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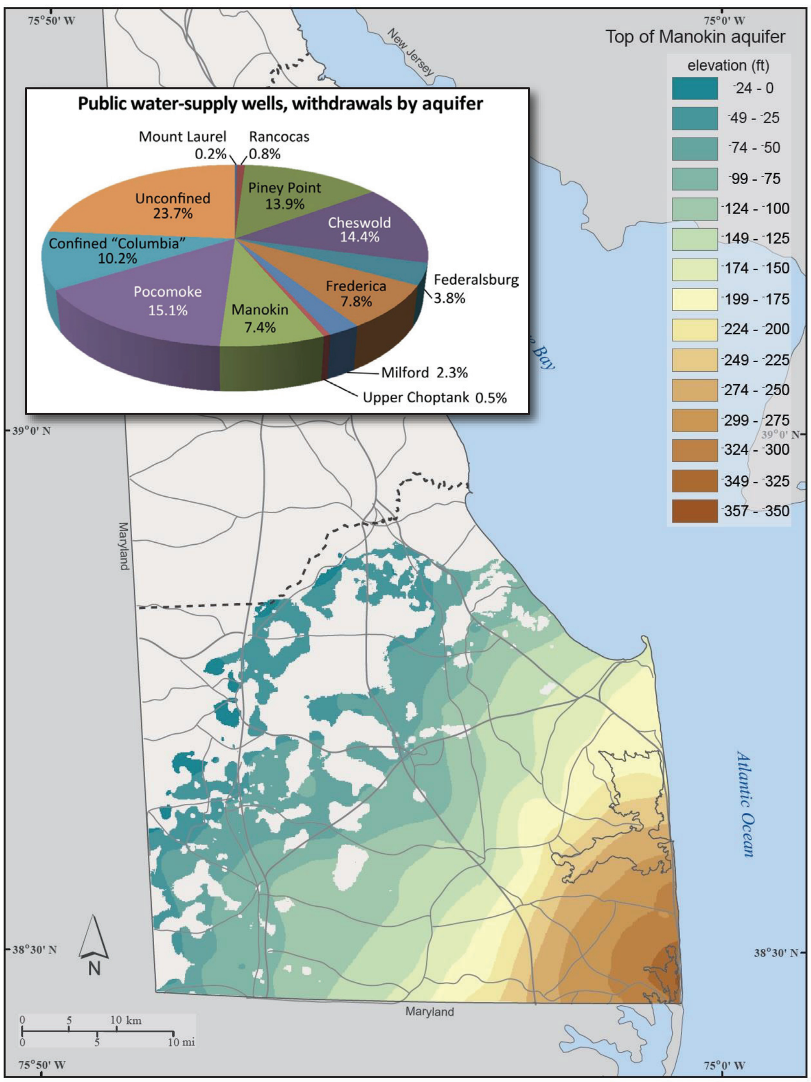
AQUIFERS AND GROUNDWATER WITHDRAWALS, KENT AND SUSSEX COUNTIES, DELAWARE

By:
Peter P. McLaughlin, Jaime L. Tomlinson, and Amanda K. Lawson



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ABSTRACT

Groundwater is the sole source of drinking water and the main source of water for agriculture and industry in central and southern Delaware. This study mapped the depth and thickness of thirteen aquifers in Kent and Sussex Counties, used these maps to assign groundwater withdrawals for 2004 to 2008 to the appropriate aquifer, and analyzed withdrawals for each type of water use by geographic area.

The geology of the Delaware Coastal Plain is characterized by a broad complex of surficial Quaternary deposits unconformably underlain by Cretaceous to Cenozoic sediments that dip gently to the southeast. Permeable sands within this succession are used as groundwater sources. The hydrogeologic framework of the study area was characterized by maps of the elevation and thickness of thirteen aquifers. The maps were created in a geographical information system by interpolating aquifer depth data extracted from a database encompassing approximately 6,600 boreholes. The unconfined aquifer occurs in surficial Quaternary and Neogene sands. It is generally less than 100 feet thick in Kent County but varies from a few feet to more than 200 feet thick in Sussex County. The confined aquifers mapped include one Cretaceous (Mount Laurel), two Paleogene (Rancocas and Piney Point), and nine Neogene sand units (lower Calvert, Cheswold, Federalsburg, Frederica, Milford, Middle Choptank, Upper Choptank, Manokin, and Pocomoke). These aquifers are typically tens of feet thick and occur at progressively greater depths southeastward from their recharge areas.

The study found that annual groundwater withdrawals for all uses in the study area ranged from approximately 89 to 144 million gallons per day annually for 2004 to 2008. Withdrawals were assigned to aquifers using the aquifer maps and well-screen elevation data. For water-use categories where withdrawals could be attributed to specific wells – public, industrial, and golf courses – aquifers were determined by analyzing well-screen elevations relative to aquifer raster surfaces. For categories in which withdrawals could not be assigned to individual wells – irrigation, domestic self-supplied, and livestock – available well depth data in each category were analyzed by census block and compared to the aquifer raster surfaces; for each block, the proportion of wells in each aquifer was used as the basis for apportioning withdrawals to aquifers.

The results indicate that the unconfined aquifer accounted for more than half of groundwater withdrawals. Three shallow, confined aquifers primarily used in Sussex County (confined Columbia, Pocomoke, and Manokin) each provided approximately between 8 and 11 percent of total withdrawals. Withdrawals for the three most important confined aquifers in Kent County (Cheswold, Frederica, and Piney Point) each represented 3 to 5 percent of total withdrawals. Estimated withdrawals were also computed by aquifer for each water-use category and each census block.

EXECUTIVE SUMMARY

Groundwater is the sole source of drinking water and the main source of water for agriculture and industry in central and southern Delaware. This report documents the aquifer geology of Kent and Sussex Counties and provides a comprehensive analysis of estimated groundwater withdrawals from 2004 to 2008. The goal of the work is to understand groundwater withdrawals in a geographical context and to relate groundwater withdrawals to their source aquifers.

The unconfined aquifer occurs within a stratigraphically complex series of surficial and near-surface Quaternary (and possibly Pliocene) deposits in most of the study area. The confined aquifers occur in the underlying succession of Cretaceous to Cenozoic sediments that dip gently to the southeast. The distribution, depth, and thickness of thirteen aquifers in the study area are delineated on maps and geologic cross sections. To create the aquifer maps, we compiled a database of the depths of the tops and bottoms of all aquifers recognized in well records from more than 6,600 sites in Kent and Sussex Counties. Aquifer elevation and thickness maps were calculated from this dataset by interpolating between elevation-corrected aquifer-depth picks using ArcGIS geographical information system software. The resulting rasters show values of aquifer surface elevation or aquifer thickness at a defined spatial resolution.

The aquifer maps created in this study provide an understanding of the distribution and thickness of groundwater sources in a three-dimensional geological framework. The confined aquifers are at progressively greater depths south-southeastward, paralleling the overall dip of the pre-Quaternary sedimentary section. Most of the confined aquifers occur in Miocene formations, but three pre-Miocene aquifers are an important water-supply source. The Mount Laurel aquifer, the oldest of the three, provides groundwater in northern Kent County. It is Late Cretaceous in age, and is composed of glauconitic quartz sands deposited in a marine shelf environment. It is approximately 300 feet below sea level (ft bsl, relative to North American Vertical Datum of 1988) in northern Kent County, commonly about 100-ft thick, and deepens south-southeastward to about 600 ft bsl in the area between south Smyrna to north Dover, where it is a finer-grained non-aquifer facies. The Rancocas aquifer is a Paleocene glauconite- and shell-rich quartz sand that yields groundwater in northernmost Kent County. The top of the Rancocas aquifer is 100 ft bsl in northwestern Kent County and becomes deeper southeastward. The aquifer sand is as much as 200-ft thick north of a narrow zone that extends approximately west-southwest to east-northeast through the south side of Smyrna. South of that zone, it becomes finer-grained and thins to a few tens of feet. The Piney Point aquifer is in a middle Eocene interval of shelly, glauconitic, quartz sand deposited in a shelf environment. The top of the Piney Point aquifer ranges from about 250 ft bsl in the Dover area to more than 700 ft bsl in northern Sussex County. Northwest of a southwest-to-northeast-trending line that runs just north of the Cheswold area, the Piney Point aquifer becomes progressively thinner as it is truncated northward under a basal Miocene erosional surface. Its thickness is nearly 300 ft in southern Kent County and decreases northwestward to as few as 55 ft.

The overlying shallow-marine Miocene section is characterized by alternating sands and muds in an overall coarsening-upward succession. A group of seven confined aquifer sands occurs in this interval, each typically shelly quartz sands separated by offshore silts and clays. In addition, shelly glauconitic sand occurs locally at the base of the Calvert Formation and functions as part of the Piney Point aquifer. Four of the seven Miocene confined aquifers occur in the Calvert Formation and are designated, in upward order, the Lower Calvert, Cheswold, "Federalsburg," and Frederica aquifers; these are most important in Kent County. The upper three sands occur in the Choptank Formation and are here referred to as the Milford, Middle Choptank, and Upper Choptank aquifers; they are more important in southern Kent County and northern Sussex County.

The Lower Calvert aquifer is a 15- to 50-foot-thick, lower Miocene sand that may locally yield groundwater in northwestern Sussex County where it occurs within 600 ft of the land surface. The Cheswold aquifer subcrops under surficial Quaternary formations in northern Kent County. Like all of the aquifers in the Cheswold-Choptank interval, the Cheswold aquifer deepens south-southeastward from its subcrop area, reaching more than 500 ft bsl in southeastern Kent County and more than 1,000 ft bsl in coastal Sussex County. The Cheswold ranges from less than 20 to more than 100-ft thick, although the thickness varies in Kent County and generally increases southeastward in Sussex County. The name "Federalsburg" aquifer is applied to the sand that overlies the Cheswold aquifer in southern Delaware, but is here recognized as a different sand unit than the Federalsburg aquifer of Maryland. Southeast of its subcrop between Dover and Smyrna, the top of the "Federalsburg" deepens to about 400 ft bsl in southeastern Kent County and more than 1,000 ft bsl in southeastern Sussex County. The thickness varies significantly, generally between 30 and 80 ft, and it commonly includes finer-grained, lower quality aquifer sands than do the other Miocene aquifers. The Frederica aquifer, which overlies the "Federalsburg," is composed of 40 to 100 ft of sand and subcrops in the Dover area. The top of the aquifer is more than 250 ft bsl in the Milford area and deepens to more than 800 ft bsl in southeastern Sussex County. The next highest unit, the Milford aquifer, is a 20- to 60-foot-thick sand that occurs at the base of the Choptank Formation and subcrops under younger surficial sands in an east-west trending belt south of Dover. The Milford aquifer deepens southeastward from its subcrop area, with the top of the aquifer occurring at about 200 ft bsl in the Milford area and more than 600 ft bsl in southeastern Sussex County. The Middle Choptank aquifer is present in eastern Sussex County and southeastern Kent County, deepening southeastward from a subcrop area between north Harrington and Frederica to about 150 ft bsl in Milford and to more than 700 ft in southeastern Sussex County. The Middle Choptank is between 15- and 30-ft thick in most of the study area but attains thicknesses of approximately 50 ft in south-central Sussex County. The Upper Choptank aquifer is characterized by 25 to 45 ft of sand that lies immediately under the St. Marys Formation, which is a regional confining unit. The Upper Choptank subcrops in a narrow zone from Harrington to the north side of Milford; the top of the aquifer is approximately 250 ft bsl in Seaford and Milford and deepens to 600 ft or more in southeastern Sussex County.

The Manokin and Pocomoke aquifers are major confined groundwater sources in Sussex County. The Manokin aquifer is the sandy upper part of a coarsening-upward succession of shallow-marine to estuarine deposits in the Cat Hill Formation. The Manokin subcrops under the Beaverdam Formation and sandy Quaternary sediments across a wide belt of northern Sussex County and occurs deeper southeastward, as much as 350 ft bsl in the southeastern corner of coastal Sussex County. The Manokin ranges in thickness from less than 20 ft in western Sussex County to more than 80 ft in most of the eastern half of the county, and in places more than 130 ft. The Pocomoke aquifer is made up of the sandy parts of the mosaic of coastal facies of the Bethany Formation. The Pocomoke aquifer sands subcrop under the Beaverdam Formation and sandy Quaternary sediments in a broad band that extends northeastward from the Laurel area through Georgetown to Milton and deepens southeastward. The top occurs as deep as 125 ft bsl in the southeastern part of the county. The net thickness of Pocomoke aquifer sand generally trends from a few tens of feet in up-dip areas to more than 100 ft down dip along the coast.

The unconfined aquifer is developed in sandy deposits of near-surface geologic formations. The unconfined aquifer is generally less than 100-ft thick in Kent County but varies from a few feet to more than 200-ft thick in Sussex County. In eastern Kent County, the unconfined aquifer occurs in Pleistocene sediments of the Delaware Bay Group; in western Kent County, the unconfined aquifer lies predominantly within the Beaverdam Formation. In much of Sussex County, the unconfined aquifer occurs in the Beaverdam Formation; in parts of the Nanticoke watershed, the Inland Bays watershed, and the Delaware Bay coast, the unconfined aquifer typically occurs in sandy zones in the Nanticoke River Group, the Assawoman Bay Group, or the Delaware Bay Group, respectively. The confining layers between the Manokin, Pocomoke, and unconfined aquifers are poorly developed or absent in many locations, so these aquifers may be hydrologically connected in parts of Sussex County.

Groundwater withdrawals were analyzed for the period from 2004 through 2008 for nine water-use categories: public community systems, public non-transient non-community systems, public transient non-community systems, industrial self-supplied, domestic self-supplied, agricultural irrigation, golf course irrigation, self-supplied lawn irrigation, and agricultural wells used for livestock. Withdrawals were assigned to the appropriate aquifer using one of two general approaches: well specific or spatially estimated. For categories where reported or estimated pumping was attributed to specific wells–public, industrial, and golf course wells in this study–aquifers were determined by comparing well screen elevations for each well to aquifer elevation maps at the same location. For categories where estimated water use could not be linked to specific, individual wells–irrigation, domestic self-supplied, and chicken house–a spatial estimation was made by comparing ranges of well depths to aquifer depths on a census block basis. From that analysis, the proportion of wells in each aquifer was determined and groundwater withdrawals allocated to each aquifer in the same proportions.

Irrigation was the largest category of groundwater use. Groundwater withdrawals for irrigation were estimated to be as much as 91 million gallons per day (Mgal/d) for a dry year and as little as 50 Mgal/d in a year with abundant, well-timed rainfall. Irrigation well withdrawals were estimated for each area of irrigated farmland identified on aerial photographs by using a daily-crop-demand model that incorporated daily rainfall and evapotranspiration data for 2005 through 2008, as well as crop type and soil type at each site. The unconfined aquifer provided an estimated two-thirds of irrigation withdrawals and the "confined Columbia," Pocomoke, and Manokin aquifers each provided approximately 10 percent. Annual groundwater withdrawals for public and industrial wells with groundwater allocations were compiled from pumping data in several state and provider databases from 2004 through 2008. Reported public well pumping was the second largest category of groundwater withdrawals, totaling between 22.8 and 26.2 Mgal/d and slightly greater withdrawals in Sussex County than in Kent County. Areas served by these public water-supply systems have estimated populations of 101,656 in Kent County and 98,964 in Sussex County. The unconfined aquifer represented approximately one-fourth of the reported public well withdrawals. The Piney Point, Cheswold, and Pocomoke aquifers each represented approximately 15 percent; and the "confined Columbia," Manokin, and Frederica aquifers each accounted for between 7 and 10 percent. Industrial wells represented the fourth largest category of groundwater withdrawals, ranging from 6.66 Mgal/d to 7.66 Mgal/d, mostly in Sussex County. The unconfined aquifer yielded more than half of industrial well withdrawals, the Pocomoke aquifer approximately one-fourth, and the Manokin and Cheswold aquifers 11 and 7 percent, respectively.

Domestic self-supplied usage was the third-largest category of withdrawals, estimated as 11.6 Mgal/d (4.23 Mgal/d in Kent, 7.37 Mgal/d in Sussex). Domestic well withdrawals were estimated on a census block basis for areas outside of public water system service areas using a per capita water-demand model that was based on five census parameters—household size, housing unit density, population density, median year of construction, and median value of owner-occupied single-family homes. Populations in self-supplied areas were estimated at approximately 61,000 in Kent County and 98,000 in Sussex County. Domestic self-supplied withdrawal rates were estimated at 72.9 gallons per day per person in the study area, or more specifically 69.9 gallons per person per day in Kent County and 76.7 gallons per capita per day in Sussex County. The unconfined aquifer provided almost two-thirds of the self-supplied domestic well supply. The "confined Columbia" aquifer supplied nearly 14 percent and other aquifers provided less than 5 percent each.

Withdrawals for smaller public systems—including community, transient non-community, and non-transient non-community—were also studied. Water use in smaller community systems was determined by census block, similar to self-supplied domestic users. Water use for non-community systems was estimated from published norms of water demands for each specific facility type and size. Estimated withdrawals for the smaller public systems only totaled about 1.8 Mgal/d; the unconfined aquifer and "confined Columbia" aquifer supplied most of this. Non-irrigation agricultural withdrawals were assumed to be principally for poultry use, which were estimated by census block using counts of active chicken houses on aerial photographs and water demands documented in the literature for chicken drinking water and for evaporative cooling systems in the houses. Chicken house usage represented more than 4 Mgal/d; more than half of this came from the unconfined aquifer and approximately one-fourth from the "confined Columbia," aquifer. Golf course well withdrawals were estimated using reported pumping data and estimates for wells with no reported pumping data. Total golf course withdrawals were approximately 2 Mgal/d, nearly half of which came from the unconfined aquifer and the rest from the "confined Columbia," Pocomoke, and Manokin aquifers (13-17 percent each). Self-supplied lawn irrigation withdrawals were estimated by using a multiplier of domestic household water use multiplied by the number of wells in each census block. This smallest category was estimated at 0.03 Mgal/d, entirely from the unconfined aquifer.

In summary, annual groundwater withdrawals for all uses in the study area ranged from approximately 89 to 144 Mgal/d. Withdrawals from the unconfined aquifer provided more than half of the groundwater pumped. The confined Columbia aquifer and the Pocomoke aquifer each supplied about 11 percent of total withdrawals and the Manokin aquifer provided approximately 8 percent. Additional withdrawals for the Cheswold, Frederica, and Piney Point, which are most important in Kent County, each represented 3 to 5 percent of the total withdrawals. Other aquifers each represented less than 2 percent of withdrawals.

INTRODUCTION

Groundwater is one of the most important natural resources in southern Delaware. All drinking water in Kent and Sussex Counties is withdrawn from aquifers. In addition, groundwater is used extensively for irrigation and local industries, as well as providing base flow for streams. The aquifer systems of southern Delaware include an unconfined aquifer composed of sandy, near-surface sediments, and a series of underlying confined aquifers that range in age from Cretaceous to Quaternary.

The study area is Kent and Sussex Counties (Fig. 1). These are average-sized counties by eastern United States standards, comprising 586 and 936 square miles of land, respectively. The area is bordered on the west and south by Maryland; Delaware Bay and the Atlantic Ocean are the eastern border.

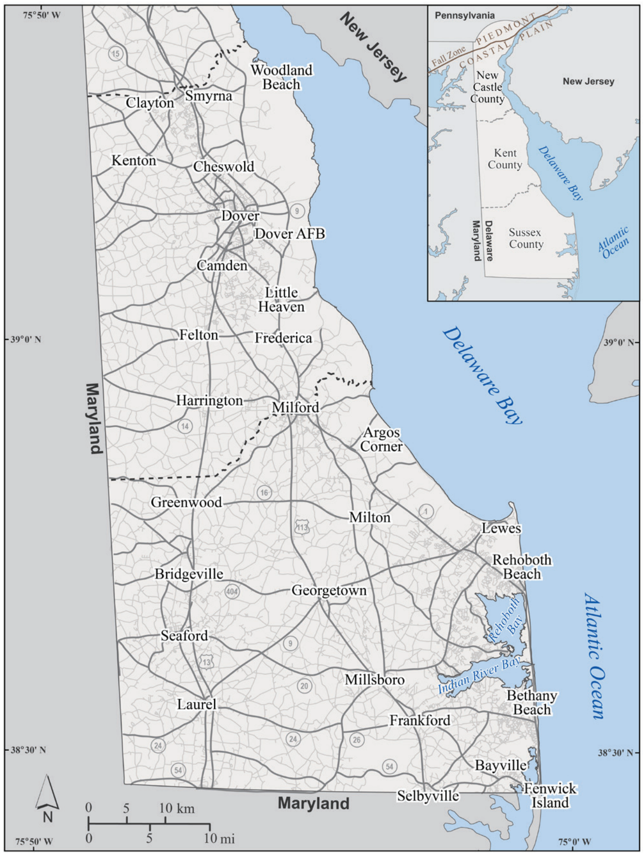

Figure 1. Location map of the study area in Kent and Sussex Counties, Delaware. Abbreviations: AFB, Air Force Base.

Both counties are in the Atlantic Coastal Plain physiographic province and, as such, are topographically flat with little relief. Streams provide natural drainage, and a drainage divide extends approximately north-to-south through the study area. Rivers and streams on the east side drain to Delaware Bay in Kent County and northern Sussex County and to the Atlantic Ocean in southern Sussex County; streams west of the divide drain into Chesapeake Bay. The geology of the southern Delaware Coastal Plain consists of a complex of nearly flat-lying surficial and near-surface Quaternary deposits underlain by sediments of Cretaceous to Miocene (and possibly Pliocene) age that have a shallow southeast dip. The subsurface formations contain a number of permeable sand bodies that yield groundwater in usable quantities and, thus, are valuable aquifers for multiple uses in southern Delaware.

Kent and Sussex Counties are predominantly rural areas. Less than one-fifth of land use is classified as urban or suburban and 80 percent is classified as agricultural, wetlands, forested, or other open-space areas (DOSPC, 2007). The population in both counties is growing. The 2010 census listed the population of Sussex County as 197,145 and the population of Kent County as 162,310 (U.S. Census Bureau, 2010), representing increases of 25.9 percent for Sussex County and 28.1 percent for Kent County since 2000 (U.S. Census Bureau, 2000). Most of the population of these counties is concentrated in areas that the U.S. Census Bureau rates as urban: 73.0 percent of the population in Kent County and 58.7 percent in Sussex County (U.S. Census Bureau, 2010). According to the 2010 census, five municipalities had more than 5,000 residents. Dover is the largest with 36,159 residents, followed by Smyrna (10,024), Milford (9,594), Seaford (6,954), and Georgetown (6,447). Another 17 municipalities have between 1,000 and 5,000 residents and more than 20 others have populations of less than 1,000, the smallest being Hartley, population 76. Much of the recent population increase is in previously undeveloped rural areas. Analyses of recent state land use and land cover (LULC) data (DOSPC, 2007) by Mackenzie (2009) shows a decrease of crop land between 2002 and 2007 (5.1 percent in Sussex, 5.7 percent in Kent) and a contemporaneous increase in residential land area (18.4 percent in Sussex, 18.2 percent Kent).

The population growth, development, and changes in land use have increased the demand for water. Groundwater withdrawals have increased in Sussex County from 18.7 million gallons/day (Mgal/d) in 1957 (Sundstrom and Pickett, 1969, 1970) to an estimated 55 Mgal/d by 2000 (Wheeler, 2003). In Kent County, groundwater demand increased from 6.5 Mgal/d in 1957 (Sundstrom and Pickett, 1968) to an estimated 27 Mgal/d by 2000 (Wheeler, 2003).

Purpose and Scope

Although groundwater is a critical natural resource in the Delaware Coastal Plain, the last comprehensive reports on the groundwater resources of Kent and Sussex Counties were published in the 1960s and 1970s (Sundstrom and Pickett, 1968, 1969, 1970). The purpose of this project is to assemble an updated summary of the groundwater resources of Kent and Sussex Counties, Delaware, to support their effective utilization and management. This report presents the results of this integrated study of aquifer geology and water use, explains the methodology used in the analyses, and discusses the implications of these findings for our understanding of groundwater systems in Kent and Sussex Counties.

The scope of work encompasses the geology of the aquifers and the distribution of groundwater withdrawals and has two specific objectives:

1. To create an updated, more detailed understanding of aquifer **geology** and
2. To analyze **groundwater withdrawals** by aquifer and type of water use.

The geologic section of the report describes the geology with respect to the distribution of the aquifers. A database of stratigraphic horizon depths or "picks" was used to create structural contour and thickness maps and to make geological cross sections that highlight the correlation of aquifers. New data were acquired by drilling and geophysical logging of test holes in areas where geological control was lacking. The resulting aquifer correlation and mapping considerably advances our understanding of the unconfined and confined aquifers of the study area.

The focus of the groundwater section is to compile data on groundwater withdrawals in Kent and Sussex Counties using reported pumping data and documented estimation methodologies for various types of water use. A comprehensive inventory of reported volumes of groundwater withdrawals was made for the years 2004 through 2008 and, where records were inadequate or did not exist, estimates were made. This inventory allowed spatial analysis of groundwater withdrawals in which location and aquifer assignments were made for each inventoried withdrawal, permitting a better understanding of water use spatially within an updated aquifer geology framework. However, there have been significant demographic changes in the study area that affect groundwater use since the 2004 to 2008 study interval. These changes include continued population growth in Kent and Sussex Counties, changes in key industries such as poultry, and expansion of the use of irrigation in agriculture. Therefore, the groundwater section of the report should be regarded as a comprehensive estimate of withdrawals for the period of study that also provides a baseline and approach for the evaluation of more recent groundwater use.

A project of this scope involves analysis of numerous datasets from different sources of variable quality and completeness. To ensure a manageable project scope, our data and methods were chosen to address three points:

1. **Data quality.** We focused analyses on selected, high-quality data, where possible. New borehole data was acquired in key areas.
2. **Estimation/interpretation.** Where high-quality data were lacking, we carefully documented methodologies for estimation and interpretation to ensure reproducibility of results.
3. **Future studies.** Because the scope of this project did not address organizational or quality-control issues of all potentially available data, an important outcome is to identify issues where a lack of adequate data indicates a need for further study.

Maps of aquifers and water use, created using ArcMap software, are included in the body of the report as column-width figures and in the appendices as full page-size maps. The analysis of groundwater withdrawals is summarized in tables in the body of the report and documented in detail in the appendices Microsoft Excel format.

The results of this project provide an improved understanding of both aquifer geology and groundwater use that will benefit our stakeholders in several ways:

- **Groundwater protection.** Accurate delineation of public water-supply resources and potential groundwater flow pathways will advance source-water protection efforts in Delaware.
- **Permits.** The geologic products will support correct identification of aquifers in the well-permitting process.
- **Planning.** The water-use products will be useful for water-supply planning efforts.
- **Drilling.** The aquifer maps will help water-well drillers understand the depths of aquifers when planning well installation and for filing well permits and completion reports.

Previous Work

The first comprehensive treatment of the aquifers of southern Delaware was addressed in a report on the geology and groundwater of Delaware by Marine and Rasmussen (1955). They recognized three confined aquifers in Kent County: an Eocene aquifer used in Clayton; a "shallower Miocene sand" used between Dover and Milford; and a "deeper Miocene sand" used between Smyrna and Dover. They characterized "sands of the Pleistocene series" as the principal and mostly water-table aquifer in Sussex County. They also noted that "red sand and gravel" of probable Pliocene age served as local aquifers, and that sands equivalent to the "shallower Miocene sand" in Kent County were used for groundwater in northern Sussex County near Milford. Rasmussen et al. (1960) further examined the water resources of Sussex County. Their report included borehole records and lithologic logs for a large number of wells, pumping data for many public-supply wells, and a review of the geological framework of the aquifers. The review of "Delaware Water" by Rasmussen et al. (1966) included updated information on aquifers and their hydrological characteristics in Kent County.

A series of reports published by Sundstrom and Pickett (1968, 1969, and 1970) represent the most recent comprehensive studies of the groundwater resources of southern Delaware. The first (Sundstrom and Pickett, 1968) examined the groundwater resources of Kent County and included aquifer maps and tabulation of water use in a number of community water systems; this was followed by similar reports on eastern Sussex County (Sundstrom and Pickett, 1969) and western Sussex County (Sundstrom and Pickett, 1970). Since then, other studies have described aspects of the groundwater resource, but no comprehensive updates have been made for either Kent or Sussex County.

The confined aquifers of Kent and Sussex Counties were examined in a review of the water resources of the Delmarva Peninsula by Cushing et al. (1973). Their report updated the regional understanding of the groundwater systems of the Aquia-Rancocas, Piney Point, Cheswold, Frederica, Manokin, and Pocomoke aquifers and documented an additional aquifer in the Miocene section, which they called the Federalsburg aquifer. The report summarized water usage, aquifer characteristics, water quality, and area of potential use for each aquifer, and provided maps of the depth, thickness, potentiometric surface, and chemical quality of groundwater for each.

Other works to address particular aspects of the groundwater system include studies of coastal Sussex County (Miller, 1971; Hodges, 1984); a statewide study of the unconfined aquifer (Johnston, 1973); and modeling of Kent County aquifers including the unconfined aquifer in Kent County (Johnston, 1977) and the confined Cheswold and Piney Point aquifers in the Dover area (Leahy, 1976, 1979, 1982).

The results of several recent Delaware Geological Survey (DGS) studies were essential to this project. For the geologic framework, we utilized work by Andres (2004) on the late Cenozoic formations of Sussex County and by Ramsey (2007, 2010) on the Quaternary and near-surface geology of Kent and Sussex Counties. For the aquifer framework, we utilized maps of the unconfined aquifer in eastern Sussex County created by Andres and Klingbeil (2006) and maps of the confined aquifers of Kent County by McLaughlin and Veléz (2006). Our knowledge of the confined aquifers of Sussex County is also considerably enhanced by detailed site studies of the Oligocene to Pleistocene section by Andres et al. (1990) in a group of boreholes just west of Lewes (Oh25-02 through -05) and by Miller et al. (2003), Browning et al. (2006), and McLaughlin et al. (2008) in a nearly continuous wireline core record from Bethany Beach (Qj32-27). The Bethany Beach site includes many biostratigraphic and strontium-isotope data points that established a reference chronostratigraphic framework for some of the aquifers.

AQUIFER GEOLOGY

Purpose and Scope

The purpose of this section on aquifer geology is to give a comprehensive update on the geology and distribution of the confined and unconfined aquifers of Kent and Sussex Counties. We review the geological units that play a significant role in the hydrological system and examine the geological character and areal distribution of each aquifer (Table 1). Maps of the depth and thickness of each aquifer are presented and the methodology for data compilation and mapping explained.

Table 1. Aquifers and use as a groundwater source by county. X = used. x = minor use.

Aquifer	Kent	Sussex
Unconfined	X	X
Confined Columbia	X	X
Pocomoke		X
Manokin		X
Upper Choptank	X	X
Middle Choptank	X	X
Milford	X	X
Frederica	X	X
"Federalsburg"	X	x
Cheswold	X	x
Lower Calvert	X	
Piney Point	X	
Rancocas	X	
Mount Laurel	X	

Geological Overview

The geology of the Delaware Coastal Plain in Kent and Sussex Counties consists of series of predominantly siliciclastic sediments ranging from Cretaceous to Recent age. The more flat-lying surficial geologic units include late Miocene, possibly Pliocene, and Quaternary deposits. The underlying Miocene and older units are clays, silts, and sands that have a gentle southeastward dip and generally thicken in the same direction. The more permeable sands commonly serve as aquifers, and the intervening less permeable clays and muds act as confining layers. The aquifer framework is simple and interrupted by no major faults, but a degree of complexity is caused by facies changes and unconformities of varying significance.

The aquifers used in Kent and Sussex Counties occur in formations ranging from latest Cretaceous to Quaternary in age. Aquifer-quality sands are also present in older Cretaceous formations (Fig. 2) but are not used for groundwater because of their great depth and expected elevated salinity (Cushing et al., 1973; Benson et al., 1985). The deepest of those units is the Potomac Formation (mid-Cenomanian and older), which consists of non-marine alluvial plain deposits of sands and multicolored mudstones (Benson and Spoljaric, 1996). Marginal-marine deposits of the Magothy Formation (Coniacian or Santonian) overlie the Potomac Formation and can be recognized in geophysical logs from the Dover-Cheswold area (Benson and Spoljaric, 1996). Age data from Dover (Je32-04), New Castle County (Benson and Spoljaric, 1996), and Millville, New Jersey (Sugarman et al., 2005) suggest the contact between the Magothy and Potomac Formations is a regional unconformity. Three other Late Cretaceous marine units occur above the Magothy Formation: the fine-grained Merchantville Formation, the sandy Englishtown Formation, and the fine-grained, glauconitic Marshalltown Formation.

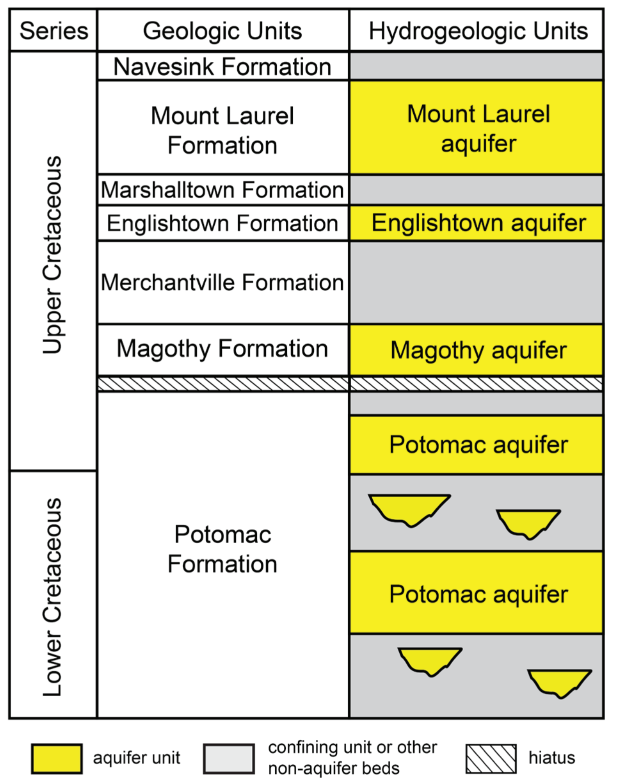

Figure 2. Stratigraphic chart of Cretaceous formations and aquifers in Kent County, Delaware.

The Upper Cretaceous (Campanian) Mount Laurel Formation overlies the Marshalltown Formation and is the oldest stratigraphic unit used as an aquifer in the study area. The formation transitions from sandy aquifer-prone facies in northern Kent County to progressively siltier and more calcareous deposits southward. Two muddy, glauconite-rich units overlie the Mount Laurel sands and contain the Cretaceous-Paleogene boundary: the Navesink Formation (Maastrichtian) and the Hornerstown Formation (Paleocene) (Fig. 3). These glauconitic units are overlain by a Paleogene section that shows significant geographic variation of lithologies. In northernmost Kent County, the Vincentown

Formation (Paleocene) is characterized by groundwater-yielding sands referred to as the Rancocas aquifer. However, just south and east of Smyrna, the Vincentown Formation becomes progressively muddier with a corresponding decrease in sand content; finer-grained facies prevail from central Kent County southward. The overlying section is composed of glauconitic, calcareous muds of the Manasquan Formation (early Eocene) and Shark River Formation (middle Eocene) that prograde into (middle Eocene) sands of the Piney Point Formation (Fig. 3). The Piney Point Formation includes highly permeable aquifer-quality sand over much of Kent County and some of northern Sussex County.

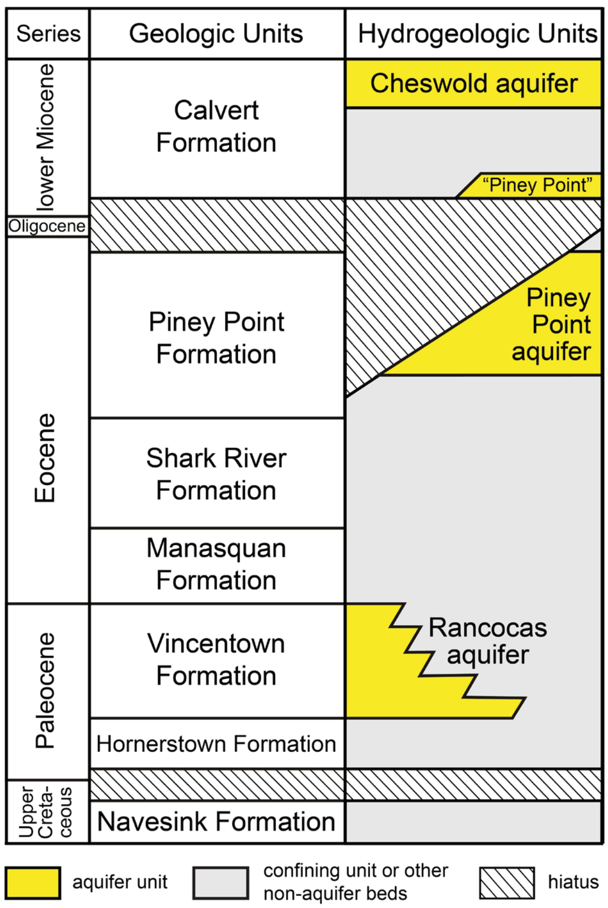

Figure 3. Stratigraphic chart of Upper Cretaceous to lower Miocene formations and aquifers in Kent County, Delaware.

Miocene deposits unconformably overlie Eocene Piney Point beds. In some places, the basal Miocene deposits are sand and shell that appear to be reworked from the Piney Point Formation; hydrostratigraphically, these can be included in the Piney Point aquifer (Benson and Spoljaric, 1996). Most of the lower and middle Miocene is represented by interbedded shoreface sands and offshore muds of the Calvert and Choptank Formations, forming a series of alternating aquifers and confining beds (Fig. 4). The transition into the upper Miocene represents a shift in sedimentary style; muddy marine sediments of the St. Marys Formation prograde upward to sandy nearshore sediments of the Cat Hill Formation and a mosaic of nearshore to estuarine sands and muds in the Bethany Formation. The Cat Hill and Bethany Formations are, for the most part, restricted to Sussex County and sandy beds in these formations comprise the important Manokin and Pocomoke aquifers (Fig. 4).

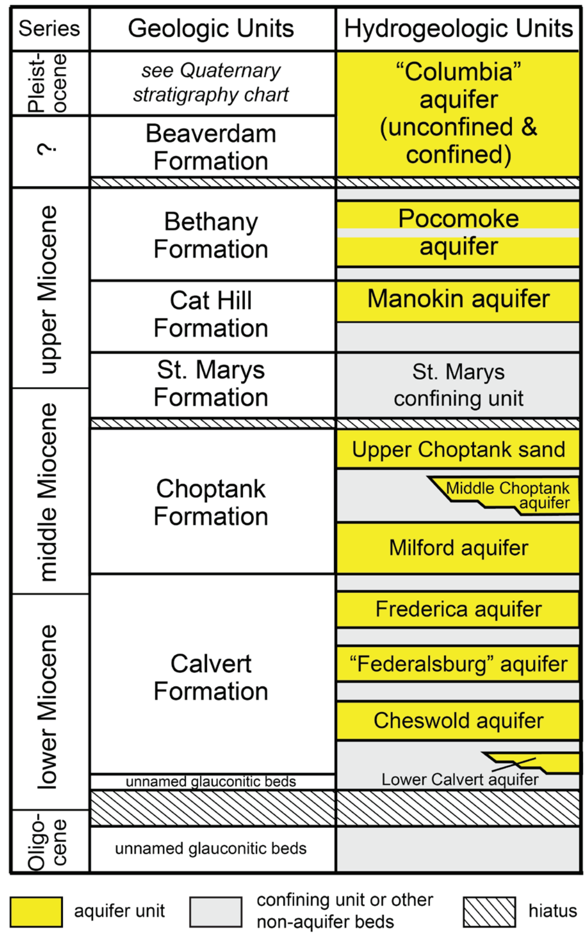

Figure 4. Stratigraphic chart of Oligocene to Pleistocene formations and aquifers in Sussex County, Delaware.

Another shift in sedimentation is evident at the unconformable contact between upper Miocene marine sediments (and in places middle or lower Miocene sediments) and the Beaverdam Formation (Fig. 4). The Beaverdam Formation is of indeterminate age, possibly late Miocene or Pliocene, and represents a complex of coarse-grained sediments laid down over the unconformity in fluvial and possibly estuarine environments. The youngest sediments are Quaternary and include a variety of formations and lithologies, many of which are separated by unconformities created by Quaternary sea-level changes (Fig. 5). Depending on location, these Quaternary sediments may comprise all or part of the unconfined aquifer, may act as confining beds, or may form a local shallow confined aquifer.

Methods and Data

The aquifer geology framework presented here was constructed using stratigraphic picks that are based on geophysical log signatures, lithologic logs, depositional models that characterize aquifer sand body continuity, and age control available from boreholes in the study area. A stratigraphic database was designed to capture borehole stratigraphic-picks data needed to construct maps and cross sections. Stratigraphic cross sections were constructed to illustrate stratigraphic relationships between confined aquifers, the unconfined aquifer, and confining beds. Depth and thickness maps were constructed for thirteen aquifers to understand the three-dimensional distribution of the groundwater sources. The methods and data in the aquifer geology part of this study are described below.

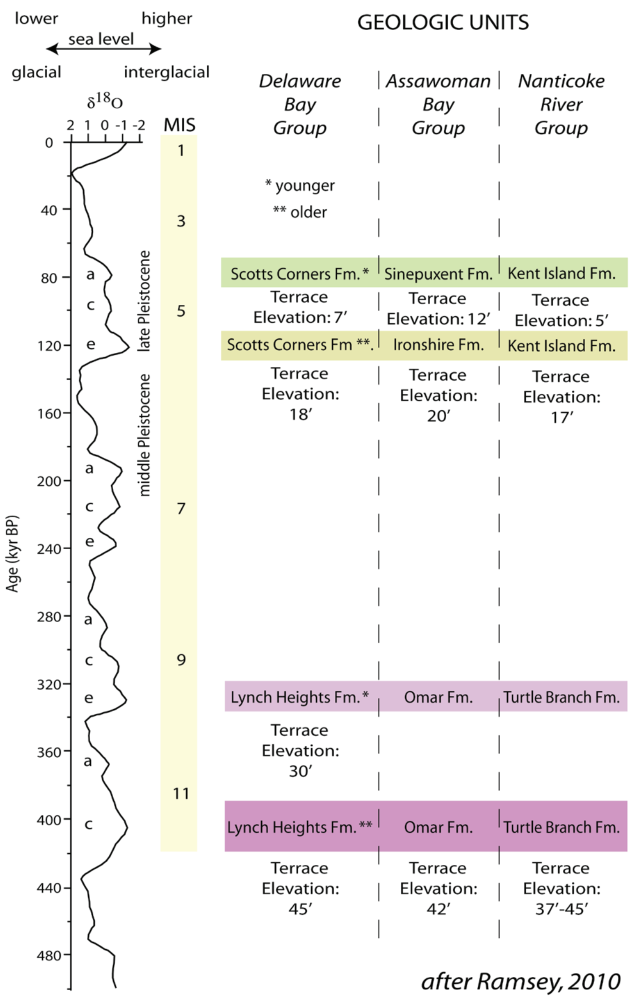

Figure 5. Stratigraphic correlation chart of Pleistocene formations and terraces in Kent and Sussex Counties with estimated marine isotope stages (MIS) and ages.

Stratigraphic Database

A large volume of well and borehole data was evaluated to construct the geologic maps and cross sections. A stratigraphic database was compiled that includes depths of picks of the tops and bottoms of aquifers in these boreholes as well as some depth picks for geologic formations.

Well locations primarily came from the DGS Oracle database. Hundreds of well locations were determined and revised by comparing location descriptions, maps, and aerial photographs in ArcMap. Well elevations in the paper well records were crosschecked against digital elevation models (DEM) in ArcMap; these vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 88). Elevation values were added where lacking or corrected where erroneous. Oracle tables were updated where necessary. In addition, new well information was obtained from water providers for a number of wells.

Stratigraphic picks were interpreted from geophysical, well driller, geologic, and engineering logs. Borehole data were obtained from logs on file at the DGS, from well completion reports submitted to the Delaware Department of Natural Resources and Environmental Control (DNREC), and from water providers. Numerous paper geophysical logs were digitized for the first time; the quality of existing digital log files was reviewed and the files were edited where needed to improve the quality of the log curves. We monitored state water-well permit notices to target new wells for geophysical logging and logged many of these with DGS logging equipment. The type of borehole log impacts data quality. For example, whereas the precision of a geophysical log is generally within a few feet, a high-quality well-driller log might only be accurate to within 10 feet.

After screening the quality of all available borehole records, including data from the Kent County confined aquifer study (McLaughlin and Veléz, 2006) and the Sussex County unconfined aquifer study (Andres and Klingbeil, 2006), stratigraphic picks from 6,600 boreholes were compiled in a Microsoft Access database that totaled approximately 14,000 records. This compilation provided dense data coverage in the study area. Data were also compiled from southernmost New Castle County and nearby areas of Maryland and New Jersey to minimize edge effects during the creation of aquifer maps. Queries were designed to export data in appropriate formats for the aquifer mapping operation.

The highest-quality data for correlation and mapping in this study were from boreholes logged by DGS staff. Although these high quality data were available for a number of public, domestic, and agricultural wells, parts of the study area had poor data coverage for deeper confined aquifers. These data gaps were filled by drilling new test boreholes. A commercial water-well contractor drilled ten test holes between July and September, 2007 in data poor areas of Sussex County (Table 2, Fig. 6), supplementing the six test holes previously drilled for the Kent County confined aquifer study (McLaughlin and Veléz, 2006). The holes ranged from 600 to 840 ft deep. Drill cuttings were collected every 10 ft and described, lithologic logs were created, and gamma-multipoint electric logs were recorded.

Table 2. Test holes drilled for this study to collect additional geological data on confined aquifer intervals in Sussex County. The locations are shown on Figure 6. fbls, feet below land surface.

Project ID	DGS ID	Site Name	Depth (fbls)
DGSDH-1	Qf21-07	Midlands Wildlife Area	820
DGSDH-2	Oh52-05	Hollyville Transfer Station	620
DGSDH-3	Nb54-04	Marshy Hope	600
DGSDH-4	Nd35-08	Owens Tract	840
DGSDH-5	Nf33-06	Ponders Tract	600
DGSDH-6	Qd23-27	Chipman Pond	600
DGSDH-7	Rh22-12	Selbyville North	840
DGSDH-8	Qc21-05	Nanticoke Wildlife Area	600
DGSDH-9	Pc14-17	Seaford North	840
DGSDH-10	Mf35-26	Argos Corner	820

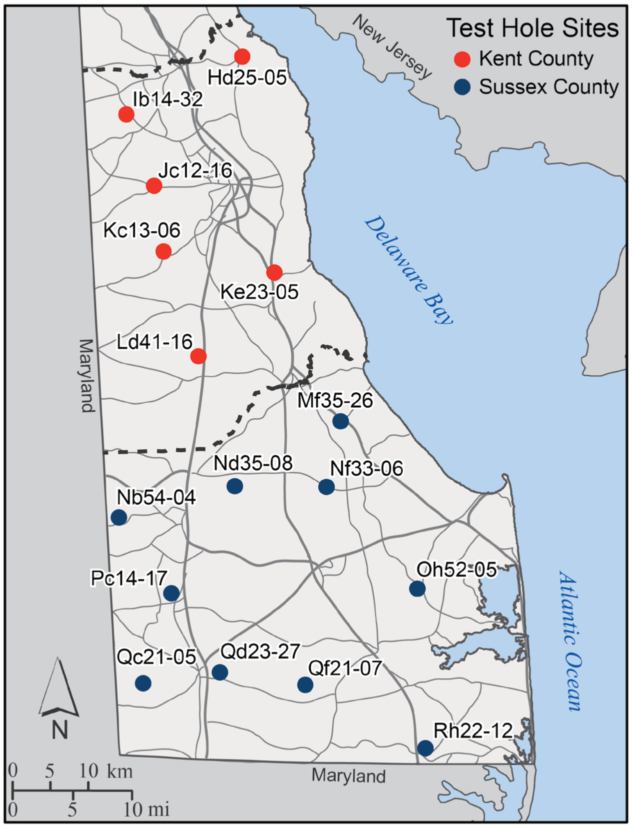

Figure 6. Map showing locations of test holes drilled in Kent County for McLaughlin and Velez (2006) and in Sussex County for this study to collect additional geological data on confined aquifer intervals. Site names and depths of test holes for Sussex County are shown on Table 2.

Aquifer Mapping

The stratigraphic well-picks database was used to construct maps of aquifer elevations and thickness. The maps were created digitally as rasters using ArcMap Geostatistical Analyst. Each raster is a georeferenced matrix of cells that contains a value of elevation, depth, or thickness for which a range of values is coded to match a defined set of colors. Vertical coordinate data are referenced in this report to NAVD88; elevations are reported as feet below sea level (ft bsl) or feet above sea level (ft asl) relative to the NAVD88 0-ft elevation. Maps of the elevation of the top and base of each aquifer were created by interpolating between data points that were extracted for each surface from the stratigraphic well-picks database. Aquifer thickness maps were created by calculating the difference between the elevation of the top and base of each aquifer.

Slightly different approaches were taken for the construction of the unconfined aquifer map and the confined aquifer maps. The unconfined aquifer map is a composite product that combines a new map constructed for Kent County in this project and an existing map created for Sussex County (Andres and Klingbeil, 2006). The mapping of the unconfined aquifer in Kent County emphasized data density to help accurately map significant thickness variations. The unconfined aquifer includes sediments belonging to one or more formations and associated erosional surfaces, resulting in highly variable thicknesses across the study area. Because the base of the unconfined aquifer is shallow, many well-driller logs were available to map it. However, the quality of these data was highly variable; drill cuttings suffer from mixing of sediments from varying depth intervals in a borehole and driller descriptions of the cuttings made in the field are often not very descriptive. Annotations about data type and quality were included in the stratigraphic-picks database to guide data choices in each round of raster creation. The Kent County unconfined aquifer raster surface was created in ArcGIS after several rounds of data evaluation and raster calculation. The raster utilized picks from 1,871 boreholes, including 165 boreholes having both geophysical logs and lithologic logs, 113 sites with geophysical logs only, and 1,593 sites with lithologic logs only (mostly well-driller logs). The borehole picks included sites from outside of the county to avoid edge effects resulting from extrapolation. The Sussex County raster of Andres and Klingbeil (2006) was sampled near the county line to ensure the Kent County raster could be seamlessly merged with the Sussex County raster. The procedure for creating the unconfined aquifer raster surfaces in ArcMap was as follows:

1. Choose appropriate Kent County and Maryland data points by querying the stratigraphic database for elevation of base of unconfined aquifer (base depth minus land surface elevation values in database).
2. Export chosen data points as Excel file.
3. Create a subset of sampled grid points for northern Sussex County by sampling the Sussex unconfined elevation raster in a regular point pattern of 100-meter (m) (328 ft) spacing in a band extending 1,500 m (4,921 ft) south of the county boundary.
4. Export the sampled grid points from ArcMap to an Excel file.
5. Combine borehole data and sampled grid points in a single Excel file.
6. Import combined Excel file into ArcMap.
7. Calculate raw raster using the Radial Basis Function method in ArcGIS Geostatistical Analyst with a 100-m (328 ft) resolution.
8. Evaluate raster for "bull's eyes" and inconsistent local thickness anomalies.
9. Return to step 1 for editing of pick list, pick depths, or land-surface elevations as needed.
10. Create corrected base aquifer elevation raster by correcting for surficial topography by substituting the land surface elevation where the calculated raw raster is higher than the land surface.
11. Create a final raster for the elevation of the base of the unconfined aquifer by combining the Kent and Sussex County rasters and clipping to the study area.
12. Create a raster of the thickness of the unconfined aquifer by subtracting the raster of the elevation of the base of the unconfined aquifer from the DEM of the land surface.

We chose to use higher-quality stratigraphic picks from geophysical logs to construct the confined aquifer maps instead of picks from the more densely spaced but lower quality well-driller logs. The confined aquifers generally have simpler and less variable stratigraphic geometries than the unconfined aquifer; for this reason, the higher-quality log-based data are most suitable for mapping the confined aquifers despite the less dense coverage of log data. In areas where data density is especially low, some thinning or thickening trends may be exaggerated because of the computer mapping process seeking to close the contours between data points. Edge effects complicate map construction near the margins of the mapped areas where the contouring is controlled only by data on one side. We incorporated borehole data from outside of the study area (southern New Castle County, Maryland, and New Jersey) to minimize the impact of edge effects on raster calculations.

The procedure for creating the confined aquifer raster surfaces in ArcMap was as follows:

1. Choose appropriate Kent County, Sussex County, Maryland, and New Jersey data points by querying the stratigraphic database for elevation of top and base of each confined aquifer (depth of horizon minus land surface elevation).
2. Export chosen data points as an Excel file.
3. Import Excel file into ArcMap.
4. Calculate raw raster using the Radial Basis Function method in ArcGIS Geostatistical Analyst with a 100-m (328 ft) resolution
5. Evaluate raster for “bull’s eyes” and inconsistent local thickness anomalies.
6. Return to step 1 for editing of pick list, pick depths, or land surface elevations as needed.
7. Compare each raw raster to the raster surface above it and raster surface below it to ensure surfaces do not intersect.
8. Where necessary, ensure that raster surfaces do not intersect in three-dimensional space by adding plausible projected values in sparse data areas and recalculating the raster.
9. Compare each raster surface to the DEM of land surface elevation and, where needed, create a corrected raster by substituting the land surface elevation where the calculated raster surface is higher than the land surface.
10. Compare each raster surface with the raster of the elevation of the base of the unconfined aquifer. If the base of unconfined aquifer occurs below the top of the confined aquifer, the confined aquifer is not confined at those locations, in which case the rasters (top and base) of the confined aquifer are clipped there.
11. Compare clipped and unclipped versions of the confined aquifer rasters to delineate “windows” where the confined aquifer body becomes unconfined and can therefore be recharged directly.
12. Create final raster surface for the top and base of each confined aquifer by clipping to the study area.
13. Create a raster of the thickness of the each confined aquifer by subtracting the raster elevation of the base from the raster elevation of the top.

The aquifer maps are included in the body of this report as text figures and as full-page maps in Appendix B in PDF format with selectable layers. Limits of the precision of these maps should be considered by the user and are explained in Appendix B.

Cross Sections

Stratigraphic cross sections show trends in the distribution and stratigraphic geometry of aquifer units in Kent and Sussex Counties. Boreholes selected were deep enough to penetrate confined aquifers of interest and had good quality geophysical logs. The 14 cross-section transects provide a representative portrayal of the study area in approximate dip and strike directions (Plates 1 and 2).

In Kent County, the two approximately north-south sections highlight up-dip to down-dip relationships (A-A', B-B', Fig. 7 and Plate 1) and six approximately west-east sections illustrate stratigraphic relationships along strike (C-C', D-D', E-E', F-F', G-G', H-H', Fig. 7 and Plate 1). These cross sections approximate the profiles in McLaughlin and Veléz (2006) and portray a few changes in aquifer correlations made since then. In Sussex County, the stratigraphy is shown on four north-south sections (I-I', J-J', K-K', L-L', Fig. 8 and Plate 2) and two east-west sections (M-M', N-N', Fig. 8 and Plate 2). The unconfined aquifer and 12 confined aquifer intervals were correlated on the cross sections: Mount Laurel, Rancocas, Piney Point, Lower Calvert, Cheswold, “Federalsburg,” Frederica, Milford, Middle Choptank, Upper Choptank, Manokin, and Pocomoke.

It is important to note that these correlations broadly encompass the aquifers and stratigraphically equivalent horizons, even where the mapped unit may be too fine-grained to be an aquifer-quality lithology.

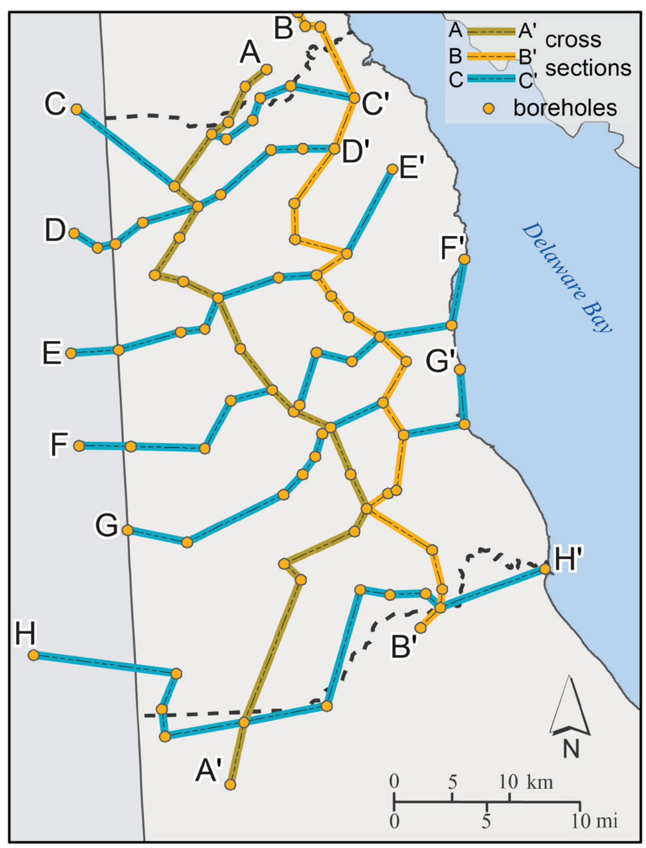

Figure 7. Map showing locations of stratigraphic cross sections in Kent County, Plate 1.

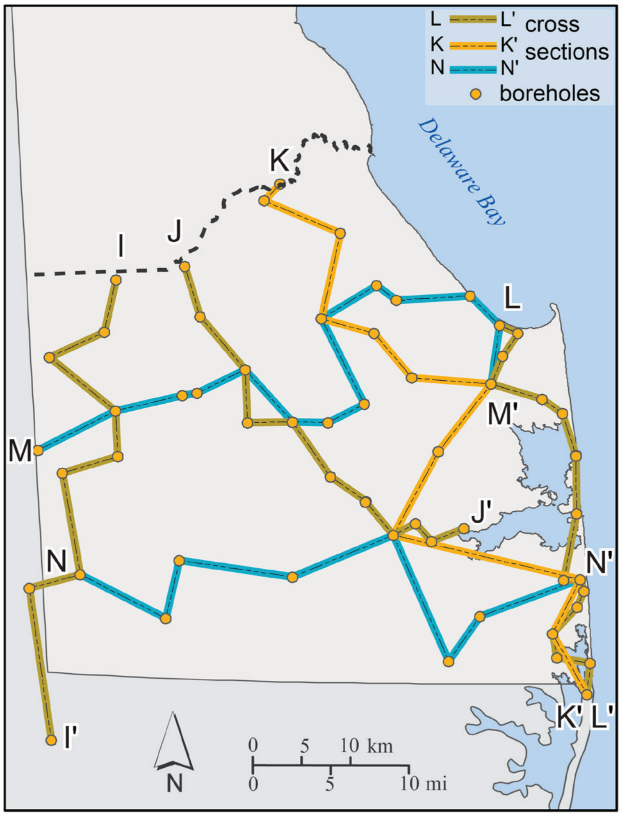

Figure 8. Map showing locations of stratigraphic cross sections in Sussex County, Plate 2.

A line representing the base of the unconfined aquifer was created by sampling the unconfined aquifer raster surface along the line of section at 100-m (328 ft) spacing. The land-surface elevations were sampled every 30 m (98.4 ft) for each section from the Delaware composite 2005-2007 3-m DEM (Delaware Geological Survey, 2008). The confined-aquifer surfaces were generally drawn as straight lines between well picks, although some editing and reshaping was done by sampling the corresponding confined aquifer raster surface. Some additional artistic representation was made of the confined aquifer boundaries, such as staggered lines for facies changes and dashed lines where correlations are more uncertain. The cross-section illustrations are included with this report as plates in PDF file format with selectable layers.

White intervals between aquifers on the cross sections (Plates 1 and 2) represent non-aquifer facies; these include confining beds as well as lithologies that are neither good aquifers nor effective confining beds. The geology and hydrology of these non-aquifer intervals is not addressed systematically in this report. The geology of the intervals between the unconfined aquifer and the shallowest confined aquifers is very complex in many areas. Those shallowest non-aquifer intervals may include more than one formation in any one location; the stratigraphic relationships between the formations can be complex and the lithologies within these units can be highly variable, especially in the case of Pleistocene deposits that represent multiple episodes of cut, fill, and/or terrace formation.

Of special note on the cross sections is the portrayal of the relationship between the unconfined aquifer and confined aquifers where they occur near the land surface. Where the sand body that comprises a confined aquifer intersects surficial sands, the older sand becomes unconfined. At those locations, the line for the base of the unconfined aquifer is drawn to dip to the elevation of the base of the older sand. At a few locations on the cross sections, new borehole data reveal a different elevation of the base of the unconfined aquifer than the raster map, which is unchanged from that of Andres and Klingbeil (2006). An alternate line labeled as "unconfined revised" traces the adjusted elevation of the base of the unconfined aquifer at those borehole locations.

Lithostratigraphy

The subsurface stratigraphy of the Delaware Coastal Plain is characterized by a gradually thickening wedge of gently dipping sediments ranging in age from Early Cretaceous to Quaternary. The aquifers used in Kent and Sussex Counties occur in the formations ranging in age from latest Cretaceous to Quaternary. In this section, we describe the formations that make up the groundwater systems of the study area, providing a lithostratigraphic framework for the aquifers and associated confining beds.

Mount Laurel Formation

The Mount Laurel Formation is an Upper Cretaceous (Campanian) shallow-marine unit originally defined in New Jersey (Carter, 1937; Owens et al., 1970; Pickett, 1970; Benson and Spoljaric, 1996; McLaughlin and Veléz, 2006; Dugan et al., 2008). This formation was initially described as the Mount Laurel sand by Clark et al. (1896) for an interval of sand in the lower part of what was then defined as the Monmouth Formation in Burlington County, New Jersey.

In New Castle County and northern Kent County, the Mount Laurel Formation is predominantly quartz sand with shells, burrows, and variable amounts of glauconite, giving it a salt-and-pepper appearance. It is locally silty, especially lower in the formation, and exhibits extensive burrowing. Shell material is abundant in places, including frequent *Exogyra costata* and *Belemnitella americana*. The lower part of the formation may have calcite cement. From central Kent County southward, the amount of sand is considerably lower and finer grained facies predominate. The lithologies are calcareous silt and clay that contain glauconite and shells, as well as abundant calcareous nannofossils in the matrix (Rasmussen et al., 1958; Benson et al., 1985, Benson and Spoljaric, 1996). These fine-grained sediments likely represent a basinward transition to an offshore shelf setting. The cleaner quartz sands within the formation comprise the Mount Laurel aquifer.

The thickness of the Mount Laurel Formation (Owens et al., 1970) ranges from 15 ft or less near St. Georges in outcrops along the Chesapeake and Delaware Canal to more than 100 ft in southern New Castle County and northern Kent County (McLaughlin and Veléz, 2006; Dugan et al., 2008). The base is in conformable contact with the underlying Marshalltown Formation, a unit characterized by high gamma values. The top of the Mount Laurel Formation is in unconformable contact with the Navesink Formation. In the nearby Eastern Shore of Maryland, the aquifer in the Mount Laurel Formation is referred to as the Monmouth aquifer (Andreasen et al., 2013).

Strontium isotopes and calcareous nannofossils indicate a Campanian age. Sugarman et al. (1995) reported an age of 71.4 million years (Ma) obtained from two strontium isotope measurements on a specimen of *Belemnitella americana* from the Chesapeake and Delaware Canal. This is consistent with upper Campanian strontium ages and calcareous nannofossil biostratigraphy in nearby southern New Jersey (Miller et al., 2004) and macrofossil occurrences that include *Belemnitella americana, Exogyra cancellata,* and a number of upper Campanian ammonite taxa (Kennedy and Cobban, 1994).

Navesink Formation

The Navesink Formation is the uppermost Cretaceous unit recognized in Delaware. In outcrops in its type area in New Jersey, it is clayey glauconite sand (Owens et al., 1970). In the Delaware Coastal Plain, it is restricted to the subsurface where it consists of similar, but finer-grained, sediments, typically dark-green to greenish-gray, clayey, sandy, calcareous silt, with the sand fraction rich (commonly greater than 50 percent) in glauconite (Benson and Spoljaric, 1996). Benson and Spoljaric (1996) noted that the glauconitic silts have relatively high gamma-ray counts distinguishing the Navesink from the sandier underlying deposits of the Mount Laurel Formation. The Navesink Formation reflects deposition in an open shelf setting during the Late Cretaceous (Maastrichtian; Benson and Spoljaric, 1996). It is not typically used as a groundwater source.

The base of the formation is considered an unconformity. In outcrop in New Jersey, the basal strata are commonly rich in fossils, mostly phosphatic internal molds; this phosphatic interval is recognized in the Delaware subsurface by a spike of high counts on gamma ray logs. The Navesink Formation is approximately 20-ft thick in Delaware, comparable to its typical 25-ft thickness in New Jersey. In Maryland, equivalent deposits are referred to as the Severn Formation.

Hornerstown Formation

The Hornerstown Formation is dark-green, clayey, calcareous quartzose glauconite sand and sandy silt (Pickett and Spoljaric, 1971; Owens et al., 1977, 1999; Benson et al., 1985; Benson and Spoljaric, 1996). The sand is most commonly fine to medium grained in a muddy greenish matrix. The Hornerstown Formation was originally described in New Jersey (Clark, 1907). It is present in the subsurface of southern New Castle County and continues into Kent County (Benson and Spoljaric, 1996) and northern Sussex County as a slightly siltier facies (McLaughlin and Veléz, 2006, reinterpretation of Talley, 1975). It is also present in the Eastern Shore of Maryland but generally not recognized west of the Chesapeake Bay (Hansen, 1992). The bright-green glauconite clay matrix of the Hornerstown Formation distinguishes it from similar Cretaceous glauconitic units (Owens and Sohl, 1969). The matrix has less abundant calcite than the similar Navesink Formation. It is not considered a significant source of groundwater and, together with the Navesink Formation, would generally function as a confining unit.

The Hornerstown Formation is early Paleocene. The base of the formation represents the unconformable contact between Cretaceous and Paleogene sediments. Its thickness is approximately 30 ft in the Dover area (Benson and Spoljaric, 1996) and reported as 20 to 30 ft in outcrops in northern Delaware and New Jersey (Owens et al., 1977). The formation has been interpreted as a mid-shelfal deposit (Owens et al., 1977; Benson and Spoljaric, 1996).

Vincentown Formation

The Vincentown Formation is a late Paleocene unit that has been broadly characterized in Delaware as fine- to coarse-grained, variably glauconitic quartz sand that is slightly to moderately silty and slightly to moderately clayey (Pickett and Spoljaric, 1971; Benson and Spoljaric, 1996; Dugan et al., 2008). Striking lateral facies changes occur in central Delaware, where a thick succession of shelly sands and sandstone near the northern border of Kent County transitions southward to muddier lithologies in central Kent County. Where sandy, it includes the Rancocas aquifer, an important groundwater source in southern New Castle County and northernmost Kent County.

The name of the Vincentown Formation originated in New Jersey as the "Vincentown limesand" of Clark et al. (1897). It exhibits variable lithofacies types in New Jersey, including quartz sand, foraminifera- and bryozoan-rich calcarenite, quartz-glauconite sand, and muddy sand lithologies (Parker et al., 1964; Owens et al., 1999; Sugarman, 2011). The sandy lithologies that occur in outcrop and the shallow subsurface pass just a few miles southeastward into more glauconitic, clay-rich lithologies (Parker at al., 1964; Zapecza, 1989). Glauconite is generally present in the formation and most abundant in the lower part (Owens et al., 1999); mica is a notable minor constituent in many places and helps distinguish it from overlying and underlying units. In the Eastern Shore of Maryland, equivalent strata are referred to as the Aquia Formation.

Similar lithologies are evident in this study area. In the subsurface of southern New Castle County and northern Kent County, the Vincentown Formation is glauconitic quartz and carbonate sand; the carbonate sand grains includes shell debris and foraminifera. Thin, hard, cemented beds are present that produce conspicuous spikes on single-point resistance and short-normal resistivity logs. The formation becomes finer grained toward the south (Benson and Spoljaric, 1996; Andres, 2001). The down-dip lithologies are predominantly micaceous, glauconitic, sandy clays in cores. This down-dip-fining trend is comparable to that noted above in New Jersey and to a similar trend in the Aquia Formation in the nearby Eastern Shore of Maryland (Andreasen et al., 2013).

