northeast of Wilmington to about 4 mi southwest of New Castle (fig. 1). The Englishtown-Mount Laurel aquifers underlie the river from about 3 mi upstream of the C&D Canal to about 3 mi downstream of the canal. The Rancocas aquifer underlies the river between the C&D Canal and the Appoquinimink River. The Piney Point Formation consists of the Piney Point aquifer (Cushing and others, 1973). The Piney Point aquifer is not a significant source of water in the study area (Leahy, 1982). The Piney Point aquifer is not in hydraulic connection with Delaware Bay (Cushing and others, 1973) and is not thought to be recharged by bay water.

Aquifers in the Potomac Formation

The predominantly fine-grained sediments of the Potomac Formation were deposited by a stream system of coalescing alluvial fans and exhibit considerable vertical and horizontal variability (Sundstrom and others, 1967). Several aquifers of highly variable transmissivity separated by generally continuous confining units have been identified (Martin and Denver, 1982). Martin (1984) found that most of the recharge for the Potomac aquifers occurred at or near the land surface where the aquifers crop out or subcrop below the unconfined aquifer or a confining unit. Water in these aquifers that is not affected by pumpage flows southeast and eventually discharges into overlying sediments and the Delaware River (Phillips, 1987).

Previous workers have divided the Potomac Formation into a hydrologic system with either two or three aquifers. Rasmussen and others (1957) divided the Potomac Formation into lower, middle, and upper Potomac aquifers. Sundstrom and others (1967) divided the Potomac Formation in the C&D Canal area into upper and lower aquifers. Woodruff (1985) agreed that most of the Potomac Formation is characterized by two aquifers, but found evidence to support the three-aquifer interpretation in some areas in New Castle County. Martin (1984) and Phillips (1987) also identified three aquifers in the formation and used them as a basis for a digital flow model of the Potomac Formation in New Castle County. The three-aquifer interpretation is used in this report (fig. 4).

Delineation of the lower Potomac aquifer north of the Delaware Memorial Bridge is difficult because of the lack of data. Data from Duran (1986) that were collected by use of marine seismic-reflection and electromagnetic-conductivity techniques indicate that, north of the Delaware Memorial Bridge, the Potomac Formation is mostly fine grained and consists of relatively thin and discontinuous sand bodies. Analysis of these data indicate that the lower Potomac aquifer underlies the river directly in some

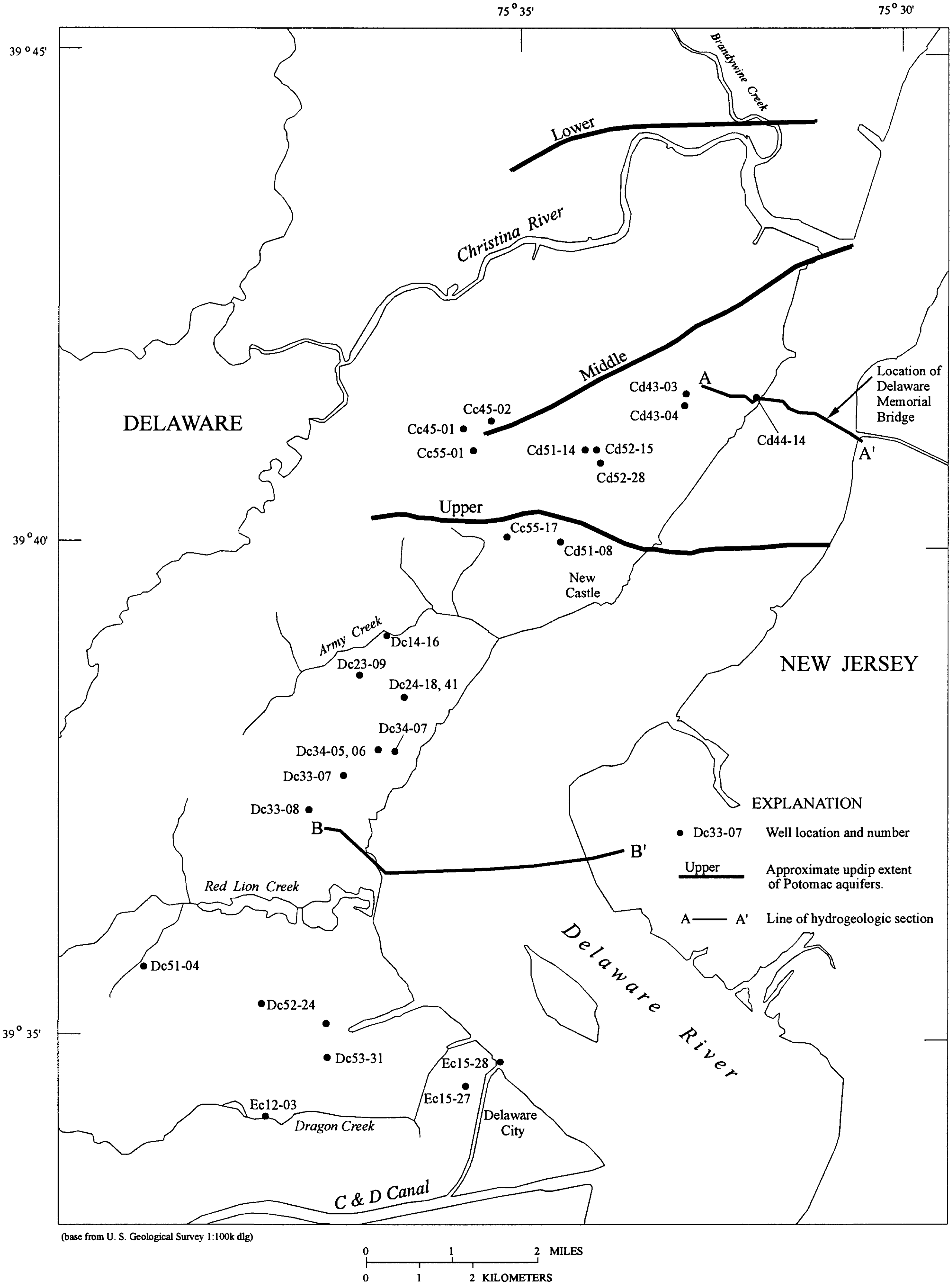

Figure 4. Location of lower, middle, and upper Potomac aquifers; hydrogeologic sections (A - A' and B - B'); and wells measured for dissolved chloride concentration.

reaches from north of the Christina River south to the Delaware Memorial Bridge (Phillips, 1987). In general, however, the lower Potomac is not a productive aquifer in this part of Delaware. As a result, this aquifer is not used for major ground-water withdrawals, and very little data exist. For this reason, this aquifer is not discussed in this report.

The middle Potomac aquifer is the most important water-producing aquifer in the area between the city of New Castle and the Delaware Memorial Bridge and is also the uppermost aquifer underlying the Delaware River in this area (fig. 4). The structure contours for the top of the middle Potomac aquifer for the entire study area are shown in figure 5. North of New Castle, in the subcrop zone where recharge occurs, depth to the top of the aquifer ranges from about sea level to about 120 ft below sea level. In this area, the aquifer is overlain only by Columbia Group sediments and by thin lenses of younger Potomac sediments. The middle Potomac aquifer underlies the river at a depth of 100 to 152 ft below sea level at the Delaware Memorial Bridge (fig. 6). The aquifer is continuous to the west, underlying the ICI and Collins Park well fields. The sand unit labeled "Kp" in figure 6 underlies the ICI well field between 60 and 76 ft below sea level, and is either part of the Potomac Formation or a paleochannel in the Columbia Group (Phillips, 1987). Since the unit is in hydraulic contact with the Potomac sand at the Collins Park well field, it funcions hydraulically as part of the middle Potomac aquifer.

The upper Potomac aquifer is the most important water-producing aquifer between the city of New Castle and Red Lion Creek (fig. 4). The structure contours of the top surface of the aquifer in the study area are shown in figure 7. A hydrogeologic section (B--B') extending between the area just north of Red Lion Creek eastward to New Jersey is shown in figure 8. The top of the upper Potomac aquifer at the west end of the section is 88 to 112 ft below sea level, with a thickness of approximately 20 ft. The aquifer is not continuous beneath the river, but could be in hydraulic connection with the river through the Columbia sand and gravel. The confining unit over the Columbia is locally thin, especially near the New Jersey coast.

Magothy Aquifer

The hydrology of the Magothy aquifer in and near its subcrop area (fig. 9) is closely associated with the upper aquifer zone of the Potomac Formation (Sundstrom and Pickett, 1971). According to Cushing and others (1973), water in this aquifer is recharged south of the C&D Canal. Locally, ground water flows north toward the canal; regional flow is south to downdip parts of the aquifer system outside the study area. The marginal-marine sediments that compose the Magothy aquifer rest directly on the fluvial sediments of the upper Potomac Formation. In the northern end of the distribution of the Magothy aquifer, where the aquifer's sands lie on the upper sands of the Potomac aquifer, the two aquifers are hydraulically connected and are considered a single aquifer in hydrologic treatment near the C&D Canal (Sundstrom and Pickett, 1971). Farther to the south, where the aquifers are more deeply buried, the Magothy Formation marine clay thickens and the Magothy aquifer is more confined. The contours showing depth to the top surface of the Magothy Formation are shown in figure 9.

