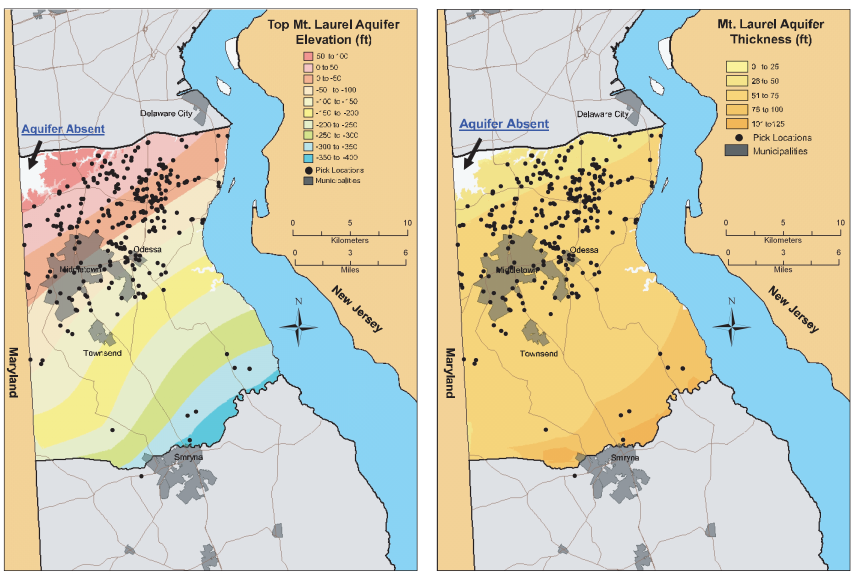
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

OPEN FILE REPORT NO. 49

HYDROLOGEOLOGIC FRAMEWORK OF SOUTHERN NEW CASTLE COUNTY



By

Bailey L. Dugan, Mark P. Neimeister, and A. Scott Andres

University of Delaware
Newark, Delaware
2008

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

HYDROGEOLOGIC FRAMEWORK OF SOUTHERN NEW CASTLE COUNTY

INTRODUCTION

Southern New Castle County (SNCC, Fig. 1) is dependent on ground water for nearly all of its water supply. The area has been undergoing development from predominately agricultural land use to urban/suburban land use (Delaware Water Supply Coordinating Council [WSCC], 2006). With this development comes a need to more accurately predict the availability of ground water to reduce the potential of overusing the resource.

Previous efforts to estimate ground-water availability in this area (i.e., Baxter and Talley, 1996; Sundstrom and Pickett, 1971; Hurd, 1998) used relatively simple water budget or analytic models. To refine and improve upon those estimates, numerical flow models need to be developed. A first step in this process is to more accurately characterize the spatial distribution and hydraulic characteristics of aquifers and confining beds. There is a substantial dataset available to map the spatial distribution of aquifers and confining beds. These data consist of hundreds of geologists' and drillers' descriptive logs and geophysical logs. There also are several published maps on selected properties of surficial and subsurface geology and hydrogeology (Woodruff, 1986, 1988, 1990; Benson and Spoljaric, 1996; Ramsey, 2005). Compared to geologic observations, there are relatively few measurements of hydraulic properties. These data consist of a few dozen pumping tests from Baxter and Talley (1996), consultant reports, and a few dozen slug tests (Wolff, 2007).

Purpose and Scope

Many investigators have identified and named lithostratigraphic (geologic) and hydrostratigraphic (aquifers and confining beds) units in SNCC. This study relies upon the most recent publication on lithostratigraphy (Ramsey, 2005) and extends that framework (Table 1) to maps of the depths and thicknesses of lithostratigraphic units, aquifers, and confining beds in the subsurface. Discussions of the historical development of lithostratigraphy and hydrostratigraphy of the area are beyond the scope of this report.

There are at least two immediate uses for the products of this study: 1) input information for digital ground-water models, and 2) analysis of the numbers and types of wells that have been installed into the different aquifers. The latter information is critical for characterizing how much water each aquifer is currently providing to wells.

This study relies on previously collected descriptive and geophysical logs and data collected from a very few drill holes of opportunity that became available during the study. No new drill holes were completed as part of this work. The mapping work was done using geographic information system (GIS) and other digital map making tools. In some respects, this study tests the accuracy and spatial coverage of the log data, how to efficiently use GIS and digital tools, and how to identify problems and potential solutions for data processing issues.

This study focuses on lithostratigraphic units, aquifers, and confining beds that occur within the geologic units above the Magothy Formation. This report also describes, in a general sense, the lithologies and hydrologic functions of the Potomac and Magothy Formations and tabulates hydraulic properties. Because of the significant depth to the Potomac and Magothy Formations over most of the study area, there are too few observations to map aquifers in these units with enough certainty to justify the effort. Mapping of aquifers in the Potomac and Magothy Formations will require substantial resources to drill, sample and log test holes, and interpret the information.

Acknowledgments

Funding for the mapping work was provided by the Delaware Geological Survey. The Delaware Water Resources Center (DWRC) supported the slug test study of Wolff (2007), and, in fact, two of the three authors are former DWRC interns. Peter P. McLaughlin, Jr. provided a thorough review of the manuscript.

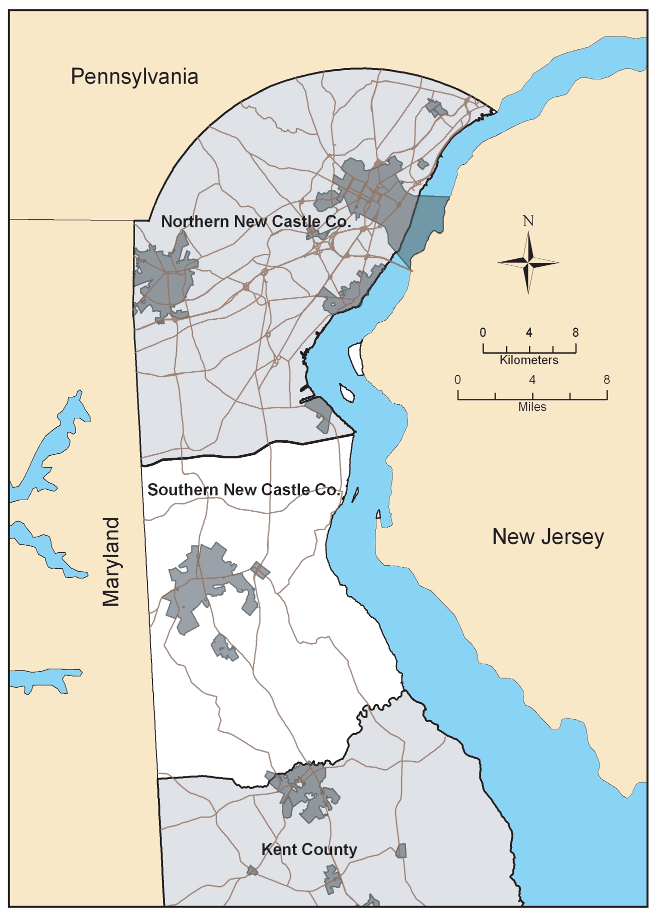


Figure 1. Location map of southern New Castle County study area.

Table 1. Lithostratigraphy and hydrostratigraphy chart.

Age	Geologic Unit	Hydrologic Unit
Holocene	Dredge spoil, marsh, swamp, alluvial deposits, undrained depressions	Confining beds and minor sand beds
Pleistocene	Scotts Corners Fm. Lynch Heights Fm. Columbia Fm.	Columbia aquifer fair to excellent yield
Miocene	Calvert Fm.	Confining beds
Eocene	Shark River Fm. Manasquan Fm.	
Paleocene	Vincentown Fm. Hornerstown Fm.	Rancocas aquifer fair to good yield interbedded confining units
Cretaceous	Navesink Fm.	Confining beds
	Mt. Laurel Fm.	Mt. Laurel aquifer poor to good yield
	Marshalltown Fm.	Confining bed
	Englishtown Fm.	Englishtown aquifer poor to fair yield
	Merchantville Fm.	Confining beds
	Magothy Fm.	Magothy aquifer fair to good yield
	Potomac Fm.	Potomac aquifers and confining units fair to excellent yields

METHODS

This study relied on published interpretations of subsurface lithostratigraphy and hydrostratigraphy (Woodruff, 1986, 1988, 1990; Ramsey, 2005; Benson and Spoljaric, 1996). Their identifications of the tops and bottoms of units, or "picks," typically were displayed on cross sections. Many of these data have also been captured and stored in a DGS database containing lithostratigraphic and hydrostratigraphic picks. Nearly all of these picks were made on the basis of geophysical log interpretations. These picks and geophysical log data were extracted from the database and were the starting points for the current study.

Lithostratigraphic and Hydrostratigraphic Picks

The first step in the mapping process was to construct six cross sections (Figs. 2, 4-8 and 10, Plate 1) and incorporate a pre-existing cross section (Fig. 9, Plate 1), which were used for interpretation of additional data points. Cross section locations were chosen where sufficient published and unpublished data were available. Profiles were constructed by extending or correlating from published picks and geophysical and descriptive logs to nearby, previously uninterpreted geophysical and descriptive logs. Geophysical logs from over 200 wells and test borings were used in this effort. The final production of the cross sections was completed in Grapher v. 7 (Golden Software, 2005).

The cross sections generated in the first step were then used to help determine the depths to the tops and bottoms of geologic and hydrologic units on remaining geophysical logs that were not used in constructing the cross sections. More than 600 additional descriptive logs from water-well completion reports and engineering and geologic test borings were evaluated. Of these records, approximately 450 had sufficient detail to warrant making picks. The elevation of land surface at each data point was determined from topographic maps or from a published digital elevation model (Mackenzie, 1999). Elevations of picks were computed as the differences between land surface elevation and depth to the pick.

Surface Mapping and Analysis

The locations of picks along with the computed elevations of the tops of the geologic and hydrologic units were mapped and evaluated using ArcMap v. 9.1 and 9.2 along with Geostatistical Analyst and Spatial Analyst software (ESRI, 2004). Using this same software, the thickness of a particular geolgic or hydrologic unit was computed as the difference between the elevations of the top of the unit and the top of the immediately underlying unit. This collection of software was also used to create maps of posted data, compute spatial statistics of elevation data, estimate elevations of geologic and hydrologic units on regular grids, and evaluate how well the grids fit the data. Maps of posted data and the spatial statistics displays were instrumental in finding and correcting data entry errors prior to and after gridding.

Multiple digital elevation models (DEMs) of the tops of geologic and hydrologic units were done on 30-m horizontal grids. The 30-m spacing was chosen to be consistent with the spacing of land surface elevations (LSE) and water-table DEMs and to allow visual renderings of the surfaces to be smoothly varying in space rather than blocky and coarsely pixelated. As will be discussed in later paragraphs, the sparse distribution of points in some portions of the study area does not support such fine detail.

Data-gridding algorithms evaluated during the study were ordinary kriging (OK), universal kriging (UK or kriging in the presence of a trend), trend surface (TS), and local polynomial regression (LPR). Spatial distributions of residuals (e.g., differences between point data and grid estimates) and visual inspection were the primary means used to evaluate how well the TS- and LPR-derived DEMs fit the pick data. Grids computed by OK and UK were evaluated by examining maps of residuals and by checking maps of the DEMs for bulls-eye patterns, which indicate the possibility of noisy or erroneous data.