The marked facies changes in this interval in Delaware has resulted in a variety of stratigraphic subdivisions and formation names through the years, including Rancocas Formation, Nanjemoy Formation, Pamunkey Formation, and, most recently, the Deal Formation (Rima et al., 1964; Sundstrom and Pickett, 1971; Benson and Spoljaric, 1996). Benson and Spoljaric (1996) proposed the name Deal Formation for the fine-grained section in central Delaware that is equivalent to the Vincentown, Manasquan, and Shark River Formations, judging the lithologies similar to those of the Deal Member of the Manasquan Formation in New Jersey. However, because the Deal was defined as a member of one of those formations in New Jersey, its use as a formation for this broader interval creates some confusion. Therefore, we prefer to set aside the concept of the Deal Formation and use the Vincentown Formation as the name for the finer-grained section that is equivalent to the up-dip Vincentown sands.

The Vincentown Formation overlies the Hornerstown Formation conformably or with a minor disconformity; it underlies the Manasquan Formation, with the contact appearing to be a minor disconformity. Microfossils indicate a late Paleocene age (Sugarman et al., 2005). It was deposited in shelf environments (Owens et al., 1999). The sandier facies represent nearshore environments, with clear waters where the foraminifera- and bryozoan-rich calcarenites were deposited; the muddier facies represent offshore shelf environments. Dugan et al. (2008) reported thicknesses of as much as 140 ft for the Vincentown Formation in southern New Castle County; in nearby New Jersey, its thickness is commonly less than 50 ft but may be as much as 125 ft (Owens et al., 1999).

Manasquan Formation

The Manasquan Formation in Delaware is composed of calcareous clay, silt, and muddy fine sand with glauconite and abundant microfossils. The name is derived from the Manasquan marl, defined by Clark (1893) in New Jersey, where this unit is characterized by dark, poorly sorted quartz sands, green clayey fossiliferous glauconite sands, and pale-gray silty clay with sparsely disseminated glauconite and quartz sand (Owens and Sohl, 1969). Two members have been recognized in New Jersey (Owens et al., 1999). The lower part was described as clayey, medium- to coarse-grained, quartz-glauconite sands and differentiated as the Farmingdale Member (Enright, 1969). The upper part was described as fine-grained quartz sands or silts and referred to as the Deal Member (Enright, 1969). Both units transition to finer silt and clay down dip in the subsurface in New Jersey (Owens et al., 1988; Enright, 1969; Olsson and Wise, 1987).

The concept of the Manasquan Formation in Delaware has been complicated due to different views of the complex lithostratigraphy of the late Paleocene and early Eocene strata. The Manasquan Formation was first used as a name in Delaware by Benson and Spoljaric (1996) at borehole Gd33-04 for sand in the upper part of an interval that Jordan (1962) previously called the Rancocas Formation. It has been described as burrowed, calcareous, glauconitic, green to gray-green clay, silt, and muddy fine sand containing abundant calcareous microfossils. However, sandy lithologies previously placed in the Manasquan Formation, such as those in Gd33-04, are difficult to differentiate lithologically from the shelly, glauconitic sands assigned to the Vincentown Formation in recent cores. Therefore, we suggest that the shelly sands be included in the Vincentown Formation and that the name Manasquan Formation be reserved in Delaware for generally muddy lithologies similar to those recognized where defined in New Jersey. Within this framework, the Rancocas aquifer would occur in the Vincentown Formation; the Manasquan Formation would be part of the thick confining interval above the Rancocas aquifer.

An additional issue for nomenclature is the down-dip transition to muddier facies recognized in the upper Paleocene to lower Eocene section of Delaware. Although Benson and Spoljaric (1996) placed the Manasquan-equivalent strata of central Delaware in their Deal Formation, we consider the range of lithologies in their Deal Formation to be similar enough to the definition of the Manasquan Formation that we set aside the concept of the Deal Formation for these strata. Instead, we refer the lower Eocene glauconite- and microfossil-rich clay, silt, and muddy fine sand of central Delaware to the Manasquan Formation.

The base of the Manasquan Formation is a glauconite-rich bed, presumed equivalent to the Farmingdale Member of New Jersey, which is separated from the underlying Vincentown Formation by a minor disconformity. The top of the formation appears to be a minor disconformity that separates it from the overlying Shark River Formation. Both contacts are marked on well logs by gamma ray spikes. Microfossils indicate that the age of the Manasquan Formation is early Eocene (Owens et al., 1999; Sugarman et al., 2005). Lithologies and microfossils indicate the unit was deposited in offshore, middle to outer neritic environments (Sugarman et al., 2005). Its thickness is most commonly about 30 ft but can be as much as 70 ft (Benson and Spoljaric, 1996; McLaughlin and Veléz, 2006; Dugan et al., 2008).

A notable additional point on regional stratigraphic relationships in this interval is that the Marlboro Clay, a lower Eocene clay unit known to occur in Maryland and New Jersey (Gibson, Bybell, and Owens, 1993), has not yet been recognized in borehole records in Delaware. The Marlboro Clay is of special scientific interest because it records the climatic events associated with the Paleocene-Eocene Thermal Maximum. Its absence in Delaware boreholes may be because the light-colored kaolinitic clays typical of the Marlboro do not occur or because Marlboro-age deposits are not present (Bybell, Self-Trail, and Gibson, 1995; Benson and Spoljaric, 1996).

Shark River Formation

The Shark River Formation is a middle Eocene unit, originally defined in New Jersey (Conrad, 1865; Clark, 1893), where it is composed of glauconite and quartz sand in a matrix of silt and clay (Miller et al., 1998; Sugarman et al., 2005). Lithologies in Delaware are similar, but quartz sand is more common in New Jersey. The Shark River lithologies tend to be finer in the lower part of the formation and sandier in the upper part. The northerly occurrences of the Shark River Formation are green and dark-gray glauconitic clayey silts and clay; lesser amounts of glauconite sand and fine- to medium-grained glauconitic quartz sands also occur. To the south in central Kent County, this interval appears to be slightly finer-grained and more clay-rich (Benson and Spoljaric, 1996; McLaughlin and Veléz, 2006). The formation is part of a thick confining bed above the Rancocas aquifer.

Benson and Spoljaric (1996) placed the Shark River-equivalent strata of central Delaware in their Deal Formation, as discussed above. However, we consider Shark River to be an appropriate name for those sediments because the lithologies in cores and well logs are consistent with the lithologies of the Shark River Formation as defined in New Jersey.

The Shark River Formation was deposited in an open-shelf setting (Owens et al. 1988; Benson et al., 1985). It is underlain by the Manasquan Formation at a minor disconformity; the boundary is generally characterized by a shift to higher values on both gamma ray and resistivity logs in the Shark River. It is overlain by the Piney Point Formation in much of the study area or by the Calvert Formation where younger Eocene units are truncated northward beneath the Eocene-Miocene unconformity. In southern New Castle County and northern Kent County, it is generally 60- to 70-ft thick.

Piney Point Formation

The Piney Point Formation is composed of clean to muddy, glauconitic, shelly quartz sand. It is middle Eocene in age and occurs in the subsurface of Kent and Sussex Counties. This formation name was originally used for Eocene glauconitic sands and shell beds in southern Maryland (Otton, 1955) and has been applied to similar deposits in Delaware since the late 1950s (Rasmussen et al., 1958). The Piney Point Formation coarsens upward and shows definite changes in character across depositional dip. In central and southern Kent County, most of the formation is clean, greenish, fine- to medium-grained shelly sand. Twenty to forty percent of the sand is glauconite (Benson and Spoljaric, 1996), giving it a salt-and-pepper appearance. The formation becomes increasingly clay-rich downward, transitioning to glauconitic silt and clay with discontinuous beds of muddy glauconitic sand (Benson and Spoljaric, 1996; Andres, 2001). The clean sands can yield abundant groundwater and are referred to as the Piney Point aquifer.

The Piney Point Formation conformably overlies the Shark River Formation. Because the Piney Point represents the upper part of a continuous coarsening-upward trend, the lower formation boundary can be difficult to discern in some locations. The Piney Point Formation is unconformably overlain by Miocene deposits of the Calvert Formation in most of Kent County; the boundary is correlated around the study area as a basal Miocene erosional unconformity. In southern Kent County, the Piney Point and equivalent strata are overlain by unnamed late Eocene and Oligocene sediments, but the precise nature of their stratigraphic relationships are unclear at present.

The Piney Point Formation becomes progressively muddier and thinner northward in northern Kent County. McLaughlin and Veléz (2006) interpreted this change due to the northward truncation of the top of the Piney Point Formation below the basal Miocene unconformity. The Piney Point Formation has steeper southeasterly dips than the overlying Miocene formations, placing progressively lower and muddier parts of the Piney Point Formation under this surface to the north. In northernmost Kent County, the Piney Point Formation is locally absent because of erosion under the unconformity.

The Piney Point Formation was deposited in an offshore, open-shelf environment. The coarsening upward lithologies suggests increasing energy and shallowing environments. It is middle Eocene in age in the subsurface of the Dover area (Benson and Spoljaric, 1996) but may extend to late Eocene in Sussex County based on trends observed in New Jersey (Sugarman et al., 2005) and preliminary microfossil observations in this study. It reaches thicknesses of more than 250 ft in southern Kent County and northern Sussex County and thins northward as it is increasingly truncated under the basal Miocene unconformity.

Unnamed Late Eocene and Oligocene Sediments

The late Eocene and Oligocene sediments in Delaware are poorly understood but merit further investigation as potential aquifer facies. Based on unpublished DGS palynological data, Ramsey and Groot (1997) identified an unnamed Eocene unit in an interval of shelly mud at the bottom of borehole Me15-29 at Milford (Fig. A1). The sand interval just above that Eocene mud has been referred to as the Piney Point aquifer (Cushing et al., 1973). However, based on foraminifera and well-log correlations, Andres et al. (1990) considered this interval an unnamed unit of Oligocene age. He considered this sand interval to be equivalent to the unnamed glauconitic silt that he recognized in borehole Oh25-02 in Lewes (Fig. A4).

Additional late Eocene and Oligocene sediments exist but are not formally named. Some test boreholes drilled for this study in western Sussex County (Nd35-08 and Pc14-17, Fig. A4) contain muddy to clean, glauconitic quartz sands below the basal part of the Calvert Formation. The lithologies are similar to the Piney Point Formation but preliminary examination of foraminifera suggests they may be Oligocene or late Eocene. Andres et al. (1990) identified similar strata as possibly Oligocene in other holes (Me15-29, Od23-01, Od23-02, Od24-01, Fig. A4) from benthic foraminiferal faunas and geophysical log patterns. Andres et al. (1990) suggested faulting as the reason for their presence down dip. However, because significant faulting is not very common in Delaware Coastal Plain sediments, we believe that the explanation is more likely stratigraphic than structural; if the strata under the unconformity dip more steeply than those above, progressively greater erosion would be expected up dip. This pattern would be similar to that seen at the top of the Piney Point Formation in Kent County.

At a continuous-core test hole drilled east of Easton, Maryland, a thin Oligocene interval was recognized on the basis of biostratigraphy and correlated to the Drummonds Corner beds, an Oligocene unit described in Virginia and Maryland (Alemán González et al., 2012). The sediments are sandy, very clayey silt with minor amounts of glauconite, shell fragments, and foraminifera. The contact with the overlying Calvert Formation is a sharp unconformity.

In New Jersey, Pekar et al. (2001) identified complexes of Oligocene sequences of similar lithologies. The stratigraphy of these sequences, revealed in seismic data, is complicated; clinoform, wedge-shaped packages of sediment are arranged laterally, rather than stacked vertically, resulting in similar Piney-Point-like sand intervals developed at different times in different places.

Calvert Formation

The Calvert Formation is a series of early to early-middle Miocene shallow-marine sediments in Kent and Sussex Counties. The unit is characterized by alternating intervals of sand, which can serve as aquifers, and mud, which may be confining beds, with shells generally abundant throughout. The Calvert Formation was described in Maryland by Shattuck (1902, 1904) as a division of the Chesapeake Group by lithology and fossil content. Ward (1998) pointed out that the name Calvert Formation was first applied in Delaware by Miller (1906) for Miocene beds on the Dover folio sheet; the name was first used in Sussex County in a water resources report by Rasmussen et al. (1960).

The sands of the Calvert Formation are typically fine- to medium-grained, silty, and quartzose; the fine-grained beds are light-gray to gray to brown clayey silt and silty clay (Andres et al., 1990; Ramsey, 1993; Ramsey and Groot, 1997). Burrows are common and bioturbation has locally homogenized the sands. The tops of sand beds may include thin calcite- or dolomite-cemented zones, especially in more down-dip localities (Miller et al., 2003; McLaughlin and Veléz, 2006; McLaughlin et al., 2008). Spikes of very high gamma ray values appear on geophysical logs at, or just below, the tops of the sand units due to the concentration of bone phosphate and/or phosphate nodules. Although the alternation of sands and muds described here is typical, overall the formation contains more sand upward and a significant thickness (typically 50 to 100 ft) of silt and clay in the lower part of the formation. This alternation of sediments traces a series of marine transgressions and regressions that produced interbedded shoreface to estuarine sands and offshore sands and muds.

The Calvert Formation unconformably overlies the Piney Point Formation in much of Kent County and in northwestern Sussex County and overlies other late Eocene or Oligocene sediments in most of Sussex County. As noted earlier, its basal unconformity appears to truncate progressively older strata up dip (Benson and Spoljaric, 1996). In contrast with the underlying units, the Calvert Formation tends to have more common intervals of quartz sand and lower amounts of glauconite. Where the Calvert Formation overlies Piney Point sands, it commonly has a basal bed of glauconitic quartz sand, a few feet to 40-ft thick, that was likely sourced from reworking of the underlying Piney Point Formation (Benson and Spoljaric, 1996). In some more basinward locations in Sussex County, lower Calvert sediments may include more glauconite than typical of the formation in Kent County. The Calvert Formation is distinguished from the overlying Choptank Formation by its overall finer-grained, less shelly character.

The character of the Calvert Formation is more or less consistent across Kent and Sussex Counties, but shows some differences in the detail up dip to down dip. The section thickens down dip to the south and east. Areally persistent sand units within the formation are recognized as the Lower Calvert, Cheswold, "Federalsburg," and Frederica aquifers. Although the aquifers mapped in this study show a general thickening trend in the same direction, more thickening occurs in the finer-grained beds. This reflects greater subsidence in down-dip directions, resulting in more vertical space available for accumulating thicker sections, and more truncation (and larger hiatuses) in up-dip directions where there was less subsidence. In addition, some differences exist within the sand units, as noted in the aquifer section. The thickness of the sand units tends to be more variable in northern Kent County and some beds are very coarse grained, likely in part reflecting high energy and erosion associated with nearshore and tidal sedimentary processes (McLaughlin and Veléz, 2006). The sand units may also exhibit fining-upward patterns in such up-dip occurrences. In more down-dip settings, for example at Bethany Beach, the sands have an overall coarsening-upward character and are slightly finer grained and/or siltier.

The Calvert Formation ranges in thickness from less than 100 ft in northern Kent County due to erosion under the base of the Quaternary section to more than 400 ft in southern Kent County (Plate 1). In Sussex County, at Bethany Beach (Qj32-27; Fig. A4; Plate 2), it is 670-ft thick (Miller et al., 2003; Browning et al., 2006; McLaughlin et al., 2008).

It is worth noting that the north-to-south correlation of the Calvert and Choptank Formations has been slightly revised in this study for the Lewes (Oh25-02) and Bethany Beach (Qj32-27) deep holes (Fig. A4; Plate 2) compared to the correlations in Andres et al. (1990), Miller et al. (2003), Browning et al. (2006), and McLaughlin et al. (2008). Additional geophysical log data in this study indicates that the lines of correlation should be shifted one sand unit higher for most of the aquifer sands at those southern sites, along with an upward shift of the Calvert-Choptank formation boundary.

The Calvert Formation is an early to early middle Miocene aged unit in Delaware. Strontium ages have been obtained from Bethany Beach (Qj32-27) (Miller et al., 2003) and gravel pits in the Cheswold area (Pollack Farm, Benson, 1998) that indicate ages range from about 21 Ma near the base to 15.8 Ma at the top. Biostratigraphic data, including dinoflagellates, calcareous nannofossils, radiolarian, and planktonic foraminifera confirm this early to early-middle Miocene assignment (Miller at al., 2003, McLaughlin and Veléz, 2006).

The implication of this study for understanding the age of the Calvert-Choptank boundary is of great interest. We place it at approximately 16 Ma based on strontium-age data and biostratigraphy reported in some of our previous papers (Miller et al., 2003; Browning et al., 2006; McLaughlin et al., 2008). This differs from ages established at well-known sections at Calvert Cliffs, Maryland, where the boundary is in the upper part of the middle Miocene, approximately 13 Ma based on strontium and diatom data (Browning et al., 2006; Barron et al., 2013). We consider this age difference due to regional facies changes.

Choptank Formation

The Choptank Formation was defined by Shattuck (1902, 1904) in Maryland as a division of the Chesapeake Group based on lithology and fossil content. Rasmussen et al. (1960) first used the name Choptank Formation in Delaware; it is generally restricted to areas south of Dover.

The Choptank and Calvert Formations are lithologically similar in Delaware, characterized by alternating coarser and finer siliciclastic sediments, but the Choptank Formation generally has a higher percentage of sand. Choptank sands are fine- to medium-grained, silty quartz sand and clayey silt and discontinuous beds of medium- to coarse-grained sand and scattered shell-rich beds (Andres et al., 1990; Ramsey, 1993; Ramsey and Groot, 1997). Indurated layers several feet thick are common (Andres et al., 1990) and may be cemented by calcite or dolomite and have porosity developed in voids left by shell dissolution. Three aquifer-quality clean sand intervals can be correlated across the study area and are designated the Milford, Middle Choptank, and Upper Choptank aquifers.

The Calvert-Choptank boundary has been postulated to be an unconformity in previous studies in Maryland (Shattuck, 1904; Kidwell, 1984). In some places in Delaware, the boundary is abrupt and placed at the contact between a granular to very coarse Choptank sand and underlying brown silty Calvert clay (Ramsey, 1993; Ramsey and Groot, 1997). However, at Bethany Beach, strontium ages indicate the contact is essentially conformable. The Choptank Formation is distinctly sandier than the St. Marys Formation, which overlies it in most of Sussex County. The Choptank Formation is overlain by Quaternary deposits in most of Kent County; the contact may be difficult to identify precisely where lithologically similar Quaternary sands overlie Choptank sands.

The Choptank Formation is composed of nearshore deposits laid down in a series of marine transgressions and regressions, producing alternating shoreface to estuarine sands and lesser amounts of finer offshore to lower shoreface sands and silts (Miller et al., 2003; Browning et al., 2006; McLaughlin and Veléz, 2006; McLaughlin et al., 2008). The paleoenvironments represent shallower water depths to the north and, especially, west; an interval of possible paleosols in the upper part of the Choptank Formation in northwestern Sussex County (Marshy Hope, Nb53-08, at 150-ft depth) indicates probable sustained subaerial exposure.

The Choptank Formation is more than 175-ft thick in Sussex County (Bethany Beach, Qj32-27) and thins gradually northward to about 150 ft in southern Kent County (Plates 1 and 2). In most of Kent County, the Choptank Formation is truncated beneath Quaternary sediments, which causes the southward-dipping formation to thin northward and disappear in the Dover area (Plate 1).

Shells have been dated using strontium isotopes (DGS unpublished data) for two core sites in the Choptank Formation in Sussex County, at Bethany Beach (Qj32-27) (Miller at al., 2003) and Marshy Hope (Nb53-08) (Fig. A4). These analyses indicate that the Choptank Formation is middle Miocene, between approximately 16 and 12 Ma. Comparison samples from the Choptank Formation in Maryland (DGS unpublished data) have yielded strontium ages of 13.9 to 12.2 Ma from the type locality at Boston Cliffs on the Eastern Shore of Maryland and 12.4 to 11.3 Ma from exposures along the western shore of the bay at Calvert Cliffs. These older strontium ages from Sussex County cores highlight the diachroneity of the Calvert-Choptank formation boundary in southern Delaware.

St. Marys Formation

The St. Marys Formation is predominantly a fine-grained interval that is found in the subsurface of Sussex County and southernmost Kent County. The St. Marys Formation was described in Maryland by Shattuck (1902) and first recognized in Delaware by Rasmussen et al. (1960) as an important Miocene low-permeability confining unit, or aquitard, in Sussex County.

St. Marys sediments are composed of gray to brown, laminated to burrowed, clayey silt and silty very fine to fine quartz sand. The formation can include beds of fine to medium quartz sand and shelly quartz sand (Andres, 1986; Ramsey, 1993, 2001; Ramsey and Groot, 1997), particularly in its northern and western up-dip limits. Basinward in southeastern Sussex County, quartz sands are less common and glauconite can be quite abundant. At Bethany Beach (Qj32-27), the formation is typically grayish, laminated, slightly micaceous, slightly glauconitic silty clay and clayey silt containing scattered shells, notably high-spired turritellid gastropods; in some horizons glauconite is quite abundant, over 50 percent (Miller et al., 2003).

The St. Marys Formation represents a shift to finer-grained deposits from the underlying Choptank Formation. The contact may be either a distinct shift from sands to muds or a gradual fining-upward transition. Where it is overlain by the Cat Hill Formation, the top of the St. Marys Formation is generally marked by a shift to sandy muds of the lower Cat Hill that coarsen upward into cleaner sands of the upper Cat Hill (Andres, 1986, 2004).

The St. Marys Formation is interpreted as a shallow- to marginal-marine deposit (Miller et al., 2003; Browning et al., 2006; McLaughlin et al., 2008). In Sussex County, where lithologies are predominantly dark silt and clay (such as at Bethany Beach Qj32-27), the St. Marys Formation was deposited in low-energy, shelfal environments in the deep part of the inner neritic zone or the middle neritic zone (25 to 75 m). Sandier lithologies in the northern and western parts of Sussex County, and in the limited Kent County occurrences of this formation, likely encompass estuarine, shoreface, and offshore deposits, as well as a possible paleosol interval.

The formation is as thick as 60 ft in the Milford area (Ramsey and Groot 1997); in southeastern Sussex County, the formation thickens to approximately 140 ft (Ri15-01) or more. Strontium isotope data, dinoflagellates, and planktonic foraminifera indicate that the St. Marys Formation ranges in Delaware from latest middle Miocene to earliest late Miocene, approximately 12 to 10.5 Ma (Miller et al., 2003; Browning et al., 2006; McLaughlin et al., 2008).

Cat Hill Formation

The Cat Hill Formation occurs exclusively as a subsurface unit in most of Sussex County. The Cat Hill Formation was established by Andres (2004) to formally name the lithologic unit that had previously been informally referred to as the "Manokin formation." The Manokin name was first used by Rasmussen and Slaughter (1955) to identify an aquifer in the Eastern Shore of Maryland. Rasmussen et al. (1960) extended the Manokin aquifer into Sussex County, Delaware. Sundstrom and Pickett (1969, 1970) identified, described, and mapped this unit in more detail in Sussex County.

The Cat Hill deposits are characterized by gray sand and some beds of gravel and locally clayey/silty, lignitic, and shelly beds (Andres, 2004). In most parts of Sussex County, it coarsens upward from the fine-grained deposits of the underlying St. Marys Formation; this pattern is evident in the type area (Andres, 1986; Miller et al., 2003; Andres, 2004; Andres and Klingbeil, 2006; McLaughlin et al., 2008). However, in its more landward western and northern occurrences, the base of the formation may be sharper and more abrupt.

The Cat Hill Formation can be subdivided into two parts in the Bethany Beach area in southeastern Sussex County. The lower interval has slightly glauconitic sandy silt coarsening upward to fine-grained sand; the upper interval is coarser-grained, composed of generally well-sorted, fine to medium sand that contains fine, disseminated plant debris, mica, and scattered phosphatic pebbles (Miller et al., 2003; McLaughlin et al., 2008). This same range of lithologies is present elsewhere in Sussex County. Ramsey (2003) described the Cat Hill Formation as having two subunits in eastern Sussex County: a finer-grained lower unit (A) consisting of gray, very fine silty sand to silty clay containing rare to common pieces of lignite; and a coarser grained upper unit (B) consisting of well-sorted, clean, white to reddish-brown, fine to medium sand. Andres et al. (1996) described a similar subdivision in western Sussex County: a finer lower unit of gray, blue-gray, and brown-gray silty to clayey sand; and a coarser upper unit of mostly gray to orangeish, fine- to coarse-grained sand that commonly includes beds of gravelly sand. Lithofacies and foraminifera at Bethany Beach (Miller at al., 2003; McLaughlin et al., 2008) indicate that the Cat Hill Formation shallows upward from offshore shelf (as much as 50-m deep), to lower shoreface, to nearshore, upper shoreface and estuarine sediments.

The Cat Hill Formation is directly overlain by the Bethany Formation in southern and eastern Sussex County. In northern and western parts of the county, the Bethany Formation is absent, and in these areas the Beaverdam Formation most commonly overlies the Cat Hill unconformably. Where the Cat Hill Formation occurs at shallow depths and the base of Quaternary deposits is a deep erosional surface, the Cat Hill may be overlain by one of the Quaternary formations. The formation boundaries may be difficult to identify precisely. Because the lower part of the Cat Hill coarsens upward gradually from the underlying St. Marys Formation, the location of the boundary between those units may be somewhat subjective. The top of the Cat Hill Formation can be difficult to distinguish where the sandy upper part of the Cat Hill are is overlain by sandy lithologies of the more heterogeneous Bethany Formation; typically the boundary is placed at a subtle shift in geophysical logs that reflects slightly cleaner sands at the top of the Cat Hill Formation.

The Cat Hill Formation is as much as 130-ft thick in Sussex County. It is thickest in the coastal southeastern parts of the county, where it commonly reaches 100-ft thickness. It thins to the north and west; in the most northern and western parts of the county, the Cat Hill is absent. The thickness trend is likely due to greater subsidence down dip, resulting in more vertical space available for accumulating thicker deposits, and progressive truncation in the opposite, up-dip direction, resulting in subcrops of the Cat Hill Formation under the erosive base of younger Quaternary deposits and the Beaverdam Formation. This reflects greater subsidence in down-dip directions and more truncation (and larger hiatuses) in up-dip directions where there was less subsidence.

The age of the Cat Hill Formation is considered late Miocene but has not been more precisely established. Strontium isotopic age data were obtained from the lower part of the unit in the Bethany Beach borehole where suitable shell material occurs (Miller at al., 2003). Samples yielded ages that range from 11.7 to 9.6 Ma, although they cluster from 10.5 to 9.6 Ma. Broad biostratigraphic control provided by palynology is consistent with this late Miocene age (Miller at al., 2003; McLaughlin et al., 2008).

Bethany Formation

The Bethany Formation is a heterogeneous unit of interbedded muds and permeable sands that occurs in the subsurface of coastal and southern parts of Sussex County (Andres, 1986, 2004; Groot et al., 1990; Ramsey, 2003). The Bethany Formation was informally named by Andres (1986) for sediments containing the aquifer sands referred to as the Ocean City and Pocomoke aquifers, as well as the confining muds above, below, and in between those sands. They were formally described as a formation in Andres (2004). Lithologically, the Bethany Formation is generally characterized by discontinuous bodies of quartzose sand that are separated by clayey and silty beds. The sands are typically fine- to medium-grained quartz and commonly include plant debris and mica as well as local layers of granules and pebbles (Miller et al., 2003; McLaughlin et al., 2008). Some of the sands are homogeneous or bioturbated in core and some are laminated with conspicuous heavy mineral laminae. Many of the sands show fining upward patterns. The muddier units include silty, organic-rich clays, sandy silty clay, sandy clayey silt, and silty sand containing plant fragments and silt laminae; rarely, light-colored clays occur that suggest exposure and paleosol formation (McLaughlin et al., 2008). Significant lateral facies changes occur within the formation. Sand intervals may be tens of feet thick, providing good aquifer material, or may be only centimeters thick. Similarly, predominantly mud intervals may be tens of feet thick, forming potentially confining beds between the sands, or may be much thinner within overall sandy intervals.

The Bethany Formation is generally underlain by the Cat Hill Formation and overlain by the Beaverdam Formation. It is differentiated from those units by its interbedded sand and mud character. Where the Bethany Formation occurs closer to the surface and the base of the Quaternary section was eroded deeply, the top of the Bethany Formation may be overlain by one of the Quaternary units. It is worth noting that precisely identifying the lower and upper boundaries of the Bethany Formation can be difficult; where sand beds occur at the top or the bottom of the formation, the resulting sand-on-sand contact makes the formation boundary difficult to determine. One criterion that can be used is the generally lower gamma log signature of the Bethany Formation sands compared to slightly higher values in Beaverdam Formation sands (Andres and Klingbeil, 2006), possibly due to silty matrix and/or potassium feldspar in the Beaverdam.

The Bethany Formation represents a complex interfingering of shallow-marine and estuarine deposits (Miller at al., 2003; McLaughlin et al., 2008). At Bethany Beach, sedimentary facies appear to reflect an overall shallowing of environments from distal upper shoreface to upper shoreface to estuarine or tidal channel, a trend punctuated by several deepening events.

The Bethany Formation is generally about 200-ft thick in the southern part of coastal Sussex County and becomes thinner to the north and west. The formation is absent in Kent

County and much of the northern and western parts of Sussex County; near the limits of its occurrence, it is only recognized where 5 or 10 ft of muds occur on well logs. As noted for the Cat Hill Formation, its greater thickness to the southeast is likely due, in part, to greater accommodation down dip and progressively greater truncation up dip beneath the erosional base of the overlying Beaverdam Formation and Pleistocene units.

The age of the Bethany is poorly constrained and age estimates rely heavily on its relative stratigraphic position. We assume in this study that it is likely late Miocene or Pliocene. No shell material has been recovered for strontium isotope dating and no age-diagnostic calcareous microfossils have been found. Only palynological analysis provides insights into the age of this unit; the presence of rare grains of exotic taxa that are no longer present in the area, such as *Pterocarya, Engelhardia*-type pollen, and *Dacrydium,* suggests a pre-Pleistocene age (Groot et al., 1990).

Beaverdam Formation

The Beaverdam Formation is widespread at shallow subsurface depths in western Kent County and most areas of Sussex County. The name Beaverdam was established in Maryland by Rasmussen and Slaughter (1955) and later applied to strata in Sussex County by Rasmussen at al. (1960) and Jordan (1962). Its occurrence in Kent County is notable because those strata were assumed to belong to the Columbia Formation before recent geological mapping (Ramsey, 2007).

The Beaverdam Formation is generally distinguished by sand that contains a whitish silt matrix. Lithologies include white to buff to greenish-gray quartz sand and some potassium feldspar, gravelly sand, and lesser amounts of light-gray to greenish-gray silty clay (Groot et al., 1990; Andres and Ramsey, 1995; Andres et al., 1996). The gravel is predominantly composed of quartz and quartzite, less commonly sandstone, chert, and other lithic clasts. Groot et al. (1990) and Andres et al. (1996) recognized a fining-upward pattern in the Beaverdam Formation in Sussex County, characterized by more abundant coarse sand and gravel in the lower part and more abundant silt matrix and intercalated mud beds toward the top. Andres and Klingbeil (2006) described three distinct facies in the Beaverdam deposits of eastern Sussex County:

- clean, grain-supported, medium to coarse sand, commonly containing gravel, that can serve as an aquifer, occurring most commonly in the lower part of the formation;
- silty, grain-supported, fine to coarse sand and some silt beds;
- sandy silt and silty sand in equal occurrences of matrix and grain-supported beds, most common in the upper part of the formation.

The base of the Beaverdam Formation is an uneven erosional surface with as much as 40 ft of relief (Ramsey, 2010) that has a general, gentle dip to the southeast. This configuration places any of several geologic units in contact with the base of the Beaverdam Formation. It is underlain by the Bethany Formation in eastern and southern Sussex County. In western and northern Sussex County, where the Bethany Formation has been removed at the basal Beaverdam surface, it is underlain by the Cat Hill Formation. In northernmost Sussex County and Kent County, it is underlain by older Miocene formations, which are progressively older units from the southeast to northwest: the St. Marys Formation in northwest Sussex, the Choptank Formation in southern Kent, and the Calvert Formation in west-central and northwest Kent (this study; McLaughlin and Veléz, 2006; Ramsey, 2007).

The Beaverdam Formation occurs at or near the land surface in many areas of central Sussex County and western Kent County (McLaughlin and Veléz, 2006; Ramsey, 2007, 2010). In other areas, the top of the Beaverdam Formation occurs deeper in the subsurface where it is an erosional unconformity overlain by Pleistocene deposits. The Columbia Formation, the oldest of the Pleistocene units, overlies the Beaverdam Formation in a narrow belt extending from northwest to south-central Kent County (Ramsey, 2007). Younger Pleistocene units commonly overlie the Beaverdam near the coast and coastal tributaries: the Lynch Heights Formation along the Delaware Bay coast; the Omar, Ironshire, or Sinepuxent Formations in the southeastern Sussex County; or the Turtle Branch or Kent Island Formations in western Sussex County. Any of these Pleistocene formations may put sands directly on top of the Beaverdam Formation that are of similar grain size; the whitish silt matrix common to Beaverdam sands can distinguish them from the Pleistocene units.

When the full thickness of the Beaverdam Formation is present, it may be more than 100-ft thick. However, because of the large amount of relief on the surface at the base of the Beaverdam Formation and even greater relief in some places at the top, the thickness of this unit is quite variable. For example, in the Bethany Beach area, the Beaverdam Formation is as little as 25-ft thick in some wells and as much as 130-ft thick in others (McLaughlin et al., 2008); the same variable thickness has been noted in the Selbyville-Fenwick area by Ramsey (2010). In Kent County and western Sussex County, the thickness may range from less than 20 ft to more than 50-ft thick (Ramsey, 2007, 2010).

The Beaverdam Formation is generally interpreted as a fluvial to estuarine deposit (Owens and Denny, 1979; Ramsey, 1993, 2007, 2010; Andres and Ramsey, 1995; Andres et al., 1996; Groot and Jordan, 1999). At the Bethany Beach core site (Qj32-27), the Beaverdam strata change upward from lower granule- to pebble-bearing, crossbedded sands suggesting fluvial environments to upper muddier strata suggesting estuarine influence (Miller et al., 2003; McLaughlin et al., 2008). In outcrop, clay drapes and burrows have been observed, supporting the estuarine interpretation.

The age of the Beaverdam Formation is poorly constrained. No shell material has been recovered for strontium isotope dating and no age-diagnostic calcareous microfossils are known. Groot et al. (1990) and Groot and Jordan (1999) reported a Pliocene age from sparse pollen data. Age estimates are otherwise based on relative stratigraphic position and regional relationships, which constrain it to be no older than late Miocene and no younger than Pleistocene. Ramsey (2010) interpreted the Beaverdam Formation as likely late Pliocene based on his analysis of regional stratigraphic relationships.

In this study, we consider the Beaverdam Formation as approximately Pliocene age.

Quaternary Units

The Quaternary sediments of Kent and Sussex Counties include numerous sand intervals that function as unconfined and shallow confined aquifers. The internal stratigraphy of this interval is complex (Fig. 5); the distribution of Quaternary formations was shaped by multiple episodes of deposition, cut, and fill related to large-amplitude sea-level changes, as summarized by Ramsey (2010). The sands of the Columbia Formation are the oldest Quaternary deposits in these study area. Three groups of younger Pleistocene estuarine deposits occur on the margins of estuarine systems in the study area: The Delaware Bay Group along the Delaware Bay coast; the Assawoman Bay Group in the areas near Delaware's Inland Bays; and the Nanticoke River Group along tributaries of the Chesapeake Bay in the western part of the study area. The stratigraphy of this interval greatly influences the character of the unconfined aquifer and recharge to confined aquifers so each formation is described below.

Columbia Formation. The Columbia Formation is a complex of Pleistocene fluvial sands and gravels found in the Delaware Coastal Plain. The name Columbia was established by McGee (1886) for deposits of brick clay, sand, and gravel in the District of Columbia. Jordan (1962, 1964) extended the name to similar Pleistocene deposits in Delaware, describing the Columbia as a broad "sheet of sand" covering nearly all of the Coastal Plain in the state.

However, recent surficial geology mapping indicates that much of the area previously considered Columbia should be mapped as different formations. New stratigraphic units were established for the younger Pleistocene deposits that occur along the Delaware Bay, inland bays, and tributaries of the Chesapeake Bay (Ramsey and Groot, 1997; Ramsey, 2007, 2010). Some sands and gravels previously considered Columbia in more inland areas were recognized as Beaverdam Formation. Because of these new findings, the Columbia Formation is now considered present in our study area only in a narrow northwest-southeast belt across Kent County and northeastern Sussex County (Ramsey, 2007).

Ramsey (2010) described the Columbia Formation as yellowish- to reddish-brown, fine to coarse, feldspathic, quartz sands that are typically crossbedded; the Columbia interval contains varying amounts of pebbles and has scattered beds of tan to reddish-gray clayey silt (also Jordan, 1962, 1974; Ramsey and Groot, 1997; Ramsey, 2007; Spoljaric and Woodruff, 1970). The base of the formation is commonly marked by a gravel bed of as much as 3-ft thickness that includes clasts of cobble to small boulder size. Ramsey (2010) noted that the upper 5 to 25 ft of the Columbia Formation in southeastern Kent County and northeastern Sussex County commonly consists of grayish- to reddish-brown silt to very fine sand overlying medium to coarse sand.

The Columbia Formation rests on an irregular erosional unconformity that cuts into Miocene marine sediments in Kent and Sussex Counties. Ramsey (2007) also recognized that it eroded and unconformably overlies the Pliocene (?) age Beaverdam Formation in a narrow zone that extends diagonally northwest to southeast across Kent County into northeastern Sussex County. Along the eastern edge of its occurrences, the Columbia Formation is eroded and overlain by the middle-to-late-Pleistocene Lynch Heights Formation. The irregular basal surface and erosion by overlying Pleistocene and Holocene sediments and surfaces gives the Columbia Formation a variable thickness that is generally between 10 and 50 ft (Ramsey, 2007, 2010).

The Columbia Formation is interpreted as fluvial deposits deposited by glacial melt water during the Pleistocene under cold to cool temperate climatic conditions (Jordan, 1962; Groot and Jordan, 1999). The unit is older than middle Pleistocene and possibly as old as early Pleistocene (Ramsey, 2010).

Delaware Bay Group. The Delaware Bay Group is composed of two units that occur near the Delaware Bay coastlines of Kent and Sussex counties, the Lynch Heights Formation and the Scotts Corners Formation (Ramsey and Groot, 1997; Ramsey, 2003, 2010). These formations are interpreted as estuarine deposits that accumulated along the shores of the ancestral Delaware Bay during middle to late Pleistocene sea-level rises and highstands (Ramsey and Groot, 1997; Ramsey, 2010). Both formations occur on bayward-dipping terraces that are east of scarps formed by shoreline erosion following exposure during Pleistocene sea-level falls and lowstands.

The Lynch Heights Formation is the older of the two units and is west of the trend of the younger Scotts Corners Formation (Fig. 5). The Lynch Heights Formation unconformably overlies the Columbia Formation in southeastern Kent County and northeastern Sussex County and the Beaverdam Formation in southeastern Sussex County (Ramsey, 2010). Deposition took place in two phases, producing an older subunit below a terrace at elevations between 40 and 45 ft above sea level (asl) and a younger subunit below a terrace at 25- to 30-ft asl (Fig. 5). The formation is as much as 50-ft thick and thins landward (Ramsey, 2010). Ramsey (2010) interpreted the Lynch Heights Formation to be middle Pleistocene, estimating the older Lynch Heights subunit to be approximately 400 ka (thousand years before present) and the younger subunit approximately 330 ka.

The sediments of the Lynch Heights Formation are fairly heterogeneous, consisting of sand, silty sand, silt, and silty clay with some organic-rich beds. The sands include medium- to coarse-grained beds, some pebbly or containing cobbles. They also include fine- to very fine-grained sands that are commonly micaceous. Shells are present in some locations. These deposits represent stream, swamp, marsh, estuarine barrier and beach, tidal flat, lagoon, and shallow offshore estuary environments (Ramsey and Groot, 1997; Ramsey, 2010).

The Scotts Corners Formation is similar to the Lynch Heights Formation but represents a younger phase of deposition (Fig. 5). It occurs just west of the western shore of the bay and east of most of the area of the Lynch Heights Formation. The Scotts Corners Formation unconformably overlies the Lynch Heights over much of its extent. Two depositional phases have been recognized (Fig. 5), producing an older subunit beneath a terrace that has a toe at approximately 18 ft asl and a tread that slopes to about 10 ft asl and a younger subunit beneath a terrace that has an elevation between approximately 7 ft asl and sea level (Ramsey, 2010). The Scotts Corners Formation is thinner than the Lynch Heights Formation, generally less than 20-ft thick and thinner westward. Ramsey (2010) summarized its age as late Pleistocene, with the older subunit approximately 120 ka and the younger subunit around 80 ka.

The sediments of the Scotts Corners Formation include comparable lithologies to those of the Lynch Heights Formation: fine to very coarse quartzose sands, discontinuous beds of organic-rich clayey silt, and clayey silt. The sandy beds may include pebble-gravel zones, feldspar, muscovite, and laminae of opaque heavy minerals. These represent stream, swamp, marsh, estuarine barrier and beach, tidal flat, and shallow offshore estuary environments (Ramsey and Groot, 1997; Ramsey, 2010).

Assawoman Bay Group. Ramsey (2010) established the Assawoman Bay Group toencompass Quaternary deposits that are found adjacent to and inland of the Atlantic coast of Delaware. Three formations are placed in this group: Omar, Ironshire, and Sinepuxent (Fig. 5). These formations are interpreted as estuarine and marine sediments deposited during middle to late Pleistocene rises and highstands of sea level, lithologically similar and age-equivalent to the Delaware Bay Group (Ramsey, 2010). These deposits underlie bayward-dipping terraces that occur east of scarps formed by erosion by transgressive shorelines following long periods of exposure.

The Omar Formation, named by Jordan (1962), is the oldest formation in the Assawoman Bay Group (Fig. 5). It occurs beneath a terrace that slopes from approximately 42 ft asl to 25 ft asl. The base of the formation is an unconformable contact with the Beaverdam Formation that has significant relief; the Omar ranges from 10- to 80-ft thick with its greatest thicknesses in paleovalleys (Owens and Denny, 1979; Ramsey 2010). Ramsey (2010) interpreted the Omar Formation as middle Pleistocene. It is approximately equivalent to the Lynch Heights Formation and includes two equivalent subunits, of approximately 400 ka and 325 ka.

The formation is composed of fine to very fine quartz sand with some laminae of medium to coarse sand, as well as dark silty clay and clayey silt that may contain scattered shell beds, most notably oysters, and beds rich in organic matter (Ramsey, 2010). Local gravel beds and rare cypress tree stumps and logs are known from the base of the formation. Ramsey (2010) interpreted the Omar deposits as principally representing lagoonal deposition and less commonly tidal stream and nearshore sand environments.

The two younger formations in the Assawoman Bay Group are equivalent to the Scotts Corners Formation of the Delaware Bay Group (Fig. 5). The Ironshire Formation is the older of these two. It was defined by Owens and Denny (1978, 1979) in southern Maryland. Ramsey (2010) described it as a terrace deposit of as much as 20-ft thickness that occurs beneath a seaward-dipping terrace that has an elevation between 15 and 20 ft asl. The base of the Ironshire Formation is an unconformable contact with the Omar Formation or the Beaverdam Formation, depending on location. Ramsey (2010) interpreted it to be late Pleistocene, approximately 120 ka, based on its interpreted equivalency to the lower part of the Scotts Corner Formation.

In Delaware, the Ironshire Formation is fine- to medium-grained quartzose sand, silty clay having flaser and wavy bedding, silty clay containing scattered organic-rich laminae, sand with scattered pebbles, and scattered shelly zones (Ramsey, 2010). These are interpreted to represent beach, nearshore, and sandy lagoonal environments associated with a transgressive coastline.

The Sinepuxent Formation is the youngest unit in the Assawoman Bay Group and is equivalent to the upper part of the Scotts Corner Formation (Ramsey, 2010). Owens and Denny (1979) first described the Sinepuxent Formation in southern Maryland. Ramsey (2010) recognized it in southeast Delaware as deposits associated with a terrace that slopes from approximately 12 ft asl to sea level. It is as much as 40-ft thick. Ramsey (2010) considered the Sinepuxent to be late Pleistocene, dating it at approximately 80 ka based on amino-acid racemization. The unconformity at its base separates it from underlying deposits of the Omar, Ironshire, or Beaverdam Formations.

The Sinepuxent Formation consists of gray, laminated, silty very fine to fine, micaceous, quartz sand to sandy silt; the conspicuous mica content is distinctive (Ramsey, 2010). It includes a few shelly zones and has bluish-gray to dark-gray clayey silt to silty clay at the base. It is interpreted as deposited in quiet-water lagoon and nearshore environments (Owens and Denny, 1979; McLaughlin et al., 2008).

Nanticoke River Group. The Nanticoke River Group encompasses Quaternary deposits associated with the paleovalleys occurring in and near the Nanticoke River and its tributaries (Ramsey, 2010). The Nanticoke River Group includes two formations: Turtle Branch and Kent Island (Fig. 5). These sediments were deposited during middle to late Pleistocene rises and highstands of sea level and are similar and age-equivalent to the terrace-associated deposits of the Delaware Bay and Assawoman Bay Groups (Ramsey, 2010).

The Turtle Branch Formation was named by Ramsey (2010) to encompass the oldest and geomorphologically highest Quaternary terrace deposit in southwest Sussex County (Fig. 5). This formation occurs beneath a terrace that slopes from approximately 42 ft to 25 ft asl and thins upstream from as much as 45-ft thick south of Seaford to less than 15-ft thick in central Sussex County. It is considered stratigraphically equivalent to the Omar Formation and to both subunits in the Lynch Heights Formation (Ramsey, 2010). This makes its age middle Pleistocene, including subunits of approximately 400 ka and possibly 325 ka based on stratigraphic and geomorphic positions (Ramsey, 2010).

The variable lithologies of the Turtle Branch Formation reflect significant lateral facies changes within a complex of estuarine and nearby environments associated with interglacial shoreline transgression. Lithologies include medium to very coarse to gravelly sands, especially at the base of the formation, organic-rich silty to clayey sand, and silty clay that contains sand-filled burrows and oyster shells in places. Ramsey (2010) suggested that the basal sands were deposited in streams that transitioned into sandy tidal flats and beaches and that the organic silts and clays were deposited in tidal marshes and swamps.

The Kent Island Formation is the youngest formation in the Nanticoke River Group (Fig. 5). This formation was originally described from the Eastern Shore of Maryland by Owens and

Denny (1979) and was mapped in Delaware by Ramsey (2010). It lies beneath a discontinuous, low-lying terrace along the Nanticoke River at elevations between 17 and 6 ft asl. The Kent Island Formation can be divided into two parts based on geomorphology: an older subunit under a terrace at 17 to 12 ft asl elevation and a younger subunit in areas adjacent to the Nanticoke River at elevations of less than 10 ft asl (Ramsey, 2010). These two subunits can be correlated to the two subunits in the Scott Corners Formation of the Delaware Bay Group and to the Ironshire and Sinepuxent Formations of the Assawoman Bay Group (Ramsey, 2010). The base of the formation is an unconformity, most commonly in contact with the lithologically similar Turtle Branch Formation and, less commonly, with the silty sands of the Beaverdam Formation. The thickness of the formation is as much as 25 ft. The age is interpreted as late Pleistocene, with the two parts of the formation estimated as approximately 120 ka and 80 ka (Ramsey, 2010).

The Kent Island Formation is lithologically heterogeneous and includes intervals of coarse-grained sand and gravel, silt and clay with shells in places, and fine- to medium-grained sand, commonly in that order. These sediments reflect the infill of an incised valley as well as significant lateral facies changes. Ramsey (2010) described a progression from fluvial and swamp deposits at the base, to estuarine muds, to intertidal and beach sands.

Aquifers

A sound understanding of aquifer geology is important to management of Delaware's groundwater resources. The depth and the thickness of aquifers vary in the Coastal Plain of Delaware; characteristics like lithofacies and aquifer quality can change in a short distance. The names applied to these aquifers are not always consistent among regulators and water-well professionals. A major objective of this project was a comprehensive re-examination of the stratigraphy and distribution of the aquifers of Kent and Sussex Counties. This work was focused on the geological characterization of the aquifers and did not treat their hydraulic properties in detail. In this section, we present an updated description of each of the aquifers and illustrate their stratigraphic relationships and areal distribution on accompanying cross sections and maps.

We have assembled a large database of stratigraphic picks of the tops and bottoms of aquifer sands in the study area using updated subsurface geologic data and data from new test boreholes drilled for this study (Fig. 6). This database was used to create the cross sections and maps of aquifer elevation and thickness for 12 confined aquifers and one unconfined aquifer. All elevations in this report are relative to sea level, defined as 0-foot elevation NAVD; depths can be determined by subtracting the elevation from the land surface elevation.

The stratigraphic relationships of the confined aquifers are illustrated in a series of 14 well-log cross sections. Eight cross sections are included for Kent County, similar to those in McLaughlin and Veléz (2006) but incorporating new data. Six are approximately strike-oriented and two are approximately dip-oriented (Plate 1, Fig. 7). Six cross sections are presented for Sussex County, two approximately strike-oriented and four approximately dip-oriented (Plate 2, Fig. 8).

Confined aquifer maps created for this study include maps of the elevation of the top of the aquifer, elevation of the base of the aquifer, and aquifer thickness. The Kent County portions of the maps are similar to the Kent County confined aquifer maps in McLaughlin and Veléz (2006) but have been updated with additional data. The confined aquifer maps include stratigraphically equivalent non-aquifer intervals where relevant. The unconfined aquifer maps for the study area represent a seamless integration of new mapping of Kent County for this project and previous mapping of Sussex County by Andres and Klingbeil (2006).The maps are included as column-width figures in the body of the report and as page-size maps in Appendix B that contain individual layers for each data type that can be selected or deselected for display. The precision of these maps can be regarded as best near the data points shown and will be less confident where interpolated in areas of sparse data. Factors affecting precision are noted in Appendix B.

The description of each aquifer interval provides general background on the aquifer, description of the sedimentary facies, and environmental interpretations. The main water producing qualities of an aquifer, notably porosity and permeability, are strongly controlled by sedimentary facies. Because sedimentary facies reflect the environment of deposition, an understanding of the environmental controls on deposition of a stratigraphic unit can provide valuable insights into the nature and distribution of aquifer facies.

Geophysical logs provide the basis for general interpretation of aquifer facies versus non-aquifer facies within each aquifer interval. Intervals with an appropriate combination of low gamma values, negative spontaneous potential trends, and high resistivity values were identified as clean, porous, fresh-water bearing sands and thus designated as aquifer-quality facies. In areas where geophysical logs do not indicate the presence of porous and permeable water-bearing facies in the aquifer interval, the strata are considered stratigraphically equivalent non-aquifer facies. Because many different types, vintages, and qualities of logs were used in this analysis, the aquifer-quality interpretations in this study should be considered generalized and subjective.

Mount Laurel Aquifer

The Mount Laurel aquifer is stratigraphically the lowest aquifer unit used in the study area. It is an important groundwater source in southern New Castle County and is tapped by a small number of wells in northernmost Kent County. Older aquifer studies described and mapped it as the Monmouth Formation in New Castle County (Rima et al., 1964).

Most of the Mount Laurel aquifer is in the sands of the Mount Laurel Formation, but in some places may extend upward into high resistivity, high gamma intervals likely assignable to the Navesink Formation. The Mount Laurel interval is aquifer-quality sand in northern Kent County but changes facies from central Kent County southward to finer-grained, calcareous, non-aquifer lithologies deposited in deeper shelfal paleoenvironments (Benson and Spoljaric, 1996; McLaughlin and Veléz, 2006).

The top of the Mount Laurel aquifer is as shallow as 250 ft bsl in northwestern Kent County and deepens to approximately 800 ft bsl in central Kent County north and west of Dover (Figs. 9, 10, and Plate 1). Stratigraphically equivalent non-aquifer facies in southern Kent County and Sussex County occur at depths of 1,500 ft or more below sea level. The greatest thickness of the Mount Laurel aquifer is in northern Kent County, where it is as much as 100-ft thick. It appears to become thinner in central Kent County as it passes southward into finer-grained facies (Fig. 11), though borehole penetrations of the entire thickness of the Mount Laurel interval are uncommon because of its greater depths

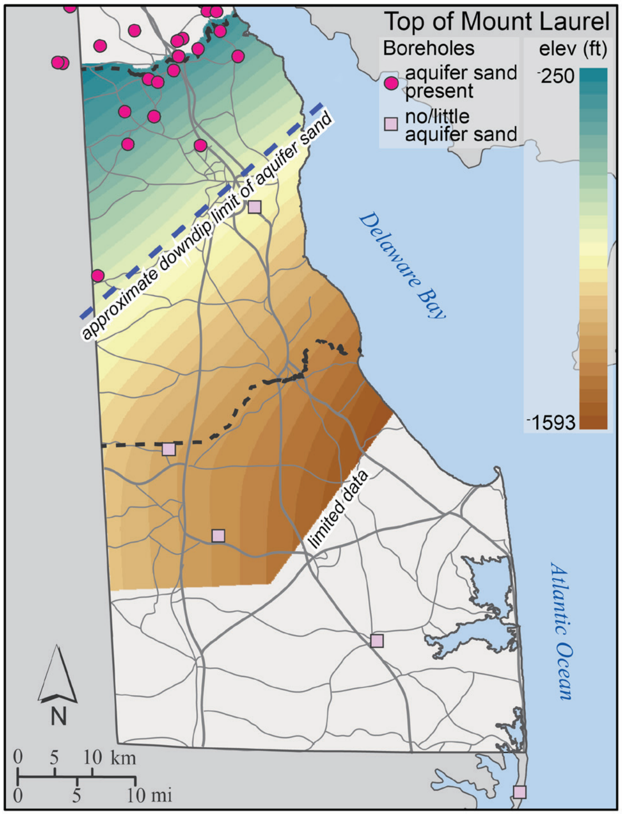

Figure 9. Map showing elevation of the top of the Mount Laurel aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Mount Laurel sand is present from locations where sand-poor Mount Laurel Formation lithologies are present. Datum is NAVD88.

Two test holes drilled for the Kent County aquifer project in northern Kent County penetrated the Mount Laurel aquifer: Ib14-32, northwest of Kenton, and Hd25-05, just north of Woodland Beach Road (Fig. 6). Samples from these holes indicate that the Mount Laurel aquifer is relatively clean, permeable, medium-grained sand. The sand is predominantly rusty quartz grains that are mostly medium-grained but up to granule size and includes 10 to 20 percent glauconite and common shell material. Geophysical logs in northern and west-central Kent County show clean, resistive responses (Plate 1). Finer grained beds in the overlying Navesink and Hornerstown Formations and the underlying Marshalltown Formation confine this aquifer.

Rancocas Aquifer

The Rancocas aquifer is an important source of groundwater in New Castle County and, to a lesser degree, in Kent County (Marine and Rasmussen, 1955; Rima et al., 1964; Rasmussen et al., 1966; Sundstrom and Pickett, 1968; Cushing et al., 1973, Dugan et al., 2008). Although it has been referred to as the Vincentown or Aquia aquifer at times, the Rancocas aquifer name has been in common use in Delaware since the work of Rima et al. (1964). This aquifer in Delaware consists of shelly sands in the updip areas of the Vincentown Formation (Fig. 3).

North and west of Smyrna, the Rancocas aquifer is thick, relatively permeable, and characterized by glauconitic carbonate sands and glauconitic, shelly quartz sands (Plate 1, sections A-A', B-B', and C-C'; Fig. 7). However, in wells southeast of Smyrna, a regional facies change is evident and the thickness of the Rancocas aquifer sand is significantly diminished. It passes into entirely fine-grained, non-aquifer muddy sand lithologies further southward in central Kent County and northwestern Sussex County (Plate 1, sections A-A', B-B', and E-E'; Fig. 7). Benson and Spoljaric (1996) proposed that the stratigraphic changes south of Smyrna were evidence of a growth-fault zone. However, newer data in this area indicate a generally continuous lithologic change and gradual increase in depth (Fig. 12) across an approximately five-mile-wide transition zone.

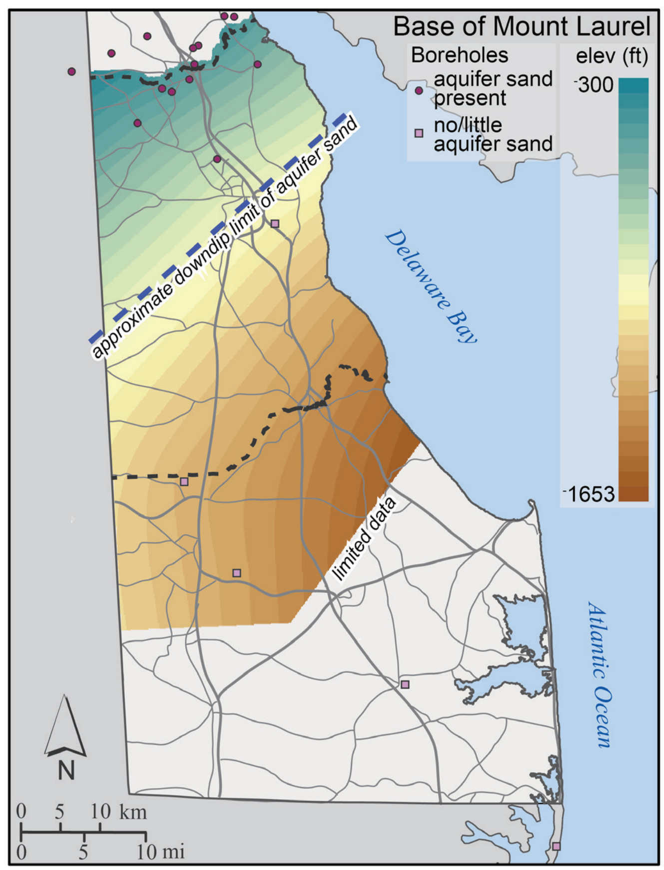

Figure 10. Map showing elevation of the base of the Mount Laurel aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Mount Laurel sand is present from locations where sand-poor Mount Laurel Formation lithologies are present. Datum is NAVD88.

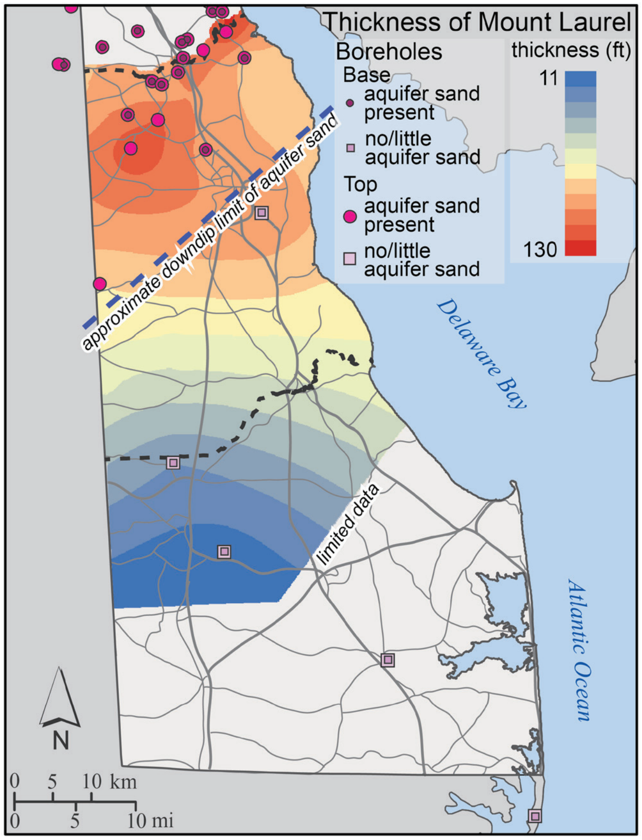

Figure 11. Map showing thickness of the Mount Laurel aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Mount Laurel sand is present from locations where sand-poor Mount Laurel Formation lithologies are present.

The Rancocas aquifer was penetrated in test holes Ib14-32 in northwestern Kent County and Hd25-05 in northeastern Kent County (Fig. 6; Plate 1, sections A-A', B-B', and C-C'). Drill cuttings from the Rancocas interval in those wells are composed of glauconitic, shell-rich sand with common fragments of shell-rich sandstone from cemented beds; the samples from at Ib14-32 had more abundant sand and sandstone than those from Hd25-05. The geophysical logs from these holes and other wells in northern and west-central Kent County suggest aquifer-quality near-shore sand north and west of Smyrna, transitioning to thinner, aquifer-quality shelf sand southeast of Smyrna, and fining further to muddy non-aquifer deeper shelf deposits in central Kent County and areas south.

The maps in this report represent the Rancocas aquifer and its down-dip non-aquifer equivalents, extending from up-dip areas that are entirely sand to down-dip areas where little or no aquifer-quality sand is present. The top of the Rancocas aquifer is shallower than 50 ft bsl in northwesternmost Kent County and deepens southeastward to around 300 ft bsl at the furthest basinward occurrence of the aquifer facies (Figs. 12 and 13).

Stratigraphically equivalent, non-aquifer horizons are projected to depths of more than 1,000 ft bsl in southern Kent County and more than 1,400 ft in northeast Sussex County. The thickness of the Rancocas aquifer is as much as 200 ft in northwestern Kent County (Fig. 14). Southeast of Smyrna, the equivalent stratigraphic interval thins to approximately 100 ft within a few miles and only the lower portion is sandy (e.g., 20 ft at Id31-26). Further south in southern Kent County and in Sussex County, no aquifer-quality sands are present; sparse data available suggest that the Rancocas-equivalent interval is generally between 90 to 110 ft thick (Fig. 14). The details of this southeastward transition from thick, aquifer sands to muddy non-aquifer beds merits future study.

The Rancocas aquifer is confined by overlying glauconitic muds of the Manasquan Formation in most of Kent County (Plate 1). However, because the basal Miocene unconformity truncates the Eocene section and cuts progressively deeper to the north (Plate 1, sections A-A' and B-B'), the Rancocas aquifer is overlain in some parts of southern New Castle County by muds of the lower Miocene Calvert Formation.

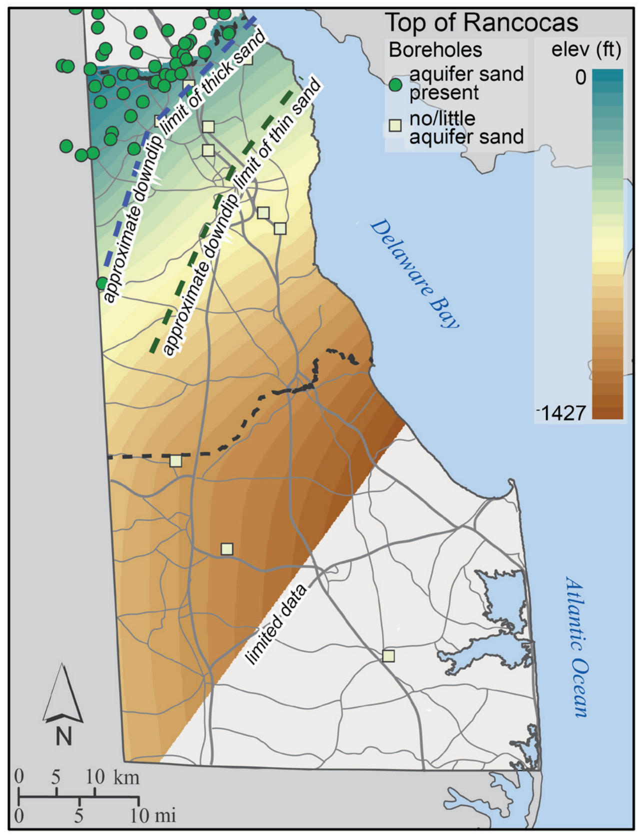

Figure 12. Map showing elevation of the top of the Rancocas aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Rancocas sand is present from locations where stratigraphically equivalent sand-poor lithologies are present. Datum is NAVD88.

Piney Point Aquifer

The Piney Point aquifer was first recognized in Delaware by Rasmussen et al. (1966). The aquifer occurs in clean sands of the upper part of the Piney Point Formation, and in places extends upward into a sand body at the base of the Calvert Formation that represents materials reworked from the Piney Point Formation.

The Piney Point aquifer is a significant source of groundwater in Kent County. It has been utilized for community water systems since the late 1930s and early 1940s and saw increasing utilization in the late 1950s and 1960s with the installation of a number of new wells near Dover Air Force Base, Woodside, Felton, and Dover (Sundstrom and Pickett, 1968). Groundwater withdrawals from the Piney Point aquifer have received special attention because the aquifer does not subcrop under sandy surficial units and is recharged only by vertical leakage through the overlying confining layer (Leahy, 1979). Although aquifer heads are currently stable, a regional decline in hydraulic heads has been a concern in the past. Water levels in Dover-area monitoring wells (Id55-01) declined approximately 70 ft from the late 1960s to late 1980s but have stabilized and rebounded slightly since then (DGS water-level database).

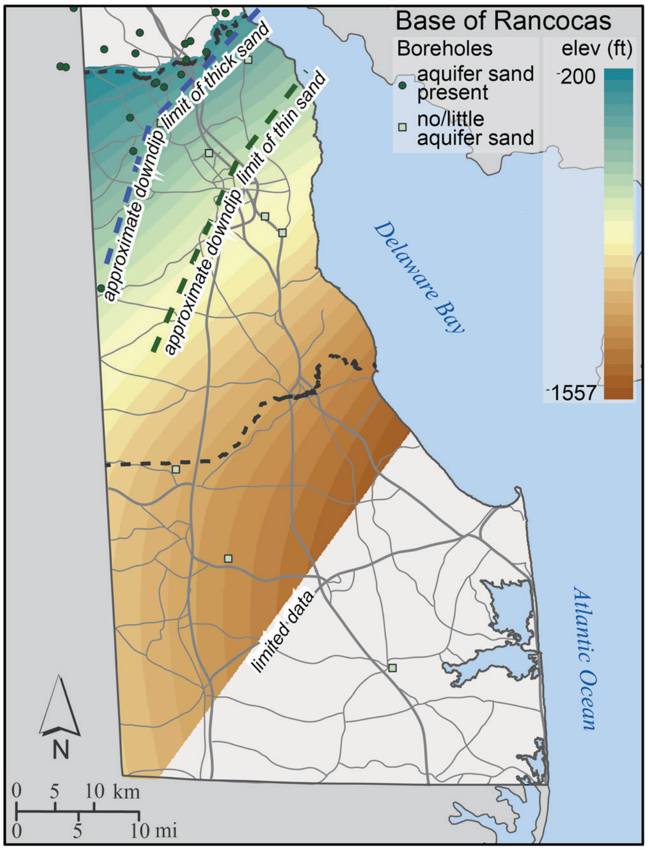

Figure 13. Map showing elevation of the base of the Rancocas aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Rancocas sand is present from locations where stratigraphically equivalent sand-poor lithologies are present. Datum is NAVD88.

The Piney Point aquifer occurs in shelly quartz sands that contain common (5-10 percent) glauconite, giving the sands a "salt and pepper" appearance (Marine and Rasmussen, 1955; McLaughlin and Veléz, 2006). The aquifer sands occur in the upper part of the Piney Point Formation, which exhibits an up-section trend of cleaner sands (Je32-04; Fig. 6; Plate 1, sections B-B', F-F'). The portion of this aquifer that overlies the Piney Point-Calvert unconformity is generally less than 20-ft thick and has been interpreted as a lag deposit of material from the Piney Point Formation that was reworked by marine transgression in the early Miocene (Benson and Spoljaric, 1996). The aquifer characteristics of the Piney Point change from north to south in Kent County. The best quality aquifer sands are in central and southern Kent County (Figs. 15 and 16) In two test holes in southeastern Kent County (Ld41-16 and Ke23-05), the sands are clean and commonly medium grained, in places coarse grained, and have clean sand signatures on geophysical logs (Plate 1, sections A-A' and B-B'). In northern Kent County, muddier lithologies are more common. Poor aquifer-quality sands in the Cheswold area transition northward to muddy, non-aquifer lithologies in the northwesternmost part of the county (Figs. 15 and 16). Cuttings from test holes in west-central Kent County (Kc13-06 and Jc12-16) are muddier, slightly shelly, glauconitic quartz sands with fragments of mud (Plate 1, sections A-A' and K-K'). These observations are corroborated by geophysical log trends on the cross sections. The northward decrease in aquifer quality is interpreted to be a consequence of differential erosion of the top of the Piney Point Formation under a basal Miocene unconformity (McLaughlin and Veléz, 2006). The strata under the unconformity dip slightly more steeply (approximately 0.25 degrees) to the south-southeast than the overlying Calvert beds (approximately 0.2 degrees). The dip difference is manifested in the upper, sandier part of the Piney Point Formation being progressively removed to the north-northwest (Plate 1, section A-A') under the unconformity.

