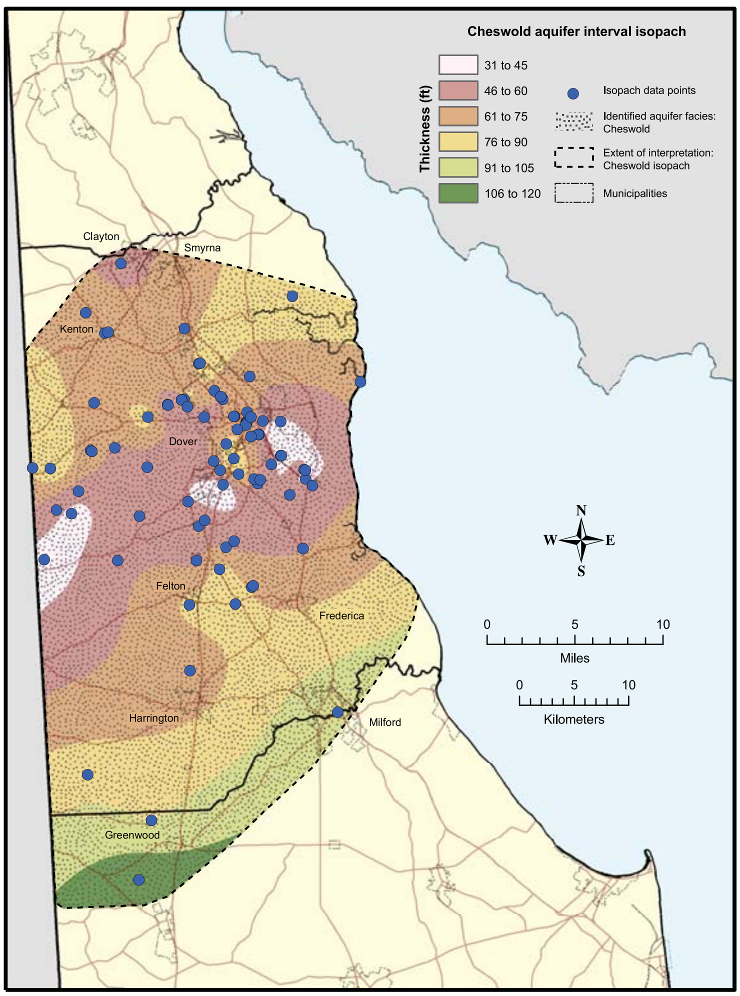
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 72

GEOLOGY AND EXTENT OF THE CONFINED AQUIFERS OF KENT COUNTY, DELAWARE

By

Peter P. McLaughlin and Claudia C. Velez



University of Delaware
Newark, Delaware
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ABSTRACT

Ground water comprises nearly all of the water supply in Kent County, Delaware. The confined aquifers of the area are an important part of this resource base. The aim of this study is to provide an up-to-date geologic framework for the confined aquifers of Kent County, with a focus on their stratigraphy and correlation.

Seven confined aquifers are used for water supply in Kent County. All occur at progressively greater depths south-southeastward, paralleling the overall dip of the sedimentary section that underlies the state. The two geologically oldest, the Mount Laurel and Rancocas aquifers, are normally reached by drilling only in the northern part of the county. The Mount Laurel aquifer is an Upper Cretaceous marine shelf deposit composed of clean quartz sands that are commonly glauconitic. It occurs at around 300 ft below sea level in the Smyrna-Clayton area and is typically just less than 100 ft thick. Southward, toward Dover, it passes into fine-grained facies that do not yield significant ground water. The Rancocas aquifer is a Paleocene to Eocene marine unit of shelf deposits consisting of glauconite-rich sands with shells and hard layers. It occurs as high as 100 ft below sea level in northwestern Kent County and deepens southeastward, rapidly changing facies to finer-grained, non-aquifer lithologies in the same direction.

The Piney Point aquifer lies above these units, and is a middle Eocene, coarsening-upward, shelly, glauconitic, quartz sand deposited in a shelf environment. It is an entirely confined aquifer that is recharged via vertical leakage through overlying units. It ranges from around 250 ft below sea level in the Dover area to more than 600 ft below sea level in southeastern Kent County. It includes more than 200 ft of aquifer sand in south-central and southern Kent County but is progressively truncated to the north-northwest by a basal Miocene unconformity. As a result, only the lower muddy portion of the Piney Point is present in northern Kent County, limiting its use as an aquifer.

The overlying Miocene section is characterized by alternation between sands and muds. Four aquifers are developed in the sands: upward, these are the Cheswold, Federalsburg, Frederica, and Milford. Each of the four sands represents the culmination of a shallowing-upward succession of shallow-marine to coastal deposits. The Cheswold aquifer is a quartz sand that is shelly in places. From near-surface occurrences in northern Kent County, it deepens to more than 400 ft below sea level in southeastern Kent County. It ranges from 30 to 120 ft thick, with an overall trend of thickening to the southeast as well as some locally significant thickness variations. The overlying Federalsburg aquifer is a similar shallow-marine sand deposit, in places more than 60 ft thick but more commonly includes thinner or muddier, lower aquifer quality sands. It occurs from the Dover area south, descending to more than 350 ft below sea level in southeastern Kent County. The Frederica aquifer occurs as far north as the Dover area and deepens to more than 250 ft below sea level in the Milford area. It is commonly around 50 ft thick. The Milford aquifer occurs in the southernmost part of Kent County. It is typically around 50 ft thick and is found as deep as 200 ft below sea level in the Milford area. In some previous studies, Milford aquifer sands were identified as the Frederica aquifer. In general, estuarine facies are more typical in the northern extent of each of the four Miocene aquifers, and shoreface facies are more typical further south in the county. In most areas, these aquifers are separated by thin but distinct, fine-grained confining layers; however, in some areas these fine-grained intervals are absent or appear to be too thin or coarse-grained to be effective confining layers.

INTRODUCTION

Ground water is an essential natural resource for the residents of Kent County, Delaware. Aquifers are the sole source of drinking water in southern Delaware, and they supply water for local industries and irrigation. Population growth, development, and changing land-use practices have resulted in increasing demands for water. Water use has increased in Kent County from 6.5 million gallons/day in 1955 to 31 million gallons/day in 2000 (Sundstrom and Pickett, 1968; Wheeler, 2000). At the same time, these changes increase the impact of human activities on the quality of the ground water available in the area, especially in the unconfined aquifer and shallow confined aquifers.

Eight aquifers are used for water supply in Kent County (Fig. 1); the Columbia aquifer is the unconfined aquifer of the area, and the Milford, Frederica, Federalsburg, Cheswold, Piney Point, Rancocas, and Mount Laurel are the confined aquifers. A sound understanding of the geology of these aquifers is increasingly important for management of ground-water resources. The last comprehensive report on ground-water availability in Kent County and the aquifer systems that supply it was published more than 35 years ago (Sundstrom and Pickett, 1968). A few smaller-scale studies have been published since then, including modeling studies of the unconfined aquifer system in Kent County (Johnston, 1977) and the confined Cheswold and Piney Point aquifers in the Dover area (Leahy, 1976, 1979, 1982). However, more recent comprehensive studies of the confined aquifers of Kent County are lacking.

The goal of this project is to establish an up-to-date geological framework for the confined aquifers of Kent County and to define their areal extent. Available well and borehole data were analyzed to delineate the stratigraphy of the Upper Cretaceous to Miocene section, which contains the confined aquifers known in Kent County. Geological cross sections have been constructed that highlight the correlation of confined aquifers, confining layers, and their stratigraphic equivalents. Derivative structural contour and isopach maps have been assembled for the seven stratigraphic intervals in which confined aquifers are developed; these intervals include the aquifers, per se, as well as stratigraphically equivalent levels with non-aquifer facies. The geological characteristics of each of these stratigraphic units are also assessed to improve understanding of the genetic factors controlling the nature and distribution of aquifer-quality facies in the county.

Data collection for this study resulted in the evaluation of a considerable volume of subsurface data that advances the understanding of confined aquifers over the previously published studies. The focus of the study was wireline geophysical log information that could be used to evaluate the depth, thickness, and geological characteristics of confined aquifers. Geologists' and drillers' logs of lithologies were also analyzed, where available. All available geophysical log data were compiled (Fig. 2), their quality assessed, and updated or edited as needed. An important element of this project was the acquisition of new data in areas where geological control was lacking; additional data, such as new geophysical logs, is essential to ensuring that the geological framework has value beyond that of the existing compilations.

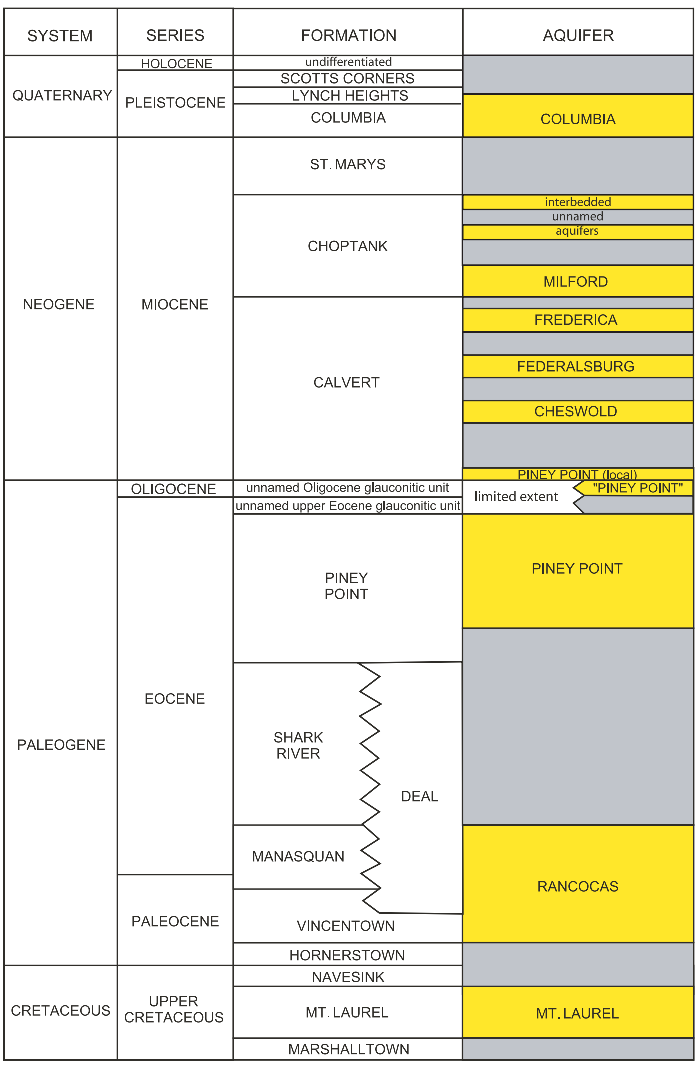

Figure 1. Kent County lithostratigraphy/hydrostratigraphy chart. The aquifers of Kent County range from Upper Cretaceous to Quaternary. This chart summarizes the names of the aquifers, the formations in which they occur, and their chronostratigraphic position

The scope of this report covers presentation of the new cross-sections and maps, the methodology used to construct them, and the implications of these findings for our understanding of aquifer distribution and quality. These products will provide useful technical documentation for agencies involved in water-resource management as well as for citizens, agriculture, and businesses that rely on confined aquifers for their water supply.

Previous Work

The first comprehensive treatment of the aquifers of Kent County was included in a report covering the geology and ground water of Delaware by Marine and Rasmussen (1955). They recognized three confined aquifers: an Eocene aquifer used in Clayton, a deeper Miocene sand used between Smyrna and Dover, and a shallower Miocene sand used between Dover and Milford.

Two later reports on the water resources of neighboring counties provided new information on aquifers that are also used in Kent County. Rasmussen et al. (1960) examined the water resources of Sussex County. They reported that the Frederica aquifer was part of the Choptank Formation and a source of ground water in the Milford area. Rima et al. (1964) focused on southern New Castle County. Their report summarized the geological and hydrological characteristics of aquifers in the "Monmouth Formation" (which includes the Mount Laurel aquifer) and the "Rancocas Formation" and provided depth maps of the bottom and top of these units.

Rasmussen et al. (1966) updated the aquifer framework of Kent County and summarized the hydrological characteristics of each aquifer. The Aquia-Vincentown designation was applied to the Eocene aquifers recognized in northern Kent County. The Piney Point designation was used for the Eocene sands that they considered likely to become an important ground-water source in southern Kent County. The name Cheswold aquifer was applied to the deeper Miocene sand recognized in Marine and Rasmussen (1955), and the name Frederica aquifer to the shallower Miocene sand.

The last comprehensive study of ground-water supplies and aquifers to focus specifically on Kent County was Sundstrom and Pickett (1968). That report included maps of aquifer depth and thickness for three confined aquifers: Piney Point, Cheswold, and Frederica. However, those maps were based on sparse data in many parts of the county. Since then, numerous DGS reports have treated discrete parts of the Kent County hydrostratigraphic framework, but no systematic re-study has been done.

The confined aquifers of Kent County received an updated treatment as part of a study of the water resources of Delmarva by Cushing et al. (1973). It provided additional information on the Aquia-Rancocas, Piney Point, Cheswold, and Frederica aquifers and documented an additional aquifer in the Miocene section, the Federalsburg aquifer. It summarized water usage, aquifer characteristics, water quality, and area of potential use for each aquifer, and it provided maps of the depth, thickness, potentiometric surface, and chemical quality of ground water for each.