Further evaluation and correction of the resultant grids were made by grid-to-grid computations in Spatial Analyst and application of the several rules and correction procedures (Fig. 3). The purpose of the corrections was to ensure that two discrete masses do not occupy the same space and that stratigraphic rules (e.g., superposition) are not violated. The

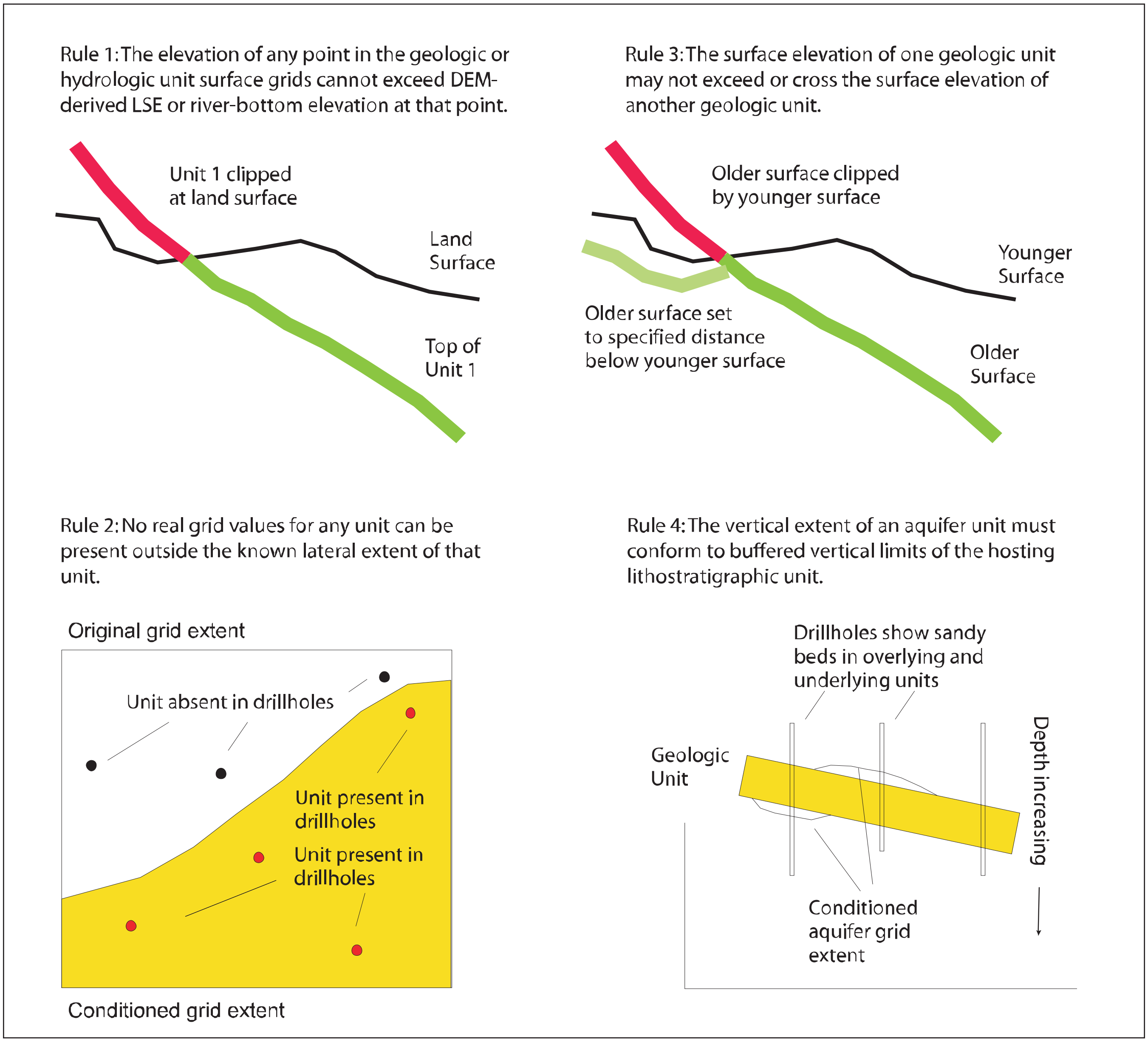


Figure 3. Illustrations of grid conditioning rules. DEM - digital elevation model; LSE - land surface elevation.

rules were applied in an iterative procedure from land surface downward. The results were then checked in the reverse direction (i.e., from the bottom up to land surface). Additional details concerning the following grid-conditioning rules are discussed later in this report.

(1) The elevation of any point in the geologic or hydrologic unit surface grids cannot exceed DEM-derived LSE or river-bottom elevation at that point. Appropriate corrections were applied to the DEMs of the geologic and hydrologic units to lower the elevations to land surface or river bottom.

(2) No real grid values for any unit can be present outside the known lateral extent of that unit. Grid values were set to null in these locations.

(3) The elevation of one geologic horizon may not cross the surface elevation of another geologic horizon. For example, at any point, the elevation of the bottom of a unit cannot exceed the elevation of the top of the same unit at that point. Grid values for a surface were set to null if the location was outside the known lateral extent of that unit. Otherwise, the elevation of the bottom unit was arbitrarily set 5 feet below the elevation of the top of the same unit, honoring its existence at that location.

(4) The vertical extent of an aquifer unit must conform to buffered vertical limits of the hosting lithostratigraphic unit. In all cases, a 15-foot buffer was applied to the top and bottom of a lithostratigraphic unit. For example, throughout the grid extents the top of the Mount Laurel aquifer must occur within 15 feet above the top and 15 feet below the bottom of the Mount Laurel Formation.

Borehole data, especially deeper than 250 ft, are sparsely distributed or lacking for one or more units in portions of the study area. Because areas with sparse data resulted in grids which exhibited serious extrapolation errors, DEM values in these areas of the grids were set to null. Next, grids were computed for these areas from contours hand drawn on regional scale maps. The two grids were then merged with the ArcMap mosaic process. The results of this process are discussed more in the results and discussion section of the report.

RESULTS AND DISCUSSION

The following sections discuss the results of this study in terms of lithostratigraphy and hydrogstratigraphy of the study area, focusing on the hydraulic properties (tabulated in Appendix 1), hydrologic functions, and three-dimensional geometries of the stratigraphic units. Because of the distribution and quality of available data, the resultant limitations of the interpretations have been identified and, where possible, quantified. The authors recognize that significant additional work is needed to improve the spatial distribution of data on hydraulic properties, ground-water levels and flow directions, and quantification of the relationships between ground water and bodies of surface water. The hydrologic information for Delaware has been compiled from previous works by the DGS and the U.S. Geological Survey (USGS) (Woodruff, 1986, 1988, 1990; Bachman and Ferrari, 1995; Baxter and Talley, 1996) and numerous consultant reports in DGS files.

All geologic units are part of the Coastal Plain physiographic province, which is underlain by a southeasterly dipping wedge of sedimentary deposits (Figs. 2 and 4 - 10, Plate 1). The deposits range in age from the Cretaceous Potomac Formation to modern alluvial and swamp deposits of stream valleys and modern marsh, tidal, and beach deposits found adjacent to Delaware Bay (Table 1). There also are significant areas covered with as much as 30 feet of dredge spoils derived from excavation and maintenance of the Chesapeake and Delaware Canal (C&D Canal).

Ground-water pumping and excavation of the C&D Canal have significantly perturbed the natural hydrologic system. For example, potentiometric surface maps (Rosman et al., 1995; Lacombe and Rosman, 2001) of the Potomac aquifer show that pumping-related drawdown caused by high capacity wells located north of the C&D Canal extend into southern New Castle County. This phenomenon has been reproduced by flow modeling studies (U.S. Army Corps of Engineers, 2007; Martin, 1984; Phillips, 1987) and indicates that some ground water now flows from southern New Castle County to northern New Castle County. Andres (2001) reports long term declines in water levels in the Mount Laurel aquifer due to pumping in the southeasternmost part of the county. The C&D Canal excavation cuts well below sea level through the Columbia, Mount Laurel, Englishtown, and Magothy Formations and into the Potomac Formation. The canal is a discharge area for aquifers in these units.

The density contrast between saline water in the canal and Delaware River and fresh ground water also has an impact on ground-water flow patterns in the study area. In general, the density contrast between the fresh and saline waters prevents them from mixing and tends to cause the slightly denser saline water to flow under fresh water (Freeze and Cherry, 1979). As long as there is sufficient fresh water pressure, the saline water will not flow very far into the aquifers under Delaware. However, when pumping reduces pressures and reverses normal flow directions, saline water will be drawn toward the pumping wells. This has happened in several areas along the Delaware River north of the C&D Canal (Martin, 1984; Phillips, 1987).

Scant data from southern New Castle County and Kent County also indicate that saline water is present at depth in the Magothy and Potomac aquifers in those areas (Groot, 1983). Data are not sufficient to adequately describe the boundary zone between fresh and saline water or show how pumping is affecting the location of the boundary zone in those aquifers. Saline ground water has also been reported in wells located adjacent to the canal and dredge spoil disposal areas (Rasmussen et al., 1958).

Surficial Geologic Units

Unless otherwise noted, the lithostratigraphic framework is directly from Ramsey (2005)

Geologic units that are described in the following paragraphs were used in the construction of cross sections (Figs. 2, 4-10, Plate 1) and/or they were used in the modeling analysis (Figs. 11-26, Plates 2 and 3). Determiniation of the hydrologic functions of the units is a result of this study. Readers interested in the development of Delaware lithostratigraphic nomenclature should consult Benson and Spoljaric (1996). A full discussion of the evolution of hydrostratigraphic nomenclature is beyond the scope of this report. Additional data from adjacent New Jersey and Maryland, consisting of picks of hydrostratigraphic units and geophysical logs, were compiled for New Jersey from Zapecza (1989), and for Maryland from Bachman and Wilson (1984), Drummond (1998), Otton et al. (1988), Vroblesky and Fleck (1991), and J. M. Wilson (written communication, 2006).

Dredge Disposal Deposits (Holocene)

Dredge spoil deposits are located primarily on uplands on the north side of the C&D Canal and in a few locations along the south side and consist of dredged material from the C&D Canal. Descriptive logs in the DGS log library show that dredge disposal deposits are a heterogeneous mixture of sand, silt, and clay from geologic units of Cretaceous age through which the canal was cut.

The highly heterogeneous composition of dredge spoil deposits allows them to function as both aquifer and confining unit. More permeable sands will readily transmit water so that composition of the spoil deposits greatly affects the locations and rates of ground-water flow into and out of the deposits. It is likely that these deposits transmit water downward to underlying aquifer units, though it is not possible to predict precisely either where this occurs or the amount of water movement. When sediment is dredged from the canal, its pore waters are saturated with saline water. These saline waters have impacted a few wells located immediately adjacent to the canal (Rasmussen et al., 1958).

Alluvial Deposits (Holocene)

Alluvial deposits consist of brown, light-yellow-orange, and gray fine to coarse quartz sand, silt, clay, and rare fine to medium gravel. The deposits are usually less than 20 feet thick and are primarily restricted to stream channels and adjacent flood plains. Alluvial deposits are present in the study area, but are not shown on Ramsey (2005) due to the scale of the map (Ramsey, oral communication).

The highly heterogeneous composition of alluvial deposits allows them to function as both aquifer and confining unit. More permeable, sandier deposits will readily transmit water so that composition of the deposits greatly affects the locations and rates of ground-water discharge. The limited thickness and near-surface location does not permit water supply wells to be completed in these deposits though more permeable deposits may facilitate movement of water from streams to nearby shallow pumping wells.

Swamp Deposits (Holocene)

Swamp deposits consist of structureless, black to brown, organic-rich, silty and clayey, fine to coarse quartz sand with thin interbeds of medium to coarse quartz sand. Organic particles consist of leaves, twigs, and larger fragments of deciduous plants in stream valleys. In stream valleys, swamp deposits fine upwards and grade laterally with salt marsh deposits toward the Delaware River. Ramsey (1997) defined swamp deposits primarily on the presence of deciduous vegetation in stream valleys. This model has been extended to the current study area. On uplands, swamp deposits consist of dark- to light-gray clayey silt and very fine to coarse sand. They are characterized by areas of seasonally standing water, internal drainage, and hydrophilic trees. The unit is from 1 to 20 feet thick.

Because of their fine-grained composition, swamp deposits function primarily as confining units. The degree to which they retard the flow of water is dependent on their thickness and degree of compaction.

Marsh and Tidal Deposits (Holocene)

Marsh deposits consist of structureless to finely laminated, black to dark-gray, organic-rich, silty clay to clayey silt with discontinuous beds of peat and rare shells (Ramsey, 1997). In-place or transported fragments of marsh grasses such as Spartina are common. The unit includes some clayey silts of estuarine channel origin. Thickness ranges between 1 and 40 feet. Marsh deposits are located primarily along the eastern edge of the study area along the Delaware Bay.

Because of their fine-grained composition, marsh and tidal deposits function primarily as confining units. The degree to which they retard the flow of water is dependent on their thickness and degree of compaction.

Undrained Depression Deposits (upper Pleistocene to lower Holocene)

A belt of upland depressions stretch across southern New Castle and northern Kent counties. These depressions, sometimes referred to as Delmarva Bays, are irregular in shape and have internal drainage not integrated with any stream network. They are filled with organic-rich, woody silts to gray medium to coarse grained quartz sand (Webb et al., 1994). Some of the depressions have a sandy rim at their margins, others do not. During wet periods, many of these depressions are filled with water. Radiocarbon dates (Webb et al., 1994) from organic-rich horizons indicate ages from 11,000 B.P. to recent.

The highly heterogeneous composition of undrained depression deposits allows them to function as both aquifer and confining unit. More permeable sandier deposits will readily transmit water (Denver, 1993) downward, whereas depressions filled with lower permeability organic, silty, and clayey deposits tend to stay wetter for longer periods of time than do depressions filled with higher permeability sandier deposits. In some depressions, water in these deposits form areally small perched water tables for portions of the year. In other depressions, water in the deposits appears to occur at the same level as the surrounding regional water table. The limited thickness and near-surface location does not permit water supply wells to be completed in these deposits.

Scotts Corners Formation (upper Pleistocene) - Columbia Aquifer

The Scotts Corners Formation is a heterogeneous unit of light-gray to brown to light-yellowish-brown, coarse to fine sand, gravelly sand and pebble gravel with rare discontinuous beds of organic-rich clayey silt, clayey silt, and pebble gravel. Sands are quartzose with some feldspar and muscovite. It is commonly capped by one to two feet of silt to fine sandy silt. Laminae of opaque heavy minerals are common. Overall thickness of the unit rarely exceeds 15 feet. The unit underlies a terrace parallel to the present Delaware River that has elevations less than 25 feet. The Scotts Corners Formation is interpreted to be a transgressive unit consisting of swamp, marsh, estuarine channel, beach, and bay deposits. Climate during the time of deposition was temperate to warm temperate as interpreted from fossil pollen assemblages (Ramsey, 1997).