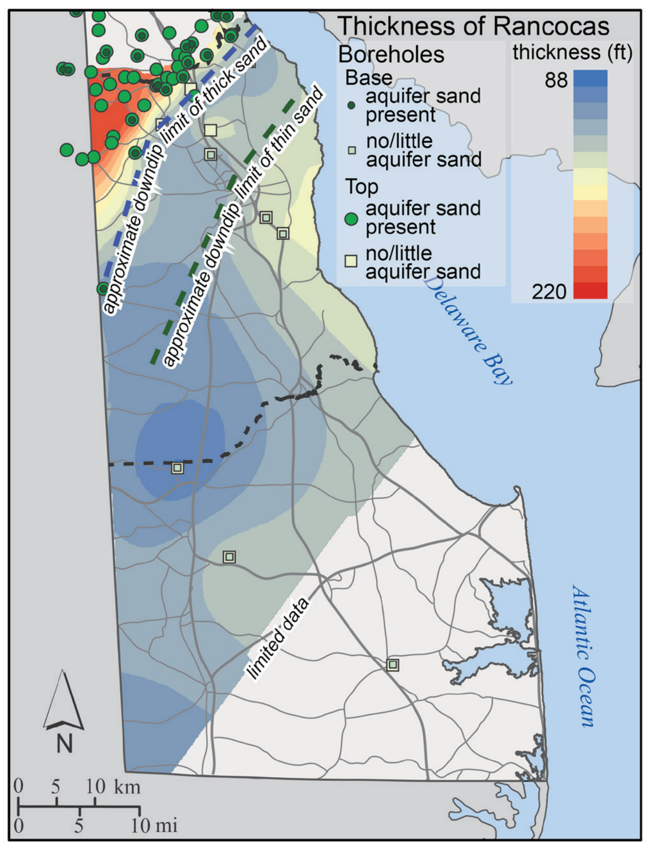

Figure 14. Map showing thickness of the Rancocas aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Symbology differentiates boreholes where Rancocas sand is present from locations where stratigraphically equivalent sand-poor lithologies are present.

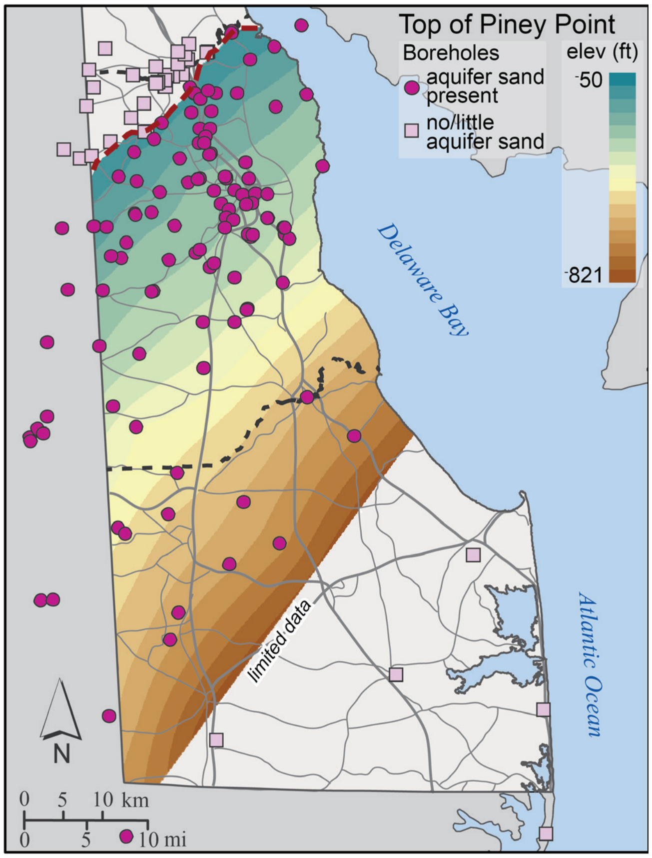

Figure 15. Map showing elevation of the top of the Piney Point aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Piney Point sand is present from locations where sand-poor Piney Point Formation lithologies are present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

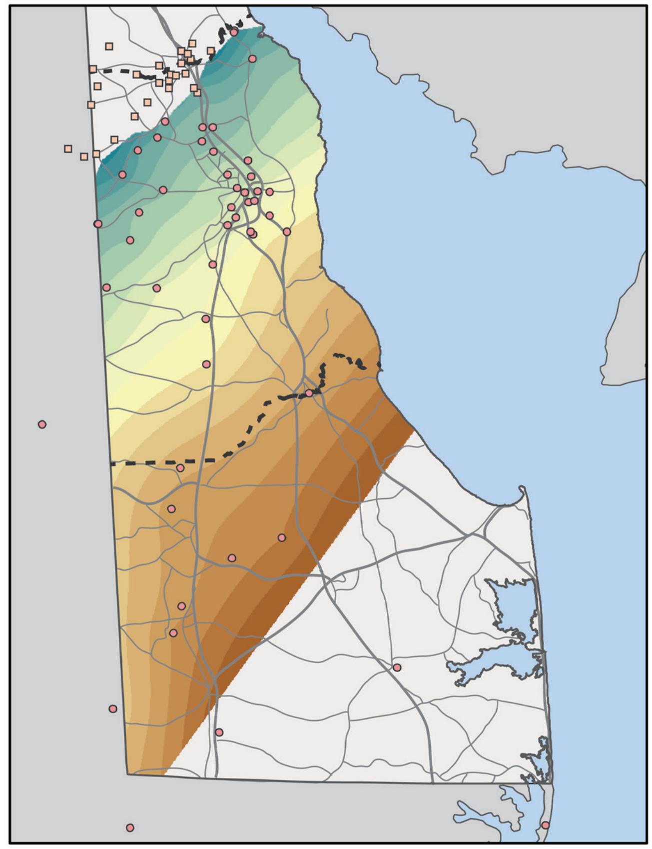

Figure 16. Map showing elevation of the base of the Piney Point aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Piney Point sand is present from locations where sand-poor Piney Point Formation lithologies are present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The top of the Piney Point aquifer ranges from as shallow as 90 ft bsl in northeastern Kent County to more than 600 ft bsl in southeastern Kent County and northwestern Sussex County to as much as 800 ft in east-central Sussex County (Fig. 15). It thickens southeastward from 55 ft in the northeastern part of the county to nearly 300 ft southeast of Dover (Fig. 17); the thickness further southeast is difficult to estimate because of the limited number of complete penetrations of the aquifer.

The Piney Point aquifer appears to have a complex stratigraphy in southernmost Kent County and Sussex County (Plate 2, Section I-I'). Sediments encountered in test holes and wells in that area are lithologically similar to the Piney Point Formation but may represent later depositional phases of the same type of sedimentary system. Previous biostratigraphic analyses have suggested this unit may be Oligocene at Milford (Andres et al., 1990; Ramsey and Groot, 1997) and preliminary analyses of foraminifera from more recent samples in north-central Sussex County (Nb24-04) and near Seaford (Pc14-17) also suggest Oligocene ages (McLaughlin and Veléz, 2006). This concept may explain why the Piney Point aquifer in Millville, New Jersey, is late Eocene (Sugarman et al., 2005). Future study should assess whether the middle Eocene, late Eocene, and Oligocene sands referred to the Piney Point aquifer are hydrologically connected.

In most of Kent County, the confining layer above the Piney Point aquifer consists of clays of the lower part of the lower Miocene Calvert Formation. Silty, non-aquifer sands of the lower part of the Piney Point Formation confine the unit from below. Because the stratigraphy and age of the Piney Point aquifer and associated strata are not as well understood in southeasternmost Kent and most of Sussex County, the stratigraphy of potentially confining layers is also poorly understood. It is possible that Oligocene glauconitic silts may occur as part of the confining layer between the Piney Point aquifer sands and the Calvert Formation; further study, including microfossil analyses, may resolve this question.

Aquifers of the Calvert and Choptank Formations

Seven aquifers are recognized in the Calvert and Choptank Formations in this study. Three concepts were used in this study to ensure consistency in the definition and correlation of these aquifers.

First is the concept of sequence stratigraphy. Each of the aquifer sands in this interval represents the culmination of a shallowing-upward sequence that is generally paralleled by an upward increase in grain size and/or sand content. The sequence boundary at the top of each sequence is an unconformity lying at or near the top of the aquifer sand, which is in some instances overlain by thin sand deposited by a transgression that followed the hiatus (and probably exposure) at the unconformity. According to this sequence model, deposition would have occurred primarily during marine transgressions and highstands in the study area. During lowstands, the study area would be subaerially exposed and little deposition recorded.

Secondly, the sedimentary section generally thickens in a basinward direction. Both the Calvert and Choptank Formations thicken overall to the southeast because of the greater degree of accommodation basinward. Lines of correlations within these formations generally diverge basinward, also reflecting that basinward thickening trend.

Third is the concept that erosion during sea-level lowstands may be more pronounced in a landward direction, resulting in "shaved" stratigraphic sequences (Kidwell, 1977) where significant parts of the top of sequences are eroded at the sequence boundary. As a result, the magnitude of hiatuses increases northwestward in these units and is most significant in northwestern Sussex County and neighboring areas of eastern Maryland. The combination of overall stratigraphic thinning in a landward direction and increased erosion at sequence boundaries is manifested in the difficulty of differentiating individual aquifers in this interval in the up dip areas of the Eastern Shore of Maryland (Andreasen et al., 2013).

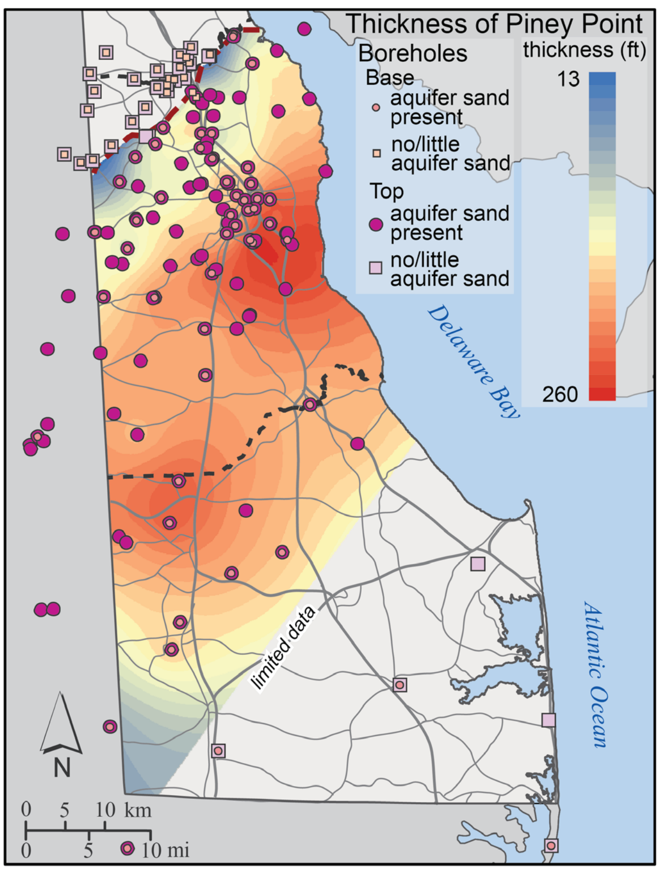

Figure 17. Map showing thickness of the Piney Point aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Piney Point sand is present from locations where sand-poor Piney Point Formation lithologies are present. Dark red dashed line represents the approximate up-dip limit of the aquifer.

Lower Calvert Aquifer

The Lower Calvert aquifer is newly recognized in this study and occurs over much of Sussex County (Figs. 18 and 19). It represents the upper, sandy part of the lowest distinct shallowing-upward sequence in the Calvert Formation and is separated from the overlying Cheswold aquifer by a muddy confining bed. Updip in Kent County and westernmost Sussex County, the Lower Calvert aquifer merges with the Cheswold aquifer and cannot be distinguished as a separate unit. It is early Miocene in age.

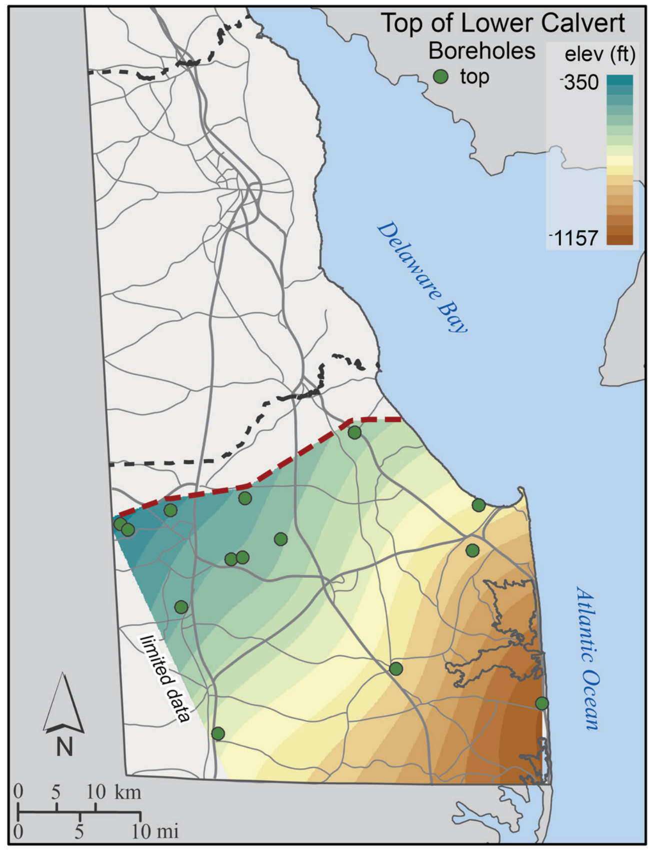

Figure 18. Map showing elevation of the top of the Lower Calvert aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

Recognition of the Lower Calvert aquifer changes some of the previous deep aquifer nomenclature in Sussex County. Sands previously identified as the Cheswold aquifer at Lewes (Oh25-02; Andres et al., 1990) and Bethany Beach (Qj32-27; McLaughlin et al., 2008) are here designated as the Lower Calvert aquifer. The Cheswold aquifer is placed at the next higher sand in most of Sussex County. Strontium isotope ages from Bethany Beach (Miller et al., 2003; McLaughlin et al., 2008) indicate the Lower Calvert aquifer is slightly older than 20 Ma.

The top of the Lower Calvert aquifer occurs at about 400 ft bsl in the northwestern corner of Sussex County and deepens to about 1,150 ft bsl in coastal southeastern Sussex County (Figs. 18 and 19). It is generally between 15- and 50-ft thick in northwest Sussex County where it is shallow enough to potentially be used for water supply and can be more than 100-ft thick in some areas of southern Sussex County (Fig. 20). It should be noted that the thinnest and thickest areas shown on the map lie between points of similar values in areas of low data density and thus are probably exaggerated by the computer mapping process.

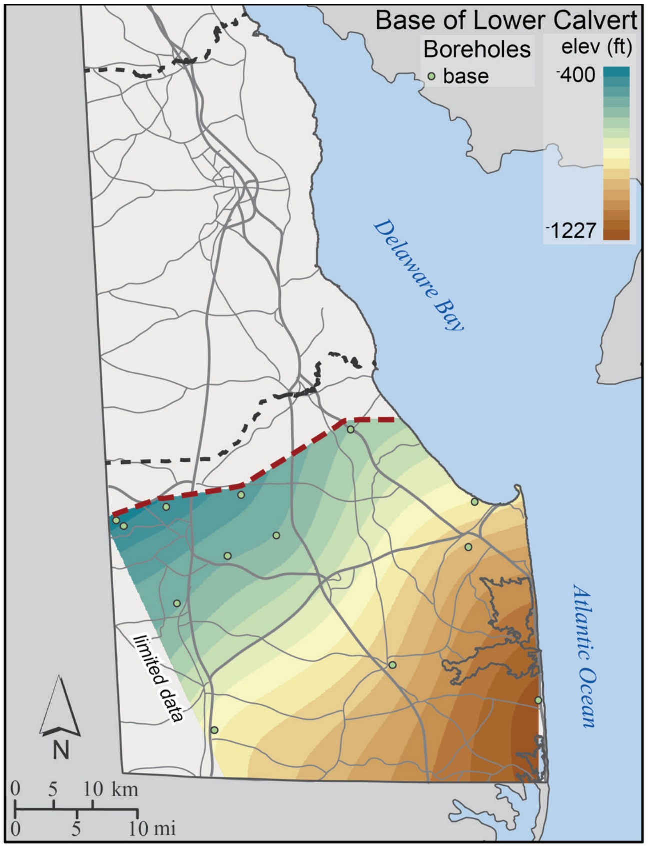

Figure 19. Map showing elevation of the base of the Lower Calvert aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The Lower Calvert aquifer represents the culmination of a shallowing-upward sequence capped by a sequence boundary. Lithologically, the Lower Calvert sands are similar to those of stratigraphically higher aquifers in the Calvert Formation. In basinward locations near the Atlantic coast (Oh25-02, Qj32-27) the Lower Calvert consists mostly of clean to slightly muddy, variably shelly, fine to coarse sands. The silt and clay content appear admixed through bioturbation. Indurated zones of cemented sand may be present. The confining unit of silt and clay that separates the Lower Calvert aquifer from the overlying Cheswold aquifer becomes thinner in northernmost Sussex County where the two aquifers merge. Because of this merging, it does not subcrop under the Quaternary section or the Beaverdam Formation. It is underlain by a thick section of silts and clays in the lower part of the Calvert Formation, an interval that thickens substantially in an offshore direction to the southeast.

The Lower Calvert aquifer is a potential groundwater source in parts of Sussex County but is not known to be commonly used. In coastal and southern Sussex County, it may have sufficient permeability to yield groundwater but occurs at great enough depths where it is likely to contain brackish water (Andres et al., 1990).

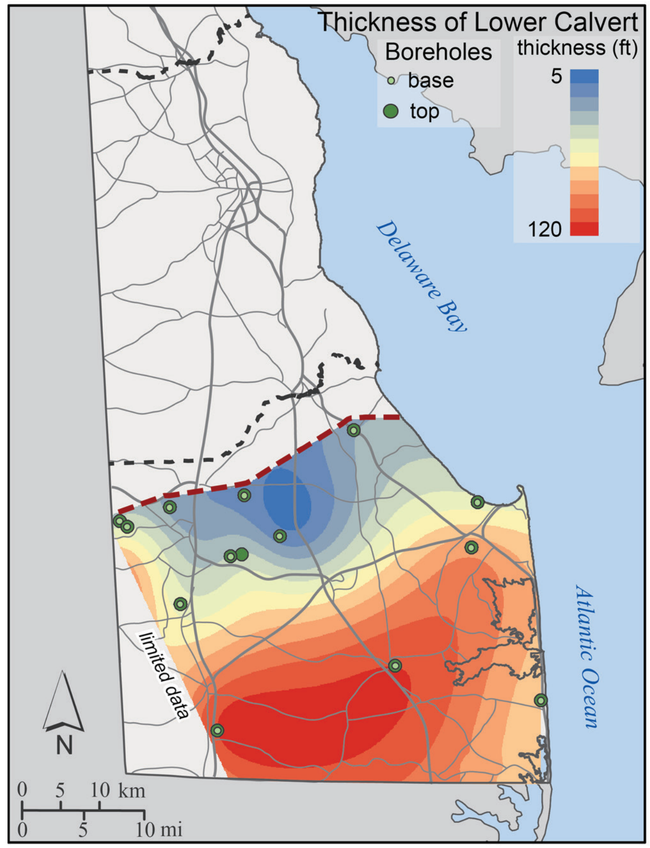

Figure 20. Map showing thickness of the Lower Calvert aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

Cheswold Aquifer

The Cheswold aquifer is the most important source of groundwater of the aquifer sands in the Calvert Formation. The name Cheswold aquifer was applied to the deeper Miocene sand of Marine and Rasmussen (1955). It is tapped by numerous public-supply wells in central Kent County and the Dover area (Andres, 2001). It was mapped previously by McLaughlin and Veléz (2006) in Kent County where it is the lowest aquifer in the Calvert Formation (Fig. 4). The Cheswold aquifer subcrops under the unconfined aquifer across a wide band in northern Kent County between Cheswold and Smyrna (Fig. 21).

Cheswold aquifer correlations in this report differ slightly from those in McLaughlin and Veléz (2006) because of additional, more recent well control. Sand intervals previously included in the lower part of the "Federalsburg" aquifer in some Dover locations are here placed in the Cheswold aquifer; a mud break in the Cheswold aquifer at those sites was previously interpreted as a confining bed between the Cheswold and "Federalsburg" aquifers. The lowest Calvert sand in southeastern Sussex County, previously correlated as the Cheswold aquifer (near Lewes, Oh25-02, Andres et al., 1990, and Bethany Beach, Qj32-27, McLaughlin et al., 2008), is now identified as the Lower Calvert aquifer. The second aquifer from the bottom of the formation in that area, previously identified as the Federalsburg aquifer (McLaughlin et al., 2008), is now correlated as the Cheswold aquifer. Strontium isotope ages from the Bethany Beach borehole indicate that the Cheswold aquifer is approximately 18.5 Ma (Miller et al., 2003; McLaughlin et al., 2008). This is close to the 17.9 Ma age reported by Jones et al. (1998) from Cheswold-equivalent sands at the Pollack Farm excavation site in central Delaware.

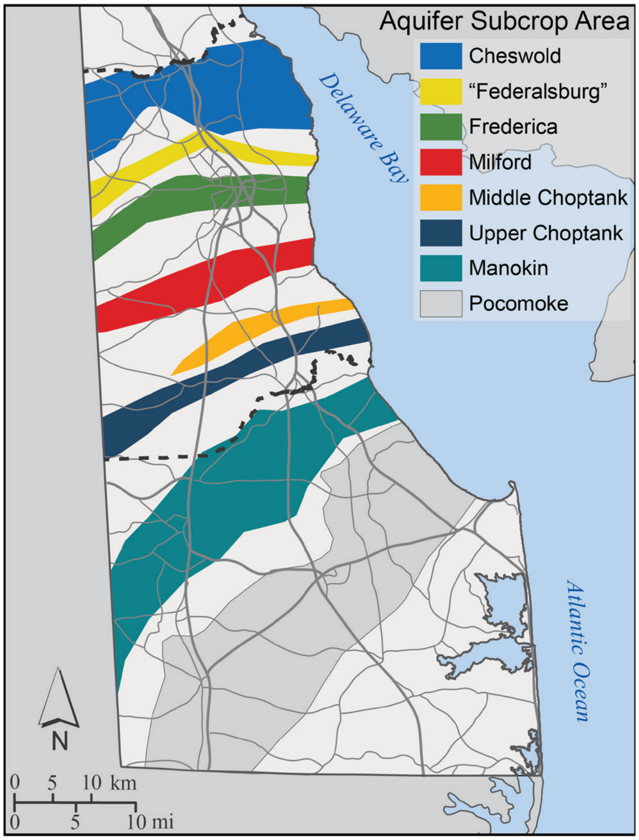

Figure 21. Generalized map of potential subcrop areas of aquifers in Kent and Sussex Counties. The outlined areas are generalized from trends of where the tops and bases of each confined aquifer intersect the base of the unconfined aquifer in the maps created for this project. The Mount Laurel and Rancocas aquifers subcrop in New Castle County and are not portrayed on this map; the Piney Point aquifer does not subcrop under the unconfined aquifer.

The Cheswold aquifer descends from about 50 ft asl in the northern part of Kent County to nearly 500 ft bsl near the Kent-Sussex County line to more than 1,100 ft bsl in southeastern coastal Sussex County (Figs. 22 and 23). Its thickness ranges from more than 100 ft to less than 30 ft and is more variable in northern and central Kent County (Fig. 24). Some of the thickness variation is due to facies change and some is due to erosional relief at the base or top of the aquifer. Erosional relief is suggested by the sharp base of the Cheswold aquifer in some areas, especially northern Kent County (Plate 2, Section C-C'); this is interpreted as erosional relief that develops in a coastal-nearshore-tidal environment (i.e., tidal channels) and not an unconformity (McLaughlin and Veléz, 2006). Erosion at the base of overlying Quaternary surficial sand units (Columbia and Lynch Heights Formations) causes patchy occurrence of confining beds over the Cheswold aquifer near its up-dip limit in northern Kent County; at these locations, the Cheswold sand functions as part of the unconfined aquifer. In Sussex County, although well control is limited, the thickness of the Cheswold aquifer appears to be more predictable, becoming thicker to the southeast and reaching approximately 100 ft in thickness near the Atlantic Coast.

The lithofacies variations in the Cheswold aquifer that control aquifer characteristics are evident on geophysical logs (McLaughlin and Veléz, 2006). In northern Kent County, many geophysical logs penetrating the Cheswold aquifer show an overall fining-upward pattern, with some upward-coarsening just below the base of the aquifer sand (Id31-26; Fig. 7; Plate 1, Section B-B'). The succession of lithofacies that creates this fining-upward pattern is evident at the Pollack Farm site (Id11-a) south of Smyrna, an outcrop described in detail by Ramsey (1998). The lithofacies there represents a 30-ft-thick shallowing-upward succession from fine-grained deposits to sandy, aquifer-quality deposits and back to finer-grained beds. The fine-grained interval at the base of the section is a shelly mud deposited in a shallow, offshore open-marine environment.

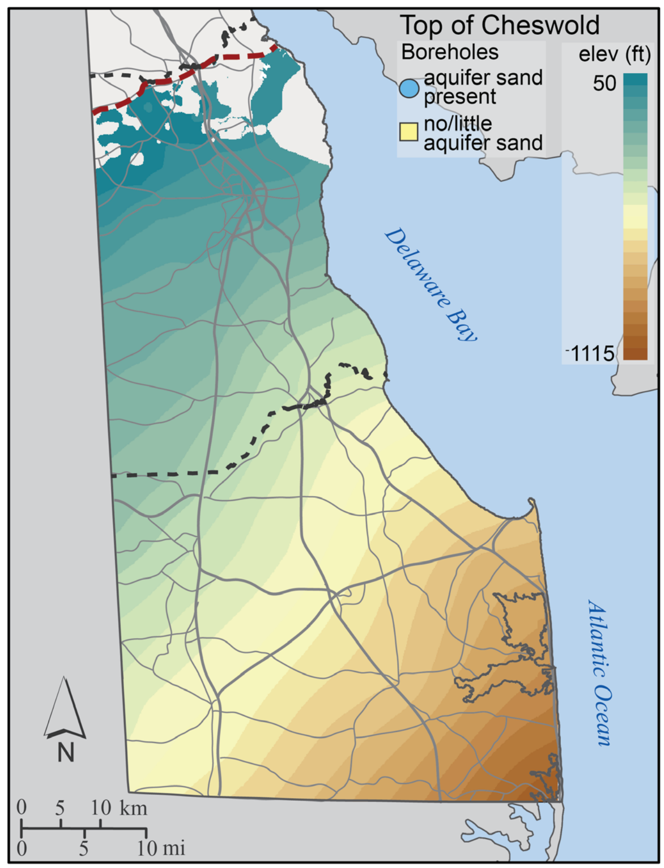

Figure 22. Map showing elevation of the top of the Cheswold aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Cheswold aquifer sand is present from locations where the stratigraphic interval can be recognized but no sand is present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

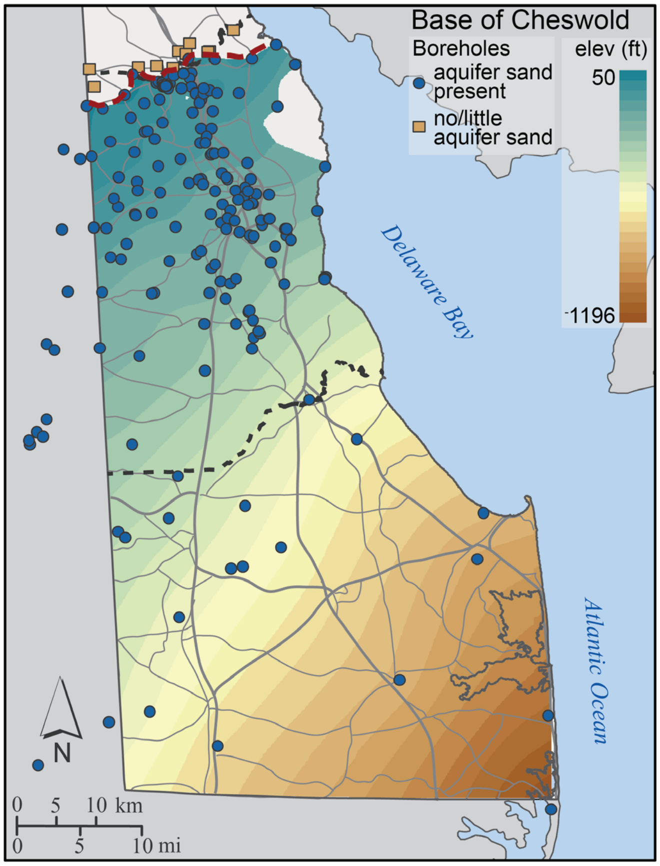

Figure 23. Map showing elevation of the base of the Cheswold aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Cheswold aquifer sand is present from locations where the stratigraphic interval can be recognized but no sand is present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

This mud is overlain by a crossbedded sandy shell bed with abundant bone material deposited in an estuarine channel or near the mouth of an estuary, which passes upward into crossbedded, shallow subtidal sand. These sands are overlain by an interval of interbedded mud and sand that represent tidal flat deposits; these are in turn overlain by crossbedded sand with shell beds, abundant burrows, mud rip-up clasts, and ripples with clay drapes deposited in a shallow subtidal environment within and near tidal channels. At the top is a muddy zone composed of homogeneous clayey silts and a few thin sands deposited in a tidal mud-flat setting. This lithofacies succession produces the fining-upward geophysical log pattern common in the Cheswold aquifer; on most logs, these nearshore deposits have a distinct shift to finer-grained offshore muds that represent an abrupt marine-flooding event.

Lithofacies of the Cheswold aquifer interval are variable in northern Kent County. In some areas, such as west Dover, muddy sands of poor aquifer quality comprise much of the Cheswold aquifer interval and were most likely deposited in a tidal flat environment. In contrast, near Smyrna, Cheswold aquifer sands commonly exhibit a blocky log pattern, with a sharp base, low gamma values, and high resistivity values (Plate 1; Hc31-07 on section C-C' and Hc45-21 on section D-D'). This pattern is interpreted to reflect a predominance of tidal channels, which is consistent with our observation of tens of feet of relief on the base of the Cheswold aquifer in the Smyrna-Clayton area.

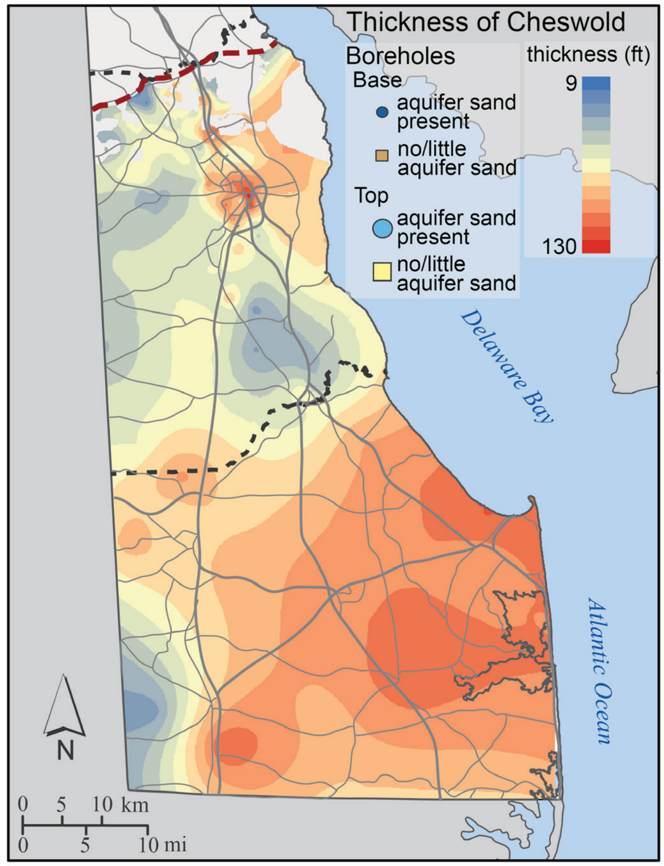

Figure 24. Map showing thickness of the Cheswold aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where Cheswold aquifer sand is present where the stratigraphic interval can be recognized but no sand is present. Dark red dashed line represents the approximate up-dip limit of the aquifer.

From south-central Kent County to Sussex County, the Cheswold aquifer commonly has a coarsening-upward pattern. In this more seaward setting, the Cheswold aquifer was likely deposited by prograding shoreline complexes in which upward shoaling is expressed as a change from offshore muds to muddy lower shoreface sands to clean upper shoreface sands. This pattern is evident in some borehole logs from southern Kent County (Plate 1, section F-F') and in most holes reaching the Cheswold aquifer in Sussex County (Plate 2, Qj32-27).

The interpretations from outcrop and geophysical logs are supported by lithologies in drill cuttings. Cuttings from boreholes drilled for this project (Mf35-26, Nb54-04, Nd35-08, Pc14-17, Qc21-05, and Qf21-07) and the Kent County study (McLaughlin and Veléz, 2006) consist of fine- to coarse-grained quartz sands including common to abundant shell fragments and as much as 10 percent dark grains (glauconite and heavy minerals).

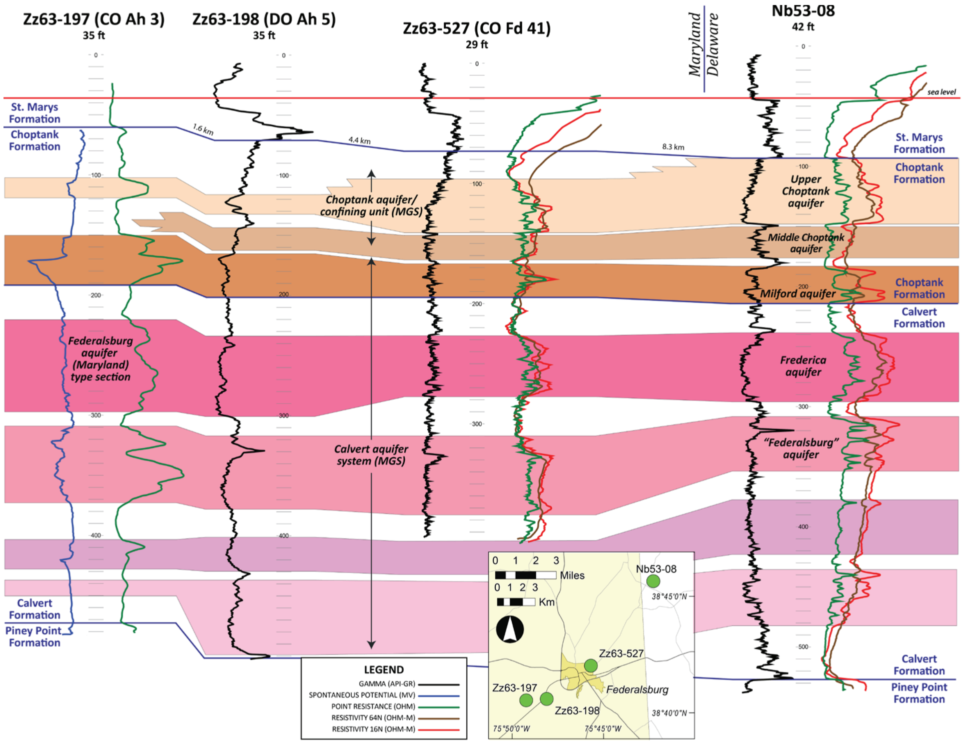

Figure 25. Cross section from Federalsburg, Maryland to northwest Sussex County, Delaware showing correlation of aquifer sand intervals. The type section of the Federalsburg aquifer, defined between 220 and 300 ft in borehole CO Ah 3 by Cushing et al. (1973), correlates to the sand interval that is referred to as the Frederica aquifer in Delaware. The Federalsburg aquifer name has long been applied to the underlying sand in Delaware. Because the Federalsburg designation is established for this sand in Delaware through long-standing use, we maintain the name "Federalsburg" but indicate the mismatch by enclosing the name in quotation marks. Maryland Geological Survey (MGS) aquifer designations are as outlined in Andreasen et al. (2013).

The Cheswold aquifer is confined above and below by silts and clays. The top confining bed is commonly a thin zone (10-20 ft) of silt or silty clay (Plates 1 and 2). However, in some areas, this interval may be thinner and/or not especially fine grained, which suggests it may not be an effective hydrologic barrier everywhere between the Cheswold and Federalsburg aquifers (e.g., Plate 1, Kc13-06 on section F-F' and Kd33-04 on section G-G'). The Cheswold aquifer is underlain by a thick zone of brown clayey mud that comprises the lower part of the Calvert Formation in Kent County (Plate 1); in contrast, in Sussex County, the interval under the Cheswold aquifer commonly includes the Lower Calvert aquifer, with only a thin, fine-grained confining interval separating the two sand bodies (Plate 2). In northern Kent County, where the upper confining bed is absent, the sands that make up the Cheswold aquifer subcrop under surficial unconfined aquifer sands (Plate 1, sections A-A' through D-D'), providing recharge areas for the Cheswold aquifer (Fig. 21).

"Federalsburg" Aquifer

Cushing et al. (1973) noted the presence of an aquifer sand between the Cheswold and Frederica aquifers that is used as a water supply in central and southern Delaware. The sand was considered equivalent to the Federalsburg aquifer that was previously defined just outside the town of Federalsburg, Maryland, in well DO Ah 3 at a depth of 220 to 300 ft. However, based on more abundant well control in this study, those correlations appear to be incorrect. Instead, the aquifer that Cushing at al. (1973) called the Frederica aquifer in Delaware is equivalent to the Federalsburg aquifer defined in the Eastern Shore of Maryland (Fig. 25). The sand that has been referred to as the Federalsburg aquifer in Delaware since the work of Cushing et al. (1973) is here correlated with an unnamed, stratigraphically lower, poorer-quality aquifer sand in the Federalsburg area. Although the Federalsburg aquifer name is therefore a misnomer in Delaware, the use of the name is well entrenched. For that reason, we refer to this aquifer sand as the "Federalsburg" aquifer in this study, acknowledging that it is known by this name in Delaware but qualifying the use of the name with quotation marks.

We have found that a key to the correlation of the "Federalsburg" aquifer at many sites in Kent County, Sussex County, and the Eastern Shore of Maryland is the recognition of a very high gamma-ray spike at or just below the top of the aquifer sand on gamma-ray logs. Though the other aquifers in the Calvert Formation may have an interval of high gamma values in their upper parts, the gamma spike for the "Federalsburg" is commonly very sharp and, thus, distinctive. Correlation of this marker is shown on Figure 25, Plate 1 (Lb35-10, Kd33-04, and Ke23-05 on section G-G'; Mb44-02, Ld55-28, and Me15-29 on section H-H') and Plate 2 (section I-I', Pc14-17 and Qc21-05; Qd52-02, Qd23-27, and Qf21-07 on section N-N'). Based on this marker and additional well-log control, we consider the "Federalsburg" aquifer to be a higher sand than previously correlated in McLaughlin et al. (2008) at Bethany Beach (Qj32-27) and Lewes (Oh25-02).

The "Federalsburg" aquifer is early Miocene in age (Fig. 4). Strontium age determinations in Qj32-27 (Bethany Beach) suggest that the top of the "Federalsburg" aquifer sand is capped by an unconformity that can be dated as approximately 18 Ma (Miller et al., 2003; McLaughlin et al., 2008).

The "Federalsburg" aquifer sand is present from its updip limit between Cheswold and Dover where it subcrops (Fig. 21) beneath mostly sandy Quaternary or Beaverdam sediments through southern Kent County and throughout Sussex County. The aquifer ranges in elevation from more than 40 ft asl in northern Kent County to around 400 ft bsl in southern Kent County, and to more than 1,000 ft bsl in coastal southeastern Delaware (Figs. 26 and 27). The thickness of the "Federalsburg" varies more because of facies changes than because of erosion associated with the base of the sand (Fig. 28). It exceeds 60 ft in thickness in westernmost Kent County and along a trend from east of Dover to east of Milford, but is less than 30-ft thick in other areas, including the Dover area and north, southwestern Kent County, and northwestern Sussex County. These maps are altered somewhat from those in McLaughlin and Veléz (2006) because additional well control indicates that some intervals previously placed in the lower part of the "Federalsburg" aquifer in the Dover area are better interpreted as part of the Cheswold aquifer. In addition, Benson (1998) and Benson and Spoljaric (1996) included some intervals in a broadly defined Cheswold aquifer that are here considered to be in the "Federalsburg" aquifer.

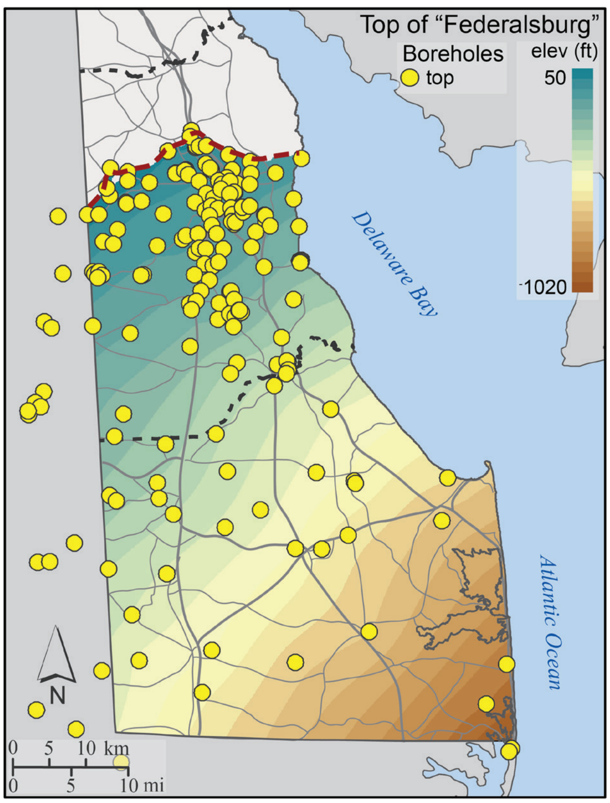

Figure 26. Map showing elevation of the top of the "Federalsburg" aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

As noted in McLaughlin and Veléz (2006), the "Federalsburg" aquifer is composed of quartz sands similar to the sedimentary facies of the Cheswold aquifer. However, "Federalsburg" sands show significant lateral variability on geophysical logs, more so than the Cheswold aquifer or the higher Miocene aquifers. The "Federalsburg" aquifer is commonly a fining-upward succession in Kent County and may include a thin coarsening-upward interval at the base (Plate 1, sections A-A' and B-B'). This type of "Federalsburg" sand likely represents shallow-marine and possibly estuarine environments. The "Federalsburg" aquifer may exhibit a coarsening-upward pattern in southern Kent County, reflecting deposition of a prograding shoreline package (Plate 1, sections G-G' and H-H'). The "Federalsburg" is clean, aquifer-quality sand in some parts of the study area and less aquifer-prone sand intervals that contain interbedded muds in other areas. The variations in aquifer quality probably represent shifts from cleaner sands in estuarine channel and shoreface settings to muddier deposits in tidal flat and low-energy estuarine settings.

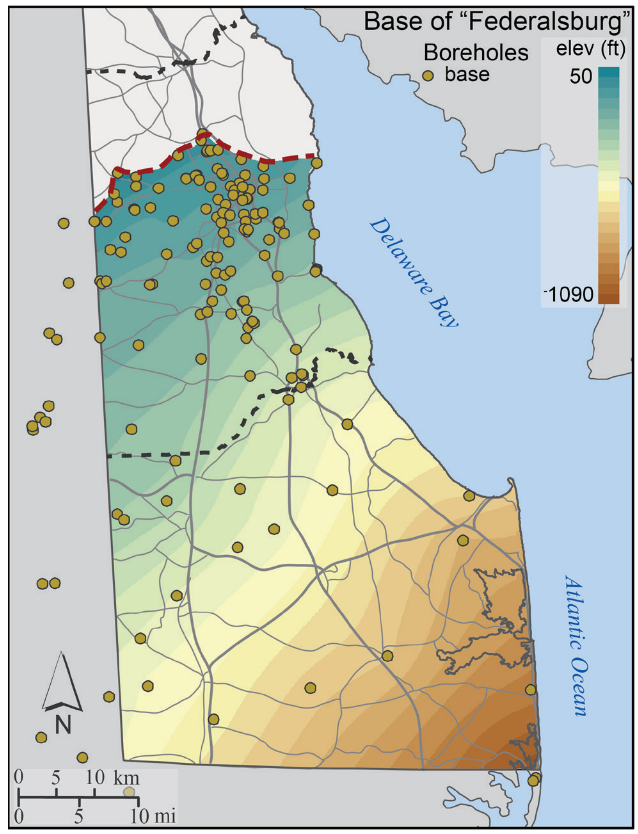

Figure 27. Map showing elevation of the base of the "Federalsburg" aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

Lithologies observed in drill cuttings are consistent with these characteristics. The "Federalsburg" aquifer occurred in four of the test holes drilled for the Kent County aquifer study. At two sites (Jc12-16 and Ke23-05), the cuttings consist of shelly, mostly medium-grained quartz sands; in contrast, at two others (Kc13-06 and Ld41-16) they are muddy, shelly, fine-to medium-grained sands. The "Federalsburg" aquifer was also penetrated in nine of the test holes drilled for this study in Sussex County (Mf35-26, Nb54-04, Nd35-08, Nf33-06, Pc14-17, Qc21-05, Qd23-27, Qf21-07, and Rh22-12) where cuttings are predominantly quartz sand, shells and shell fragments, small phosphate fragments, dark shell material, some cemented sand beds and as much as 10 percent glauconite, mostly fine. The southwesternmost test hole (Qc21-05) yielded muddy sands that would likely have poor aquifer qualities.

The gamma-ray-log spike common at the top of the "Federalsburg" aquifer may reflect a concentration of bone phosphate and/or authigenic minerals at the unconformity/ sequence boundary that caps the shoaling-upward, nearshore sand sequence. The thin interval of sand above the spike in many wells may have been laid down at the beginning of the subsequent marine transgression. Although the sand intervals below and above the sequence boundary are genetically separate, they function as a single aquifer unit.

The "Federalsburg" aquifer may have comparatively poor confining beds separating it from the immediately overlying or underlying confined aquifer compared to other Miocene confined aquifers. The confining layer under the "Federalsburg" aquifer is commonly thin (less than 20 ft) and generally thinner in the western part of the study area than the eastern. In some places, such as in northwest Sussex County (Nb54-04, Plate 2, section I-I', and nearby core site Nb53-08), the lower confining bed is essentially absent and the "Federalsburg" aquifer sand is almost amalgamated with the underlying Cheswold aquifer sand. The confining layer between the "Federalsburg" aquifer and the overlying Frederica aquifer is typically thicker (about 30 ft), but may locally be as thin as 10 ft (Plate 1, Kd23-02 on section G-G' and Ld55-28 on section H-H').

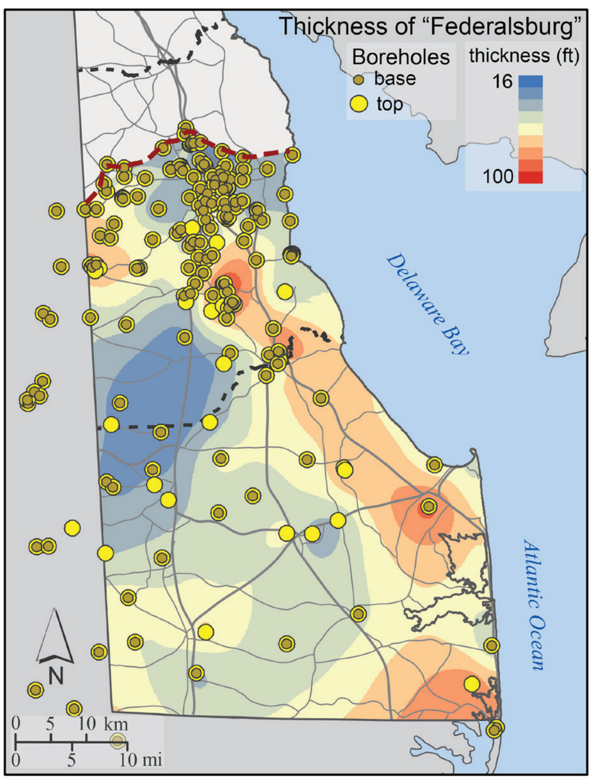

Figure 28. Map showing thickness of the "Federalsburg" aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

Frederica Aquifer

The Frederica aquifer is the stratigraphically highest aquifer in the Calvert Formation (Fig. 4) and an important groundwater source in communities south of Dover. Marine and Rasmussen (1955) referred to a "shallow" Miocene sand used for water supplies between Camden and Milford; Rasmussen et al. (1958) designated this sand the Frederica aquifer. Some of the shallow Miocene sands referred to as Frederica aquifer in older studies (Rasmussen et al., 1958; Sundstrom and Pickett, 1968) were shown by Ramsey and Groot (1997) to be assignable to a higher unit, which was designated the Milford aquifer.

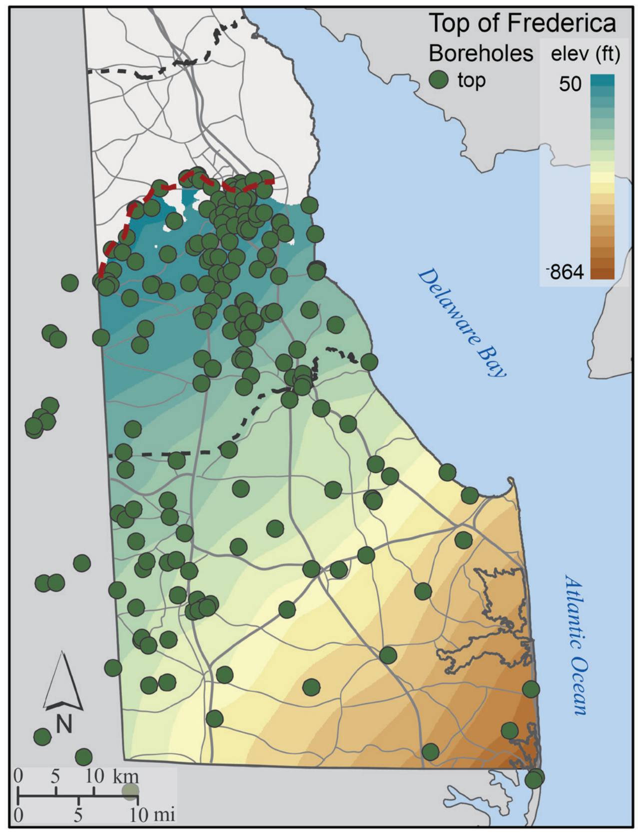

Figure 29. Map showing elevation of the top of the Frederica aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The Frederica aquifer is present over most of southern Kent County (McLaughlin and Veléz, 2006) and Sussex County. Its northern limit is in the Dover area, where it subcrops under Quaternary-age or Beaverdam Formation unconfined aquifer sands (Fig. 21). The elevation of the aquifer ranges from more than 30 ft asl in west-central Kent County to more than 250 ft bsl in the southeast Kent County and northwest Sussex County to more than 850 bsl in coastal southern Sussex County (Figs. 29 and 30). It is typically 50 to 60-ft thick in Kent and Sussex Counties, but it may be less than 30-ft thick near its subcrop and locally more than 75-ft thick where the base of the sand is lower or the transgressive sand over the sequence boundary is thicker (Fig. 31).

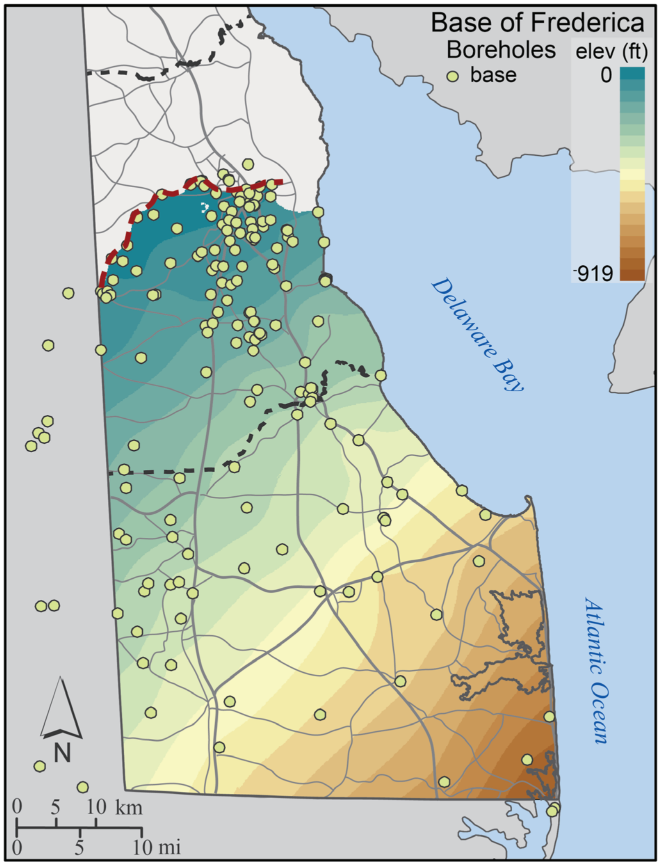

Figure 30. Map showing elevation of the base of the Frederica aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The depth of the Frederica aquifer is now interpreted differently than shown on the Milford to Bethany Beach cross section in McLaughlin et al. (2008). Correlations of the Calvert and Choptank Formations in Sussex County (Plate 2) that include additional well-log control indicate that the Frederica aquifer should be assigned to the next stratigraphically higher sand in coastal Sussex County (the interval identified as Milford aquifer in Oh25-02, Qj32-27, and Ri15-01 in McLaughlin et al., 2008). Strontium data from Bethany Beach (Miller et al., 2003; McLaughlin et al., 2008) indicate the Frederica aquifer is approximately 16.5 Ma.

The Frederica aquifer is composed of clean quartz sands that are commonly shelly. These sands are interpreted as nearshore-marine and estuarine deposits. In places, intercalated finer-grained beds occur that might diminish aquifer quality (Plate 1, section F-F', Kd12-07). Most geophysical logs through the aquifer in Kent County indicate an overall fining-upward pattern; in places, a thin coarsening-upward interval is evident at the base (Plates 1 and 2). These log patterns probably represent an upward succession from shoreface or estuarine sands to slightly muddier intertidal or estuarine facies. At sites in southern Kent County and Sussex County, the log patterns indicate a degree of coarsening upward, reflecting shoreline progradation (Plate 1, section H-H', Ld55-28; Plate 2, section M-M', Of41-02 and Of44-10). The Frederica aquifer commonly has a high gamma-ray zone or a sharp gamma-ray spike near its top, above which is a thin fining-upward interval (Plate 1, section F-F', Jc55-10 and section G-G', Ke24-05; Plate 2, section K-K', Qj32-27 and section N-N', Rh22-12). The high gamma-ray zone is interpreted as a condensed section just above a composite sequence boundary/transgressive surface where concentrations of phosphate (much of it bone origin) and glauconite occur. The fining-upward interval at the top of the aquifer that overlies this condensed section represents transgressive systems tract sands over the sequence boundary/transgressive surface.

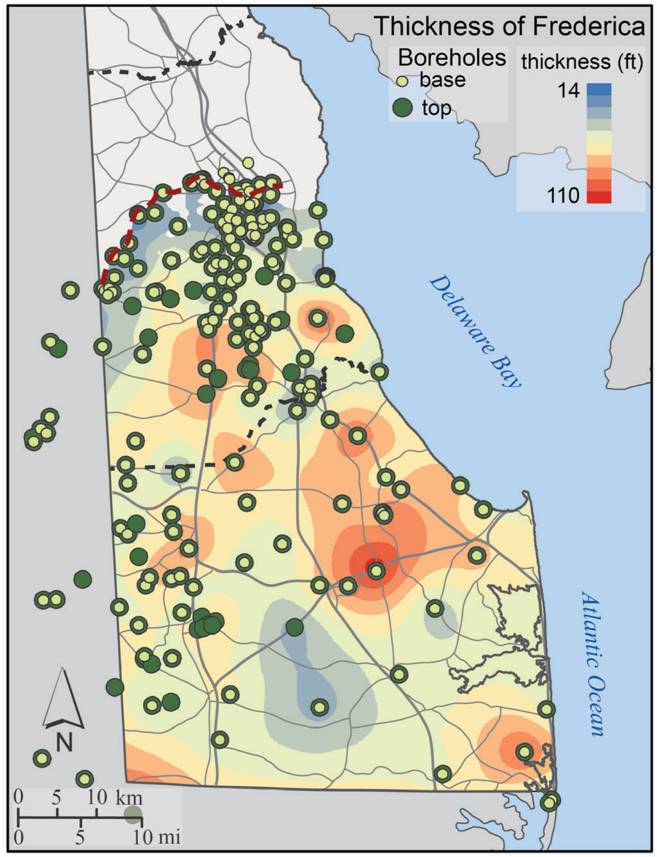

Figure 31. Map showing thickness of the Frederica aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

The Frederica aquifer sand was encountered in several test holes drilled for the Kent County aquifer study (Kc13-06, Ke23-05, Ld41-16), in all ten of the test holes drilled for this study, and in wireline cores drilled at Bethany Beach (Qj32-27) and Marshy Hope (Nb53-08). The test-hole cuttings have medium- to coarse-grained quartz sand or muddy fine- to medium-grained sand, both with common shell material. In the Bethany Beach cores (Qj32-27), the Frederica aquifer mostly consists of unconsolidated fine- to medium-grained quartz sand with shell debris, heavy mineral concentrations in cross laminae, scattered thin silts, and some beds of indurated, shelly, calcareous sandstone. Lithologies are similar in the Marshy Hope (Nb53-08) cores in northwestern Sussex County, but the sand is overall coarser, mostly medium grained and some coarse.

The Frederica aquifer is overlain in most areas by a 20- to 30-ft thick muddy confining layer that comprises the upper part of the Calvert Formation. A muddy zone of more variable thickness underlies the Frederica aquifer sand, commonly around 30 ft, but in places thinner due to an erosional surface at the base of the sand (Plate 1, section A-A', Nc43-02 and section F-F', Kc13-06). Where the base of the Frederica aquifer is erosional, the underlying confining layer may be locally too thin to be an effective hydrologic barrier between the Frederica and "Federalsburg" aquifers.

Milford Aquifer

The Milford aquifer is the lowest aquifer sand in the Choptank Formation (Fig. 4); the base of the aquifer marks the base of the formation. Ramsey and Groot (1997) recognized that the sand referred to as the Frederica aquifer around Milford (Sundstrom and Pickett, 1968, 1969; Cushing et al., 1973; Talley, 1982) was a stratigraphically higher sand, so assigned it a new name, the Milford aquifer.

The Milford aquifer occurs as far north as a zone trending from southeast of Dover to west of Felton, where it subcrops and is recharged under Quaternary or Beaverdam strata (Fig. 21). It is present throughout southern Kent County and all of Sussex County. New geophysical log data from Sussex County allow revised correlation of the Milford aquifer as the next stratigraphically higher sand in coastal Sussex County boreholes (Oh25-02, Qj32-27, and Ri15-01) than in previous work (McLaughlin et al., 2008). Based on the revised interpretation of the stratigraphy in Qj32-27 (Bethany Beach), strontium isotope dates from core material reported in Miller et al. (2003) indicate the Milford aquifer is slightly younger than 16 Ma.

The Milford aquifer occurs as shallow as approximately 20 ft asl just south of its subcrop area in central Kent County and deepens to more than 700 ft bsl in the southeast corner of Sussex County (Figs. 32 and 33). It thickens unevenly in the same direction from as little as approximately 10-ft thick near its northern limit to between 30 and 50 ft from most of southern Kent County and central Sussex County. Its greatest thicknesses occur deep in the subsurface in Sussex County, reaching more than 100-ft thick in southwest Sussex County and near the Atlantic Coast (Fig. 34).

The Milford aquifer was described by Ramsey and Groot (1997) as quartz sand that commonly includes coarse-grained or granule-bearing intervals near the base; shelly intervals were noted in its higher parts. In Kent County and much of northern and western Sussex County, the Milford aquifer exhibits a blocky or fining-upward log pattern, which is consistent with deposition in estuarine environments that may have been channelized (McLaughlin and Veléz, 2006). Shell appears to be more abundant in a down-dip/basinward southeast direction. In coastal Sussex County, the Milford aquifer is the lower part of an interval of very shelly sands that characterizes the Choptank Formation.

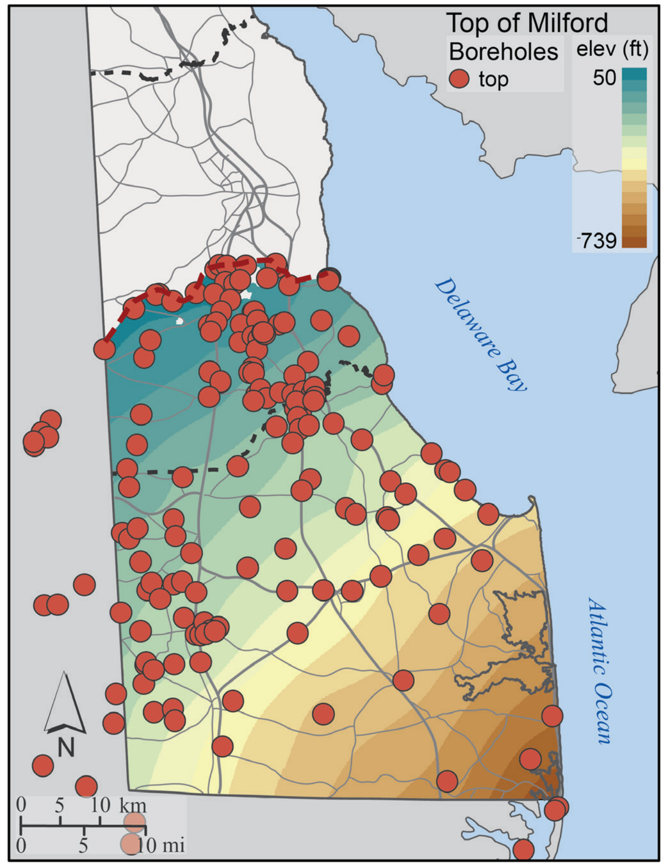

Figure 32. Map showing elevation of the top of the Milford aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The Milford aquifer was penetrated in two test holes drilled for the Kent County aquifer study (Plate 1, section G-G', Ke23-05; and section A-A', Ld41-16), in all of the Sussex County test holes (Plate 2), and in cores from Bethany Beach (Qj32-27) and Marshy Hope (Nb53-08). In the Kent County holes, the cuttings consist of medium to coarse to very coarse quartz sands that include granules and pebbles in places (Ke23-05) and in other places are muddy (Ld41-16); these generally lack shell material. However, shells are more common in the Milford aquifer sands to the south in Sussex County. Cores from the Milford aquifer at Bethany Beach (Plate 2, section L-L', Qj32-27) have shelly sands with some cemented zones and some slightly muddy zones (Miller et al., 2003; McLaughlin et al., 2008). Lithologies from the equivalent interval near Lewes (Oh25-02) are similar (Andres et al., 1990). In northwest Sussex County, at Marshy Hope (Nb53-08; near Nb54-04, Plate 1, section I-I'), the Milford aquifer is also shelly sand but is thinner than in coastal Sussex County.

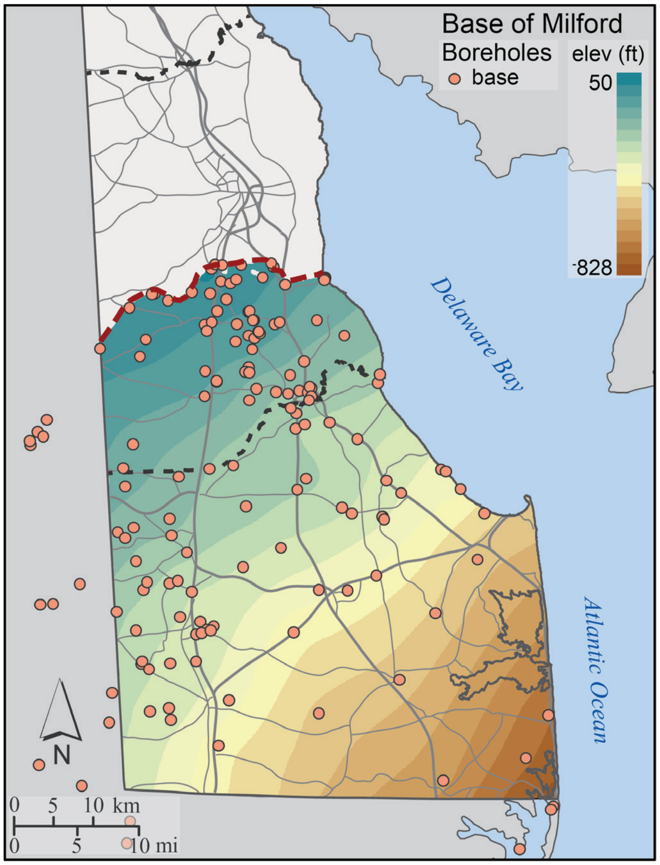

Figure 33. Map showing elevation of the base of the Milford aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

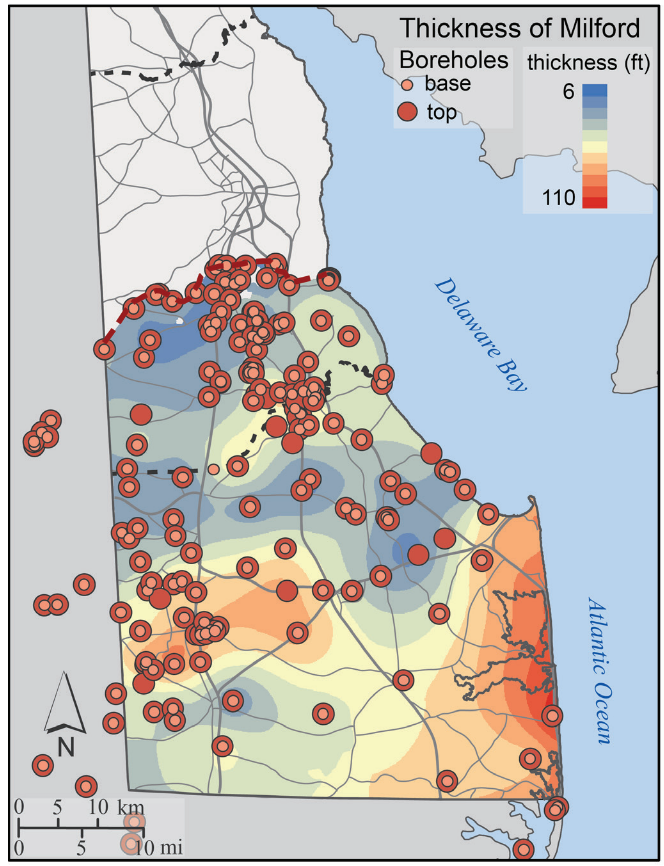

Figure 34. Map showing thickness of the Milford aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

In Kent County and northern Sussex County, the Milford aquifer is generally overlain by a thin (in places less than 20 ft) confining layer that separates it from stratigraphically higher sands in the Choptank Formation. Further south in Sussex County, the Choptank Formation tends to have few distinct mud beds; the aquifer sands are separated by silty sands and/or sandy silts that may not be very effective confining beds. The irregular occurrence of a well-developed confining layer can make it difficult to differentiate the Milford aquifer from overlying Choptank sands in many areas. Because of the rarity of thick confining beds, the sands of the Choptank Formation may be better thought of as an aquifer system rather than as individual, isolated confined aquifers.

In Kent County and northern Sussex County (e.g. Nb53-08, Marshy Hope cores), the confining layer at the top of the Calvert Formation underlying the Milford aquifer is commonly a relatively thick (30 to 50 ft), brown clayey silt (Ramsey and Groot, 1997). In cores from Bethany Beach (Qj32-27), the Milford aquifer is underlain by bioturbated, slightly clayey silt of the uppermost Calvert Formation, a lithology that probably characterizes this interval in much of Sussex County.