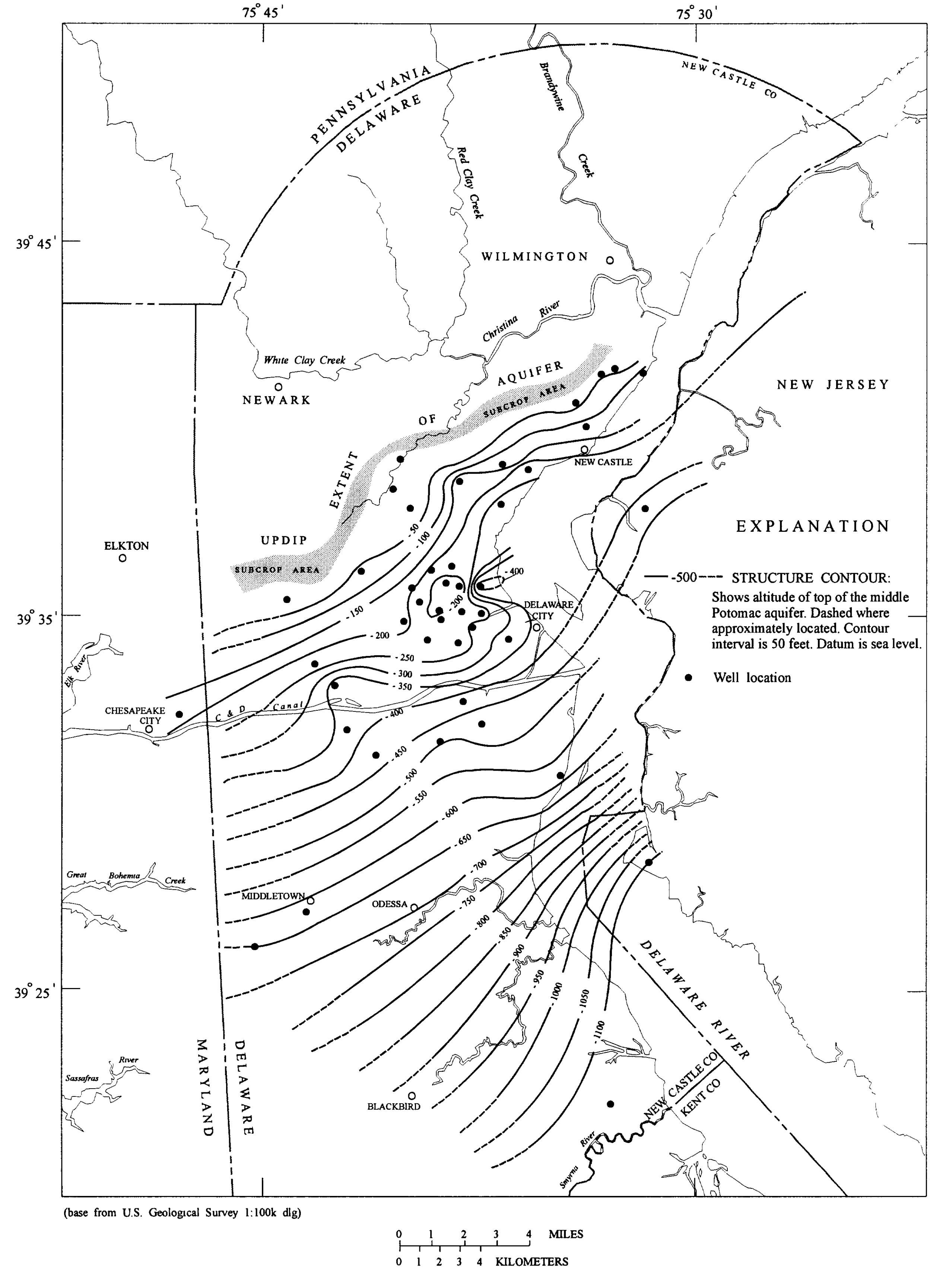

Figure 5. Altitude and configuration of the top of the middle Potomac aquifer (from Martin, 1984, fig.6).

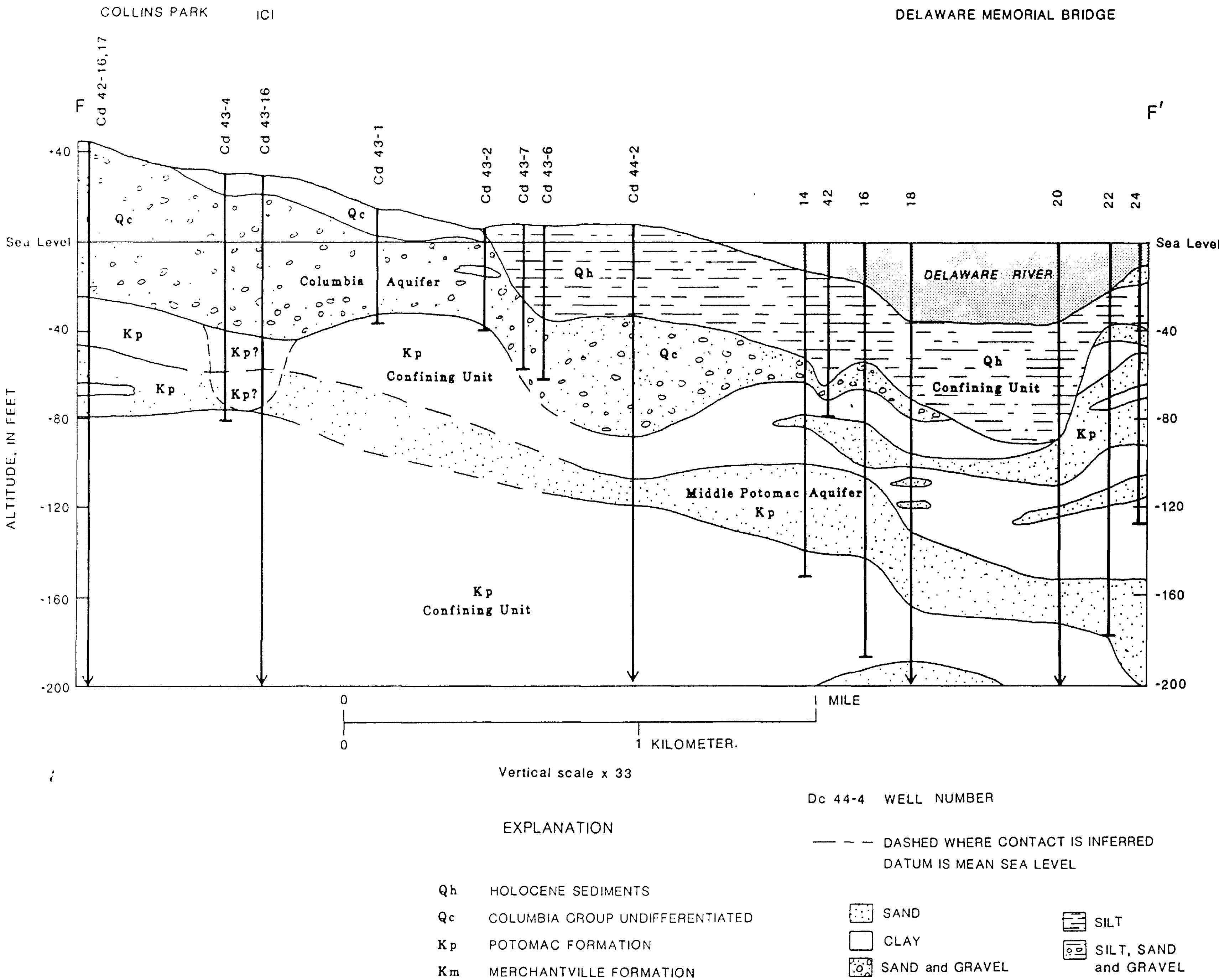

Figure 6. Hydrogeologic section A-A' of the shallow hydrologic system under the Delaware River (from Phillips, 1987). (location of section shown in fig. 4.)