The Scotts Corners Formation typically functions as part of the Columbia aquifer. Where the Scotts Corners Formation is present, the water table usually occurs in the unit because of its near-surface position. As a result, the Scotts Corners Formation has a large influence on rates and locations of ground-water recharge. Many streams are incised into or through this unit. The limited thickness, stream incision, and near-surface location does not permit water supply wells to be completed in this unit.

Lynch Heights Formation (upper Pleistocene) - Columbia Aquifer

The Lynch Heights Formation is a heterogeneous unit of light-gray to brown to light-yellowish-brown, medium to fine sand with discontinuous beds of coarse sand, gravel, silt, fine- to very fine-grained sand, and organic-rich clayey silt to silty sand. The upper part of the unit commonly consists of fine, well-sorted sand. Small-scale cross-bedding within the sands is common. Some of the interbedded clayey silts and silty sands are burrowed. Beds of shell are rarely encountered. Sands are quartzose and slightly feldspathic,

Table 2. Summary of hydraulic properties of hydrologic units.

	Columbia				Rancocas				Mount Laurel			
	Min	Mean	Max	No.	Min	Mean	Max	No.	Min	Mean	Max	No.
Transmissivity (ft^2/day)	4500	4500	4500	1	530	2098	2767	7	330	1096	5600	9
Hydraulic Conductivity (ft/day)	0.7	43	140	33	0.15	38	110	7	4.2	4.2	4.2	1
Storage Coefficient	0.003	0.003	0.003	1	0.00019	0.00044	0.0011	4	0.0001	0.001251	0.0077	7
Specific Capacity (gpm/ft)	5.8	7.8	12.1	5	0.4	4.3	9.1	5	0.4	1.5	11.4	14
	Magothy				**Potomac**				**Unknown**			
	Min	Mean	Max	No.	Min	Mean	Max	No.	Min	Mean	Max	No.
Transmissivity (ft^2/day)	410	1088	1760	8	455	2031	5350	13	N/A	N/A	N/A	N/A
Hydraulic Conductivity (ft/day)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	6.5	46	140	8
Storage Coefficient	0.000037	0.0001	0.0003	7	0.00005	0.003791	0.033	9	N/A	N/A	N/A	N/A
Specific Capacity (gpm/ft)	3	4.4	5.7	2	1.7	3.8	8	6	N/A	N/A	N/A	N/A

and typically micaceous where very fine to fine grained. The unit underlies a terrace parallel to the present Delaware River that has elevations between 50 and 30 feet. The Lynch Heights Formation is interpreted to be a fluvial to estuarine unit of fluvial channel, tidal flat, tidal channel, beach, and bay deposits (Ramsey, 1997). Overall thickness of the unit rarely exceeds 20 feet.

The Lynch Heights Formation typically functions as part of the Columbia aquifer. Where the Lynch Heights Formation is present, the water table usually occurs in the unit because of its near-surface position. As a result, the Lynch Heights Formation has a large influence on rates and locations of ground-water recharge. Many streams are incised into or through this unit. The limited thickness, stream incision, and near-surface location does not permit water supply wells to be completed in this unit.

Columbia Formation (middle Pleistocene) - Columbia Aquifer

The Columbia Formation is a yellowish- to reddish-brown, fine to coarse feldspathic quartz sand with varying amounts of gravel. It is typically cross-bedded with cross-sets ranging from a few inches to over three feet in thickness. Scattered beds of tan to reddish gray clayey silt are common. In places, the upper 5 to 25 feet of the Columbia consists of a grayish- to reddish-brown silt to very fine sand overlying medium to coarse sand. Near the base of the unit, clasts of cobble to small boulder size have been found in a gravel bed ranging from a few inches to three feet thick. The gravel fraction consists primarily of quartz with lesser amounts of chert, but clasts of sandstone, siltstone and shale from the Valley and Ridge, and pegmatite, micaceous schist, and amphibolite from the Piedmont are also present. The Columbia Formation fills an eroded surface and ranges from less than 10 feet thick to over 100 feet thick and is primarily a body of glacial outwash sediment (Jordan, 1964; Ramsey, 1997). Pollen from the clayey silt beds indicate that it was deposited in a cold climate during the middle Pleistocene (Groot and Jordan, 1999).

The Columbia Formation typically functions as part of the Columbia aquifer. Where the Columbia is present, the water table usually occurs in the unit because of its near-surface position. Because of this near-surface position, contact with streams and underlying aquifers, and permeable nature, the Columbia Formation has a large influence on rates and locations of ground-water recharge to the Columbia aquifer and to underlying aquifers; and it has a major influence on the rates and locations of ground-water discharge to streams and swamps. Many streams are incised into or through the Columbia Formation, and in some areas local relief and highly permeable sediments couple to produce ground-water depths in excess of 35 feet (Martin and Andres, 2005).

Hydrogeologic Properties of the Columbia Aquifer

The Columbia aquifer is the hydrologic unit located closest to land surface (Woodruff, 1986, 1988, 1990). It is formed from multiple geologic units that usually function together as a water-table aquifer, although the Columbia aquifer can be stratified into unconfined and confined sections. Prior to development of the C&D Canal and to pumping of ground water in the region, all fresh ground water in the study area likely began as precipitation that infiltrated into the Columbia aquifer somewhere on the Delmarva Peninsula. Most of this water flowed from topographically higher areas to streams and swamps where it discharged as stream baseflow, while some leaked downward into underlying aquifers where it flowed to more distant discharge points, most likely to the southeast in Delaware Bay or the Atlantic Ocean (Groot, 1983; Fleck and Vroblesky, 1996).

Drillhole data evaluated in this study indicate that the Columbia aquifer ranges from less than 5 ft thick to about 70 ft thick. Where the saturated thickness of the Columbia aquifer is greater than 40 feet, the aquifer is capable of yielding relatively large quantities of water to wells. In some locations, the Columbia aquifer will support domestic water supply wells where the saturated thickness is as little as 5 feet.

The results of hydraulic tests of wells finished in the Columbia aquifer are consistent with the lithologies reported for the stratigraphic units that form the aquifer. Slug tests of 33 wells (Table 2, Appendix 1) had an average hydraulic conductivity (K) of 94 ft/d with a range of 0.7 to 140 ft/d. The results of one pumping test had a transmissivity (T) of

4500 ft^2/d and a storage coefficient of 0.003. The small value of the storage coefficient indicates that the aquifer may be under partially confined conditions at the location of that test.

Subsurface Geologic Units and Hydrogeologic Properties of Confined Aquifers and Intervening Confining Beds

Beneath the Columbia aquifer are several additional aquifers that are hosted in older Coastal Plain units. The names of most of the aquifers are taken from the names of the hosting lithologic units, e.g., the Potomac, Magothy, Englishtown, and Mount Laurel aquifers. The Rancocas aquifer is hosted in two lithologic units-the Vincentown and Manasquan Formations. These aquifers receive water from the overlying Columbia aquifer.

Calvert Formation (Miocene) Confining Bed

The Calvert Formation is a gray- to grayish-brown clayey silt to silty clay interbedded with gray to light-gray silty sands, to fine-to-coarse quartz sands. Discontinuous beds of shell are common in the sands and in the clayey silts. It is interpreted to be a marine deposit (Ramsey, 2007).

Through much of Kent and Sussex counties, the Calvert Formation is hundreds of feet thick and hosts three aquifers important for water supply: the Cheswold, Federalsburg, and Frederica (McLaughlin and Velez, 2006). However, at its updip extent in southern New Castle County, the unit ranges up to about 90 feet thick and the aquifers are absent. The Calvert Formation usually functions as a confining unit and forms the base of the Columbia aquifer in southern New Castle County.

Shark River Formation (Eocene) - Confining Bed

The Shark River Formation is glauconitic clayey silt and clay, with some glauconitic sand and fine glauconitic quartz sand. It was deposited in the middle Eocene (Benson and Spoljaric, 1996). Thickness observed in drillholes range from 3 to 100 ft (this study). Based on the microfossils (unplublished DGS file data) deposition occurred in an open-shelf environment.

The Shark River Formation typically is described as fine grained and should function as a confining unit. We cannot determine if any wells are completed in this unit.

Manasquan Formation (Paleocene to Eocene) - Rancocas Aquifer and Confining Bed

The Manasquan Formation is a glauconitic silty and shelly fine sand that ranges up to about 70 ft thick (this study). Some drillers' logs indicate that the Manasquan is less silty in some locations and some wells have well screens set in the Manasquan. In these areas, we suggest that it functions as part of the Rancocas acquifer. In areas where this unit is siltier, the Manasquan likely functions as a leaky confining unit.

Vincentown Formation (Paleocene) - Rancocas Aquifer

The Vincentown Formation is a glauconitic sand that ranges from slightly silty to moderately silty and slightly to moderately clayey. The dominant constituent is subrounded to subangular clear quartz sand that ranges from medium to fine grained. Fine-grained glauconite is a secondary constituent ranging from 5 percent in the clayey zones to 15 percent where cleaner. Towards the bottom of the unit, glauconite percentages are report to be 40 to 50 percent of the sand fraction. The silty and clayey zones are thin to thick laminae ranging from 0.01 to 0.5 feet thick. Colors range from olive-gray to dark-yellowish-brown in zones where iron cement is present. It is interpreted to be marine in origin. It rarely occurs in outcrop and is covered by colluvium along the stream valley bluffs. The Vincentown Formation is a marine unit deposited in nearshore to shelf environments (Benson and Spoljaric, 1996). Sandier facies are reported to have been deposited in high energy shallow water nearshore environments (McLaughlin and Velez, 2006). Drillhole data indicate that the Vincentown ranges up to 140 feet in thickness in the subsurface (this study). Thickness is reduced in updip areas where it is cut by younger deposits. The Vincentown is approximately equivalent to the Aquia Formation of Drummond (1998) in adjacent Maryland.

The Vincentown Formation is the primary lithostratigraphic unit hosting the Rancocas aquifer. In adjacent Maryland, the same stratigraphic interval is known as the Aquia aquifer. Limited water-level data indicate that the Rancocas and Columbia aquifers likely function as a single hydrologic unit in updip locations where sandy sediments of the Vincentown and/or Manasquan Formations are in contact with the overlying Columbia, Lynch Heights, or Scotts Corners Formations. Drillhole data confirm that the Rancocas aquifer is thicker than the Vincentown Formation. In updip locations where the overlying units are thin to absent, the water table occurs within the Rancocas aquifer and receives recharge directly from precipitation and discharges ground water to streams and swamps. In some areas, it is likely that there is substantial flow of water between the Rancocas and underlying Mount Laurel aquifer. This may occur at updip locations where the underlying Hornerstown Formation is sandier and the Navesink Formation is sandier and thin (approximately 10 feet thick) although we are not aware of head measurements to support this.

Well records indicate that the Rancocas aquifer is capable of yielding as much as 300 gallons per minute (gpm) to wells. Higher well yields are usually found in wells located in downdip locations where the aquifer is located at greater depths and has greater available drawdown. The results of slug tests on seven wells (Table 2, Appendix 1) had an average K of 38 ft/d and a range of 0.15 to 110 ft/d. These slug tests were run in wells located in updip portions of the aquifer so it is not certain if these values are representative of downdip portions of the aquifer. Aquifer tests at seven locations had an average T of 2098 ft^2/d and a range of 530 to 2767 ft^2/d. The average storage coefficient from four tests is 4.4×10^{-4}. Specific capacities (Table 2, Appendix 1) range from 0.4 to 9.1 gpm/ft and average 4.3 gpm/ft. Additional measurements of hydraulic properties are needed to improve predictions of water availability from this aquifer.

Hornerstown Formation (Paleocene) - Rancocas Aquifer and Confining Bed

The Hornerstown Formation is a glauconite sand that is silty and slightly to moderately clayey with scattered shell beds. Glauconite forms approximately 90 to 95 percent of the sand fraction and quartz 5 percent to 10 percent. Near the top of the unit, silt-filled burrows are present. Lower, the unit is commonly laminated with silty sand and moderately clayey sand. The silt and clay matrix is calcareous. The color is uniformly a dark-greenish-gray. Some drillers' logs report the Hornerstown to be colored black. It is interpreted to be marine in origin. It rarely occurs in outcrop and is covered by colluvium along the stream valley bluffs. The Hornerstown ranges from less than 5 to about 55 feet thick. The Hornerstown is roughly equivalent to the Hornerstown Formation of Drummond (1998) in adjacent Maryland.

Sandier sections of the Hornerstown Formation also host the Rancocas aquifer. It functions as part of the Columbia aquifer in updip locations where it is in contact with the overlying Columbia, Lynch Heights, or Scotts Corners Formations. In some areas where the Hornerstown is composed of clean sands, the Rancocas aquifer is separated from the underlying Mount Laurel aquifer by less than 25 feet of confining beds, and so the two units may function as a single aquifer.