Ramsey and Groot (1997) previously suggested that the presence of an unconformity at the base of the Milford aquifer because of the distinct change in grain size. However, in this report the base of the Milford aquifer is interpreted as a normal shift in facies from shallow-offshore muds to shallower coastal facies having erosion associated with emplacement of tidal channel sands and gravels. We place an unconformity at or near the top of the aquifer and interpret that surface as a composite sequence boundary/transgressive surface. Shifts in strontium age data at Bethany Beach (Qj32-27) support the presence of this unconformity (Miller et al., 2003; McLaughlin et al., 2008).

Middle Choptank Aquifer

The Middle Choptank aquifer is newly defined in this report as an aquifer sand that occurs in the middle part of the Choptank Formation in southern Delaware. This aquifer sand is one of the "minor Miocene aquifers" recognized by Sundstrom and Pickett (1968). The Middle Choptank aquifer can be traced on geophysical logs around much of the eastern half of Sussex County and southeasternmost Kent County (Plate 1, sections A-A', B-B', and H-H'; Plate 2, all sections). It occurs above the Milford aquifer and below the Upper Choptank aquifer (Fig. 4). Strontium data from Bethany Beach cores (Qj32-27) indicate the Middle Choptank aquifer is middle Miocene, approximately 13.5 Ma (Miller et al., 2003; McLaughlin et al. 2008).

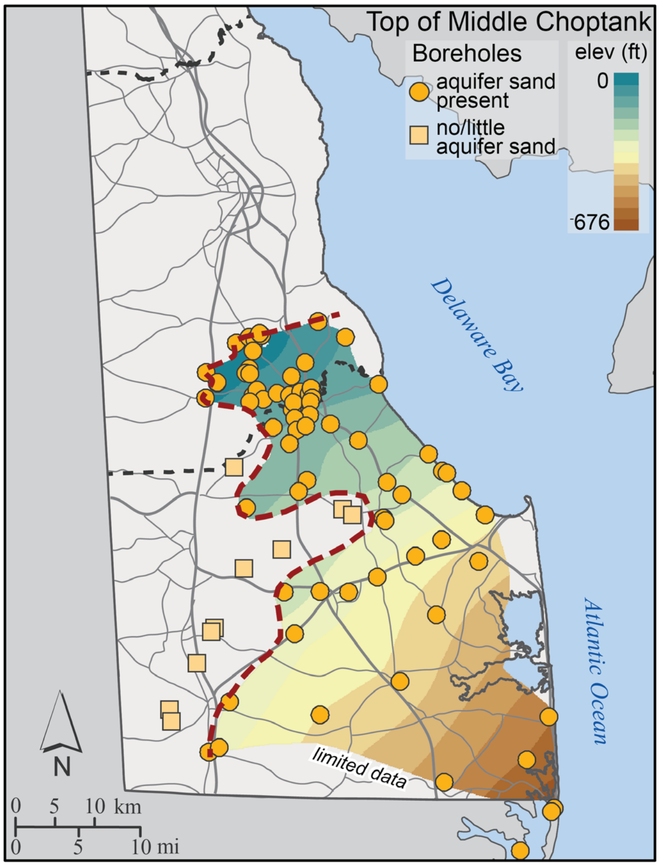

Figure 35. Map showing elevation of the top of the Middle Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where the Middle Choptank aquifer is present from locations where the aquifer pinches out and is not present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

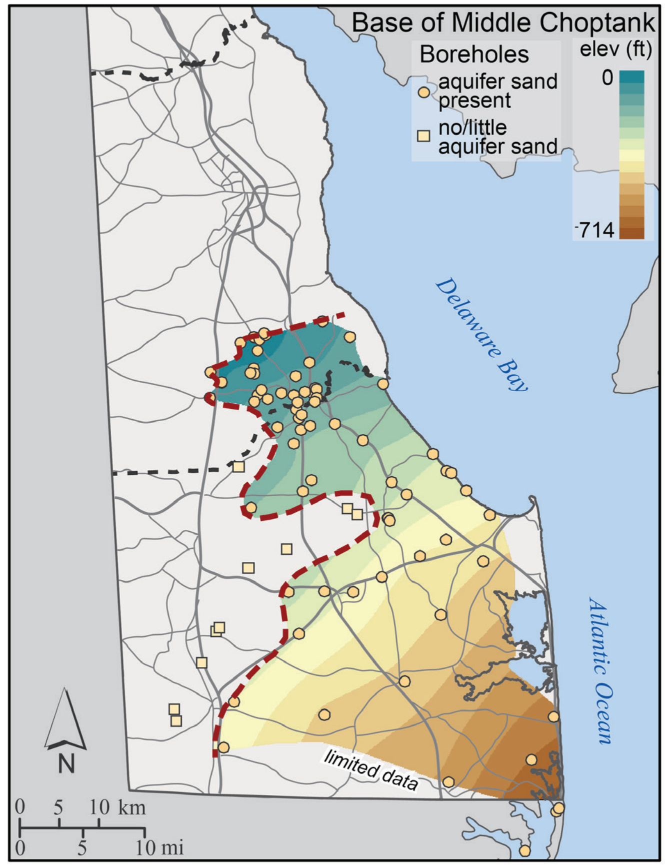

Figure 36. Map showing elevation of the base of the Middle Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where the Middle Choptank aquifer sand is present from locations where the Middle Choptank sand pinches out and is not present. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The Middle Choptank aquifer has limited areal extent. It is present south of its subcrop under the base of Quaternary or Beaverdam sediments in southeastern Kent County and throughout much of the eastern two-thirds of Sussex County (Figs. 35 and 36). The aquifer dips southeastward from elevations near sea level south of its subcrop area to more than 650 ft bsl in southeastern Sussex County. Its thickness increases from as little as 10 ft along its northern and western limits to more than 50 ft in southern Sussex County (Fig. 37). The western limit of the Middle Choptank aquifer is mostly controlled by stratigraphic pinch-out and facies change; cross sections reveal westward thinning of the sand and a transition to finer-grained sediments. This thinning may be due, in part, to progressively greater truncation of sequences in a landward direction by the top-bounding sequence boundary, which creates what Kidwell (1997) referred to as "shaved" sequences. Such "shaving" appears to be more significant in the Choptank Formation than in Calvert strata, as reflected in the closer spacing and longer duration of Choptank unconformities indicated by strontium ages at Bethany Beach (Miller et al., 2003; McLaughlin et al., 2008).

The lithology of the Middle Choptank aquifer is like most of the sandy zones in the Choptank Formation in Sussex County: clean to slightly silty sand with common shell material. In cores from Bethany Beach, this interval consists of interlaminated silts and sands that coarsen-upward to progressively cleaner and coarser, medium to very coarse sand with abundant shell material and interbedded indurated cemented sandstone having biomoldic porosity where preexisting shells were cemented and subsequently dissolved. Andres et al. (1990) described similar lithologies from the same zone at Lewes. Drill cuttings have yielded common phosphate grains (e.g., Plate 2, Section N-N', Rh22-12).

The Middle Choptank aquifer probably does not function as an individual, isolated well-confined aquifer in all of the study area. The overlying and underlying Choptank lithologies are generally thin (less than 20 ft) and commonly consist of silty sands and sandy silts (Miller et al., 2003; McLaughlin et al., 2008); these type of lithologies may be best characterized as leaky non-aquifer beds rather than true confining beds.

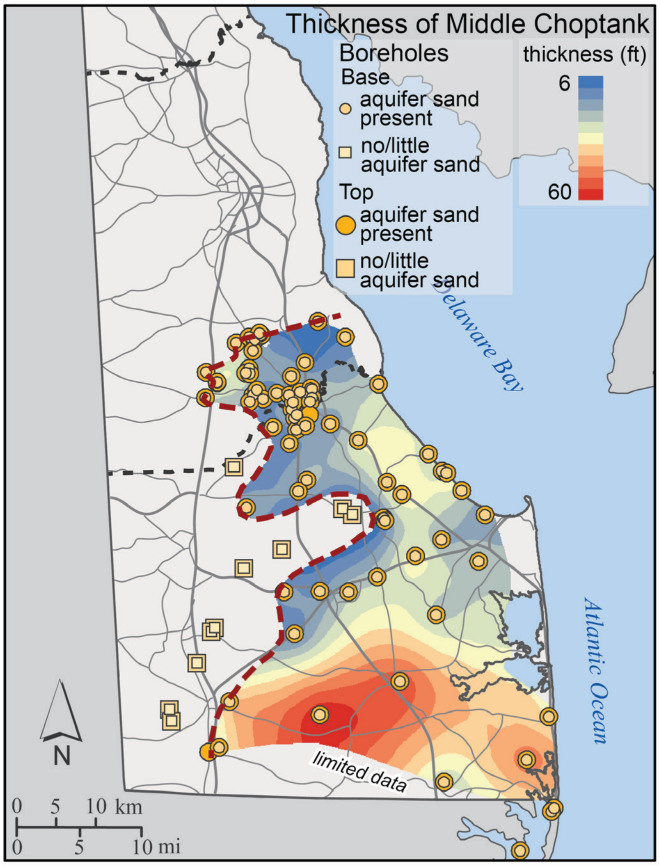

Figure 37. Map showing thickness of the Middle Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Borehole symbology differentiates locations where the Middle Choptank aquifer sand is present from locations where the Middle Choptank sand pinches out and is not present. Dark red dashed line represents the approximate up-dip limit of the aquifer.

Upper Choptank Aquifer

The Upper Choptank aquifer, like the Middle Choptank aquifer, is newly defined in this report. It occurs at the top of the Choptank Formation (Fig. 4) and was one of the minor Miocene aquifers in older DGS studies (e.g., Sundstrom and Pickett, 1968). This aquifer can be traced on geophysical logs in much of the eastern half of Sussex County and in southeasternmost Kent County (Plate 1, sections A-A', B-B', and H-H'; Plate 2, all sections). It occurs above the semi-confining beds that top the Middle Choptank aquifer and below the thick confining unit of the St. Marys Formation. Strontium isotope ages indicate that the Upper Choptank aquifer is late Miocene, approximately 13 Ma in Bethany Beach cores (Qj32-27), (Miller et al., 2003; McLaughlin et al., 2008) and approximately 12 Ma in Marshy Hope cores (Nb53-08) (unpublished data).

The Upper Choptank aquifer extends from its subcrop zone in southern Kent County, on a trend from Harrington to the north side of Milford, and across Sussex County. The top of the aquifer, which corresponds to the top of the Choptank Formation, dips from slightly asl just south of its subcrop to more than 600 ft bsl in southeastern Sussex County (Figs. 38 and 39). Unlike most of the other aquifers, it generally becomes thinner to the southeast. In southwestern Kent County and northwestern Sussex County it can attain 50 ft in thickness, but in much of southwestern Sussex County it is less than 25-ft thick (Fig. 40).

The Upper Choptank aquifer has typical Choptank Formation sand lithologies: clean to slightly silty sand with common shell material. In southeastern Sussex County, geophysical logs typically have a blocky character and commonly a fining-upward interval or bed on top. In cores from Bethany Beach (Qj32-27), most of the Upper Choptank aquifer is variably cemented, shelly sand with minor sandy silt that changes upward to gravelly silty sand; above that, the upper part of the unit fines to shelly, poorly sorted sand, in places weakly cemented, transitioning upward into muddy sand with progressively more common bioturbation (Miller et al., 2003; McLaughlin et al., 2008). Andres et al. (1990) noted similar deposits containing indurated layers and pebbles in the uppermost part of the Choptank Formation near Lewes (Oh25-02). Similar lithologies are also present in cuttings from boreholes drilled for this study in central and southeastern Sussex County. This lithologic succession is interpreted as reflecting shallowing of shoreface environments, followed by a hiatus at a sequence boundary, and then followed by marine flooding laying down progressively deeper water shoreline deposits during transgression.

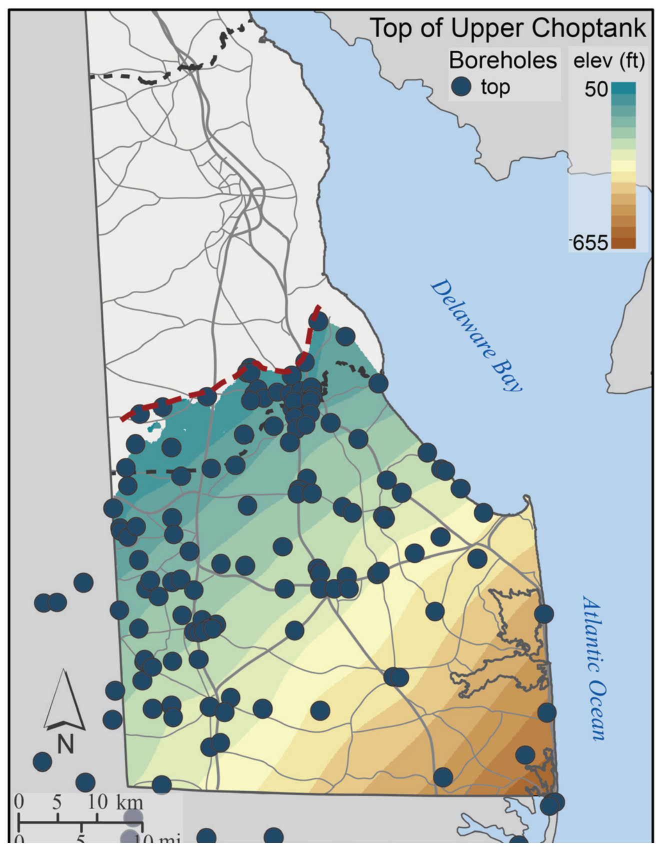

Figure 38. Map showing elevation of the top of the Upper Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

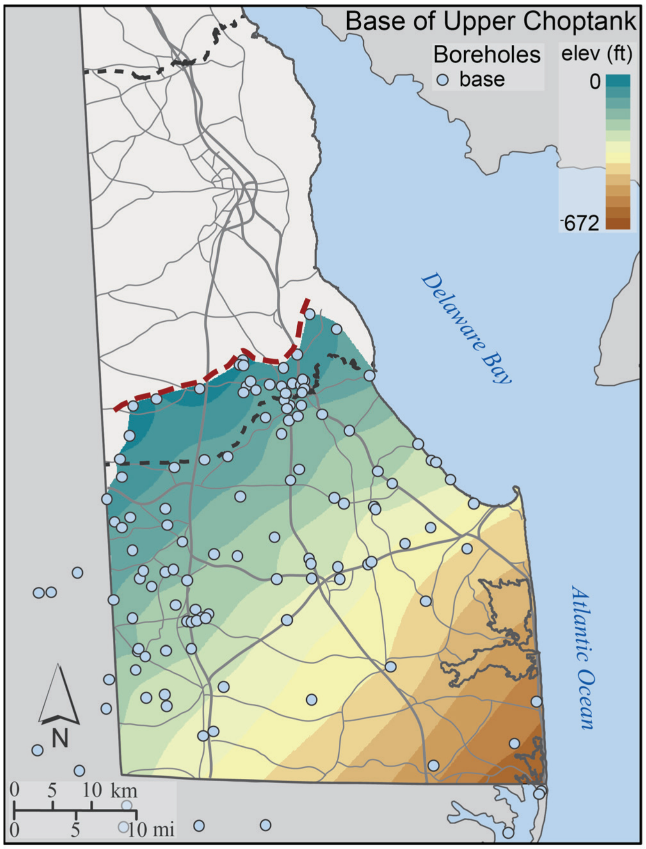

Figure 39. Map showing elevation of the base of the Upper Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

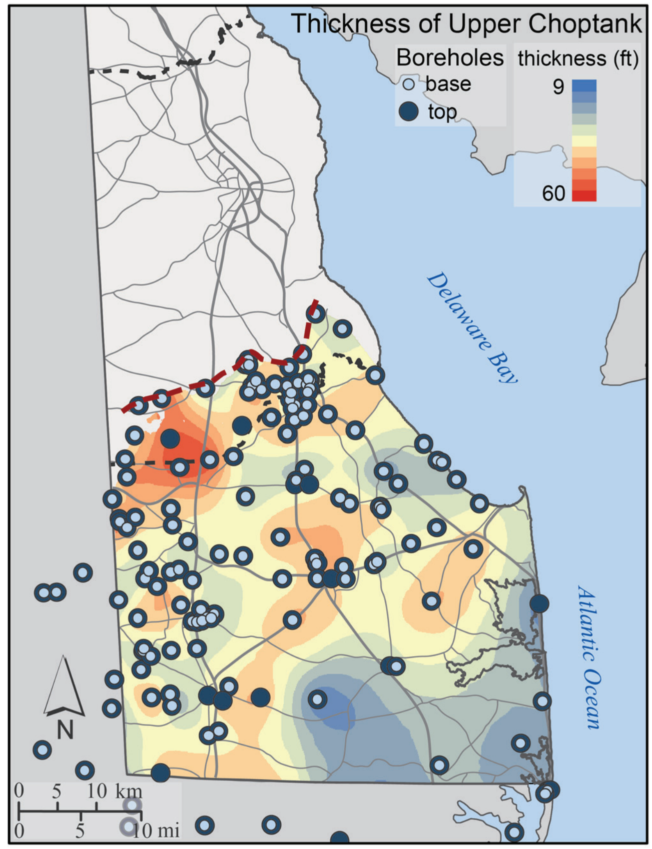

Figure 40. Map showing thickness of the Upper Choptank aquifer and stratigraphic equivalents and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

The Upper Choptank aquifer has a different character in northwestern Sussex County (Plate 2, Nb54-04, Nb53-08) where it is thicker and shows distinct fining up-section. In cores from Marshy Hope (Nb53-08), the sands at the bottom of the aquifer are mostly medium-grained, some coarse-grained, and contain abundant shell fragments. These sands transition to progressively finer sediments, consisting of very fine to fine-grained sand with thin silty laminae and plant debris at the top of the Upper Choptank. This same pattern is evident on geophysical logs through the Upper Choptank aquifer sand interval in northern and western Sussex County (Plate 2, sections I-I' and M-M'). This succession of aquifer lithologies reflects shallowing from shoreface to estuarine environments.

The Upper Choptank aquifer is confined by the thick zone of mostly silty sediments of the St. Marys Formation (Fig. 4). Near the up-dip limit of this aquifer, the St. Marys Formation locally includes sandy lithologies that reduce its effectiveness as a confining unit (Plate 1, sections B-B' and H-H'; Plate 2, section J-J'). A thin zone of finer grained, non-aquifer Choptank sediments separates it from the underlying Middle Choptank aquifer. In northern and western Sussex County, this underlying zone tends to be muddier, possibly reflecting estuarine environments in these more landward locations. In eastern and southern Sussex County, this interval is commonly sandy silt or silty sand and may only be semi-confining within a leaky Choptank aquifer system.

Manokin Aquifer

The Manokin aquifer is a major source of groundwater in much of Sussex County. The lithologies of the Manokin aquifer are generally fine- and medium-grained sand with beds of coarse sand and gravel. The Manokin aquifer represents the portion of the Cat Hill Formation (Fig. 4) that is part of a confined aquifer or confined aquifer system. Strontium isotope determinations from the lower part of this aquifer in cores from Bethany Beach cluster from 9.6 to 10.5 Ma, suggesting a late Miocene age.

Rasmussen and Slaughter (1955) first differentiated a “Manokin aquifer” in Maryland. Rasmussen et al. (1960) recognized it in Sussex County and Sundstrom and Pickett (1969, 1970) and Hodges (1984) described it in more detail. Additional data and study have advanced understanding of this aquifer; in particular, the establishment of the Cat Hill Formation by Andres (2004) for the interval that includes the Manokin aquifer has helped to better define the stratigraphic context for this groundwater source.

The Manokin aquifer is similar to the stratigraphically higher Pocomoke aquifer. Both are composed of shallow-marine to estuarine sands of variable grain sizes. However, the Manokin aquifer occurs within the Cat Hill Formation, which is a laterally extensive and continuous complex of sand with only scattered fine-grained breaks. In contrast, the Pocomoke aquifer is composed of one or more sands that occur in the Bethany Formation, and these sands are variable in vertical and lateral extent. In this study, we defined the Cat Hill Formation boundary, and thus the top of the Manokin aquifer, at the depth where the occurrence of mostly uninterrupted sand was consistently identified. As a result, though sands of the Bethany Formation rest directly on top of the Cat Hill Formation and Manokin aquifer in some wells, the top of the Manokin aquifer was placed at a level below which the surrounding wells indicate the consistent occurrence of sand (Plate 2).

The Manokin aquifer occurs as far north as the Kent-Sussex County line and subcrops (Fig. 21) beneath the Beaverdam Formation and sandy Quaternary sediments across a wide belt of northern Sussex County. The aquifer occurs irregularly in up-dip areas depending on the depth of the base of the unconfined aquifer. Its top occurs at approximately sea level south of its subcrop and it descends to more than 350 ft bsl in the southeastern corner of coastal Sussex County (Figs. 41 and 42). It is thinnest in the western half of Sussex County, where it can be less than 20-ft thick but to the east is locally thicker than 130 ft (Fig. 43).

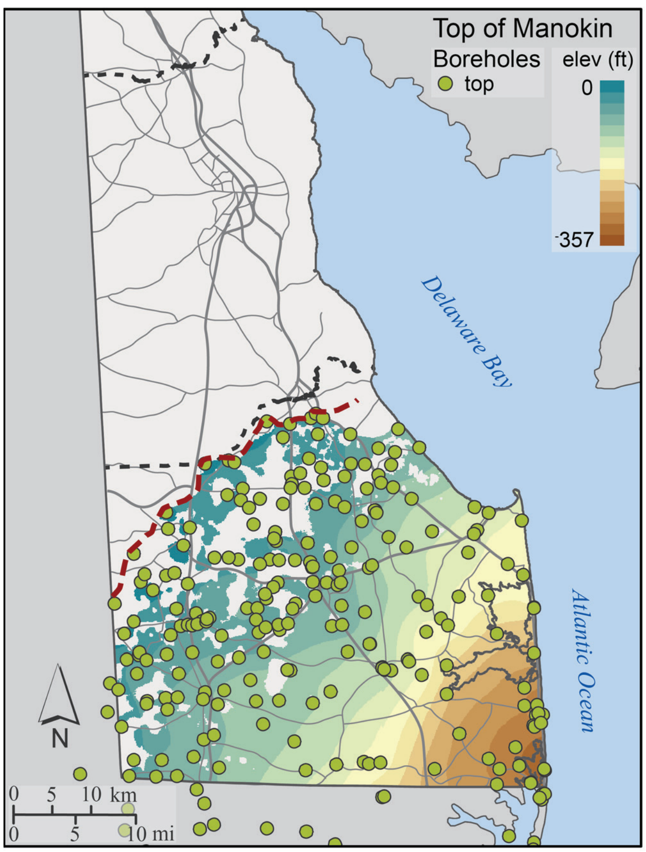

Figure 41. Map showing elevation of the top of the Manokin aquifer and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The Manokin aquifer is part of a coarsening upward succession. Silts of the St. Marys Formation transition upward into non-aquifer silty sands of the lower part of the Cat Hill Formation and to cleaner, aquifer-quality sands of the upper part of the Cat Hill Formation. The transition from lower Cat Hill sandy silts to clean Manokin aquifer sands occurs at slightly different levels in different parts of Sussex County (Plate 2, sections L-L' and K-K'), which produces aquifer thickness variations (Fig. 43). The stratigraphically lowest, aquifer-quality sands may have a sharp base rather than a gradual transition, especially in more up-dip areas (Plate 2; section I-I', Pc14-17 and V K-K', Nf33-06). Scattered fine-grained beds and other grain-size variations may break the general upward-coarsening nature of the unit (Plate 2, section J-J'). However, overall the Manokin aquifer is a generally sheet-like aquifer sand having a consistent upward-coarsening character.

The most detailed description of the lithology of the Manokin aquifer is from cores taken near Bethany Beach (Qj32-27) (Miller et al., 2003; McLaughlin et al., 2008). There it can be divided into a lower, finer grained, slightly glauconitic part and an upper, coarser grained part. The lower part coarsens from silty sand to fine- and then medium-grained, slightly glauconitic quartz sand with quartz granules, whole shells (*Mercenaria*), and shell hash. The upper part is mostly well-sorted, fine- to medium-grained sand that contains fine plant debris, mica, and scattered phosphatic pebbles; shell material is rare.

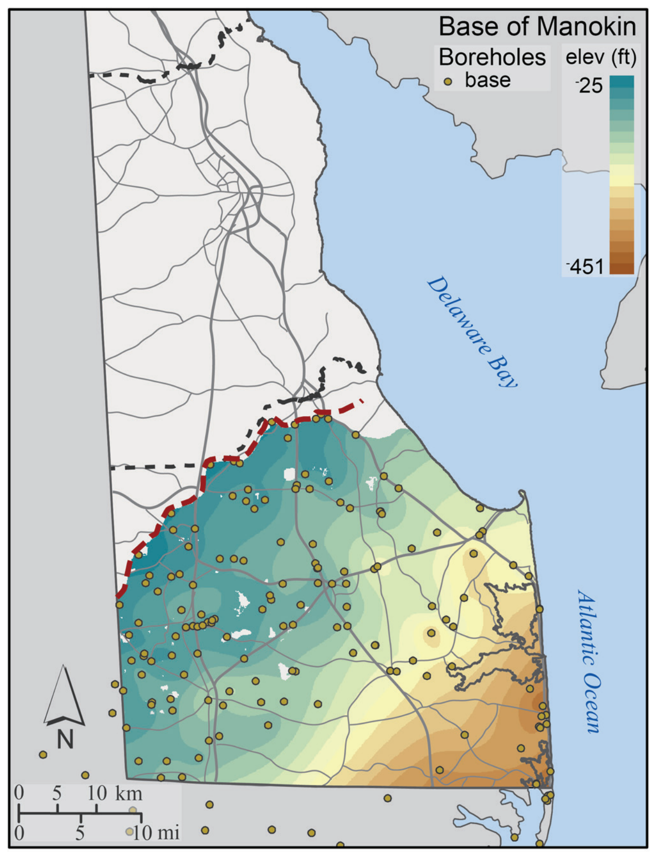

Figure 42. Map showing elevation of the base of the Manokin aquifer and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

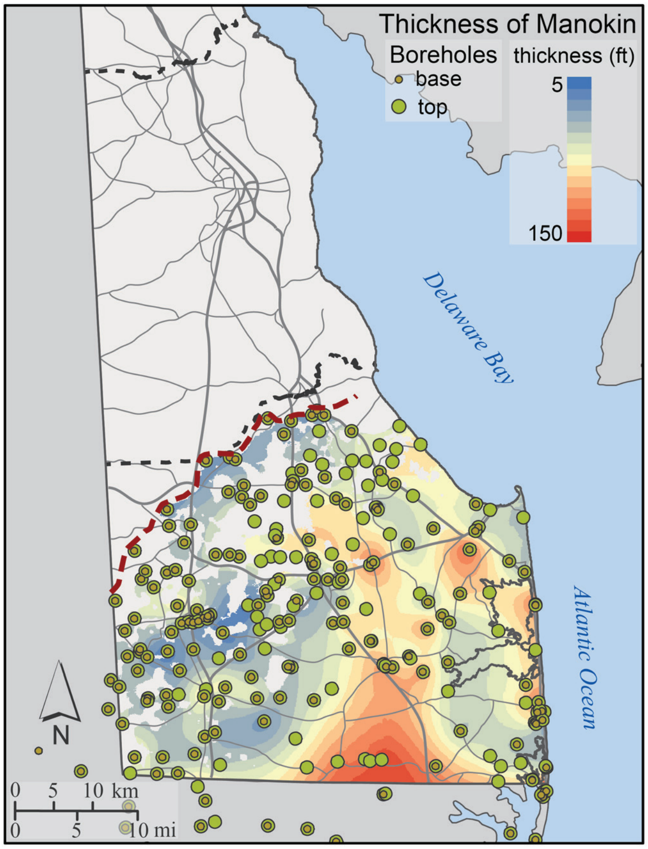

Figure 43. Map showing thickness of the Manokin aquifer and locations of boreholes used to make the map. Dark red dashed line represents the approximate up-dip limit of the aquifer.

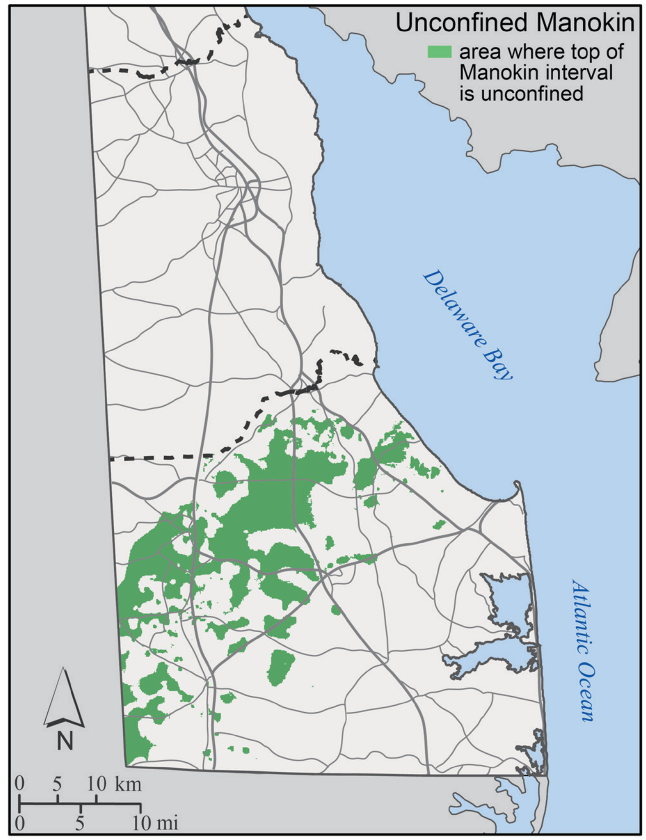

Figure 44. Map showing areas where the top of the Manokin interval is unconfined, defined where the elevation of the base of the unconfined aquifer is deeper than the projected elevation of the top of the Manokin aquifer using the rasters made in this study.

A significant complication in understanding the role of the Manokin aquifer in the groundwater system is its stratigraphic relationship to the unconfined aquifer and, to a lesser extent, the Pocomoke aquifer. The Cat Hill Formation sands are unconfined in many areas of Sussex County, so in those areas they are part of the unconfined aquifer and not the confined Manokin aquifer. A comparison of the "confined area" and "full extent" maps of the top, base, and thickness of the Manokin aquifer illustrate the difference between the full areal extent of the Cat Hill/Pocomoke and the occurrence of the Manokin aquifer as an actual confined aquifer (see layers on Figs. 41, 42, 43). This is highlighted on a "windows" map (Fig. 44) that shows where the base of the unconfined aquifer as mapped by Andres and Klingbeil (2006) is below the projected depth of the top of the Manokin aquifer, and thus giving areas where the unconfined aquifer has windows (and flow pathways) into the Manokin aquifer. The windows are generally of two types. One type is areas where Manokin aquifer sand beds are overlain by a continuous section of sand through the overlying Bethany Formation (Pocomoke aquifer), the Beaverdam Formation, and/or Quaternary formations without intervening confining layers. The other type of window is in the up-dip parts of the Manokin aquifer that are shallow enough to be cut by erosion under the base of the overlying Beaverdam Formation or Quaternary sediments.

These relationships complicate the delineation of the top of the Manokin aquifer and differentiation of the Manokin aquifer from the overlying Pocomoke aquifer. Identification of the top of the Manokin aquifer is clear at locations where the basal part of the Bethany Formation is characterized by a thick (ten to tens of feet) clay-silt confining bed. However, at some locations, Manokin aquifer sands may be overlain by a few feet to tens of feet of basal Bethany Formation sands with no real confining bed between them. In these cases, we have defined the top of the Manokin aquifer at the elevation we interpret as the top of consistent Cat Hill Formation sand occurrences in an area, whether a confining bed is present or not. The implication of this observation is that the Manokin aquifer is likely to be hydrologically connected to the Pocomoke aquifer in many areas; this idea is based on geologic observations and should be tested with hydrologic data.

Pocomoke Aquifer

The Pocomoke aquifer is one of the most important groundwater sources in the coastal areas of Sussex County. Rasmussen and Slaughter (1955) named this aquifer in southern Maryland; its use was extended into Delaware by Rasmussen et al. (1960). The Pocomoke aquifer occurs within the lithologically heterogeneous Bethany Formation (Fig. 4). We use the Pocomoke aquifer name for any sand body in the Bethany Formation that geophysical log signature or lithologic description indicates is likely to be thick and permeable enough to yield water to wells. As a result, the Pocomoke aquifer may be locally composed of multiple sand bodies.

Rasmussen and Slaughter (1955) recognized four hydrologic units in the upper Miocene (-Pliocene) section of southern Maryland, which were later recognized in Delaware in Rasmussen et al. (1960): the Manokin (lower) sand, Pocomoke (higher) sand, and two confining units that overlie each of them. An additional hydrologic unit, the "Ocean City" aquifer, was later designated by Weigle (1974) for sands that had previously been included in the Manokin aquifer by Rasmussen and Slaughter (1955). Hodges (1984) attempted to correlate this aquifer as a discrete unit in Sussex County. Hansen (1981) and Andres (1986) recognized that the Ocean City and Pocomoke aquifers represent lenses of sand within a succession that also includes abundant fine-grained sediment. Andres (1986) informally named these deposits the Bethany formation, which was defined formally by Andres (2004) as the Bethany Formation.

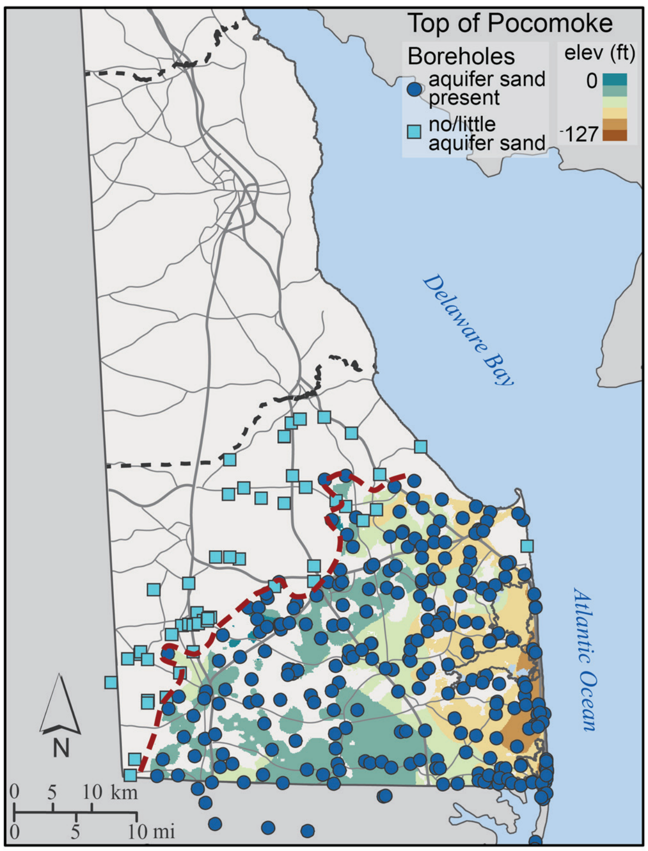

Figure 45. Map showing elevation of the top of the Pocomoke aquifer and locations of boreholes used to make the map. Borehole symbology differentiates locations where Pocomoke aquifer sands are present from locations where no Pocomoke sands occur in the Bethany Formation. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

The hydrostratigraphy of the Pocomoke aquifer and its relationship with the underlying Manokin aquifer is complex. In places, the Manokin aquifer and one, two, or more Pocomoke aquifer sands may be separated by thick confining beds but only a short distance away, thick intervals of Pocomoke aquifer sand may be directly in contact with the underlying and/or overlying formations with no intervening confining bed. These stratigraphic observations suggest that the Manokin aquifer, the Pocomoke aquifer, "confined Columbia" aquifer sands, and various unconfined aquifer sands are all associated in a complex of locally confined or locally unconfined aquifer sands that will function differently in different areas depending on the local geology and hydrologic conditions. Weigle (1974) and Hansen (1981) proposed that these aquifers are an upper Miocene aquifer system, which may be an appropriate way to deal with the hydrostratigraphy of this interval.

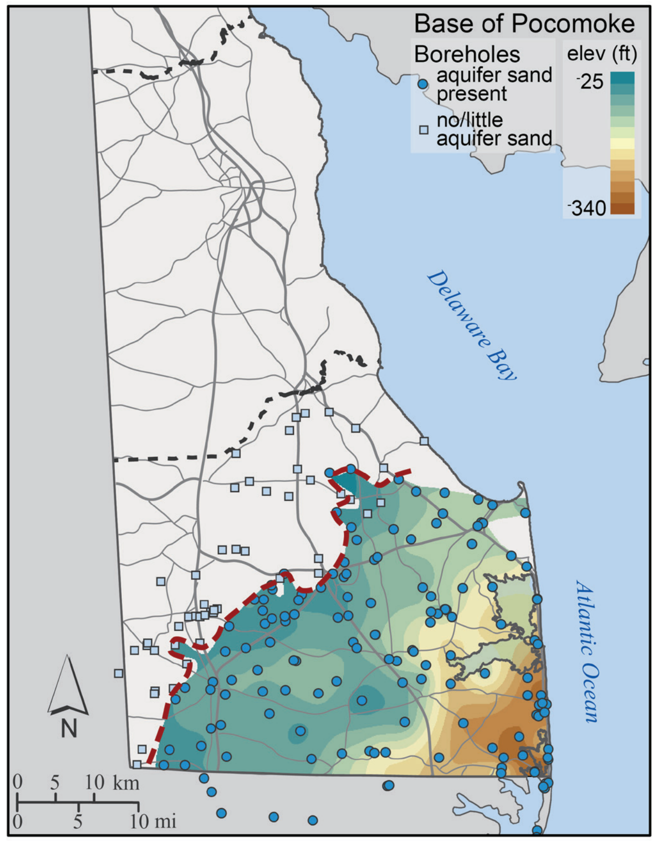

Figure 46. Map showing elevation of the base of the Pocomoke aquifer and locations of boreholes used to make the map. Borehole symbology differentiates locations where Pocomoke aquifer sands are present from locations where no Pocomoke sands occur in the Bethany Formation. Dark red dashed line represents the approximate up-dip limit of the aquifer. Datum is NAVD88.

This concept is reflected in our mapping of the Pocomoke aquifer. We have defined all confined aquifer sands within the Bethany Formation as the Pocomoke aquifer, whether or not a confining bed separates them from the Manokin aquifer sands in the underlying Cat Hill Formation. The picks for the top and bottom of the Pocomoke aquifer (Figs. 45 and 46) were placed at the top of the highest sand in the Bethany Formation and the base of the lowest sand in the Bethany Formation, respectively, whether those horizons were sand on sand contacts or were delineated by confining beds. The thickness of the Pocomoke aquifer (Fig. 47) is mapped as net sand thickness in this study because the Pocomoke aquifer is commonly recognized to encompass more than one sand unit. This approach ensured that the muddy, non-aquifer beds common between the top and bottom Pocomoke surfaces were not included in the aquifer thickness calculations.

The Pocomoke aquifer occurs only in Sussex County and has its up-dip limit along an uneven, northeast to southwest trend across the middle of the county. Because of its relatively shallow dip under the generally more flat-lying strata in the surficial Beaverdam Formation and Quaternary formations, it potentially subcrops under unconfined surficial sands across a broad area (Fig. 21). The top of the Pocomoke aquifer sand interval occurs approximately 25 ft bsl (in places shallower) near its up-dip limits and deepens to about 125 ft bsl along the Atlantic coast (see the full extent layer on the individual PDF for Fig. 45). The sands of the Pocomoke aquifer intersect the unconfined aquifer in many places, as is evident on the map version that shows only areas where it is confined (see confined extent layer, Fig. 45). The sand net thickness map (Fig. 47) shows the sum of Pocomoke thicknesses irrespective of whether the top of the Pocomoke aquifer is confined. The thickness of aquifer sand in the Pocomoke generally increases from northwest to southeast, from less than 25 ft near its mappable up-dip limit to nearly 200 ft in southeastern Sussex County.

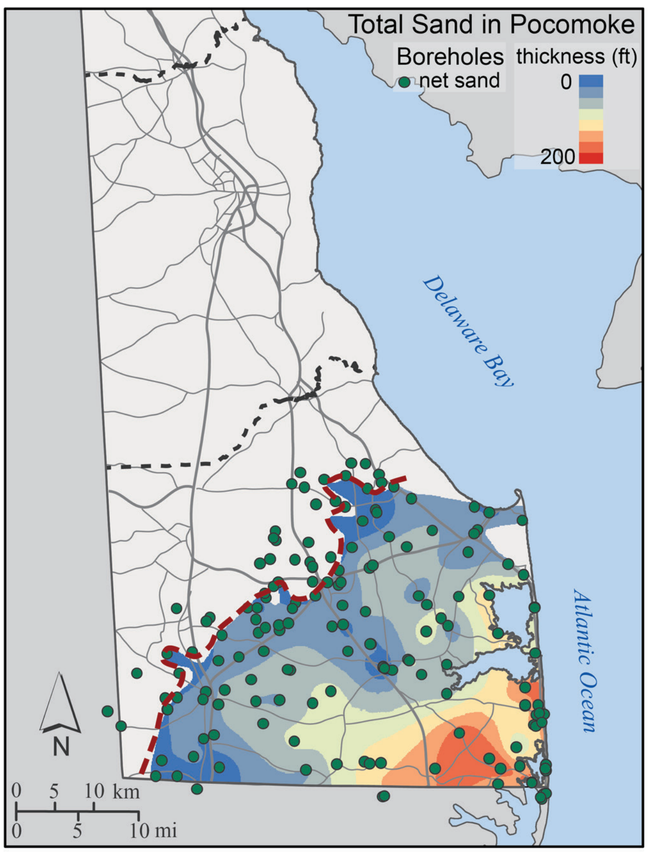

Figure 47. Map showing net thickness of sand bodies in the Pocomoke aquifer and locations of boreholes used to make the map. The net thickness represents the additive thickness of sands in the Bethany Formation that together comprise the Pocomoke aquifer. Borehole symbology differentiates locations where Pocomoke aquifer sands are present from locations where no Pocomoke sands occur in the Bethany Formation. Dark red dashed line represents the approximate up-dip limit of the aquifer.

The sands of the Pocomoke aquifer are typically fine- to medium-grained quartz, commonly including plant debris and mica and locally granule and pebble layers (Miller et al., 2003; McLaughlin et al., 2008). In core from Bethany Beach, the sand facies are varied. The lower sands are bioturbated, very fine to medium sands that coarsen upward and were likely deposited in a lower shoreface environment. Sands in the middle part of the Pocomoke are generally well-sorted, cross-laminated sands, the laminae highlighted by concentrations of opaque heavy minerals. This interval probably represents shoreface, tidal delta, or foreshore deposits, depending on their areal extent and geometry. The upper sands are fine to coarse grained and commonly contain granules. They vary from moderately well sorted with a few burrows to very poorly sorted and pebbly. These beds are interpreted as lower estuarine and bay or back barrier deposits.

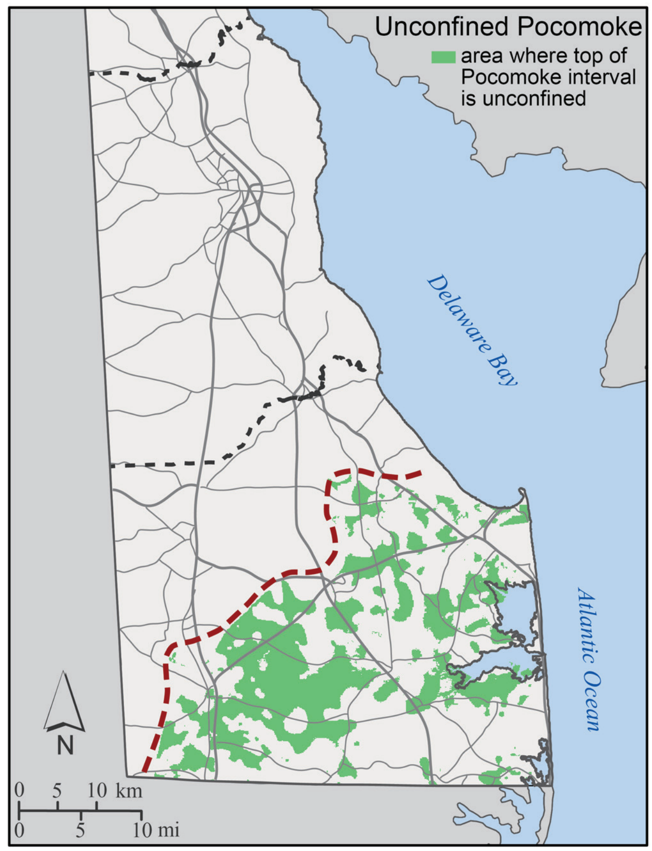

Figure 48. Map showing areas where the top of the Pocomoke interval is unconfined, defined where the elevation of the base of the unconfined aquifer is deeper than the projected elevation of the top of the Pocomoke aquifer using the rasters made in this study.

Some or all of the Bethany Formation sands are unconfined and, thus, mapped as part of the unconfined aquifer. Comparison of the full extent and confined area maps (layers in digital versions of Figs. 45 and 46) clearly shows the differences in areal extent of all Pocomoke-equivalent sand bodies within the Bethany Formation and only those areas where the sands are confined. This difference is also evident on a “windows” map (Fig. 48) that identifies areas where the base of the unconfined aquifer occurs deeper than the projected depth of the top of the Pocomoke aquifer, creating potential groundwater flow pathways.

The windows are generally of two types, similar to those in the Manokin aquifer. One type, generally closer to the coast, occurs where Pocomoke aquifer sands at the top of the Bethany Formation are overlain, without a confining layer, by a continuous section of sand through the overlying Beaverdam Formation and/or Quaternary sediments. The other type of window is in up-dip areas where significant erosion can be recognized at the unconformity at the base of the overlying Beaverdam Formation or Quaternary sediments.

Unconfined Aquifer

The unconfined aquifer has been mapped for this project in Kent County and merged with the Sussex County digital version of the unconfined aquifer map in Andres and Klingbeil (2006). The unconfined aquifer is a complex unit, but it is now better understood due to high-quality new data and new concepts developed over the last two decades.

The Columbia aquifer has been examined in numerous studies (Sundstrom and Pickett, 1968, 1969, 1970; Johnston, 1973, 1977; Talley, 1982, 1988; Denver, 1983; Andres, 1986; Andres and Klingbeil, 2006). The surficial sands in Delaware have been referred to as the Columbia Formation since Jordan (1964) established the use of this name for the assumed Pleistocene mantle of sands that covers the state's Coastal Plain. Because these surficial sands comprise an unconfined, water-table aquifer, the formation name was also used for this aquifer. As Johnston (1973) wrote: "Within the 1,500 square mile area underlain by 25 to 180 ft of saturated section, the Columbia deposits are essentially the water-table aquifer, or represent the most permeable section of the water-table aquifer… With a few local exceptions, the water-table aquifer in central and southern Delaware can be considered as the saturated section of the Columbia deposits."

Improved knowledge of the near-surface geology and hydrology has helped better understand the nature and distribution of this unconfined aquifer. Geologic mapping (Ramsey, 1993, 2001, 2003, 2007, 2010, 2011; Ramsey and Groot, 1997; Ramsey and Tomlinson, 2011, 2012; Andres and Howard, 2002) and aquifer recharge mapping (Andres, 2003a, 2003b, 2004) at the DGS have added large volumes of new near-surface data. Thousands of new boreholes have been drilled, providing numerous well-driller logs, geologist logs, geophysical logs, and other data. DGS surficial geologic mapping has differentiated a number of new Pleistocene geological formations that occur across large areas of the Delaware Bay coast, Atlantic coast, and tributaries of the Nanticoke River in the southwestern part of the state. This phase of surficial geologic mapping (i.e., Ramsey, 2007) has also recognized that some surficial sediments that were previously considered Columbia Formation are now recognized as Beaverdam Formation. One outcome of this improved understanding is that very little of the area long referred to as the Columbia aquifer belongs to its namesake Columbia Formation.

Andres and Klingbeil (2006) considered the unconfined aquifer of Sussex County to include deposits from the Cat Hill, Bethany, Beaverdam, Lynch Heights, Scotts Corners, Omar, Sinepuxent, and Cypress Swamp Formations, as well as Holocene upland, shoreline, marine, and dune deposits. In addition, deposits of several other recently established Quaternary formations (Ramsey, 2010) — the Ironshire, Turtle Branch, and Kent Island Formations — would also be included in the unconfined aquifer in places. In Kent County, the unconfined aquifer includes deposits from the Calvert, Choptank, Beaverdam, Columbia, Lynch Heights, and Scotts Corners Formations. Andres and Klingbeil (2006) recognized that the Beaverdam Formation makes up the largest portion of the unconfined aquifer in Sussex County; the results of this study indicate that this is also the case in Kent County.

The maps of the elevation of the base of the unconfined aquifer (Fig. 49) and the thickness of the unconfined aquifer (Fig. 50) reflect underlying geologic controls. The unconfined aquifer is generally less than 100-ft thick in Kent County. In eastern Kent County, the unconfined aquifer is associated with the Pleistocene sediments of the Delaware Bay Group, an interval that has several erosional unconformities, any of which could define the base of the unconfined aquifer. The base of the unconfined aquifer is commonly between 20 and 60 ft bsl in eastern Kent County and has notable irregularity related to the erosion (Fig. 49). However, the land-surface elevations are low in those same areas, so low elevations of the base of the unconfined aquifer do not necessarily equate to a greater unconfined aquifer thickness

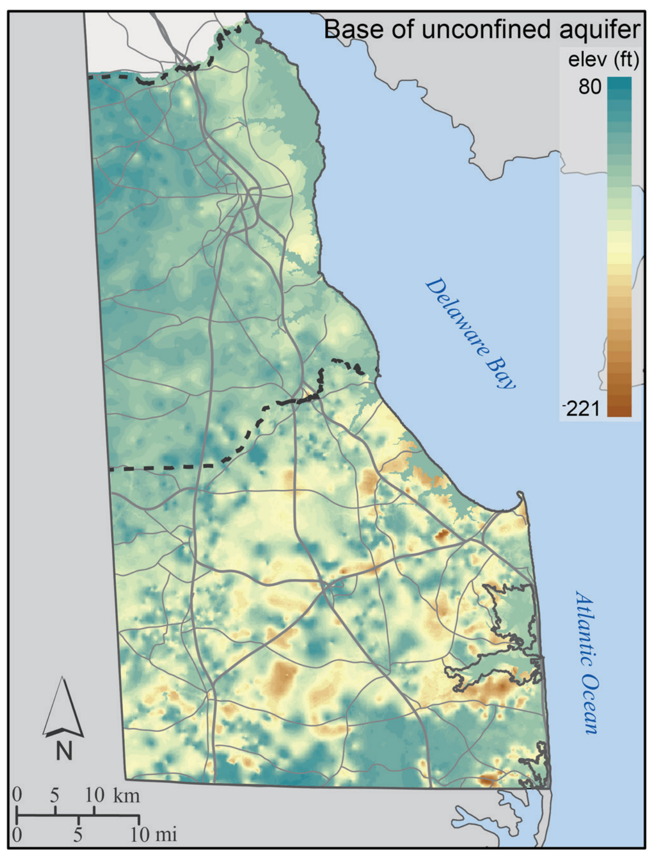

Figure 49. Map showing elevation of the base of the unconfined aquifer combining Kent County map (this study) and Sussex County map (Andres and Klingbeil, 2005). Areas with the thickest unconfined aquifer tend to occur where young surficial sands like directly above areas of stacked sandy lithologies in older formations. Datum is NAVD88.

In western Kent County, much of the unconfined aquifer lies within the Beaverdam Formation. Compared to the base of the Delaware Bay Group sediments, the base of the Beaverdam Formation is a less variable surface. As a result, the base of the unconfined aquifer has more gentle relief in that area and is commonly above sea level in northwest Kent County and about sea level in the southwest. The western part of the county also has higher elevations than near the bay, so the unconfined aquifer can be thick. The thickness of unconfined Beaverdam sand generally increases from north to south, from less than 40 ft to more than 50 ft (Fig. 50).

The unconfined aquifer occurs in the Columbia Formation in a narrow northwest- to southeast-trending belt near the center of Kent County, west of the zone where the unconfined aquifer is in the Delaware Bay Group and east of the zone where it is in the Beaverdam Formation. This belt corresponds to the area mapped as Columbia Formation on the surficial geologic map of Ramsey (2007). The unconfined aquifer is generally relatively thin there, commonly in the 20- to 40-ft range, thickening south of Dover to about 50 ft (Fig. 50).

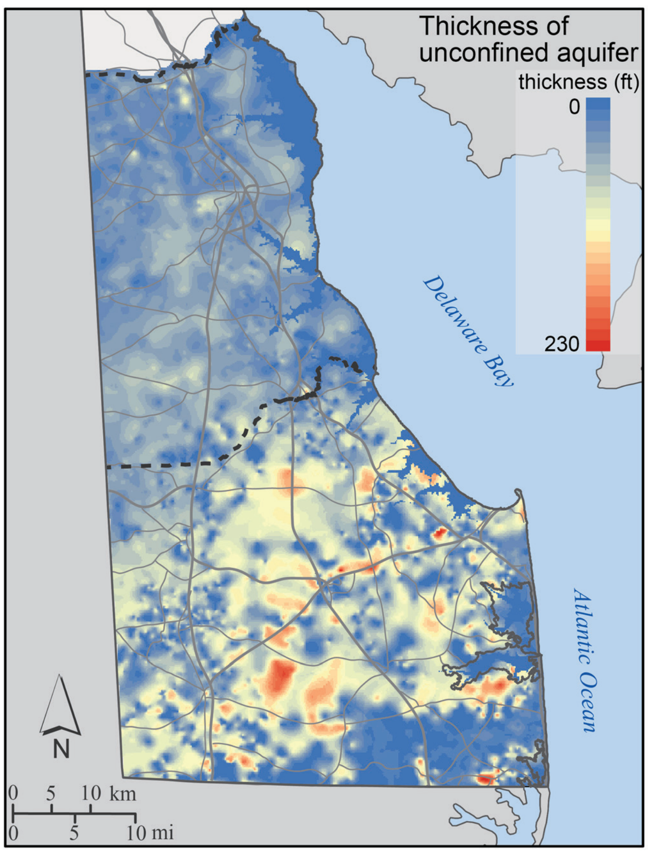

Figure 50. Map showing thickness of the unconfined aquifer derived from the base unconfined aquifer elevation maps made for Kent County (this study) and Sussex County (Andres and Klingbeil, 2005). Areas with the thickest unconfined aquifer tend to occur where young surficial sands lay directly above areas of stacked sandy lithologies in older formations.

The stratigraphic relationships between the surficial Pleistocene and (?Mio-)Pliocene formations and the underlying Miocene formations are responsible for some of the unconfined aquifer thickness variations in Kent County. Where Quaternary or Beaverdam sands lie directly over one of the aquifer sands of the Calvert or Choptank Formations, commonly in the subcrop belts for these aquifers, the unconfined aquifer may be thicker, adding additional tens of feet of Miocene sand to the bottom of the unconfined aquifer. A few locally thick areas occur in Kent County where the unconfined aquifer may total 100 ft, generally due to unusual vertical superimposition of sandy facies.

The Sussex County unconfined aquifer map rasters are based on Andres and Klingbeil (2006) and show a more significant degree of variability than the Kent County unconfined aquifer raster surfaces. The base of the unconfined aquifer in Sussex County can be as high as 70 ft asl to as low as more than 200 ft bsl, with significant variations across short distances (Fig. 49). This results in large thickness variations, from as much as 200-ft thick in locations in eastern Sussex County to as little as 10-ft thick in approximately 11 percent of the map area. Despite these large variations, the thickness of the unconfined aquifer is between 50- and 100-ft thick in slightly more than half the area of the map of Andres and Klingbeil (2006).

The greater variation in Sussex County is largely a function of the different geologic units that make up the unconfined aquifer. The greatest thicknesses tend to be where sandy Quaternary formations are superimposed on an unusually sandy Pocomoke interval that generally lacks mud beds which, in turn, directly overlies the normally sandy Manokin aquifer interval. The areas of thin or absent unconfined aquifer (Fig. 50) mostly occur in one of these settings: 1) where the Cypress Swamp Formation (Andres and Howard, 2000) and associated Holocene wetlands occur at the land surface; 2) in marshes along the Delaware Bay coast; 3) where muds of the Omar Formation occur near the surface (Andres and Klingbeil, 2006); and 4) in areas of Holocene wetland deposits near the Atlantic coast and Inland Bays.

Besides the geological differences, the greater variation in unconfined aquifer maps between Kent and Sussex Counties may be due in part to slightly different mapping methods. The unconfined aquifer maps rely on a large volume of drillers logs of variable quality. For Kent County, two rounds of unconfined aquifer mapping work were done. The results of the first round of raster calculations were evaluated to identify trends and reevaluate use of especially high or low outlier points. Borehole records that caused anomalies and were of questionable quality were excluded from the raster calculation process in the second round. The resulting Kent County raster surfaces could be expected to have less variable elevation and thickness values compared to Sussex County raster surfaces that may not have been subjected to the same level of data screening.

The unconfined aquifer typically consists of unconsolidated quartz sands in the Delaware Coastal Plain. In Kent County, wells producing water from the unconfined aquifer penetrate lithologies belonging to any of several formations. In western Kent County, the lithologies are normally fine to coarse, sometimes gravelly sands of the Beaverdam Formation. In northern Kent County, where the unconfined aquifer is thick and yields significant volumes of water, much of it is composed of fine- to coarse-grained sands of the Calvert Formation that make up the Cheswold aquifer where confined. In the Dover area, most unconfined aquifer wells are screened in coarser-grained sand (and some gravel) zones of the lithologically variable Lynch Heights Formation. Unconfined aquifer wells along the U.S. Route 13 corridor south of Dover and west of the Route 13 corridor north of Dover, are in fluvial sand and gravel of the Columbia Formation. Differences in lithologies and hydrologic characteristics that are related to the formations in which the unconfined aquifer occurs would be a good topic for future study.

In Sussex County, the most widespread surficial geologic unit is the Beaverdam Formation, which functions as the unconfined aquifer in more areas than any other formation. Sands of several Quaternary formations are also common surficial deposits (Ramsey, 2010) and may make up shallow unconfined aquifer materials (Andres and Klingbeil, 2006). The deeper part of the unconfined aquifer, where it is especially thick, may include Bethany Formation and/or Cat Hill Formation sands (which would be Pocomoke or Manokin aquifer if confined) that are similar in lithology and permeability to the surficial deposits above them. Areas where the normally confined Manokin and Pocomoke sands subcrop under these surficial deposits are outlined on the "windows" maps (Figs. 44 and 48).

The unconfined aquifer is underlain by fine-grained beds of several formations. The first confining bed below the unconfined aquifer in Sussex County is typically clay and silt but can also contain thin sand beds or admixtures of sand, more common in some formations than others (Andres and Klingbeil, 2006). Even though these more permeable lithologies are uncommon in the confining intervals, they can provide conduits for leakage. However, Andres and Klingbeil (2006) suggested that most groundwater flow was confined by these fine-grained beds and leakage was minimal.

Although we use the unconfined aquifer maps created for Sussex County by Andres and Klingbeil (2006), newer borehole data is included in our cross sections; as a result, there are minor differences between the profile of the base of the unconfined aquifer extracted from their map and the base of the unconfined aquifer refined from newer boreholes. Therefore, the cross sections on Plate 2 include an interpretation of the unconfined aquifer (darker yellow) derived from the Andres and Klingbeil (2006) map, as well as a superimposed lighter yellow profile interpreted from our new boreholes (Plate 2, sections K-K', L-L', and M-M').

"Confined Columbia" Aquifer

We recognize a "confined Columbia" aquifer in our analysis of water use in this study. The "confined Columbia" is not an aquifer with specific characteristics or origins, but rather an informal term that is used for any water-producing or potentially water-producing confined aquifer sand that is younger than the youngest named aquifer sands of the Pocomoke aquifer (Fig. 4). The name "Columbia" is informally applied because of the historically loose application of this name as aquifer and formation for almost all near-surface sands in the Delaware Coastal Plain.

Intervals that we identify as "confined Columbia" aquifer are most often aquifer-quality sands in the Beaverdam Formation that are overlain by fine-grained upper Beaverdam, Pleistocene, or Holocene beds; however, the name can also be used for sands in any of the Pleistocene Formations that are capped by Pleistocene or Holocene fine-grained sediments. The "confined Columbia" aquifer is most commonly recognized in Sussex County. Because there is no geologic reason for it to exist as a distinct body with any kind of areal extent or connectivity, there is no practical reason to map its elevation or thickness. Such a map would essentially contour unrelated data. The "confined Columbia" aquifer is not included on the cross sections because of the complex stratigraphy of the Pleistocene units and lack of detailed mapping of them in parts of Sussex County.

Confining Units Summary

A number of muddy intervals serve as confining units in southern Delaware. The Upper Cretaceous Navesink Formation and the lower Paleogene Hornerstown Formation are muddy units, rich in glauconite sand, which overlie and confine the Mount Laurel aquifer.

The stratigraphy of the confining units above the Rancocas aquifer change as the facies of the aquifer interval change southward. The Eocene Manasquan and Shark River Formations make up an approximately 100-ft thick confining unit of silts and clays above the Rancocas aquifer where the aquifer is thickest and sandiest in northern Kent County. South of Smyrna, where the Rancocas aquifer is thinner, the aquifer sand occurs only in the lower part of the Vincentown Formation and the upper part of the formation is part of the confining unit (Hc45-21, Plate 1, section D-D'; Kb32-01, Plate 1, section F-F'). Further south in central Kent County, the Rancocas-equivalent interval is entirely muddy with no aquifer quality sands present.

The confining beds above the Piney Point aquifer are muds of the lower part of the lower Miocene Calvert Formation in areas of Kent County where the aquifer is most extensively used. However, in northern and western Sussex County, the confining beds immediately over the Piney Point sands include unnamed glauconitic muds that are likely Oligocene age based on preliminary microfossil data. These beds are absent in Kent County, likely due to erosion beneath a basal Miocene unconformity but may be related to Oligocene deposits encountered in boreholes at Lewes (Oh25-02, Andres et al., 1990) and Bethany Beach (Qj32-27, Miller et al., 2003; McLaughlin et al., 2008).

The aquifers of the Calvert and Choptank Formations are, with the exception of the uppermost aquifer, confined by intraformational muds (Fig. 4). Within the Calvert Formation, the Lower Calvert, Cheswold, "Federalsburg", and Frederica aquifers are overlain by silt, clay, and/or sandy mud confining beds of the Calvert Formation. These confining beds are typically a few tens of feet thick and laterally continuous; however, in some places they may be thinner, either because of overall northward and westward thinning of the Calvert Formation or because of local erosion at the base of the overlying aquifer sand. In the Choptank Formation, silts and sandy muds overlie the Milford aquifer and Middle Choptank aquifer; however, these muddy zones are commonly thin and do not appear to be very clayey on geophysical logs. Therefore, they are probably not very effective confining layers.

Silts and clays of the St. Marys Formation overlie the Upper Choptank aquifer. These dark muds comprise a thick confining zone for the Upper Choptank aquifer and for the entire complex of aquifers in the Calvert-Choptank interval.

The mosaic of lithofacies present in the Bethany Formation include numerous zones of silt, clay, and muddy sand that, depending on their lateral extent, function locally as confining beds for the Manokin aquifer and Pocomoke aquifer sand bodies.

The Quaternary deposits of coastal Kent and Sussex Counties include beds of estuarine or shallow-marine muds and muddy sands, although individual beds are not regionally extensive. Fine-grained Quaternary beds can confine a variety of aquifers, depending on which aquifer subcrops underneath them. In coastal Kent County, the aquifers of the Calvert-Choptank interval may subcrop beneath the Delaware Bay Group. This configuration results in muddy confining beds of the Delaware Bay Group overlying the Cheswold aquifer in parts of coastal northern Kent County and progressively younger aquifers similarly confined southward. Delaware Bay Group muds may also confine Manokin or Pocomoke aquifer sands near the Delaware Bay in Sussex County. Muds within the Assawoman Bay Group function as confining beds in some areas of southeastern Sussex County where they overlie aquifer sands of the Pocomoke aquifer or the "confined Columbia" aquifer. In southwestern Sussex County, fine-grained intervals within the Nanticoke River Group confine aquifer sands of the Manokin, Pocomoke, or "confined Columbia" aquifers.

Discussion

Thickness and Facies Trends

The geology of the aquifers of Kent and Sussex Counties has considerable bearing on understanding the availability of groundwater resources. The basic configuration of the geologic framework is relatively simple: a near-surface series of Quaternary sediments of variable thickness is underlain by a succession of gently southeastward-dipping Late Cretaceous to late Cenozoic formations. The pre-Quaternary deposits show an overall thickening trend from the northwest to southeast, accompanied by facies changes from more proximal to more distal coastal environments.

Within the pre-Quaternary section, individual aquifers generally show an overall trend of increasing depth and thickness toward the southeast. However, some aquifers exhibit patterns that are more complex. The younger confined aquifers, the Pocomoke and Manokin aquifers, have the most variable thickness patterns owing to the numerous facies changes in the coastal deposits that typify them. Other confined aquifers have more regular thickness trends, but may show variations caused by local paleoenvironmental factors, such as erosion by coastal channels.

Sedimentary facies changes typically parallel the trend of increasing thickness from northwest to southeast; more proximal (nearshore) facies are to the northwest and more distal (offshore) facies are to the southeast. This trend of facies changes explains the occurrence of aquifer-quality sands in the Mount Laurel and Rancocas aquifer intervals in the northern part of the study area and their absence in the central and southern part. Both change from glauconitic to shelly shelf sands in northern Kent County to muddier, deeper-water, non-aquifer facies in central and southern Kent County. Interestingly, the Piney Point aquifer appears to show the opposite trend, with less aquifer sand and more muddy facies northwestward. However, this trend is not actually a facies change, but instead a progressive northwestward truncation of the sandier upper part of the Piney Point Formation beneath a regional unconformity (McLaughlin and Veléz, 2006).

Benson and Spoljaric (1996) and Andres (2001) have postulated southwest-to-northeast trending faults in northern Kent County to explain an interpreted down-dip increase in thickness of the Paleocene-Eocene section and associated facies change from aquifer sand to muds. The presence of faults has been supported by the identification of slickensides in cores of Paleogene sediments in northern Kent County (Andres, oral communication, 2013). However, the availability of more closely spaced well data in this study indicates that the down-dip facies and thickness changes can be interpreted as a continual trend rather than as abrupt increases in thickness controlled by faults.

Aquifers of the Calvert Formation also show facies changes from up-dip to down-dip areas (McLaughlin and Veléz, 2006). The aquifer sands commonly have a sharp base and blocky to fining-upward log patterns northwest near their up-dip pinch outs. The upward shift to aquifer sand reflects shoaling from muddy offshore non-aquifer facies in approximately 30 to 50 ft water depths to sandy nearshore aquifer facies. The upward fining can be interpreted as tracing further shoaling from tidal channels and deltas to quiet-water estuarine deposits or tidal flats. A sharp basal contact likely reflects erosion by estuarine or tidal channels cutting into the underlying finer-grained confining beds. Where such erosion leaves thin confining layers, the aquifers in the Calvert Formation are more likely to behave as a leaky system rather than as distinct aquifers. Between the most up-dip and down-dip areas, these aquifers tend to have a thin, coarsening-upward interval at the bottom overlain by a thicker fining-upward pattern. Such a pattern reflects the same type of upward shoaling succession as the previous one but a bit further offshore; as a result, erosive channel facies are less common and more of the coarsening-upward shoreface package under the cap of estuarine deposits is preserved. In down-dip, southeasterly locations, these aquifers exhibit a coarsening-upward pattern that reflects shoaling and shoreline progradation; the facies change upward from offshore muds in as much as 100 ft of water depth, to muddy or fine lower shoreface sands, to coarser upper shoreface sands in 5 to 20 ft of water depth. Up-dip to down-dip facies trends are similar but less pronounced in the Choptank Formation.

The aquifer correlations, and resulting depth and thickness maps created in this study, could be tested in future studies using hydraulic head data. Analysis of heads versus withdrawals that are assumed to be in the same aquifer could confirm hydraulic connections and lateral continuity of the aquifers as correlated, as well as allow evaluation of potential hydraulic connectivity between different aquifer units. For example, Drummond et al. (2012) examined the aquifers of the

Eastern Shore of Maryland, where the Calvert and Choptank Formations are present but are generally thinner, sandier, and contain fewer fine-grained intervals than in Delaware. Utilizing aquifer test data, they concluded that sand bodies within the Calvert Formation act as an interconnected system, rather than individual aquifers, and so combined these sands into a single hydrologic unit, a "Calvert aquifer system."