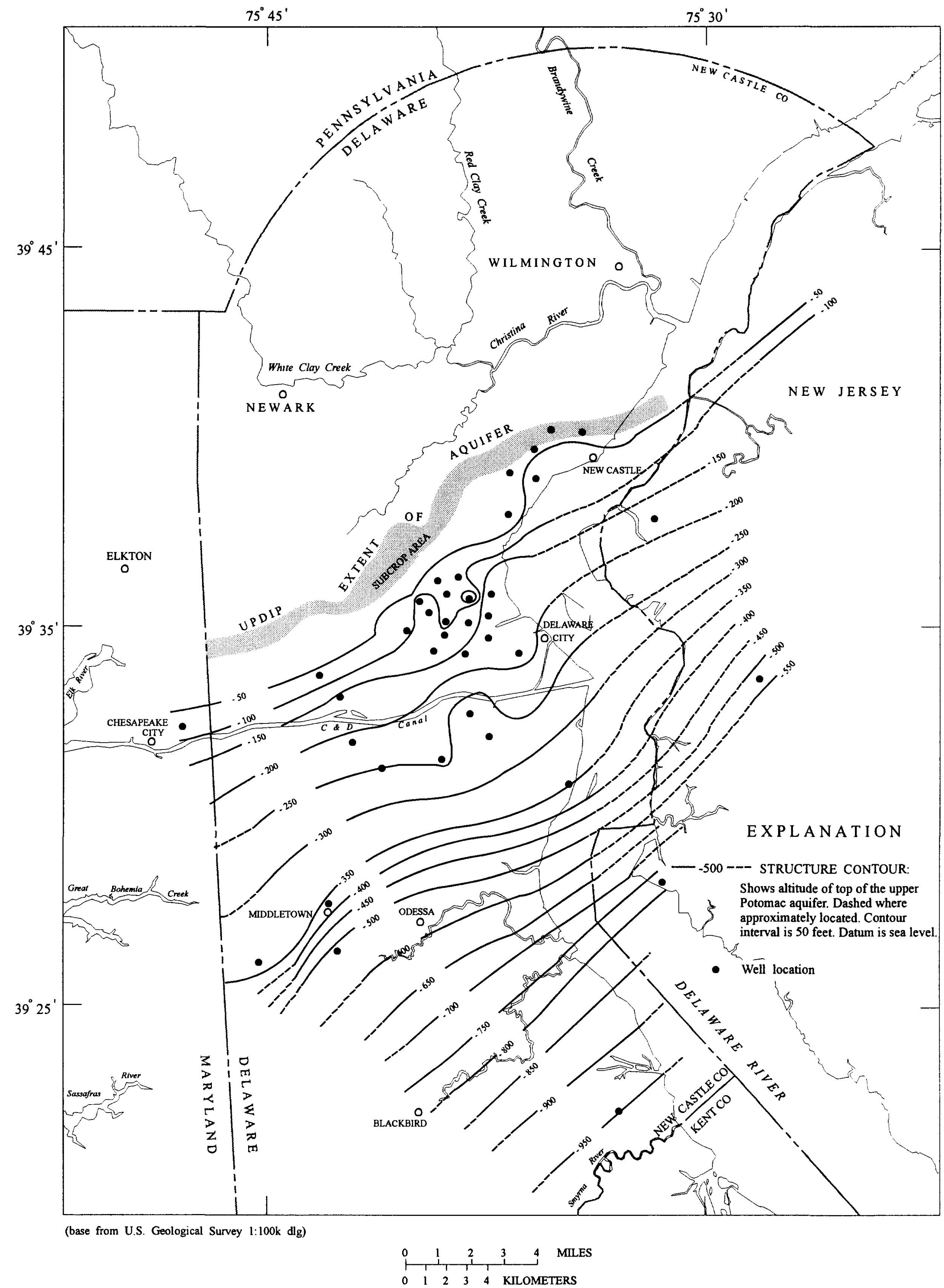

Figure 7. Altitude and configuration of the top of the upper Potomac aquifer (from Martin, 1984, fig.4).

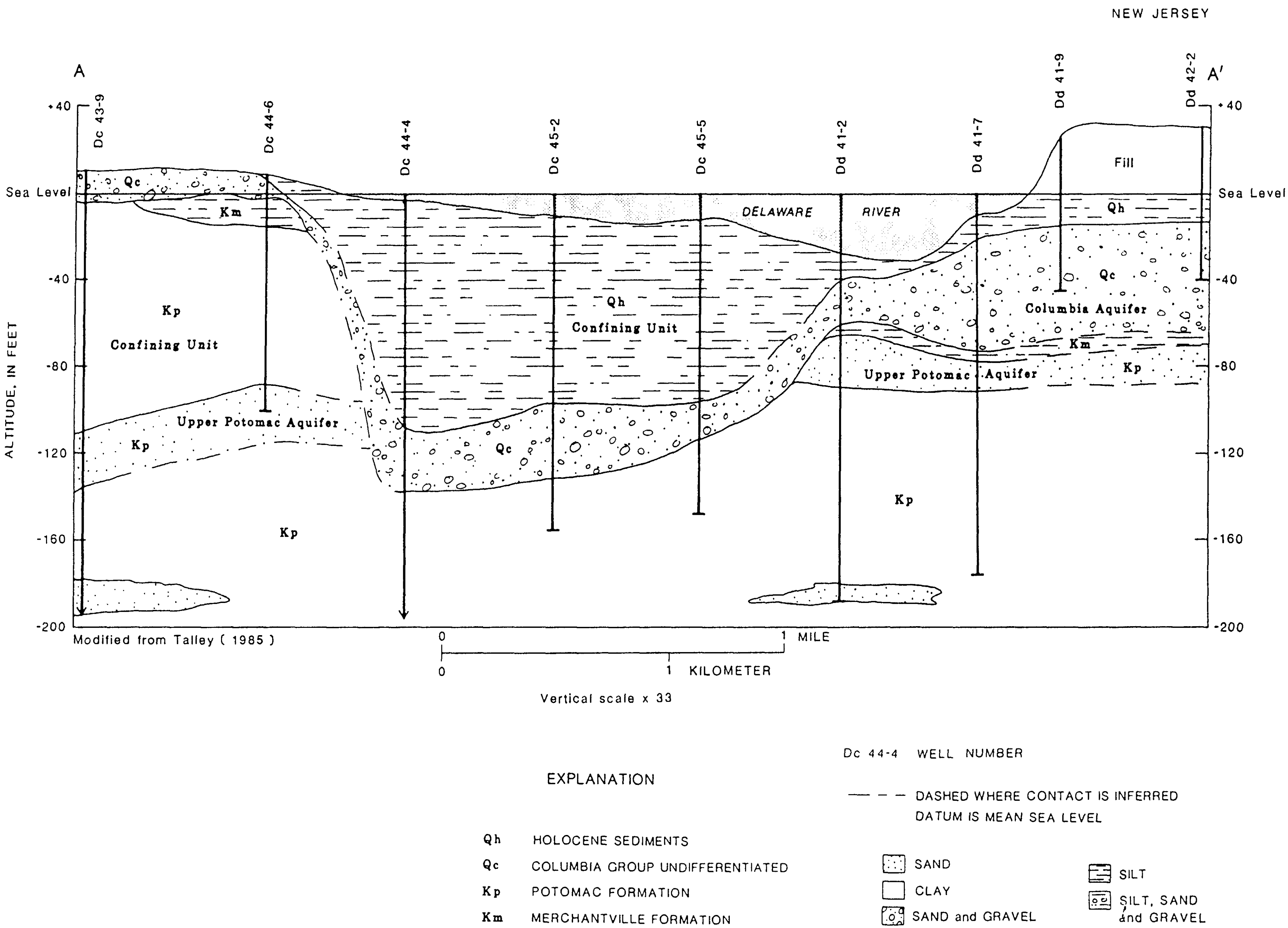

Figure 8. Hydrogeologic section B-B' of the shallow hydrologic system under the Delaware River (from Phillips, 1987). (Location of section shown in fig. 4.)