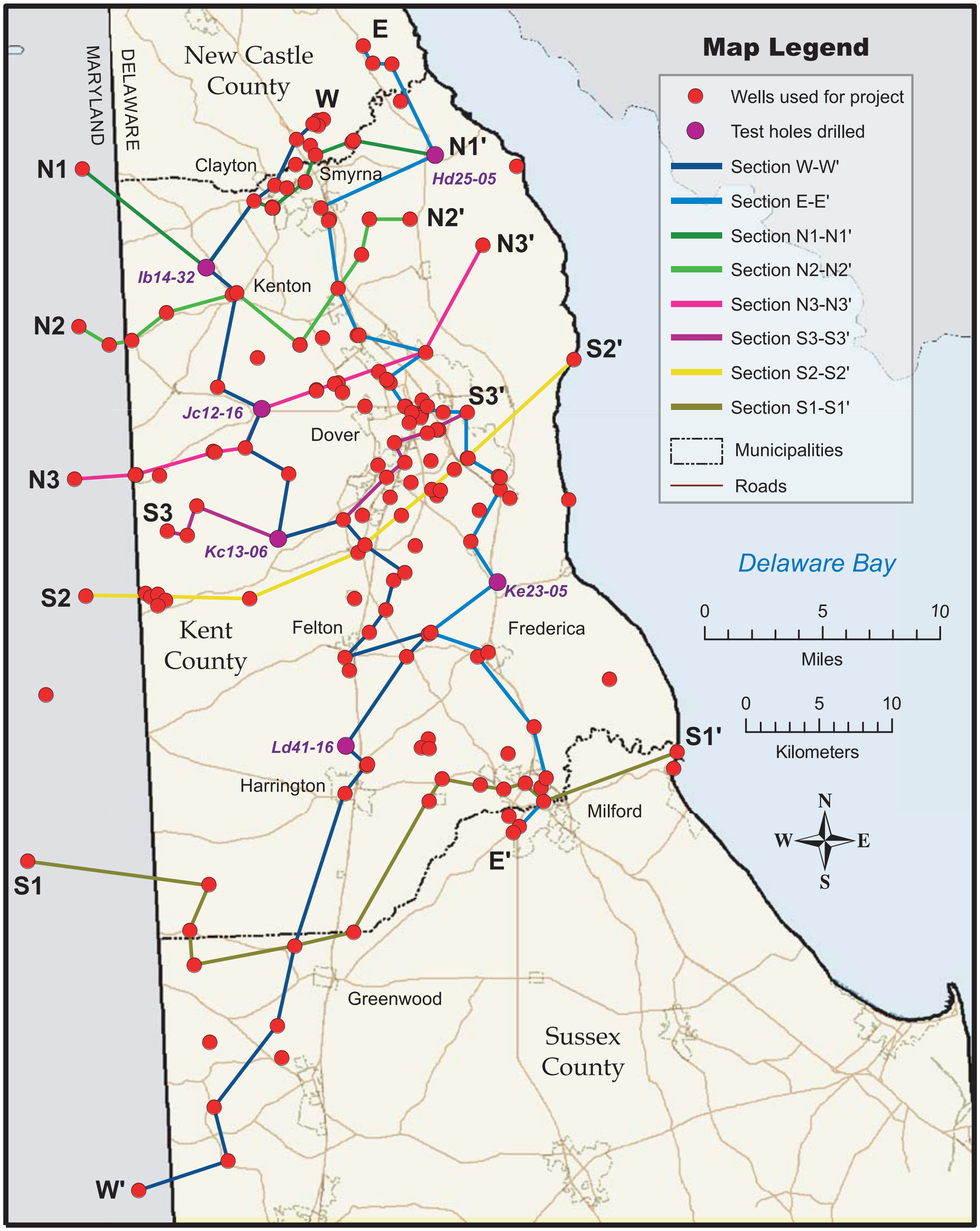

Figure 2. Kent County well and cross section location base map. Geophysical logs were utilized from numerous existing deep wells (depth > 200 ft) for this project, including sites in nearby areas of Maryland, northernmost Sussex County, and southernmost New Castle County. Six test holes were drilled and logged. Eight cross-sections were constructed using selected wells to show stratigraphic relationships along strike (west-east cross sections) and dip (north-south cross sections) directions.

Our study takes advantage of the understanding developed in these previous studies and updates it, based on a considerable amount of more recent data. Our goal is to combine this knowledge with new stratigraphic concepts to more clearly define the geology and distribution of the confined aquifers of Kent County.

Acknowledgments

This study was undertaken with the financial support of the Water Supply Section, Division of Water Resources, Delaware Department of Natural Resources and Environmental Control (DNREC). We gratefully acknowledge the support of John T. Barndt, Program Manager. Drilling and equipment expenses were also partially defrayed by the Delaware Geological Survey; we also gratefully acknowledge John H. Talley for supporting the cost of additional drilling. Reviews of several preliminary versions of this report by Peter J. Sugarman (New Jersey Geological Survey), Richard N. Benson (DGS), Stefanie J. Baxter (DGS), John T. Barndt (DNREC), Stewart Lovell (DNREC), and Scott A. Strohmeier (DNREC) considerably improved the content. Field assistance at the well sites was provided by Paul S. McCreary, Jr. (DGS), Kelvin W. Ramsey (DGS), Eduardo Leorri (UD Department of Geology), and DGS student assistants Richard Alborn and Christine McCarthy. The kind cooperation of personnel of American Water Well Systems, particularly Christopher McFarland and John McFarland, ensured productive drilling operations and access to drilling sites. We are grateful for access to land allowed by property owners Gale Voshell (Voshell Brothers Welding) and Jeffrey Bowers (Beracah Homes). We also appreciate the assistance of Wayne Lehman (DNREC Division of Fish and Wildlife) and of Reinhold Betschel (Wastewater Facilities Division, Kent County Department of Public Works,) for access to property managed by their departments. DGS student worker Jennifer Anné helped with sample preparation in the lab. We thank Douglas Rambo (DNREC) for providing additional information on water-quality issues. We also appreciate assistance in access to geophysical log data provided by Gerald R. Baum and Sasha Lanham (Maryland Geological Survey), Jeremy Kalmbacher and Christopher Walker (Tidewater Utilities), Andrew Riggi (City of Dover Department of Public Works), and Michael Collison (A.C. Schultes of Delaware). Special thanks are owed to Stephen E. Curtin (U.S. Geological Survey, Annapolis) for the loan of a gamma-multipoint electric geophysical logging tool.

DATA AND METHODS

Data collection for this study emphasized compilation of all available geological data for wells penetrating confined aquifers in Kent County, and acquisition of new information in areas of low data coverage and likely high future development. The first phase of work included compilation, evaluation, and quality control of all geophysical log data in Kent County held by the DGS. Well records from southernmost New Castle County, northernmost Sussex County, and nearby areas of Maryland were included in the compilation to ensure that interpretations were consistent beyond the borders of the study area (Fig. 2). An inventory of all wells with geophysical logs was compiled, and an estimation was made of which well records likely extended into confined aquifers. An inventory of digitized geophysical logs was also made; this was crosschecked against a list of all geophysical logs in DGS files to identify those needing to be digitized.

All geophysical logs deeper than 60 ft in Kent County and bordering areas were digitized; this totaled more than 100 logs. The quality of all digitized logs was evaluated and a quality rating assigned to each; generally, only those logs judged moderate-to-high quality were used for analysis.

One goal in data collection was to obtain additional geophysical logs from the study area. With the help of the Well Permits Branch of the Delaware Department of Natural Resources and Environmental Control (DNREC), we were able to make arrangements with drillers to log 11 holes drilled into confined aquifers. We obtained a number of geophysical logs from the files of local governments, water utilities, and water-well drillers. In addition, we obtained digitized geophysical logs for 10 nearby Maryland wells from the Maryland Geological Survey.

This study included a cross-verification of thousands of paper well records and entries in the Delaware Geological Survey's Oracle database to ensure consistency and accuracy. Because the maps produced for the project include data read directly from the database, data verification was essential to accurately place wells and post data. In many cases, well locations were more accurately determined and revised based on comparison of location descriptions, maps, and aerial photographs in ArcMap. Because the cross sections produced for the project are corrected for sea level, existing elevations were revised for all the wells by cross checking the elevation reported in the paper records against topographic maps and digital elevation models (DEM) in ArcMap. New elevation values were determined for those wells lacking altitude data. Oracle data tables were updated where necessary.

With the data organization and verification complete, the next phase of work was identification of deep wells for inclusion on the cross sections. This effort focused on identifying deep wells with data of sufficient quality to be confidently assigned aquifer designations. Well locations were selected to obtain maximum coverage of the county (Fig. 2; Appendix 1).

Areas lacking geophysical logs were identified in ArcMap and targeted as potential locations for acquisition of new data through drilling. These areas were ranked in order of importance based on likely development trends and proximity to existing data. A list of six test hole locations was established, a drilling contractor was secured, property owners were contacted to obtain permission to drill, and drilling permits were obtained from DNREC. Drilling was conducted at six sites in May and June 2004: Ib14-32 (Blackiston State Wildlife Management Area), Hd25-05 (Woodland Beach State Wildlife Management Area), Jc12-16 (Pearsons Corner), Kc13-06 (Norman G. Wilder State Wildlife Management Area Willow Grove Unit), Ke23-05 (Kent County Wastewater Pumping Station 8), and Ld41-16 (Hopkins Cemetery Road) (Fig. 2). The holes were drilled using a mud-rotary rig to depths ranging from 460 to 680 ft, each with a specifically targeted deep aquifer. Cuttings samples were collected every 10 ft and lithologic logs were compiled based on the cuttings and drilling behavior. Upon completion of drilling, geophysical logging was conducted using a gamma-multipoint electric tool (either Century Geophysical Corporation Model 8043 or Model 8044). These sites were especially valuable in allowing calibration of geophysical log signatures to lithologic characteristics of the formations encountered while drilling.

With the final selection of well locations complete, six west-east oriented lines of section were selected to illustrate stratigraphic relationships along strike, and two north-south lines were selected to highlight updip-downdip relationships (Fig. 2). Seven confined-aquifer intervals were correlated on the cross-sections: Mount Laurel, Rancocas, Piney Point, Cheswold, Federalsburg, Frederica, and Milford. It is important to note that the stratigraphic packages shown on the cross-sections and maps in this report represent more than the aquifer unit; they are approximately time-stratigraphic units that encompass the aquifers themselves as well as equivalent stratigraphic levels that contain non-aquifer facies.

Based on these correlations, values of elevation of the top of each aquifer-bearing unit (relative to sea level, for structural contour maps) and its thickness (for isopach maps) were compiled. In addition, all other available wells with geophysical logs of adequate quality between the cross sections were evaluated and aquifer elevation and thickness picks added to those compiled from the cross sections (Appendix 2). The resulting data files were composed of lists of wells and corresponding values of aquifer elevation and thickness. Maps were constructed using Surfer software to grid the data, ArcMap software to integrate and manipulate the grids and associated area and point data, and Adobe Illustrator to edit the graphics for final figures.

Two important points to consider in evaluation of these maps are data density and contouring problems near the map margins. The depth and thickness grids should be generally accurate in areas where data density is reasonably high. However, in areas with widely scattered well control, the computer-generated contouring provides only an approximate projection between data points. The possible error is even greater around the margins of the mapped areas where the contouring is controlled only by data on one side.

LITHOSTRATIGRAPHY

The confined aquifers of Kent County occur in formations ranging in age from Late Cretaceous to Miocene (Fig. 1). The lithostratigraphy of this interval is subdivided by three significant breaks in deposition: a Cretaceous-Paleogene unconformity, an Eocene-Miocene unconformity, and a Miocene-Pleistocene unconformity.

Three Upper Cretaceous formations are treated in this study. The lowest, the Marshalltown Formation, is a Campanian-age unit composed of dark, homogenous, bioturbated, highly glauconitic, silty fine sand and sandy silt (Carter, 1937; Pickett, 1970; Owens et al., 1970; Benson and Spoljaric, 1996). It can be recognized by high gamma values on geophysical logs. The abundance of glauconite and silt suggests deeper-shelf environments (Owens and Sohl, 1969). It ranges from 10 to 15 ft thick near the Chesapeake and Delaware Canal and attains a thickness of more than 30 ft in Kent County (Benson and Spoljaric, 1996).

The Mount Laurel Formation overlies the Marshalltown Formation and is also placed in the Campanian. In southern New Castle County and northern Kent County, it is characterized by quartz sand with shells, burrows, and variable amounts of glauconite, which gives it a salt-and-pepper appearance (Carter, 1937; Owens et al. 1970; Pickett, 1970; Benson and Spoljaric, 1996). These sands represent nearshore environments (Owens and Sohl, 1969). In central and southern Kent County, calcareous silts of the same age (based on biostratigraphy) have been assigned to the Mount Laurel Formation by Benson and Spoljaric (1996); these likely reflect a downdip transition to offshore shelf environments. The Mount Laurel Formation is commonly between 85 and 95 ft thick in Kent County.

The Navesink Formation is the highest Cretaceous unit recognized in Delaware. It is Maastrichtian in age and is separated from the Mount Laurel Formation by a minor unconformity. In the study area, it is composed of dark, clayey, sandy, calcareous silt, with glauconite comprising much of the sand fraction (Benson and Spoljaric, 1996). The base of the formation is recognized in Delaware based on its high counts on gamma ray logs; this may reflect the presence of phosphatic molluscan molds such as described in the basal Navesink in New Jersey (Owens et al., 1977). The Navesink Formation is generally around 20 ft thick in the subsurface of Delaware. It reflects deposition in a middle-to-outer shelf setting (Owens and Sohl, 1969).