Navesink Formation (Upper Cretaceous) - Confining Bed

The Navesink Formation is generally a calcareous silt that is slightly to moderately sandy and slightly to moderately clayey. The sand is fine to very fine grained and is composed of about 50 percent glauconite, 40 percent peloids, and 10 percent quartz. The proportions of glauconite, quartz, and peloids vary spatially. The sediment is laminated, marked by lesser or greater amounts of clay and sand. The peloids are yellow to yellowish-brown, flat to ovoid pellets that are calcareous and may contain flakes of chitin and grains of glauconite or quartz. Scattered shell fragments are present but form a minor constituent of the sediment. The color is uniformly dark-greenish-gray and slightly lighter in color than the overlying Hornerstown Formation. Some drillers' logs describe the color of the Navesink Formation as black. The Navesink Formation is less than 5 to just over 60 feet thick (this study).

Because of the dominantly fine-grained composition of the Navesink Formation, it is likely that its primary function is that of a confining unit. Some drillers' logs report that well screens are set in sandier zones in the Navesink Formation continuing down into the underlying Mount Laurel. In these locations, the Navesink Formation is likely to be functioning as part of the Mount Laurel aquifer or as part of the combined Mount Laurel-Rancocas aquifer.

Mount Laurel Formation (Upper Cretaceous) - Mount Laurel Aquifer

The Mount Laurel Formation is a slightly calcareous, glauconitic, quartz sand that is medium to fine grained. The sand is subrounded to subangular and slightly silty with a few moderately silty zones. Scattered belemnites are present as well as a few scattered shell fragments or thin shell beds. The color is a uniform dark-olive-gray or yellowish-brown where weathered. Many drillers' logs describe the Mount Laurel Formation as "salt and pepper" sand with the salt being the quartz grains and pepper being the glauconite. In outcrop, the Mount Laurel Formation is reported to be extensively burrowed. Where it is the surficial deposit south of the C&D Canal, the Mount Laurel Formation can be confused with the Columbia Formation, especially where the color of the two units is similar. They can be differentiated by the ubiquitous presence of glauconite and generally better sorting of sands of the Mount Laurel Formation. The Mount Laurel Formation is marine in origin and the sandier beds forming the more productive portions of the aquifer are reported to have been deposited in high-energy shallow water nearshore to shoreface environments (McLaughlin and Velez, 2006).

The Mount Laurel Formation is the primary unit hosting the Mount Laurel aquifer. In adjacent Maryland, the same stratigraphic interval is known as the Matawan aquifer. The Mount Laurel Formation and Columbia aquifers function as a single hydrologic unit in updip locations where sandy sediments of the Mount Laurel Formation are in contact with the overlying Columbia, Lynch Heights, or Scotts Corners Formations. In updip locations where the overlying units are thin to absent, the water table occurs within the Mount Laurel Formation and receives recharge directly from precipitation and discharges ground water to streams and swamps.

The Mount Laurel aquifer is a fair to good aquifer with maximum well yields reported to be approximately 400 gpm. Transmissivities from pumping tests in nine wells have an average of 1100 ft^2/d and a range of 330 to 5600 ft^2/d (Table 2, Appendix 1). Storage coefficients from seven tests have an average of 1.2×10^{-3} and range from 1×10^{-4} to 7.7×10^{-3} Specific capacities from 14 locations average 1.5 gpm/ft and range from 0.4 to 11.4 gpm/ft. Additional measurements of hydraulic properties are needed to improve predictions of water availability from this aquifer.

Marshalltown Formation (Upper Cretaceous) - Confining Bed

The Marshalltown Formation is a greenish-gray, slightly silty, fine-grained glauconitic quartz sand with glauconite comprising 30 to 40 percent of the sand fraction. It ranges from less than 5 to 110 feet in thickness (this study). The unit is extensively burrowed. The Marshalltown Formation is interpreted to be marine in origin.

The silty character of the Marshalltown Formation causes its likely primary function to be that of a leaky confining unit. Head measurements are not adequate to quantify the amount of leakage to overlying and underlying units although it is likely that the leakage rate is greater where the unit is thinner and sandier.

Englishtown Formation (Upper Cretaceous) - Englishtown Aquifer to Confining Bed

The Englishtown Formation is a light-gray to white, micaceous, slightly silty to silty, fine-grained, slightly glauconitic quartz sand. In outcrop, it is extensively burrowed with *Ophiomorpha* burrows. Distinction of the Englishtown Formation from overlying and underlying units is difficult on a majority of descriptive logs because all are described as green, silty sand. The Englishtown Formation ranges from less than 5 to about 75 feet in thickness (this study). It is interpreted to be nearshore marine to tidal flat in origin at its updip limit along the C&D Canal and deposited in lower-energy deeper water environments downdip in southernmost New Castle and Kent counties (Benson and Spoljaric, 1996). In these down-dip areas the Englishtown Formation is much finer grained and is not used for water supply.

Sands in the Englishtown Formation function as an aquifer (Woodruff, 1990), commonly referred to as the Englishtown aquifer. Because it is relatively thin (5 to 34 ft thick) and somewhat silty the Englishtown is a poor aquifer, yielding minor quantities (< 20 gpm) of water to wells. In limited areas where the overlying Marshalltown Formation is sandier, a few higher capacity irrigation wells are screened through the Mount Laurel, Marshalltown, and Englishtown Formations. The Englishtown aquifer is thought to function as a confined aquifer in updip areas where the Englishtown Formation is sandier or part of a leaky confined aquifer system in the study area.

Merchantville Formation (Upper Cretaceous) - Confining Bed

The Merchantville Formation is a light- to dark-gray, very micaceous, glauconitic, very silty, fine to very fine grained sand to fine sandy silt. The Merchantville Formation ranges from less than 5 to more than 200 feet in thickness (this study) with the unit thickening toward the south. The Merchantville Formation is marine in origin. The Merchantville Formation is thought to function as a leaky confining layer (Woodruff, 1990).

Magothy Formation (Upper Cretaceous) - Magothy Aquifer

The Magothy Formation is a dark-gray to gray silty clay to clayey silt that contains abundant fragments of lignite that grades downward into a very fine to fine sand with scattered and discontinuous thin beds of clayey silt with lignite fragments. Thickness of the unit is spatially variable and ranges from 15 to about 85 feet (this study). Updip in the vicinity of the C&D Canal, the Magothy aquifer fills channels incised into the Potomac Formation and is discontinuous in its extent. It is interpreted to have been deposited in coastal to nearshore environments.

Because the Magothy Formation has a heterogeneous composition and variable thickness, the Magothy aquifer ranges from a fair to good aquifer. Observed thicknesses of the aquifer ranges from 5 to 56 ft. Thicker and sandier zones of the Magothy aquifer are capable of yielding more than 100 gpm to wells. Most wells using the Magothy aquifer are located north of Middletown. Specific capacities from two wells (Table 2, Appendix 1) range from 3 to 5.7 gpm/ft. Transmissivities (Table 2, Appendix 1) from eight tests average 1100 ft^2/d and range from 410 to 1760 ft^2/d. Storage coefficients from seven tests average 1.0×10^{-4} and range from 3.7×10^{-5} to 3×10^{-4}, indicating that the Magothy aquifer functions as confined aquifer in the study area.

Heavy pumping by water supply wells located north of the C&D Canal in Delaware and in New Jersey and Maryland has lowered the potentiometric surface in the Magothy aquifer south of the canal (Otton et al., 1988; Rosman et al., 1995 Lacombe and Rosman, 2001).

Potomac Formation (Lower to Upper Cretaceous)

The Potomac Formation is a dark red, gray, pink, and white silty clay to clayey silt with very fine to medium sand beds. Beds of gray clayey silt to very fine sand that contain pieces of charcoal and lignite are common. It was deposited in a fluvial setting in a tropical to subtropical environment as indicated by abundant paleosol horizons within the formation. The Potomac Formation ranges from over 500 feet in the northwestern portion of the study area to over 1600 feet thick in southern New Castle County.

Fine-grained beds in the Potomac Formation function as confining units. Within the study area, areally and vertically discontinuous sandy beds function as important confined aquifers. Hydraulic connections between individual aquifers are not always predictable, even over short lateral and vertical distances. Where thicker and more extensive, the aquifers in the upper portions of the Potomac Formation are capable of yielding more than 300 gpm to wells. Specific capacities from six wells (Table 2, Appendix 1) in the upper portion of the unit range from 1.7 to 8 gpm/ft and average 3.8 gpm/ft. Transmissivities from 13 tests range from 455 to 5350 ft^2/day and average 2031 ft^2/d. Storage coefficients from 9 tests average 3.8×10^{-3} and range from 5×10^{-5} to 3.3×10^{-2} indicating that the Potomac aquifers function as confined aquifers in the study area.

Heavy pumping by many water supply wells located north of the C&D Canal in Delaware and in New Jersey and Maryland has lowered the potentiometric surface in the Potomac aquifers in the study area (Otton et al., 1988; Rosman et al., 1995; Lacombe and Rosman, 2001).

Because of the significant thickness of this unit and the high cost of drilling to deeper aquifer levels, there are relatively few geologic and hydrologic observations of the deeper Potomac south of the C&D Canal compared to the younger and shallower units. Most of what is known about the Potomac aquifer comes from wells drilled north of the canal and a few wells in the northern portion of the study area and in adjacent Maryland and New Jersey. In fact, data from drillhole Gd33-04 (circa 1960) located in southeastern New Castle County, provides the only information about this unit in the southern half of the study area.

The scant data listed above are inadequate to accurately characterize this extremely important water resource in the study area. It is reasonable to expect that the Potomac is capable of yielding large quantities of water to properly located and designed wells. It is also likely that aquifers in the Potomac, where they are saturated with saline water (total dissolved solids >10,000 mg/L) could accept large quantities of wastewater. However, estimates of the safe yield of this unit or its suitability for waste-water disposal are speculative and adequate planning for potential locations of supply or injection wells would require significant additional subsurface data and analysis.

Computation of Three-Dimensional Geometries of Lithostratigraphic, Aquifer, and Confining Beds

In this discussion, we are describing the results of modeling three-dimensional geometries of hydrostratigraphic units. The results are expressed as a series of grid-based maps (Figs. 11-26, Plates 2 and 3) of surfaces and volumes. It is important to recognize that these grids are estimates of the actual surfaces. Software to create lattice, or voxel-based solid conformal models was not available for this study.

In general, computed models of the three-dimensional (3-D) geometries of solids are highly sensitive to the spatial distribution of data and the variability of those data from point to point (Davis, 1986). There are many data points for shallow depths and fewer data for greater depths. Quality geophysical and descriptive geologist logs, though thought to provide reliable data for lithostratigraphic picks, are relatively sparsely distributed throughout the study area. Also challenging is a lack of definitive paleontologic data, reducing the certainty of many of the lithostratigraphic picks. Descriptive logs from well completion reports supplement these data and provide better overall spatial coverage; however, the lower accuracy of picks made on these data undoubtedly adds an unknown but significant degree of error.

These data-variability and error issues had significant impacts on the methods used to compute the 3-D geometries. The gridding algorithms used for this study were LPR trend-surface estimators supplemented by hand-contouring. Hand-contouring was used to extend the grids into areas of sparse data. The grids estimated using this algorithm represent the lithostratigraphic contacts as complex but smoothly dipping surfaces (Figs. 11 - 19, Plate 2). These grids are thought to be most representative of the actual surfaces because the Cretaceous and Tertiary lithostratigraphic units in the study area are thought to have been deposited in shallow- to moderate-depth marine shelf environments (Benson and Spoljaric, 1996; McLaughlin and Velez, 2006). Point kriging methods, because they heavily weight the closest data points, tended to result in very irregular or dimpled surfaces; therefore, they were not used for these maps. The sizes of the dimples appear to be more closely related to density of data points rather than to any geologic trends.

A local weighting factor of 50 to 75 percent used in the LPR algorithm reproduced some local scale variability in elevations of surfaces and thicknesses of units but did smooth the grids relative to the point data. Comparison of point statistics and surface statistics (Table 3) show the effects of spatial clustering of point data at shallower depths and extrapolation of grids southward (lower elevations) beyond the extent of data; that is, minimum and average grid values are much more negative than point values, and grid and point maxima show closer agreement. These results indicate that the grids likely do not provide highly accurate predictions of geologic horizon elevations in areas of sparse data.

One of the primary uses of the grids is for input to numerical and conceptual ground-water flow models and flow analysis. In these studies, lithostratigraphic units are commonly grouped into hydrologic units by spatial proximity and similar hydraulic characteristics (Anderson and Woessner, 1992). For example, two sandy aquifer units that are in direct contact would typically be combined into one aquifer. Table 4 shows the conceptual model of grouping lithostratigraphic units into 11 hydrologic units by their hydraulic properties and spatial distributions. Because most units have heterogeneous compositions, the distinction between aquifer and confining unit designations does not hold for all areas; hence, some units appear in both the aquifer and confining unit columns.