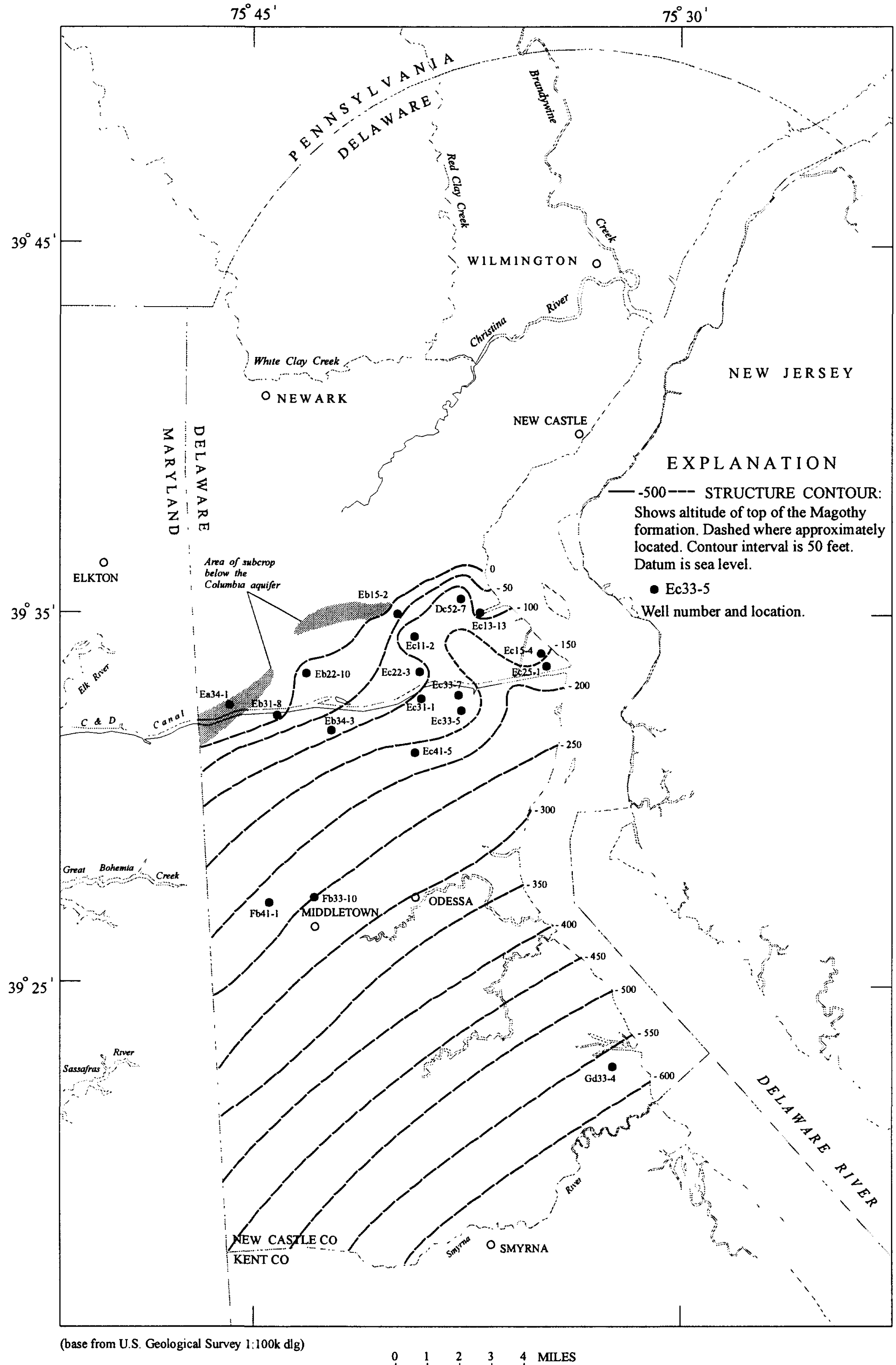

Figure 9. Altitude and configuration of the top of the Magothy Formation.
(from Sundstrom and Picket, 1971, fig. 10))

Englishtown-Mt. Laurel Aquifer System

The Englishtown-Mt. Laurel aquifer system is located within the Matawan and Monmouth Groups (Sundstrom and Pickett, 1971; Groot and others, 1983). Only the Englishtown (Matawn Group) and Mt. Laurel (Monmouth Group) Formations are sufficiently permeable to be used as aquifers (table 1; Bachman and Ferrari, 1995) and are in hydraulic contact with one another. Over much of their extent in the study area, sediments of the Englishtown-Mt. Laurel aquifer system are in hydraulic connection with the Columbia Formation and Rancocas Group. Even the combined aquifer sediments are relatively thin, and have not, historically, been a heavily exploited source of water.

Rancocas Aquifer

The Rancocas aquifer is comprised of the Rancocas Group sediments, which include the Hornerstown and Vincentown Formations (Groot and others, 1983; Bachman and Ferrari, 1995). This aquifer reaches a thickness of approximately 50 ft at the Appoquinimink River (Cushing and others, 1973). In the study area, the Columbia Formation and Rancocas Group form a water-table aquifer that is recharged in uplands and discharged to perennial streams, including Drawyer Creek and the Appoquinimink River (Bachman and Ferrari, 1995). Like the Englishtown-Mt. Laurel system, the Rancocas aquifer has not been heavily exploited as a source of water, although, according to historical records of water use (Sundstrom and Pickett, 1971), it provides up to 25 percent of ground-water withdrawals in New Castle County south of the C&D Canal.

Confining Units Underlying the Delaware River

Information about the stratigraphy of the sediments under the Delaware River is limited to seismic reflection records (Duran, 1986), drillers' logs, and geophysical logs taken during the construction of the Delaware Memorial Bridge and the installation of powerlines across the Delaware Bay (Phillips, 1987), and a set of vibracores taken in the dredged channel by the COE in 1991. Cross sections and a map of the thickness of Holocene sediments in the river were constructed by Phillips (1987, figs. 6, 8, and 10).

In the area investigated by Phillips (1987), geologic events during the Pleistocene resulted in the erosion of Potomac Formation sediments in the river channel and the deposition of the sand, gravel, and clay of the Columbia Formation, which constitute the Columbia aquifer (table 1). Overlying sediments, deposited during Holocene time, are primarily silt and silty sand that act as confining units, separating river water from the aquifers. The thickness of the Holocene sediments underlying the Delaware River ranges from less that 20 ft close to the current shoreline to more than 100 ft in the Pleistocene paleochannel (fig. 10). Only generalized cross sections can be constructed from available drilling and geophysical logs because of the wide spacing between core holes and the highly variable nature of the Holocene and Pleistocene sediments. Based on the cross sections shown in figures 6 and 8, the confining unit underlying the river consists of Holocene sediments and fine-grained clays of the Potomac Formation. In some places, the Columbia Formation, which consists mostly of sand and gravel, is present. The permeability of the Columbia Formation reduces the effectiveness of the confining unit in preventing flow from the river into the underlying aquifers.

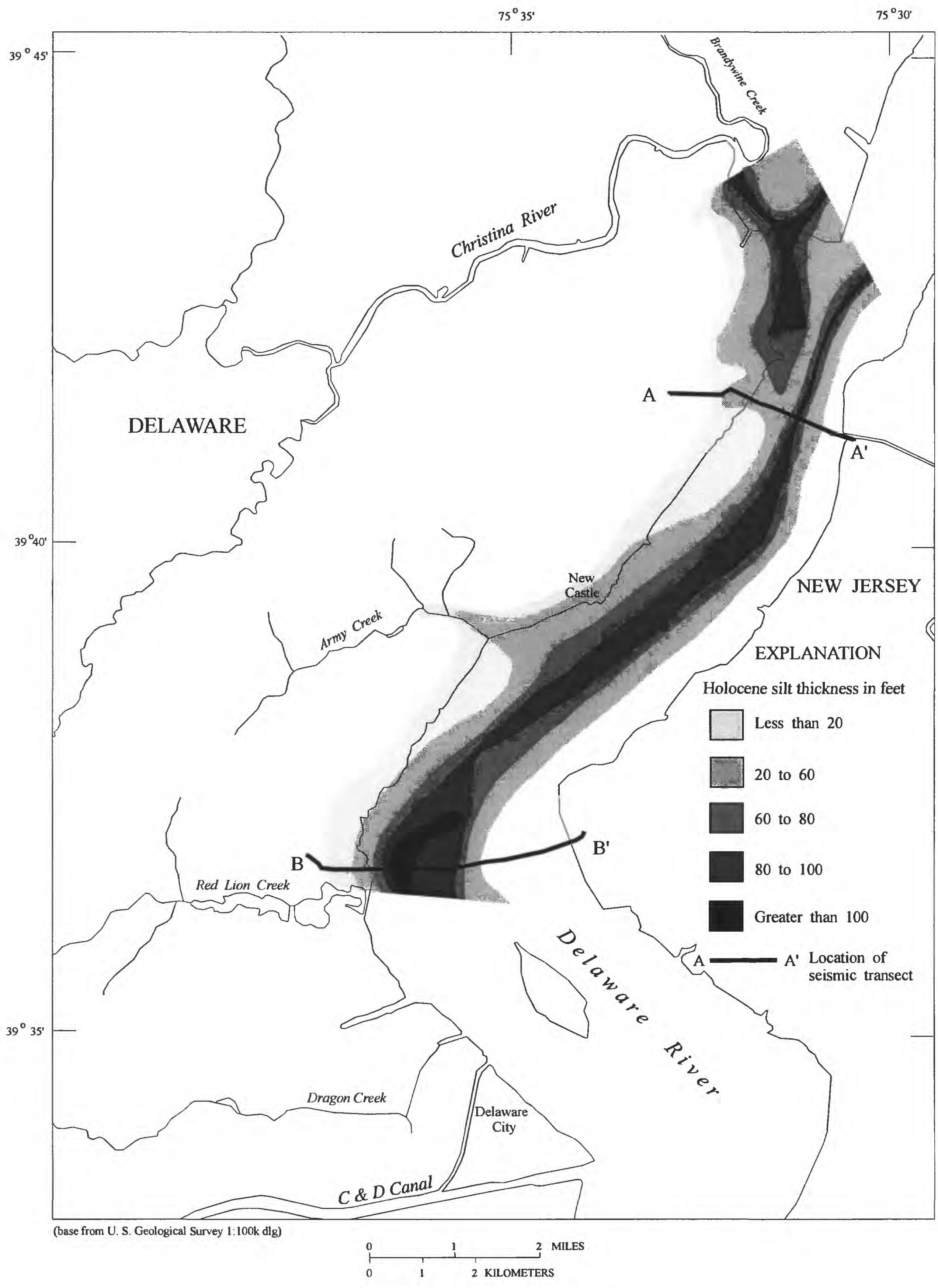

Figure 10. Thickness of the Holocene silt between the Christina River and the Red Lion Creek.
(Modified from Phillips, 1987, fig.10)

Water Levels and Water Use in the Aquifers

Ground-water discharge by pumping began in the study area in the early 1900's and became significant after 1955 (Martin and Denver, 1982). Most ground-water withdrawals are made to supply public water systems and industry.