Above an unconformity that marks the end of the Cretaceous, a series of deeper-shelf deposits characterizes the Paleocene to middle Eocene section. This interval is typically glauconitic, and much of the section is composed of fine-grained deposits. The lowest of these is the lower Paleocene Hornerstown Formation. It is composed of dark green, clayey, calcareous glauconite sand and sandy silt (Pickett and Spoljaric, 1971; Owens et al., 1977; Benson and Spoljaric, 1996); a bright green glauconitic clay matrix distinguishes it from the underlying glauconitic Cretaceous units (Owens and Sohl, 1969). It is exposed in a few streams and road cuts in southern New Castle County (Johnson and Richards, 1952; Owens et al., 1970) and extends in the subsurface southward into Kent County (Benson and Spoljaric, 1996) and northern Sussex County (our reinterpretation of Talley, 1975). The facies are siltier at Dover (Benson and Spoljaric, 1996) than in New Castle County. It is generally 20 to 30 ft thick (Benson and Spoljaric, 1996; Owens et al., 1977). The Hornerstown Formation reflects deposition in a mid-shelf environment (Owens et al., 1977).

The Vincentown Formation represents a shift to more quartz-rich sands over the glauconite of the Hornerstown Formation. In southern New Castle County and northern Kent County, it is slightly glauconitic quartz sand with some silt (Pickett and Spoljaric, 1971; Benson and Spoljaric, 1996) and around 100 ft thick; southward in Kent County it is thinner and includes more fine-grained material (Benson and Spoljaric, 1996; Andres, 2001). The Vincentown

Formation was deposited in a nearshore to shelf setting (Owens and Sohl, 1969) and is considered an upper Paleocene unit in Delaware (Benson and Spoljaric, 1996).

The next highest unit, the Manasquan Formation, consists of around 30 ft of silty, shelly sands that are commonly glauconitic (Benson and Spoljaric, 1996). It was deposited during the latest Paleocene to early Eocene (Benson and Spoljaric, 1996). The overlying Shark River Formation is finer grained overall and consists of glauconitic clayey silt and clay, with some glauconite sand and glauconitic quartz sand. It is placed in the middle Eocene (Benson and Spoljaric, 1996) and is generally around 60 to 70 ft thick. Based on the microfossils in these strata in Delaware (unpublished DGS file data), both the Manasquan and Shark River Formations can be characterized as open shelf deposits.

Geophysical log correlations by Benson and Spoljaric (1996) frame a down-dip shift in Kent County of the upper part of the Vincentown Formation, the Manasquan Formation, and the Shark River Formation to fine-grained facies. Benson and Spoljaric (1996) applied the name Deal Formation to these deposits. The Deal Formation is composed of grayish, calcareous glauconitic silt and clay with abundant microfossils (Benson and Spoljaric, 1996). It is present in central and southern Kent County and is approximately 300 ft thick.

The Piney Point Formation caps the Eocene section in the subsurface of Kent County. It is characterized by quartz sands with 20 to 40 percent glauconite and common shell material (Benson and Spoljaric, 1996). The formation becomes coarser grained upward; the lower part includes glauconitic silt and clay and is transitional with the underlying Deal Formation (Benson and Spoljaric, 1996; Andres, 2001). The Piney Point Formation is considered to be middle Eocene based on limited biostratigraphic evidence in the subsurface of the Dover area (Benson and Spoljaric, 1996). However, very similar strata assigned to the Piney Point Formation in Millville, New Jersey, have been demonstrated to be upper Eocene (Sugarman et al., in preparation). According to Benson et al. (1985), the Piney Point Formation represents a complex of prograding shelf deposits. It reaches thicknesses of up to 250 ft in southern Kent County and thins northward as it is progressively truncated under the basal Miocene unconformity; in parts of northern Kent County, this unconformity completely removes the formation.

Over most of Kent County, the basal Miocene unconformity separates middle Eocene glauconitic deposits of the Piney Point Formation from siliciclastic lower Miocene deposits. However, other Eocene and Oligocene deposits have been cited locally. Ramsey (1997) delineated an Unnamed Eocene Unit for an interval of shelly mud in a well in Milford (Me15-29), based on unpublished palynological data provided by J.J. Groot. Benson (1990) delineated an Oligocene Unnamed Glauconitic Silt in the same well based on foraminifera and on geophysical log correlation to known Oligocene strata to the south.

Above the basal Miocene unconformity, the Miocene section is characterized by repeated alternations between nearshore sands and shallow-marine muds. This interval is divided into two formations, the Calvert and Choptank Formations. Both units were defined by Shattuck (1902, 1904) in Maryland as divisions of the Chesapeake Group based on lithology and fossil content; Rasmussen et al. (1960) first applied these names in Delaware. The Calvert Formation is the finer grained of the two units and is characterized by interbedded gray to brown clayey silt and silty quartz sand (Benson, 1990; Ramsey, 1993, 1997). It generally has no more than a trace of glauconite. Sands increase in abundance upward and commonly include shell beds. It reflects a series of coastal transgressions and regressions during the early Miocene that produced interbedded shallow-marine to estuarine sands and offshore sands and muds (Miller et al., 2003). The thickness of the Calvert Formation ranges 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.

The base of the Calvert Formation has been defined by Benson and Spoljaric (1996) to include an interval of glauconitic sand, commonly up to 40 ft thick, which is referred to as "reworked Piney Point." This sand bed is similar lithologically to the underlying Piney Point Formation, but it is dated as early Miocene, so it was placed in the Calvert Formation by Benson and Spoljaric (1996); this convention is followed in this report. The unconformity that separates the Calvert Formation from underlying middle Eocene (and possibly local Oligocene) deposits appears to truncate progressively older strata updip (Benson and Spoljaric, 1996), separating the Calvert Formation from the Piney Point Formation in central and southern Kent County and the Calvert Formation from the slightly older Deal or Shark River Formations in northernmost Kent County.

The Choptank Formation overlies the Calvert Formation. It is characterized by a similar succession of interbedded shallow-marine to estuarine sands and offshore sands and silts; however, it is sandier than either the Calvert Formation or the overlying St. Marys Formation (Ramsey, 1997). It typically consists of silty quartz sand interbedded with clayey silt; shell-rich beds are common (Benson, 1990; Ramsey, 1993, 1997). The base of the formation is defined where the section shifts to more sand beds than silt or clay; in some places, the boundary is marked by a granular to very coarse sand overlying a brown silty clay (Ramsey, 1993, 1997). As in the Calvert Formation, the alternation of sands and silts in the Choptank Formation traces a series of coastal transgressions and regressions (Benson et al., 1985; Miller et al., 2003). It ranges in age from latest early Miocene to middle Miocene (Miller et al., 2003). From a thickness of around 200 ft in southern Kent County, the Choptank Formation thins northward as a result of stratigraphic thinning and truncation under the overlying Quaternary section.

The St. Marys Formation is the youngest of the pre-Quaternary formations in Kent County and is restricted to the southern part of the county. It is composed of dark silt and lesser silty quartz sand with some shelly beds (Ramsey, 1993, 1997, 2001), representing a shift to finer-grained deposits over the sandy Choptank Formation. Occurrences of the St. Marys Formation in Delaware are interpreted to be shallow- to marginal-marine deposits and middle to late

Miocene in age (Miller et al., 2003). It is up to 60 ft thick (Ramsey, 1997).

The Quaternary section of Kent County comprises a thin veneer that unconformably overlies these older Cenozoic formations. The unconformity truncates successively older units northward, overlying middle Miocene strata in much of the southern part of the county and lower Miocene strata in much of the northern part.

Three Quaternary formations are recognized in the county. The oldest is the Columbia Formation. It is typically composed of yellow to dark reddish brown, mostly coarse, commonly gravelly, cross-bedded quartz sand with scattered thin beds of silt (Jordan, 1962, 1964). Sedimentary facies indicate deposition by braided fluvial systems produced by melting of glaciated areas to the north of Delaware during Pleistocene climatic transitions from cold to temperate conditions (Jordan, 1964; Groot and Jordan, 1999). The thickness of the formation is variable, with significant channeling, but generally less than 100 ft.

Two terrace-forming Pleistocene units occur along the margin of the Delaware Bay. The older of the two is the Lynch Heights Formation. It is a lithologically heterogeneous unit, composed predominantly of quartz sands with discontinuous beds of gravel, silt, and organic-rich material (Ramsey, 1997). It underlies terraces with elevations of 20 to 30 ft, and attains a thickness of up to 20 ft (Ramsey, 1997). These deposits represent a complex of middle Pleistocene estuarine and marsh sediments (Ramsey, 1993, 1997; Groot and Jordan, 1999).

The Scotts Corners Formation is the second of the terrace-forming Pleistocene units. Like the Lynch Heights Formation, it is a heterogeneous unit composed of quartz sands, clayey silt, some organic-rich beds, and gravel (Ramsey, 1993, 1997). Its base is typically marked by a coarse sand or gravel that overlies a paleosol at the top of the Lynch Heights Formation; the top is commonly capped by one to two feet of silt (Ramsey, 1997). It is thinner than the Lynch Heights Formation, rarely more than 15 ft thick. It represents late Pleistocene deposition of estuarine and marsh deposits that are typically associated with terraces with elevations of 15 ft or less.

AQUIFER STRATIGRAPHY

The focus of this study is the geology of the confined aquifers of Kent County. In most parts of Kent County, more than one confined aquifer is available as a potential source of ground water. However, the geologic characteristics of some of the aquifer-bearing intervals vary from one part of the county to another. A significant issue complicating this understanding is the lack of up-to-date information about the distribution of characteristics of these aquifers. Aquifer designations made by drillers or government agencies are, as a result, not always correct.

In this section, each of the seven confined aquifer intervals present in Kent County is examined, its geological characteristics discussed, and distribution delineated. As noted previously, the discussion of each aquifer interval in this report treats more than just the aquifer unit itself. It represents an approximate time-stratigraphic package that includes the aquifer and stratigraphically equivalent non-aquifer facies.

The description of each aquifer interval includes general knowledge of the aquifers derived from previous studies as well as site specific information obtained as part of this study. The emphasis here is on geological characterization; as such, this report does not treat the hydrology of these aquifers in any detail.

The stratigraphic relationships of the confined aquifers are delineated in a series of eight cross sections that cross the county (Fig. 2), six approximately strike-oriented and two approximately dip-oriented (Plate 1). Correlations are indicated for aquifer intervals interpreted on the logs, as well as for projected positions of the aquifer intervals below well-log control. Correlations are not carried into areas where the confined aquifer interval merges with the overlying unconfined Columbia aquifer.

The areal extent of each of the seven aquifer intervals is shown in a series of maps. Structural contour maps (Figs. 3, 5, 7, 9, 11, 13, and 15) show the depth to top of interval. Isopach maps (Figs. 4, 6, 8, 10, 12, 14, and 16) define the thickness of each interval in the study area.

The sedimentary facies and depositional environments that characterize each aquifer interval are also covered in this section. The main water producing qualities of a sedimentary body, 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 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, water-bearing facies in the aquifer interval, the strata are treated as stratigraphically equivalent non-aquifer facies. Because many different types, vintages, and qualities of logs were used in this analysis, no firm quantitative basis could be established for identification of aquifer-quality sand; the interpretations are based on the judgment of the authors. From these interpretations, the estimated distribution of aquifer facies in each of the aquifer intervals is indicated on the cross sections and maps.

The unconfined Columbia aquifer is not included in the present study; its variable thickness, north to south change in geological characteristics, and difficulties in recognizing the base where it is in contact with sands in the underlying Miocene section, all create challenges that warrant separate study.

Mount Laurel aquifer interval

The Mount Laurel aquifer interval includes all strata assigned to the Mount Laurel Formation in the study area. It is composed of aquifer-quality sands in southern New Castle County and northern Kent County and changes facies to finer-grained, non-aquifer lithologies in central and southern

Kent County (Fig. 3). The depth below sea level of the top of the Mount Laurel aquifer interval is as shallow as 300 ft in northwestern Kent County, and the equivalent horizon may be found at depths of more than 1,200 ft in the southernmost part of the county (Fig. 3). The thickness of this interval is between 85 and 95 ft over most of the county, but is more than 100 ft thick just to the north in southernmost New Castle County (Fig. 4).

The Mount Laurel aquifer is the stratigraphically lowest aquifer unit used in Kent County. Rima et al. (1964) discussed the potential of the Mount Laurel Formation as an aquifer in southern New Castle County and noted a southward trend of diminishing specific capacities of wells in this unit. Wells have been completed into the Mount Laurel aquifer just north of the county line at the Delaware Correctional Center (Hc14-17) and just south of the county line at the Windsong Farms subdivision near Clayton (Hc31-08). It has been reported to be a good aquifer at the correctional center, yielding 350 gallons per minute (gpm) of good-quality water with low levels of dissolved solids (Andres, 2001); the well completion report for the Windsong well shows similar good yields (tested at 250 gpm). Water-level observations in the area (Gd33-04, southeastern New Castle County) trace a modest decline likely attributable to the long term increase in regional water use (Andres, 2001).

The Mount Laurel aquifer was penetrated in two of the test holes drilled for this project in northernmost Kent County: Ib14-32, northwest of Kenton, and Hd25-05, just north of Woodland Beach Road. In both holes, cuttings samples indicate that the Mount Laurel aquifer is a relatively clean, permeable, medium-grained sand; the sand is predominantly rusty quartz grains, mostly medium but up to granule size, with common (10-20 percent) glauconite and common shell material. Geophysical logs in northern and west-central Kent County show clean, resistive responses (Plate 1). These confirm the potential for aquifer-quality, near-shore sand facies in the area. Finer-grained beds in the overlying Navesink and Hornerstown Formations and the underlying Marshalltown Formation confine this aquifer.