Recharge

We created a map of subcrop areas for each formation that highlight where confined aquifer recharge may be taking place (Fig. 21). These subcrop areas are identified where the aquifer maps suggest that surficial sands of Quaternary formations or the Beaverdam Formation are in direct contact with otherwise confined aquifer sands of older geologic formations. In many cases, the lithologies are so similar that differentiation of the surficial sand formations from intersecting older sand formations is difficult without sample materials or a detailed lithologic log. Although groundwater flow regimes may locally create discharge areas, most of the extent of these subcrop areas will likely be recharge pathways where appropriate permeable lithologies are present in the surficial geologic unit.

We first identified the intersection of raw elevation rasters of the top and base of each confined aquifer with the elevation raster for the base of the unconfined aquifer. The recharge area of each confined aquifer includes the areas of intersection with the unconfined aquifer and nearby areas where they could potentially be connected because confining beds are thin or of limited areal extent.

A pattern is evident in which older aquifers subcrop progressively farther northwestward. The youngest confined aquifers, the Pocomoke and Manokin (Fig. 4), subcrop widely over Sussex County; the Pocomoke subcrop areas are closer to the Atlantic coast and the Manokin subcrop areas are further inland. The Upper Choptank, Middle Choptank, Milford, Frederica, "Federalsburg," and Cheswold aquifers subcrop from south to north in Kent County. The minor Lower Calvert aquifer does not subcrop in Delaware. The Piney Point aquifer does not subcrop under the surficial sands because it is progressively eroded northward in the subsurface under the base of the Calvert Formation (Fig. 3); as a result, the Piney Point has only indirect recharge. The oldest aquifers examined in this study, the Rancocas and Mount Laurel, subcrop in New Castle County.

The aquifer sands of the Calvert and Choptank Formations are likely recharged where they subcrop under the base of the overlying Beaverdam Formation or sandy Quaternary strata. In general, the shallow-marine Calvert and Choptank sands differ from the younger units in their overall finer grain sizes, common presence of shells, and more regular nature of their stratigraphic character. However, in some places near their up-dip limits, these Calvert/Choptank sands may show a transition to marginal-marine and estuarine deposits. This change is manifested in less-shell-rich facies, more erosive bedding surfaces, and variable lithologies that range from coarse sands to muds. The gross similarity of these marginal-marine Calvert/Choptank deposits to the overlying Beaverdam sands or Quaternary sediments can make it difficult to identify the contact between them on well-driller logs and geophysical logs.

The Manokin and Pocomoke aquifers subcrop under surficial deposits near their up-dip limits away from the coast in Sussex County (Fig. 21). However, as noted earlier, lithologic heterogeneities in the Bethany Formation and Quaternary formations locally create thick unconfined aquifer sands where sandy Quaternary sediments lie directly on predominantly sandy Bethany Formation sediments and/or directly on the sandy upper part of the Cat Hill Formation. This configuration (e.g., Plate 2, section K-K', Oh52-05; section M-M', Pg31-01) results in direct recharge "windows" that can be mapped for the Manokin (Fig. 44) and Pocomoke aquifers (Fig. 48).

Sequence Stratigraphy of Aquifers

The concepts of sequence stratigraphy can be used to help distinguish the aquifers of Kent and Sussex County. A sequence is a genetically related, unconformity-bound stratigraphic unit. The sequence can be subdivided into smaller units called systems tracts based on patterns of facies change; each systems tract can generally be related to certain conditions of relative sea-level change (Fig. 51). Understanding the sequence stratigraphic controls on the deposition of aquifers and confining beds provides a genetic frame of reference that can improve the quality of interpretations in areas with sparse well control.

The alternation of aquifers and confining layers in the Calvert-Choptank section of central Delaware reflects sea-level rise and fall and can be characterized using the concept of sequence stratigraphy (McLaughlin and Veléz, 2006). The aquifer sands in this interval generally occur at the top of shallowing-upward shallow-marine packages. In most places, they are overlain by confining beds of silt or clay that reflect a deepening of water depths. The contact between the shoaling-upward package and the transgression commonly shows some evidence of an unconformity. A cemented zone (marine hard-ground) may be present at this contact; in other places, concentrations of authigenic minerals like phosphate are noted; and, in other places, a transgressive lag deposit of shells or other coarse material may be present (Miller et al., 2003, for examples).

In the context of system tracts, the Calvert-Choptank section is predominantly highstand systems tract deposits, characterized by a shoaling-upward transition from offshore muds and muddy sands to nearshore sand deposits that comprise the aquifers. The unconformity near the top of this shoaling-upward succession is interpreted as a sequence boundary formed by exposure of the formerly inundated coastal areas during a period of sea-level fall and the subsequent lowstand; in some cases, subaerial exposure may have persisted for as much as a few hundred thousand years (Miller, 2002; Miller et al., 2003). The overlying thin, generally fining-upward, interval of lag deposits and muds is interpreted as transgressive systems tract deposits produced by the subsequent rise of sea level. Miller (2002) estimated that the amplitude of some early and middle Miocene sea-level changes might have been as much as 100 ft or more. This means that Miocene locations in Delaware would have experienced significant changes in shoreline position through time.

The deposition of the Calvert-Choptank system ends with a marked shift in depositional style to predominantly silt and clay beds in the St. Marys Formation in most of Sussex County. The contact between the Choptank and St. Marys Formations is associated with a sequence boundary. The sequence boundary occurs slightly below the formation contact. A thin zone of sand preserved as a transgressive lag above the sequence boundary is typically placed in the Choptank Formation. Above that lag sand, the muddy facies of the St. Marys Formation form a regional confining layer.

Other aquifer intervals can also be understood in the context of sequence stratigraphy. The Mount Laurel aquifer overlies a thin interval of muddy glauconite sands of the Marshalltown Formation and is overlain by muddy glauconite sands of the Navesink Formation. The Marshalltown beds are interpreted as transgressive systems tract deposits with an associated maximum flooding surface; the Mount Laurel Formation represents progradation of highstand systems tract sands over the Marshalltown (Miller at al., 2004). A gamma-ray spike occurs at many localities at or near the top of the Mount Laurel Formation and reflects the presence of phosphate pebbles (Miller at al., 2004). This high-gamma horizon is interpreted as a sequence boundary with the phosphate occurring within a lag deposit. In some places (e.g. Plate 1, section C-C', Hc34-51) this sequence boundary occurs at the top of the Mount Laurel aquifer. In other locations, this sequence boundary may be marked at the base of a high gamma zone below the top of the Mount Laurel aquifer, in which case the sands above it are interpreted as a thin zone of reworked Mount Laurel sands in the transgressive systems tract of the next higher sequence (e.g., Plate 1, section A-A', Ib34-07).

The sequence stratigraphic character of the Piney Point Formation is similar to the Mount Laurel, with the difference being the northward truncation of the top of the Piney Point Formation under an unconformity at the base of the Miocene. In central and southern Kent County, the Piney Point is a rather thick coarsening-upward package that is increasingly sandy above its contact with the underlying Shark River Formation, which represents a highstand systems tract. The cleanest, best aquifer-quality sands occur near the top of the unit. A gamma-ray log spike commonly occurs a few feet to tens of feet below the top of the Piney Point aquifer. The sands above that spike are interpreted as a zone of Miocene sediments reworked from the underlying Eocene Piney Point Formation, but nevertheless hydrologically part of the Piney Point aquifer.

The sequence stratigraphy of the Rancocas aquifer is more difficult to characterize. In New Jersey, the equivalent interval in the Vincentown Formation generally includes two stratigraphic sequences, with the details depending on location (Harris et al., 2010). In Delaware, the sequence framework is less clear. The Rancocas aquifer is a thick (more than 100 ft) stack of glauconitic carbonate sands and shelly quartz sands in southern New Castle County and northern Kent County; the most conspicuous vertical changes are a slight upward increase in mud content and decrease in shell content in the Smyrna area. This stack of sand becomes thinner and transitions

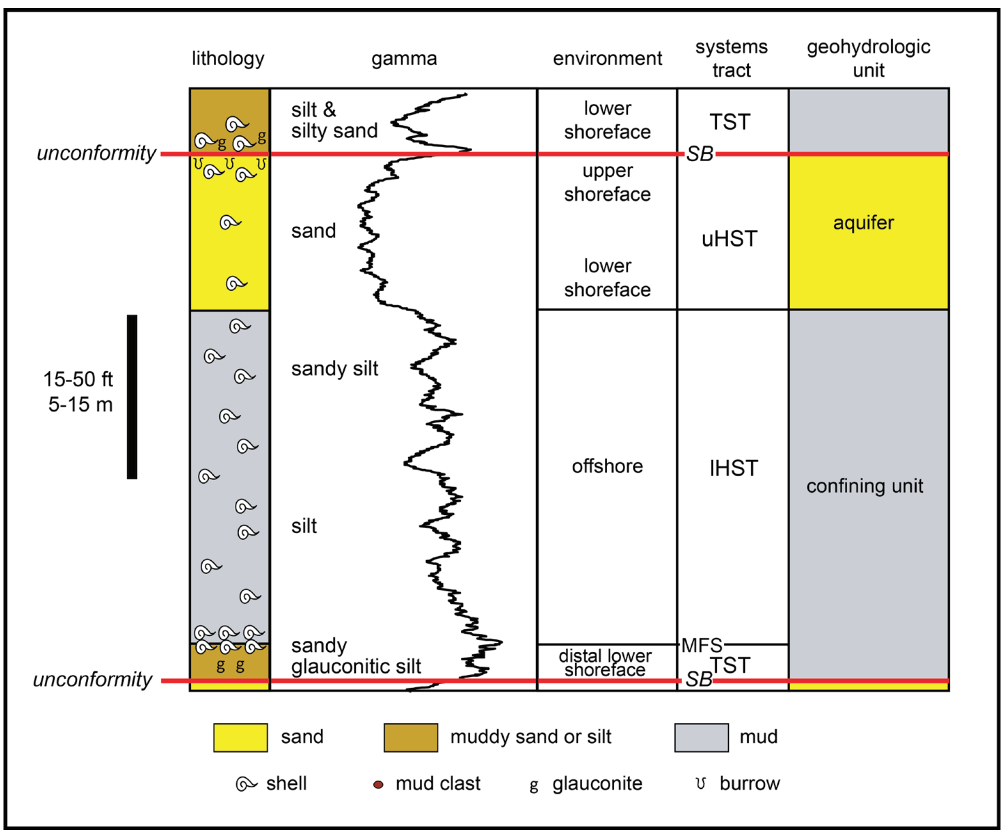

Figure 51. Idealized diagram of stratigraphic sequences in the shallow-marine interval that includes the Calvert and Choptank Formations in Kent and Sussex Counties (after McLaughlin et al., 2008). TST, transgressive systems tract; SB, sequence boundary; uHST, upper highstand systems tract; lHST, lower highstand systems tract; MFS, maximum flooding surface.

into muddy facies south of Smyrna. The exact nature of this transition and the associated sequence stratigraphic framework will require further study to decipher.

The sequence stratigraphy of the Cat Hill and Bethany Formations and the Manokin and Pocomoke aquifers within them is difficult to interpret with the data available. The variable nature of the lithofacies present in these coastal and marginal marine deposits requires more and better data to interpret sequences confidently. More closely spaced data points that extend through the entire interval are necessary to understand stratigraphic continuity. Additional high-quality descriptions of borehole geology, optimally based on core, will permit better characterization of key stratigraphic surfaces.

GROUNDWATER WITHDRAWALS

Purpose and Scope

Groundwater is the sole source of drinking water in the Coastal Plain of Delaware and the most important source of water for farms and industries in Kent and Sussex Counties. The goal of our water-use study is to understand groundwater withdrawals in Kent and Sussex Counties in three dimensions through time. This requires the analysis of groundwater use from multiple angles: volumes of withdrawals, source aquifer, geographic location of withdrawal, and type of water use. Understanding water use from each of these perspectives can be of significant benefit to managing this valuable public natural resource.

The analyses of groundwater use presented here are not a definitive “final word” on the subject. This study examines groundwater withdrawals from 2004 through 2008. The results presented here should provide reasonable first-pass estimates of groundwater withdrawals on an aquifer-by-aquifer basis for the period of the study, revealing both trends and normal year-to-year variations. However, it should be kept in mind that there have been significant demographic changes that affect groundwater use in the years since 2008, the last data year analyzed here. These include continued population growth, changes in key industries such as poultry, and expansion of crop irrigation to new acreage. Therefore, our results represent a snapshot of groundwater use for the period of study that can also be used as a baseline and methodological framework for evaluating more recent trends.

Groundwater withdrawals are categorized in this study by water-use types that are generally comparable to the classification of well types used by the Division of Water at the Delaware Department of Natural Resources and Environmental Control (DNREC) with some additional subdivisions that facilitate our water-use analysis (Table 3). These categories are similar to those used by the U.S. Geological Survey (USGS) for nationwide and state-by-state tallies of water use (e.g. Hutson et al., 2004; Kenney et al., 2009). The USGS analysis of water use examines both surface water and groundwater withdrawals for the following categories:

- Public supply
- Domestic self-supplied
- Industrial self-supplied
- Irrigation
- Aquaculture
- Livestock
- Mining
- Thermoelectric power

Table 3. Water-use categories used in this report to classify reported and estimated groundwater withdrawals.

Reported withdrawals
Public water systems (PWS) (large, all types)
Industrial self-supplied
Irrigation: golf course (subset)
Estimated withdrawals
By well
Public: community water systems (CWS) (small non-reporting)
Public: transient non-community water systems (TNC) (small non-reporting)
Public: non-transient non-community water systems (NTNC) (small non-reporting)
Irrigation: golf course (subset)
By area
Domestic self-supplied
Irrigation: agricultural
Irrigation: lawn self-supplied
Livestock

The USGS and DNREC water-use categories differ in a few ways. DNREC subdivides public water-supply (PWS) withdrawals into three subtypes to correspond to U.S. Environmental Protection Agency (EPA) categories (U.S. Environmental Protection Agency, 2012).

- Community water systems (CWS) supply water to the same population year-round.
- Transient, non-community water systems (TNC) supply water at facilities such as a gas station or campground where users are typically short-term and differ day-to-day or week-to-week.
- Non-transient, non-community water systems (NTNC) supply water to non-residential populations of the same people at facilities such as schools, factories, office buildings, and hospitals that have their own water systems.

Another difference is that irrigation and/or agricultural water encompasses several DNREC well categories. Crop irrigation is termed irrigation water use. Two other uses are grouped as agricultural wells by DNREC: poultry house water use, which corresponds to the USGS livestock category; and lawn irrigation wells, which are not included in the USGS tally.

Withdrawals for some categories of water use are estimated from reported data; other categories are uncalibrated or loosely calibrated estimates based on available user demographic data and/or geographic characteristics. DNREC requires that users who withdraw more than 50,000 gallons per day obtain a water allocation permit and to report monthly volumes. Typically, these users include larger public community water-supply systems, industrial systems, golf course irrigators, and agricultural irrigators. Monthly withdrawal data are submitted annually by the permit holders to the Water Allocation Branch, which collects, stores in database format, and uses these data to manage groundwater resources.

Many users withdraw less than 50,000 gallons per day and, as such, are not required to report water use. We have estimated groundwater withdrawals for these users. Domestic self-supplied users fall into this category. Withdrawals are also not typically reported for agricultural wells used for livestock (almost all livestock use in Delaware is for poultry). Smaller community systems and most non-community systems, for both transient and non-transient user populations, may also withdraw less than the required reporting level. Methods for estimation are documented in this report.

Even though agricultural irrigation and golf-course irrigation are categories where reporting is normally required, the pumping records for those well types are less complete than are records from reporting public and industrial wells. For that reason, we estimated water use in both categories. Crop- and climate-based estimation is used for analysis of irrigation water use in lieu of the very incomplete records of reported irrigation withdrawals. For golf course irrigation, we estimated water use for the permitted users who did not report as required by regulations. Methods for estimating these categories are also documented in this report.

A significant volume of groundwater withdrawals in Kent and Sussex Counties are associated with specific wells. A geographic location and depth are assigned to withdrawal data for every well with required annual reporting based on the well permit and completion report. For wells in categories in which reporting is not required, such as smaller public water systems, some withdrawals can be associated with a specific well with a known location and depth. However, most categories with estimated withdrawals are not associated with individual wells but instead estimated using area-specific geographic information such as census data (for census blocks) and agricultural data (for irrigated areas). Categories estimated in this manner include domestic self-supplied, agricultural irrigation, lawn irrigation, and livestock water use.

Water use categories are summarized in Table 3. We have grouped all public water-supply wells that report pumping into the category of public water-supply systems (PWS); many of these systems are mixed use that supply water for domestic, commercial, industrial, and other institutional users. Smaller public water-supply systems that are not required to report pumping are categorized in our inventory as community (CWS), transient non-community (TNC), and non-transient non-community (NTNC).

Background

Groundwater is the most important source of water for human needs in southern Delaware. Although some surface water is used for industrial and agricultural applications, groundwater comprises the vast majority of the water supply in Kent and Sussex Counties and is the source of all drinking water.

An unconfined aquifer and a number of confined aquifers are used in the Delaware Coastal Plain. An unconfined aquifer is also known as a water-table aquifer and is a saturated, water-bearing body in which the upper boundary is the contact between saturated and overlying unsaturated materials where the water pressure head equals the atmospheric pressure. Unconfined aquifers are shallow and easy to access, but also are more susceptible to the effect of human activities. A confined aquifer is a saturated water-bearing body overlain by a relatively impermeable confining layer and containing groundwater under pressure greater than atmospheric pressure. These aquifers are generally at greater depths where the presence of a confining layer isolates the groundwater from the Earth's surface, but the greater depth may make well installation more costly.

In southern Delaware, the unconfined aquifer is most commonly composed of highly permeable sandy sediments. Although the name Columbia aquifer has historically been used for these sediments, in this report the term unconfined aquifer is used. Twelve confined aquifers are identified in this report. These occur in formations ranging in age from Cretaceous to Quaternary, including sands that are designated as "confined Columbia."

Water use has increased steadily over the decades since the last comprehensive summaries of the groundwater resources of Kent and Sussex Counties by Sundstrom and Pickett (1968, 1969, and 1970). Groundwater withdrawals have grown from approximately 48 million gallon per day (Mgal/d) in 1966 (17.856 Mgal/d in Kent County, 30.272 Mgal/d Sussex) (Sundstrom and Pickett, 1968, 1969, and 1970), to 54 Mgal/d in 1985 (23.06 Mgal/d in Kent, 31.44 Mgal/d in Sussex) (U.S. Geological Survey, 2001), to 94 Mgal/d in 2005 (34.25 Mgal/d in Kent, 60.23 Mgal/d in Sussex County) (Kenny et al., 2009). This increase in water use parallels an increase in population, from 162,248 in 1970 (81,892 in Kent County, 80,356 in Sussex) to 209,300 in 1985 (102,800 in Kent, 106,500 in Sussex) to 320,516 in 2005 (143,968 in Kent, 176,548 in Sussex) (Delaware Population Consortium, 2006) — a doubling of the population in 35 years. In the same period, agricultural water use has also increased significantly as acreage under irrigation has grown. In 1966, irrigation water use was estimated at 2.17 Mgal/d for Kent County (Sundstrom and Pickett, 1968) and 6.0 Mgal/d for Sussex County (Sundstrom and Pickett, 1969, 1970). By 1985, groundwater withdrawals for irrigation were estimated at 6.86 Mgal/d for Kent County and 11.22 Mgal/d for Sussex County (U.S. Geological Survey, 2001). The USGS estimate of irrigation withdrawals for 2005 had increased to 16.54 Mgal/d for Kent County and 37.3 Mgal/d for Sussex County (Kenny et al., 2009).

A few general geographic patterns of groundwater use have taken shape in Kent and Sussex Counties over the last decades, driven by demographic changes (Table 4). In the late 1960s, groundwater withdrawals were concentrated in and near cities and towns. Municipal water utilities provided most of the public water supplies. As more suburban residential developments were built in the countryside and near the coast in 1970s and later, associated privately owned public water systems expanded the footprint of public groundwater withdrawals.

Table 4. Water-user populations and irrigated acreage in 2005 for Kent and Sussex Counties from federal government sources (Kenny et al., 2009; U.S. Department of Agriculture, 2009a).

2005	Population	Public water supplied population	Domestic self-supplied population	Acres irrigated
Kent	143,968	101,810	42,158	31,830
Sussex	176,548	147,030	29,518	90,810

Coincident with this increase in groundwater use for public water supplies, irrigation water use has increased in rural areas, driven by higher commodity prices (especially for corn) and government programs supporting irrigation. Acreage under irrigation has increased dramatically in recent decades (Table 4), from 17,443 acres in Kent and Sussex Counties in 1969 (10,902 in Kent, 6,541 in Sussex), to 59,741 acres in 1992 (Kent 20,283 in Kent and 39,458 in Sussex), to 101,851 in 2007 (29,066 in Kent, 72,785 in Sussex) (U.S. Department of Agriculture, 1972, 1994, 2009a). Interestingly, overall farm acreage has decreased over the last two decades. In the 1992 Census of Agriculture (U.S. Department of Agriculture, 1994), land in farms totaled 197,375 acres in Kent County and 304,680 acres in Sussex County; in contrast, the 2012 acreage numbers totaled 172,251 for Kent County and 272,232 for Sussex County (Cadwallader, 2012).

Categories and Volumes of Use

Most recent compilations of water use for Delaware by usage category have been made by the USGS. The Maryland-Delaware-DC USGS regional water resources office periodically issues water-use Fact Sheets summarizing water use in Delaware (Wheeler, 1999, 2003). In addition, the water use for each category has been estimated in USGS national compilations (Kenny et al., 2009; Hutson et al., 2004; Solley et al., 1998, 1993). Water-use estimates for 2000 (Wheeler, 2003) and 2005 (Kenny et al., 2009) are shown in Table 5. An advantage of the USGS water-use estimates is the documented, nationally consistent format and methodology. However, a disadvantage is the lack of access to detailed primary data. The USGS data are focused on groundwater use totals in each category by county; although the compilations estimate some of the usage by aquifer, the use by aquifer is not analyzed in a geographic context.

Groundwater Allocation and Reporting

The use of groundwater in Delaware is regulated by DNREC. The Water-Supply Section in the Division of Water conducts the agency's water permit, allocation, and protection programs. A brief, simplified version of some of the processes that DNREC uses to manage groundwater use is included in this report to help understand the source of much of the well and water-use data available and to evaluate the strengths and weaknesses of this dataset.

Before drilling, DNREC requires well permits and compliance with regulations to ensure that wells are located, drilled, and constructed in a manner that protects the public groundwater resource, the environment, and public health. The permits are recorded in a DNREC well database. If the proposed well will use more than 50,000 gallons per day, then a water allocation permit is required. The allocation permit sets limits for the maximum daily, monthly, and yearly water use. Water allocation permits are issued for a duration of 30 years and the permittee must report water use to DNREC annually. The totals of allocations for each use category and county as of year 2012 are summarized in Table 6.

DNREC requires a completion report after drilling to document the construction and status of each well. The basic details of the completion report are added to the well permit record in the DNREC database. For public, irrigation, and industrial wells where a water-use allocation is required, DNREC staff work with permittees to ensure that annual water-use data are submitted and entered into the DNREC water-use database. However, because DNREC does not classify wells consistent with USGS water-use categories, water use is categorized differently in this report than in USGS reports.

Additionally, DNREC has a Source Water Assessment and Protection Program (SWAPP) that closely monitors public wells. The SWAPP data are linked to related data maintained at the Division of Public Health's Office of Drinking Water (ODW). The SWAPP and ODW records provide reasonably complete data on the locations and depths of most public water-supply wells as well as the type of system that each well serves: community (CWS), non-transient non-community (NTNC), and transient non-community (TNC). The SWAPP and ODW records provide good estimates of the size of the population served and information on the type of water use for systems that do not report withdrawals, both of which are instrumental to making good estimates of water use.

Population Demographics

Kent and Sussex Counties have growing populations (Table 7), and this population growth is accompanied by increasing water demands. The population of Kent County was 162,310 in the 2010 census (U.S. Census Bureau, 2010), which represents an increase of 28 percent from 2000 (U.S. Census Bureau, 2000). Sussex County had a population of 197,145 in 2010, which represented a growth of 26 percent from the 2000 population. This represents an interesting shift from the prior decade, between 1990 (U.S. Census Bureau, 1990) and 2000 (U.S. Census Bureau, 2000), when the population increased less in Kent County (14 percent) than in Sussex County (38 percent).

The population is distributed between many large and small incorporated communities, numerous unincorporated communities, and rural areas. The land area of Kent County is approximately 597 square miles and Sussex County approximately 976 square miles (Table 8). Agriculture is the largest category of land use (DOSPC, 2007). In Kent County, 46 percent of the land is classified as agricultural and Sussex County has 42 percent in agriculture (Table 8). Urban areas only comprise 16 percent of land use in Kent County and 15 percent in Sussex County.

The distribution of population in these areas influences water needs and ground-water use. The 2010 Census recorded approximately 65,000 housing units in Kent County and more than 123,000 units in Sussex County (U.S. Census Bureau, 2010) (Table 7). However, many of these housing units in

Table 5. Groundwater withdrawal estimates for Kent and Sussex Counties by the U.S. Geological Survey (Wheeler, 2003; Kenny et al., 2009). Mgal/d, million gallons per day.

Year	County	Public (Mgal/d)	Domestic self-supplied (Mgal/d)	Industrial (Mgal/d)	Irrigation (Mgal/d)	Aqua-culture (Mgal/d)	Stock (Mgal/d)	Mining (Mgal/d)	Power (Mgal/d)	Total (Mgal/d)
2000	Kent	10.45	4.53	1.53	10.17	0.07	0.63	0	0	**27.38**
	Sussex	12.6	6.26	7.88	23.65	0	3	0	0.47	**53.86**
2005	Kent	12	3.37	1.19	16.54	0.1	0.4	0.33	0.32	**34.25**
	Sussex	13.24	2.36	6.1	37.3	0	1.04	0.19	0	**60.23**

Sussex County were not permanent residences but used as vacation housing. The number of housing units increased 29.4 percent in Kent County and 32.2 percent in Sussex County between 2000 and 2010 (U.S. Census Bureau, 2010) (Table 7). The greater increase of housing units in Sussex County than in Kent County, despite less of a population increase, probably reflects growth of non-resident seasonal/vacation housing in Sussex County.

Although rural areas make up more than 80 percent of the land area in both counties (Table 8), the majority of the population lives in urban areas (Table 7). In Kent County, approximately 73 percent of residents were living in urban areas versus 27 percent in rural areas (Table 7). The population distribution in Sussex County is decidedly more rural, with 58 percent of residents in urban areas and 41 percent in rural (U.S. Census Bureau, 2010). Population density is greater in Kent County with 277 residents per square mile compared to 211 in Sussex County. However, the housing density comparison is reversed because of the large number of vacation housing units in Sussex County. Kent County has 112 housing units per square mile versus 131 for Sussex County. Eastern Sussex County near the Atlantic Coast and Inland Bays accounted for half of the residential building permits issued between 2003 and 2006 (DNREC, 2014). These population and land-use trends can provide useful insights into water-use patterns.

Methods and Data

We used a combination of reported and estimated pumping data from the years 2004 through 2008 to arrive at our groundwater results. Required pumping records were evaluated for completeness in the following water-use categories: larger public systems (allocations >50,000 gal/d, required to report withdrawals), industrial systems, agricultural irrigation, and golf course irrigation. Pumping records for the larger public and industrial systems, as well as some of the golf courses, were reasonably complete and usable with editing. Water use was estimated where pumping records were too incomplete to determine groundwater withdrawals, such as for agricultural

Table 6. Groundwater allocations for Kent and Sussex Counties as of 2012 (Stewart Lovell, DNREC, written communication, August 22, 2012). Mgal/d, million gallons per day.

County	Use	Daily maximum supply (Mgal/d)	Monthly maximum supply (Mgal/d)	Yearly maximum supply (Mgal/d)
Kent	Public	39.2	28.1	21
	Domestic	4.3		
	Farm irrigation	157.3	125.1	19.5
	Golf course	2.2	0.9	0.2
	Industrial	5.7	4.5	6.2
	Total	208.7	158.6	46.9
Sussex	Public	61.9	50.7	31.6
	Domestic	8.1		
	Farm irrigation	619.4	454.3	72.2
	Golf course	12.2	7	1.4
	Industrial	30	23.3	19.1
	Total	731.6	535.3	124.3
Study Area Total	Public	101.1	78.8	52.6
	Domestic	12.4		
	Farm irrigation	776.7	579.4	91.7
	Golf course	14.4	7.9	1.6
	Industrial	35.7	27.8	25.3
	Total	940.3	693.9	171.2

irrigation and some golf courses. Water use was also estimated for smaller public systems (CWS, TNC, NTNC), self-supplied domestic users, livestock wells, and lawn irrigation wells that were not required to report pumping.

Table 7. Demographics for Kent and Sussex Counties (U.S. Census Bureau, 2000, 2010).

Census measure	Kent County	Sussex County
2000 population	126,697	156,638
2010 population	162,310	197,145
Percent population change	28.1	25.9
Percent population urban	73	58.7
Percent population rural	27	41.3
Population density	276.9	210.6
Housing density	111.5	131.4
Housing units	65,338	123,036
Percent housing change	29.4	32.2

Table 8. Land use statistics for Kent and Sussex Counties in 2007 (Delaware Office of State Planning Coordination, 2007).

Land Use	2007	2007 percent
Kent County	597	
Urban/suburban	97	16
Agriculture	272	46
Forest/wetlands/open	210	35
Water	18	3
Sussex County	976	
Urban/suburban	150	15
Agriculture	407	42
Forest/wetlands/open	369	38
Water	50	5

An important goal of this study was to understand the spatial distribution of water use in three dimensions, both by geographic location and by aquifer. Groundwater use for public and industrial systems was defined geographically using the x-y location of each associated well. Aquifer assignment was based on the elevation of the well screen in each well, providing a z-dimension location. Groundwater usage was estimated areally, by census block, for the categories of agricultural irrigation, self-supplied domestic, livestock supply, and lawn irrigation. Aquifer assignments within each category were based on the estimated proportions of wells in each aquifer in each census block, as explained below for each water-use category.

Data Sources

Information for analyzing groundwater withdrawals came from many sources. This included databases of well information, basic geographic GIS datasets, census data, and water-use data from DNREC and water providers that are listed on Table 9.

Well locations from DGS and DNREC databases were carefully reviewed for quality control. The DGS maintains well location and construction information in WAYSTS, an Oracle-based internal database that is regularly updated using database extractions from the DNREC well-permit database. Well location and screen-depth data were verified and corrected using data from various versions of DNREC's SWAPP and water-use databases. The SWAPP database is likely the highest quality DNREC database for well location and construction information because of careful review and correction of data over the years. The availability of data from multiple sources facilitated data verification. In addition, most public water-supply well locations were verified using aerial photographs and information supplied by public water providers, most notably, Artesian Water Company and Tidewater Utilities.

Basic geographic locations were obtained from DGS geospatial datasets. Data from 2008 aerial photography were particularly useful to ensure up-to-date locations. DGS roadway centerline, geographic boundaries, tax parcel, hydrography, and digital elevation model (DEM) datasets were also utilized.

U.S. Census Bureau datasets provided geospatial population and socioeconomic demographic data used in analyses of domestic water use. James Adkins of the University of Delaware College of Agriculture and Natural Resources kindly provided a copy of a dataset that included digitized outlines of irrigated agricultural areas based on his analysis of 2008 aerial photography on Google Earth (Adkins, 2012, personal communication). We added several other areas of irrigation in the course of our analyses. Total agricultural irrigated acreage is shown in Table 10. USDA spatial datasets used included the 2008 cropland data layer (U.S. Department of Agriculture, 2009b) and the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) (Soil Survey Staff, 2006) data, as well as daily precipitation and evapotranspiration data relevant to the calculation of crop irrigation needs that were downloaded from the Delaware Environmental Observing System (http://www.deos.udel.edu/monthly_retrieval.html).

Water-use data from various generations and versions of DNREC water-use databases were used for our compilations and analyses. These included an extraction from a comprehensive water-use database (dbo prefix), data tables corresponding to water-use reporting forms that DNREC staff updated in the late 2000s, and a new DNREC compilation made in the early 2010s.

We compiled water-use data for the years 2004 through 2008 for 444 wells (366 public water systems, 62 industrial, 16 golf course) (Table 11). We also compiled location and construction information for 403 additional lower-volume, non-reporting public system wells for which we were able to estimate water use. These include 180 CWS wells, 154 TNC wells, and 69 NTNC wells (Table 11).

Table 9. Data sources used for the analysis of groundwater withdrawals. WATSYS is the DGS well database system. SWAPP is the Source Water Assessment and Protection Program.

Well locations
DGS WATSYS database
DNREC well permit database (via DGS WATSYS)
DNREC SWAPP database
DNREC water-use database
Tidewater Utilities well reports
Artesian Water Company water facility reports
Basic geographical data
DGS Grand Central Data
Population data
U.S. Census Bureau
Agricultural data
University of Delaware College of Agriculture (Adkins) irrigation location map
USDA web soil survey (2006)
USDA crop data layer (2008)
Delaware Office of the State Climatologist climate records
Water use
DNREC water-use databases (various versions)
DNREC public water systems service area GIS dataset
Artesian Water Company water service area shape files

Table 10. Irrigated agricultural acreage identified on aerial photography in Kent and Sussex Counties (Adkins, 2012, written communication and this study).

County	Acres irrigated
Kent	28,370
Sussex	74,206

Although agricultural irrigation wells are associated with water allocations and are required to report water use, the database of reported pumping was insufficient for an analysis of that category of use. A total of 704 wells were listed under an inventory of allocations provided in August 2012 by DNREC Division of Water (Stewart Lovell, written communication, 2012). However, our compilation of well pumping data from all sources only yields records for 409 irrigation wells compared to more than 2400 individual sites that we identified in a spatial analysis of irrigation areas. In addition, the quality of the reported irrigation well data was poor. Data for many wells were inconsistently reported from year to year (Table 12) and, in some cases, the same numbers were entered for multiple years or for multiple wells under the same allocation. Most reported data are somewhat flawed because pump timers with estimated flow rates were used instead of flow meters. Therefore, we combined the irrigation polygon dataset and acreages (Table 10) with the agricultural census and climate data for irrigated areas to calculate estimated irrigation water applications for the years 2005 through 2008.

The three other categories of water use—domestic self-supplied, lawn self-supplied, and livestock—do not require reporting of pumping data because of the small volumes of groundwater withdrawn. Well location data and current well status for these categories was not as closely scrutinized as for public wells and wells with allocations. As a result, we estimated water use for those categories for geographic areas that are treated as aggregates of wells and/or users.

Table 11. Number of wells used for water-use analyses in Kent and Sussex Counties in categories with verifiable well locations.

Allocated systems: reported water use	Number of wells
Public systems (PWS) (large, all types)	366
Industrial self-supplied	62
Irrigation: golf course (subset)	16
Allocated systems: estimated water use	
Irrigation: golf course (subset)	11
Non-allocated systems: estimated water use	
Public systems: community (CWS) (small non-reporting)	180
Public systems: transient non-community (TNC) (small non-reporting)	154
Public systems: non-transient non-community (NTNC) (small non-reporting)	69

Table 12. Inventory of reported pumping data for agricultural irrigation wells in Kent and Sussex Counties, 2004 through 2008.

Number of wells	Reported data
383	Total irrigation wells with reported pumping
93	*4 yrs missing data*
23	*3 yrs missing data*
68	*2 yrs missing data*
63	*1 yrs missing data*
136	*0 yrs missing data*
704	Wells with irrigation allocations
2408	Irrigation areas mapped

Reported Water Use

We compiled water-use data for the years 2004 through 2008 using various databases obtained from DNREC. This compilation required a considerable quality-control effort to compare and merge the individual databases, eliminate duplicate reports, resolve conflicting data, and obtain missing data where possible. We were able to compile and analyze relatively complete pumping records for public and industrial systems that were required to report data to DNREC. These records included 366 public wells and 62 industrial wells. In addition, pumping data for 16 golf course wells (8 for all years) of the 27 required to report were included.

Estimated Water Use

Domestic Water Use: Public Community and Domestic Self-Supplied. Domestic Water use must be estimated outside of areas served by large public water systems that report withdrawals. In our classification, this includes two categories of water use: (1) small community water systems (CWS) that are not required to report withdrawals; and (2) households with their own well, which are classified as domestic self-supplied. We developed a domestic water-use model using an approach similar to Horn et al. (2008) for a USGS water-use study in the Seacoast region of New Hampshire. The Horn et al. (2008) study identified a suite of census factors that could be related to metered domestic water use. Our domestic water-use model compared similar census factors to reported pumping in parts of public water systems dominated by domestic use. The relationship of withdrawals to census factors in those areas served as the basis for estimating domestic water use in the absence of well pumping data.

Domestic Water-Use Model Estimation. A domestic water-use model was created for Kent and Sussex Counties using population data from the 2010 census, which should be generally representative of populations in 2004 through 2008 except for small areas developed in 2009 and 2010. The steps followed in the development of the model are summarized below.

1. Identify networks of public water systems with known supply wells that serve domestic users (35 networks).
2. Determine census-based population total for each network.
3. Determine average pumping (2004-2008 reported pumping) for each network.
4. Calculate average gallons pumped per capita per day (GPCD) in network.
5. Evaluate and select water-use-related census factors for analysis (five factors from 2010 and 2000 census).
6. Establish domestic water-use model using a multiple regression comparing pumped GPCD for each network to the network average of census factors from each block weighted by block population.
7. Check model by comparing modeled domestic water use to reported pumped water use for both GPCD and annual gallons used.

For step 1, using service area maps and aerial photography, we identified areas served by public water supply (PWS) where pumping was reported and where the areas were entirely or mostly characterized by domestic water use. These were grouped as networks of principally domestic PWS areas supplied by the same well or group of wells. Care was used to consider system interconnections and isolate systems where the supply wells were exclusively used for domestic water.

For step 2, we determined network populations by identifying the census blocks located in the public water system service areas for each network. Some census blocks lie only partly within a service area; in this case, the population was subdivided into public-supplied and self-supplied areas, or sub-blocks, according to the portion of tax parcels inside and outside of the service area, respectively (which required extensive manual editing). To account for seasonal populations not tabulated in the census, we assumed that the difference between housing units and households represented vacation rentals. The seasonal population was assumed to average 3 people per unit, which was annualized assuming an average occupancy of 66 summer and weekend days per year. The annualized seasonal population addition (SPA) for each census block, or proportionally calculated addition for sub-blocks, was represented by this equation:

$$SPA = (\text{housing units} - \text{households}) \times 3 / (66 / 365)$$

A seasonally corrected population (PopSC) was then totaled for each network as:

$$PopSC = Pop + SPA$$

For step 3, we used reported pumping data for 2004 through 2008 and calculated a sum of withdrawals from the wells in each network for each year. Several networks had highly variable year-to-year pumping numbers; these were excluded from the analysis because of low confidence in how representative or complete some of the reporting was. Thus, 35 domestic-use-dominated networks were chosen for analysis (Table 13). Average annual pumping values in gallons (PumpAvg) were calculated for each network. Horn et al. (2008) used metered household water-use data on a census-block basis to develop their water-use model; the aggregated network-scale data we used cover more than a single census block so provide slightly more geographically averaged sums of water use.

For step 4, similar to the approach in Horn et al. (2008), we calculated a value of gallons pumped per capita per day (GPCD) water use. A raw average GPCD (AvgGPCD) value was derived for each network (Table 13) by dividing the average annual pumping (PumpAvg, from step 3) by the seasonally corrected population (PopSC, from step 2) of all contained census blocks and sub-blocks in the network over 365 days.

$$AvgGPCD = PumpAvg / (PopSC \times 365)$$

For step 5, we chose five census factors to analyze the relationship of pumped water-use values to population characteristics in the census, similar to those used in Horn et al. (2008). These five factors were:

1. Household size
2. Housing unit density
3. Population density
4. Median year of construction
5. Median value of owner-occupied single-family homes

Household size, housing unit density, and population density were obtained from the 2010 census and compiled on a census block level (U.S. Census Bureau, 2010). We used household size in lieu of population per housing unit (which was used by Horn et al., 2008) to exclude seasonal housing units that were empty during the census. Median year

Table 13. Public water-supply system networks that principally serve households that were used to calibrate census-based modeled domestic water use to reported pumping data. GPCD, gallons per capita per day.

Pumping networks	Utility	Average GPCD	Model GPCD
Beaver Creek	Artesian Water Company	84	80
Cape Windsor	Cape Windsor	93	120
Canterbury Crossing	Tidewater Utilities	105	83
Clearbrooke Estates	Tidewater Utilities	61	76
Dover Meadows	Tidewater Utilities	58	56
Forest Grove	Tidewater Utilities	83	67
Grants Way	Tidewater Utilities	87	101
Gander Woods	Tidewater Utilities	72	88
Holly Hill Estates	Holly Hill Estates	96	116
Hunters Mill Estates	Tidewater Utilities	66	86
Indian River Acres	Tidewater Utilities	62	92
Love Creek Woods	Tidewater Utilities	60	92
Long Farm Estates	Tidewater Utilities	92	67
Mallard Lakes	Mallard Lakes	74	91
Misty Pines	Tidewater Utilities	69	72
Oak Crest Farms	Tidewater Utilities	84	79
The Point Farm	Tidewater Utilities	94	84
Southwood Acres MHP	Tidewater Utilities	61	96
Sandy Ridge	Tidewater Utilities	68	65
Sea Winds	Tidewater Utilities	73	98
Swann Keys	Swann Keys	121	97
Voshells Cove	Tidewater Utilities	60	73
The Woodlands of Millsboro	Tidewater Utilities	68	70
Webbs Landing	Tidewater Utilities	90	80
Willow Lake	Tidewater Utilities	58	71
Cooper Farm	Tidewater Utilities	58	54
Deer Meadows	Artesian Water Company	64	71
Felton	Tidewater Utilities	67	73
Henlopen Acres	Town of Henlopen Acres	147	153
Whitetail Run	Tidewater Utilities	95	71
Magnolia	Artesian Water Company	66	71
Meadows	Tidewater Utilities	94	80
Smyrna Clayton	Artesian Water Company	60	70
Stonewater Creek	Artesian Water Company	123	77
Viola	Tidewater Utilities	61	73

of construction and median value of owner-occupied single family homes were not available for the 2010 census at the time of this analysis; we substituted data from the 2000 census at the block group level (U.S. Census Bureau, 2000) for the 2010 census blocks within those block groups. The proportion of housing units in urban areas, a factor used in Horn et al. (2008), was not used in this study because our self-supplied domestic analyses were in mostly rural and suburban areas. After these data were compiled, a population-weighted average of the census factors for each census block was calculated for every network. Seasonally adjusted populations from each census block were used to make the network weighted averages for three of the factors—year house built, household size, and house value. Unadjusted raw census population data were used for the two density-related factors—housing density and population density—because of the complexity of data manipulations that would be required to calculate weighted densities using seasonal populations.

For step 6, we compared the per-capita water use (from step 4) to the five census factors (from step 5) using a similar

Table 14. Regression coefficients and other variable statistics for the per-capita water-demand model to predict water use per census block on the basis of 2004 to 2008 pumping data and 2000 and 2010 census data from 35 domestic-use-dominated public water system networks in Kent and Sussex Counties. >=, greater than or equal to; <=, less than or equal to.

Variable	Regression Coefficient	Area (census year)	Units	Range (network averages)	Weighted Average	Cap (census block/sub-block)	Standard error	t-statistic	p-value
Median year of construction	-0.00689	Block Group (2000)	Median year built minus 1900	68-92	83		0.00731	-0.738	0.466
Household size	-0.218	Block (2010)	People per unit	2.2-3.7	2.7	>=2.0	0.120	-1.42	0.165
Median value of owner-occupied single family homes	0.00000185	Block Group (2000)	dollar	173,900-600,000	226,658	<=600,000	3.11E-07	2.13	0.0411
Housing unit density	0.000113	Block (2010)	Units per square mile	27-2,000	921	<=2,000	6.24E-05	0.114	0.910
Population density	0.0000307	Block (2010)	People per square mile	47-8,702	4067		4.59E-05	0.462	0.647
Intercept	4.93	--	--	--	--	--	0.758	6.56	2.52E-07

Multiple regression coefficient of determination (R^2) = 0.546.

multiple regression as Horn et al. (2008). The left side of the equation was determined using the water use calculations in step 4. The variables in the right side of the equation are the five census factors described in step 5. The variable coefficients were determined by solving for the equation below:

$$ln(PC) = \beta0 + \beta1\ (X1) + \beta2\ (X2) + \beta3\ (X3) + \beta3\ (X4) + \beta5\ (X5) + E$$

where:

- *ln*(*PC*) = natural log of the domestic per capita water-demand coefficient, census-block value for gallons per day per person (GPCD);
- *X1* through *X5* = independent variables (census factors 1 through 5 above);
- β1 though β5 = regression coefficients for each variable;
- β0 = intercept;
- *E* = random error.

The regression coefficients and related statistics calculated are listed in Table 14.

Several iterations were necessary to establish a model that reasonably fit the data. Initial calculations suggested that unrealistically low or high values of some census factors would produce unreasonable values of modeled water use in some census blocks. Therefore, after considering values in comparable areas with known water use, we have set minimum or maximum limits for such factors, beyond which the limit values were substituted for the reported census values. The maximum house value used was $600,000; the maximum housing unit density used was 2000 units per square mile; and the minimum household size used was 2.0.

For step 7, we evaluated the results of the model by comparing the values of modeled domestic water use to values of reported pumped water use for each pumping network, both in GPCD and annual gallons used. To evaluate our domestic water use model, we first calculated modeled use for each census block/sub-block using the equation below, where DWmod is the total modeled domestic water use in gallons for the block/sub-block, PC is the domestic per capita water-demand coefficient for the census-block (from step 6) in gallons per day per person (GPCD) and PopSC is the seasonally corrected population (from step 2):

$$DWmod = PC \times PopSC$$

Next, we determined the total modeled annual domestic use for each pumping network by calculating the sum of the DWmod values from each block/sub-block in the network. Finally, we calculated a modeled per-capita domestic water-use value for each pumping network by dividing total modeled annual domestic use of the network by the total population of the network (Table 13, model GPCD column). These network-based comparisons of modeled versus actual pumping indicate that the model provides reasonable estimates of domestic water use, given the inherent inexactness of the data. A graph of the model versus reported pumping for annual water use yields a relationship of y = 0.931x + 1E+06 with a coefficient of determination R^2 = 0.9876 (Fig. 52). A similar plot of per capita use yields a relationship of y = 0.6864x + 30.589 with R^2 = 0.409 (Fig. 53).

With the model established and tested, we were able to estimate domestic water use for areas identified as self-supplied or served by a non-reporting community-water system. A value of modeled water use (model GPCD) was calculated for each census block or sub-block in these areas using the model equation (from step 6), the final calculated coefficients and intercept (Table 14), and the values of the five census factors in each census block/sub-block (from step 5).

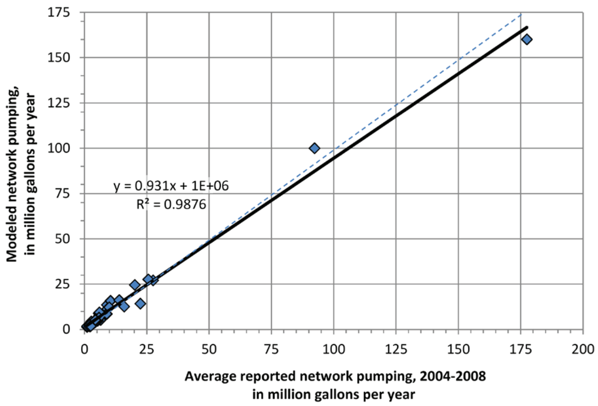

Figure 52. Graph of total modeled pumping versus average reported pumping from 2004 to 2008 for 35 public water system networks predominantly used for domestic supply in Kent and Sussex Counties. R^2, coefficient of determination.

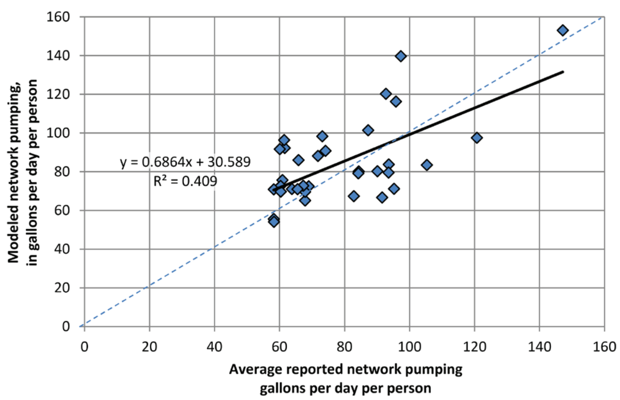

Figure 53. Graph showing modeled network pumping versus average reported network pumping from 2004 to 2008 for 35 public water system networks predominantly used for domestic supply in Kent and Sussex Counties. R^2, coefficient of determination.

Model Assumptions and Limitations. Our domestic water-use model provides only a first-pass estimate. Horn et al. (2008) highlighted five inherent assumptions underlying their domestic water-use model that should also apply to our study, but with some minor differences. The assumptions are (after Horn et al., 2008): (1) the functional form of the model is correct in terms of the variables included and their role in the model; (2) the error term (E, in equation above) is independent across the range of observations, implying that there is no correlation in the errors among the well pumping data used to calibrate the model; (3) the residuals of the model are normally, or nearly normally, distributed; (4) the residuals are "homoscedastic," meaning the distribution of the residuals is similar throughout the range of predicted values; and (5) the domestic users we model use for — smaller public community water systems and self-supplied households — have water-use behaviors similar to users in larger community water systems where the model was established. The fact that we could not test for these assumptions is a limitation of the validity of the model results.

Furthermore, our model has the limitation of being developed using broader-brush data. The model relies on network-scale pumping averages for reported pumping (spatial average), averages of pumping for multiple years (temporal average), broader block-group (rather than census block) data for two variables used to calculate modeled pumping, and the inherent random error in this type of analysis. The model also assumes that all water use in the model census blocks was for domestic use. Averaging the pumping data used may increase accuracy by generalizing across spatial and temporal variations of domestic water-use factors. However, the averaging also makes the data less precise. Ideally, this model should be tested and refined by detailed study of metered water use versus census factors in public water systems and for self-supplied domestic users.

Public Non-Community. Groundwater withdrawals were estimated for both transient (TNC) and non-transient (NTNC) categories of non-community systems by anticipated water use for the facility type. Two approaches were utilized, depending on the facility type. Water use was estimated using published rates of water use per person at many facilities. These rates were multiplied by the estimated population served according to the Delaware ODW web site and the SWAPP database. Such facilities included schools, offices, hotels, and campgrounds. Water use was estimated for other facilities such as gas stations and restaurants based on a water-use factor for the facility type and size class determined from review of the literature. For a few facility types such as shopping centers and grocery stores, water use was estimated from approximate square footage. Facilities types and water-use factors are listed in Table 15.

A large number of assumptions underlie the water-use estimates for these non-community public water systems. The most significant assumption is that water-use patterns are the same in all facilities in the same usage class; in reality, activity level and water consumption vary widely. Many estimates are based on the reported population served and rely on those numbers being accurate and representative of water use. Some estimates are based on square footage because of documented relationships of water use to area in the literature; however, square footage is not recorded in the SWAPP database and was estimated for this study, in some cases using aerial photography. For some facility estimates normally based on square footage, we used a per capita approach because data were available for population served where square footage could not be estimated. Finally, for withdrawal estimates for individual wells in a system served by multiple wells, we have assumed that all wells in the system have equal pumping usage; this provides a reasonable approximation but is not accurate for a detailed analysis.

Despite these assumptions, the calculations reported in this study can nevertheless be regarded as reasonable estimates of water use for non-community wells. The error inherent in numbers for individual wells only makes a minor impact in the understanding of overall water use in Kent and Sussex Counties.

Agricultural Irrigation. Because the pumping database for irrigation wells is too incomplete, agricultural irrigation withdrawals were estimated by a daily crop-water-demand model using the irrigation scheduling software KanSched2. Scientists at Kansas State University developed KanSched2 to assist farmers in determining irrigation needs (timing and amount) according to crop type, evapotranspiration, rainfall, and soil water storage capacity (Rogers and Alam, 2008). We used KanSched2 to determine daily crop water needs and model how much water a crop would have needed in the past. This approach assumes that that the average irrigator applied amounts approximating crop irrigation needs because of successful harvests in the modeled period.

Table 15. Water-use factors for estimating annual water use at facilities served by public non-community systems. Kgal/yr, thousand gallons per year.

Facility type	Water-use factor (Kgal/yr)	User unit	Usage category	Number of wells	Reference
Agricultural industrial	4	Population served	Transient non community	1	AWWA, 1984 (factory)
Bar/tavern	150	Facility	Transient non community	1	Horn et al., 2008 (small restaurant)
Camp/RV	7.5	Population served	Transient non community	38	Snodgrass, 2007
Gas station with store, small	350	Facility	Transient non community	9	San Antonio Water System, 2009; Albemarle County Planning, 2009
Gas station with store, large	700	Facility	Transient non community	6	New Jersey Department of Environmental Protection, 2013
Homes, seasonal	7.5	Population served	Transient non community	3	this study
Hotels	22	Population served	Transient non community	1	Dziegielewski et al., 2000
Lodge/club	150	Facility	Transient non community	2	Horn et al., 2008 (small restaurant)
Marina	0.75	Population served	Transient non community	2	Ameen, 1984
Medical office	2	Population served	Transient non community	1	State of Utah, 2014
Mobile homes, seasonal	8.5	Population served	Transient non community	10	this study
Offices	5	Population served	Non transient non community	9	AWWA, 1984
Park water/ lavatory	1	Population served	Transient non community	8	AWWA, 1984
Restaurant	1000	Facility	Transient non community	27	Dziegielewski et al., 2000; Morales et al., 2009; Mays, 2001
Restaurant, deli	75	Facility	Transient non community	1	Dyer Partnership, 2009
Restaurant, fast food	750	Facility	Transient non community	3	Morales et al., 2009; Mays, 2001
Shopping center	0.087	Square feet	Transient non community	12	Morales et al., 2009
Shopping center, seasonal	0.036	Square feet	Transient non community	1	Morales et al., 2009
Sports club	7	Population served	Transient non community	15	AWWA, 1984
Store, large	650	Facility	Transient non community	1	Morales et al., 2009
Store, small	65	Facility	Transient non community	3	Morales et al., 2009

We examined estimated irrigation needs for 2,407 irrigated areas for each year from 2005 through 2008. The procedure followed these steps:

1. For precipitation input to KanSched2, define Thiessen polygons for seven weather stations with daily precipitation data (Bethany Beach, Dover, Georgetown, Greenwood, Laurel, Lewes, and Sandtown). The Theissen polygons encompass all locations that are closer to each station than to the other stations (Fig. 54).
2. For evapotranspiration input, define Thiessen polygons for four weather stations with daily evapotranspiration data (Bethany Beach, Laurel, Georgetown, and Sandtown) (Fig. 54).
3. Define ten combined climate polygons as the intersection of the two sets of Thiessen polygons.
4. For available soil water-holding capacity input, calculate an average capacity for each climate polygon from the NRCS Soil Survey Geographic dataset (SSURGO) (Soil Survey Staff, 2006) (Fig. 55). Ideally, the average available water capacity in each irrigated area polygon should be used but the computation would be too complex given the 2,407 individual irrigated areas used in this study.
5. Using KanSched2, calculate irrigation needs in each weather station polygon for four crop classes—field corn, soy beans, sweet corn, and double crop of soy beans and winter wheat—as a value of gallons per acre for each year.
6. Calculate an annual irrigation value (gallons per year) for each year for all 2,407 irrigation areas using the appropriate gallons per acre for the crop type in that defined area derived from the 2008 Cropland Data Layer (U.S. Department of Agriculture, 2009b) (Fig. 56). The Cropland Data Layer was created from remote sensing data and has local inaccuracies. As a result, many of our irrigation areas initially included areas of more than one crop type; significant manual editing was necessary to assign each a single crop type. Minor crop types, such as dry beans or sweet corn, were assigned to a larger class with similar water needs.
7. Calculate irrigation totals (gallons per year) for each year for each census block using the irrigation values for each irrigated area with a center-point in the census block.

During the preparation of this report, a USGS report (Levin and Zarriello, 2013) was published that supports our methods. Levin and Zarriello (2013) concluded “In most eastern coastal states that do not have quality irrigation data, the crop-water-demand model can be used more reliably.” The USGS study also used a daily crop-water-demand model that incorporated weather data, crop type, and soil type. However, whereas our model used KanSched2, their models followed guidelines from the University of Georgia Cooperative and Colorado State University Cooperative Extension to estimate crop irrigation volumes.

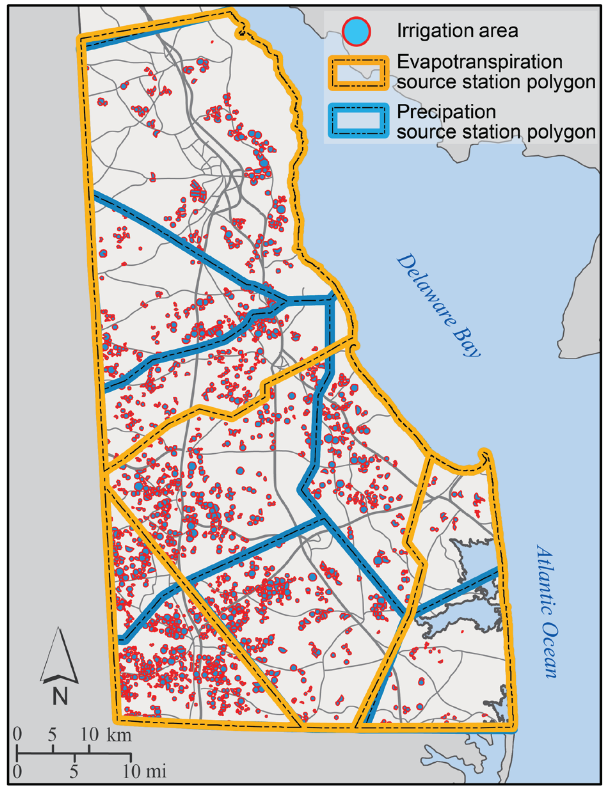

Figure 54. Map showing irrigated areas and climate data sources. Thiessen polygons for climate data were defined for localities with daily irrigation and evapotranspiration data. Each polygon included all locations closest to each Delaware Environmental Observing System (DEOS) weather station.

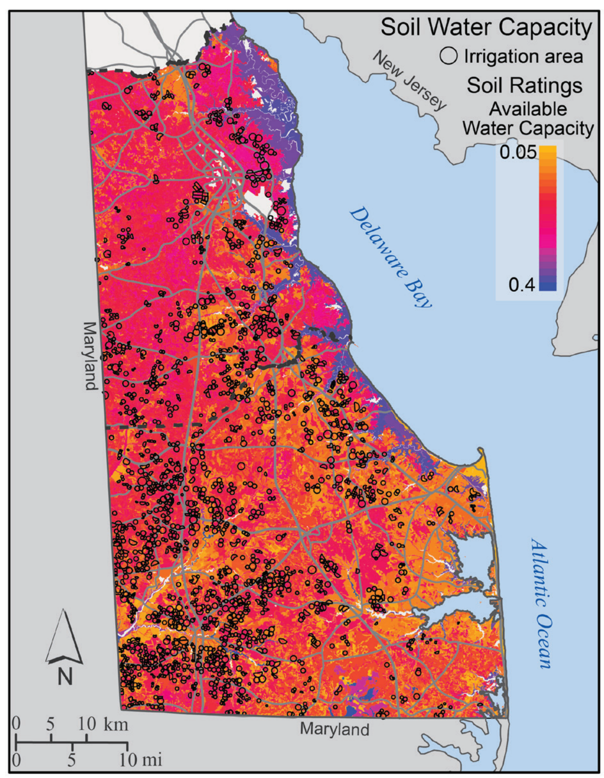

Figure 55. Map showing soil water-holding capacity and irrigated areas. Soil types and associated available water-holding capacity were obtained from the NRCS Soil Survey Geographic dataset (SSURGO) (Soil Survey Staff, 2006).

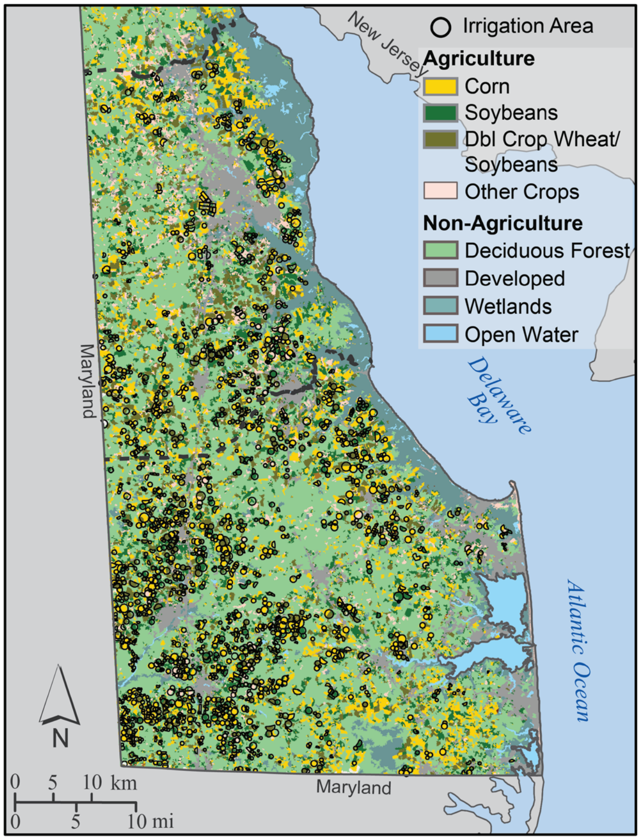

Figure 56. Map showing land use, including crop types, and irrigated areas. Crop types were obtained from the 2008 Cropland Data Layer (U.S. Department of Agriculture, 2009b).

Livestock. The vast majority of water used for livestock in Delaware is for poultry. According to the USDA, Delaware produced more than 240 million chickens from 2004 to 2008 (Cadwallader, 2012). In contrast, cattle and hog inventories were reported as 23,000 head combined. Therefore, our analysis of livestock water use only examines demand from the poultry industry.

Because wells at poultry operations typically pumped less than the reporting requirement of 50,000 gallons per day (gpd), poultry water use is estimated. Well records associated with poultry operations are historically incomplete, especially with regard to abandonment, and well locations are commonly imprecise. Consequently, the well databases used for this study were not adequate for precise well counts or locations. Therefore, our analysis of pumping volumes is based on an inventory of chicken houses instead of an inventory of wells.

Aerial photography from 2008 was compared with older aerial images to identify the location and numbers of chicken houses. To distinguish active from inactive chicken houses, we used vehicle tracks around and to chicken houses to verify that they were active. We identified 2,727 active chicken houses in 2008, 442 in Kent County and 2285 in Sussex County.

Water serves two purposes for a chicken house: drinking water for the birds and water for evaporative cooling systems. Water use depends on the size of the house, number of chickens, types of chicken, and weather. Generic parameters (Table 16) were used to make a simplistic estimate that the average chicken house in Delaware might use approximately 575,000 gallons per year.

Drinking water use was estimated for a generic chicken house by these steps:

1. Calculated 68,000 gallons of water used per flock (WFL) using published formula (Czarick, 2011) for daily water demands per thousand birds (WD), where D equals bird age in days, for 35,700 birds per house and a maturity of 49 days per flock:
   $W_{FL} = W_1 + W_2 \ldots + W_{49} = 68,000$ *gallons/flock*
   where: $W_D = (-2.78 + 4.7D + 0.128D^2 - 0.00217D^3) \times 0.26$
2. Calculated 367,000 gallons of drinking water needs for an average-sized house:
   5.4 flocks/year x 68,000 gallons/flock = 367,000 gallons

Evaporative cooling water use for a generic house was estimated by these steps:

1. Calculated 340 hours per year of system operation from these relationships:
   0.25 years x 3 weeks/flock x 5.4 flocks/year x 7 days/week x 12 hours/day = 340 hours/year
2. Calculated 204,000 gallons per house per year (Campbell and Donald, 2012):
   340 hours/year x 60 minutes/hour x 10 gpm = 204,000 gallons/year

The sum of these two numbers (367,000 + 204,000) was rounded up to 575,000 gallons per year per chicken house to account for other incidental uses of water, such as cleaning. For any individual chicken house, these numbers can be significantly different, but they provide an approximate water use that can be used to estimate groundwater withdrawals.

Because the location and depth could not be determined of every active non-irrigation agricultural well used for poultry, water use for this category was subtotaled areally by census blocks. We calculated estimated subtotals of poultry-related withdrawals for each census block by multiplying the number of chicken houses counted in the block by the assumed annual rate of 575,000 gallons per house.

Lawn Irrigation. Installation of lawn irrigation wells in public water service areas has become more common in the last decade, but the small volume of withdrawals does not require pumping to be reported. Therefore, a simple approach to estimation was used.

First, the location of areas with lawn irrigation wells was identified by a spatial query for agricultural wells located in public water service polygons. An estimate of the volume of withdrawals associated with these wells was calculated by these steps:

1. Determined the number of lawn wells per census block as of 2008.
2. Calculated water use per household (not per capita) per month in those blocks using domestic water-use total for block divided by number of households in the 2010 census.
3. Identified general suburban lawn irrigation demands through demonstrated changes in pumping data for

public water systems where the general lack of lawn irrigation wells suggested that lawn watering utilized the public water supply; in these systems, water use increases by approximately 50 percent in summer months over the baseline water use (Fig. 57).

4. Calculated lawn irrigation water use for each census block by multiplying the number of lawn irrigation wells by 0.5 x household water demand increase for 3 months of the year.

Table 16. Factors underlying estimates of water use for poultry.

Assumption	Comment
50 x 500 ft house	Majority of poultry houses are about 50 x 500 ft, but range from as small as 40 x 450 ft to large as 66 x 600 ft.
5.4 flocks/year	Assumed 5 to 5.5 flocks/year for 6 to 8 week flocks
35,700 birds/house	Assumed for 50 x 500 ft house with 6 to 8 week broilers
¼-year cooling window	Assume evaporative cooling used only in June, July, and August when temperature exceeds 80°F and humidity is less than 80 percent (80/80)
12 hours/day operation	Assume system only used in hot daylight hours (80/80)
3 weeks/flock need	Assume cooling only needed for summer flock from 4 or 5 weeks age to market age at 7 or 8 weeks
10 gpm system use	If the average 50 x 500 ft house uses a 6-inch pad, peak water use would be 11.2 gallons per minute (gpm) (Campbell and Donald, 2012); 10 gpm is a reasonable estimate

Aquifer Assignment

One of the primary objectives of this study was to delineate the volumes of water withdrawn from each aquifer. Because groundwater withdrawals were determined for some water-use categories on a well-by-well basis and for other categories by geographic areas, aquifer assignments were made using different approaches.

Well Specific: Public, Industrial, and Golf Course Irrigation. The aquifer used for groundwater withdrawals was analyzed on a well-by-well basis for three categories of use: public, industrial, and golf course irrigation. The relative completeness of location and construction information (screen depths) for wells in these classes allowed aquifer assignments by comparing screen coordinates in three-dimensional space (northing, easting, and elevation) to aquifer raster surfaces. Note that the aquifer was analyzed on a well-by-well basis for all categories of public wells, not just those categories that were required to report pumping.

The procedure for well-specific aquifer assignment was as follows:

1. Tabulated elevation of well, depth of top and bottom of well screen, depth of top and base of gravel pack, and hole depth by cross comparisons of DGS, DNREC, and SWAPP databases.
2. Converted depths to elevations using tabulated well elevation or, where missing, elevation sampled from digital elevation model.
3. Sampled elevation from top and base aquifer raster surfaces at each well location.
4. Compared the top and bottom screen elevations (or, where missing, their proxies: elevation of bottom hole or gravel pack) to the sampled top and bottom of each aquifer.
5. Assigned the well to an aquifer(s) based on the comparison of screen and aquifer elevations:
    - assignment was clear where the screen occurred between the top and bottom of one aquifer;
    - further investigation and manual assignment was needed where the screen occurred between aquifers;
    - "confined Columbia" aquifer was assigned where the aquifer screen occurred between the top of the highest confined aquifer and the base of the unconfined aquifer.
6. Assigned estimated water use for the well to the identified aquifer(s); where the analysis indicated that wells were screened across multiple aquifers (contrary to regulations), results were manually verified and water use was subdivided proportionally between the aquifers.

Non-Well Specific. Water withdrawals were analyzed by geographical areas for four categories of use: domestic self-supplied, agricultural irrigation, livestock, and lawn irrigation. The methodology for each of these categories is described below.