Water-Level Data

In 1971, Sundstrom and Pickett reported that "...under most conditions, the water-table aquifer is protected from the saltwater of the Delaware Estuary...by the impermeable sediments of the bed of the Estuary...from Memorial Bridge southward past the New Castle County line," and also reported that the hydraulic gradient in the water-table aquifer was "toward the estuary." However, by 1979, Apgar reported declines in the potentiometric surface in the middle Potomac aquifer below sea level adjacent to the estuary (fig. 11). By 1982, pumpage had become the major source of discharge from the Potomac aquifers and local cones of depression had formed (Martin, 1984). Declines in aquifer water levels up to 1985 were documented and the resulting cones of depression in the upper and middle Potomac aquifers were mapped by Phillips (1987; fig. 12). The cones of depression at that time had spread locally under the Delaware River, and the hydraulic gradient was from the Delaware River to the Potomac aquifers (Phillips, 1987). Ground-water-flow models prepared by Martin (1984) and Phillips (1987) simulated this reversal of gradient for various pumping conditions.

Although companies that supply public water and major industrial users in New Castle County are required to report volumes pumped by well, reporting of records of measurements of water levels has not always been required and water levels measured at pumped wells are often not at equilibrium conditions. Most water-supply wells north of the C&D Canal in the study area were screened in the middle and upper Potomac aquifers and the Columbia aquifer. No uniform system of data collection and maintenance has been employed. The location of wells can be difficult to identify because of multiple naming conventions instituted by companies, the county, DNREC, and DGS. The U.S. Geological Survey data base contains well-construction information for most wells registered with DGS, including water level at time of construction. However, long-term records of water levels within the study area are available at only two wells--Dc 34-05 and Dc 34-06 (fig. 4). Water levels for these wells during 1978-93 are shown in figure 13. No long-term changes in water levels are evident from these graphs.

Water-Use Data

Ground water is used for many purposes in the study area, including public supply, domestic (self-supplied), commercial, industrial, livestock watering, and irrigation. A comparison of ground-water withdrawals in 1985 and 1990 by category of use and percentage of change is shown in table 2. Total combined use rose 11 percent between 1985 and 1990. Ground-water sources provided about 28 percent of total freshwater withdrawals in the study area in 1985 compared to 30 percent of withdrawals in 1990. Public suppliers withdrew the most ground water (approximately 64 percent) in both 1985 and 1990. During 1985, public-supply withdrawals were 14.45 Mgal/d and increased 10 percent to 15.93 Mgal/d during 1990. Domestic (self-supplied) and commercial ground-water withdrawals increased significantly over the

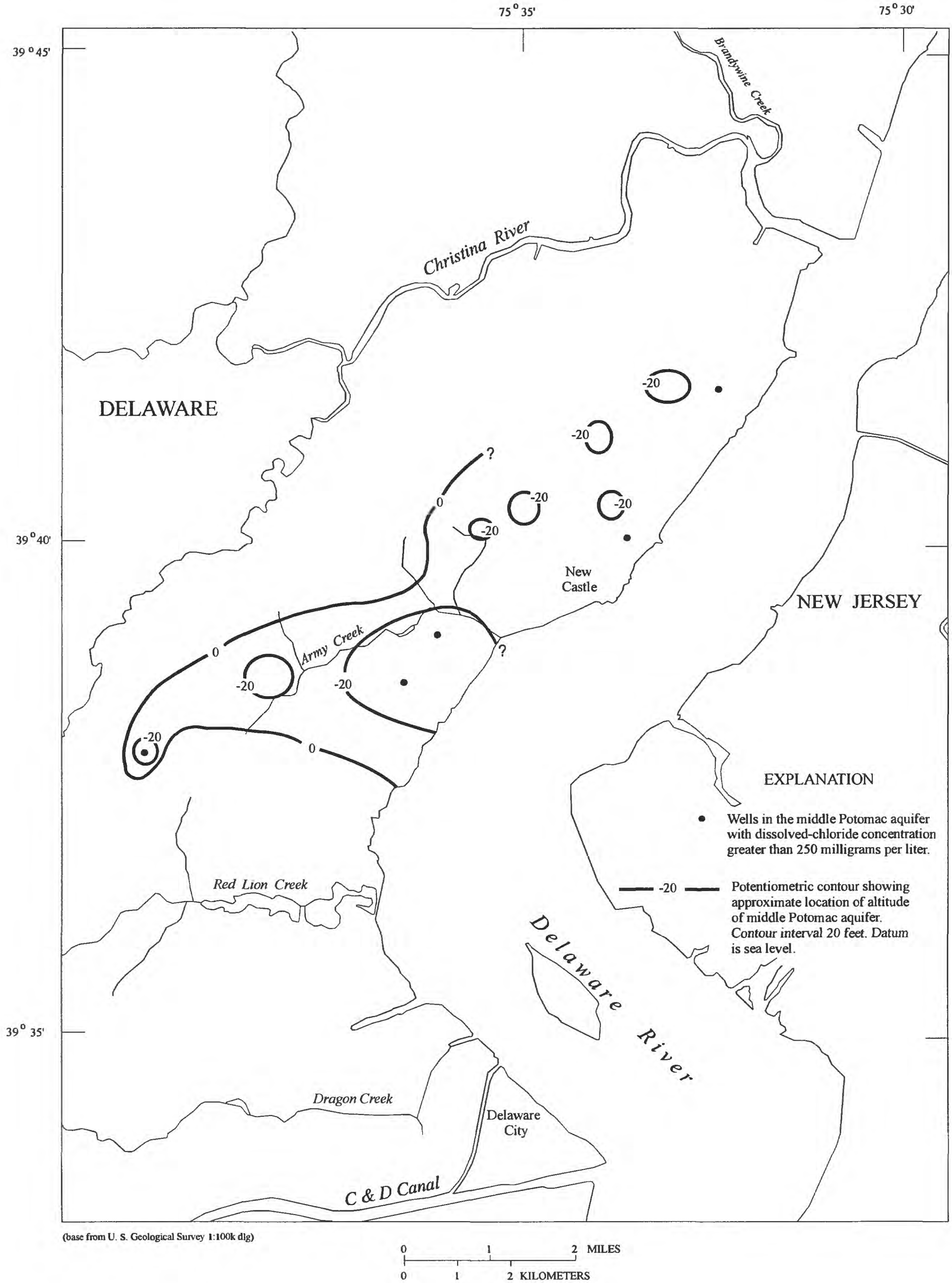

Figure 11. Potentiometric surface in the middle Potomac aquifer in spring 1979 and location of wells measured for dissolved chloride concentration. (Apgar, 1979)