The Mount Laurel aquifer interval becomes finer grained to the south and southeast; gamma and resistivity logs (e.g., Id 31-26, Je32-04; see Plate 1) indicate the prevalence of non-aquifer facies in most of east-central and southern Kent County (Fig. 3). Benson and Spoljaric (1996) identified the Mount Laurel Formation in a hole at Dover Air Force Base where it consists of calcareous silt, with clayey silt, abundant calcareous nannofossils, and lesser glauconite and shell calcite. Although these strata contrast lithologically with the sands that characterize the Mount Laurel Formation to the north, biostratigraphy indicates that they are age equivalent.

Rancocas aquifer interval

The Rancocas aquifer (also under the names Eocene series, Vincentown, and Aquia) has long been reported as a ground-water resource in southern New Castle County and northern Kent County (Marine and Rasmussen, 1955; Rima et al., 1964; Rasmussen et al., 1966; Sundstrom and Pickett, 1968; Cushing et al., 1973). The Rancocas aquifer interval, as used in this report, more broadly encompasses aquifer-quality upper Paleocene to lower Eocene sands and stratigraphically equivalent non-aquifer facies.

In Kent County, aquifer-quality facies are known only in the northernmost part of the county, in a zone north of an east-northeasterly line that trends from Kenton to the south side of Smyrna (Fig. 5). In this area, the Rancocas aquifer is composed of glauconitic sands that have been placed in the Vincentown and Manasquan formations by Benson and Spoljaric (1996). Geophysical log patterns (e.g., Id 31-26, Je32-04; see Plate 1) indicate that the Rancocas aquifer interval becomes finer grained to the south and southeast, comprising non-aquifer facies in central and southern Kent County. Correlations based on geophysical log signatures and biostratigraphy (Je32-04; Benson and Spoljaric, 1996) tie it to the Vincentown Formation and lower part of the Deal Formation (as defined by Benson and Spoljaric, 1996).

The top of the Rancocas aquifer interval is shallower than 100 ft below sea level in northwestern Kent County and becomes deeper southeastward (Fig. 5); the stratigraphically equivalent, non-aquifer horizons are projected to depths of more than 1,000 ft below sea level in the southern part of the county. It ranges in thickness from around 100 ft in eastern Kent County to more than 200 ft on the western side of the county (Fig. 6).

The Rancocas aquifer was penetrated during drilling for this project in test holes Ib14-32, northwest of Kenton, and Hd25-05, just north of Woodland Beach Road. Cuttings samples from the Rancocas interval in both wells consist of muddy glauconitic sand with shells and numerous hard layers. Geophysical logs in these two holes, and other wells in northern and west-central Kent County, suggest somewhat cleaner sand facies than the test-hole cuttings (Plate 1). These observations confirm the presence of aquifer-quality near-shore sand facies in the area.

The Rancocas aquifer is confined by overlying glauconitic muds of the Shark River Formation in Kent County (Plate 1). However, because the basal Miocene unconformity seen in Kent County cuts progressively deeper to the north (Plate 1, Cross Sections E-E' and W-W'), the Rancocas aquifer appears to be overlain in some parts of southern New Castle County by muds of the lower Miocene Calvert Formation.

Wells completed into the Rancocas aquifer at the Delaware Correctional Center and in Clayton yield up to 300 gpm of good-quality water (Andres, 2001). However, water quality is an issue locally. A private water utility reported that a Rancocas well west of Clayton (Hc31-06) exceeded maximum contaminant levels permitted for arsenic and as a result would be replaced (Middletown Transcript, September 6, 2001). Two Clayton Water Department wells (Hc32-15, Hc32-24) in the Rancocas aquifer have tested slightly above permitted arsenic levels (DNREC and Office of Drinking Water databases; Douglas Rambo, personal communication).

Piney Point aquifer interval

The Piney Point aquifer interval, as mapped in this report, is a combination of two geologic units that function as one unit hydrologically: the Piney Point Formation and the basal sand of the Calvert Formation. Although the Piney Point aquifer largely occurs within the middle Eocene Piney Point

Formation, the aquifer and formation are not exactly the same. The best aquifer facies occur only the upper part of the Piney Point Formation. In many places, the Piney Point Formation is unconformably overlain by an interval of clean sand at the base of the lower Miocene Calvert Formation. Where this basal Calvert sand occurs, it is in direct contact with the underlying sands of the top of the Piney Point Formation and thus can be treated as a single aquifer. Lines of correlation are carried for both parts of the aquifer on the cross sections (Plate 1).

The Piney Point aquifer is a major source of ground water in Kent County. It is characterized by quartz sands with common glauconite. It is an entirely confined aquifer unit and lacks outcrops and areas of subcrop under overlying aquifers; therefore, all recharge is via vertical leakage through the overlying confining layer (Leahy, 1979). This aquifer has long been used as a source of ground water in the Dover area. Marine and Rasmussen (1955) noted the presence of an Eocene "salt and pepper" glauconitic sand aquifer in Kent County and suggested it might be equivalent to the Piney Point Formation of southeastern Maryland. Wells tapped the Piney Point aquifer as far back as the late 1930s and early 1940s in northeastern Kent County (Bombay Hook, Port Mahon). In the late 1950s and 1960s, it became increasingly utilized, with new wells at Dover Air Force Base, Woodside, Felton, and Dover (Sundstrom and Pickett, 1968). Today, it is a major source of ground water for central Kent County communities.

The top of the Piney Point aquifer interval ranges from as shallow as 90 ft below sea level in northeastern Kent County to more than 600 ft below sea level in the southeastern part of the county (Fig. 7). It thickens southeastward from 55 ft in the northeastern part of the county to nearly 300 ft southeast of Dover (Fig. 8); the thickness further southeast is difficult to estimate because of the rarity of complete penetrations of the aquifer.

The Piney Point aquifer interval generally exhibits an upsection trend of sandier lithologies (Je32-04; see Plate 1), a trend recognized at least as far back as the early 1970s (Cushing et al., 1973). Aquifer facies are typically developed in the upper part of the interval, whereas lithologies near the bottom of the formation commonly are muddy and therefore marginal- or non-aquifer facies.

An areal trend is evident in which better quality aquifer facies are generally encountered in central and southern Kent County (Fig. 8). This is largely controlled by the interplay of the coarsening-upward trend of the Piney Point Formation with erosion by the Eocene-Miocene unconformity. This unconformity cuts progressively deeper into the Eocene section in a northwesterly direction (Plate 1, Cross Section W-W′). As a result, the upper, highest-quality aquifer facies of the Piney Point aquifer are not present northwest of a southwest-to-northeast-trending line that runs through the north side of Dover (Fig. 8). Poor aquifer-quality, silty facies of the lower part of the Piney Point Formation are most common northwest of that line to the approximate updip erosional limit of the unit along a line trending from south of Kenton to just south of Smyrna (Fig. 8).

This unconformity also controls the confining layers associated with this aquifer interval. In south-central Kent County, the Piney Point aquifer is overlain by clays of the lower part of the lower Miocene Calvert Formation and is underlain by silty, non-aquifer sands of the lower part of the Piney Point Formation. In north-central Kent County, the down-cutting puts the Calvert Formation (in places muds, in places a very thin lag sand) directly on the lower Piney Point Formation. In the northwesternmost part of the county, the Piney Point Formation may be absent, with the Calvert Formation resting directly on green clays of the Eocene Shark River Formation.

The basal Miocene sand that commonly overlies the unconformity is a thin (generally < 20 ft thick) aquifer-quality glauconitic sand. It is interpreted as a lag deposit of reworked sand from the Piney Point Formation (Benson and Spoljaric, 1996) laid down by marine transgression at the start of the Miocene. Although it is genetically separate from the underlying Piney Point Formation and more than 10 million years younger, the lag deposit and the Piney Point Formation function together as a single aquifer unit. Therefore, both are included in the Piney Point aquifer interval for this report.

In the wells drilled for this study, the Piney Point aquifer consists of shelly quartz sand with common (5-10 percent) glauconite. In the more southern and easterly holes drilled (Ld41-16 and Ke23-05), the upper part of the Piney Point aquifer was encountered, and the sands are clean and commonly medium grained, in some places even coarse grained, and have clean sand signatures on geophysical logs (Plate 1, Cross Sections E-E′ and W-W′). In the two holes in west-central Kent County (Kc13-06 and Jc12-16), the Piney Point aquifer appeared to be of lesser quality. The cuttings samples are predominantly slightly shelly, glauconitic quartz sand, but fragments of mud are also common, indicating the presence of siltier facies. These observations are corroborated by the higher gamma values and lower resistivity values on the geophysical logs (Plate 1, Cross Section W-W′). The fine-grained facies and reduced thickness of the Piney Point aquifer at these two sites indicate that the higher-quality, upper part of the Piney Point aquifer is absent and only the lower, finer-grained portion of the Piney Point beds are present (Plate 1, Cross Section W-W′).

In southeasternmost Kent County (Me15-29), an interval of glauconitic sand encountered under the Calvert Formation has been interpreted as the Piney Point Formation (see maps of Cushing et al., 1973). However, recent biostratigraphic analysis has suggested it may be Oligocene in age (Benson, 1990; Ramsey, 1997). This leaves the question open as to whether the sand referred to as Piney Point in the Milford area is or is not hydrologically connected with the Piney Point aquifer used elsewhere in Kent County. For the purpose of this report, it is included in the Piney Point aquifer.

The Piney Point aquifer is known for high-quality water, except for local reports of elevated (> 0.01 mg/L) arsenic levels (at Felton, Dover Air Force Base, and east of Woodside) (DNREC, 2003; US HHS, 2003; DNREC and Office of Drinking water databases; Douglas Rambo, written communication). Because it is such a critical resource and is only recharged indirectly from the surface, water allocations are carefully managed. Although heads are currently stable, the Piney Point aquifer suffered from declining heads in the past. Monitoring-well water levels in the Dover area (Id55-01) declined by approximately 70 ft from the late 1960s to late 1980s but have stabilized, and even rebounded slightly, since then (DGS water-level database).

Cheswold aquifer interval

Miocene aquifers have long been recognized as important sources of ground water in Kent County. Marine and Rasmussen (1955) described two Miocene sands that were known as ground-water sources in the early 20th century: a deeper one used mostly between Smyrna and Dover, and a shallower one used between Camden and Milford. Rasmussen et al. (1958) referred to the lower of these as the Cheswold aquifer.

As the aquifer framework of Kent County is currently defined, the Cheswold aquifer is the lowest of three aquifer sands in the Calvert Formation. It is an important source of ground water in northern and central Kent County and is tapped by numerous public supply wells in the Dover area (Andres, 2001). It lies in the lower part of the Calvert Formation, confined above by a thin zone (10 to 20 ft) of silt or silty clay and underneath by a thick zone of brown clayey mud that typically comprises the lower part of the Calvert Formation (Plate 1). The Cheswold sand functions as part of the unconfined Columbia aquifer where it subcrops under the base of the Columbia Formation in southernmost New Castle County and northern Kent County (Pickett, 1976; Andres, 2001). In these areas, the boundary between the Quaternary-age Columbia Formation and the Miocene-age Cheswold sand may be difficult to recognize, and so the Cheswold sand is not delineated separately there (see Plate 1, Cross Sections N2-N2′, N3-N3′, and north end of E-E′ and W-W′).

South of the unconfined areas of the Cheswold sand, the top of the confined aquifer descends from up to 50 ft above sea level in the northern part of the county to more than 400 ft below sea level in the southeastern part of the county (Fig. 9). It ranges from 30 to more than 100 ft thick in Kent County and exhibits an overall southward thickening trend (Fig. 10). However, there are significant local variations of thickness; it is less than 40 ft thick in areas south and east of Dover and near the state line southwest of Dover (Fig. 10). In addition, significant elevation changes are known to occur on the base of the Cheswold sand near its updip limit near Smyrna and Clayton (not mapped here).

The geophysical log patterns seen in the Cheswold aquifer reflect the sedimentary facies present and are important indicators of aquifer characteristics. Detailed study of exposures of the Cheswold sand south of Smyrna (Ramsey, 1998) provides a basis for calibration of sedimentary facies to geophysical log patterns in this unit. Construction excavation at the Pollack Farm site (Id11-a) revealed 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 under the sand is a shelly mud deposited in an open-marine offshore environment that was perhaps 30 ft deep. This is overlain by a cross-bedded sandy shell bed with abundant bone material deposited in an estuarine channel or near the mouth of an estuary. This is, in turn overlain by a cross-bedded, shallow subtidal sand; a finer-grained break composed of interbedded mud and sand that represent tidal flat deposits; and a cross-bedded sand with shell beds, abundant burrows, mud rip-up clasts, and ripples with clay drapes, representing a shallow subtidal environment within and near tidal channels. The sand is capped by a muddy zone composed of homogenous clayey silts and a few thin sands deposited in a tidal mud-flat setting.

This same upward succession of lithologies can be interpreted on geophysical logs in the Cheswold aquifer around much of north-central Kent County. It is expressed as an overall fining-upward pattern with some upward-coarsening just below the base of the aquifer sand. The base of the aquifer facies corresponds to the base of the sandy shell bed at Pollack Farm and continues to the top of the upper sand. The top of the aquifer may be marked by a thin interval of tidal flat muds followed by open-marine muds. The succession of facies represents shoaling from offshore to subtidal to intertidal environments followed by flooding that brought offshore muds back over the sand. In some areas (such as Voshell Cove, Ic54-06/-07, west of Dover), muddy sands make up much of the Cheswold aquifer interval, probably due to local areas of tidal flat facies; this may explain locally poor aquifer quality. The overall fining-upward pattern is typical of localities in central to north-central Kent County (Id31-26; see Plate 1). It generally reflects upward shoaling in an estuarine setting, with fine-grained tidal-flat deposits capping the succession.