Domestic Self Supplied. The assignment of domestic self-supplied water use to specific aquifers was challenging. The study area has a large number of domestic wells but generally incomplete records on these wells in state databases. Location and construction data are missing or are poor quality for most of the older wells. Many self-supplied parcels have recent replacement wells but the record of abandonment of older wells is inconsistent. However, even though reliable domestic well location and depth data are only available for some of the domestic wells, the usable records are nevertheless abundant and provide thousands of data points that allowed us to establish geographic patterns in domestic well depths. As a result, we were able to identify clusters of well-screen depths within each census block and to assign each cluster to an aquifer using the aquifer elevation rasters.

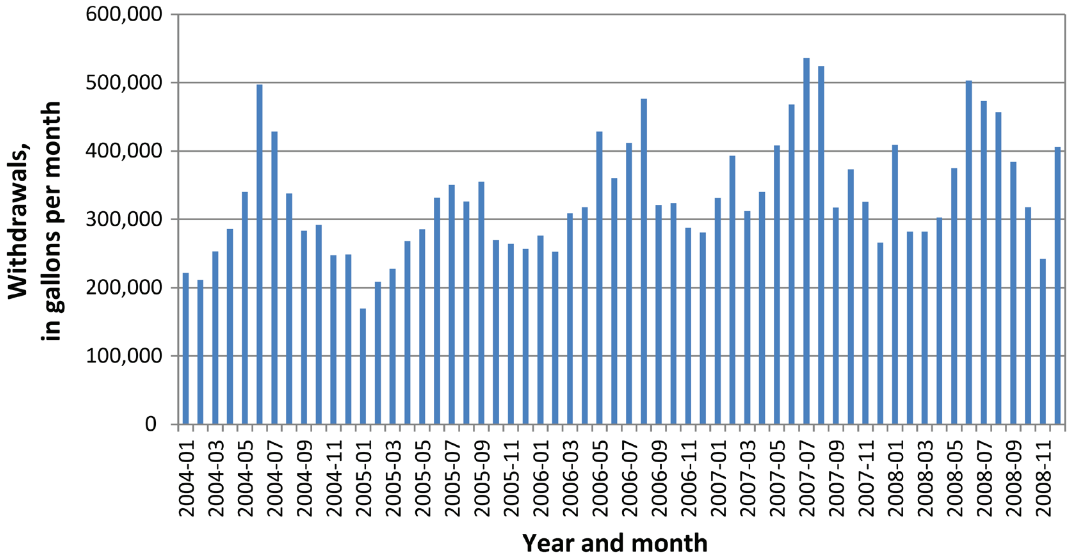

Figure 57. Graph showing monthly groundwater withdrawals for a small public water system in Kent County (Tidewater Utilities, Viola District) that provides lawn irrigation water. Summer water use is commonly approximately 50 percent higher than rates in winter.

The assignment procedure used is as follows:

1. Selected census blocks (or sub-blocks) that lay outside of the public water-system service areas and had reported populations and households in the 2010 census.
2. Analyzed the distribution of well screen depths for this well class in each such census block (or sub-block):
    - where the top and/or bottom of screen was missing for the well record, used the depth of bottom hole or gravel pack as a proxy ;
    - where a narrow range of depths, assumed one average depth;
    - where a wide range of depths, identified two or three clusters of depths as depth groups that were assigned average depths, noting relative proportions of wells in each group.
3. Designated coordinates (northing and easting) of a hypothetical, composite well-pumping center at the center point of each census block.
4. Established elevations of each depth group at the center point of each census block.
5. Determined aquifer elevations by sampling the rasters of the top and base aquifer elevations at the center point of each census block (or sub-block).
6. Compared depth group elevation to the sampled top and bottom of each aquifer for each census block (or sub-block).
7. Assigned each combination of depth groups and block center points to an aquifer(s);
    - assignment was clear where the depth group occurred between the top and bottom of one aquifer;
    - further investigation and manual assignment was needed where the depth group occurred between aquifers;
    - "confined Columbia" aquifer was assigned where the depth group occurred between the top of the highest confined aquifer and the base of the unconfined aquifer.
8. Assigned estimated water use for the block to the identified aquifer(s); where multiple aquifers were identified, water use was subdivided proportionally to the number of wells in each depth group.

Agricultural Irrigation. Similar to domestic water use,Similar to domestic water use, assigning irrigation water use to aquifers was a challenge given the large number of wells and the incompleteness of the well database. However, usable irrigation well records are similarly abundant and provide thousands of data points that reveal geographic patterns in irrigation well depths. As a result, we were able to identify clusters of well-screen depths within each census block and to assign each cluster to an aquifer using the aquifer-elevation raster surfaces.

The first step in the assignment procedure used was to identify census blocks that contained the center points of digitized irrigation areas. Then, for those blocks, the analysis followed the same procedures as steps 2 through 8 of the domestic self-supplied analysis described above.

Livestock. For livestock (specifically poultry) water use, as for domestic and irrigation water use, we used patterns in well screen data to assign estimated groundwater withdrawals to aquifers. However, our assignment process differed slightly because of the smaller number of wells used for poultry.

The first step in the assignment procedure used was to identify census blocks that contained a chicken house that could be identified as active based on a review of aerial photography. We then identified wells classified as agricultural (not irrigation) within a 150-m (492-ft) radius of the center of the chicken house as the basis for aquifer assignments in the census block. Where no agricultural wells existed in the database for the census block, we used well data from the nearest census block with agricultural wells. Then, for the census blocks with active chicken houses, the analysis followed the same procedures as steps 2 through 8 of the domestic self-supplied analysis described above.

Lawn Irrigation. A survey of records for wells drilled under an agricultural permit for lawn irrigation revealed that most are drilled to very shallow depths. Therefore, we considered all lawn irrigation wells to withdraw groundwater from the unconfined aquifer.

Overview of Results

The analysis of groundwater withdrawals in this study utilized reported pumping data from 2004 to 2008 and estimated pumping data for categories of water use that were not required to report or had insufficient usable data. Because of the large volume of data for multiple categories and multiple years, the figures and tables in the body of this report are limited to representative years and examples that support the discussion of water-use results. The complete results for reported and estimated groundwater withdrawals are included in Appendix C (maps) and Appendix D (tables).

The results of our analysis suggest that annual values for groundwater withdrawals for all uses in Kent and Sussex Counties ranged from approximately 100 to 145 million gallons per day (Mgal/d) (Table 17). Although the population of Sussex County is only 20 percent larger than that of Kent County (Table 18), groundwater withdrawals were approximately three times greater in Sussex County. This difference between counties largely reflects the higher demand for irrigation water in Sussex County. Public and domestic water demands are also increased in Sussex County by visitors and non-permanent seasonal residents.

Crop irrigation was the largest groundwater use category in the study (approximately 50-91 Mgal/d), followed by public-water supply (about 26 Mgal/d). Domestic self-supplied water was the third largest category of withdrawals (estimated 11.6 Mgal/d) and industrial wells were the fourth (approximately 7 Mgal/d). Four smaller categories—livestock, golf course irrigation, non-reporting smaller community systems, and lawn irrigation—each accounted for less than 4 Mgal/d annually (Table 17).

Table 18. Estimated populations served by public water-supply systems and domestic self-supply wells in Kent and Sussex Counties. These numbers differ slightly with census data in Table 7 due to rounding in the subdivision of public-supplied versus domestic-supplied populations in some census blocks. Populations from 2010 census; public water-supply system service area boundaries as of 2008.

	Public water-supplied population	Domestic self-supplied population	Total population
Kent County	101,656	60,575	162,231
Sussex County	98,964	96,472	195,436
Total	200,620	158,591	359,211

Table 17. Groundwater withdrawals in for water-use categories examined in this study. High-end and low-end estimates for each county and study area total were made where data were available. Study area totals are calculated an individual year; where indicated with an asterisk, the totals do not equal the sum of county values because high-use and low-use cases occurred in different years. Mgal/d, million gallons per day; CWS, community water system; TNC, transient non-community water system; NTNC, non-transient non-community water system.

Use		Kent (Mgal/d)	Sussex (Mgal/d)	Study Area (Mgal/d)
Irrigation: agricultural	*modeled high use (2007)*	19.12	71.69	90.82
	modeled low use (2006)	5.62	44.53	50.16
Public reported	*high use year (2007)*	11.00	15.18	26.18
	low use year (2004)	10.07	12.73	22.79
Domestic self-supplied *(modeled)*		4.24	7.37	11.61
Industrial self-supplied	*high use years (2004/2008/2008)*	1.35	6.96	7.66*
	low use years (2008/2005/2005)	0.70	5.56	6.66*
Agricultural: livestock *(estimated, for poultry)*		0.70	3.60	4.30
Irrigation: golf course *(median reported and estimated)*		0.17	2.00	2.17
Public non-reported *(estimated, CWS + TNC + NTNC)*		0.58	1.23	1.81
Agricultural: lawn wells *(estimated)*		0.008	0.022	0.030
Total	sum of high use years	37.2	108.1	144.6*
	sum of low use years	22.2	77.0	99.5*

Public Reported

Total and County

Reported pumping for wells in Public Water Systems (PWSs) with allocations represents the second largest category of groundwater withdrawals in the study area. Withdrawals were reported for 366 wells in this category for the period of 2004 through 2008. Totals withdrawals were approximately 24 Mgal/d on an annual basis (Table 19) or approximately 9 billion gallons per year (Fig. 58).

Table 19. Reported annual withdrawals from public water-supply systems in Kent and Sussex Counties. Total differs slightly from sum of county numbers due to rounding. Mgal/d, million gallons per day.

	2004 (Mgal/d)	2005 (Mgal/d)	2006 (Mgal/d)	2007 (Mgal/d)	2008 (Mgal/d)
Kent County	10.07	10.59	10.53	11.00	10.89
Sussex County	12.73	13.63	14.05	15.18	13.12
Total	22.79	24.21	24.59	26.18	24.01

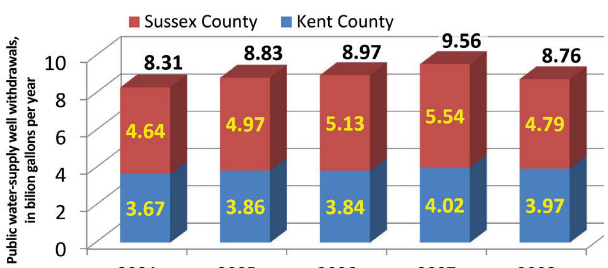

Figure 58. Graph showing reported annual groundwater withdrawals from public water-supply systems, 2004 to 2008.

Withdrawals were slightly greater in Sussex County, between approximately 13 and 15 Mgal/d, compared to reported withdrawals of 10 to 11 Mgal/d in Kent County (Table 19). Total withdrawals for the two counties increased from 22.80 Mgal/d in 2004 to 26.18 Mgal/d in 2007; the total for 2008 is slightly lower, probably due to missing data at the time of this database compilation. Much of this growth was in Sussex County; withdrawals increased only slightly in Kent County.

Using 2010 census data and the boundaries of public water system service areas as of 2008, we estimate that the population served by PWSs was 200,620, with 101,656 in Kent County and 98,964 in Sussex County (Table 18). The overwhelming majority of those who live in PWS service areas are served by systems that are permitted to withdraw more than 50,000 gallons per day and are required to report groundwater withdrawals. Although the numbers in reporting versus non-reporting public systems have not been rigorously analyzed by census block, a rough estimate is that the population is slightly more than 175,000 within the systems that must report water use.

By Well and System

The volume of withdrawals by PWS wells between 2004 and 2008 is summarized in a series of maps in Appendix C. Several clusters of PWS wells are evident on the maps and reflect significant pumping volumes; the larger volume wells are mostly operated by municipal water providers. In Kent County (Fig. 59), clusters are in the Dover area, Smyrna, and Milford. The largest volumes were pumped by two City of Dover wells that withdrew approximately 400 and 250 million gallons per year (Mgal/yr), respectively from the Piney Point aquifer. The City of Dover operates other wells that pumped volumes in the range of 100 to 200 Mgal/yr from the Piney Point and Cheswold aquifers. Two City of Milford wells utilizing aquifers in the Calvert and Choptank Formations are also among the larger pumpers, withdrawing approximately 200 Mgal/yr. The Town of Smyrna operates a well that withdrew about 130 Mgal/yr.

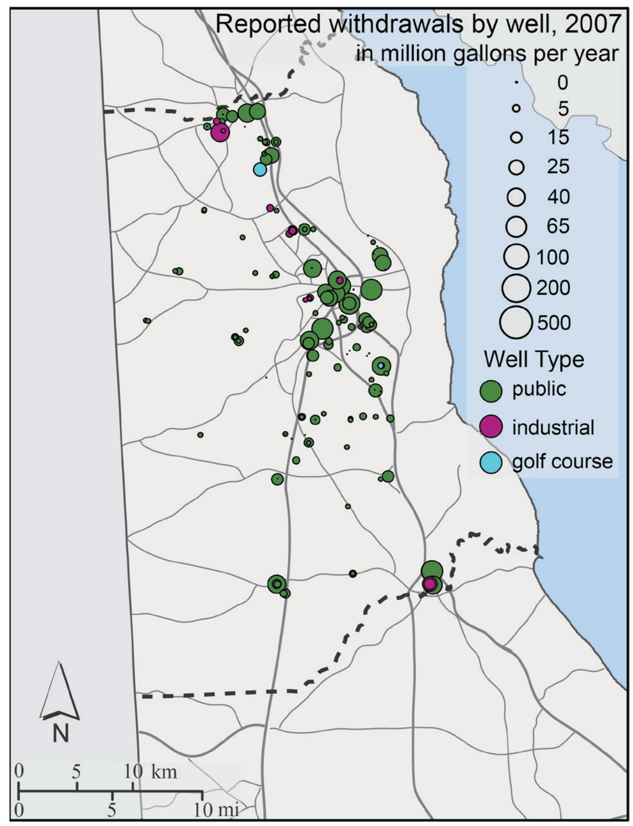

Figure 59. Map showing reported groundwater withdrawals by well for public, industrial, and golf course use in Kent County in 2007. This map is generally representative of all years examined. More detailed data and maps for other years are in the appendices.

Coastal Sussex County has numerous clusters of PWS wells (Fig. 60), including Lewes-Rehoboth, Bethany, Seaford, and west of Fenwick Island. The largest withdrawals were from two Rehoboth wells that pumped an average of approximately 190 and 140 Mgal annually from the unconfined aquifer. Two large community wells operated by the City of Seaford withdrew an average of 125 Mgal/yr over the study interval from the Manokin aquifer. Other major wells in

Sussex County include three City of Lewes wells reporting average withdrawals ranging from 93 to 113 Mgal/yr from the Pocomoke aquifer; an Artesian Water Company well at Bayville reporting withdrawals of more than 125 Mgal/yr from the Pocomoke aquifer; and three wells operated by Tidewater Utilities, two in the Rehoboth area and one in the Bethany Beach area, that each pumped more than 100 Mgal/yr from the unconfined aquifer or the confined Columbia aquifer.

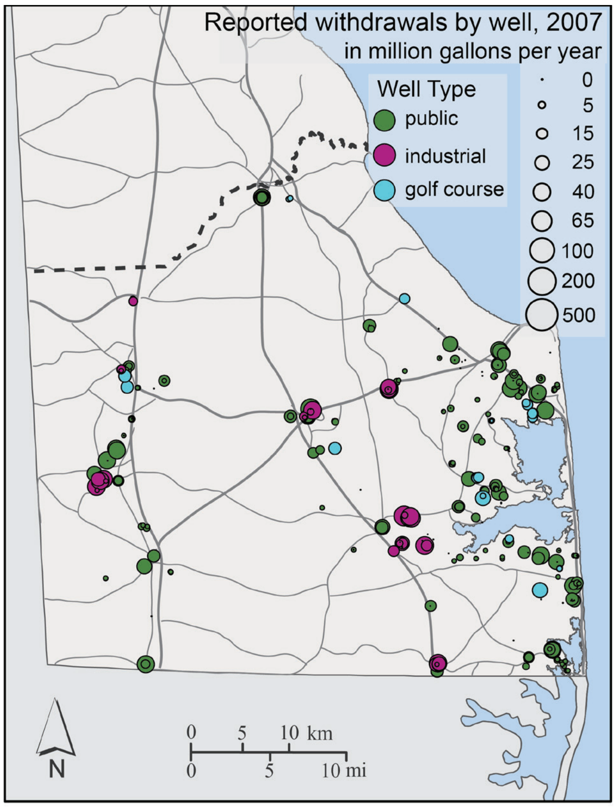

Figure 60. Map showing reported groundwater withdrawals by well for public, industrial, and golf course use in Sussex County in 2007. This map is generally representative of all years examined. More detailed data and maps for other years are in the appendices.

Annual reported pumping totals were compiled for each PWS in Kent and Sussex Counties (Table 20). The largest volume was used by the City of Dover, which averaged more than 1.8 billion gallons per year over the study period. The Dover water system serves a larger population than any other system in the study area, more than 38,000 residents (Table 21), and provides water for multiple uses. The City of Milford was the second largest provider with approximately 890 Mgal/yr serving fewer than 10,000 residents in its service area. The cluster of high withdrawals in the Lewes-Rehoboth area reflects pumping in three systems, the City of Lewes (435 Mgal/yr), the City of Rehoboth (541 Mgal/yr), and the Rehoboth District of Tidewater Utilities (493 Mgal/yr). The system averages in Table 20 may vary considerably during the year and from year to year. Detailed well and system data are in Appendix D.

Pumping data for PWSs serving principally domestic household users were identified and analyzed to understand domestic water use. Groundwater withdrawals were subtotaled for individual PWSs and interconnected PWSs served by a common group of wells, here referred to as pumping networks. The per capita domestic water use calculated for each pumping network is shown in Table 22. For comparison, the census-based modeled per capita water use for each system is also shown in Table 22.

By Aquifer

The unconfined aquifer was the largest source of PWS groundwater in the study area. Unconfined aquifer withdrawals comprised approximately one-fourth of pumping volumes and wells (Fig. 61 and Table 23), approximately one third of withdrawals in Sussex County and 10 percent in Kent County. Withdrawals were at a rate of approximately 6 Mgal/d for 2005 through 2008 from 98 wells. The unconfined aquifer was more extensively used for pumping larger volumes than the confined aquifers; nearly two dozen wells each withdrew more than 50 Mgal in at least one year from the unconfined aquifer.

The next three most important sources, the Pocomoke, Cheswold, and Piney Point aquifers, each accounted for approximately 15 percent of reported PWS withdrawals in the study area (Table 23). The Piney Point and Cheswold aquifers are most important in Kent County; they each provided approximately one-third of reported PWS withdrawals in Kent County (Table 23). The largest withdrawals in the study area were made from two wells in the Piney Point aquifer operated by the City of Dover, totaling approximately 400 Mgal/yr for one (permit 031640, Dover well 2) and 250 Mgal/yr for the other (permit 010212, Dover well 7). The Pocomoke aquifer was the most important confined aquifer for PWSs in Sussex County and accounts for approximately one-fourth of reported PWS withdrawals in the county (Table 23).

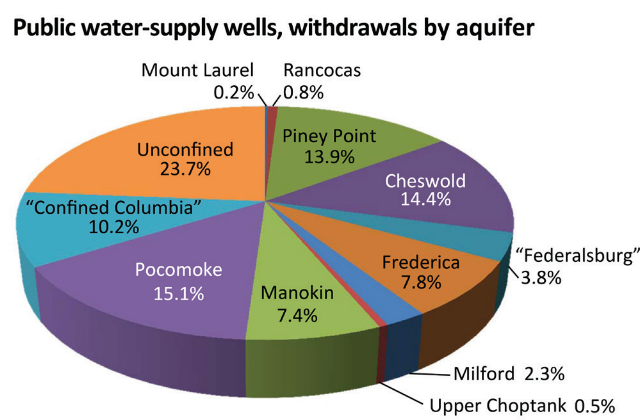

Figure 61. Pie chart showing percentage of groundwater withdrawals by aquifer reported for public wells for 2007. This graph is generally representative for 2004 through 2008; data for other years are in the appendices. Percentages were rounded to one decimal place.

Table 20. Average annual reported well withdrawals for public water-supply systems in Kent and Sussex Counties for years with reported pumping data between 2004 and 2008. Mgal/d, million gallons per day; gal/yr, gallons per year.

System ID	System Name	Years Reported	Average Reported Pumping (gal/yr)	Average Reported Pumping (Mgal/d)
DE0000571	Dover Water	2004-2008	1,830,912,200	5.016
DE0000616	Milford Water Department	2004-2008	892,154,684	2.444
DE0000723	Rehoboth Water	2004-2008	540,782,618	1.482
DE0000991	Tidewater Utilities (Rehoboth District)	2004-2008	493,493,635	1.352
DE0000602	Lewes Water	2004-2008	434,809,660	1.191
DE0000246	Seaford Water	2004-2008	424,107,563	1.162
DE0000592	Georgetown Water	2004-2008	299,004,084	0.819
DE0000221	Tidewater Utilities (Bethany Bay District)	2004-2008	278,816,464	0.764
DE0000124	Tidewater Utilities (Camden District)	2004-2008	254,066,103	0.696
DE0000657	Smyrna Water	2005-2008	243,811,000	0.668
DE00A0323	Artesian Water Company (South Bethany)	2004-2008	205,408,380	0.563
DE0000625	Long Neck Water	2004-2008	202,452,480	0.555
DE0000833	Perdue (Georgetown)	2004-2008	196,947,060	0.540
DE0000579	Dover Air Force Base	2004-2008	191,141,002	0.524
DE0000622	Millsboro Water	2004-2008	184,724,976	0.506
DE0000271	Tidewater Utilities (Meadows District)	2004-2008	159,646,280	0.437
DE0000556	Bethany Beach Water	2004-2008	159,570,800	0.437
DE0000563	Camden Wyoming Sewer and Water Authority	2004-2008	150,680,395	0.413
DE0000126	Harrington Water Department	2004-2008	139,908,800	0.383
DE0000567	Delmar Water	2004-2008	122,354,163	0.335
DE0000004	Tidewater Utilities (Garrison Lake District)	2004-2008	121,581,120	0.333
DE0000597	Laurel Water	2005-2008	118,251,005	0.324
DE0000654	Selbyville Water	2004-2008	104,241,465	0.286
DE0000557	Sussex Shores	2004-2008	98,550,080	0.270
DE0000248	Tidewater Utilities (Angola District)	2004-2008	88,181,040	0.242
DE0000629	Milton Water	2004-2008	84,869,420	0.233
DE0000565	Clayton Water Department	2004-2008	81,105,440	0.222
DE0000559	Bridgeville Water	2004-2008	72,370,427	0.198
DE00A0428	Artesian Water Company (Church Creek)	2004-2008	68,937,900	0.189
DE0000865	Blades Water	2004-2008	39,512,075	0.108
DE0020003	Artesian Water Company (Heron Bay)	2005-2008	38,004,381	0.104
DE00A0837	Tidewater Utilities (Bayside)	2005-2008	37,700,753	0.103
DE0001303	Mountaire	2005-2008	36,650,850	0.100
DE0000242	Frankford Water	2004-2008	35,686,800	0.098
DE0000580	Felton Water Department	2004-2008	34,905,320	0.096
DE0000595	Delaware State Fair	2004-2008	30,514,400	0.084
DE0000474	Eagle Meadows	2004-2005,2008	28,977,331	0.079
DE0000587	Frederica Water Department	2006-2008	28,036,000	0.077
DE0000465	Swann Keys	2004-2008	27,533,435	0.075
DE0000949	Tidewater Utilities (Bridgeville District)	2004-2008	25,655,020	0.070
DE00A0159	Tidewater Utilities (Wild Quail)	2004-2008	25,501,680	0.070
DE0000469	Tidewater Utilities (Felton District)	2004-2008	22,657,517	0.062
DE0000265	Laurel Village	2005-2007	21,044,990	0.058
DE0000610	Magnolia Water Department	2004-2006,2008	19,387,250	0.053
DE0000939	Holly Hill Estates	2004-2008	19,231,006	0.053
DE0000537	Sussex County Industrial Airpark	2004-2008	17,287,370	0.047

Continued on next page

Table 20. Continued

System ID	System Name	Years Reported	Average Reported Pumping (gal/yr)	Average Reported Pumping (Mgal/d)
DE00A0337	Tidewater Utilities (The Glade)	2004-2008	16,202,070	0.044
DE00A0348	Tidewater Utilities (Canterbury Crossing)	2004-2008	14,587,020	0.040
DE0000669	Reichold Chemicals	2006-2008	14,393,629	0.039
DE0000546	Tidewater Utilities (Lakeland)	2004-2008	13,690,200	0.038
DE0000558	Greenwood Water	2005, 2007-2008	13,468,618	0.037
DE0000251	Henlopen Acres	2004-2008	12,960,182	0.036
DE00A0740	Artesian Water Company Burtonwood	2004-2008	11,378,860	0.031
DE0000276	Stockley Center	2005	10,567,800	0.029
DE00A0169	Mallard Lakes	2004-2008	10,468,380	0.029
DE0000439	Cape Windsor	2004-2008	9,887,906	0.027
DE00A0847	Artesian Water Company (Beaver Creek)	2007-2008	9,543,700	0.026
DE00A0673	Artesian Water Company (Windsong Farms)	2004-2008	8,137,620	0.022
DE00A0326	Tidewater Utilities (Clear Brooke Estates)	2004-2008	8,099,660	0.022
DE0000960	Tidewater Utilities (Forest Grove)	2004-2008	6,410,140	0.018
DE0000613	Southwood Acres	2004-2008	6,006,654	0.016
DE00A0753	Tidewater Utilities (Oak Crest Farms)	2004-2008	6,003,380	0.016
DE00A0379	Tidewater Utilities (Point Farm)	2004-2008	5,985,620	0.016
DE0000220	Tidewater Utilities (Hunter Mill Estates)	2004-2008	5,980,280	0.016
DE0000319	Treasure Beach	2004-2008	5,808,606	0.016
DE00A0424	Artesian Water Company (Cedar Landing)	2004-2008	5,648,131	0.015
DE0000273	Tidewater Utilities (Sweet Briar)	2004-2005, 2007-2008	4,868,825	0.013
DE0000125	Tidewater Utilities (Voshell’s Cove)	2004-2008	4,690,144	0.013
DE0000118	Tidewater Utilities (Cooper Farms)	2004-2008	4,234,321	0.012
DE00A0279	Tidewater Utilities (Woodlands of Millsboro)	2004-2008	4,196,400	0.011
DE00A0787	Artesian Water Company (Deer Meadows)	2004-2008	4,055,780	0.011
DE00A0401	Tidewater Utilities (Mt. Vernon Estates)	2004-2008	4,005,930	0.011
DE0000104	Tidewater Utilities (Hunter’s Pointe)	2004, 2007-2008	3,534,433	0.010
DE00A0420	Tidewater Utilities (Misty Pines)	2004-2008	3,447,060	0.009
DE0000155	Tidewater Utilities (Bridgeville Mall)	2004-2008	3,195,660	0.009
DE00A0699	Tidewater Utilities (Sandy Ridge)	2004-2008	3,071,024	0.008
DE00A0767	Tidewater Utilities (Dover Meadows)	2004-2008	3,021,220	0.008
DE00A0327	Tidewater Utilities (Green Acres)	2004-2008	2,895,660	0.008
DE00A0329	Tidewater Utilities (Love Creek Woods)	2004-2008	2,719,900	0.007
DE00A0522	Tidewater Utilities (Grants Way)	2004-2008	2,675,460	0.007
DE0020020	Tidewater Utilities (Country Grove)	2008	2,423,000	0.007
DE00A0411	Tidewater Utilities (Long Farm Estates)	2004-2008	2,272,860	0.006
DE00A0369	Tidewater Utilities (Webb's Landing)	2004-2008	1,940,600	0.005
DE00A0516	Tidewater Utilities (Sea Winds)	2004-2008	1,921,780	0.005
DE00A0757	Tidewater Utilities (Willow Lake)	2004-2008	1,913,763	0.005
DE00A0868	Tidewater Utilities (Whitetail Run)	2006-2008	1,817,867	0.005
DE0020022	Tidewater Utilities (Ponds at Willow Grove)	2008	1,815,100	0.005
DE00A0575	Tidewater Utilities (Laurel District)	2004-2008	1,586,060	0.004
DE0000227	Tidewater Utilities (Indian River Acres)	2004-2008	1,034,160	0.003
DE00A0770	Tidewater Utilities (Gander Woods)	2004-2008	1,025,100	0.003
DE0020007	Tidewater Utilities (Frederica District)	2007-2008	596,350	0.002
DE0020002	Ocean View Station	2004-2008	346,680	0.001
DE0020021	Tidewater Utilities (Pepper Creek District)	2008	275,700	0.001

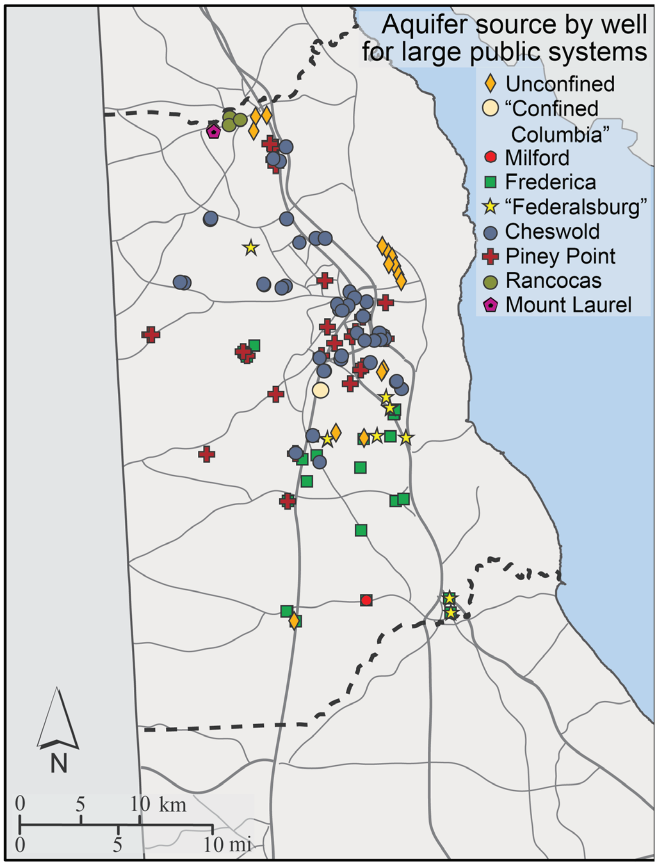

Figure 62. Map showing aquifer source by well for public water-supply systems with reported groundwater withdrawals in Kent County.

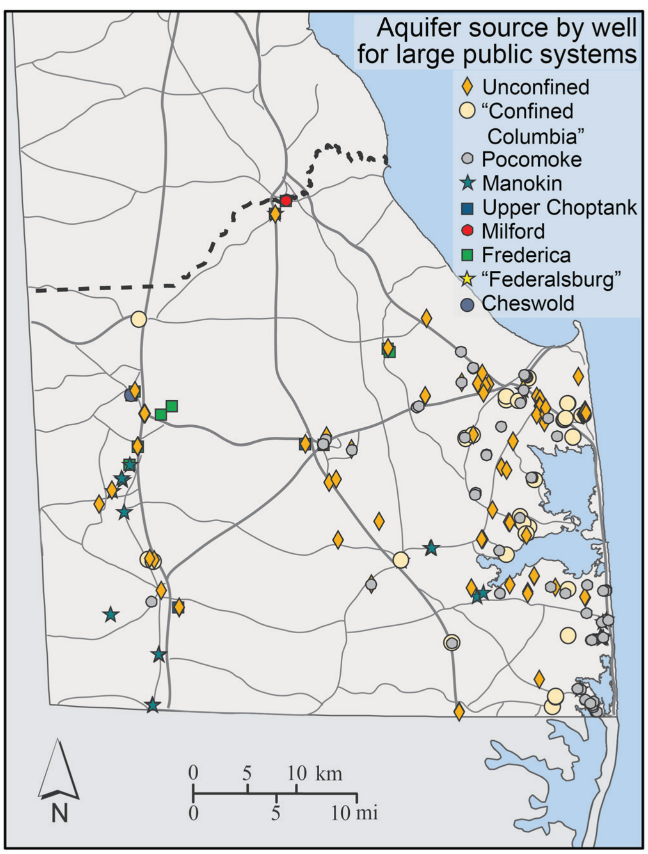

Figure 63. Map showing aquifer source by well for public water-supply systems with reported groundwater withdrawals in Sussex County.

The largest number of wells in the reported PWS category in Kent County was in the Cheswold and Piney Point aquifers, which have 29 and 48 wells, respectively (Table 23). The wells are concentrated in the Dover area and northward to south of Smyrna (Fig. 62). In Sussex County, the largest number of PWS wells was in the unconfined and Pocomoke aquifers, 83 and 66 wells, respectively (Table 23). Along the Atlantic Coast and around the Inland Bays, most of these wells are in the unconfined, confined Columbia, or Pocomoke aquifers; further inland in central and western Sussex County, the largest numbers of wells are in the unconfined and Manokin aquifers (Fig. 63). The Frederica aquifer was the source for many reporting PWS wells in southern Kent County and northwestern Sussex County.

Table 21. Population and number of households within the service area boundaries of selected municipal public water-supply systems in Kent and Sussex Counties. Populations from 2010 census; public water-supply system service area boundaries as of 2008.

System ID	Municipal utility	Population	Number of households
DE0000571	Dover	38,206	14,702
DE0000657	Smyrna	10,391	3,846
DE0000616	Milford	9,884	3,862
DE0000246	Seaford	6,924	2,685
DE0000592	Georgetown	6,322	1,829
DE0000563	Camden Wyoming	4,451	1,729
DE0000622	Millsboro	3,807	1,587
DE0000597	Laurel	3,597	1,235
DE0000126	Harrington	3,586	1,398
DE0000602	Lewes	3,484	1,706
DE0000723	Rehoboth	3,251	1,650
DE0000565	Clayton	2,920	993
DE0000629	Milton	2,685	1,145
DE0000654	Selbyville	2,269	858
DE0000559	Bridgeville	1,972	807
DE0000556	Bethany Beach	1,492	783
DE0000567	Delmar	1,431	531
DE0000580	Felton	1,323	536
DE0000865	Blades	1,247	430
DE0000558	Greenwood	1,035	415
DE0000587	Frederica	758	274
DE0000610	Magnolia	450	166
DE0000251	Henlopen Acres	119	65

Public Non-Reported

Total and County

Groundwater withdrawals were estimated for 403 smaller public systems that withdrew volumes below the reporting threshold of 50,000 gallons of water per day. This list includes non-reporting public supply wells serving community systems (CWS), transient non-community systems (TNC), and non-transient non-community (NTNC) systems.

Table 22. Groundwater use in pumping networks of individual or interconnected groundwater systems. Reported pumping is the average total pumping of all wells serving the network for 2004 through 2008 for wells with normal pumping over an entire year. The seasonally adjusted population incorporates annualized seasonal population increases as described in methods section and serves as basis for pumping rates. GPCD, gallons per capita per day; gal/yr, gallons per year.

Pumping network	Utility	Average reported pumping (gal/yr)	2010 Population	Seasonally adjusted population	Reported pumping (GPCD)	Modeled pumping (GPCD)
Meadows	Tidewater Utilities	177,499,033	4621	5199	94	80
Magnolia	Artesian Water Company	92,284,750	3858	3858	66	71
Swann Keys	Swann Keys	27,533,435	394	625	121	97
Felton	Tidewater Utilities	25,566,730	1041	1041	67	73
Stonewater Creek	Artesian Water Company	22,401,762	471	497	123	77
Holly Hill Estates	Holly Hill Estates	20,204,857	578	578	96	116
Canterbury Crossing	Tidewater Utilities	15,912,625	414	414	105	83
Smyrna-Clayton	Artesian Water Company	13,967,450	634	634	60	70
Mallard Lakes	Mallard Lakes	10,468,380	212	387	74	91
Henlopen Acres	Henlopen Acres	9,935,125	119	185	147	153
Clearbrooke Estates	Tidewater Utilities	9,131,833	411	411	61	76
Cape Windsor	Cape Windsor	9,003,111	189	266	93	120
Oak Crest Farms	Tidewater Utilities	8,949,100	281	291	84	79
Beaver Creek	Artesian Water Company	8,713,100	274	283	84	80
Forest Grove	Tidewater Utilities	6,410,140	212	212	83	67
Southwood Acres	Tidewater Utilities	6,006,654	268	268	61	96
Hunters Mill Estates	Tidewater Utilities	5,980,280	239	249	66	86
Deer Meadows	Artesian Water Company	5,844,467	251	251	64	71
The Point Farm	Tidewater Utilities	5,327,850	152	156	94	84
Voshells Cove	Tidewater Utilities	4,690,144	213	213	60	73
Viola	Tidewater Utilities	4,357,067	196	196	61	73
Cooper Farm	Tidewater Utilities	4,234,321	199	199	58	54
Sandy Ridge	Tidewater Utilities	3,715,973	150	150	68	65
Misty Pines	Tidewater Utilities	3,447,060	137	137	69	72
Dover Meadows	Tidewater Utilities	3,398,825	160	160	58	56
Woodlands of Millsboro	Tidewater Utilities	3,295,000	133	133	68	70
Love Creek Woods	Tidewater Utilities	2,719,900	112	124	60	92
Grants Way	Tidewater Utilities	2,675,460	77	84	87	101
Whitetail Run	Tidewater Utilities	2,503,000	72	72	95	71
Long Farm Estates	Tidewater Utilities	2,272,860	68	68	92	67
Willow Lake	Tidewater Utilities	2,125,533	100	100	58	71
Webbs Landing	Tidewater Utilities	1,940,600	57	59	90	80
Sea Winds	Tidewater Utilities	1,921,780	69	72	73	98
Indian River Acres	Tidewater Utilities	1,034,160	35	46	62	92
Gander Woods	Tidewater Utilities	1,021,800	35	39	72	88

Table 23. Reported groundwater withdrawals and number of wells by aquifer for public water systems for 2007 in Kent and Sussex Counties. The relative volumes of each aquifer are generally representative for all years of this study (2004-2008); data for other years are in the appendices. Mgal/d, million gallons per day.

2007	Withdrawals (Mgal/d)	Number of wells
Unconfined	5.94	98
Confined Columbia	2.66	36
Pocomoke	4.19	66
Manokin	1.92	26
Upper Choptank	0.14	3
Milford	0.6	4
Frederica	2.03	39
"Federalsburg"	1.01	11
Cheswold	3.82	48
Piney Point	3.62	29
Rancocas	0.21	5
Mount Laurel	0.04	1
Total	26.18	366

One of the strengths of the analysis of this category is that the location and construction data for public water-supply wells are well documented by state programs that oversee public water systems (DNREC and Department of Public Health). However, a weakness is the lack of pumping data. Water use for smaller CWSs was estimated using the domestic water-use model created in this study and census data for the system service areas. Water use for TNCs and NTNCs was estimated using weakly calibrated relationships between facility types, population served, and water use documented in water industry literature. Usage was divided evenly among all pumping wells for systems with more than one well. This analysis provides only general estimates of withdrawals for these systems; though the numbers are probably reasonable overall, a significant degree of potential error exists for any individual well.

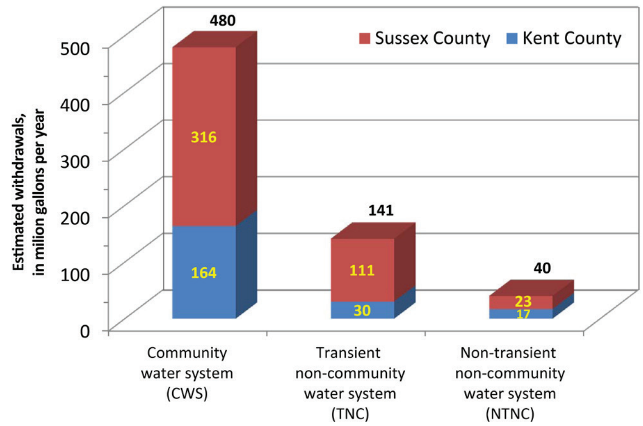

Figure 64. Graph showing estimated annual groundwater withdrawals for community, transient non-community, and non-transient non-community public water systems with no reported pumping data.

Total estimated withdrawals for the smaller, non-reporting public water-supply systems in Kent and Sussex County were approximately 1.8 Mgal/d or around 660 Mgal/yr (Fig. 64; Table 24), which is an order of magnitude smaller than withdrawals for the larger PWSs that report pumping. We estimated that the CWSs had the largest volume of withdrawals, totaling

Table 24. Estimated groundwater withdrawals and number of wells by aquifer for community, transient non-community, and non-transient non-community water systems in the study area. Total may differ slightly from sum of corresponding column due to rounding. Mgal/d, million gallons per day.

Aquifer	Community water systems		Transient non-community water systems		Non-transient non-Community water systems	
	Withdrawals (Mgal/d)	Number of wells	Withdrawals (Mgal/d)	Number of wells	Withdrawals (Mgal/d)	Number of wells
Unconfined	0.338	51	0.1453	48	0.0247	21
Confined Columbia	0.26	32	0.0722	25	0.0153	9
Pocomoke	0.107	17	0.0691	27	0.0158	5
Manokin	0.066	13	0.003	2	0.0014	5
Upper Choptank	0.008	3	0.0002	1	0.0003	1
Middle Choptank	0.018	4	0.0028	1	0.0001	1
Milford	0.159	15	0.0106	5	0.0076	3
Frederica	0.073	9	0.0233	14	0.0102	12
"Federalsburg"	0.024	8	0.0035	3	0.0012	3
Cheswold	0.253	25	0.0377	15	0.0051	4
Piney Point	0.008	3	0.0046	4	0.0235	2
Unknown			0.0152	9	0.0053	3
Total	1.314	180	0.3874	154	0.1106	69

1.31 Mgal/d (Table 24); Sussex County was 0.87 Mgal/d and Kent County was 0.45 Mgal/d. Withdrawals for TNC systems, such as campgrounds, stores, and parks, were estimated to be 0.387 Mgal/d; Sussex County was 0.304 Mgal/d and Kent County was 0.083 Mgal/d. Withdrawals for NTNC systems, which includes churches, daycare centers, and businesses, were estimated to be 0.111 Mgal/d for the study period; Sussex County was 0.064 Mgal/d and Kent County was 0.047 Mgal/d.

By Well and System

The High Point system in south-central Kent County (Fig. 65) was estimated to withdraw more than 37 Mgal/yr, representing an average of approximately 100,000 gallons per day (GPD), the largest volume of the non-reporting CWS category. This estimate is based on the demographics of a 2010 census population of 1,036 residents and reflects an average usage of just under 100 GPCD (gallons per capita per day). Although the Source Water Assessment report (DNREC, 2005) lists only one well serving this development, two other permits are also located in this development; therefore, we have split the pumping between the three wells and have estimated withdrawals for each as 12.4 Mgal/yr, all from the Milford aquifer. Another area of estimated larger withdrawals among small CWSs is in north-central Kent County where we estimate the Fox Pointe and Pinewood Acres systems pumped between 20 and 30 Mgal/yr from the Cheswold aquifer, distributed among several wells each.

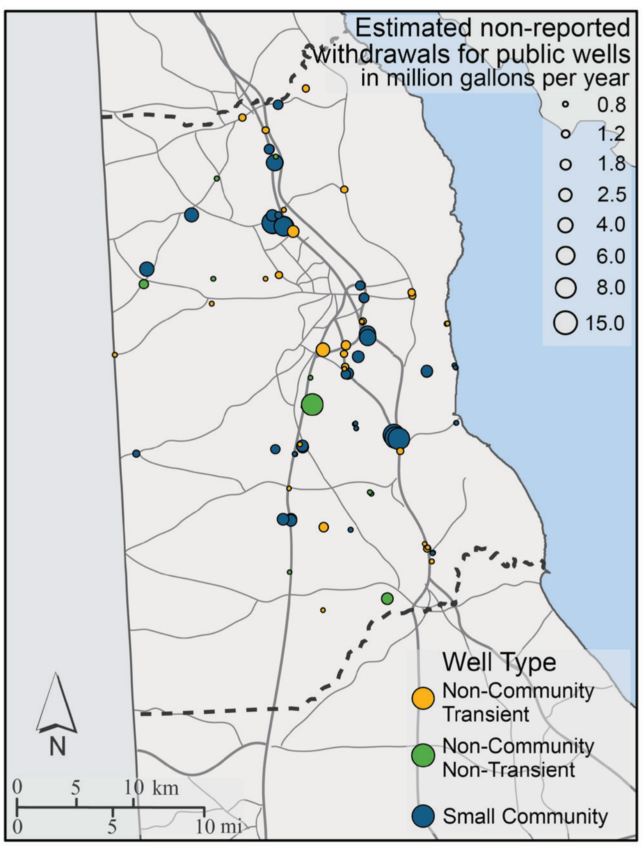

Figure 65. Map showing estimated annual groundwater withdrawals by well for community, transient non-community, non-transient non-community public water systems with no reported pumping data in Kent County.

In Sussex County, the more significant of the smaller CWS wells are scattered (Fig. 66). Usage by three small CWSs in the Inland Bays area—Angola Beach Estates (3 wells), Rehoboth Bay Community (5 wells), and Carey Estates (2 wells)—was estimated to be between approximately 15 and 20 Mgal/yr, which was divided among the wells in each system at rates of 3.5 to 8 Mgal per well per year. Other high-pumping wells were in the Seaford area in the Village of Cool Branch (2 wells at 7.2 Mgal/yr) and Mobile Gardens (1 well at 11.6 Mgal/yr) systems.

Campgrounds and vacation trailer parks located in Sussex County appear to be the largest groundwater users among the TNC systems. Wells in those systems were mostly estimated to pump between 2 and 7 Mgal/yr, the majority from the unconfined aquifer. A well at Gull's Way Campground was estimated to withdraw more than 12 Mgal/yr based on a population served of 1,617 residents at an estimated 7,500 gallons per user per year.

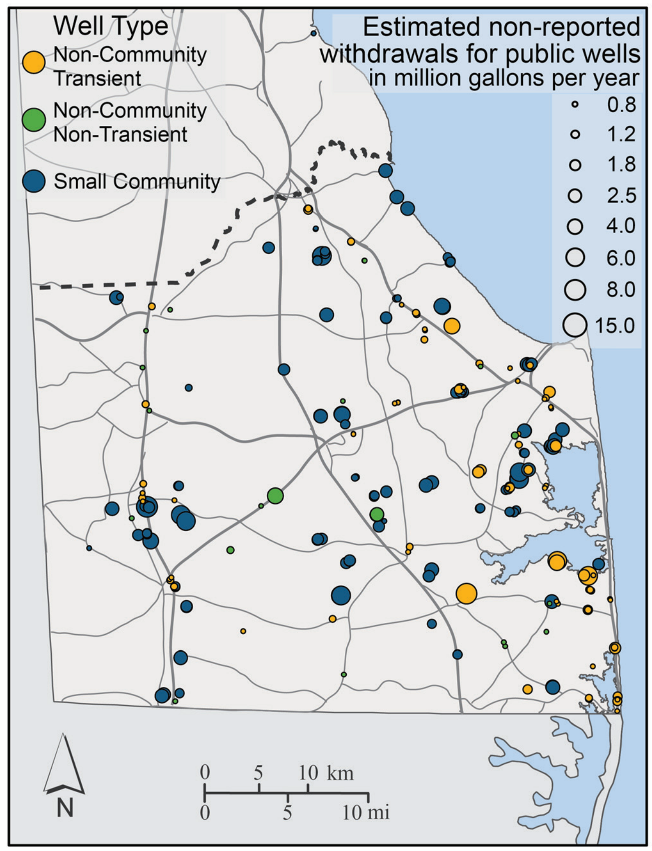

Figure 66. Map showing estimated annual groundwater withdrawals by well for community, transient non-community, non-transient non-community public water systems with no reported pumping data in Sussex County.

Schools comprised seven of the top ten users among the NTNC systems. The largest users (Polytech High School, Sussex Central High School) were estimated to withdraw 7 to 8 Mgal/yr based on the school type and the number of users. Estimated withdrawals for most NTNC wells were generally small, between 0.1 and 0.4 Mgal/yr.

By Aquifer

The unconfined aquifer was the largest source of groundwater for smaller public water systems in all three categories: CWS, TNC, and NTNC (Table 24). The confined Columbia in Sussex County and the Cheswold in Kent County appear to be nearly as important as the unconfined aquifer for smaller CWSs, making up an estimated 20 percent of withdrawals (Fig. 67). The Milford aquifer also supplies a number of small community systems in southern Kent County and northern Sussex County (Figs. 68 and 69), totaling more than 12 percent of estimated withdrawals (Fig. 67).

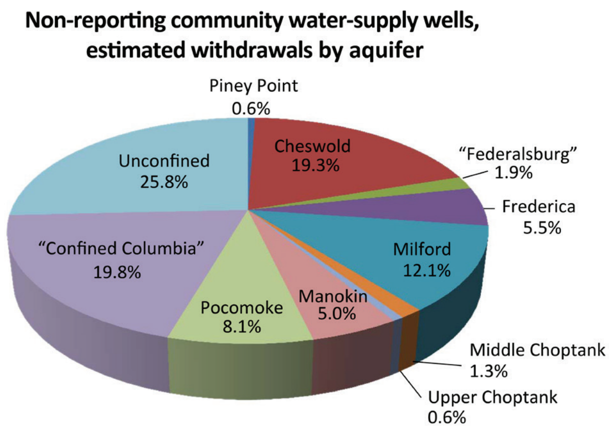

Figure 67. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for community public water system wells with no reported pumping data. Percentages were rounded to one decimal place; data are in the appendices.

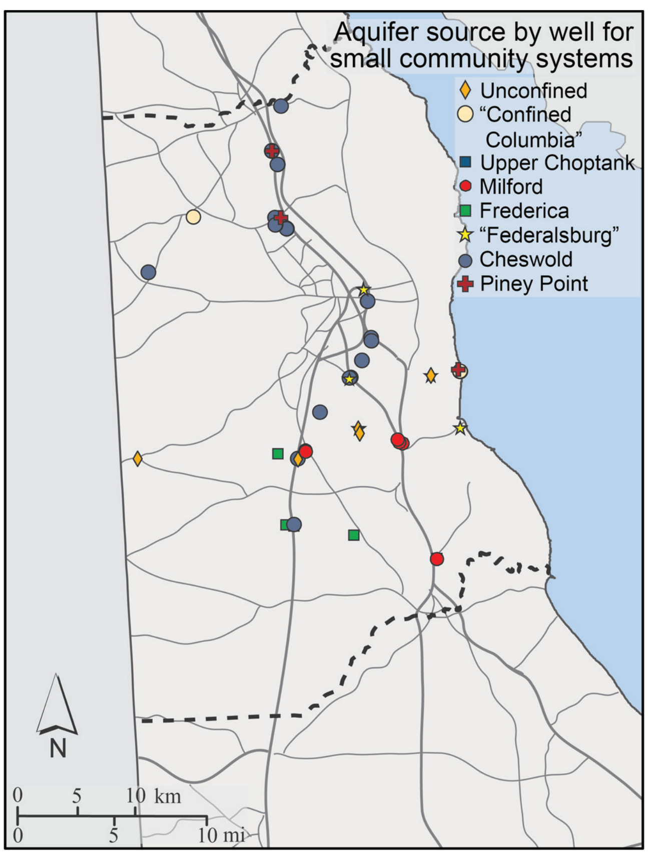

Figure 68. Map showing aquifer source by well for small community public water systems with no reported pumping data in Kent County.

More than half of withdrawals for the TNCs were from the unconfined aquifer and confined Columbia aquifer (Fig. 70). The most important confined aquifers for Kent County TNCs were the Cheswold aquifer in the north and the Frederica aquifer in the south (Fig. 71). The largest number of TNC wells in Sussex County were associated with the main shallow aquifers — unconfined, confined Columbia, and Pocomoke — especially in coastal areas, commonly at campgrounds and seasonal trailer parks (Fig. 72).

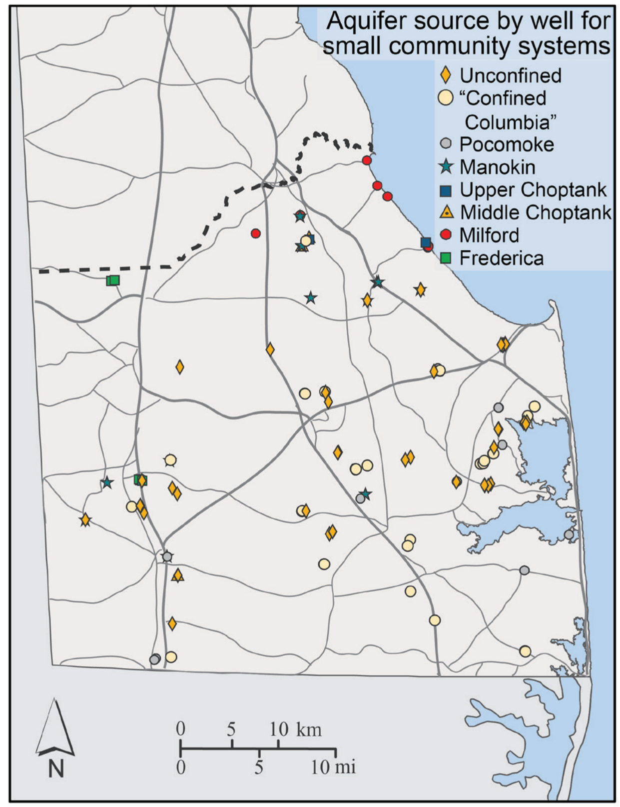

Figure 69. Map showing aquifer source by well for small community public water systems with no reported pumping data in Sussex County.

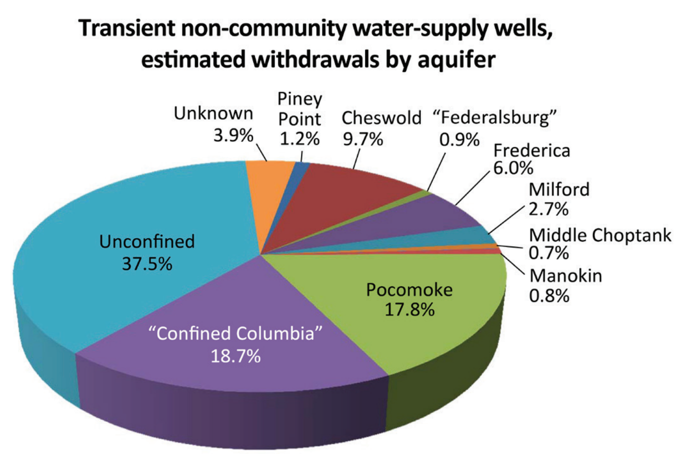

Figure 70. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for public transient non-community wells with no reported pumping data. Percentages do not add to 100% because of rounding to one decimal place; data are in the appendices.

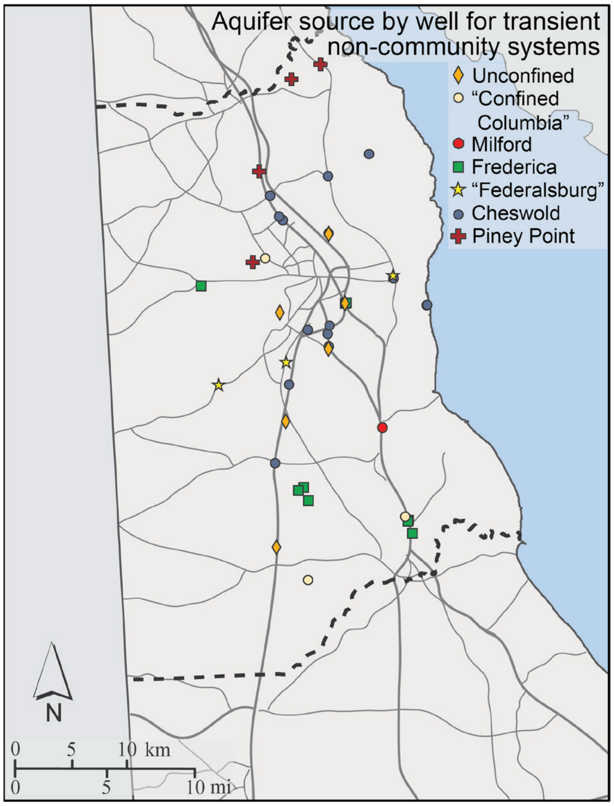

Figure 71. Map showing aquifer source by well for transient non-community public water systems with no reported pumping data in Kent County.

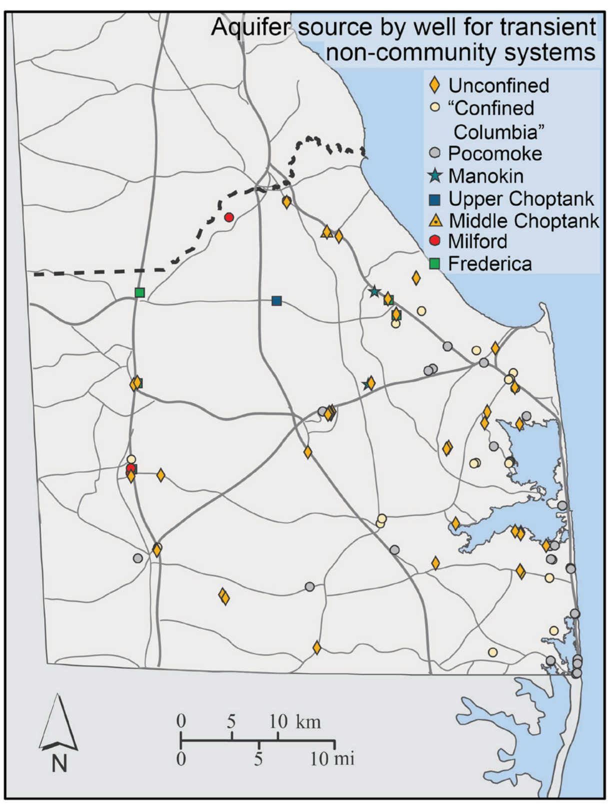

Figure 72. Map showing aquifer source by well for transient non-community public water systems with no reported pumping data in Sussex County.

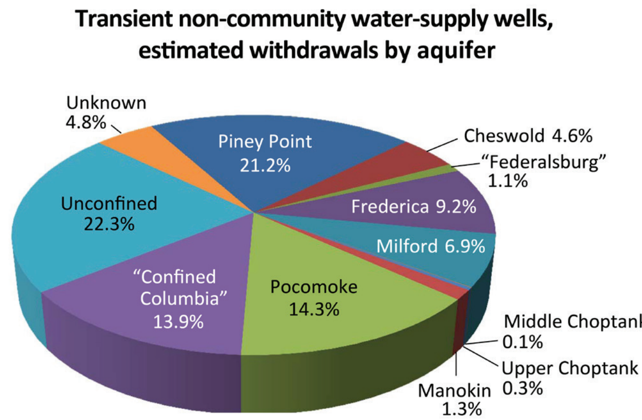

Figure 73. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for public non-transient non-community water system wells with no reported pumping data. Percentages were rounded to one decimal place; data are in the appendices.

The NTNCs use a variety of aquifers (Fig. 73). The largest number of NTNC wells is in the unconfined aquifer. The Frederica aquifer is the source for many wells in Kent County (Figs. 74 and 75; Table 24). The unconfined and Piney Point aquifers had the largest estimated withdrawals (Fig. 73). The Piney Point volumes are large because of estimated withdrawals for the well serving Polytech High School, south of Dover (Fig. 74).

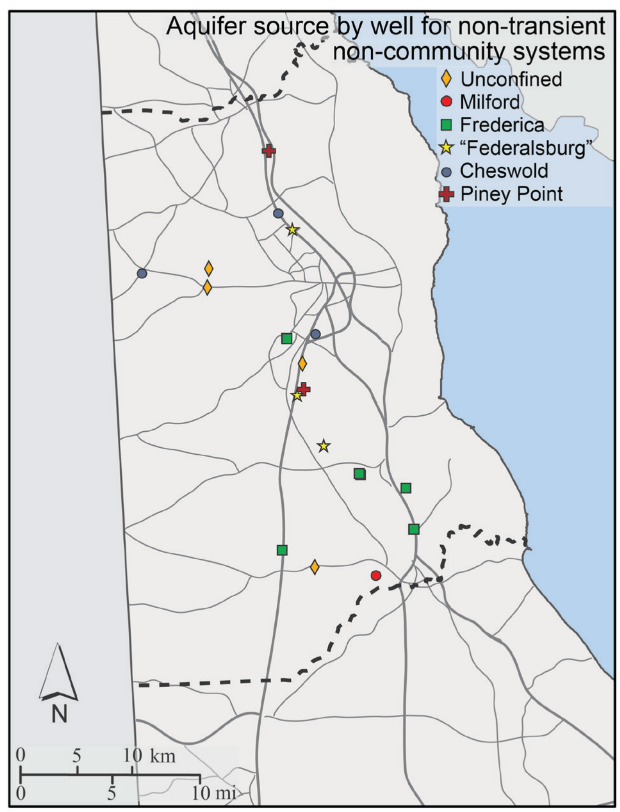

Figure 74. Map showing aquifer source by well for non-transient non-community public water systems with no reported pumping data in Kent County.

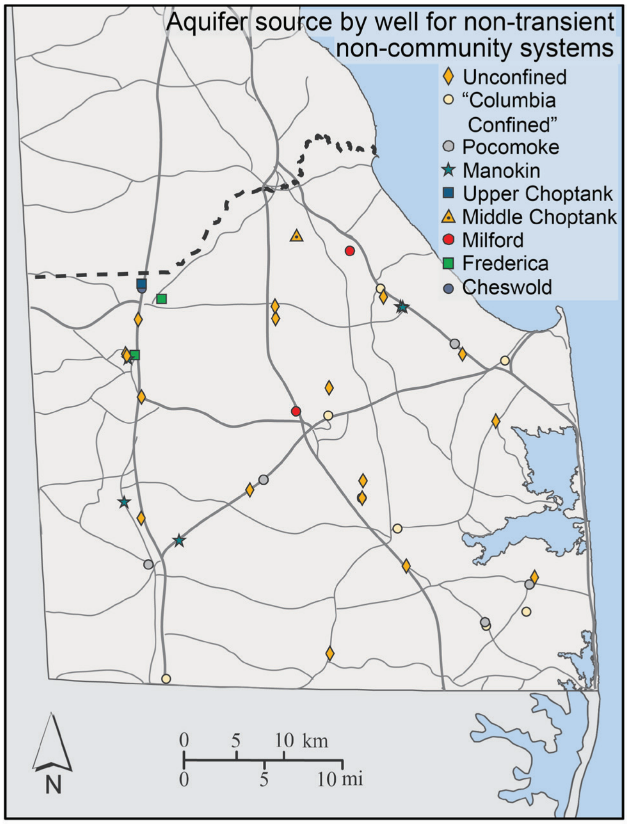

Figure 75. Map showing aquifer source by well for non-transient non-community public water systems with no reported pumping data in Sussex County.

Domestic Self-Supplied

Total and County

Domestic self-supplied water use was estimated using a census-based model created in this study based on the approach of Horn et al. (2008). A multiple linear regression of five census measures was calibrated to reported pumping in public water systems that are dominated by domestic use. We identified 4,733 populated census blocks or sub-blocks that lie outside of public-water service areas and, thus, were assumed to rely on household wells for domestic water supply.

Total self-supplied domestic water use for the study area was estimated at 11.607 Mgal/d, making this the third largest category of groundwater withdrawals (Table 25). This is an average rate of 73.9 gallons per capita per day (GPCD). In Kent County, withdrawals were estimated at 4.23 Mgal/d for 60,575 self-supplied residents in 1,570 full or partial census blocks; this represents an average water use of 69.9 GPCD. In Sussex County, estimated withdrawals were 7.37 Mgal/d for 96,472 residents of 3,163 census blocks or partial blocks, representing an average water use of 76.4 GPCD. The higher estimated per capita domestic use in Sussex County compared to Kent County is likely attributable to water use by occupants of non-resident seasonal housing that are not included in the census populations.

The domestic water-use model was created using groundwater withdrawal data derived from public water systems and was not calibrated to actual metered domestic water use in self-supplied areas. In public water systems, a customer pays for water used and consequently has an incentive to limit household use. A self-supplied domestic user does not have the same cost constraint after the initial investment in a well and hence may use more water. Nevertheless, our water-use model likely provides reasonable estimates.

Table 25. Estimated self-supplied domestic water-use withdrawals, user population, and per capita groundwater usage values for Kent and Sussex Counties and for the study area overall. gal/yr, gallons per year; Mgal/d, million gallons per day; GPCD, gallons per capita per day.

	Withdrawals (gal/yr)	Withdrawals (Mgal/d)	Self-supplied residents	Per capita usage (GPCD)
Kent County	1,545,696,504	4.235	60,575	69.9
Sussex County	2,690,755,366	7.372	96,472	76.4
Total	4,236,451,870	11.607	157,047	73.9

By Census Block

Because self-supplied domestic water use was modeled and could not be tied to individual wells, census blocks were used as the smallest geographic unit for estimating groundwater withdrawals.

The areas with the highest estimated self-supplied domestic water use are in subdivisions in the countryside that do not have a public water supply, typically close to towns but outside of their public system service areas (Figs. 76 and 77). Self-supplied domestic well withdrawals for any individual census block are not especially large compared to public water-supply well withdrawals. The reporting threshold of 50,000 gal/d is equivalent to 18.2 Mgal/yr; the highest values of domestic self-supplied water use were less than 15 Mgal/yr (Figs. 76 and 77). The blocks having lower estimated withdrawals are in rural areas with lower housing and population density.
Per capita estimates of withdrawals for the census blocks ranged from 15 to 246 GPCD (Figs. 78 and 79) with a median value of 72.8 GPCD. However, the highest and lowest per capita values reflect the effect of small quirks of the census data: 57.8 GPCD is 10th percentile, 96.7 GPCD is 90th percentile. Modeled values in the lower 10 percent are mostly in rural blocks with small populations (15-50 GPCD, Fig. 79) and the blocks with modeled values in the upper 10 percent are mostly where summer visitors increase the domestic use above that of the permanent resident population (111-247 GPCD, Fig. 79).

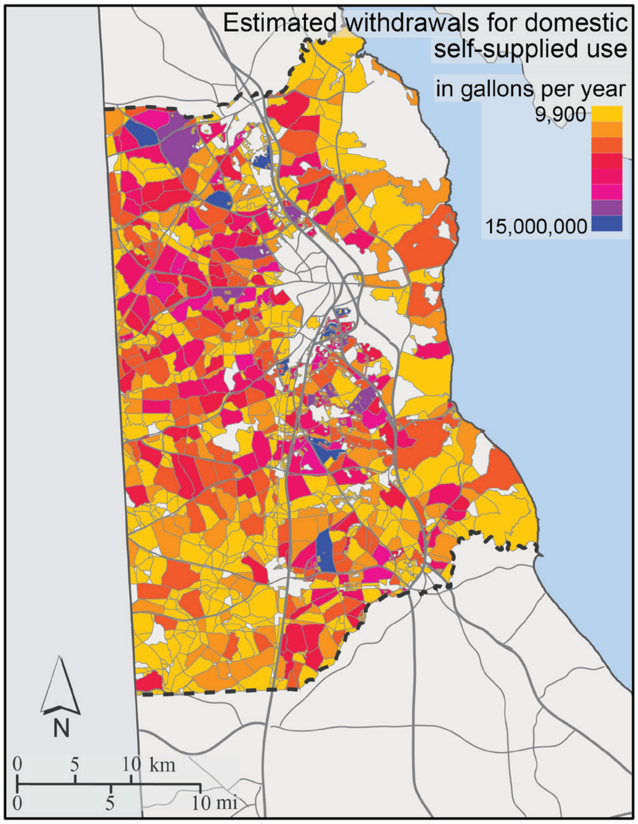

Figure 76. Map showing estimated annual groundwater withdrawals by census block or sub-block for domestic self-supplied water use in Kent County.