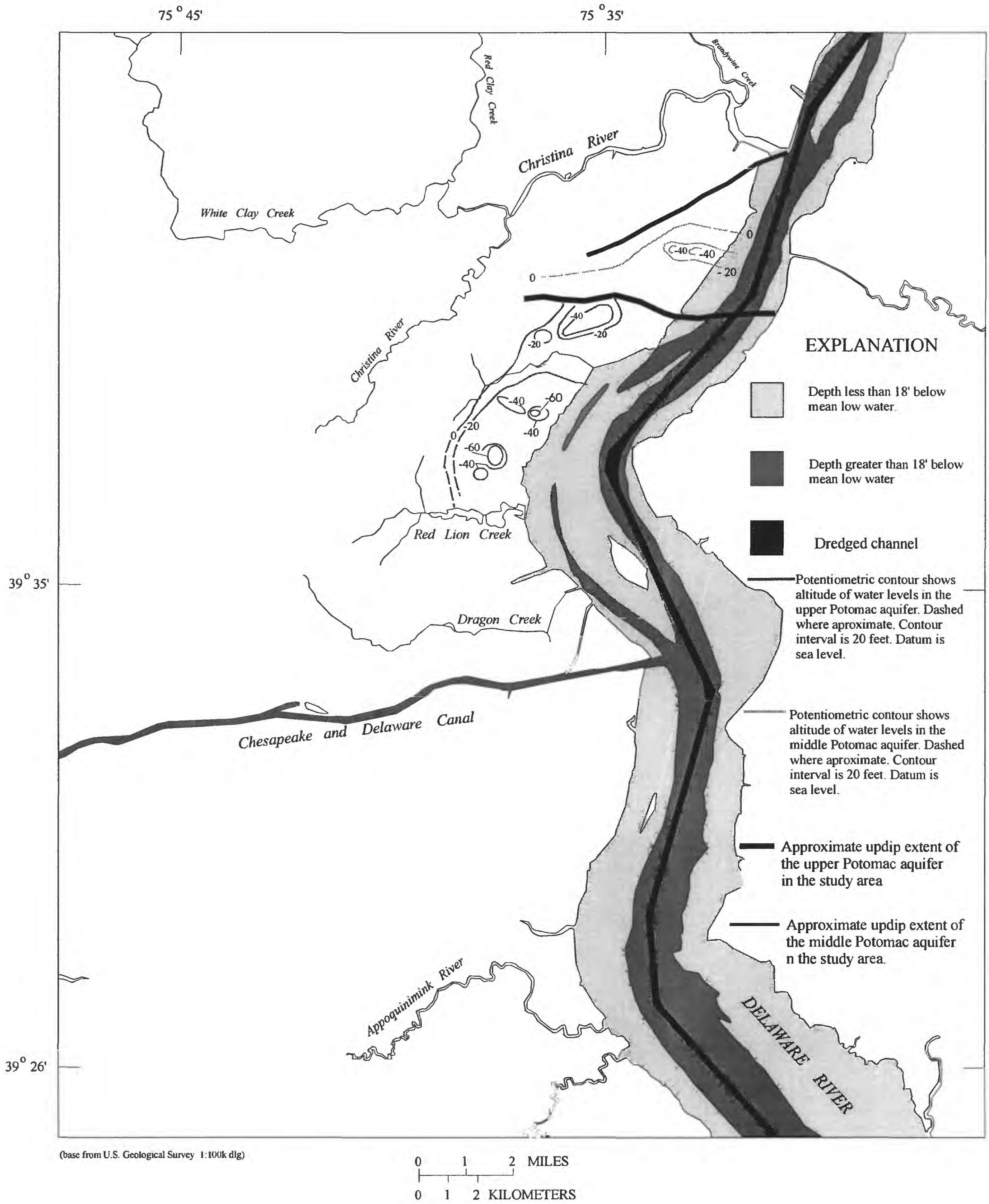

Figure 12. Bathymetry of the Delaware River and potentiometric surfaces of the upper and middle Potomac aquifers during May 1985. (Modified from National Oceanic Atmospheric Administration, 1983; and Phillips, 1987)

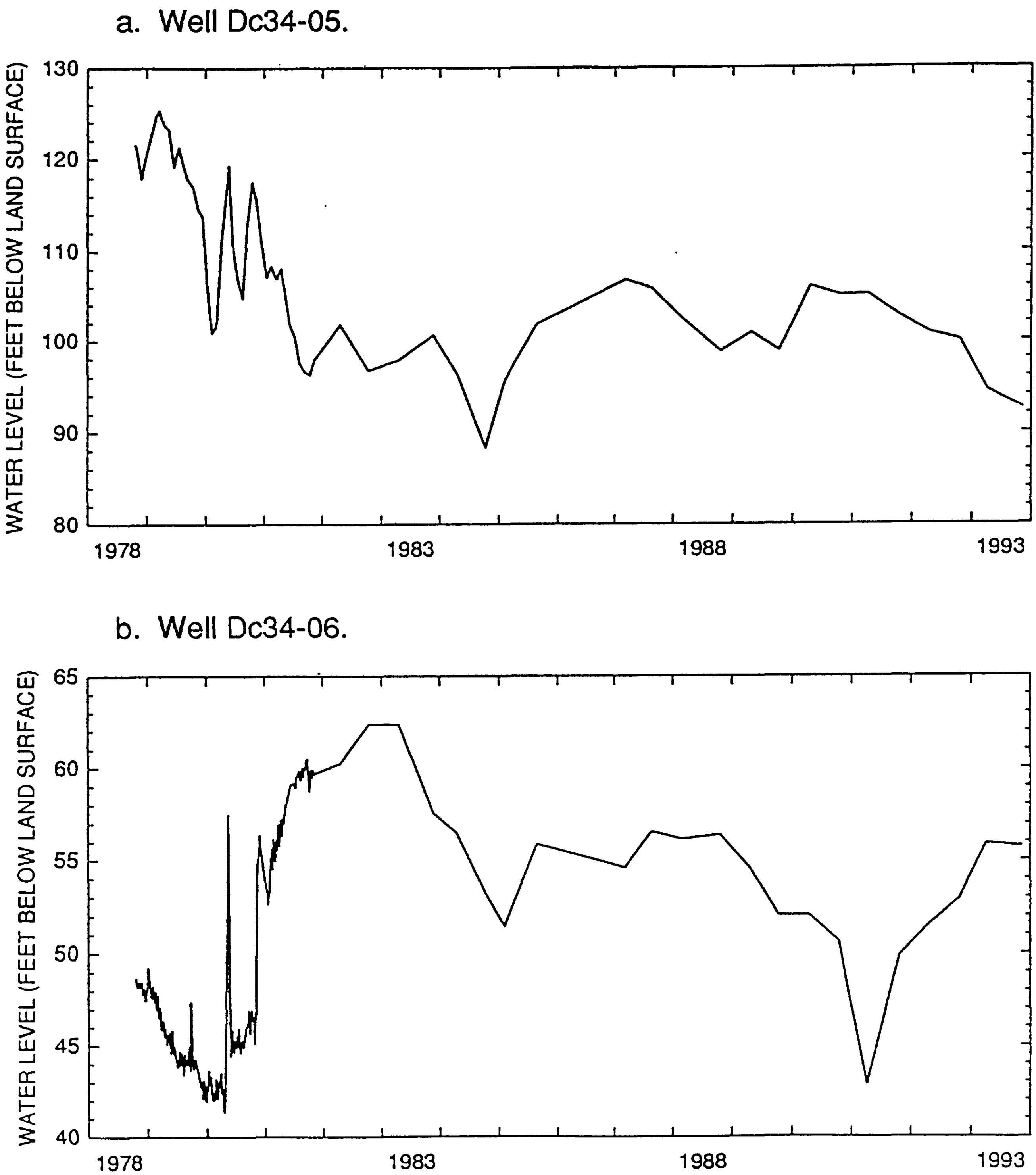

Figure 13. Hydrographs showing water levels for wells (a) Dc34-05 and (b) Dc34-06 screened in the Potomac aquifer, 1978-93.

Table 2. Ground-water withdrawals, by water-use category, in northern and central New Castle County, Delaware, 1985 and 1990

[Source: U.S. Geological Survey Aggregated Water-Use Database System (AWUDS)]

Water-use category	Ground-water withdrawals (million gallons)		Percent change
	1985	1990	
Public supply[1]	14.45	15.93	10
Domestic (self-supplied)[2]	.70	1.96	180
Commercial[1]	.15	.30	100
Industrial[1]	6.71	6.30	-6
Livestock watering[2]	.06	.08	33
Irrigation[2]	.38	.42	11
Total	22.45	24.99	11
Total ground-water and fresh surface-water withdrawals	74.26	88.00	
Percentage of total withdrawals from ground water	30	28	

1 Reported withdrawals.

2 Estimated withdrawals.

period--180 percent and 100 percent, respectively--whereas industrial ground-water withdrawals decreased 6 percent from 1985 to 1990.

The principal aquifers that are used for water supply include the Columbia Group, Rancocas, Magothy, Mt. Laurel, and Potomac Group. Withdrawals by aquifer for selected water users in the study area from 1988 to 1993 are shown in table 3. The Potomac Group aquifer supplied the most water (over 17 Mgal/d) for the period of record. The least amount of water (0.05 Mgal/d or less) was withdrawn from the Rancocas aquifer.

Continued population growth and commercial and industrial development in the study area are expected to result in increased water demand (Metcalf & Eddy, 1991b). Increased demand could result in lower aquifer water levels, and that could increase the potential for river-water intrusion into the aquifers. Projected ground-water demand for selected water users in the study area for the period 1995 to 2040 is shown in table 4. The data presented are from a water-supply plan report series prepared for the Water Resources Agency of New Castle County and are based on projected growth and present water-use trends. Estimates of potential reduction in future water demand with the implementation of additional water conservation measures are also shown in the table.

The largest ground-water public-water supplier in the study area is the Artesian Water Company (AWC) (table 3), which has installed water-supply wells in numerous locations. In 1993, total ground-water withdrawals by AWC were about 16.77 Mgal/d. By the year 2040, AWC is expected to withdraw nearly 26 Mgal/d, an increase of about 55 percent (table 4; Metcalf & Eddy, 1991b). It is estimated that implementation of water conservation measures could reduce this increase to 25 percent. Ground-water withdrawals for public supply by Delaware City are projected to increase 24 percent from 0.17 Mgal/d in 1993 to 0.21 Mgal/d by 2040. Most of this water demand will be for residential use and will come from the Potomac aquifer system.