Because of the general correlation of lithostratigraphic with hydrologic units, there is general correspondence between the structure contour maps of lithostratigraphic units (Figs. 11 - 19, Plate 2) with hydrologic units (Figs. 20 - 25, Plate 3). The Englishtown Formation and aquifer (Figs. 18, Plate 2, and 24 - 25, Plate 3) are problematic in that the Englishtown Formation can typically be recognized in geophysical and descriptive logs, and thus mapped; however, it is not possible to determine if the Englishtown Formation actually functions as an aquifer throughout most of the study area. Because of extremely limited data, maps of the Magothy and Potomac Formations and aquifers are not shown.

The inverse relationship between thickness of the Columbia aquifer (Fig. 26, Plate 3) and land-surface topography is indicated by the correspondence of modern stream valleys with areas of thin aquifer. The Columbia aquifer is absent along many of the valleys of the streams tributary to the Delaware River. The thickness of the Columbia aquifer as computed by the difference between the DEMs of land surface and the base of the aquifer (about 120 ft) far exceeds the maximum thickness observed in drillhole data (about 70 ft) whereas the maximum gridded thickness is about 120 ft. The discrepancy appears to be an artifact of the gridding process.

Limitations of the Solids Models

Analysis of the grids resulted in refinement of the 3-D mapping rules that are generally described in the methods section (Fig. 3). Enforcement of these rules corrected a vast majority of the problems in the resultant grids. Gridding software computes individual grids according to mathematical equations and conditions; it does not use rules and procedures typically used by geologists. As a result, the computed grids need to be conditioned to follow geologic rules (Fig. 3). Because the shallower lithostratigraphic units incorporated more picks with higher confidence, the gridded aquifers and geologic units were conditioned to the aforementioned rules from land surface downward. Grid analysis resulted in the following refinements to the 3-D mapping rules.

(1) Areal extents of units and aquifers are limited to areas determined by drillhole (pick) data. Because of high extrapolation errors, areas outside the pick domain were initially set to null, then they were assigned elevations interpreted from hand-drawn contours derived from regional-scale maps.

(2) Aquifers occur within the specified lithostratigraphic units. All aquifer-bearing units were-buffered by 15 feet in the vertical direction. This rule reflects cases (locations) where geologic units that typically function as confining units are sandier and function as part of the primary aquifer. The 15-ft buffer allows for spatially variable (e.g. noisy data) and sparsely distributed observations.

Table 3. Statistical summaries of LPR grid and point data for confined aquifers. The negative values in the differences between mean point and mean grid values show that the point data are clustered at higher elevations, whereas the grid data are distributed throughout the map area. Only tops are shown for lithostratigraphic units.

Lithostratigraphic Units

Grid Data	Calvert	Shark River	Manasquan	Vincentown	Hornerstown	Mt. Laurel	Marshalltown	Englishtown	Merchantville
No. of active grid cells:	79	220	464	504	496	632	699	752	1426
Minimum Elevation:	-24	-160	-423	-433	-437	-557	-638	-693	-1392
Maximum Elevation:	54	59	40	70	58	74	60	58	39
Mean Elevation:	15	-50.5	-191.5	-181.5	-189.5	-241.5	-289	-317.5	-673.512623
Standard Deviation:	22.803509	63.507874	133.944951	145.491981	143.182576	182.442457	201.783713	217.083509	411.672464
Mean of grid-point elevations	-11.568417	-62.047346	-160.79922	-173.61243	-152.54035	-203.551563	-220.05161	-245.79708	-626.415941
Point Data									
Count:	139	260	244	490	258	371	155	137	211
Minimum Elevation:	-13	-111	-235	-263	-369	-705	-462	-493	-532
Maximum Elevation:	70.5	65	60	65.2	58.7	66	53	65	67
Mean Elevation:	26.568417	11.547346	-30.700779	-7.887571	-36.959651	-37.948437	-68.948387	-71.70292	-47.096682
Standard Deviation:	17.316144	42.776328	59.713434	58.452676	74.67887	91.592912	104.566986	114.820166	111.041582

Aquifer Units

Grid Data	Rancocas (top)	Rancocas (bottom)	Mt. Laurel (top)	Mt. Laurel (bottom)	Englishtown (top)	Englishtown (bottom)
No. of active grid cells:	553	500	631	722	816	946
Minimum Elevation:	-487	-452	-542	-653	-762	-895
Maximum Elevation:	66	47	88	68	53	51
Mean Elevation:	-210.001808	-202.5	-227	-292.5	-354.5	-421.501057
Standard Deviation:	159.64022	144.337279	182.153781	208.423247	235.558733	273.088356
Mean of grid-point elevations	-263.479267	-138.8698	-189.87652	-200.78942	-248.84808	-299.733749
Point Data						
Count:	488	488	310	310	52	52
Minimum Elevation:	2	-362	-369	-487	-493	-530
Maximum Elevation:	173	43	71	45	8	3
Mean Elevation:	53.477459	-63.630205	-37.123484	-91.710581	-105.65192	-121.767308
Standard Deviation:	33.689617	71.6353872	71.597599	81.4071452	137.623597	143.7110605

Table 4. Groupings of lithostratigraphic units for ground-water modeling. Parentheses indicate units that function as both aquifer and confining units. Names (shown in brackets) for several of the confining units identify the areas where those confining units are best developed.

Lithostratigraphic Units	Aquifer	Confining	Notes
dredge disposal, swamp, marsh, tidal flat, tidal channel, alluvium		1	Leaky confining unit
Scotts Corners, Lynch Heights, Columbia	Columbia		
Calvert, Shark River, Manasquan		2 [Blackbird]	
(Manasquan), Vincentown, (Hornerstown)	Rancocas		
Hornerstown, Navesink		3 [Armstrong]	
Mt. Laurel, (Marshalltown)	Mt. Laurel		
Marshalltown, Englishtown, Merchantville	(Englishtown- poor to fair aquifer)	4 [Summit]	Leaky confining unit
Magothy	Magothy		
Potomac C	Potomac	5	Leaky confining unit to excellent aquifer

Table 5. Statistics describing differences between observed and predicted surface elevations (residuals).

Unit	Statistic	Picks	Grids	Residual All Data	Residual Drillers' Log Data	Residual Geophysical Log Data
Calvert (Tc)	Count:	139	79	92	54	38
	Minimum:	-13.00	-24.00	-27.15	-27.15	-20.50
	Maximum:	70.50	54.00	23.15	20.12	23.15
	Sum:	3693.01	1185.00	-35.47	43.66	-79.12
	Mean:	26.57	15.00	-0.39	0.81	-2.08
	Standard Deviation:	17.32	22.80	9.50	9.61	9.06
Shark River (Tsr)	Count:	260	220	213	131	82
	Minimum:	-111.00	-160.00	-74.17	-74.17	-51.78
	Maximum:	65.00	59.00	34.45	34.45	26.41
	Sum:	3002.31	-11110.00	-23.93	-15.47	-8.47
	Mean:	11.55	-50.50	-0.11	-0.12	-0.10
	Standard Deviation:	42.78	63.51	13.49	13.76	13.03
Manasquan (Tmq)	Count:	244	464	195	147	48
	Minimum:	-235.00	-423.00	-88.55	-88.55	-20.27
	Maximum:	60.00	40.00	92.19	92.19	39.60
	Sum:	-7490.99	-88856.00	-16.41	-145.64	129.23
	Mean:	-30.70	-191.50	-0.08	-0.99	2.69
	Standard Deviation:	59.71	133.94	16.25	17.48	11.27
Vincentown (Tv)	Count:	490	504	481	291	190
	Minimum:	-263.00	-433.00	-71.35	-71.35	-26.07
	Maximum:	65.20	70.00	92.33	92.33	50.08
	Sum:	-3864.91	-91476.00	-42.18	-33.99	-8.19
	Mean:	-7.89	-181.50	-0.09	-0.12	-0.04
	Standard Deviation:	58.45	145.49	13.99	14.30	13.50
Hornerstown (Th)	Count:	258	496	249	157	92
	Minimum:	-369.00	-437.00	-54.07	-46.99	-54.07
	Maximum:	58.70	58.00	51.28	42.09	51.28
	Sum:	-9535.59	-93992.00	38.29	-18.51	56.81
	Mean:	-36.96	-189.50	0.15	-0.12	0.62
	Standard Deviation:	74.68	143.18	13.85	13.27	14.79
Mt. Laurel (Kml)	Count:	371	632	357	213	144
	Minimum:	-705.00	-557.00	-73.87	-73.87	-38.57
	Maximum:	66.00	74.00	41.37	29.84	41.37
	Sum:	-14078.87	-152628.00	-142.82	30.32	-173.14
	Mean:	-37.95	-241.50	-0.40	0.14	-1.20
	Standard Deviation:	91.59	182.44	12.88	13.41	12.02
Marshalltown (Kmt)	Count:	155	699	141	38	103
	Minimum:	-462.00	-638.00	-70.70	-35.91	-70.70
	Maximum:	53.00	60.00	26.78	26.20	26.78
	Sum:	-10687.00	-202011.00	-146.84	-186.13	39.29
	Mean:	-68.95	-289.00	-1.04	-4.90	0.38
	Standard Deviation:	104.57	201.78	15.07	15.41	14.69
Englishtown (Ket)	Count:	137	752	115	26	89
	Minimum:	-493.00	-693.00	-71.30	-38.81	-71.30
	Maximum:	65.00	58.00	33.08	33.08	29.98
	Sum:	-9823.30	-238760.00	-20.20	-39.33	19.13
	Mean:	-71.70	-317.50	-0.18	-1.51	0.21
	Standard Deviation:	114.82	217.08	13.83	14.75	13.53
Merchantville (Kmvt)	Count:	211	1426	133	41	92
	Minimum:	-532.00	-1392.00	-478.41	-478.41	-186.19
	Maximum:	67.00	39.00	36.95	36.95	33.36
	Sum:	-9937.40	-960429.00	-1202.38	-1174.67	-27.70
	Mean:	-47.10	-673.51	-9.04	-28.65	-0.30
	Standard Deviation:	111.04	411.67	62.14	103.20	24.28

(3) Rules applied to the geologic units follow basic laws of superposition. The rules ensure a surface from an older unit does not overlie a younger surface. For example, the top of the Hornerstown Formation is conditioned to be at the base of Vincentown Formation The same rule was applied to all surfaces with elevations above land surface; in this case, the land surface elevation would be considered the elevation of the formation top. Due to gridding extrapolation, the bottom of a unit may be projected above the top of the same unit. In this extreme case, the elevation of the unit's base was conditioned to be 5 feet below the elevation of the top of that same unit, honoring its existence. Where needed, 5 feet was also applied to corresponding aquifer surfaces. The 5-ft value allows for some noise data. It is noted that application of this rule can lead to a problematic interpretation in which a grid-predicted unit is absent at a location but is present when well-log picks are made.

In terms of goodness-of-fit between pick data and the grids, means of residuals for each surface are close to 0 (Table 5), which is a direct result of using a least-squares trend fitting algorithm. The magnitudes of minimum and maximum absolute residuals tend to be larger for the older (and deeper) units. These errors are likely due to having fewer data to work with from these units and the resultant error caused by extrapolation.

Means of residuals (Table 5) for grids generated from descriptive log data and geophysical log data subsets are similar by t-test analysis although comparison of these subsets by one-way analysis of variance indicates that they have different variances. The differences between minimum and maximum residuals and standard deviations (square-root of variance) of the descriptive log subset are larger than those for the geophysical log subset (Table 5), which suggests that the descriptive log subset is noisier than the geophysical log subset. Ideally we would use only the lower variance or lower noise data. However, the spatial distribution of geophysical logs does not adequately cover the study area.

The spatial distributions of residuals for groups of surfaces and individual surfaces do not indicate consistent spatial clustering of residuals between surfaces (Figs. 27 - 28). The locations where multiple surfaces have consistently larger residuals are where future test drilling work is necessary for improving the accuracy of the estimated elevation of surfaces.

Additional Uses of the Grids

The grids can be used to compute the vertical distance between aquifers and thus help to assess the connectivity of aquifers. For example, in areas where the Rancocas aquifer intersects the Columbia aquifer (Fig. 29), it is clear that the Rancocas and Columbia function as a single aquifer. Figure 29 also indicates that the Mount Laurel Formation and Mount Laurel aquifer intersect the Columbia aquifer. It is highly likely that the areas where deeper aquifer units intersect the Columbia aquifer there is increased recharge to the deeper aquifers.

There also are areas where the confining unit between the Rancocas and Mount Laurel aquifer is relatively thin, in some areas less than 25 ft (Fig. 30). It is likely the two aquifers have a higher degree of connectivity in these areas; however, without data on hydraulic properties of the confining unit, it is not possible to assess the degree of connectivity. This area is partially coincident with the areas of intersection of the Rancocas and Mount Laurel aquifers with the Columbia aquifer (Fig. 29). There is a high probability of greater well yields in this area and also a high probability that contaminants added to the Columbia aquifer will migrate quickly into the underlying aquifers.

The grids have been compared to well completion records to assign wells to the appropriate aquifer from which they are pumping water. In this analysis the midpoint elevation of well screens of more than 85 percent of wells occurs between the top and bottom of an aquifer. This proportion increases to over 95 percent when a 10 ft buffer is applied to the top and bottom elevations of the aquifers. These findings reflect the same factors that affect residuals between pick data and grids.