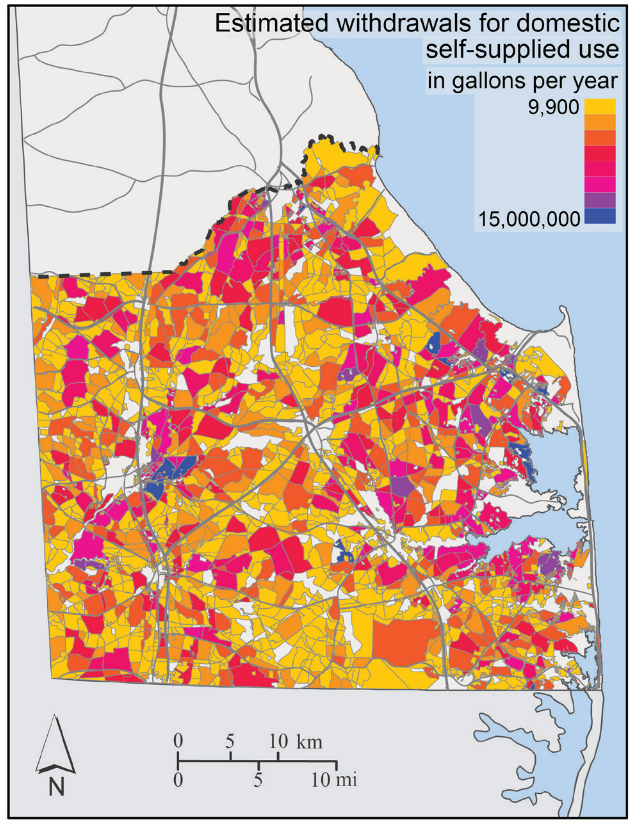

Figure 77. Map showing estimated annual groundwater withdrawals by census block or sub-block for domestic self-supplied water use in Sussex County.

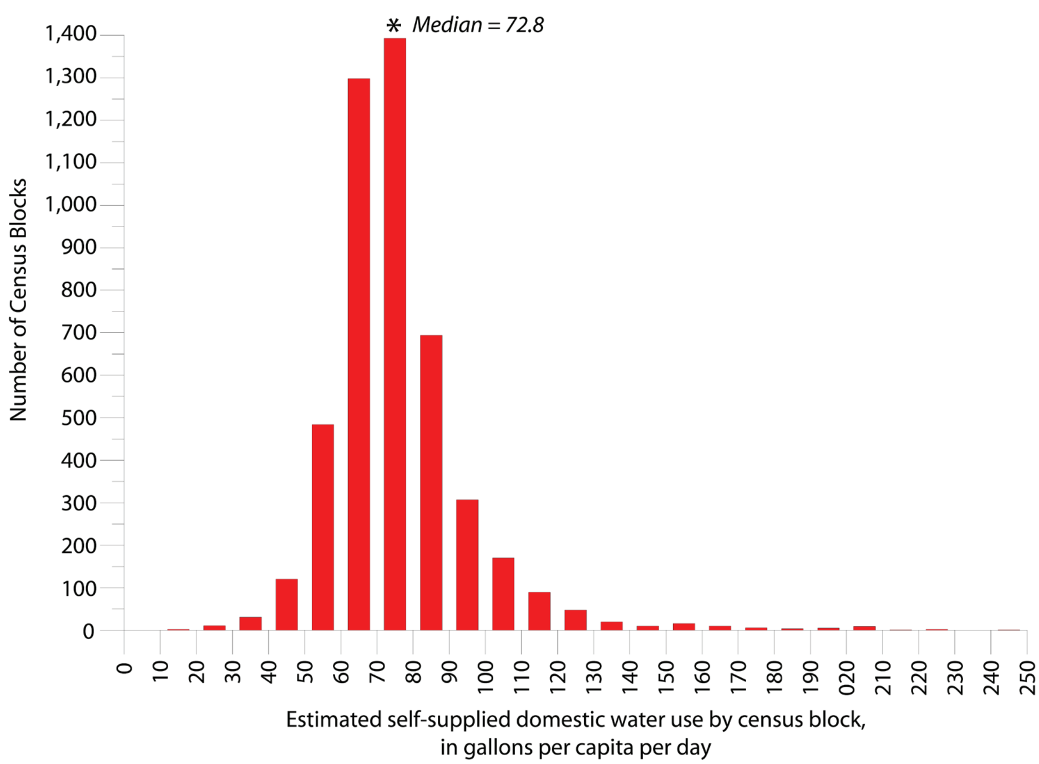

Figure 78. Histogram of estimated annual domestic self-supplied water use by census block.

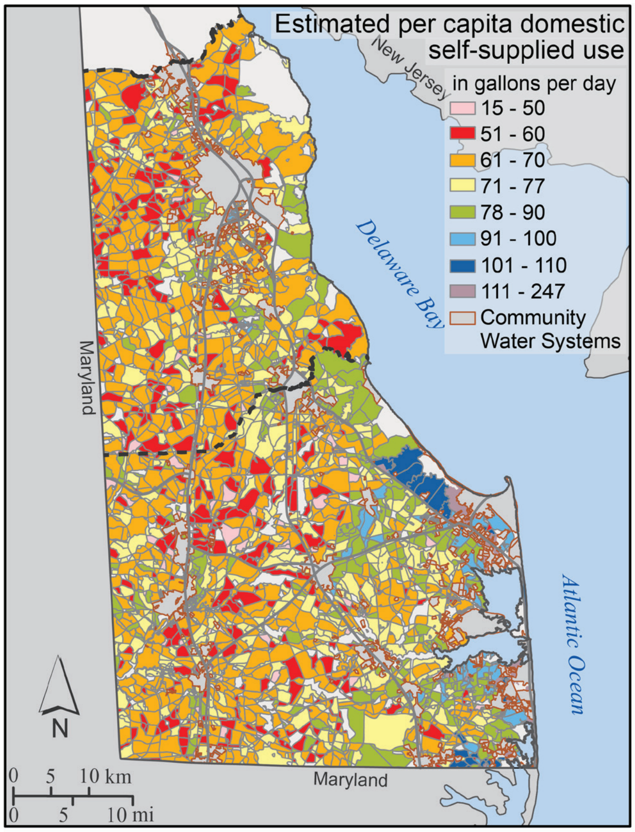

Figure 79. Map showing estimated per capita domestic self-supplied water use by census block or sub-block in Kent and Sussex Counties.

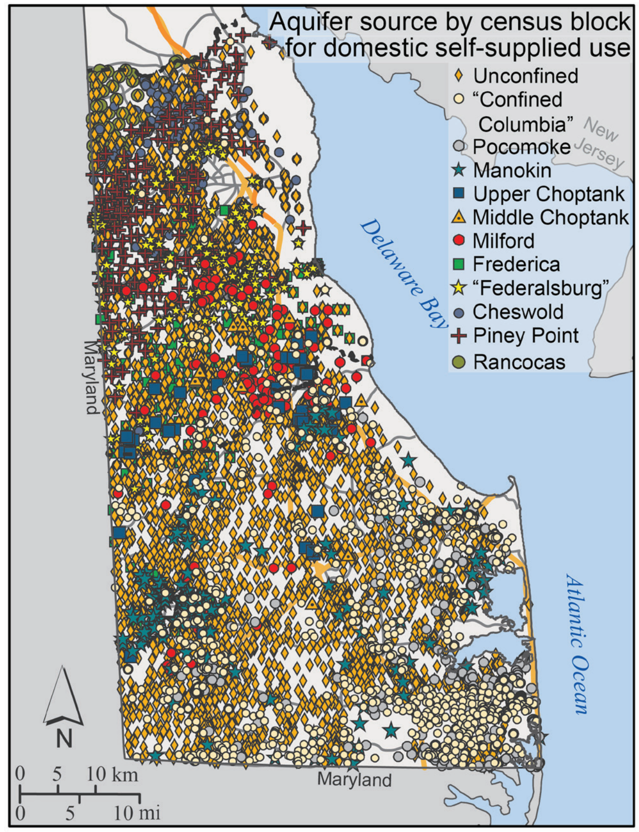

Figure 80. Map showing aquifer source by census block for estimated self-supplied domestic water withdrawals for up to three aquifers per block. The high density of data allows geographic trends in aquifer utilization to be generalized from the trends in symbol distribution in the cloud of map data; the map is not intended to clearly show individual data points.

By Aquifer

Aquifers supplying water for domestic self-supplied use are shown on Figure 80. The number of wells in each aquifer in each self-supplied block was tallied from an analysis of screen depths versus aquifer depths. The proportions of wells in each aquifer served as the basis for dividing estimated total withdrawals among the aquifers.

The unconfined aquifer is the largest source of self-supplied domestic water, representing almost two-thirds of the total (Table 26 and Fig. 81). The confined Columbia aquifer provided nearly 14 percent and all other aquifers provided no more than 6 percent each.

The Cheswold aquifer was the most used of the confined aquifers for domestic wells In Kent County, yielding an estimated 0.647 Mgal/d (Table 26). It is followed in importance by the Frederica (0.198 Mgal/d) and Piney Point (0.190 Mgal/d) aquifers. The confined aquifers most commonly used for domestic wells in Sussex County were, in descending order of estimated volumes, the confined Columbia (1.543 Mgal/d), Pocomoke (0.456 Mgal/d), and Manokin (0.287 Mgal/d) (Table 26).

Table 26. Estimated groundwater withdrawals by aquifer for domestic self-supplied water users in Kent and Sussex Counties. Total may differ slightly from sum of corresponding column due to rounding. Mgal/d, million gallons per day.

Aquifer	Kent County withdrawals (Mgal/d)	Sussex County withdrawals (Mgal/d)	Total withdrawals (Mgal/d)
Unconfined	2.759	4.967	7.727
Confined Columbia	0.078	1.513	1.592
Pocomoke	0	0.456	0.456
Manokin	0	0.287	0.287
Upper Choptank	0.028	0.011	0.04
Middle Choptank	0.004	0.011	0.015
Milford	0.09	0.051	0.141
Frederica	0.198	0.067	0.266
"Federalsburg"	0.154	0.001	0.156
Cheswold	0.647	0.006	0.653
Piney Point	0.19	0	0.19
Rancocas	0.085	0	0.085
Total	4.235	7.372	11.607

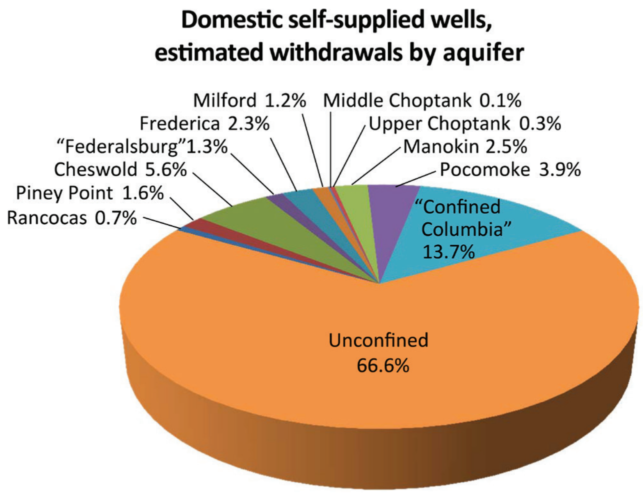

Figure 81. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for domestic self-supplied wells. Percentages do not add to 100% because of rounding to one decimal place; data are in the appendices.

Industrial

Total and County

Industrial pumping was the fourth largest category of groundwater withdrawals. Pumping records for 62 industrial wells in Kent and Sussex Counties indicate total groundwater withdrawals in excess of 7 Mgal/d annually from 2004 through 2008 (Fig. 82; Table 27).

Withdrawals were significantly greater in Sussex County, between approximately 5.5 and 7 Mgal/d (Table 27), mostly for poultry processing. In comparison, reported withdrawals in Kent County were only between 0.8 and 1.4 Mgal/d (Table 27), mostly for manufacturing and chemical operations. The data suggest industrial pumping slightly increased in Sussex County and slightly decreased in Kent County between 2004 and 2008.

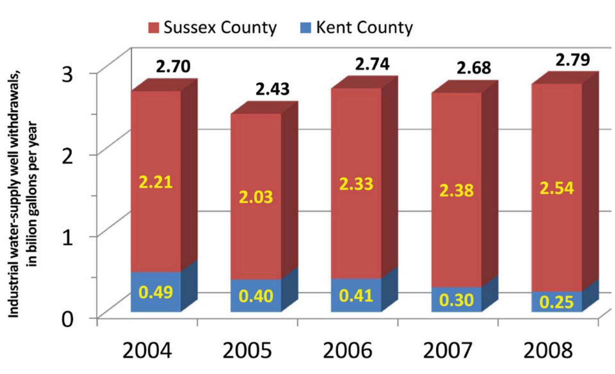

Figure 82. Graph showing reported annual groundwater withdrawals for industrial water systems, 2004 to 2008.

Table 27. Annual reported groundwater withdrawals from industrial wells in Kent and Sussex Counties. Total may differ slightly from sum of corresponding column due to rounding. Mgal/d, million gallons per day.

	2004 (Mgal/d)	2005 (Mgal/d)	2006 (Mgal/d)	2007 (Mgal/d)	2008 (Mgal/d)
Kent County	1.35	1.10	1.13	0.83	0.70
Sussex County	6.06	5.56	6.38	6.52	6.96
Total	7.41	6.66	7.50	7.35	7.66

By Well

Industrial water withdrawals were examined well-by-well basis for each year between 2004 and 2008. Industrial supply wells are located in a limited number of areas associated with larger industrial operations outside of municipal water systems.

Only a few industrial wells pumped large quantities of groundwater in Kent County (Figs. 59 and 83). Hanover Foods in Clayton operated one well that pumped in excess of 100 Mgal/yr during the study period; they also operated two other wells that pump smaller and/or more variable amounts. A well at a west Dover power plant also exceeded 100 Mgal/yr of withdrawals in some years. Two wells at the Purdue plant in Milford commonly withdrew at least 20 Mgal/yr each.

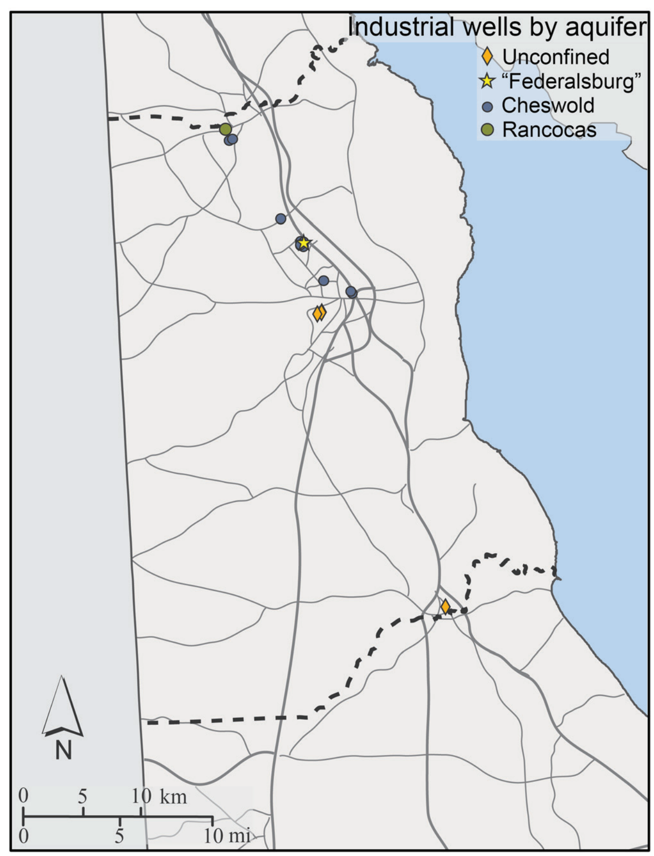

Figure 83. Map showing aquifer source by well for industrial water systems in Kent County.

In Sussex County, the largest withdrawals were commonly at poultry facilities near Millsboro and Georgetown (Fig. 60 and 84). Wells at both facilities withdrew more than 200 Mgal/yr. A number of other industrial wells withdrew more than 100 Mgal in a year during the study period, including several at the Millsboro poultry complex, several at DuPont's Seaford plant, and one at the Indian River Power plant.

By Aquifer

The pumping data reported for 2006 provide a generally representative understanding of the distribution of industrial groundwater withdrawals in Kent and Sussex Counties. The unconfined aquifer was the largest source of groundwater, comprising more than half of the industrial withdrawals (Table 28, Fig. 85). In Kent County, the unconfined aquifer and Cheswold aquifer were approximately equal as sources for industrial wells (Table 28). In Sussex County, more than half of the industrial withdrawals were from the unconfined aquifer and slightly less than two-thirds were from the Pocomoke aquifer (Table 28). The Manokin aquifer was also an important source in western Sussex County (Fig. 84).

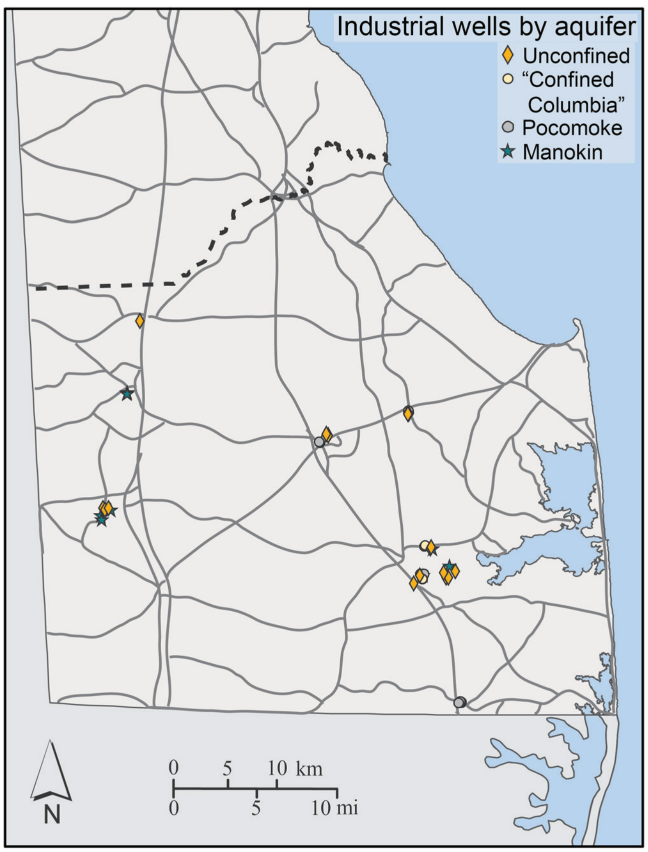

Figure 84. Map showing aquifer source by well for industrial water systems in Sussex County.

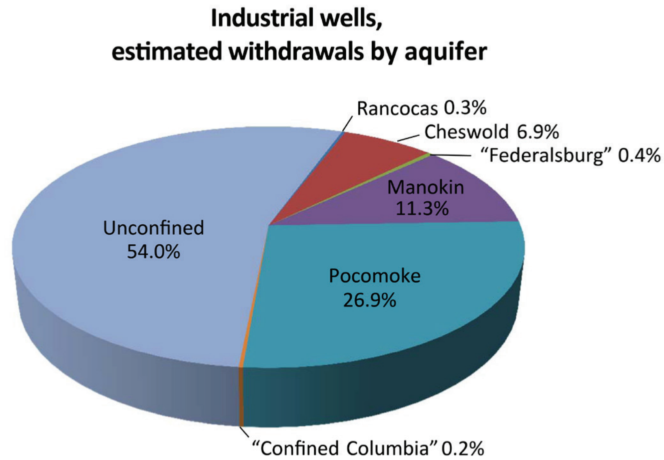

Figure 85. Pie chart showing percentage of groundwater withdrawals by aquifer for industrial wells for 2006. The relative volumes of each aquifer are generally representative for 2004 through 2008; data for other years are in the appendices. Percentages do not add to 100 percent because of rounding to one decimal place.

Agricultural Irrigation

Total and County

Cropland irrigation is the largest use of groundwater in the study area. Although surface water is used for irrigation locally, the vast majority of irrigation uses groundwater. Cropland irrigation needs were estimated for the years 2005 through 2008 using a dataset of 2,407 irrigation areas and a daily crop water-demand model that utilized crop type, soil type, and climate data. Withdrawals to meet these needs ranged from approximately 50 Mgal/d (18 billion gallons) in a wet year (2006) to about 90 Mgal/d (33 billion gallons) in a dry year (2007) (Tables 17 and 29, Fig. 86).

Sussex County had the largest irrigation use, with estimated withdrawals of approximately 45 to 72 Mgal/d (or 16 to 26 billion gallons per year). In Kent County, the withdrawals were much smaller, estimated at 5 to 19 Mgal/d (or 2 to 7 billion gallons per year). To facilitate comparisons to rainfall totals, the irrigation estimates were converted to equivalent inches of water per acre based on a conversion of 1 inch of water over an acre representing 27,154 gallons. The crop-water-demand model produced 1.5- to 3-times larger estimates of irrigation water use per acre in Sussex County than Kent County, mostly because of the generally sandier nature of Sussex County soils (Table 29).

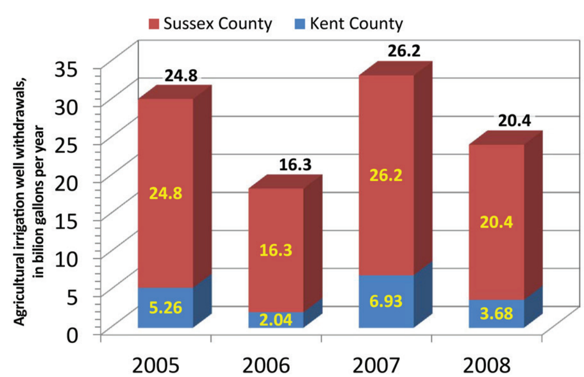

Figure 86. Map showing aquifer source by well for industrial water systems in Sussex County.

Table 28. Reported groundwater withdrawals and number of wells by aquifer for industrial wells for 2006 in Kent and Sussex Counties. The relative volumes of each aquifer are generally representative for all years of this study (2004-2008); data for other years are in the appendices. Mgal/d, million gallons per day.

Aquifer	Kent County withdrawals (Mgal/d)	Sussex County withdrawals (Mgal/d)	Total withdrawals (Mgal/d)	Number of wells
Unconfined	0.561	3.492	4.053	23
Confined Columbia	0	0.017	0.017	2
Pocomoke	0	2.018	2.018	15
Manokin	0	0.851	0.851	9
"Federalsburg"	0.033	0	0.033	1
Cheswold	0.514	0	0.514	11
Rancocas	0.019	0	0.019	1
Total	1.127	6.378	7.505	62

Table 29 includes a comparison of our estimated irrigation totals for years 2005 through 2008 to the total precipitation for the growing season months of May through September (National Climatic Data Center, 2014). The reported rainfall totals represent normal to slightly below-normal precipitation for 2005, above normal precipitation for 2006, a major shortfall for 2007, and normal to slightly above normal for 2008. Estimated irrigation demands were lowest in 2006 when precipitation was highest; estimated demands were greatest in 2007 when precipitation totals were lowest.

Precipitation totals were nearly normal in 2005 and 2008; however, estimated groundwater withdrawals for irrigation were notably higher for 2005. The reason for the difference in modeled irrigation needs was the timing of the precipitation events. In 2005, the majority of the rain in May occurred in one day, so had a limited effect on crop needs; dry weather in August and September would have prompted irrigation of corn in the early part of the period and soybeans throughout. In contrast, rain was more evenly distributed through the summer of 2008, except for a dry August, so less irrigation was needed to maintain adequate soil moisture.

Our irrigation water-use estimates come with some caveats. They were derived from a model that was uncalibrated and utilized generalized data. Soil moisture capacity was averaged over relatively large areas (climate polygons) from soil maps. Climate data used for the model were assumed to be the same within a Thiessen-polygon-based area, but precipitation most certainly varied to a degree across each of these polygons. The crop type was derived from the USDA 2008 Cropland Data Layer (U.S. Department of Agriculture, 2009b), which has some imperfections at the scale of an individual irrigation polygon. In addition, the model assumed that all farmers showed ideal behavior and irrigated the ideal amount as calculated by KanSched2 (Rogers and Alam, 2008).

However, despite these caveats, we feel the model provided reasonable estimates. Total reported pumping for the year 2007, a dry year, was on average 1.7 times the total reported for 2006, a wet year. From another perspective, 65 percent of the wells with data for both years reported pumping volumes for 2007 that were 1.5 times greater than those for 2006. These ratios are comparable to the ratio of modeled use between 2007 (about 90 Mgal/d) and 2006 (about 50 Mgal/d) calculated in this study. A similar daily crop-water-demand model that incorporates weather data, crop type, and soil type was evaluated in a recent USGS study (Levin and Zarriello, 2013); that model yielded comparable or better quality estimates than models based on sites with weekly meter data.

Table 29. Sum of estimated annual withdrawals for agricultural irrigation in Kent and Sussex Counties. Equivalent inches of irrigation per acre was computed using a volume of 27,154 gallons per inch per acre. Precipitation data are from weather stations in Dover (Kent County) and Lewes (Sussex County) (National Climatic Data Center, 2014). Total of withdrawals may differ slightly from sum of corresponding column due to rounding. Mgal/d, million gallons per day.

	2005	2006	2007	2008
Irrigation withdrawals (Mgal/d)				
Kent County	14.42	5.60	18.99	10.08
Sussex County	67.97	44.58	71.90	55.97
Total	82.35	50.16	90.84	66.03
Irrigation (average inches/acre)				
Kent County	6.81	2.65	8.97	4.77
Sussex County	12.31	8.08	13.02	10.14
Precipitation May to September (inches)				
Kent County	18.4	22.1	12.0	18.7
Sussex County	21.2	24.0	11.0	21.4

By Census Block and Polygon

Water use was estimated for each of 2,407 irrigated areas identified in Kent and Sussex Counties. These irrigated areas represent a total of more than 102,000 acres, which nearly equals the estimated irrigated acreage for the entire state (104,562 acres) in the 2007 Census of Agriculture (U.S. Department of Agriculture, 2009a). Approximately half of the irrigated acreage was mapped as corn; soy and a double crop of soy and winter wheat each represented nearly one quarter of the remaining acreage (Table 30).

Irrigation water use was tallied for each census block that contained an irrigated area, totaling 247 census blocks in Kent County (Fig. 87) and 640 in Sussex County (Fig. 88). The greatest estimated irrigation withdrawals in Kent County were in a census block east of Smyrna, an arc across the east side of Dover, and a belt across south side of the county (Fig. 87). Irrigation is more intensive in Sussex County; blocks with the greatest estimated withdrawals are located in an arc west of Bridgeville, a ring around Laurel, several census blocks west of Georgetown, and a cluster of census blocks southeast of Milford (Fig. 88).

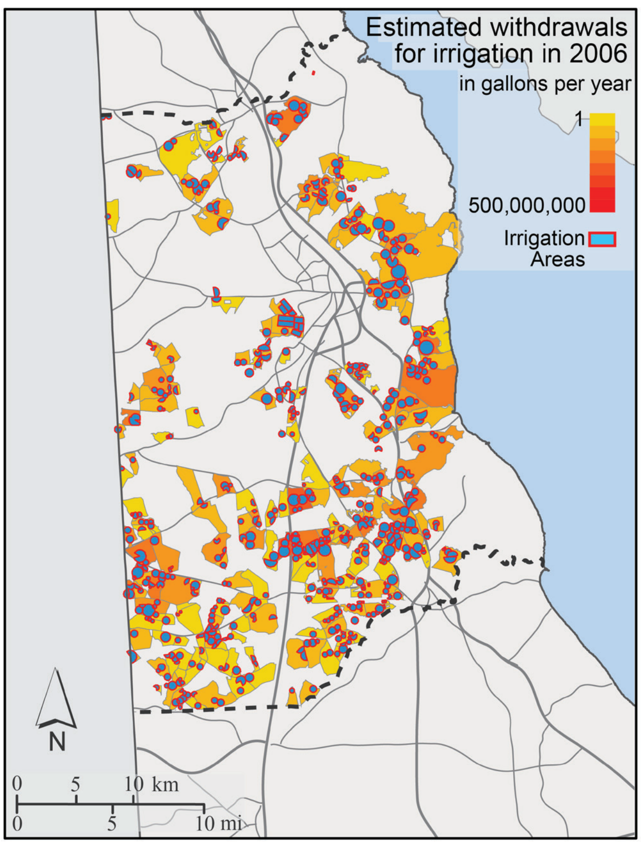

Figure 87. Map showing estimated groundwater withdrawals by census block for agricultural irrigation in Kent County in 2006 with locations of irrigated areas. Data and maps for other years are in the appendices.

Table 30. Estimated acreage of irrigated cropland in Kent and Sussex Counties calculated using the sum of acreage of individual irrigation areas and the crop types present according to the USDA 2008 Cropland Data Layer.

Crop	Acres
Corn	51,402
Soy	26,806
Double crop soy and winter wheat	22,255
Sweet corn	2,113
Total	102,576
Kent County	28,370
Sussex County	74,206

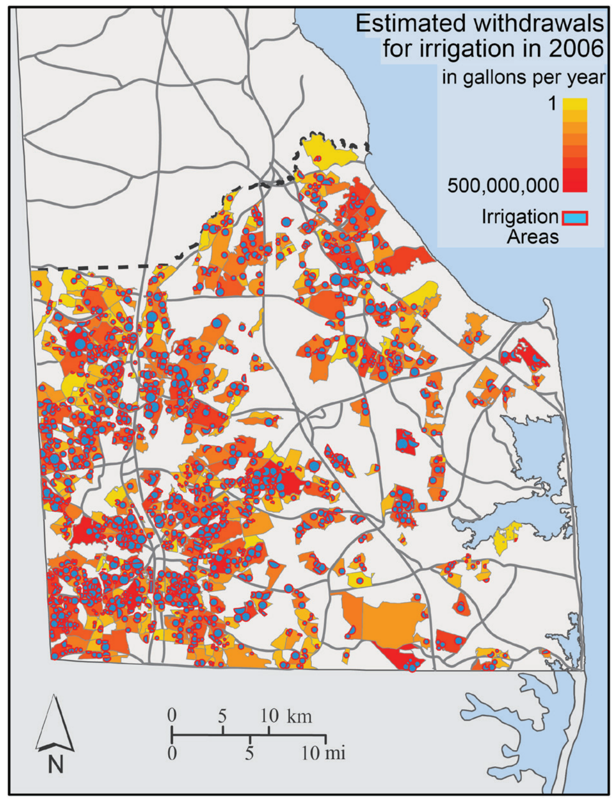

Figure 88. Map showing estimated groundwater withdrawals by census block for agricultural irrigation in Sussex County in 2006 with locations of irrigated areas. Data and maps for other years are in the appendices.

By Aquifer

Geographic trends in groundwater withdrawals for agricultural irrigation by aquifer are shown on Figure 89. Aquifer assignments were made in each census block by analyzing the distribution of well screen elevations relative to aquifer-elevation raster surfaces. Where multiple aquifers were identified, groundwater use was proportionally assigned among the three most-used aquifers based on the number of wells in each. Our analysis suggests that many irrigation wells were screened across more than one aquifer (contrary to state regulations).

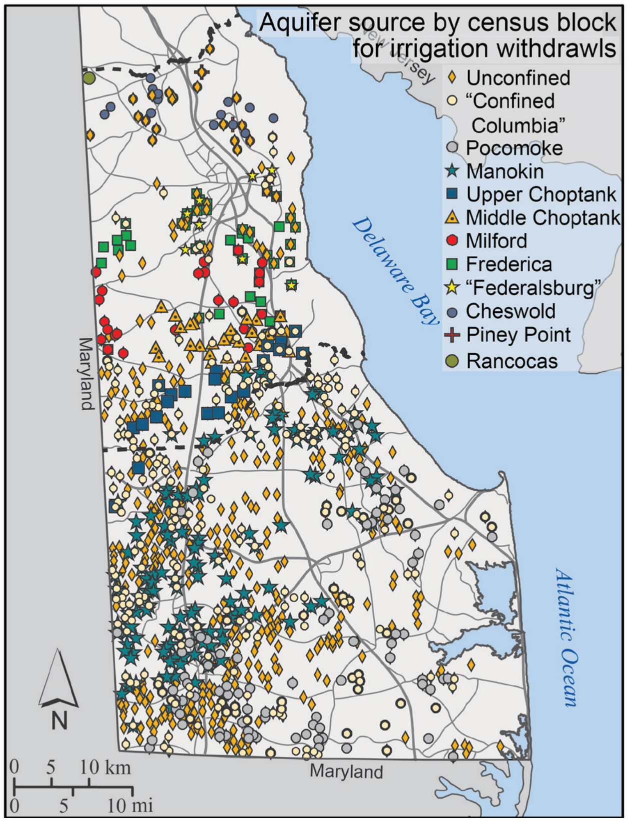

Figure 89. Map showing aquifer source by census block for estimated agricultural irrigation groundwater withdrawals for up to three aquifers per block.

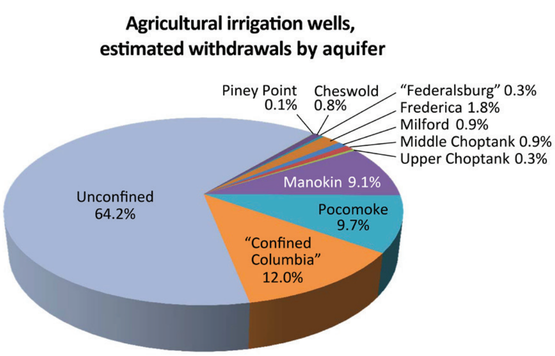

Figure 90. Pie chart showing percentage of estimated groundwater withdrawals by aquifer estimated for agricultural irrigation wells for 2006. This graph is generally representative for 2004 through 2008; data for other years are in the appendices. Percentages were rounded to one decimal place.

The unconfined aquifer was the most used source of agricultural irrigation water, representing almost two-thirds of groundwater withdrawals (Fig. 90). Three confined aquifers — confined Columbia, Pocomoke, and Manokin — each provided approximately 10 percent of the withdrawals, mostly in Sussex County. The confined Columbia aquifer was most commonly used in the southeastern half of Sussex County, the Manokin aquifer in the northwestern half, and the Pocomoke aquifer in scattered clusters. Other aquifers were minor sources of irrigation water. The Cheswold aquifer was used locally in northern Kent County, the Frederica aquifer was a local source in central Kent County, and various sands of the Choptank Formation (Milford, Middle Choptank, Upper Choptank) were used in southern Kent County (Fig. 89).

Golf Course Irrigation

Total and County

Golf course irrigation is a minor use of groundwater in Delaware (Table 17), but it can be significant locally. Most of the withdrawals tallied in this study were in Sussex County. Determination of annual pumping rates was complicated by incomplete or inconsistent reporting of water use for the 27 wells with allocations. By combining reported water-use data and estimated data for wells with no reporting or missing years, golf course irrigation was estimated at between 1.75 and 2.75 Mgal/d or 638.1 million and 1.0 billion gallons per year (Table 31). The minimum estimate was based on the smallest reported pumping number for each well or, where data were lacking, the estimated proportion of allocated water use (the system allocation divided by number of wells). The maximum estimate was based on the largest reported pumping number for each well; for missing data, we assumed double the estimated proportion of allocated water use because most wells withdraw more than their allocation.

Table 31. Estimated minimum and maximum groundwater withdrawals for golf course wells reported and estimated for 2004 to 2008 in Kent and Sussex Counties. Total may differ slightly from sum of corresponding column due to rounding. Mgal/yr, million gallons per year; Mgal/d, million gallons per day

	Wells	Minimum (Mgal/yr)	Maximum (Mgal/yr)	Minimum (Mgal/d)	Maximum (Mgal/d)
Kent County	3	41.5	83	0.11	0.23
Sussex County	24	596.6	919.4	1.63	2.52
Total	27	638.1	1,002.4	1.75	2.75

By Well

The largest reported annual withdrawals for golf course irrigation wells were between 63 and 66 Mgal/yr (Bear Trap Dunes and Peninsula on Indian River, both near Millsboro). Withdrawals for several other wells were estimated to be in the same general range based on their allocations. More than two-thirds of golf course irrigation wells were reported or estimated to withdrawal less than 30 Mgal/yr and around half of those (1/3 of total) less than 10 Mgal/yr. Although the large users in this class withdraw less than the largest public or industrial wells, their withdrawal rates exceed those of most public or industrial wells.

By Census Block

Golf courses commonly have multiple wells with high pumping rates located close to each other, which can result in a large volume of withdrawals in a small area. For example, three irrigation wells used by the Rehoboth Beach County Club had a total withdrawal of as much as 100 Mgal/yr from the Pocomoke aquifer in a single small census block, mostly during summer months. Such locally high golf course withdrawals may affect groundwater availability in nearby census blocks. In the case of the Rehoboth census block, the wells appear to have been the only major users of groundwater from the Pocomoke aquifer; other large users in nearby census blocks were public wells that pumped from the unconfined and confined Columbia aquifers.

By Aquifer

Most golf course irrigation wells in the study area have well screens in the unconfined aquifer (Table 32). Reported data and estimates for 2007 indicate that nearly half of the withdrawals were from the unconfined aquifer. The Kent County wells used the Piney Point and Frederica confined aquifers. The Sussex County wells mostly utilized the unconfined aquifer and, to a lesser degree, the confined Columbia, Pocomoke, and Manokin aquifers (Figs. 91 and 92).

Table 32. Number of wells by aquifer reported for golf course irrigation for 2004 through 2008 in the study area.

Aquifer	Number of wells
Unconfined	14
Confined Columbia	4
Pocomoke	3
Manokin	3
Frederica	2
Piney Point	1
Total	27

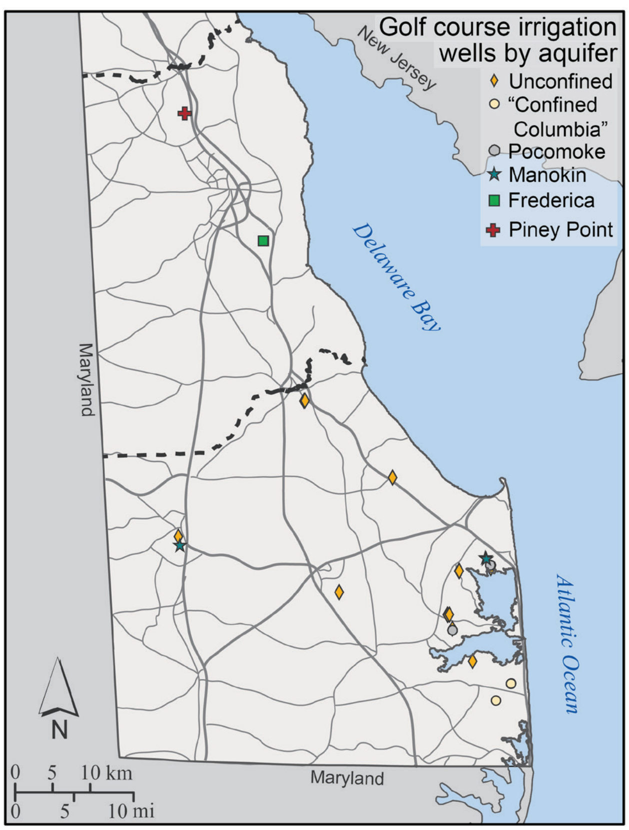

Figure 91. Map showing aquifer source by well for reported and estimated golf course irrigation groundwater withdrawals in Kent and Sussex Counties.

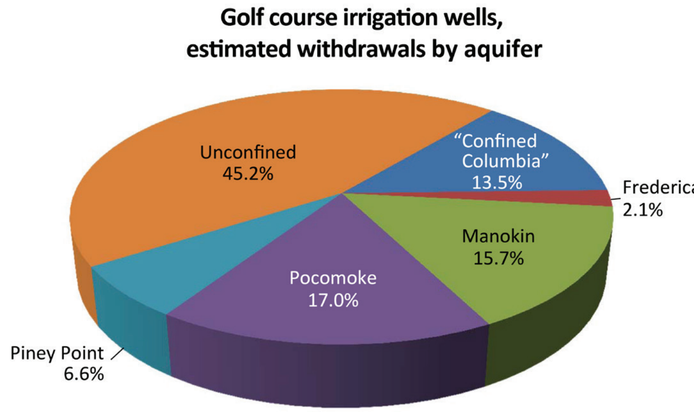

Figure 92. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for golf course irrigation wells for 2007. The relative volumes of each aquifer are generally representative for 2004 through 2008; data for other years are in the appendices. Percentages do not add to 100% because of rounding to one decimal place.

Livestock

Total and County

Groundwater withdrawals for livestock use, specifically poultry, represent a minor but notable class of water use. The dataset for poultry water use was estimated from 2,727 poultry houses that appeared to be active in 2008, 442 in Kent County and 2285 in Sussex County. Poultry house wells provide drinking water for the animals and water for the operation of evaporative cooling systems, which we estimate to represent 64 and 35 percent of use in this category, respectively.

Total withdrawals for poultry use were estimated at approximately 4.3 Mgal/d, with 3.6 Mgal/d in Sussex County and 0.7 Mgal/d in Kent County (Table 33). These estimates were not calibrated to metered water-use data. They should be considered approximations because of the number of variables that were estimated, averaged, or assumed including: lifespan of bird; size of chicken houses; assumed full-time use of chicken houses; and the assumption that all chicken growers use water in a manner consistent with our methodology.

By Census Block and Farm

Assuming a water demand of 575,000 gal/yr per chicken house, groundwater withdrawals were calculated for each census block that contained at least one chicken house. In Kent County, 124 blocks were recognized with chicken houses (Fig. 93); in Sussex County, 566 blocks were recognized (Fig. 94). The highest estimated withdrawals were 25 Mgal/yr in a census block east of Frankford where 43 chicken houses were located (Fig. 94). Withdrawals were estimated as more than 10 Mgal/yr in five blocks that had 20 or more chicken houses. For perspective, withdrawals in the census blocks of heaviest use for poultry were less than withdrawals reported for most public water-supply wells.

Table 33. Estimated groundwater withdrawals by aquifer for poultry use for Kent and Sussex Counties. Total may differ slightly from sum of corresponding column due to rounding. Mgal/d, million gallons per day.

Aquifer	Kent County (Mgal/d)	Sussex County (Mgal/d)	Total (Mgal/d)
Unconfined	0.35	2.02	2.36
Confined Columbia	0.08	0.97	1.04
Pocomoke	0	0.26	0.26
Manokin	0	0.14	0.14
Upper Choptank	0.02	0.02	0.04
Milford	0.02	0.05	0.08
Frederica	0.07	0.15	0.22
"Federalsburg"	0.02	0	0.02
Cheswold	0.08	0	0.08
Piney Point	0.04	0	0.04
Rancocas	0.02	0	0.02
Total	0.7	3.61	4.3

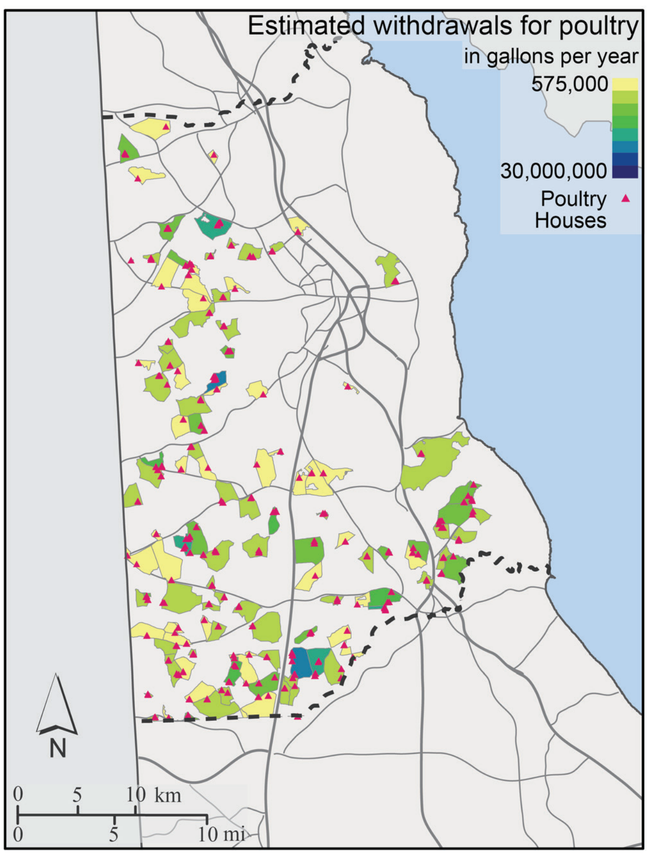

Figure 93. Map showing estimated groundwater withdrawals by census block for poultry house use in Kent County.

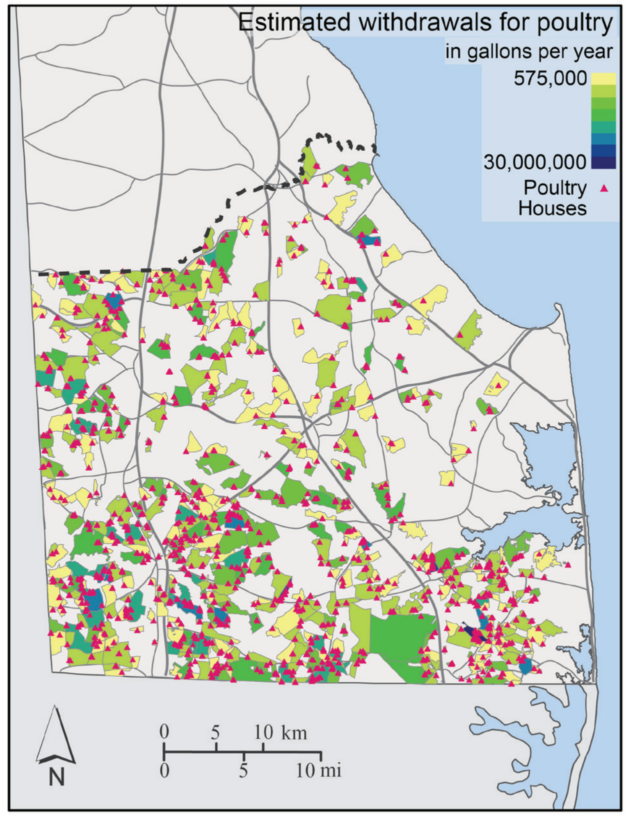

Figure 94. Map showing estimated groundwater withdrawals by census block for poultry house use in Sussex County.

By Aquifer

Approximately 80 percent of the groundwater used for poultry houses is pumped from the unconfined aquifer or the confined Columbia aquifer (Fig. 95). In Kent County, the Cheswold and Frederica aquifer are also important sources; in Sussex County, the Pocomoke, Manokin, and Frederica aquifers are also important (Table 33).

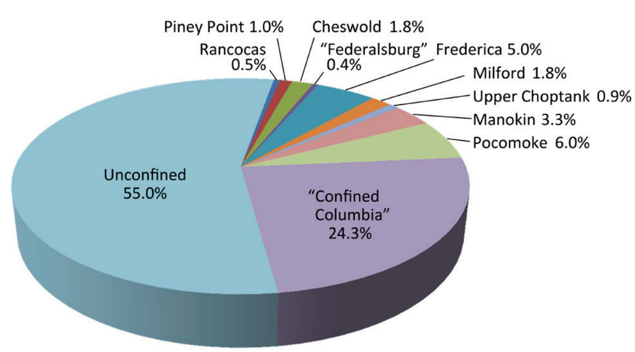

Figure 95. Pie chart showing percentage of estimated groundwater withdrawals by aquifer for poultry use. Percentages were rounded to one decimal place; data are in the appendices.

Lawn Irrigation

Total and County

Water use for lawn irrigation was the category with the smallest volume of withdrawals (Table 17). Lawn irrigation wells are typically installed in subdivisions served by public water utilities where residents have a cost incentive to use their own wells instead of public water supply at a per-unit cost.

As of 2008, 1,074 wells were identified in 177 census blocks. Annual withdrawals per well were estimated to be 10,281 gallons per year; total withdrawals were approximately 0.030 Mgal/d or 11 Mgal/yr, 2.9 Mgal/yr in Kent County and 8.1 Mgal/yr in Sussex County (Table 34). No metered lawn well data were available to calibrate these estimates. Water use behavior of residents with lawn irrigation wells can be expected to be highly variable. However, the overall estimates are comparable to the expected water needs of a 0.2-acre lot that has a 10,000-ft^2 lawn. Assuming a lawn needs 1 inch of water per week over 12 weeks of summer and that a semi-dry summer has 10 inches of rain, the water shortfall would be 2 inches. Given that 1 inch of rain over 10,000 ft^2 equals 6,200 gal/wk, the 2-inch shortfall would result in a hypothetical need of 12,400 gal for the summer, which is fairly close to the estimated average per well withdrawals for the study area.

Lawn irrigation wells are typically shallow; the distribution of well depths indicates that nearly all of these wells pump from the unconfined aquifer.

Table 34. Estimated groundwater withdrawals for lawn irrigation from agricultural wells in census blocks in public water service areas in 2008 in Kent and Sussex Counties. gal/yr, gallons per year; Mgal/d, million gallons per day.

	Number of lawn wells	Census blocks	Total lawn irrigation withdrawals (gal/yr)	Total lawn irrigation withdrawals (Mgal/d)	With-drawals per well (gal/yr)
Kent County	292	61	2,896,192	0.008	9,918
Sussex County	782	116	8,146,045	0.022	10,417
Total	1074	177	11,042,237	0.030	10,281

By Census Block

Water use for lawn irrigation was calculated for each census block that contains "agricultural" wells in a public water-supply service area, which are assumed here to be for watering lawns. In Kent County, 292 lawn irrigation wells were identified in 61 blocks (Fig. 96); in Sussex County, 782 lawn wells were identified in 116 blocks (Fig. 97). For the majority of the blocks, estimated withdrawals were less than 50,000 gallons per year. Areas with the largest estimated lawn irrigation withdrawals were in the Lewes-Rehoboth and Inland Bays areas in Sussex County, and two blocks west and south of Dover in Kent County.

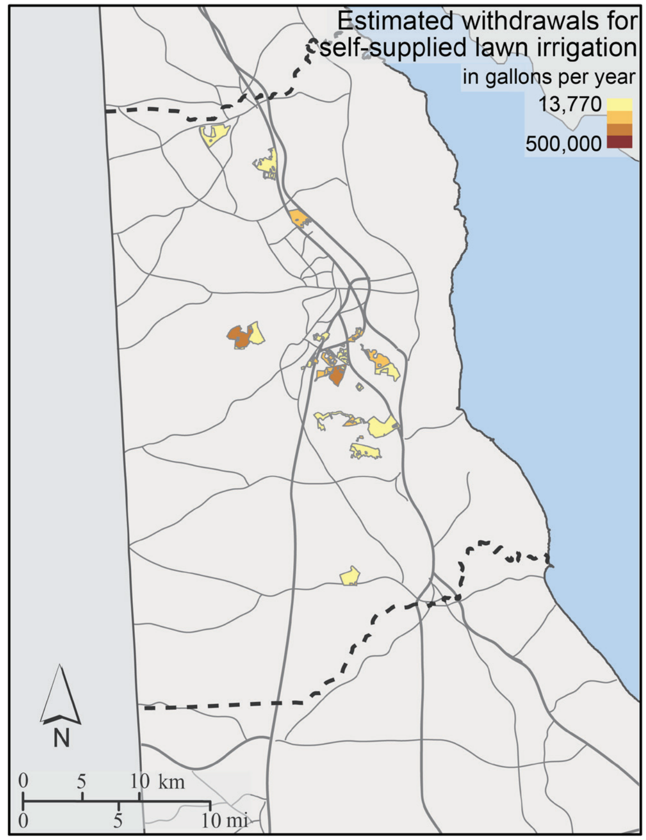

Figure 96. Map showing estimated groundwater withdrawals by census block for self-supplied lawn irrigation use in Kent County.

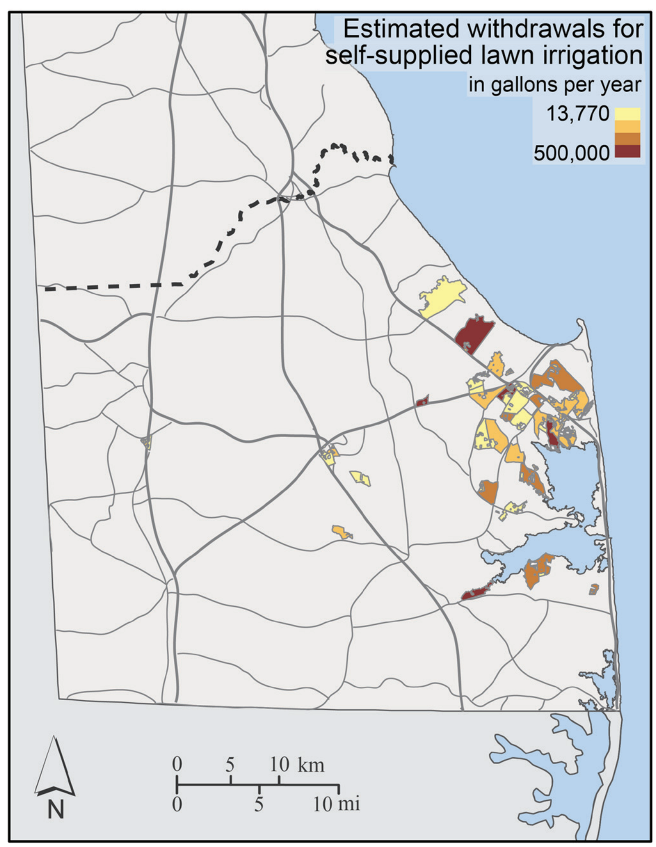

Figure 97. Map showing estimated groundwater withdrawals by census block for self-supplied lawn irrigation use in Sussex County.

Usages Not Specifically Accounted For

The categories of groundwater use reviewed above do not account for all groundwater withdrawals in southern Delaware. Several other types of usage are known in Kent and Sussex Counties: non-poultry livestock such as cattle, hogs, and dairy production; non-center pivot irrigation and microirrigation for fruit and vegetables; and aquaculture.

Although these uses of water may be notable locally, the withdrawn volumes were minor relative to the categories in this study. Cattle, hogs, and dairy operations are a much smaller part of Delaware's agricultural economy than poultry. The acreage of vegetable and fruit crops that use irrigation systems is a fraction of the acreage that uses center-pivot irrigation systems. A large effort would be required to estimate the small volume of these minor water uses in a spatial context and the results would have high uncertainty. Therefore, they were not analyzed in this study.

All Groundwater Uses

Total and County

Estimates of total water use can be calculated by using the estimated maximum and minimum withdrawals from each census block. The maxima and minima reflect annual variations in reported pumping data for public and industrial wells and other estimated withdrawals that may vary significantly according to season. Because these totals reflect maximum and minimum estimates on a block-by-block basis, the highs are higher and the lows are lower than the totals derived from adding high-use and low-use estimates on a category-by-category basis. They can be regarded as hypothetical maximum and minimum values because the numbers do not reflect estimated withdrawals for an individual year (Table 35).

Table 35. Estimated maximum and minimum values of groundwater withdrawals in each census block in Kent and Sussex Counties computed from the maximum and minimum estimated withdrawals for each water-use category.

	Total of maxima	Total of minima
Withdrawals in gallons per year		
Kent County	15,416,888,984	7,060,573,159
Sussex County	43,102,737,250	26,296,218,611
Total	58,519,626,234	33,356,791,770
Withdrawals in million gallons per day		
Kent County	42.24	19.34
Sussex County	118.09	72.04
Total	160.33	91.39

By Census Block

Total groundwater withdrawals can be evaluated geographically by adding all uses for every census block. Two sets of maps illustrate geographic trends in total groundwater withdrawals: one pair shows the sum of the maximum estimated value for all types of water use in each block (Figs. 98 and 99) and the other pair shows the sum of the minimum estimated value for all types of water use in each block (Figs. 100 and 101).

Some census blocks on these maps show no known groundwater withdrawals. Many of these blocks are in rural areas where census data indicate no population and well permit records indicate no wells for irrigation or poultry. Other blocks are in populated areas where the water was supplied by a PWS well located outside the block.

At the other end of the water-use spectrum are census blocks that had the greatest total groundwater withdrawals, greater than 250 Mgal/yr. These generally fall into one of two categories: a) in towns, blocks that contain high capacity public supply wells and/or industrial wells; or b) in rural areas, blocks that contain several irrigated areas with associated irrigation wells. In Kent County, examples from towns include a block in Milford with both municipal and industrial wells and several blocks in Dover with large capacity municipal wells (Fig. 98). In Sussex County, examples from towns include wells in Lewes adjacent to Cape Henlopen High School, and clusters of wells in Georgetown and Millsboro that served poultry industry facilities (Fig. 99). Of the rural areas, only two census blocks, both in Sussex County, had a total of estimated withdrawals exceeding 250 Mgal/yr (Fig. 99). Such large volumes of total withdrawals occurred in dry years in which irrigation needs were the greatest; both were in areas where the majority of the area of the census block was irrigated land.

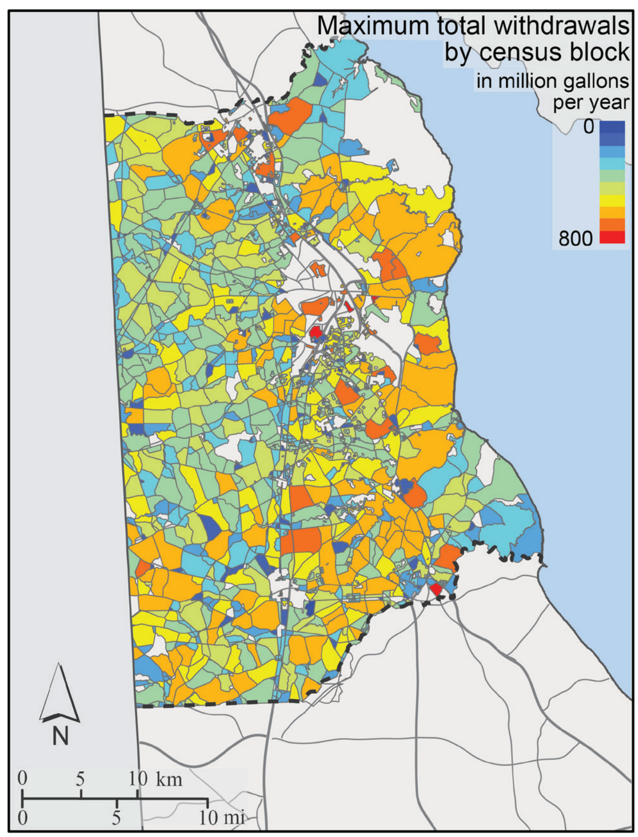

Figure 98. Map showing maximum estimate of total annual groundwater withdrawals by census block based on the sum of high-use year values between 2004 and 2008 in Kent County.

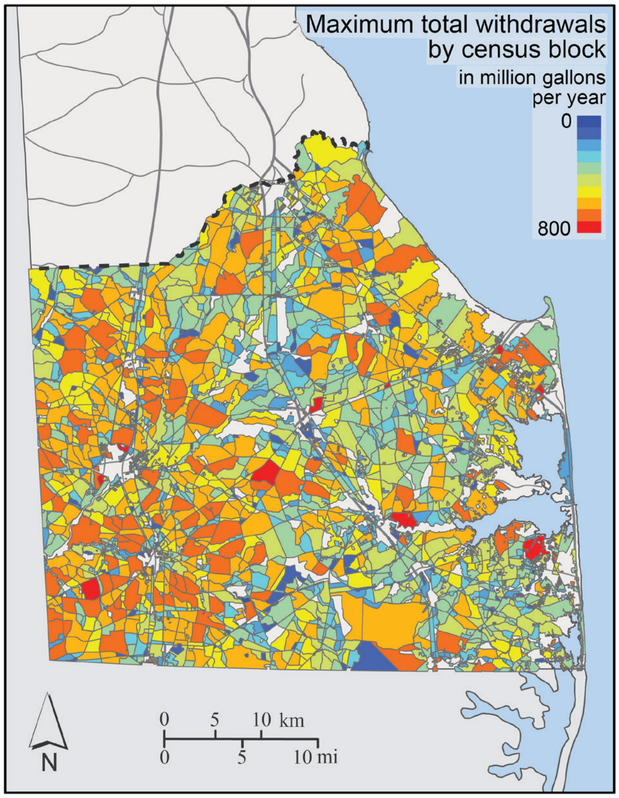

Figure 99. Map showing maximum estimate of total annual groundwater withdrawals by census block based on the sum of high-use year values between 2004 and 2008 in Sussex County.

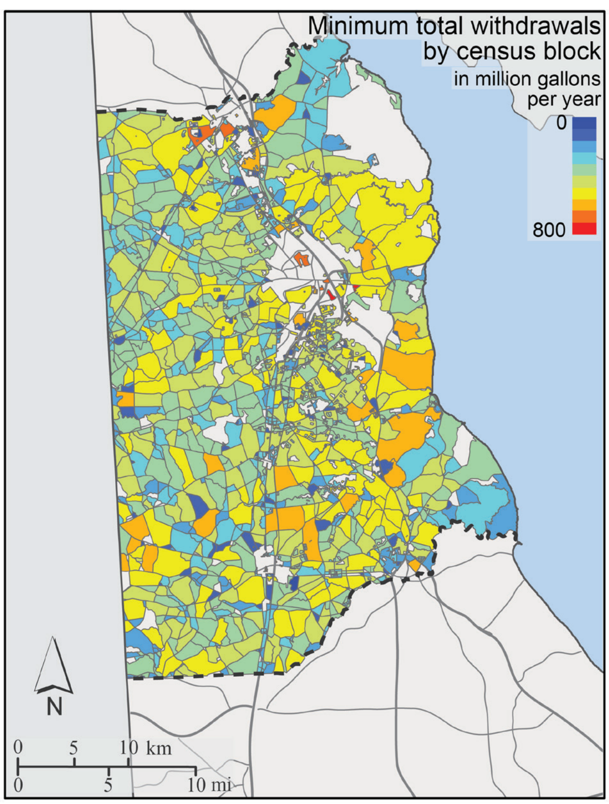

Figure 100. Map showing minimum estimate of total annual groundwater withdrawals by census block based on the sum of low-use year values between 2004 and 2008 in Kent County.

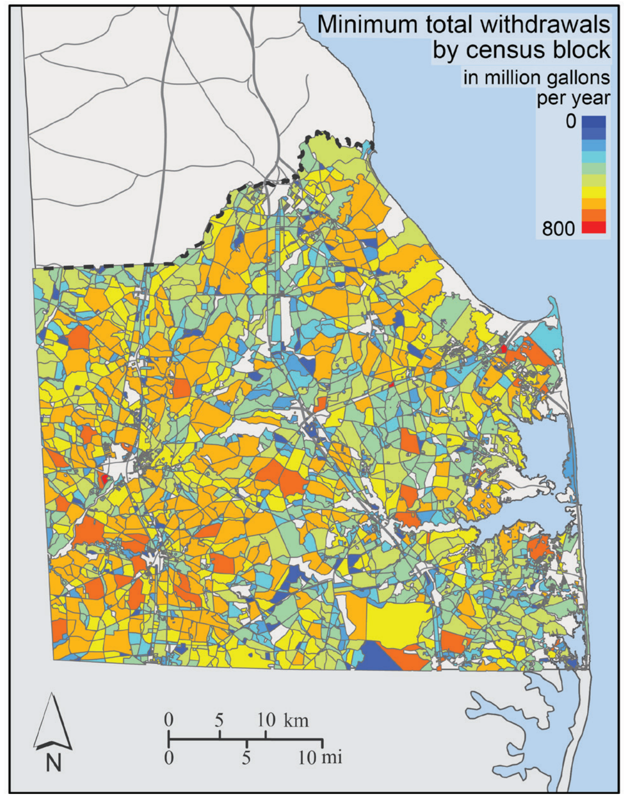

Figure 101. Map showing minimum estimate of total annual groundwater withdrawals by census block based on the sum of low-use year values between 2004 and 2008 in Sussex County.

Between the maxima and minima, the overall geographic trends in water use can be characterized as follows:

- total withdrawals were generally on the high side in rural census blocks in Sussex County that had extensive irrigation (Fig. 99);
- total withdrawals were generally on the low side in rural census blocks in Kent County block that had no or small withdrawals for irrigation (Fig. 100);
- total withdrawals were generally on the low side in blocks near towns that had moderate-density residential use but no public or irrigation withdrawals (Figs. 100 and 101).

By Aquifer

Estimated groundwater withdrawals also can be subtotaled by aquifer (Table 36). However, these estimates were complicated by the different nature of water-use estimates for each water-use category. Public water use, industrial water use, and golf course irrigation withdrawals varied annually in data compiled for this project, so higher use years and lower use years were factored into the analysis of withdrawals by aquifer. Therefore, these subtotals represent approximations derived from the sum of numerous estimates. The organization of the analysis allows aquifer subtotals to be examined across the entire study area or to focus on smaller scale areas such as census blocks.

Our compilation of water-use estimates from high-use and low-use years indicates that the unconfined aquifer was the largest source of groundwater. Withdrawals from the unconfined aquifer represented more than half of the groundwater pumped. Our estimates range from as little as 45 Mgal/d in a low-demand year to more than 71 Mgal/d in a high-demand year; most of this variation was due to year-to-year differences in irrigation demands (Table 36).

The confined Columbia aquifer and the Pocomoke aquifer were estimated to have the next highest level of withdrawals, each accounting for about 11 percent of the total. Both aquifers ranged from about 10 Mgal/d in a low demand year to 14 or 15 Mgal/d in a high-demand year. Withdrawals from the Pocomoke aquifer were principally in Sussex County. Estimated withdrawals from the Manokin aquifer were slightly lower, from 7.5 to 11 Mgal/d, again mostly from wells in Sussex County (Table 36; Fig. 102).

The next tier of source aquifers includes three units that are principally used in Kent County: two in the Calvert Formation, the Cheswold and Frederica, and the aquifer immediately underneath the Calvert Formation, the Piney Point aquifer. The Cheswold aquifer was the most important of these, with estimated withdrawals between 4.2 and 6.3 Mgal/d. Estimated withdrawals from the Frederica aquifer were between 3.0 and 5.0 Mgal/d. The Piney Point aquifer is an important source of public drinking water but not generally used for irrigation; estimated withdrawals were between 3.9 and 4.6 (Table 36; Fig. 102).

Table 36. Estimated total withdrawals of groundwater in the study area by aquifer. High-end and low-end estimates are the sum of values from high-use and low-use years in Kent and Sussex Counties, respectively. Values are rounded. gal/yr, gallons per year; Mgal/yr, million gallons per year.

Aquifer	Sum of highs (Mgal/yr)	Sum of lows (Mgal/yr)	Sum of highs (Mgal/d)	Sum of lows (Mgal/d)
Unconfined	25,919	16,279	71.01	44.60
Confined Columbia	5,498	3,484	15.06	9.54
Pocomoke	5,087	3,691	13.94	10.11
Manokin	4,013	2,728	10.99	7.47
Upper Choptank	347	126	0.95	0.35
Middle Choptank	510	167	1.40	0.46
Milford	796	476	2.18	1.31
Frederica	1,812	1,111	4.97	3.04
"Federalsburg"	612	338	1.68	0.92
Cheswold	2,297	1,539	6.29	4.22
Lower Calvert	0	0	0.00	0.00
Piney Point	1,694	1,409	4.64	3.86
Rancocas	111	85	0.30	0.23
Mount Laurel	14.6	3.1	0.04	0.01
Unknown	7.5	7.5	0.02	0.02

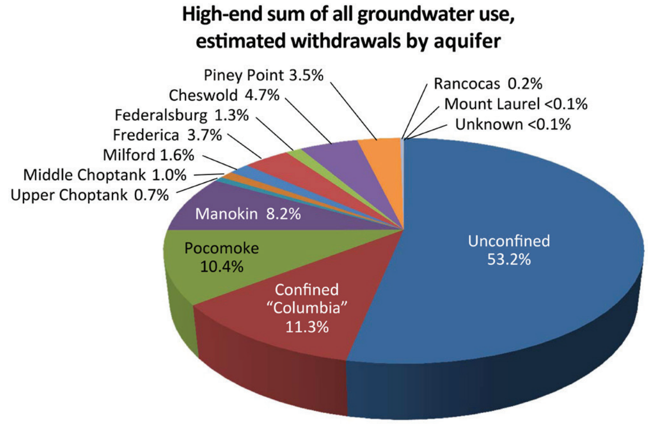

Figure 102. Pie chart showing percentage of estimated total groundwater withdrawals by aquifer based on the sum of high-use year values between 2004 and 2008 in Kent and Sussex Counties. Percentages do not add to 100% because of rounding to one decimal place

Each of the other aquifers had estimated withdrawals of less than approximately 3 Mgal/d (Table 36). Three aquifer sands in the Choptank Formation—Upper Choptank, Middle Choptank, and Milford—and one in the Calvert Formation—"Federalsburg"—are minor aquifers that are locally important, particularly in Kent County. The Rancocas and Mount Laurel aquifers are the least tapped sources of groundwater, with estimated withdrawals less than 0.3 Mgal/d each and usage limited to northern Kent County.

Discussion

Scope

The overarching goal of this investigation was to estimate the withdrawals from each aquifer for each water-use type in a spatial context for the period of 2004 through 2008. The scope of the work undertaken was focused on developing a reasonably accurate spatial understanding of the use of each groundwater source from reported pumping data or, where reported data were lacking, developing estimates based on efficient and justifiable methodologies.