In northernmost Kent County, around Smyrna, the Cheswold aquifer commonly exhibits a “blocky” log pattern, where it has a sharp base and similar low gamma values and high resistivity values through most of the aquifer (Plate 1; see Hc45-21 on Cross Section E-E′ and Hc31-07 on W-W′). This pattern probably reflects a predominance of tidal channels in a more proximal depositional setting than the fining-upward packages described above. This is consistent with our observations of considerable relief (tens of feet) on the base of the Cheswold sand in the Smyrna-Clayton area.

In south-central and southern Kent County, the Cheswold aquifer commonly has a coarsening-upward pattern. In this area, 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.

The Cheswold aquifer is commonly overlain by a muddy confining layer of around 10 to 20 ft thick (Plate 1). However, in some areas, this interval appears to be thinner and/or not especially fine grained which suggests it may not everywhere be an effective hydrologic barrier between the Cheswold and Federalsburg aquifers (e.g., Jd25-09 and Kd33-04; see Plate 1, Cross Sections S3-S3′ and W-W′).

The interpretations from outcrop and geophysical logs are supported by cuttings recovered from the test holes drilled for this study. The Cheswold aquifer was penetrated in all six text holes (although it was unconfined at site Hd25-05). Cuttings samples consist of medium- to fine-grained quartz

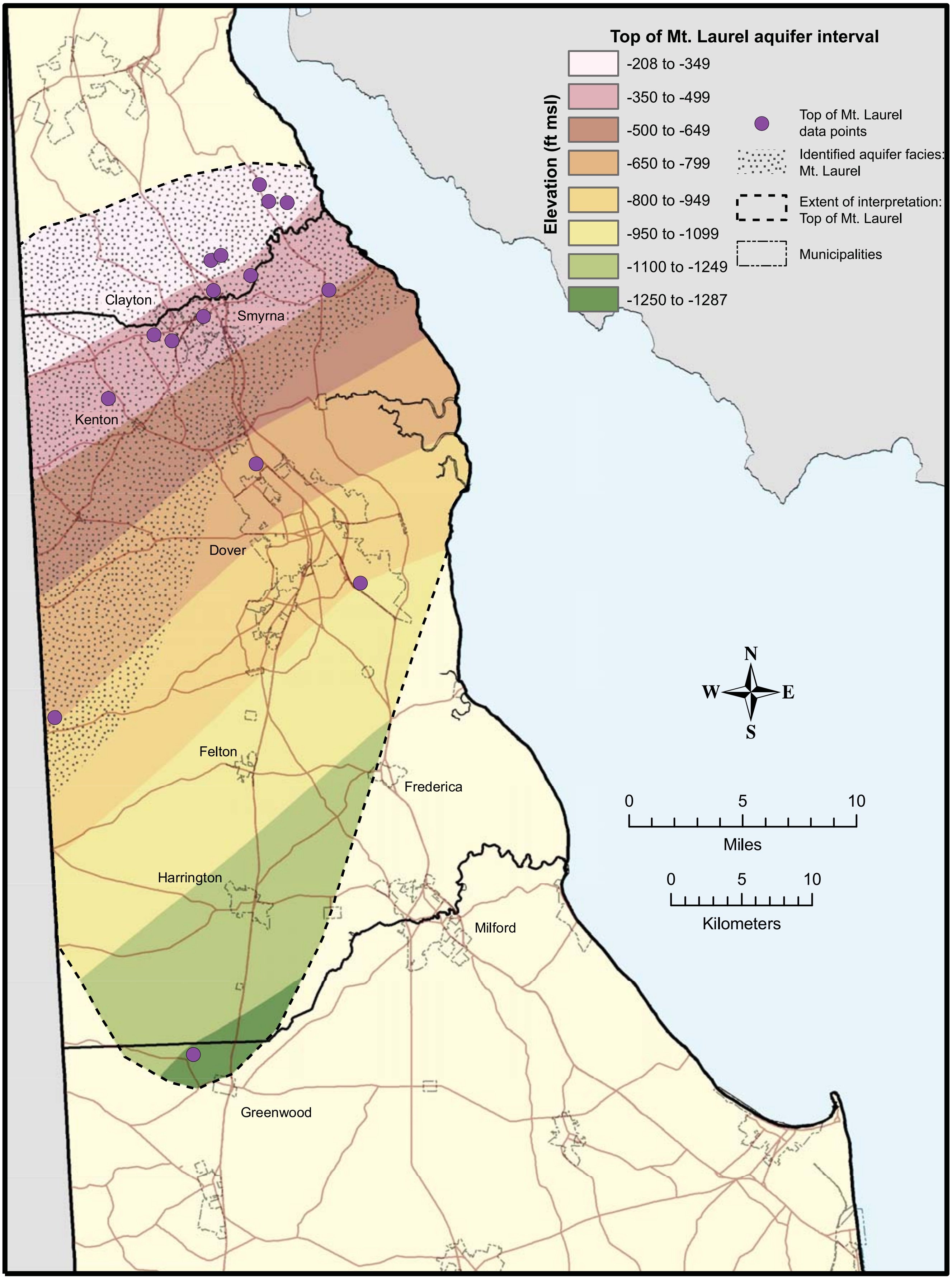

Figure 3. Elevation of the top of the Mount Laurel aquifer and stratigraphic equivalents. The elevation of the top of the Mount Laurel aquifer deepens from around 200 ft below sea-level in northern Kent County to more than 1,200 ft in southern Kent County. Well control is densest in northern Kent County where it is locally used as an aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

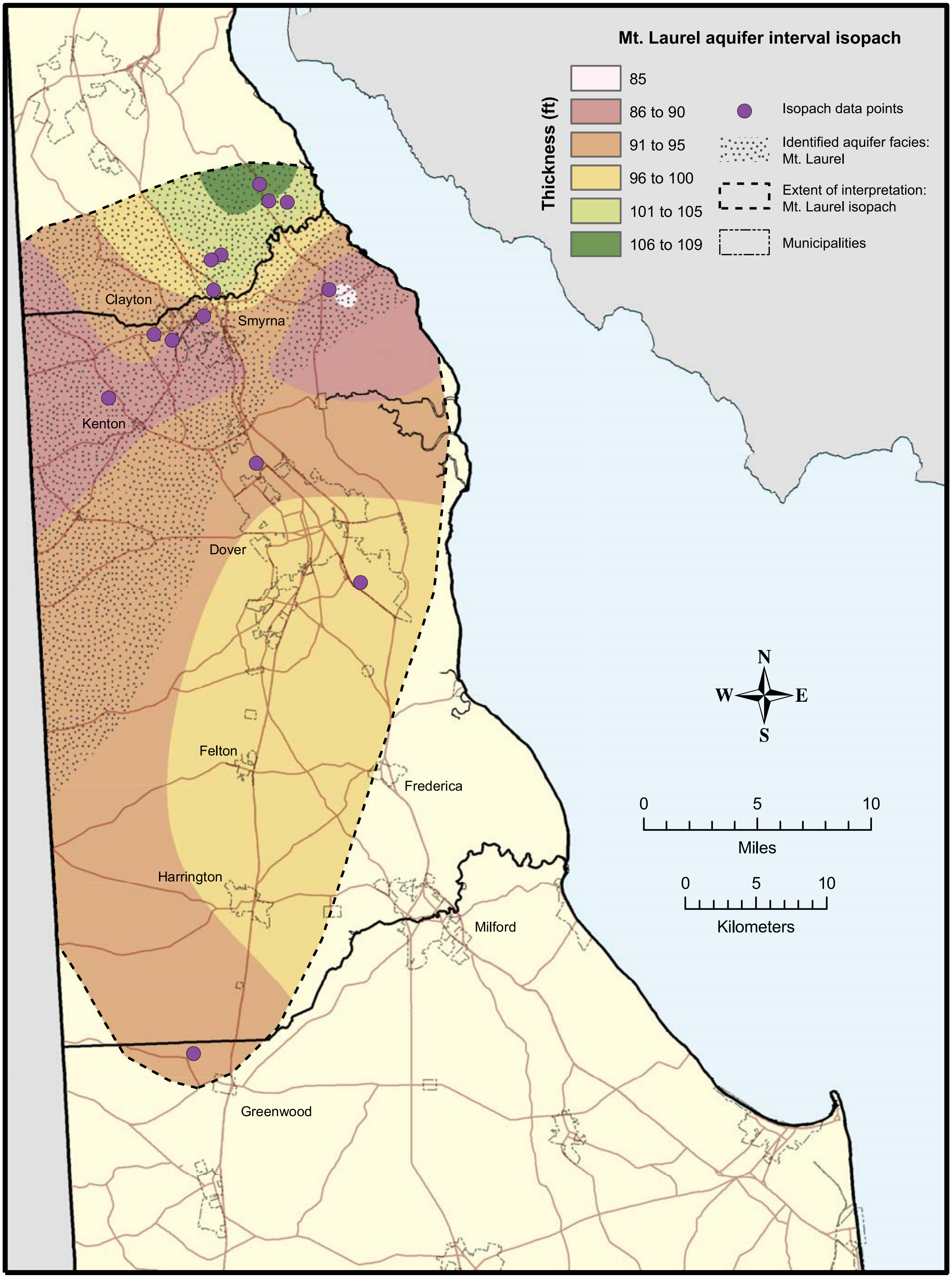

Figure 4. Isopach map of the Mount Laurel aquifer and stratigraphic equivalents. The Mount Laurel aquifer has a fairly consistent thickness in Kent County and surrounding areas, ranging in thickness from just over 100 ft in southeastern New Castle County to just under 90 ft in northern Kent County. Clean sands well suited to aquifer use are known only in the northern part of the county and pass into finer-grained facies southward. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

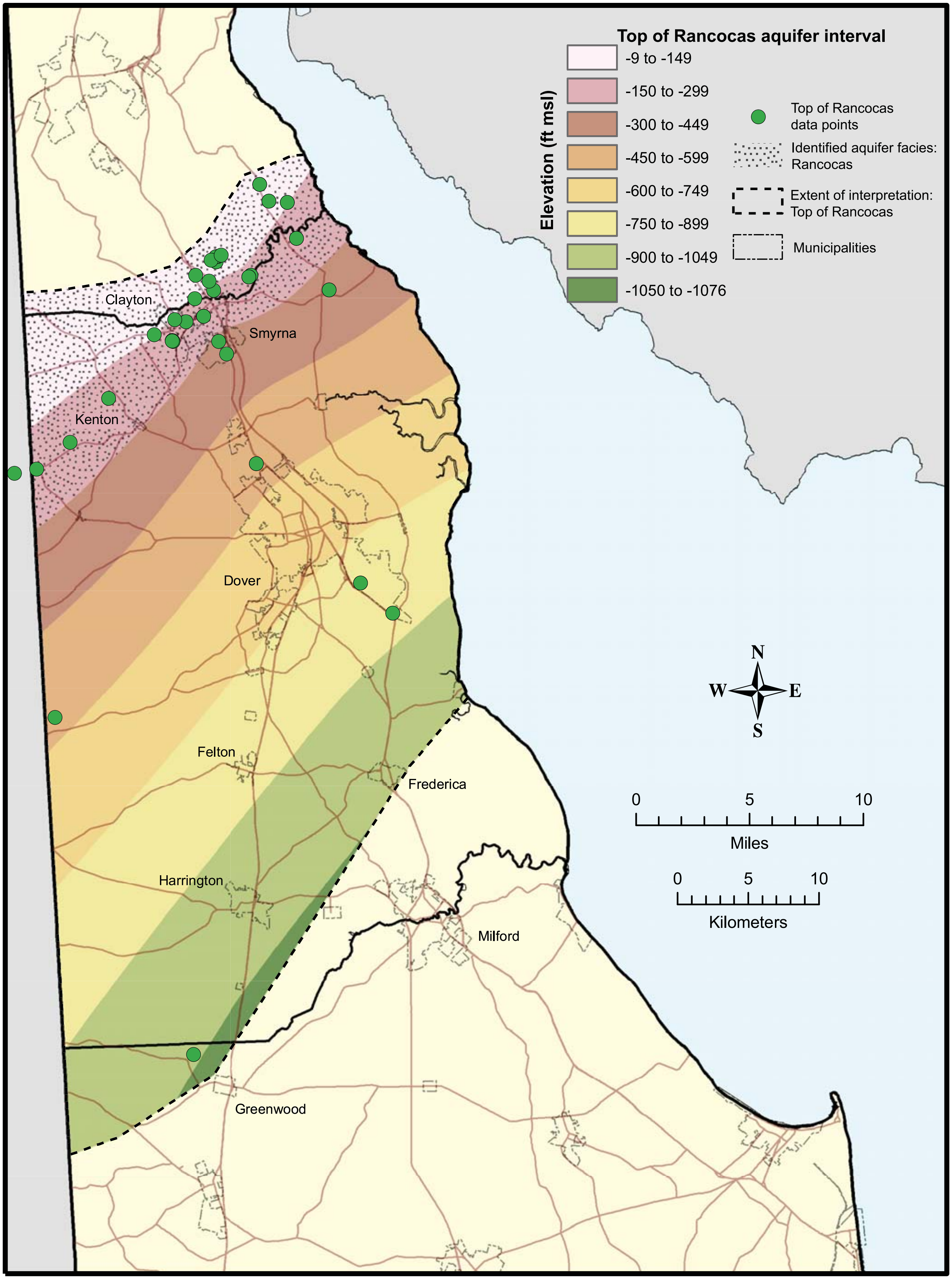

Figure 5. Elevation of the top of the Rancocas aquifer and stratigraphic equivalents. The elevation of the top of the Rancocas aquifer deepens from just below sea-level in northern Kent County to more than 1,000 ft in southern Kent County. Well control is densest in northern Kent County where it is locally an important aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