The town of Middletown supplied 0.41 Mgal/d of ground water to users during 1993 (table 3)--83 percent from the upper Potomac aquifer and 17 percent from the Magothy and Mt. Laurel aquifers. By the year 2040, ground-water demand for Middletown is expected to increase to 0.95 Mgal/d (table 4), about 132 percent of current demand. With the implementation of conservation measures, however, the percentage of water-demand increase could be reduced to 75 percent (Metcalf & Eddy, 1991b). Water demand for the Townsend service area was the smallest in the study area during 1993 (0.04 Mgal/d; table 3). Projected water demand for 2040 is 0.06 Mgal/d (table 4)--a 5-percent increase over the period.

For self-supplied systems north of the C&D Canal, the majority of water demand is for industrial and irrigation uses. Total water demand (ground and surface water) was about 12.68 Mgal/d during 1993 (table 4). By 2040, water demand is projected to be 14.28 Mgal/d without conservation measures (Metcalf & Eddy, 1991b). With conservation, the demand could be reduced to 13.79 Mgal/d. For self-supplied systems south of the C&D Canal, total water demand for 2040 is projected to be 13.32 Mgal/d without conservation measures. Conservation measures could reduce demand to 10.86 Mgal/d.

Table 3. Annual ground-water withdrawals, by aquifer, by selected water users in northern and central New Castle County, Delaware, 1988-93

[Source: Delaware Department of Natural Resources and Environmental Control; -- = data not available]

Aquifer	Ground-water withdrawals (million gallons per day)					
Water user	1988	1989	1990	1991	1992	1993
Columbia Group						
Artesian Water Company	0.30	0.32	0.14	0.28	0.39	0.36
DuPont Glasgow	.23	.20	.21	.16	--	.19
Getty Refining	--	--	--	.04	.04	--
ICI	--	--	--	--	.55	.54
Julian	--	--	--	--	--	.24
Newark, City of	1.74	1.52	.83	.60	.65	[1].24
Standard Chlorine	.02	.03	.18	.13	.15	.15
Aquifer total	2.29	2.07	1.36	1.21	1.78	1.72
Rancocas						
Townsend	.04	.04	.04	.05	.05	.04
Aquifer total	.04	.04	.04	.05	.05	.04
Magothy-Mt. Laurel						
Middletown	.10	.14	.16	.13	.10	.07
Van Wingerden Nurseries	.02	.04	.02	.04	.04	.03
Aquifer total	.12	.18	.18	.17	.14	.10
Potomac Group						
Artesian Water Company	14.56	14.90	15.43	15.69	15.98	[2]16.41
Delaware City	.19	.18	.09	.10	.18	.17
Middletown	.33	.25	.26	.31	.35	.34
Board of Water & Light	.77	1.06	.89	.78	1.02	.81
Newark, City of	.45	.48	.47	.52	.52	[1].07
Star Enterprise	.88	4.40	.60	4.00	4.00	3.57
Aquifer total	17.18	21.27	17.74	21.40	22.05	21.37

[1] Surface-water supply (White Clay Creek) was activated December 1992.

[2] Amounts for 1988-93 estimated from Metcalf and Eddy (1991b, table 3.4, p. 3-9).

Table 4. Projected ground-water demand, with and without conservation measures, for selected water users in northern and central New Castle County, Delaware, 1995-2040

[Source: Water-supply plan for New Castle County, Delaware--Future water demands, v. IV. W/O CONS, without conservation measures; CONS, with conservation measures]

Water user	Projected ground-water demand (million gallons per day)												
	1993	1995		2000		2010		2020		2030		2040	
		W/O CONS	CONS	W/O CONS	CONS	W/O CONS	CONS	W/O CONS	CONS	W/O CONS	CONS	W/O CONS	CONS
Artesian Water Company	16.77	17.55	16.20	19.19	16.77	21.74	17.95	23.41	18.86	24.76	19.95	25.98	20.96
Delaware City	.17	.20	.19	.20	.19	.20	.18	.21	.18	.21	.18	.21	.18
Middletown	.41	.48	.46	.53	.48	.68	.56	.76	.60	.85	.66	.95	.72
Board of Water & Light	.81	.49	.47	.51	.47	.53	.48	.55	.50	.60	.53	.63	.55
City of Newark 1	.31	.32	.32	.33	.33	.35	.35	.36	.36	.37	.37	.38	.38
Townsend	.04	.05	.05	.05	.05	.06	.05	.06	.05	.06	.05	.06	.05
Self-supplied systems 2													
North of C&D Canal	12.68	12.68	12.63	12.86	12.74	13.13	12.92	13.51	13.20	13.90	13.46	14.28	13.79
South of C&D Canal	6.28	6.28	6.14	6.74	6.39	8.33	7.38	9.96	8.39	11.74	9.68	13.32	10.86
Total	37.47	38.05	36.46	40.41	37.42	45.02	39.87	48.82	42.14	52.49	44.88	55.81	47.49

1 Projected ground-water demands based on 1993 data using 4-percent increase for each 5-year increment.
2 Includes projected ground- and surface-water demand.

CHLORIDE-CONCENTRATION DATA

Chloride concentrations are used as an indication of salinity levels (Cohen, 1957). Chloride-concentration data are available from studies of water quality in the Delaware River and of ground-water withdrawals in the study area.

Dissolved Chloride Concentrations in the Delaware River

The term "salinity" refers to the total concentration of dissolved salts in seawater (Bates and Jackson, 1987). Salinity is usually computed from some other factor, such as chloride concentration or electrical conductivity relative to normal seawater. In this report, chloride concentrations are used to indicate salinity.

Seawater has a chloride concentration of approximately 19,000 mg/L (White, 1993). Water with chloride concentrations in excess of 250 mg/L [U.S. Environmental Protection Agency (EPA) drinking water regulation for chlorides] is usually considered undesirable for domestic use. In addition, water with chloride concentrations in excess of 50 mg/L is unsatisfactory for some industrial uses (White, 1993). The zone in an estuary where chloride concentrations equal or exceed 250 mg/L is commonly known as the salt front.

Salinity in the Delaware River at any location is dependent on the distance from the ocean, the freshwater flow of the river, the quantity of salty water moving upstream from the ocean, the stage of the tide, and the range of the tide (Cohen, 1957). In general, salinity increases downstream from very low values near Philadelphia, Pa., and Camden, N.J., to seawater concentration at the mouth of the Delaware Bay.

The Delaware River Basin Commission (DRBC) tracks and controls salinity levels in the Delaware River (Hull and Titus, 1986). Salinity level is controlled by regulating the flow of freshwater in the river by releasing water from various reservoirs and limiting consumption in times of drought (Hull and Titus, 1986). The annual mean chloride concentration at the Delaware Memorial Bridge (river mile 68) for a year with average precipitation could be about 530 mg/L, and a wet year mean could be about 200 mg/L (Apgar, 1979). The most severe drought of record was that of the 1960's. The annual mean chloride concentration at the Delaware Memorial Bridge for 1965 was about 1,230 mg/L. The salt front, located on average at river mile 69 (south of Wilmington, Del.), advanced up the estuary as far as river mile 102, just above the Benjamin Franklin Bridge in Philadelphia (Hull and Titus, 1986). During the 1960's drought, saltwater recharged the Potomac-Raritan-Magothy aquifer system, from which water supplies for Philadelphia and Camden are withdrawn (Hull and Titus, 1986). Elevated chloride levels persisted in the aquifer system for more than 10 years. Since that time, the DRBC has used this drought as the basis for water-supply planning, with the goal that the maximum salinity measured in the river during the drought will not be met or exceeded under current conditions.

Advance and retreat of salinity in the river occurs seasonally and daily as the result of freshwater inflow to the river and the range and stage of the tide. During summer and early fall, freshwater inflow is generally at a minimum and sea level is at a maximum--conditions favorable for the advance upstream of more saline water. The daily tidally-generated variations in salinity are locally and regionally significant (DiLorenzo and others, 1993). For example, salinity measurements taken in 1956 at the Reedy Island jetty, located in the river between the C&D Canal and the Appoquinnimink River, ranged between about 80 and 5,500 mg/L (Cohen, 1957).

Dissolved Chloride Concentrations in Ground Water

Phillips (1987) established a well network based on that of Martin and Denver (1982) to sample chloride concentrations and water levels in the area between the C&D Canal and the Christina River. Phillips found areas of brackish river-water intrusion into the Potomac aquifers in the vicinity of the ICI, New Castle, Crown Zellerbach, and Llangollen Estates well fields.

Part of Phillips' well network has been sampled at intervals for chloride concentrations by DNREC since 1979 (table 5, fig. 4). Chloride levels show no apparent trends and have been well below the 250 mg/L EPA drinking water regulation, except in wells Cd 43-03 and Cd43-04 in the ICI well field (figs. 4 and 14). Phillips' data indicated that pumpage at the ICI well field had caused a cone of depression in the middle Potomac aquifer. Consequently, the hydraulic head in the Columbia aquifer under the Delaware River (just south of section A-A', shown in fig. 4) fell below sea level. As a result, brackish water infiltrated downward from the river and was drawn toward the cone of depression, entering the Potomac aquifer where the confining unit is thin or nonexistent. The increased chloride concentrations in the ICI well field have persisted, although they were somewhat lower by 1989 than they were in the late 1970's. Farther south, in the Llangollen well field (fig. 14), another area of river-water infiltration has occurred (Phillips, 1987). Chloride concentrations in well Dc24-18 averaged about 62 mg/L between 1991 and 1993, slightly higher than the 55 mg/L average chloride concentration for this well between 1978 and 1985.