The project was not intended to provide a precise, definitive answer for every water-use category. A variety of aspects of groundwater use could be topics for more detailed future studies. Specifically, agricultural irrigation, domestic self-supplied water use, and the use of water by poultry farmers could benefit from detailed water-use analyses incorporating calibration data. This could be accomplished by metering withdrawals at selected sites and collecting additional detailed information on factors that influence water demands. For example, installation of flow meters on irrigation wells would allow irrigation water use to be tied to climate, crop type, and soil type at specific sites. For domestic water use, metered pumping and resident surveys at individual self-supplied households would provide better control on the range of water use and sources of error for residences of specific demographics. For poultry growing operations, water demands could be better modeled if selected test sites with known levels of poultry production had metered pumping data.

Another issue that influenced the scope of this study was the regulatory requirement for annual reporting of pumping data. State regulations require groundwater allocations for wells that withdraw more than 50,000 gallons per day. Some categories, namely public and industrial, have relatively full compliance in reporting of monthly withdrawal data. However, reporting rates are low for the largest category of water use, irrigation. Additionally, the overall quality of data on irrigation withdrawals is poor because reported data are mostly estimated from pump timer data. As a result, DNREC databases are not a sufficient basis for the analysis of irrigation withdrawals, and our approach focused on estimation methods. It may be impossible to ever achieve full reporting for irrigation pumping. The geographically dispersed nature and large number of irrigators are a data acquisition challenge; the focus of farmers on farming operations rather than water supply presents a compliance challenge; and the small number of DNREC staff available to follow-up with non-reporting farmers is an enforcement challenge. In lieu of complete reporting, better estimates of irrigation might be achieved by combining estimation methods with a program promoting the use of flow meters at chosen calibration sites.

Consumptive use is a focus of many water-use studies. Consumptive use is the part of water withdrawn from available supplies that is not returned to the water resource system. Analysis of consumptive use goes beyond the analysis of withdrawals and must consider how much was consumed and how much returned to the immediate water environment. Consumptive use was beyond the scope of this project; we examined groundwater withdrawals only, emphasizing the distribution of use by aquifer.

Another aspect of water-use analysis that is valuable to planning is peak demand. Well-pumping data examined for this study indicates that water use fluctuates through the year, with peak demand normally occurring in the summer months. We did not analyze groundwater withdrawals specifically at peak demand. However, we did compile monthly data for each category of reported water use, so the data are available to examine monthly variations and peak demands within each year.

Trends in groundwater withdrawals beyond the period examined in this report are also of interest, particularly to assess future demands on the groundwater system. Changes in the volume and distribution of withdrawals since 2008 will reflect demographic changes and related demand for water resources. This study does not address the potential use of water-use trends identified here for future demand projections, but the results will provide a starting point for such analyses.

Comparisons with Other Estimates

The USGS periodically publishes estimates of groundwater use for Delaware. Those estimates address water use by usage type, by county, and, in some instances, by aquifer; in contrast, our focus was to estimate the withdrawals from each aquifer in a spatial context. The estimates of groundwater withdrawals made in this study compare reasonably well with USGS estimates of groundwater withdrawals for 2000 (Wheeler, 2003) and 2005 (Kenny et al., 2009) (Table 37). The similarity of estimated volumes among these studies lends strength to the soundness of our analyses.

Public and industrial water-use estimates are similar in this study and in USGS estimates for 2000 and 2005. The higher volume of industrial water use estimated by USGS for 2000 likely reflects actual higher use at that time. USGS estimates of irrigation water withdrawals for 2005 are comparable to our low-usage year estimates. The USGS 2000 estimate is lower, consistent with a smaller number of irrigated acres. The USGS 2000 estimate of domestic self-supplied water withdrawals compares well with our estimate, but the USGS domestic estimate for 2005 is only half the volume that we calculated. USGS estimates for livestock are lower than our estimates. Overall, the USGS estimate of total groundwater withdrawals for 2005 is generally comparable with low-use year numbers from this study; however, our results suggest that annual withdrawals can be significantly higher or lower depending on irrigation needs.

The groundwater withdrawal estimates reported here differ somewhat from the numbers used in county comprehensive plans for water demand. According to the Kent County Comprehensive Plan (Kent County, 2008) and the Delaware Water Supply Coordinating Council (DNREC, 2014), approximately 122,000 residents are served by PWSs with an estimated demand of 18.3 Mgal/d. The results of this study suggest lower numbers. Using populations in year 2010 census blocks or parts of blocks that lie within PWS areas, we estimated that 102,000 residents were served by PWSs in Kent County (Table 18) with associated groundwater withdrawals of approximately 10.7 to 11.6 Mgal/d between 2004 and 2008 (Table 37). Based on the Sussex County Comprehensive Plan Update (Urban Research & Development Corporation, 2008), the Delaware Water Supply Coordinating Council (DNREC, 2014) estimated a normal public water demand of 17.7 Mgal/d. In contrast, we estimated 13.9 to 16.4 Mgal/d of annual withdrawals for PWSs between 2004 and 2008 (Table 37), serving a user population of approximately 99,000 in Sussex County (Table 18).

Irrigation withdrawals were estimated using irrigated acreages identified from 2008 aerial photographs. We identified a total of 102,576 acres under irrigation (Table 30); this total includes 28,370 acres in Kent County and 74,206 acres in Sussex County. This compares well with estimated acreage in the 2007 USDA Census of Agriculture (U.S. Department of Agriculture, 2009a) of about 29,000 acres in Kent County and 72,349 acres in Sussex County. The irrigated acreage for corn was estimated by the USDA to be 10,505 and 41,000 acres for Kent and Sussex County respectively, which almost exactly matches the total of 51,402 acres estimated in our study (Table 30). The USDA estimated irrigated soy bean acreage as 7,338 in Kent County and 16,785 in Sussex County, totaling slightly less than the 26,806 acres estimated herein (Table 30). Our estimate of 22,255 acres for a double crop of soy and winter wheat (Table 30) is significantly larger than the USDA estimate of approximately 10,000 irrigated acres of wheat.

Allocations

It is interesting to compare the pumping totals compiled in this study to groundwater allocations made by DNREC. Table 38 shows groundwater allocations tabulated by the DNREC Water-Supply Manager in 2012 (Stewart Lovell, written communication, August 2012). Agricultural irrigation had the largest allocation with 83 percent of the total, followed by public water supply (11 percent), industrial use (4 percent each), golf course irrigation (2 percent), and domestic wells (1 percent) (Gerald Kauffman, written communication, 2013).

The maximum values of groundwater withdrawals for irrigation calculated in this study are very close to the annual total DNREC allocations for agricultural irrigation. However, we identified irrigation wells with well permits that were not in the list of allocations available from DNREC. Some of these irrigation wells may have allocations but were not included in the allocation totals tabulated in 2012; some wells may not have allocations.

Groundwater withdrawals from PWS wells with allocation permits are well within the total of public well allocations. The highest reported values of PWS withdrawals are 11 and 15.8 Mgal/d for Kent and Sussex Counties (Table 37), respectively, compared with PWS well allocations of 21 and 31.6 Mgal/d.

Industrial well pumping documented in this study is significantly less than total industrial well allocations. The highest annual values of 1.35 and 6.96 Mgal/d for Kent and Sussex, respectively, versus allocations of 6.2 and 19.1 Mgal/d likely reflect that fact that allocation permits, which have a duration of 30 years, were issued at a time when industrial groundwater withdrawals were greater.

Golf course pumping substantially exceeded volumes in the water allocation permits. Total withdrawals of 2.17 Mgal/d in the study area compare to allocations that total 1.6 Mgal/d. Our analysis of pumping data agrees with the views of DNREC staff (William Cocke, verbal communication, 2013) that allocations for many golf course wells were significantly smaller than actual irrigation water needs; as a result, pumping commonly exceeded permitted allocations.

Table 38. Groundwater allocations in Kent and Sussex Counties in 2012 for wells pumping more than 50,000 gallons per day (DNREC, Stewart Lovell, written communication, August 2012) compared with the highest reported annual values in 2004 through 2008 for the same water-use categories tabulated for this study. Mgal/d, million gallons per day.

County	Use	Annual maximum supply allocation (Mgal/d)	Highest annual reported value (Mgal/d)
Kent	Public	21	11.00
	Farm irrigation	19.5	19.12
	Golf course	0.2	0.17
	Industrial	6.2	1.35
	Total	46.9	
Sussex	Public	31.6	15.18
	Farm irrigation	72.2	71.69
	Golf course	1.4	2.00
	Industrial	19.1	6.96
	Total	124.3	
Study Area Total	Public	52.6	26.18
	Farm irrigation	91.7	90.82
	Golf course	1.6	2.17
	Industrial	25.3	7.66
	Total	171.2	

Table 37. Groundwater withdrawal totals for each water-use category in this study compared with corresponding U.S. Geological Survey water-use estimates from the years 2000 (Wheeler, 2003) and 2005 (Kenny et al., 2009). Where data were available for individual years, high-end and low-end estimates are provided. Totals for USGS columns include thermoelectric groundwater withdrawals not identified in this study and do not equal the sum of rows. Mgal/d, million gallons per day; NR, not reported.

Use		This study (Mgal/d)	USGS 2005 (Mgal/d)	USGS 2000 (Mgal/d)
Irrigation: agricultural	*modeled high use (2007)*	90.82	53.84	33.82
	modeled low use (2006)	50.16		
Public total (reported and estimated non-reported)	*high-use year (2007)*	27.99	25.24	23.05
	low-use year (2004)	24.60		
Domestic self-supplied *(modeled)*		11.61	5.73	10.79
Industrial self-supplied	*high-use year (2008)*	7.66	9.41	9.41
	low-use year (2005)	6.66		
Agricultural: livestock *(estimated, for poultry)*		4.30	1.44	3.63
Irrigation: golf course *(median reported and estimated)*		2.17	NR	NR
Agricultural: lawn wells *(estimated)*		0.030	NR	NR
Total	*sum of high-use years*	144.6	94.5	81.2
	sum of low-use years	99.5		

Strengths and Weaknesses of Analysis

The analysis of groundwater withdrawals in this study provides the first comprehensive examination of withdrawals in Kent and Sussex Counties in the context of geography and aquifer stratigraphy. However, by its nature, the exercise of estimation of water use and groundwater withdrawals has many sources of potential error.

We based our tallies of withdrawals on annual reported pumping data for public water system wells with allocations, industrial wells, and some golf course irrigation wells. Data for public and industrial withdrawals were carefully scrutinized, including error checking reported annual pumping and verifying well locations, depths, and elevations. The quality of well construction data was good for most of these wells because they were extracted from carefully reviewed data in the DNREC Source Water Assessment and Protection Program database. The greatest uncertainties are likely associated with aquifer assignments for wells where screen depths were not known with high confidence.

A sound estimate of agricultural irrigation demand is important for a complete picture of the spatial distribution of groundwater withdrawals. Agricultural irrigation represents the largest use of groundwater in the study area but pumping data are incomplete. A notable strength of the irrigation estimates in this study is the reproducible methodology that accounts for use at all known areas of irrigation identified on aerial photography. The method uses a model accepted by irrigators (KanSched2) to determine daily crop water demands. The crop and soil types incorporated into those calculations are derived from widely accepted USDA sources. A recent USGS study used a similar daily crop-water-demand model (Levin and Zarriello, 2013) and achieved comparable or better quality estimates than correlation-based models derived at sites with weekly meter data.

Potential weaknesses in the methodology and data include the difficulty of accounting for the use of surface water for some irrigation. The assumption that all irrigation utilizes groundwater may yield a slight overestimate of withdrawals. Data provided by DNREC identified 70 permitted intakes with surface-water allocations at approximately 30 farms. Given that the irrigation analysis herein is based on the locations of more than 2400 center-pivot and similar systems, it seems likely that the 70 surface-water intakes supply water to a small percentage of these systems. In comparison, previous USGS work estimated surface-water use for irrigation at about 15 percent, which may be an overestimate.

Other weaknesses of the irrigation withdrawal analyses are related to the generalization of spatial data used. The daily crop water-demand model generalizes climate data for nine climate polygons that comprise significant parts of the study area. In reality, precipitation amounts can vary significantly in a short distance because of the patchiness of many summer rainstorms. The model also generalizes crop and soil data. The crop data are derived from the USDA Crop Data Layer, which is mapped using remote sensing, but commonly more than one crop type is mapped in an individual center-pivot irrigation area. In such cases, we assigned crop types based on the crop present at the center point or the crop with the greatest fraction of the irrigated area. Even broader generalizations were made from soil data. Soil maps were used to determine the moisture-holding capacity of the soil in the daily crop water-demand calculation. However, because of the computational complexity of using the soil type in each individual irrigated area, we calculated an average soil moisture-holding capacity for each climate polygon and used that to model daily crop water demands in each irrigated area. These generalizations of climate, crop, and soil data may result in considerable error of water-demand estimates for an individual irrigated site, but that error should be less when averaged on the scale of a census block. These generalizations should be even less significant on a county scale.

Estimating self-supplied domestic groundwater withdrawals is inherently difficult because of variability of physical, socioeconomic, and individual behavioral factors that affect water use in a household. The strength of our results is that they are based on a model for household water use that uses census factors associated with demand. However, a weakness is that no metered water-use data are available for self-supplied domestic areas. In lieu of this, domestic water use was modeled using public water systems where usage is documented but the volume-based cost of water may affect user behavior. The estimation method used in this study is supported by the application of similar census parameters to water-use modeling in a USGS study of the Seacoast region of New Hampshire (Horn et al., 2008). The calibration dataset used in our study was more spatially generalized than that in the Seacoast study, which used water-meter data for individual households. Lacking water-meter data, we modeled water use for each census block by calculating per-capita water-use rates for PWS networks using the relationship of pumping to average census block factors in the network. This approach leaves some potential for systematic overestimates or underestimates in the household water-use model, and thus in the estimates of self-supplied domestic withdrawals. An additional potentially smaller source of error is the seasonal component of self-supplied domestic water use. Our calculations of additional seasonal use were based on gross, generalized estimates of the occupancy of non-household housing units and are essentially uncalibrated.

Despite these issues, the accuracy of estimates of self-supplied domestic groundwater withdrawals presented here is considered sufficient for the purpose of this study. Although errors arising from the generalizations discussed above may affect calculations of modeled use on the scale of an individual census block, the impact should be less at larger county or state scales because of averaging. Our calculated per capita water-use values are supported by the similarity of our results to others with similar settings and populations.

Although poultry farms comprise only a small part of the overall groundwater withdrawals, they may account for a large share of withdrawals in many rural census blocks. Detailed location data for poultry houses compiled for this study allowed water use to be accurately assessed in a spatial context. However, the lack of pumping data to calibrate our water-demand model limits our confidence in the withdrawal estimates. Furthermore, we assumed all poultry houses were the same size and used the same volume of water to simplify our analysis, which is unlikely. However, our review of literature on drinking water and cooling water demands of poultry flocks indicates that our estimates are reasonably close.

We also significantly generalized well data used for aquifer assignments for irrigation, domestic, and poultry-house withdrawals. Because withdrawals cannot be assigned to individual wells in those categories and because associated well records are incomplete, relative proportions of wells in each aquifer were estimated from the distribution of well depths in each census polygon for each category. These proportions were used as a proxy for percentages of withdrawals from each aquifer. The accuracy of these withdrawal estimates is reduced by the incompleteness of the dataset and the variability of well diameters, screen lengths, pump sizes, and water-user behavior for each well.

Finally, the reader is reminded that this report is an analysis of groundwater withdrawals from a decade ago, for the period from 2004 through 2008. Groundwater use will certainly have changed since then as demographics of the study area have changed. As context, the population of Kent County has grown from approximately 163,000 to 177,000 between 2010 and 2017 and the population of Sussex County has grown even more, from almost 198,000 to more than 225,000 (U.S. Census Bureau, 2018). At the same time, water use has been impacted by broad factors such as the expansion of crop irrigation in Delaware agriculture, changes in industries that are normally large water users (such as poultry processing), and the increasing availability of higher efficiency water fixtures for residencies and businesses. Therefore, these results provide a snapshot of groundwater withdrawals for the period of study rather than a current estimate. Beyond that, this study provides a methodological framework for evaluating more recent trends in groundwater use and a baseline against which newer trends can be measured.

SUMMARY

The purpose of this report is to present the results of a project that examined the distribution and utilization of groundwater resources of Kent and Sussex Counties using well and census datasets compiled for the years 2004 through 2008. The results of this study provide water-resource agencies, scientists, policy makers, and water-related businesses with an understanding of the areal extent and thickness of the aquifers that provide Delaware's groundwater resources and a snapshot of how much water was being withdrawn from each aquifer for each type of water use in the study period.

Groundwater resources are critical to the citizens of Delaware. Kent and Sussex Counties encompass a predominantly rural area of more than 1,500 square miles and have a population of nearly 360,000. Between the many towns and small cities, the rural areas are a patchwork of farmland, undeveloped areas, poultry operations, and residences. The rate of population growth has increased recently in Kent and Sussex Counties, expanding by 27 percent between 2000 and 2010. Much of that growth has been in areas converted from farmland to residential space. Such growth increases demands for groundwater.

Aquifers are the source of all drinking water in Kent and Sussex Counties and the most important source of water for agriculture and industry. This project has examined groundwater resources from two perspectives: first, the geology, defining the areal extent and thickness of the aquifers used in the study area; and secondly, water use, understanding groundwater withdrawals in Kent and Sussex Counties in three dimensions, geographically and by aquifer, through time.

Summary of Aquifer Geology Findings

The geology of the Delaware Coastal Plain can be characterized generally as a complex of nearly flat-lying surficial and near-surface Quaternary deposits, underlain by sediments of Cretaceous to Cenozoic age that dip gently to the southeast. The subsurface formations include a number of permeable sand bodies that yield groundwater and serve as valuable aquifers for multiple uses in Kent and Sussex Counties.

Most of the confined aquifers occur in Miocene formations, but three pre-Miocene aquifers are also an important part of the water supply. The stratigraphically lowest is the Mount Laurel aquifer of Late Cretaceous (Campanian) age. The Mount Laurel interval is characterized by glauconitic quartz sands in northern Kent County where it functions as an aquifer; stratigraphically equivalent strata in central Kent County southward are finer grained non-aquifer facies. The Mount Laurel aquifer is approximately 300 ft bsl in northern Kent County and deepens south-southeastward to about 600 ft bsl between south Smyrna and north Dover. The aquifer interval is approximately 100-ft thick; the interval becomes thins to a few tens of feet where aquifer lithologies are not present. The Mount Laurel interval is overlain by two aquifers of Paleogene age, the Rancocas and Piney Point.

The Rancocas aquifer is a thick interval of glauconite- and shell-rich carbonate and quartz sand present in northernmost Kent County. It was deposited in a shelf setting during the Paleocene epoch. The Rancocas interval changes dramatically southward across a narrow zone south of Smyrna. North of this zone, the Rancocas aquifer exceeds 100-ft thickness; south of this zone, the aquifer sands transition to mostly muddy sediments with a few tens of feet of sand at the base, ultimately completely transitioning to mud in central Kent County. The top of the aquifer occurs as high as 50 ft bsl in northwestern Kent County and becomes deeper southeastward to about 300 ft bsl near its southern limit in central Kent County.

The Piney Point aquifer is middle Eocene age and characterized by shelly, glauconitic, quartz sand deposited in a shelf environment. The top of the Piney Point aquifer ranges from about 250 ft bsl in the Dover area to more than 700 ft bsl in northern Sussex County. Northwest of a southwest- to northeast-oriented trend just north of the Cheswold area, the Piney Point aquifer becomes progressively thinner and finer grained. The Piney Point Formation coarsens upward and the best aquifer sand occurs in the youngest part of the unit. It is truncated to the north under a basal Miocene unconformity; as a result, little aquifer-quality sand is present in northern Kent County. The Piney Point aquifer thickens southeastward across Kent County from as little as 55 ft to nearly 300 ft.

The Miocene shallow-marine sediments of the Calvert and Choptank Formations include seven aquifers. The Calvert Formation includes the Lower Calvert, Cheswold, Federalsburg, and Frederica aquifers in upward order; Choptank Formation contains the Milford, Middle Choptank, and Upper Choptank aquifers. The Cheswold and Frederica aquifers are the most important sources of groundwater of this group, each supplying 3.5 percent to 5 percent of withdrawals in the study area. The Lower Calvert, Middle Choptank, and Upper Choptank aquifer are minor aquifers that have been newly defined in this study from aquifer mapping results. These seven aquifers are the cleanest, most permeable sand bodies in the Calvert-Choptank succession.

The Calvert and Choptank Formations have repeated shallowing-upward intervals in an overall coarsening upward, progradational coastal succession. The aquifers are typically developed in shelly quartz sand intervals at the top of each cycle that represent the shallowest of the marine facies. Laterally, the Calvert-Choptank succession shows a geographic trend from a thinner up-dip succession composed of shallow-marine deposits in the north and west to a thicker down-dip succession to the south and east. The thicker down-dip succession includes greater thicknesses of finer-grained open marine deposits between the aquifer sands. The thinner up-dip section commonly has thin confining layers between the aquifers, creating a locally leaky aquifer system where adjacent aquifers may be in hydrologic communication.

The Lower Calvert aquifer is a local lower Miocene sand body that could potentially be used as a groundwater source in northwestern Sussex County. It is generally between 10 and 50-ft thick. The top of the aquifer deepens from about 400 ft bsl near its northwestern limit to more than 1,000 ft in southeastern Sussex County.

The Cheswold aquifer is shelly quartz sand that is widely used in northern and central Kent County. It subcrops under surficial Quaternary formations in northern Kent County and deepens to more than 500 ft bsl in southeastern Kent County. It occurs deeper than the range of most drilled water wells in Sussex County, reaching more than 1,000 ft bsl in coastal areas. The Cheswold aquifer varies from less than 20 to more than 100-ft thick, with variable thickness in Kent County and a general increase southeastward in Sussex County. In Kent County, it is thickest in the Dover and Cheswold areas; locally significant thickness variations also occur near its up-dip limit that may reflect erosion associated with tidal channel environments.

The name "Federalsburg" is applied to the aquifer sand that overlies the Cheswold aquifer in southern Delaware. It is not the same as the true Federalsburg aquifer originally defined in Maryland. Our correlations indicate that the Frederica aquifer of Delaware is the same sand unit as the Federalsburg aquifer of Maryland. We maintain the "Federalsburg" name in this study in quotes because of its longstanding use for this sand in Delaware. The "Federalsburg" aquifer subcrops between Dover and Smyrna, deepening southeastward to about 400 ft bsl in southeast Kent County and more than 1,000 ft in southeast Sussex County. It has significant thickness variations, mostly between 30- and 80-ft thick, and is commonly thinner and muddier than the other Calvert aquifer sands.

The Frederica aquifer is stratigraphically the highest of the Calvert Formation sands. It is an important groundwater source, especially for public water systems, in much of Kent County south of Dover and in northwestern Sussex County. From its subcrop zone in the Dover area, the Frederica aquifer deepens to more than 250 ft bsl in the Milford area and more than 800 ft bsl in southeastern Sussex County. The aquifer is between 40- and 100-ft thick across most of the study area.

The Milford aquifer is the lowest aquifer sand in the Choptank Formation and is used for smaller public systems, domestic supplies, and irrigation in southern Kent County and northeastern Sussex County. It is composed of shelly sands that subcrop under younger surficial sands in an east-west trending belt south of Dover. The top of the Milford aquifer deepens south-southeastward to approximately 200 ft bsl in southern Kent County, and more than 600 ft bsl in southeastern Sussex County. It is between 20- and 60-ft thick in most of the study area. The Milford aquifer is typically separated from the underlying Frederica aquifer by a well-developed confining layer, commonly a brown mud. However, the confining layer that separates the Milford aquifer from the overlying Choptank sands may be poorly developed.

The highest aquifers in the Calvert-Choptank interval are the Middle and Upper Choptank aquifers. Both are minor aquifers that provide a small percentage of irrigation and domestic water supplies in southern Kent County and northwestern Sussex County, as well as a few public systems in central and western Sussex County. The Middle Choptank aquifer occurs in eastern Sussex County and southeastern Kent County; it changes facies to less sandy lithologies and pinches out westward. This aquifer subcrops in a narrow belt extending from north of Harrington to near Frederica. It deepens to the southeast, reaching about 150 ft bsl in Milford and more than 700 ft in southeastern Sussex County. The Middle Choptank aquifer is between 15- and 30-ft thick in most of the study area but attains thicknesses of approximately 50 ft in south-central Sussex County.

The Upper Choptank aquifer is stratigraphically the highest aquifer in the Calvert-Choptank succession and immediately underlies the silts and clays of the regional St. Marys Formation confining unit. It subcrops in a narrow zone from Harrington to the north side of Milford and deepens into the subsurface southward. The top of the formation is approximately 250 ft bsl in Seaford and Milford and 600 ft or more in southeastern Sussex County. The Upper Choptank aquifer is generally between 25- and 45-ft thick; facies changes result in thicknesses of more than 50 ft in some northwestern areas, but generally thinner intervals in southeastern Sussex County.

The Manokin and Pocomoke aquifers are major groundwater sources in Sussex County. The Manokin aquifer is a laterally extensive and continuous complex of sand in most of Sussex County. It is the sandy upper part of a coarsening-upward succession of shallow-marine to estuarine deposits in the Cat Hill Formation. The Manokin aquifer subcrops under the Beaverdam Formation and sandy Quaternary sediments across a wide belt of northern Sussex County, south of which it descends to more than 350 ft bsl in the southeastern corner of the county. This aquifer is thinnest in the western half of Sussex County, where it can be less than 20-ft thick, and thickens southeastward to more than 130-ft thick in some parts of southeastern Sussex County. Manokin-equivalent sands are commonly in direct contact with shallower sands without an intervening confining layer, making them part of the unconfined aquifer. Areas where such contact may occur were outlined in this study to create a map of potential recharge windows where groundwater in the unconfined surficial aquifer can pass directly into the normally confined Manokin aquifer sands.

The Pocomoke aquifer overlies the Manokin aquifer and is best developed in eastern and southern Sussex County. Rather than being a single, uniform sand body, the Pocomoke aquifer is a complex of sand bodies of variable thickness that occur within the mosaic of coastal facies in the Bethany Formation. The Pocomoke aquifer subcrops under surficial sands in a broad band that extends northeastward from the Laurel area through Georgetown and Milton. The top of the aquifer deepens southeastward to as much as 125 ft bsl in the southeastern part of the county. Because this aquifer is composed of multiple sand bodies, the net thickness of sand was mapped instead of the thickness between its top and base. The net thickness of Pocomoke aquifer sand shows a general thickening trend southeastward, increasing from a few tens of feet in up-dip areas to nearly 200 ft down dip along the coast.

As with the Manokin aquifer, Pocomoke-equivalent sands are commonly in direct contact with sands of overlying unconfined formations. As a result, some or all of the sand bodies that would, if confined, make up the Pocomoke aquifer are instead unconfined; we have created a map of these potential recharge windows. Furthermore, the contact between the Pocomoke aquifer and the underlying Manokin aquifer may be difficult to define where there is no clear confining bed at the contact. Hence, the Pocomoke aquifer has a high likelihood of direct sand-on-sand contact with the overlying unconfined aquifer and/or the underlying Manokin aquifer in some areas and thus is likely hydrologically connected with those aquifers locally.

The unconfined aquifer provides a shallow and typically high-yielding source of groundwater in most of Kent and Sussex Counties. It generally consists of unconsolidated quartz sands. Because this aquifer was associated in early studies with the Columbia Formation, the name Columbia aquifer has been historically applied. However, because of recent surficial geological mapping and additional data generated in the last two decades, the unconfined aquifer is now recognized to include sands belonging to a number of formations; we refer to it as the unconfined aquifer instead of Columbia aquifer. The Pliocene (?) age Beaverdam Formation comprises the largest part of the unconfined aquifer in Kent and Sussex Counties. Pleistocene fluvial sands and gravels of the Columbia Formation also comprise a small part of the unconfined aquifer, mostly in central Kent County. In eastern Kent County and northeastern Sussex County, the unconfined aquifer is in the Pleistocene sands and some gravel of the lithologically variable Lynch Heights and Scotts Corners Formations. In eastern Sussex County, the unconfined aquifer may include Pleistocene sands of the Omar, Sinepuxent, or Ironshire Formations; in south-central Sussex County, the Cypress Swamp Formation; and in western Sussex County, the Turtle Branch or Kent Island Formations. Locally, the unconfined aquifer also includes older sand bodies that normally act as confined aquifers: sands of the Bethany and Cat Hill Formations in Sussex County; and sands of the Calvert or Choptank Formation in Kent County where they subcrop up dip under younger surficial sands.

The unconfined aquifer is generally less than 100-ft thick in Kent County. It is significantly more variable in Sussex County, where it is most commonly between 50 and 100-ft thick but may range from as little as a few feet thick to more than 200-ft thick. The greatest thicknesses tend to occur in eastern Sussex County, where sandy Quaternary formations are superimposed on an unusually sandy Pocomoke interval that lacks significant confining beds, which in turn directly overlies the normally sandy Manokin aquifer interval. The unconfined aquifer may be thin or absent over broad areas where the surficial geologic materials are made up of Cypress Swamp Formation, muddy portions of the Omar Formation, or muddy coastal and inland Holocene wetland deposits.

In some areas of Kent and Sussex Counties, confined aquifer sands may occur in the same formations that more typically make up the unconfined aquifer. We use the name confined Columbia aquifer for these water producing, or potentially water producing, confined sands that occur between the overlying unconfined aquifer and an underlying named confined aquifer. The confined Columbia name is applied most often to aquifer-quality sands in the Beaverdam Formation in Sussex County that are overlain by fine-grained upper Beaverdam or Pleistocene or Holocene beds; however, it can also be used for sands in any of the Pleistocene formations that are capped by Pleistocene or Holocene fine-grained sediments. Because these confined Columbia sands do not represent a geologically or hydrologically coherent unit, there was no practical reason to map the elevation or thickness; and the complexity of stratigraphic relationships in this interval made depiction of this unit on the cross sections impractical.

Summary of Groundwater Withdrawal Findings

The analysis of groundwater withdrawals in this study examined the years 2004 through 2008. The intent of this analysis was to establish reasonable estimates of total groundwater withdrawals for Kent and Sussex Counties in that period and to understand these withdrawals from three perspectives: 1) by water-use category; 2) by geography; and 3) by aquifer. We succeeded in comprehensively treating withdrawals from these perspectives, but the estimates presented here should not be considered a definitive final word on water use. Some categories of water use have been analyzed by well-pumping records, but other categories have been estimated due to a lack of reliable data and are generally uncalibrated and unverified. Issues such as varying water use within individual years, including peak demand, have not been examined nor have issues such as consumptive use or recent trends been addressed. In addition, groundwater withdrawals today will differ from the withdrawals during the period examined in this report, 2004 through 2008, because of population growth and changes in the ways groundwater is used in households, industry, and agriculture. The findings presented here provide a detailed understanding of withdrawals during the study period, a methodological framework for evaluating more recent trends in groundwater use, and a starting point for more detailed future analyses of site- or problem-specific questions.

Estimated annual groundwater withdrawals for all uses in the study area ranged from approximately 100 to 145 million gallons per day (Mgal/d). Although the population of Sussex

County was only 20 percent larger than Kent County in the study period, groundwater withdrawals were approximately three to four times greater in Sussex County. This difference between counties largely reflects the higher demand for irrigation water in Sussex County. Withdrawals from the unconfined aquifer represent more than half of the groundwater pumped in the study area. The confined Columbia aquifer and the Pocomoke aquifer are each estimated to be the source of approximately 11 percent of total withdrawals and the Manokin aquifer accounts for approximately 8 percent. The next tier of withdrawals is for the most important aquifers in Kent County, the Cheswold, Frederica, and Piney Point, each of which represent 3 to 5 percent of total estimated withdrawals. Other aquifers each represent less than 2 percent of withdrawals.

Crop irrigation was the largest use category for groundwater. Although irrigation use was modeled for this study, annual irrigation demands vary greatly according to climate conditions. To estimate agricultural irrigation withdrawals, we calculated irrigation needs for 2,407 individual irrigated areas for the years 2005 through 2008 using KanSched2 irrigation scheduling software. This package accounts for crop type, soil water-storage capacity, precipitation, and evapotranspiration to determine daily crop-water demand (Rogers and Alam, 2008). A recent USGS report (Levin and Zarriello, 2013) used a similar daily crop water-demand model in studies of agricultural sites in the eastern U.S. Coastal Plain and concluded it superior to the other approach tested. Our results suggest that groundwater withdrawals for irrigation totaled as much as 91 Mgal/d for a dry year, 2007, and as little as 50 Mgal/d in a year with abundant, well-timed rainfall, 2006. Aquifer assignments were made by identifying clusters of well-screen elevations in each census block and comparing them to aquifer raster surfaces. The proportions of withdrawals in the block were assigned by the proportion of wells in each cluster. The unconfined aquifer was the largest source of irrigation water, representing almost two-thirds of the withdrawals. The confined Columbia aquifer, Pocomoke aquifer, and Manokin aquifer each provided approximately 10 percent of the irrigation groundwater withdrawals; other aquifers contributed very small amounts.

Public water supply (PWS) was the second largest category of groundwater withdrawals. Analysis of 2010 census data for census blocks, or parts of blocks, that were located within areas served by public water-supply systems in 2008 identified a population of 200,620 residents, with 101,656 in Kent County and 98,964 in Sussex County. Public water-supply withdrawals are reported annually to DNREC by most providers, allowing us to compile monthly pumping data for most of the larger public wells (366) for the period from 2004 through 2008. These withdrawals were more spatially concentrated at pumping centers in populated areas. In the period from 2004 to 2008, public water-supply withdrawals were between 22.8 Mgal/d in 2004 and 26.2 Mgal/d in 2007. Approximately half of the public water use was in three areas: Dover (5.0 Mgal/d), the Lewes-Rehoboth area (4.0 Mgal/d), and Milford (2.4 Mgal/d). Withdrawals were slightly greater in Sussex County than Kent County despite a smaller population of permanent residents there; this is due, in part, to additional water demands of visitors and non-permanent seasonal residents.

Because PWS well location and construction data are relatively well documented in state databases, such as the Source Water Assessment and Protection Program (SWAPP) database, each well could be assigned to an aquifer by comparing the elevation of the well screen to the elevation of each aquifer raster surface at that location. The unconfined aquifer provided approximately one-fourth of reported public well withdrawals, making it the largest source. The Piney Point, Cheswold, and Pocomoke aquifers each comprised approximately 15 percent of the public supply, the former two in Kent County and the latter in Sussex County. The confined Columbia aquifer was about 10 percent. The Manokin and Frederica aquifers provided 7 to 8 percent of the public supply in general and other aquifers represented smaller percentages.

Pumping data from areas where portions or combinations of public systems serve principally domestic household users helped us understand domestic water-use patterns. Household consumption in these areas mostly ranged between 60 and 100 gallons per person per day. We developed a domestic water-use model from these data by calibrating annual pumping data from interconnected domestic-use-dominated networks of PWSs to water-related factors from the 2010 census. This model was used to estimate unreported water use by small community water systems (CWS) and by domestic self-supplied water users.

We estimated an additional 1.8 Mgal/d of withdrawals from smaller public water systems that are not required to report pumping—smaller community (CWS), transient non-community (TNC), and non-transient non-community (NTNC) systems. For transient (TNC) and non-transient (NTNC) non-community systems, we estimated withdrawals from documented use reported in the literature for each specific system or facility type. For the smaller public community water systems (CWSs), we assumed use was predominantly domestic and estimated withdrawals from our domestic water-use model and census block data within the CWS boundaries. Aquifer assignments were made by comparing the elevation of the well screen to the elevation of each aquifer raster surface at the well location. The unconfined aquifer and confined Columbia aquifer are the most used aquifers for these smaller public water systems, but the Cheswold, Pocomoke, and Piney Point aquifers are notable in some areas.

Domestic self-supplied water use makes up the third largest category of groundwater withdrawals. Individual wells typically withdraw small volumes but are widely distributed and abundant, in contrast with the concentrated distribution and high withdrawals of public water-supply wells. Withdrawals for this category were estimated from our domestic water-use model and census data for each block, or parts of blocks (sub-blocks), beyond public water system boundaries. The total of withdrawals was 11.6 Mgal/d for the study area, with 4.23 Mgal/d in Kent County and 7.37 Mgal/d in Sussex County. Census data suggests that more Kent County residents utilized public water supplies (101,656) than their own domestic wells (60,575), whereas Sussex County had nearly equal numbers of public supplied (98,964) and self-supplied (96,472) residents. Self-supplied withdrawals were estimated as 69.9 gallons per person per day in Kent County and 76.4 gallons per capita per day in Sussex County; the average is likely higher in Sussex

County than in Kent County, at least in part, because of self-supplied household use by occupants of non-resident seasonal housing. Aquifer assignments for domestic self-supplied water use were made in the same manner as for agricultural irrigation. Clusters of well-screen elevations were identified for domestic wells in each census block; each cluster was assigned to an aquifer by comparing to the aquifer raster surfaces; and the percentage of withdrawals in the block were assigned according to the percentage of wells in each cluster. The unconfined aquifer provided almost two-thirds of the domestic self-supplied groundwater. The confined Columbia aquifer provided nearly 14 percent of withdrawals and other aquifers each providing no more than 5 percent.

Industrial wells represented the fourth largest category of groundwater withdrawals. Pumping data were reported to DNREC for 62 industrial wells. Withdrawals between 2004 and 2008 ranged from 6.66 Mgal/d for 2006 to 7.66 Mgal/d for 2008, mostly from Sussex County. Even more than public-well withdrawals, industrial withdrawals were spatially concentrated at large pumping centers. Aquifers were assigned by comparing the elevation of the well screen to the elevation of each aquifer raster surface at the well location. The unconfined aquifer was the source of more than half of the volume of reported industrial well withdrawals and the Pocomoke aquifer provided approximately one-fourth. The Manokin (11 percent) and Cheswold (7 percent) aquifers were the only other significant sources.

Three additional categories represented smaller percentages of withdrawals. Livestock water use for the poultry industry was estimated assuming a demand of 575,000 gallons per year for drinking water and evaporative cooling systems for 2,727 chicken houses identified on aerial photographs. Total withdrawals for poultry were estimated as more than 4 Mgal/d, mostly in Sussex County. Using the same method as used for irrigation wells, we estimated that the unconfined aquifer represented more than half of the volume of estimated withdrawals for poultry houses and the confined Columbia aquifer accounted for approximately one-fourth. Groundwater use for golf course irrigation was principally in Sussex County and estimated from a combination of reported and assumed pumping volumes. Total withdrawals were estimated to be approximately 2 Mgal/d from 27 golf course wells. Well screen elevations of golf course wells were compared to aquifer raster surfaces, allowing us to assign nearly half of the withdrawals to the unconfined aquifer and significant portions (13-17 percent) to the confined Columbia, Pocomoke, and Manokin aquifers. Agricultural wells used for lawn irrigation had the smallest total of withdrawals, 0.03 Mgal/d, all from the unconfined aquifer.

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REFERENCES

Alemán González, W.B., Powars, D.S., Seefelt, E.L., Edwards, L.E., Self-Trail, J.M., Durand, C.T., Schultz, A.P., McLaughlin, P.P., 2012, Preliminary physical stratigraphy, biostratigraphy, and geophysical data of the U.S. Geological Survey South Dover Bridge core, Talbot County, Maryland: U.S. Geological Survey Open-File Report 2012-1218, 16 p.

Ameen, S., 2004, Community water systems source book: commercial, institutional, residential, industrial applications: 5th edition, Technical Proceedings, High Point, North Carolina.

American Water Works Association (AWWA), 1984, Design and construction of small water systems: a guide for managers: an AWWA small-systems resource book: American Water Works Association, Denver, CO, 112 p.

Andreasen, D.C., Staley, A.W., and Achmad, G.J., 2013, Maryland Coastal Plain Aquifer Information System: hydrogeologic framework: Maryland Geological Survey Open-File Report 12-02-20, 121 p.

Andres, A.S., 1986, Stratigraphy and depositional history of the post-Choptank Chesapeake Group: Delaware Geological Survey Report of Investigations No. 42, 39 p.

_____, 2001, Geohydrology of the Smyrna-Clayton Area, Delaware: Delaware Geological Survey Hydrologic Map 10, scale 1:24,000.

_____, 2003a, Ground-water recharge potential, Kent County, Delaware: Delaware Geological Survey Hydrologic Map 11, scale 1:24,000.

_____, 2003b, Ground-water recharge potential, Sussex County, Delaware: Delaware Geological Survey Hydrologic Map 12, scale 1:24,000.

_____, 2004, The Cat Hill Formation and Bethany Formation of Delaware: Delaware Geological Survey Report of Investigations No. 67, 8 p.

Andres, A. S., Benson, R. N., Ramsey, K. W., and Talley, J. H., 1990, Geologic and hydrologic studies of Oligocene-Pleistocene section near Lewes, Delaware, Benson, R. N., ed.: Delaware Geological Survey Report of Investigations No. 48, 34 p., 1 pl.

Andres, A.S. and Howard, C.S., 2000, The Cypress Swamp Formation, Delaware: Delaware Geological Survey Report of Investigation No. 62, 13 p.

_____, 2002, Results of hydrogeologic studies of the Cypress Swamp Formation, Delaware: Delaware Geological Survey Report of Investigations No. 64, 16 p.

Andres, A.S. and Klingbeil, A.D., 2006, Thickness and transmissivity of the unconfined aquifer of eastern Sussex County, Delaware: Delaware Geological Survey Report of Investigations No. 70, 19 p., 1 plate.

Andres, A.S., and Ramsey, K.W., 1995, Geologic map of the Seaford area, Delaware: Delaware Geological Survey Geologic Map No. 9, scale 1:24,000.

Andres, A.S., Ramsey, K.W., and Groot, J.J., 1996, Geology of the Seaford area, Delaware: Delaware Geological Survey Report of Investigations No. 53, 22 p.

Andres, A.S., Ramsey, K.W., and Schenck, W.S., 1995, Basic data for the geologic map of the Seaford area, Delaware: Delaware Geological Survey Open File Report No. 39, 39 p.

Barron, J.A., Browning, J.V., Sugarman, P.J., and Miller, K.G., 2013, Refinement of late early and middle Miocene diatom biostratigraphy for the eastern coast of the United States: Geosphere, v. 9, p. 1286-1302.

Benson, R. N., 1998, Radiolarians and diatoms from the Pollack Farm site, Delaware: Marine-terrestrial correlation of Miocene vertebrate assemblages of the Middle Atlantic Coastal Plain, *in* Benson, R.N, ed., Geology and paleontology of the lower Miocene Pollack Farm fossil site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 5-19.

Benson, R.N., Jordan, R.R., and Spoljaric, N., 1985, Geological studies of Cretaceous and Tertiary section, test well Je32-04, central Delaware: Delaware Geological Survey Bulletin No. 17, 69 p., 3 pl.

Benson, R.N., and Spoljaric, N., 1996, Stratigraphy of the post-Potomac Cretaceous-Tertiary rocks of central Delaware: Delaware Geological Survey Bulletin No. 20, 28 p., 5 pl.

Browning, J.V., Miller, K.G., McLaughlin, P.P., Kominz, M.A., Sugarman, P.J., Monteverde, D., Feigenson, M.D., and Hernández, J.C., 2006, Quantification of the effects of eustasy, subsidence, and sediment supply on Miocene sequences, mid-Atlantic margin of the United States: Geological Society of America Bulletin, v. 118, p. 567-588.

Bybell, L.M., Self-Trail, J.M., and Gibson, T.G., 1995, Cenozoic calcareous nannofossil biostratigraphy of the Dover Je32-04 drillhole, Kent County, Delaware: U. S. Geological Survey Open-file Report 95-478, 20 p.

Cadwallader, C., 2012, Delaware agricultural statistics and resource directory: 2011-1012: U.S. Department of Agriculture, National Agricultural Statistics Service.

Carter, C.W., 1937, The Upper Cretaceous deposits of the Chesapeake and Delaware canal: Maryland Geological Survey, v. 13, no. 6, p. 237–281.

Campbell, J., and Donald, J., 2012, Poultry farm water supply: Delmarva Poultry Conference, September, 2012, Ocean City, Maryland. http://extension.umd.edu/sites/default/files/_docs/2012_DPI-PoultryFarmWaterSupply-Campbell.pdf.

Clark, W.B., 1893, A preliminary report on the Cretaceous and Tertiary formations of New Jersey: New Jersey Geological Survey Annual Report 1892, part II, p. 167-239.

_____, 1907, The classification adopted by the U. S. Geological Survey for the Cretaceous deposits of New Jersey, Delaware, Maryland and Virginia: Johns Hopkins University Circular, new ser., 1907, no. 7, p. 1-4.

Clark, W.B., Bagg, R.M., and Shattuck, G.B., 1897, Upper Cretaceous formations of New Jersey, Delaware and Maryland: Geological Society of America Bulletin, v. 8, no. 1, p. 315-358.

Conrad, T.A., 1865, Observations on the Eocene lignite formation of the United States: Proceedings of the Academy of Natural Sciences, Philadelphia, v. 17, p. 70-73.

Cushing, E.M., Kantrowitz, I.H., and Taylor, K.R., 1973, Water resources of the Delmarva Peninsula: U.S. Geological Survey, Professional Paper 822, 58 p., 12 pl.

Czarick, M., 2011, Pad system installation tips. 2011 Tunnel Ventilation Workshop, May 2011, The University of Georgia, College of Agricultural and Environmental Sciences, Cooperative Extension. https://www.poultryventilation.com/sites/default/files/workshops/section%2011.pdf, 25 p.

Delaware Geological Survey, 2008, Continuous 3-meter DEM of the State, DMRASTER.DE_DEM3. Delaware Geological Survey, University of Delaware, http://www.dgs.udel.edu/data.

Delaware Office of State Planning Coordination, 2007, 2007 Delaware land use and land cover: Office of Management and Budget, State of Delaware. http://stateplanning.delaware.gov/info/lulcdata/2007_lulc.shtml.

Delaware Population Consortium, 2006, Annual population projections: version 2006. http://udspace.udel.edu/bitstream/handle/19716/13091/DPC2006v0.pdf, 60 p.

Denver, J.M., 1983, Configuration of the base and thickness of the unconfined aquifer in southeastern Sussex County, Delaware: Delaware Geological Survey Open File Report No. 20, 12 p.

Delaware Department of Natural Resources and Environmental Control, 2005, Source Water Assessment of the public water-supply wells for High Point South system, Kent County, Delaware: Division of Water Resources, Source Water Protection Program, 8 p.

_____, 2014, Twelfth Report to the Governor and General Assembly regarding the Progress of the Delaware Water Supply Coordinating Council, Estimates of Water Supply and Demand for Kent County and Sussex County through 2030: Division of Water, Delaware Geological Survey at the University of Delaware, and the University of Delaware Institute for Public Administration Water Resources Agency, 59 p.

Dugan, B.L., Neimeister, M.P., and Andres, A.S., 2008, Hydrogeologic framework of southern New Castle County: Delaware Geological Survey Open-File Report No. 49, 22 p., 3 pl.

Dyer Partnership, 2009, City of Brookings, Curry County, Oregon, System development charges. Update for water, wastewater and storm drainage, May 2009, Project No. 145.03: The Dyer Partnership Engineers & Planners, Inc., www.brookings.or.us/Archive/ViewFile/Item/231, 69 p.

Dziegielewski, B., Kiefer, J.C., Opitz, E.M., Porter, G.A. and Lantz, G.L., 2000, Commercial and institutional end uses of water: AWWA Research Foundation and the American Water Works Association, Denver, Colorado, 264 p.

Enright, R., 1969, The stratigraphy and clay mineralogy of Eocene sediments of the northern New Jersey Coastal Plain, *in* Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Rutgers University Press, Geological Society of America, 82nd Annual Meeting, Atlantic City, NJ, p. 14-20.

Gibson, T.G., Bybell, L.M., and Owens, J.P., 1993, Latest Paleocene lithologic and biotic events in neritic deposits of southwestern New Jersey: Paleoceanography, v. 8, issue 4, p. 495-514.

Groot, J.J. and Jordan, R.R., 1999, The Pliocene and Quaternary deposits of Delaware: palynology, ages, and paleoenvironments: Delaware Geological Survey Report of Investigations No. 58, 36 p.

Groot, J.J., Ramsey, K.W., and Wehmiller, J.F., 1990, Ages of the Bethany, Beaverdam, and Omar Formations of southern Delaware: Delaware Geological Survey Report of Investigations No. 47, 19 p.

Hansen, H.J., 1981, Stratigraphic discussion in support of a major unconformity separating the Columbia Group from the underlying upper Miocene aquifer complex in eastern Maryland: Southeastern Geology, v. 22, p. 123-138.

_____, 1992, Stratigraphy of Upper Cretaceous and Tertiary sediments in a core-hole drilled near Chesterville, Kent County, Maryland: Maryland Geological Survey Open-File Report No. 93-02-7, 38 p.

Harris, A.D., Miller, K.G., Browning, J.V., Sugarman, P.J., Olsson, R.K., Cramer, B.S., Wright, J.D., 2010, Integrated stratigraphic studies of Paleocene–lowermost Eocene sequences, New Jersey Coastal Plain: Evidence for glacioeustatic control. Paleoceanography, v. 25, issue 3, p. PA3211, 18 p.

Hodges, A.L., 1984, Hydrology of the Manokin, Ocean City, and Pocomoke aquifers of southeastern Delaware: Delaware Geological Survey Report of Investigations No. 38, 60 p.

Horn, M.A., Moore, R.B., Hayes, Laura, Flanagan, S.M., 2008, Methods for and estimates of 2003 and projected water use in the Seacoast region, southeastern New Hampshire: U.S. Geological Survey Scientific Investigations Report 2007–5157, 87 p., plus 2 appendixes on CD-ROM.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, revised 2005, Estimated use of water in the United States in 2000. U.S. Geological Survey Circular 1268, 46 p., 15 figures, 14 tables.

Johnston, R.H., 1973, Hydrology of the Columbia (Pleistocene) deposits of Delaware: an appraisal of a regional water-table aquifer: Delaware Geological Survey Bulletin No. 14, 78 p.

_____, 1977, Digital model of the unconfined aquifer in central and southeastern Delaware: Delaware Geological Survey Bulletin No. 15, 47 p.

Jones, D.S., Ward, L.W., Mueller, P.A., and Hodell, D.A., 1998, Age of marine mollusks from the lower Miocene Pollack Farm site, Delaware, determined by $^{87}Sr/^{86}Sr$ geochronology, *in Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm fossil site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 21–25.*

Jordan, R.R., 1962, Stratigraphy of the sedimentary rocks of Delaware: Delaware Geological Survey Bulletin No. 9, 51 p., 4 pl.

_____, 1964, Columbia (Pleistocene) sediments of Delaware: Delaware Geological Survey Bulletin No. 12, 69 p.

_____, 1974, Pleistocene deposits of Delaware, in Oaks, R.Q., and DuBar, J.R., eds., Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain: Logan, Utah, Utah State University Press, p. 30-52.

Kennedy, W.J. and Cobban, W.A., 1994, Upper Campanian ammonites from the Mount Laurel Sand at Biggs Farm, Delaware: Journal of Paleontology, v. 68, no. 6, p.1285-1305.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

Kent County, 2008, 2007 Kent County Comprehensive Plan. http://www.co.kent.de.us/media/776419/Adopted-Comp-Plan-Full.pdf, 193 p.

Kidwell, S.M., 1984, Outcrop features and origin of basin margin unconformities in the lower Chesapeake Group (Miocene), Atlantic Coastal Plain, in Schlee, J.S., ed., Interregional Unconformities and Hydrocarbon Accumulation. American Association of Petroleum Geologists Memoir 36, p. 37-56.

_____, 1997, Anatomy of extremely thin marine sequences landward of a passive-margin hinge zone; Neogene Calvert Cliffs succession, Maryland, U.S.A.: Journal of Sedimentary Research, v. 67, no. 2, p. 322-340.

Leahy, P.P., 1976, Hydraulic characteristics of the Piney Point aquifer and overlying confining bed near Dover, Delaware: Delaware Geological Survey Report of Investigations No. 26, 24 p.

_____, 1979, Digital model of the Piney Point aquifer in Kent County, Delaware: Delaware Geological Survey Report of Investigations No. 29, 81 p.

_____, 1982, Ground-water resources of the Piney Point and Cheswold aquifers in central Delaware as determined by a flow model: Delaware Geological Survey Bulletin No. 16, 68 p.

Levin, S.B. and Zarriello, P.J., 2013, Estimating irrigation water use in the humid eastern United States, U.S. Geological Survey Scientific Investigations Report 2013–5066, 34 pp.

Mackenzie, J., 2009, Land-use/land cover transitions in Delaware, 2002-2007: College of Agriculture & Natural Resources, University of Delaware, http://www.udel.edu/johnmack/research/DE_LULC_transitions_2002_2007.pdf, 7 p.

Marine, I.W., and Rasmussen, W.C., 1955, Preliminary report on the geology and ground water resources of Delaware. Delaware Geological Survey Bulletin No. 4, 336 p., 10 pl.

Mays, L.W., 2001, Water Resources Engineering: 1st edition. John Wiley & Sons, Inc., 768 p.

McGee, W.J., 1886, Geological formations underlying Washington and vicinity: American Journal of Science, 3rd series, v. 31, p. 473-474.

McLaughlin, P.P., Miller, K.G., Browning, J.V., Ramsey, K.W., Benson, R.N., Tomlinson, J.L., and Sugarman, P.J., 2008, Stratigraphy and correlation of the Oligocene to Pleistocene section at Bethany Beach, Delaware: Delaware Geological Survey Report of Investigations No. 75, 41 p.

McLaughlin, P.P., and Velez, C.C., 2006, Geology and extent of the confined aquifers of Kent County, Delaware: Delaware Geological Survey Report of Investigations No. 72, 40 p., 1 pl.

Miller, B.L., 1906, Dover folio, Delaware-Maryland-New Jersey: U.S. Geological Survey Folios of the Geologic Atlas No. 137, p. 1-10, 2 maps, scale 1:25,000.

Miller, J.C., 1971, Ground water geology of the Delaware Atlantic seashore: Delaware Geological Survey, Report of Investigations No. 17, 33 p.

Miller, K.G., 2002, The role of ODP in understanding the causes and effects of global sea-level change: JOIDES Journal, v. 28, no. 1, p. 23-28.

Miller, K.G., Mountain, G.S, Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E., and Wright, J.D., 1998, Cenozoic global sea-level, sequences, and the New Jersey Transect: Results from coastal plain and slope drilling: Reviews of Geophysics, v. 36, p. 569-601.

Miller, K.G., McLaughlin, P.P., Browning, J.V., Benson, R.N., Sugarman, P.J., Hernandez, J., Ramsey, K.W., Baxter, S.J., Feigenson, M.D., Aubry, M.-P., Monteverde, D.H., Cramer, B.S., Katz, M.E., McKenna, T.E., Strohmeier, S.A., Pekar, S.F., Uptegrove, J., Cobbs, G., Cobbs, G., III, and Curtin, S.E., 2003, Bethany Beach site, *in* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., eds., Proceedings of the Ocean Drilling Program, Initial reports, Volume 174AX (Supplement): College Station, TX, Ocean Drilling Program, p. 1–84.

Miller, K.G., Sugarman, P.J., Browning, J.V., Kominz, M.A., Olsson, R.K., Feigenson, M.D., Hernandez, J.C., 2004, Upper Cretaceous sequences and sea-level history, New Jersey coastal plain: Geological Society of America Bulletin, v. 116, issue 3-4, p. 368–393.

Morales, M.A., Martin, J.M., and Heaney, J.P., 2009, Methods for estimating commercial, industrial and institutional water use. Proceedings of Fall 2009 FSAWWA Water Conference, Orlando. http://www.conservefloridawater.org/publications/10327351.pdf, 18 p.

National Climatic Data Center, National Oceanic & Atmospheric Administration. Annual Climatological Summary, Years 2004-2008. http://www.ncdc.noaa.gov/cdo-web/search, accessed 09/25/14.

New Jersey Department of Environmental Protection, 2013, Division of Water Quality, New Jersey Pollutant Discharge Elimination System (NJPDES) Rules, 7:14A-23.3, Projected flow criteria http://www.state.nj.us/dep/dwq/7_14a/sub23rule.pdf, accessed June, 2013.

Olsson, R.K. and Wise S.W., Jr., 1987, Upper Paleocene to middle Eocene depositional sequences and hiatuses in the New Jersey Atlantic margin: *in* Ross C.A. and Haman, D., eds., Timing and depositional history of eustatic sequences: Constraints on seismic stratigraphy: Cushman Foundation for Foraminiferal Research, Special Publication No. 24, p. 99-112.

Otton, E.G., 1955, Ground-water resources of the southern Maryland coastal plain: Maryland Geological Survey Bulletin 15, 347 p.

Owens, J.P., Bybell, L.M., Paulachok, G., Ager, T.A., Gonzalez, V.M., and Sugarman, P.J., 1988. Stratigraphy of the Tertiary sediments in a 945-foot-deep corehole near Mays Landing in the southeastern New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1484, 39 p.

Owens, J.P. and Denny, C.S., 1978, Geologic map of Worcester County, Maryland: Maryland Geological Survey County Geologic Map, scale 1:62,500.

_____, 1979, Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware: U.S. Geological Survey Professional Paper 1067-A, 28 p.

Owens, J.P., Minard, J.P. Sohl, N.F. and Mello. J.F., 1970. Stratigraphy of the outcropping post-Magothy Upper Cretaceous formations in southern New Jersey and northern Delmarva Peninsula, Delaware and Maryland: U.S. Geological Survey Professional Paper 674, 60 p.

Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous and Tertiary formations of the New Jersey Coastal Plain, *in* Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: New Brunswick, NJ, Rutgers University Press, p. 235-278.

Owens, J.P., Sohl, N.F., and Minard, J.P., 1977. A field guide to the Cretaceous and lower Tertiary beds of the Raritan and Salisbury Embayments, New Jersey, Delaware and Maryland: American Association of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists Annual Meeting, Washington, D.C., 113 p.

Owens, J.P., Sugarman, P.J., Sohl, N.F., Parker, R.A., Houghton, H.F., Volkert, R.A., Drake, A.A., and Orndorff, R.C., 1999, Bedrock geologic map of central and southern New Jersey: U.S. Geological Survey Miscellaneous Investigations Series Map I-2540-B, scale 1:100,000, 8 cross sections, 4 sheets.

Parker, G.G., Hely, A.G., Keighton, W.B., and Olmsted, F.H., and others, 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.

Pekar, S.F., Christie-Blick, N., Kominz, M.A., and Miller, K.G., 2001, Evaluating the stratigraphic response to eustasy from Oligocene strata in New Jersey: Geology, v. 29, no. 1, p. 55-58.

Pickett, T.E., 1970, Geology of the Chesapeake and Delaware Canal area, Delaware: Delaware Geological Survey Geologic Map No. 1, scale 1:24,000.

Pickett, T.E. and Spoljaric, N., 1971, Geology of the Middletown-Odessa area, Delaware: Delaware Geological Survey Geologic Map No. 2, scale 1:24,000.

Ramsey, K.W., 1993, Geology of the Milford and Mispillion River quadrangles: Delaware Geological Survey Geologic Map Series No. 8, scale 1:24,000.

_____, 1998, Depositional environments and stratigraphy of the Pollack Farm site, Delaware, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm fossil site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 27–40.

_____, 2001, Geology of the Ellendale and Milton quadrangles, Delaware: Delaware Geological Survey Geologic Map Series No. 11, Scale 1:24,000.

_____, 2003, Geology of the Lewes and Cape Henlopen quadrangles, Delaware: Delaware Geological Survey Map Series No. 12, scale 1:24,000.

_____, 2007, Geologic map of Kent County, Delaware: Delaware Geological Survey Geologic Map Series No. 14, scale 1:100,000.

_____, 2010, Stratigraphy, correlation, and depositional environments of the middle to late Pleistocene interglacial deposits of southern Delaware: Delaware Geological Survey Report of Investigations No. 76, 43 p.

_____, 2011, Geologic map of the Fairmount and Rehoboth Beach quadrangles, Delaware: Delaware Geological Survey Geologic Map No. 16, scale 1:24,000.

Ramsey, K.W., and Groot, J.J., 1997, Geology of the Milford and Mispillion River quadrangles: Delaware Geological Survey Report of Investigations No. 55, 40 p.

Ramsey, K.W. and Tomlinson, J.L., 2011, Geologic Map of the Harbeson quadrangle, Delaware: Delaware Geological Survey Geologic Map No. 17, scale 1:24.000.

_____, 2012, Geologic Map of the Bethany Beach and Assawoman Bay Quadrangles, Delaware: Delaware Geological Survey Geologic Map No. 18, scale 1:24,000.

Rasmussen, W.C., Groot, J.J., and Depman, A.J., 1958, High-capacity test well developed at the Air Force Base, Dover, Delaware: Delaware Geological Survey Report of Investigations No. 2, 36 p.

Rasmussen, W.C., Odell, J.W., and Beamer, N.H., 1966, Delaware water: U.S. Geological Survey Water-Supply Paper 1767, 106 p.

Rasmussen, W.C. and Slaughter, T.H., 1955, The water resources of Somerset, Wicomico, and Worcester counties: Maryland Department of Geology, Mines, and Water Resources Bulletin 16, 533 p.

Rasmussen, W.C., Wilkens, R.A., and Beall, R.M., 1960, Water resources of Sussex County Delaware: Delaware Geological Survey Bulletin No. 8, 228 p., 10 pl.

Rima, D.R., Coskery, O.J., and Anderson, P.W., 1964, Groundwater resources of southern New Castle County, Delaware: Delaware Geological Survey Bulletin No. 11, 54 p.

Rogers, D.H., and Alam, M. 2008, KanSched2: An ET-based irrigation scheduling tool: Kansas State Research and Extension. (Electronic Only Publication) EP129. http://www.ksre.ksu.edu/bookstore/pubs/EP129.pdf, 12 p.

San Antonio Water System, 2009, Infrastructure planning equivalent dwelling unit (EDU) calculation sheet: https://www.saws.org/business_center/developer/subdivision/docs/educalcsheet.pdf, 1 p.

Shattuck, G.B., 1902, The Miocene formations of Maryland (abstract): Science, v. XV, no. 388, p. 906.

Shattuck, G.B., 1904, Geological and paleontological relations, with a review of earlier investigations, *in* Clark, W.B., Shattuck, G.B., and Dall, W.H., The Miocene deposits of Maryland: Maryland Geological Survey, Miocene, v. 1, p. xxxiii–cxxxvii.

Snodgrass, K., 2007, Water use in Forest Service Recreation areas: Guidelines for water system designers. United States Department of Agriculture, Forest Service, Technology & Development Program, 10 p.
Soil Survey Staff, 2006, Gridded soil survey geographic (gSSURGO) database for Delaware: U.S. Department of Agriculture, Natural Resources Conservation Service, http://datagateway.nrcs.usda.gov/.
Solley, W.B., Pierce, R.R., and Perlman, H.A., 1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 76 p.
_____, 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p.
Spoljaric, N. and Woodruff, K.D., 1970, Geology, hydrology, and geophysics of Columbia sediments in the Middletown-Odessa area, Delaware: Delaware Geological Survey Bulletin No. 13, 156 p.
Sugarman, P.J., 2011, Bedrock Geology of the Runnemede Quadrangle, Camden and Gloucester Counties, New Jersey, N. J. Geological Survey Open-File Map 86, scale 1:24,000.
Sugarman, P.J., Miller, K.G., Bukry, D., and Feigenson, M.D., 1995, Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain: Geological Society of America Bulletin, v. 107, no. 1, p. 19-37.
Sugarman, P.J., Miller, K.G., Browning, J.V., McLaughlin, P.P. Jr., Brenner, G.J., Buttari, B., Cramer, B.S., Harris, A., Hernandez, J. Katz, M.E., Lettini, B., Misintseva, S., Monteverde, D.H., Olsson, R.K., Patrick, L., Roman, E., Wojtko, M.J., Aubry, M.-P., Feigenson, M.D., Barron, J.A., Curtin, S., Cobbs, G., Cobbs, G., III, Bukry, D., and Huffman, B.A., 2005, Millville site, *in* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., eds., Proceedings of the Ocean Drilling Program, Initial reports, Volume 174AX (Supplement): College Station, TX, Ocean Drilling Program, p. 1–94.
Sundstrom, R.W. and Pickett, T.E., 1968, The availability of water in Kent County Delaware with special reference to the Dover area: Water Resources Center, University of Delaware, Newark, 123 p.
_____, 1969, The availability of ground water in eastern Sussex County, Delaware: Water Resources Center, University of Delaware, Newark, 136 p.
_____, 1970, The availability of ground water in western Sussex County, Delaware: Water Resources Center, University of Delaware, Newark, 117 p.
Talley, J.H., 1975, Cretaceous and Tertiary section, deep test well, Greenwood, Delaware: Delaware Geological Survey Report of Investigations No. 23, 51 p.
_____, 1982, Geohydrology of the Milford Area, Delaware: Delaware Geological Survey Hydrologic Map 4, scale 1:24,000.
Urban Research & Development Corporation, 2008, Sussex County comprehensive plan update. https://www.sussexcountyde.gov/sites/default/files/PDFs/CompPlan_FullDocument.pdf, 206 p.
U.S. Census Bureau, 1990, Census 1990: http://factfinder2.census.gov.
_____, 2000, Census 2000: http://factfinder2.census.gov.
_____, 2010, Census 2010: http://factfinder2.census.gov.
_____, 2018, QuickFacts: https://www.census.gov.
U.S. Environmental Protection Agency, 2012, Public drinking water systems: Facts and figures: U.S. Environmental Protection Agency (EPA), http://water.epa.gov/infrastructure/drinkingwater/pws/factoids.cfm.
U.S. Department of Agriculture, 1972, Census of Agriculture, 1969: Delaware, state and county data, Chapter 2, county summary data for selected items, Geographic Area Series, Volume 1, Part 22: U.S. Department of Agriculture, National Agricultural Statistics Service (NASS), http://usda.mannlib.cornell.edu/usda/AgCensusImages/1969/01/22/483/Table-03.pdf.
_____, 1994, Census of Agriculture, 1992: Delaware, state and county reports, county level data, Volume 1, Geographic Area Series, Part 8: U.S. Department of Agriculture, National Agricultural Statistics Service (NASS), http://www.agcensus.usda.gov/Publications/1992/Volume_1_Chapter_2_County_Tables/Delaware/de2_01.pdf.
_____, 2009a, Census of Agriculture, 2007: Delaware, state and county data, Volume 1, Geographic Area Series, Part 8: U.S. Department of Agriculture, National Agricultural Statistics Service (NASS), http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Delaware/dev1.pdf.
_____, 2009b, National Agricultural Statistics Service, 2008 Delaware Cropland Data Layer: http://nassgeodata.gmu.edu/CropScape/.
U.S. Geological Survey, 2001, National Water Information System data available on the World Wide Web (Water Data for the Nation), accessed June 25, 2014, at URL http://waterdata.usgs.gov/de/nwis/water_use/.
Utah, 2014, Utah Administrative Code, R309, Environmental Quality, Drinking Water, Rule R309-510, Facility Design and Operation: Minimum Sizing Requirements, R309-510-7, Source Sizing, Table 510-2, Source Demand for Individual Establishments: http://www.rules.utah.gov/publicat/code/r309/r309-510.htm.
Ward, L.W., 1998, Mollusks from the lower Miocene Pollack Farm site, Kent County, Delaware: A preliminary analysis, *in* Benson, R.N., ed., Geology and paleontology of the lower Miocene Pollack Farm fossil site, Delaware: Delaware Geological Survey Special Publication No. 21, p. 59-131.
Weigle, J.M., 1974, Availability of fresh ground water in northeastern Worcester County, Maryland with special emphasis on the Ocean City area: Maryland Geological Survey Report of Investigations No. 24, 64 p.
Wheeler, J.C., 1999, Freshwater use in Delaware, 1995: U.S. Geological Survey Fact Sheet FS-126-99, 5 p.
_____, 2003, Freshwater use in Delaware, 2000. U.S. Geological Survey Fact Sheet 111-03, 2 p.
Zapecza, O.S., 1989. Hydrogeologic framework of the New Jersey coastal plain. U.S. Geological Survey Professional Paper 1404-B, 49 p., 24 pl.

END NOTE

The PDF maps found in Appendices A, B, and C provide larger versions of many of the maps in the text figures as well as additional maps and illustrations that may be of interest to the reader. The maps have been created with multiple layers. A user may display any combination of layers that best meet the user's purpose. Layers that may be turned on and off include geographic elements, roads, of aquifer elevations and thickness rasters, and data points. Available layers can be seen using layers view in the navigation pane in Adobe Acrobat. An index that allows cross-referencing of the appendix figures to the text figures is provided below.

Cross-reference index of appendix figures to corresponding text figures.

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