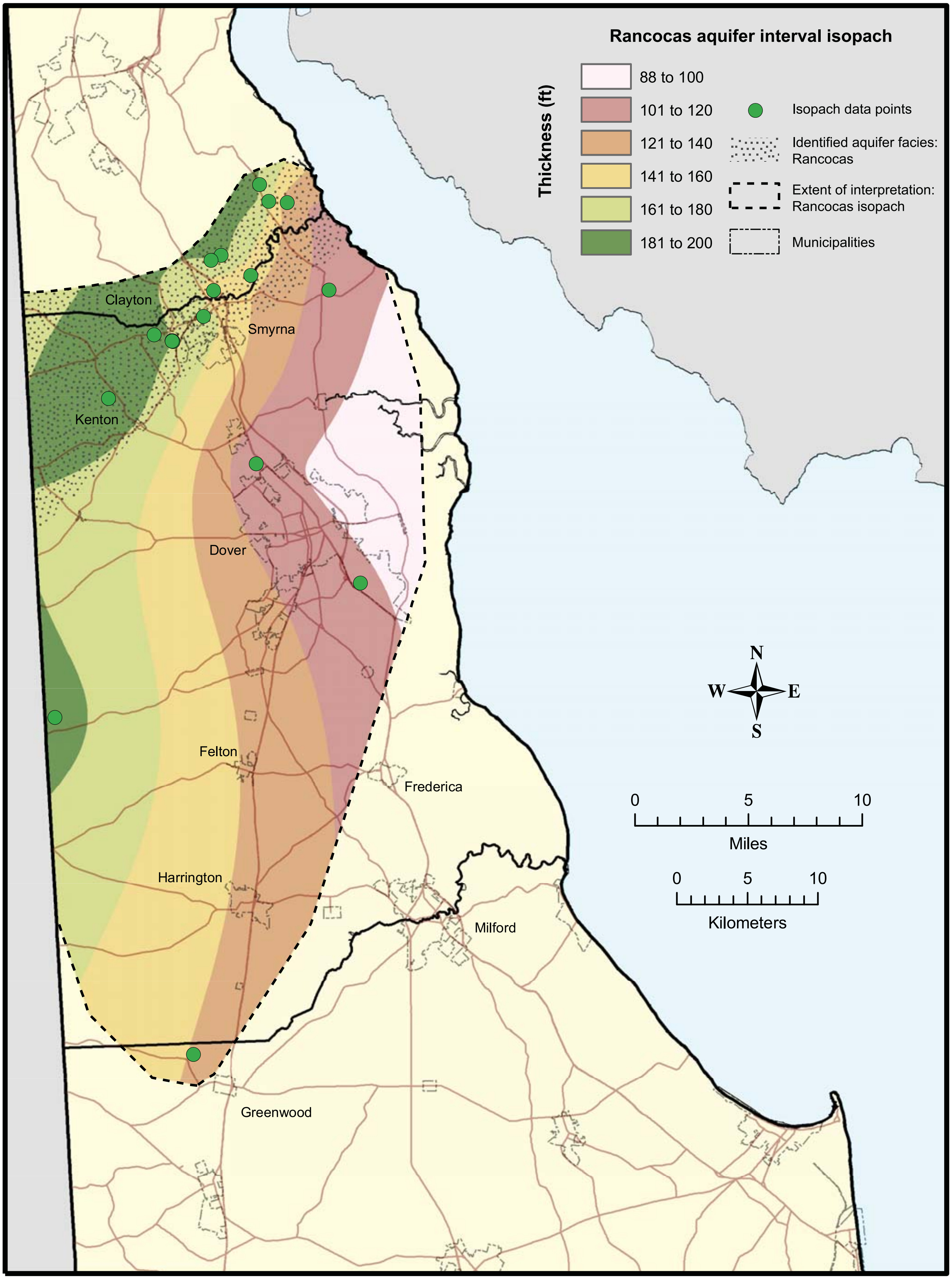

Figure 6. Isopach map of the Rancocas aquifer and stratigraphic equivalents. The Rancocas aquifer shows an overall trend of thinning to the east-southeast from nearly 200 ft in northwest Kent County to less than 100 ft in east-central Kent County. Clean sands well suited to aquifer use are known only in the northern part of the county and pass into finer-grained facies southeastward. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

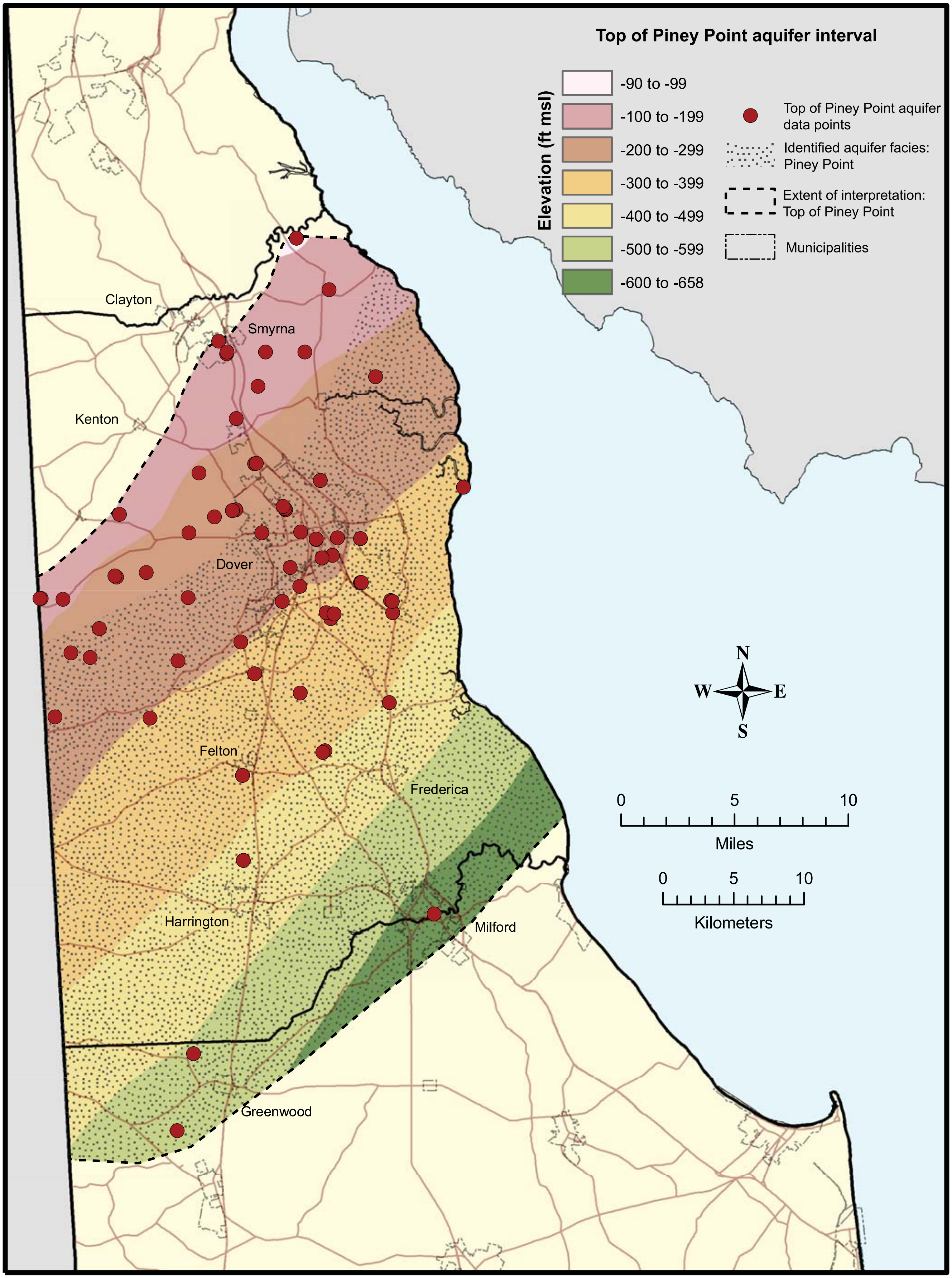

Figure 7. Elevation of the top of the Piney Point aquifer and stratigraphic equivalents. The elevation of the top of the Piney Point aquifer deepens 90 ft below sea-level in northern Kent County to more than 600 ft in southern Kent County. Well control is densest in central Kent County where it is an important aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

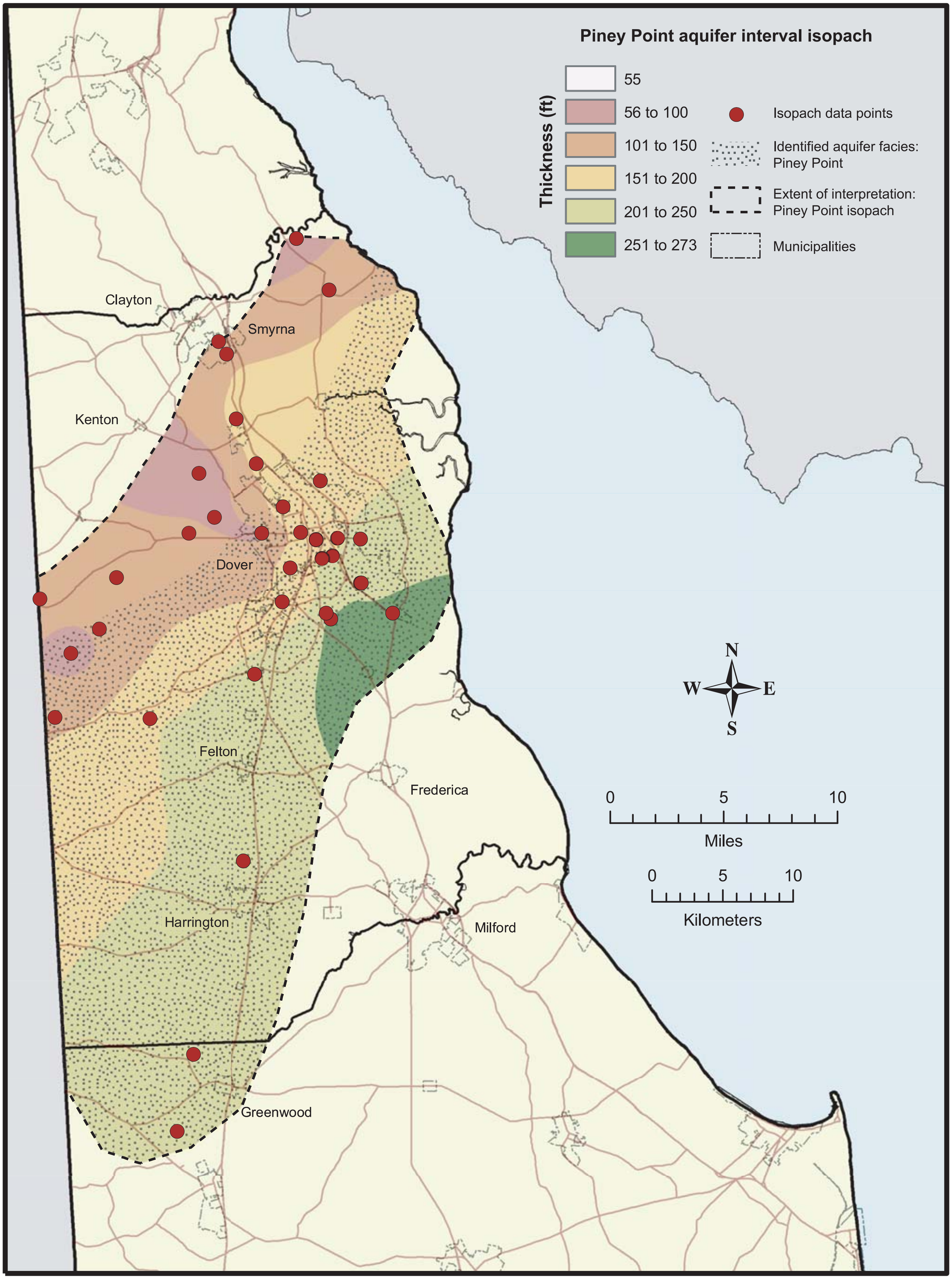

Figure 8. Isopach map of the Piney Point aquifer and stratigraphic equivalents. The Piney Point aquifer generally thickens from the northwest to the southeast in Kent County, with thicknesses ranging from less than 60 ft to more than 250 ft. It is characterized by clean aquifer-quality sands in the Dover area and to the south and east; to the north and west, it is increasingly eroded under a basal Miocene unconformity, with muddier facies characterizing the remaining Piney Point beds in those areas. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