Water levels in the well network have not generally been measured. No other systematic collection of chloride-concentration data or routine water-level measurements have been conducted in the Potomac aquifer system. Low demand for public ground-water supply in the southern half of the study area, combined with the relative thinness of the aquifers, have resulted in a lack of records of chloride concentration or water levels in this area.

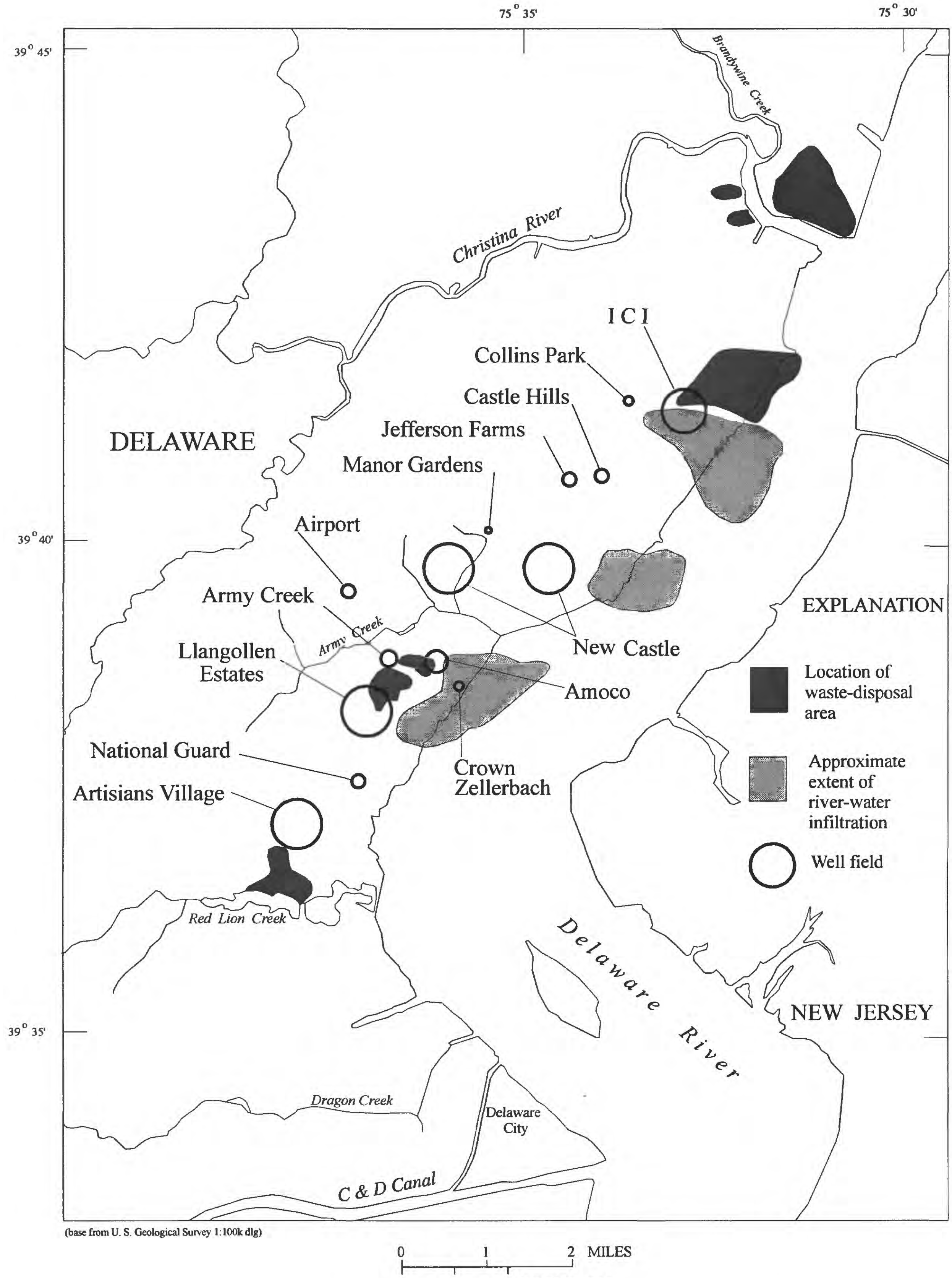

Figure 14. Location of waste-disposal sites and areas of infiltration of river water in the uppermost Potomac aquifer. (Modifidied from Phillips, 1987)

Table 5. Chloride-concentration data for selected wells in northern and central New Castle County, Delaware

[Source: Delaware Department of Natural Resources and Environmental Control and U.S. Geological Survey. < = less than; -- = data not available]

Date	Concentrations of chloride, in milligrams per liter								
	Site name and corresponding State identification number								
	Castle Hills 1 Cd52-15	Jefferson Farm Cd51-14	Castle Hills 3 Cd52-28	New Castle Basin Road Cd51-08	School House Lane Cc55-17	Texaco #10 Dc51-04	Texaco #10a Permit #53065	Delaware Ec15-27	James River Corp*
1985 Fall	--	--	--	--	--	12.8	--	--	--
1986 Spring	22.5	--	22.5	16.3	--	17.2	--	--	--
1986 Fall	24.6	14.7	24.6	--	--	18.4	--	--	--
1988 Spring	15	17	20	20	12	16	--	--	37
1988 Fall	21	15	31	16	13	17	--	--	61
1989 Spring	20.8	14.5	36.1	19	11.3	10	--	--	59
1989 Fall	11	10	17	13	7	10	--	--	34
1990 Spring	23	2.5	35	25	14	14	--	--	77
1990 Fall	31	2.5	15	14	60	8	--	--	20
1991 Spring	21	20	29	25	13	15	--	--	69
1990 April	23	--	35	--	--	--	--	--	--
1990 October	31	--	19	14	--	--	--	--	--
1991 November	30	19	--	28	12	17	--	--	--
1992 July	18	16	--	--	6	12	--	--	38
1993 January	22	--	--	42	14	15	--	9	74
1993 October	23.1	21.8	--	46.3	14.2	--	5.8	9.5	79.3

* No State identification number available for this site

Date	Concentrations of chloride, in milligrams per liter					
	Site name and corresponding State identification number					
	Llangollen #3 Dc23-09	Llangollen G3 Dc24-18	Llangollen #7 Dc24-41	National Guard 1 Dc34-07	Artisans Village 1 Dc33-07	Texaco #16 Ec13-06
1979 Fall	65	--	--	--	--	--
1980 Spring	75	--	30.3	--	--	7
1980 Fall	52	--	33	--	--	7
1981 Spring	48	--	54	--	81	5
1981 Fall	48	--	36	--	6	6
1982 Spring	47	--	47	--	10	19
1982 Fall	50	--	--	--	7	7
1983 Spring	--	--	--	--	8	7
1983 Fall	33	--	48	--	8	--
1984 Spring	--	--	--	--	13	--
1984 Fall	--	--	--	--	10	--
1985 Spring	--	--	--	--	--	4.9
1985 Fall	51.6	--	--	--	11	--
1986 Spring	50.9	--	12.1	5.1	10.8	11.7
1986 Fall	--	--	13.4	--	12.8	8
1988 Spring	2.5	--	55	7	15	9
1988 Fall	--	--	14	9	15	2.5
1989 Spring	--	--	12.9	8	15.1	2.5
1989 Fall	10	--	8	2.5	10	2.5
1990 Spring	15.5	--	15.5	10	17	5
1990 Fall	15	--	15	9	63	4.9
1991 Spring	67	--	13	7	13	16.5
1991 November	--	65	16	--	16	--
1992 July	--	57	13	--	11	--
1993 January	--	59	14	--	15	--
1993 October	--	67.2	16	--	15.2	--

Table 5. Chloride-concentration data for selected wells in northern and central New Castle County, Delaware--Continued

Date	Concentrations of chloride, in milligrams per liter		
	Site name and corresponding State identification number		
	ICI #9 Cd43-03	ICI #10 Cd43-04	ICI #12 Cd44-14
1967	375.9	241.1	--
1968	302.6	231.4	--
1969	270	215.5	--
1970	230.2	242.4	--
1971	368.1	212.5	--
1972	385.3	145.3	--
1973	695.4	114.2	13.6
1974	596	103	14.2
1975	511.6	416.5	43.7
1976	709.8	672	21.8
1977	670.3	485.5	30.3
1978	413.5	409.4	21.1
1979	218	396.8	11
1980	319	429	--
1981	291	329	25
1982	239.5	277	7
1983	105	175	6
1984	254.5	245	9
1985	207	125	4
1986	184	62	5
1987	179	91	6.5
1988	137	65	23
1989	158.5	104	8
1990	176	325	12
1991 November	--	145	14
1993 January	--	--	5

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