Additional Data Needs

Deep drillholes and data on aquifer hydraulics and water quality are especially sparse in the southern part of southern New Castle County. Eight sites are recommended from which to collect these data (Fig. 31). Four drillholes into the lower Potomac Formation would greatly improve our understanding of the spatial geometries of deep aquifers in the Magothy and Potomac Formations and intervening confining units (Fig. 31, locations 1-4). Installation of multi-level observation wells in these drillholes would allow us to assess all of the aquifers present at each location. Observation wells in the Potomac aquifers would provide an opportunity to assess the suitability of deep aquifers for water supply, or to determine if these deeper aquifers contain salty water and thus pose a threat to wells in the northern part of southern New Castle County.

This work has also highlighted the problems caused by inaccurate and erroneous locational data. Locational data include both the surface position and the depths to the different horizons. This problem is certainly responsible for some of what we have labeled noise in the dataset. More accurate positions and depths would likely improve the efficiency and accuracy of the gridding and grid-conditioning processes.

CONCLUSIONS

Our review of data confirms previously published reports that state the geologic units that host the best producing aquifers are the Columbia, Vincentown, Mount Laurel, Magothy, and Potomac Formations. It should be noted that these units are heterogeneous and, as a result, are not highly permeable throughout their areal and vertical extents. The Manasquan, Hornerstown, and Englishtown Formations also function as aquifers in some locations. The

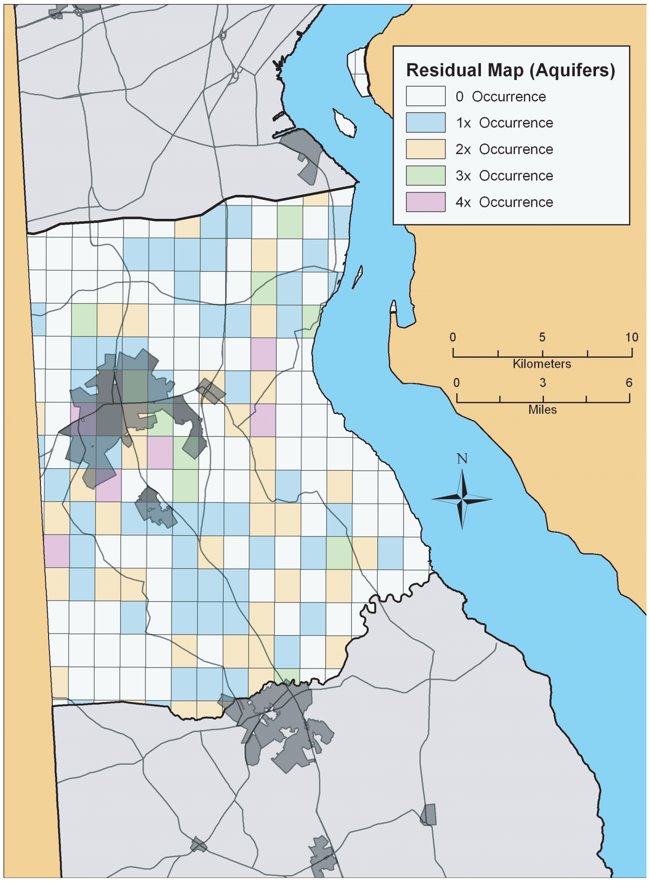


Figure 27. Summary of residuals (observed top - predicted top) within DGS 1-minute blocks for all aquifer units. The colors represent the number of surfaces in each one-minute block that have average residuals less than -10 ft or greater than 10 ft. Blocks having larger numbers are locations where the estimated surfaces fit the pick data poorly. This can indicate noisy data, erroneous picks, or unanticipated geologic trends. There are no apparent spatial trends in the distribution of residuals.

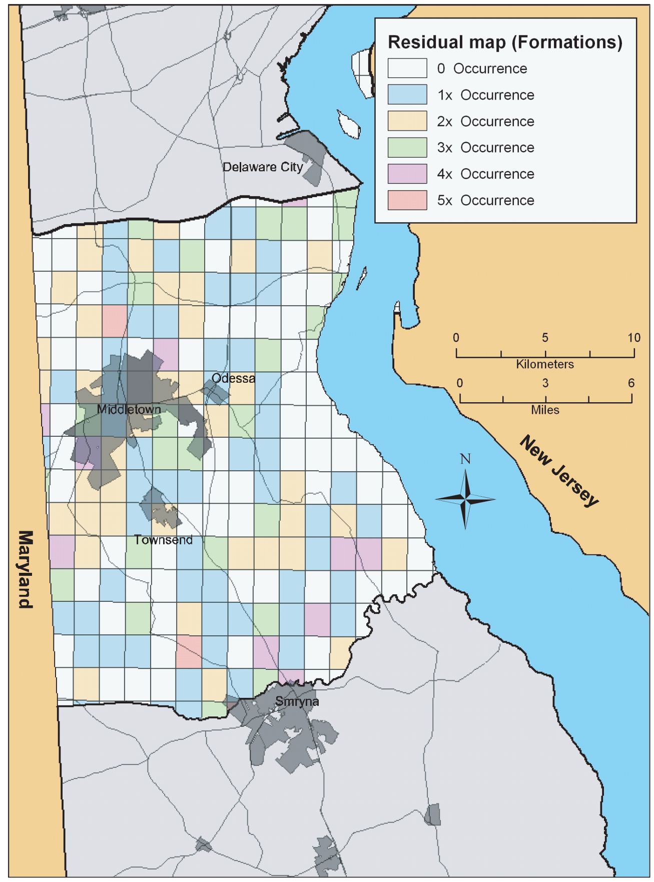


Figure 28. Summary of residuals (observed top - predicted top) for all lithostratigraphic units. The colors represent the number of surfaces in each one-minute block that have average residuals less than -10 ft or greater than 10 ft. Blocks having larger numbers are locations where the estimated surfaces fit the pick data poorly. This can indicate noisy data, erroneous picks, or unanticipated geologic trends. There are no apparent spatial trends in the distribution of residuals.

Calvert, Navesink, Merchantville, and Marshalltown Formations usually function as confining beds. These units are heterogeneous and, as a result, may yield enough water to wells to serve as a domestic supply in some areas. These geologic units or their age-equivalents are present in adjacent Maryland and New Jersey.

The grids produced in this project are useful, though rough, proxies for actual surfaces. They are better than older, hand-contoured maps primarily because of the rules used to condition the grids and the addition of numerous new observations. The conditioning rules minimize the occurrence of improperly intersecting geologic and physiographic horizons. The addition of new observations provides an improved understanding of the compositions of geologic units and updated interpretation of their hydrologic properties.

Grids of hydrologic unit properties are key data for use in ground-water models, water-resource evaluations, and resource planning. The grids can be used to identify areas where aquifers intersect and thus provide enhanced probability of greater well yields. They also can be used to locate thin confining units and thus indicate where confined aquifers may potentially be recharged.

Data are fairly noisy and the noise (residuals) are caused by a combination of multiple factors: uneven and sparse spatial distribution of data, data location errors, errors in identification of geologic and hydrologic horizons, possibly by unrecognized geologic features (e.g., structures (Andres, 2001) and/or facies changes (McLaughlin and Velez, 2006), and use of overly simplistic surface models. Because of these problems, the grids will not be released as published digital products until additional data are available to improve their quality; however, the grids will be available on request to interested users.

Review of the data and grids and characterization of residuals highlight the need for additional test drilling and geophysical logging in the southern part of county. Drilling sites include 4 locations targeted to the base of the Mount Laurel Formation and 4 locations targeted to aquifers in the Potomac Formation. Hydraulic data are sparse and indicate the need for additional hydraulic testing of the confined aquifers. Such tests should include pumpingtests with multiple observation wells and single well aquifer tests. The recommended sites for test drilling are located in areas where monitoring wells should be installed.

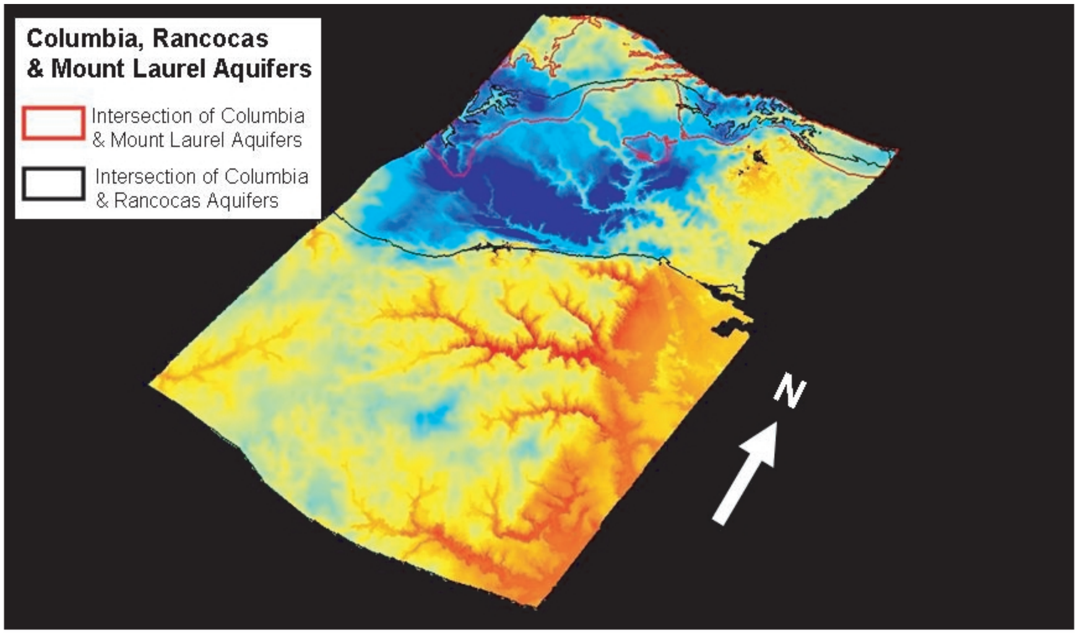


Figure 29. Oblique view of areas where Columbia aquifer intersects the Rancocas and Mt. Laurel aquifers. The illustration was rendered in ArcScene. Color ramps on the surfaces indicate thicknesses of the aquifers.

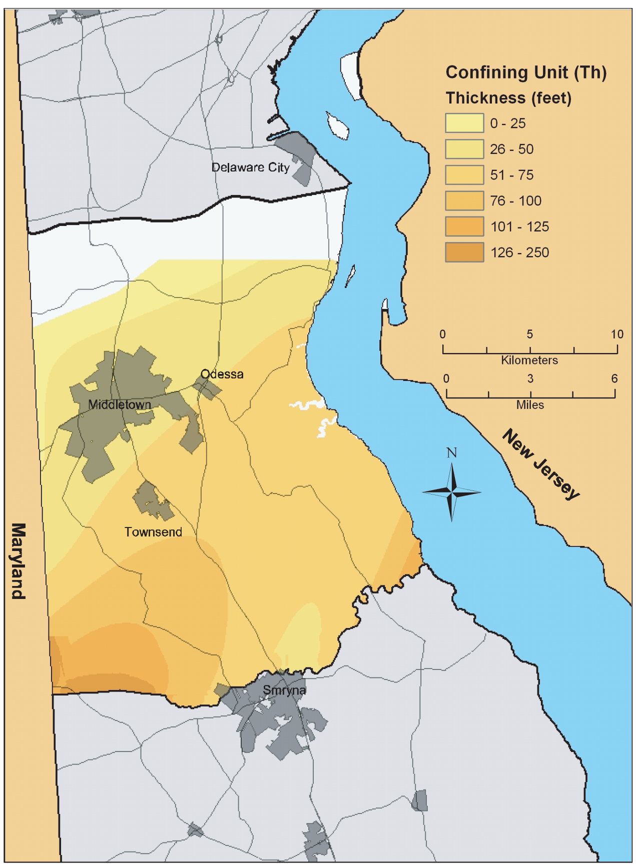


Figure 30. Thickness of the confining unit between the Mt. Laurel and Rancocas aquifers. There is an increased potential for connection between the aquifers in areas where the thickness is less than 25 ft.