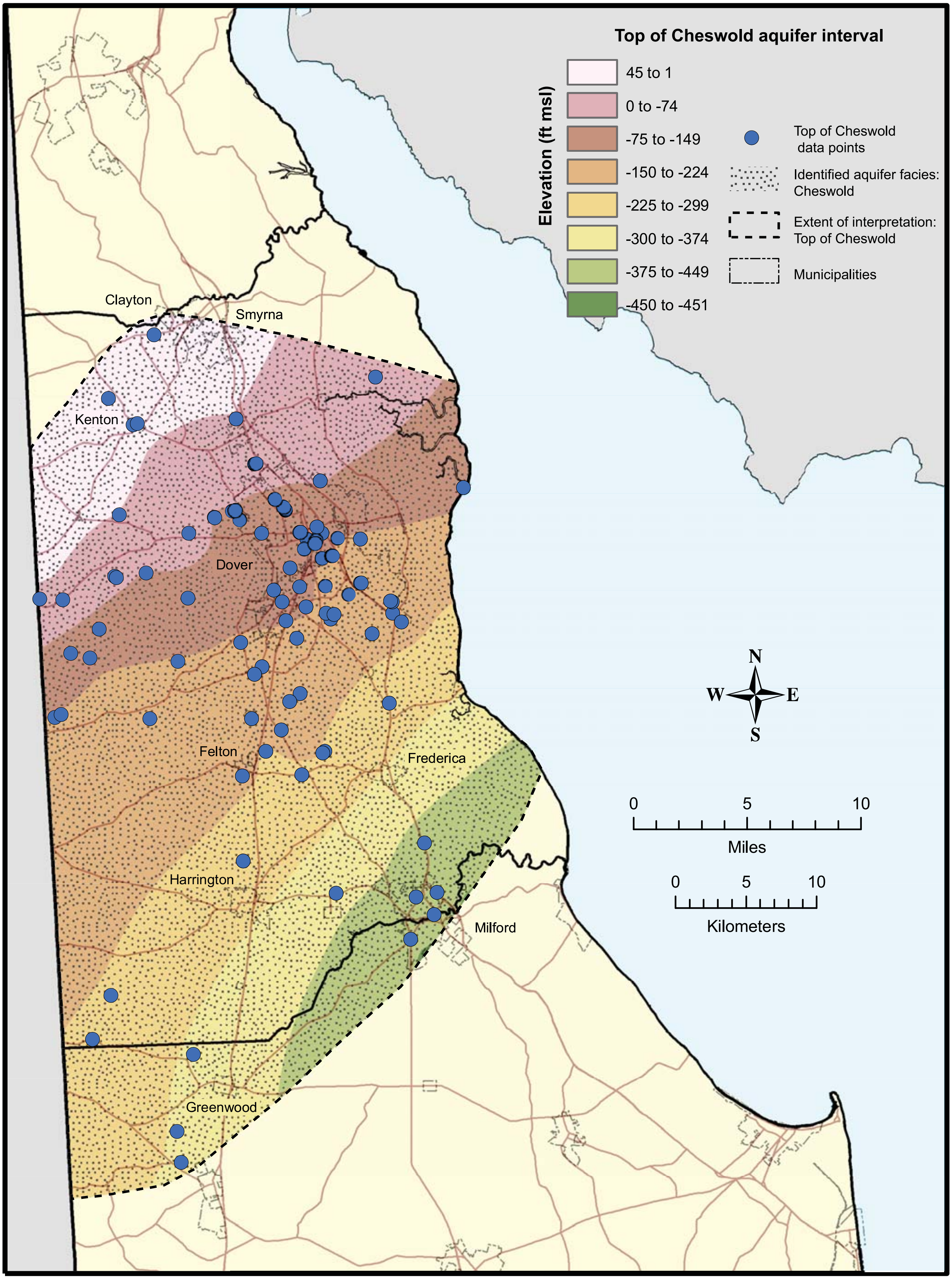

Figure 9. Elevation of the top of the Cheswold aquifer and stratigraphic equivalents. The elevation of the top of the Cheswold aquifer deepens from just below land surface in northern Kent County to more than 400 ft below sea-level in southern Kent County. Well control is densest in central Kent County where it is an important aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

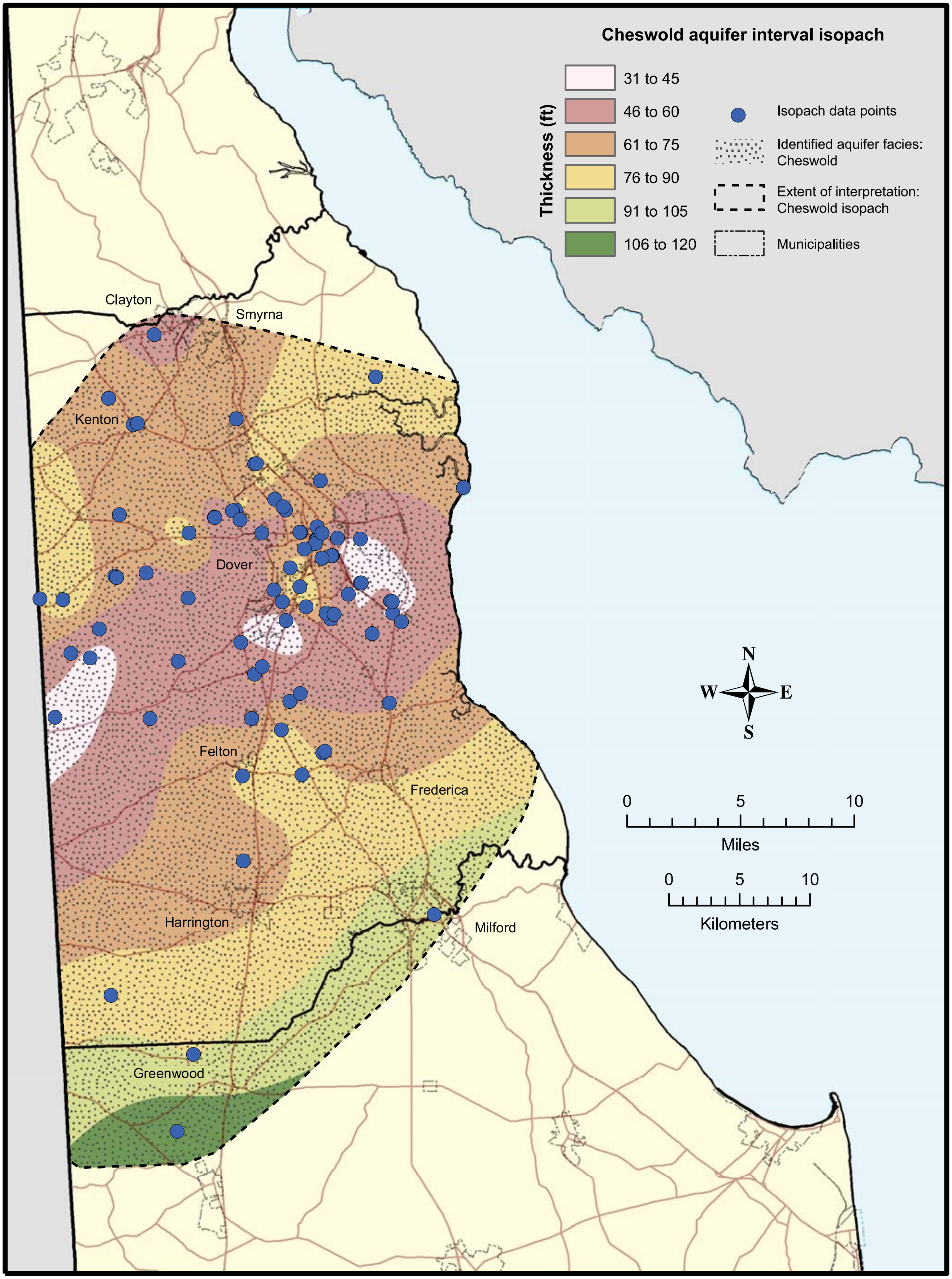

Figure 10. Isopach map of the Cheswold aquifer and stratigraphic equivalents. The thickness of the Cheswold aquifer ranges from 30 ft to nearly 100 ft in Kent County, with a subtle southward thickening trend. The thickness may be more variable than shown here near its northern limit where it subcrops under sands of the Columbia Formation; lithologic similarity makes the contact difficult to identify clearly. The Cheswold aquifer is composed of clean aquifer-quality sands in most of Kent County. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

sands and contain shell fragments and a few percent dark grains (likely heavy minerals).

The Cheswold aquifer is placed in the lower Miocene. A series of strontium age determinations were made through the Miocene section at a continuously cored hole at Bethany Beach (Qj32-27) in southeastern Sussex County. Age determinations just above and below the Cheswold sand indicate the top of the sand is marked by an unconformity from approximately 19.5 to 20 Ma. A slightly younger strontium isotope age determination of 17.9 +/- 0.5 Ma was made on shell material from the Cheswold sand at the Pollack Farm site (Jones et al., 1998), but the age difference may be due in part to the different strontium age calibration used.

Federalsburg aquifer interval

The Federalsburg aquifer is the next highest of the aquifers in the Calvert Formation in Kent County. Cushing et al. (1973) noted the presence of a sandy Miocene unit, between the Cheswold and Frederica aquifers, that is used as a water supply in central and southern Delaware. They considered this interval to be equivalent to an aquifer that occurs from 220 to 300 ft depth in well DO Ah 3 just outside Federalsburg, Md. Based on this, the unit is called the Federalsburg aquifer in Delaware.

The Federalsburg aquifer is present from its updip limit between Cheswold and Dover, where it subcrops under the Columbia Formation, to the south past the Kent-Sussex county line. South of its subcrop area, it is typically confined by an overlying zone of mud that separates it from the Frederica aquifer and an underlying mud that separates it from the Cheswold aquifer. The top of the aquifer ranges in elevation from more than 40 ft above sea level in northern Kent County to more than 350 ft below sea level in southern Kent County (Fig. 11). It is variable in thickness because of facies changes (Fig. 12); it exceeds 60 ft in thickness in western Kent County and along a path from Dover to Milford, but is less than 20 ft thick in a nearly parallel trend from west Dover to Greenwood. Sands of the Federalsburg aquifer have been included in a more broadly defined Cheswold sand in some previous studies; for example, in the Cheswold area (Benson, 1998) and at Dover Air Force Base (Je32-04; Benson and Spoljaric, 1996).

The Federalsburg aquifer is composed of quartz sands that represent similar sedimentary facies as described for the Cheswold aquifer. On geophysical logs, the Federalsburg aquifer is commonly a fining-upward succession and, in many cases, includes a thin coarsening-upward interval at the base (Plate 1, Cross Sections E-E′ and W-W′); these likely represent shallow-marine to estuarine environments. In more southerly locations, a coarsening-upward pattern may be common (Plate 1, Cross Section S-S′), reflecting deposition of a prograding shoreline package. However, more than the Cheswold sand or the higher Miocene aquifers, the Federalsburg aquifer shows significant lateral variability in sandiness on geophysical logs. It appears to be clean, aquifer-quality sand only in local areas of the county (Fig. 11, 12, stippled areas). In between, interbedded mud reduces its utility as a ground-water source. The variations probably represent shifts from cleaner sands in estuarine channel and shoreface settings to muddier deposits in tidal flat and quiet estuarine settings.

The cuttings recovered from the test holes drilled for this study are consistent with these patterns. The Federalsburg aquifer was encountered in four of the test holes: Jc12-16, Kc13-06, Ke23-05, and Ld41-16. In some holes (Jc12-16, Ke23-05), the cuttings consist of shelly, mostly medium-grained quartz sands; in other holes, they are muddy, shelly, fine-to medium-grained sands (Kc13-06, Ld41-16).

The Federalsburg aquifer in most areas has only a thin confining layer (commonly less than 20 ft) between it and the underlying Cheswold aquifer. The confining layer between it and the overlying Frederica aquifer is typically thicker (around 30 ft), but is locally thin. Some of the variability of the thickness of the aquifer and confining layers is due to the sometimes channelized nature of the estuarine depositional systems that deposited the sands; a sharp-based aquifer reflects cutting and coarse-grained deposition at the beginning of deposition of the sand, and it may locally remove part or all of the confining layer that separates it from the underlying unit. In some of these instances, the confining layer may be absent or too thin to be an effective hydrologic barrier between aquifers. Areas with a thin confining layer between the Federalsburg and the underlying Cheswold aquifer were noted in the previous section; examples of thin to non-existent confining beds between the Federalsburg and overlying Frederica aquifer are evident at Nc43-02 (Plate 1, Cross Section W-W′), Kc13-06 (S3-S3′), and Kd23-02 (Woodside area).

An interesting feature of the Federalsburg aquifer evident on many logs is the presence of a distinct spike on the gamma-ray log a few to ten feet below the top of the sand (Plate 1; Nb24-04, Ld55-28, and Me15-29 on Cross Section S1-S1′; Ke23-05 and Le55-12 on E-E′; Kd33-04, and Ld41-16 on W-W′). This is interpreted as reflecting a concentration of authigenic minerals produced at a minor unconformity at the top of the shoaling-upward, nearshore sand package. The thin interval of sand above that is interpreted as a lag deposit of reworked sand laid down at the beginning of the subsequent marine transgression. Although it is genetically separate from the underlying sand, they function together as a single aquifer unit (similar to the Eocene sand and Miocene transgressive lag that together comprise the Piney Point aquifer).

The Federalsburg aquifer is early Miocene in age, like the Cheswold aquifer but slightly younger. Strontium age determinations in Qj32-27 (Bethany Beach) suggest the top of the Federalsburg aquifer sand is capped by a minor unconformity of approximately 18.5 Ma in age (Miller et al., 2003).

The label Federalsburg for this aquifer warrants further consideration. In this study, an attempt was made to correlate the sands identified as the Federalsburg aquifer in Delaware to the type section in Maryland using geophysical logs. The correlation is uncertain; the possibility is just as likely that the Federalsburg aquifer at the type section may be equivalent to the Frederica aquifer in Delaware. Because this determination can only be made with further study, the Federalsburg name is still retained in this report for this aquifer zone in Delaware.