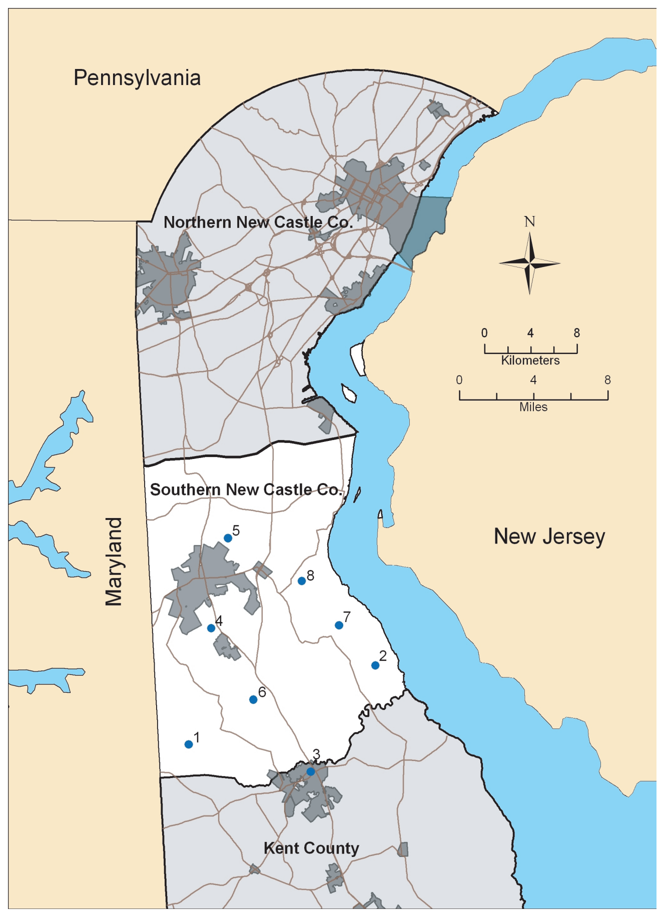


Figure 31. Map showing locations where additional drillholes and monitoring wells should be installed: (1) Blackbird State Forest (headquarters), (2) Woodland Beach Wildlife Area, (3) Smyrna-Clayton (Town property), (4) Wiggins Mill Park. Drillholes and observation wells should also be installed in the Mt. Laurel and Rancocas aquifers at four additional areas: (5) Water Farm 2, (6) Blackbird Forest Tybouts Tract, (7) Cedar Swamp Wildlife Area, and (8) Odessa National Country Club.

REFERENCES CITED

Andres, A. S., 2001, Geohydrology of the Smyrna-Clayton area, Delaware: Delaware Geological Survey Hydrologic Map Series No. 10, 1:24,000.

Anderson, M. P., and Woessner, W. W., 1992, Applied groundwater modeling: San Diego, CA, Academic Press, Inc., 381 p.

Bachman, L. J., and Ferrari, M. J., 1995, Quality and geochemistry of ground water in southern New Castle County, Delaware: Delaware Geological Survey Report of Investigations No. 52, 31 p.

Bachman, L. J., and Wilson, J. M., 1984, The Columbia aquifer of the eastern shore of Maryland: Maryland Geological Survey Report of Investigations No. 40, 144 p.

Baxter, S. J., and Talley, J. H., 1996, Design, development, and implementation of a ground-water quality monitoring network for southern New Castle County, Delaware, Phase II - Evaluation of ground-water availability: Delaware Geological Survey unpublished report to New Castle County Department of Public Works, 47 p.

Benson, R. N., 2006, Internal Stratigraphic Correlation of the Subsurface Potomac Formation, New Castle County, Delaware and Adjacent Areas in Maryland and New Jersey: Delaware Geological Survey Report of Investigations No. 71, 15 p. and 3 plates.

Benson, R. N., and Spoljaric, N., 1996, Stratigraphy of the post-Potomac Cretaceous-Tertiary rocks of central Delaware: Delaware Geological Survey Bulletin 20, 28 p.

Davis, J. C., 1986, Statistics and data analysis in geology, 2nd edition, New York, John Wiley and Sons, Inc., 646 p.

Delaware Water Supply Coordinating Council, 2006, Ninth annual report to the Governor and the General Assembly, 29 p.

Denver, J. M., 1993, Herbicides in shallow ground water at two agricultural sites in Delaware: Delaware Geological Survey Report of Investigations No.51, 28 p.

Drummond, D. D., 1998, Hydrogeology, simulation of ground-water flow, and ground-water quality of the upper Coastal Plain aquifers in Kent County, Maryland: Maryland Geological Survey Report of Investigations No. 68, 76 p.

ESRI, 2004, ArcMap v. 9.1 and 9.2: Redlands, CA.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater, Englewood Cliffs, NJ, Prentice-Hall, Inc. 604 p.

Fleck, W. B., and Vroblesky, D. A., 1996, Simulation of ground-water flow of the Coastal Plain aquifers in parts of Maryland, Delaware, and the District of Columbia, 41 p.

Golden Software, 2005, Grapher v. 7: Golden CO.

Groot, J. J., 1983, Salinity distribution and ground-water circulation beneath the Coastal Plain of Delaware and the adjacent Continental Shelf: Delaware Geological Survey Open-File Report No. 26, 24 p.

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, 41 p.

Hurd, M., 1998, Water demand trends and future water needs, New Castle County, Delaware: Dover, DE, Delaware Department of Natural Resources and Environmental Control.

Jordan, R. R., 1964, Columbia (Pleistocene) deposits of Delaware: Delaware Geological Survey Bulletin 12, 69 p.

Lacombe, P. J., and Rosman, R., 2001, Water levels in, extent of freshwater in, and water withdrawls from ten confined aquifers, New Jersey and Delaware coastal plain, 1998, Water-Resources Investigation Report 00-4143, 10 sheets.

Martin, M. M., 1984, Simulated ground-water flow in the Potomac aquifers, New Castle County, Delaware: U.S. Geological Survey Water-Resources Investigation Report 84-4007, 85 p.

Martin, M. J., and Andres, A. S., 2005, Digital water-table data for New Castle County, Delaware: Delaware Geological Survey Digital Product DP05-04, ESRI grid format.

Mackenzie, John, 1999, Watershed delineation project, alpha data release: www.udel.edu/FREC/spatlab/basins/

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.

Otton, E.G., Willey, R.E., McGregor, R.A., Achmad, G., Hiortdahl, S.N., and Gerhart, J.M., 1988, Water resources and estimated effects of ground-water development, Cecil County, Maryland: Maryland Geological Survey Bulletin 34, 133 p.

Phillips, S. W., 1987, Hydrogeology, degradation of ground-water quality, and simulation of infiltration from the Delaware River into the Potomac aquifers, northern Delaware: U.S. Geological Survey Water-Resources Investigation Report 87-4185, 86 p.

Ramsey, K. W., 1997, Geology of the Milford and Mispillion River quadrangles: Delaware Geological Survey Report of Investigations No. 55, 40 p.

___2005, Geologic map of New Castle County, Delaware: Delaware Geological Survey Geologic Map Series No. 13, 1:100,000.

___2007, Geologic map of Kent County, Delaware: Delaware Geological Survey Geologic Map Series No. 14, 1:100,000.

Rasmussen, W. C., Groot, J. J., and Beamer, N. H., 1958, Wells for the observation of chloride and water levels in aquifers that cross the Chesapeake and Delaware Canal: Delaware Geological Survey Report of Investigations No. 3, 22 p.

Rosman, R, Lacombe, P. J., and Storck, D. A., 1995, Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1988: U.S. Geological Survey Water-Resources Investigations Report 95-4060, 74 p.

Sundstrom, R. W., and Pickett, T. E., 1971, The availability of ground water in New Castle County, Delaware: Water Resources Center, University of Delaware, 156 p.

U.S. Army Corps of Engineers, 2007, Updated draft ground-water model production run report Upper New Castle County, Delaware: Philadelphia, PA, U.S. Army Corps of Engineers, 25 p.

Vroblesky, D. A., and Fleck, W. B., 1991, Hydrogeologic framework of the Coastal Plain of Maryland, Delaware, and the District of Columbia, as developed for the Northern Atlantic Regional Aquifer Systems Analysis (RASA), U.S. Geological Survey, 45 p.

Webb, R. S., Newby, P., and Webb, T., 1994, Palynology and paleohydrolgy of Delaware, in Kellogg, D. C., and Custer, J. F., eds., Paleoenvironmental studies of the State Route 1 corridor: contexts for prehistoric settlement, New Castle and Kent counties, Delaware: Delaware Department of Transportation Archeology Series No. 114, p. 36-47.

Woodruff, K. D., 1986, Geohydrology of the Chesapeake and Delaware Canal area, Delaware, Sheet 1, basic geology: Delaware Geological Survey Hydrologic Map Series No. 6, 1:24,000.

___1988, Geohydrology of the Chesapeake and Delaware Canal area, Delaware, Sheet 2, thickness of confining unit beneath the water-table aquifer: Delaware Geological Survey Hydrologic Map Series No. 6, 1:24,000.

___1990, Geohydrology of the Middletown-Odessa area, Sheet 1, basic geology and hydrology: Delaware Geological Survey Hydrologic Map Series No. 8, 1:24,000.

Wolff, E. A., 2007, unpublished report to the Undergraduate Internship Program, Delaware Water Resources Center, University of Delaware, 27 p.

Zapecza, O. S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain, Regional Aquifer-System Analysis—northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p.

APPENDIX 1. Hydraulic Properties Data

DGSID	TOP OF SCREEN (FT BLS)	BOTTOM OF SCREEN (FT BLS)	AQUIFER	TEST DATE (yymm dd)	WELL TYPE	DISCHARGE (GPM)	DURATION (HOURS)	DATA SOURCE	ANALYSIS METHOD	HYDRAULIC CONDUC-TIVITY (FT/D)	TRANS-MISSIVITY (FT-SQ/D)	STORAGE COEF-FICIENT	SPECIFIC CAPACITY (GPM/FT)	MAP INDEX
Ea33 -01	580	585	pt	660930	P	250	1	R	OT				2.6	1
Ea44 -12	85	105	m	950607	O	127	9.5	G	TD		900	0.0003		2
Ea45 -05	670	705	pt	980713	P	584	71.5	R	OT		2675		8	3
Eb15 -04	510	541	pt	551021	P	400	0	R	OT		2575		1.7	4
Eb33 -40	14	24	cl	060801				G	BR	47				5
Eb33 -41	31	40	cl	060801				G	BR	25				6
Eb33 -42	19	29	cl	060801				G	BR	55				7
Eb33 -43	19	29	cl	060801				G	BR	40				8
Eb33 -44	10	20	cl	060803				G	BR	61				9
Eb33 -45	22	32	cl	060801				G	BR	33				10
Eb33 -46	12	22	cl	060613				G	BR	50				11
Eb44 -10	355	370	pt	751001	O	250	47	S	OT		660	0.000096		12
Eb45 -09	330	380	pt	751001	O	250	47	S	OT		960	0.00007		13
Eb45 -10	344	384	pt	751001	O	250	47	S	OT		1140	0.000095		14
Eb51 -11	161	177	m	950516	O	74	14	G	TD		690	0.000085		15
Eb51 -13	161	176	m	950516	O	74	14	G	TD		410	0.000085		16
Eb55 -08	400	420	m	940117	O	250	72	G	TD		800	0.000058		27
Eb55 -09	400	420	m	940117	O	250	72	G	TD		860	0.000037		28
Ec51 -16	80	95	ml	950509	O	40	6	G	TD		440	0.0077		29
Ec52 -07	73	116	ml	780621	P	20	6	N	OT				0.7	20
Ec52 -08	73.5	121	ml	780715	P	30	5	N	OT				1.1	21
Ec52 -21	55	60	ml	950322	O	107	24	G	TD		710	0.0001		22
Ec52 -22	40	120	ml		P	250	5	N	OT				11.4	23
Ec52 -24	424	454	pt	950110	O	466	72	R	CJ		5350	0.00052		24
Ec52 -25	400	450	pt	950110	O	466	72	R	CJ		4250	0.000081		25
Fa15 -06	190	210	m	950613	O	92	8	G	TD		1620	0.000068		26
Fa15 -07	190	210	m	950613	O	92	8	G	TD		1660	0.000069		27
Fa45 -10	15	30	cl	060707				G	BR	32				28
Fa55 -07	20	105	cl		P	75	6	D	OT				6.2	30
Fa55 -08	20	105	cl		P	75	6	D	OT				6.8	31
Fa55 -10	20	105	cl		P	60	5	D	OT				5.8	32
Fa55 -12	15.5	30.5	cl	060724				G	BR	30				33

Key to abbreviations:
BLS - below land surface; GPM - gallons per minute
Aquifer: cl - Columbia; ml - Mt. Laurel; pt - Potomac; ptu - upper Potomac; m - Rancocas; U - uncertain
Well Type: P - pumping; O - observation
Data Source: D - driller; G - DGS; N - DNREC; R - other reported; S - USGS
Analysis Method: BR - Bouwer and Rice; CJ - Cooper-Jacob straight line; OT - Other; TD - Theis drawdown; TR - Theis recovery; TM - Theis modified
Storage Coefficient column also reports Specific Yield for wells in the Columbia aquifer
Specific Capacity is measured as gallons per minute per foot of drawdown

APPENDIX 1. Hydraulic Properties Data

DGSID	TOP OF SCREEN (FT BLS)	BOTTOM OF SCREEN (FT BLS)	AQUIFER	TEST DATE (yymmdd)	WELL TYPE	DISCHARGE (GPM)	DURATION (HOURS)	DATA SOURCE	ANALYSIS METHOD	HYDRAULIC CONDUCTIVITY (FT/D)	TRANSMISSIVITY (FT-SQ/D)	STORAGE COEFFICIENT	SPECIFIC CAPACITY (GPM/FT)	MAP INDEX
Fb11-07	512	537	pt	960903	P	350	72	R	CJ		880		3.7	34
Fb11-08	213	238	pt	960909	P	412	8	N	OT				5.3	35
Fb11-09	830	870	m	980727	P	474	72	R	TR		1760		5.7	36
Fb14-12	415	435	pt	931108	O	250	73	G	TD		1010	0.000076		37
Fb14-13	418	438	pt	931108	O	250	73	G	TD		960	0.00013		38
Fb23-32	5	20	U	060609				G	BR	6.5				39
Fb23-33	23	38	U	060808				G	BR	22				40
Fb23-34	15	30	U	060808				G	BR	22				41
Fb24-06	106	160	ml	950405	O	39	24	G	TD		330	0.0001		42
Fb32-07	4	19	U	060609				G	BR	24				43
Fb32-08	5	20	U	060609				G	BR	42				44
Fb33-02	470	493	m	990101	P	90	0	R	OT				3	45
Fb33-22	460	536	ptu	770711	O	52	3.5	G	TR		4734	0.033		46
Fb33-27	20	35	U	060808				G	BR	29				47
Fb33-28	5	20	U	060712				G	BR	84				48
Fb33-29	4	19	U	060712				G	BR	140				49
Fb34-17	64	74	cl	700507	O	70	24	G	TD		4500	0.003		50
Fb34-23	606	626	pt	970603	P	285	71.5	R	TR		455		1.7	51
Fb41-12	15	30	cl	060613				G	BR	18				52
Fb41-13	14	29	cl	060606				G	BR	73				53
Fb41-14	9	24	cl	060606				G	BR	83				54
Fb42-02	134	226	ml	610419	O	80	49	G	TD		360	0.00028		55
Fb42-17	12	27	cl	060726				G	BR	28				56
Fb42-18	10	25	cl	060606				G	BR	62				57
Fb51-16	3	18	cl	060606				G	BR	110				58
Fb51-17	17.5	32.5	cl	060606				G	BR	79				59
Fb51-18	13	28	cl	060726				G	BR	25				60
Fb51-19	11	26	cl	060724				G	BR	51				61
Fb51-20	15	30	cl	060724				G	BR	39				62
Fb51-21	11	26	cl	060726				G	BR	140				63
Fb51-22	8	23	cl	060606				G	BR	110				64
Fb51-23	10	25	cl	060712				G	BR	8.7				65
Fc12-07	84	122	ml	801113	P	20	4	N	OT				0.4	66

Key to abbreviations:
BLS - below land surface; GPM - gallons per minute
Aquifer: cl - Columbia; ml - Mt. Laurel; pt - Potomac; ptu - upper Potomac; m - Rancocas; U - uncertain
Well Type: P - pumping; O - observation
Data Source: D - driller; G - DGS; N - DNREC; R - other reported, S - USGS
Analysis Method: BR - Bouwer and Rice; CJ - Cooper-Jacob straight line; OT - Other; TD - Theis drawdown; TR - Theis recovery; TM - Theis modified
Storage Coefficient column also reports Specific Yield for wells in the Columbia aquifer
Specific Capacity is measured as gallons per minute per foot of drawdown

APPENDIX 1. Hydraulic Properties Data

DGSID	TOP OF SCREEN (FT BLS)	BOTTOM OF SCREEN (FT BLS)	AQUIFER	TEST DATE (yymm dd)	WELL TYPE	DISCHARGE (GPM)	DURATION (HOURS)	DATA SOURCE	ANALYSIS METHOD	HYDRAULIC CONDUC - TIVITY (FT/D)	TRANS- MISSIVITY (FT-SQ D)	STORAGE COEF - FICIENT	SPECIFIC CAPACITY (GPM/FT)	MAP INDEX
Fe12 -08	78.6	122	ml	801204	P	20	3	N	OT				0.4	67
Fe12 -09	110	120	ml	810123	P	15	3	N	OT				0.4	68
Fe12 -10	103	113	ml	810127	P	20	3	N	OT				0.6	69
Fe12 -11	110	120	ml	810228	P	20	2	N	OT				0.6	70
Fe12 -12	108	118	ml	850216	P	20	1.5	N	OT				0.4	71
Fe12 -16	100	160	ml	950322	O	107	24	G	TD		740	0.00014		72
Fe12 -22	130	160	ml	950202	O	80	24	G	TD		360	0.00028		73
Fe13 -06	74	120	ml	780623	P	20	5	N	OT				0.6	74
Fe13 -07	74	120	ml	780708	P	25	6	N	OT				0.7	75
Fe15 -06	130	150	ml	940117	O	246	72	G	TD		815	0.00016		76
Fe32 -08	30	45	rn	060816				G	BR	17				77
Fe32 -09	64	69	rn	060707				G	BR	0.15				78
Fe32 -10	5	20	cl	060707				G	BR	14				79
Fe32 -13	55	65	cl	060822				G	BR	23				80
Fe42 -09	34	44	rn	060822				G	BR	40				81
Fe42 -11	220	260	ml	061109				G	BR	31				82
Fe42 -15	35	50	rn	060816				G	BR	41				83
Fe42 -21	37	47	rn	060816				G	BR	51				84
Fe42 -23	40	50	rn	060822				G	BR	7.1				85
Fe42 -24	25	35	rn	060822				G	BR	110				86
Fe42 -25	5	15	cl	060707				G	BR	62				87
Fe42 -31	180	230	ml	010723	P	75	6	N	OT				0.6	88
Fe43 -04	200	270	ml	970208	P	238	72	R	TR		505		1.6	89
Fe51 -26	650	770	pt	940808	O	425	72	R	TD		760	0.00005		90
Ga25 -08	31	141	rn	030317	P	102	4	D	OT				3.7	91
Gb11 -11	10	25	cl	060712				G	BR	13				92
Gb11 -12	10	25	cl	060803				G	BR	44				93
Gb11 -13	14	29	cl	060712				G	BR	13				94
Gb11 -14	14	29	cl	060608				G	BR	14				95

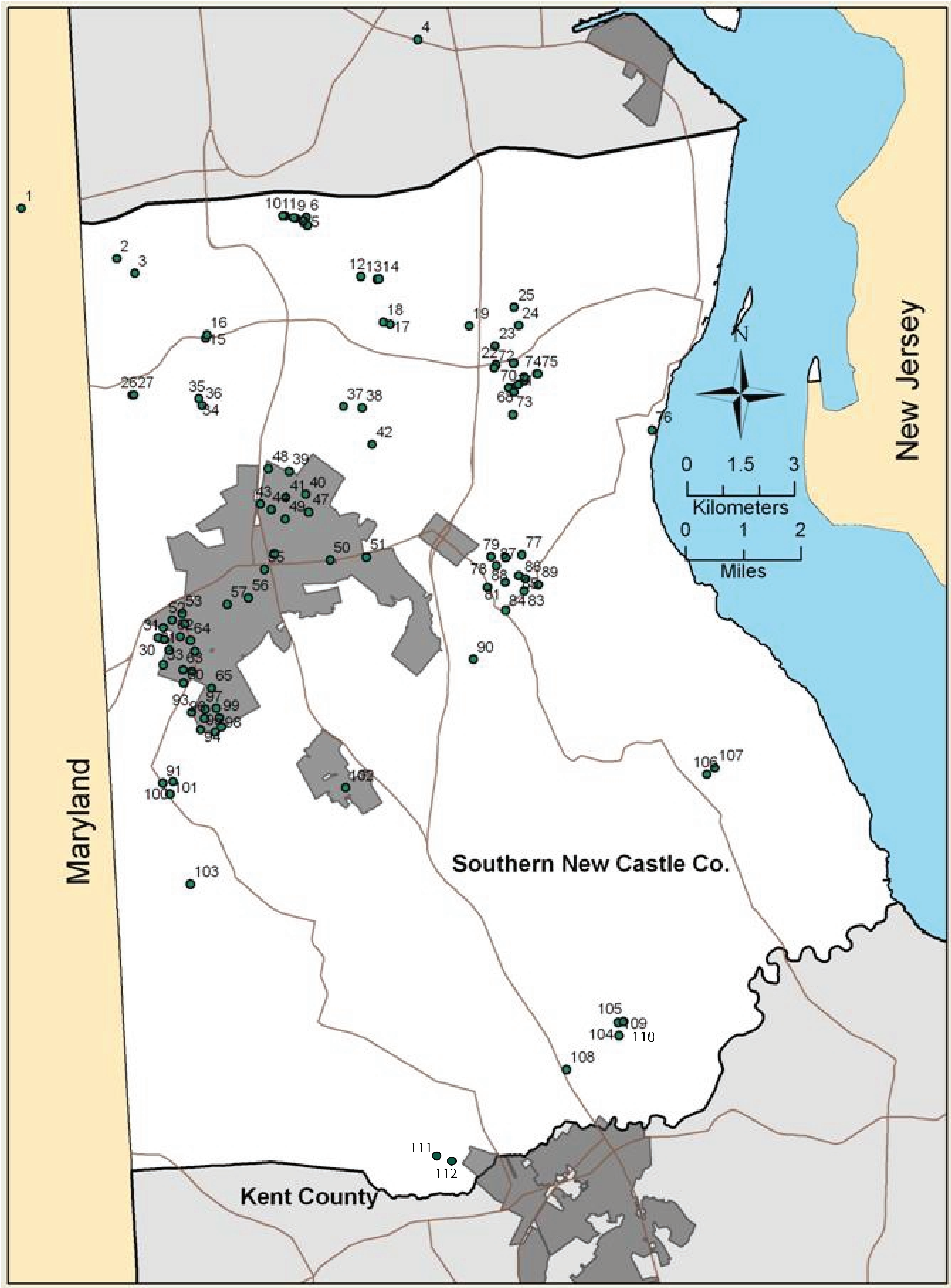
Key to abbreviations:
BLS - below land surface; GPM - gallons per minute
Aquifer: cl - Columbia; ml - Mt. Laurel; pt - Potomac; ptu - upper Potomac; rn - Rancocas; U - uncertain
Well Type: P - pumping; O - observation
Data Source: D - driller; G - DGS; N - DNREC; R - other reported; S - USGS
Analysis Method: BR - Bouwer and Rice; CJ - Cooper-Jacob straight line; OT - Other; TD - Theis drawdown; TR - Theis recovery; TM - Theis modified
Storage Coefficient column also reports Specific Yield for wells in the Columbia aquifer
Specific Capacity is measured as gallons per minute per foot of drawdown

APPENDIX 1. Hydraulic Properties Data

DGSID	TOP OF SCREEN (FT BLS)	BOTTOM OF SCREEN (FT BLS)	AQUIFER	TEST DATE (yymmdd)	WELL TYPE	DISCHARGE (GPM)	DURATION (HOURS)	DATA SOURCE	ANALYSIS METHOD	HYDRAULIC CONDUC-TIVITY (FT/D)	TRANS-MISSIVITY (FT-SQ/D)	STORAGE COEF-FICIENT	SPECIFIC CAPACITY (GPM/FT)	MAP INDEX
Gb11-15	12.5	27.5	cl	060724				G	BR	28				96
Gb11-16	13	28	cl	060724				G	BR	4.1				97
Gb12-12	10	25	cl	060608				G	BR	0.7				98
Gb12-13	10	25	cl	060608				G	BR	4				99
Gb21-14	20	138	cl	980422	P	319	4	D	OT				12.1	100
Gb21-16	20	138	cl	980427	P	299	4	D	OT				8.1	101
Gb24-19	85	155	rn	040110	P	247	24	N	OT				9.1	102
Gb31-05	120	140	rn	940401	O	175	72	G	CJ		1520	0.0011		103
Gc54-02	225.8	247.8	rn	670328	O	500	12	S	TM		2550	0.0002		104
Gc54-03	159	247	rn	670328	O	500	12	S	TM		2570	0.00027		105
Gd21-07	60	120	rn	971030	P	300	8.3	D	TD		2767			106
Gd21-08	-	134	rn	971107	P	300	5.5	D	TD		2510		7.7	107
Hc13-02	175	210	rn	660930	P	150	24	G	CJ		530			108
Hc14-03	188	268	rn	950607	O	-	-	S	TM		2240	0.00019		109
Hc14-17	415	465	ml		P	400	72	R	CJ		5600		2.0	110
Hc21-02	170	200	rn	790703	P	20	5	N	OT				0.4	111
Hc22-05	165	175	rn	820323	P	35	1.5	N	OT			0.00019	0.7	112

Key to abbreviations:
BLS - below land surface; GPM - gallons per minute
Aquifer: cl - Columbia; ml - Mt. Laurel; pt - Potomac; ptu - upper Potomac; rn - Rancocas; U - uncertain
Well Type: P - pumping; O - observation
Data Source: D - driller; G - DGS; N - DNREC; R - other reported; S - USGS
Analysis Method: BR - Bouwer and Rice; CJ - Cooper-Jacob straight line; OT - Other, TD - Theis drawdown; TR - Theis recovery; TM - Theis modified
Storage Coefficient column also reports Specific Yield for wells in the Columbia aquifer
Specific Capacity is measured as gallons per minute per foot of drawdown

APPENDIX 2. Map of Hydraulic Data Point Locations.



Delaware Geological Survey
University of Delaware
Newark, Delaware 19716