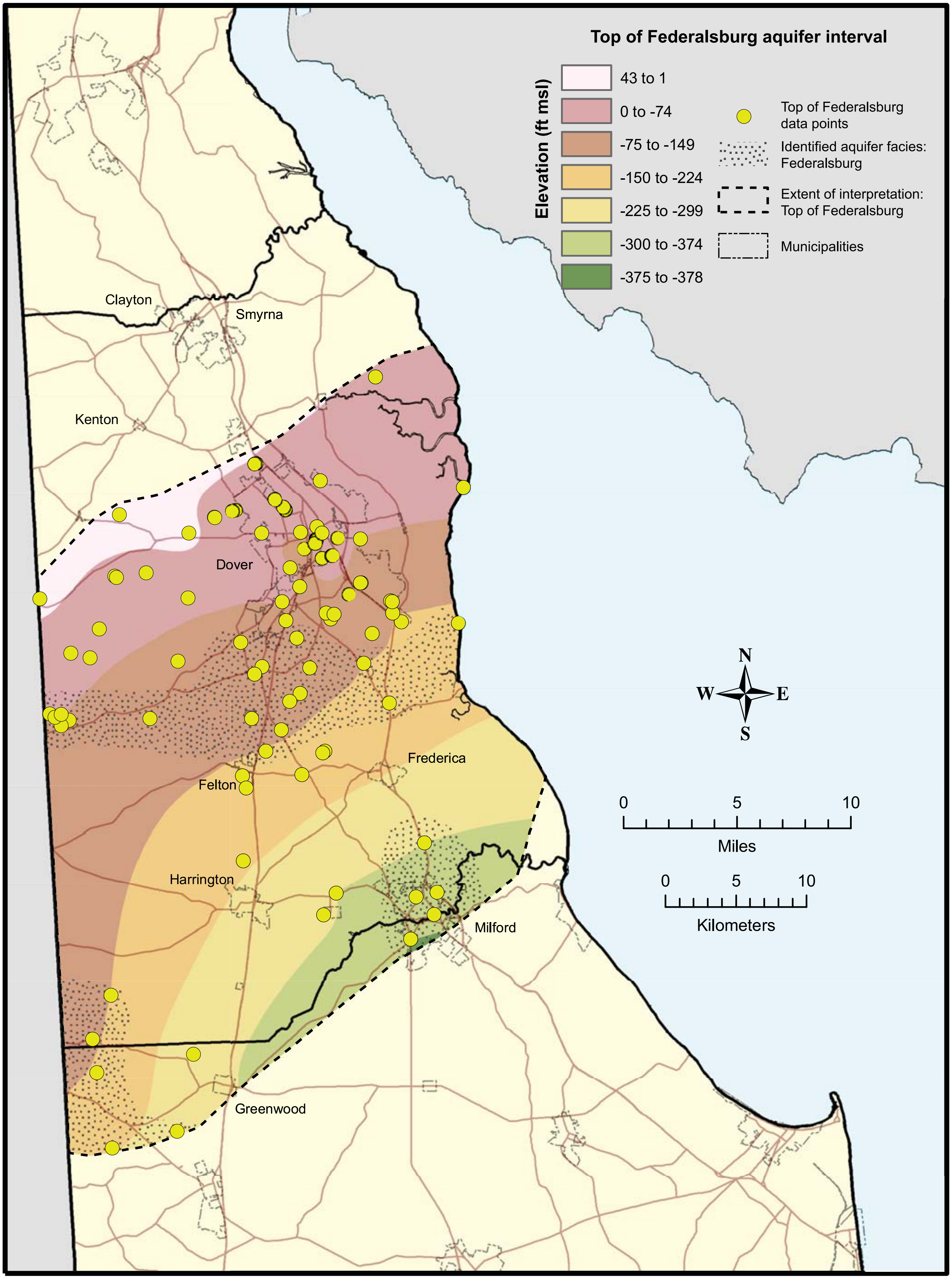

Figure 11. Elevation of the top of the Federalsburg aquifer and stratigraphic equivalents. The elevation of the top of the Federalsburg aquifer deepens from just below land surface in north-central Kent County to approximately 350 ft below sea level in southern Kent County. Well control is densest in central Kent County where it is locally used as an aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

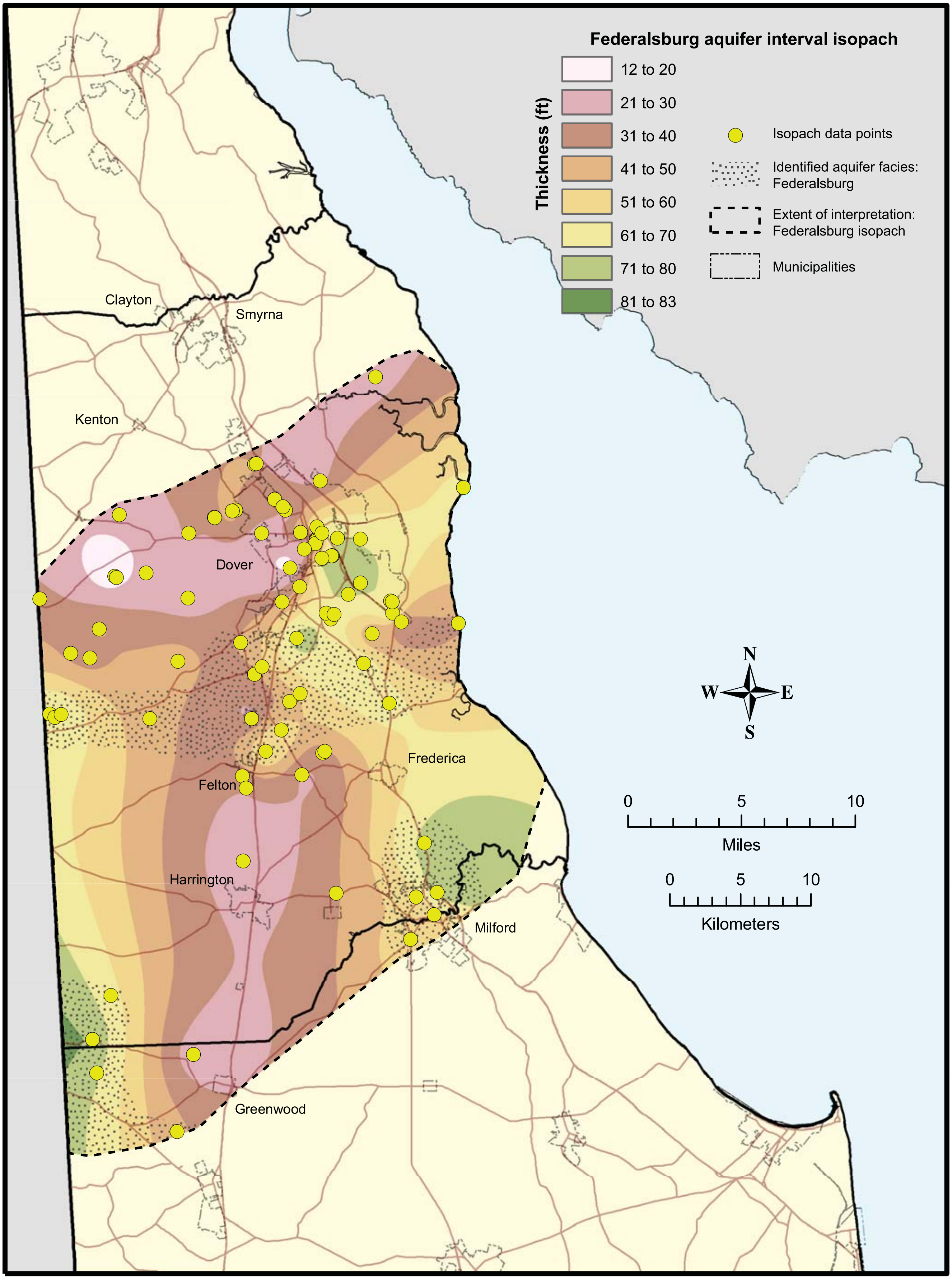

Figure 12. Isopach map of the Federalsburg aquifer and stratigraphic equivalents. The thickness and aquifer quality of the Federalsburg aquifer are highly variable in Kent County. The thickness ranges from less than 20 ft to more than 80 ft, with greater thicknesses noted in wells near the Maryland state line. The distribution of clean sand well-suited to aquifer use is patchy. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

Frederica aquifer interval

The Frederica aquifer is the uppermost of the three aquifers in the Calvert Formation. It is long known as a ground-water source in Kent County. Marine and Rasmussen (1955) referred to a "shallow" Miocene sand used between Camden and Milford and Rasmussen et al. (1958) used the name Frederica aquifer for this unit.

The Frederica aquifer is present over most of southern Kent County. Its northern limit is in the Dover area, where it subcrops under the Quaternary-age unconfined aquifer sands of the Columbia Formation. The elevation of the top of the Frederica aquifer ranges from more than 30 ft above sea level in west-central Kent County to more than 250 ft below sea level in the Milford area (Fig. 13). It is typically around 50 ft thick, but it may be less than 30 ft thick near its northern subcrop area and more than 75 ft thick locally in the southwest part of the county (Fig. 14).

Like the Cheswold and Federalsburg aquifers, the Frederica aquifer is composed of quartz sands, commonly shelly, and was deposited in nearshore-marine and estuarine environments. It commonly exhibits a fining-upward pattern and, in places, a thin coarsening-upward interval at the base (Plate 1, Cross Sections S1-S1′ and S2-S2′); these likely represent shallow-marine to estuarine environments. Although the Frederica aquifer consists of clean, aquifer-quality sand over most of the county (Figs. 13, 14, stippled areas), locally it may contain intercalated finer-grained beds which would diminish aquifer quality (Kd12-07, Plate 1, Cross Section S2-S2′); these may represent intervals of muddy intertidal or estuarine facies. The coarsening-upward pattern recognized in the underlying Miocene aquifers at more southerly sites is not recognized in the Frederica aquifer in the study area, probably because the shallow-marine shoreface environments were located further to the south.

The Frederica aquifer was encountered in test holes Kc13-06, Ke23-05, and Ld41-16; well Jc12-16 appears to be located in the recharge area for the Frederica where it subcrops. The cuttings samples from the Frederica aquifer commonly consist of medium- to coarse-grained quartz sand or muddy fine- to medium-grained sand, both with common shell material, similar to the Cheswold and Federalsburg aquifers.

The Frederica aquifer is typically overlain by a fairly thick (30 ft or more) confining layer of muddy facies that comprise the top of the Calvert Formation. It is underlain by a muddy zone of more variable thickness, commonly around 30 ft but in places thinner due to erosion on the base of the Frederica aquifer (Kc13-06 and Nc43-02; Plate 1, Cross Sections S3-S3′ and W-W′). In such areas, the confining layer may be too thin to be an effective hydrologic barrier between the Frederica and the underlying Federalsburg aquifer.

The distribution of the Frederica aquifer presented in this report is considerably different than that in older reports such as Sundstrom and Pickett (1968). The designation Frederica aquifer was commonly used for the interval considered the "shallower" Miocene aquifer in southern Kent County. Based on newer information, Ramsey (1997) recognized that the interval referred to as the Frederica aquifer in the Milford area was, in fact, a higher sand than the Frederica aquifer around the town of Frederica; he designated it as the Milford aquifer, which will be discussed in the next section. The correlations in this report follow his aquifer assignments in the Milford area and, as a result, allow more accurate mapping of aquifer depths and thickness.

The Frederica aquifer is the highest lower Miocene aquifer unit. In cores from Qj32-27 (Bethany Beach), strontium isotope data suggest it is capped by a significant unconformity representing a break from approximately 18 to 17.2 Ma (Miller et al., 2003).

Milford aquifer interval

The stratigraphically highest aquifer treated in this report is the Milford aquifer. The name Milford aquifer was established by Ramsey (1997), who recognized that the shallow Miocene aquifer referred to as the Frederica aquifer around Milford (Sundstrom and Pickett, 1968, 1969; Cushing et al., 1973; Talley, 1982) was actually a stratigraphically higher sand. The type section is drill hole Me14-20.

The Milford aquifer lies at the base of the Choptank Formation; the base of the aquifer marks the base of the formation. It is composed of quartz sands that are commonly coarse-grained or even granule-bearing near the base; shelly intervals have been noted in its higher parts (Ramsey, 1997). It occurs in southern Kent County, extending southward into Sussex County and is commonly used for domestic water supplies in the Milford area.

The Milford aquifer occurs as far north as a zone trending from west of Harrington to southeast of Dover, where it subcrops under the Columbia Formation and has its recharge area. The top of the Milford aquifer deepens to the southeast, reaching nearly 200 ft below sea level in the Milford area (Fig. 15). It thickens in the same direction, from as little as 15 ft thick in the northwest to more than 60 ft thick in the southeast (Fig. 16). In southern Kent County, it exhibits a blocky or fining-upward log pattern consistent with deposition in estuarine (and likely channelized) environments. As a note, in this report, a greater thickness of sandy facies is included in the Milford aquifer than in Ramsey (1997); as an example, Ramsey includes only the basal 15 ft of blocky sand in Me14-20, whereas this report includes the entire sandy interval of more than 60 ft in thickness.

The Milford aquifer was encountered in two test holes drilled for this study (Ke23-05, Ld41-16). The cuttings samples consist of medium to coarse to very coarse quartz sands that include granules and pebbles in places (Ke23-05) and are in other places muddy (Ld41-16). No shell material was noted in the Milford aquifer in these holes.

The Milford aquifer is generally overlain by a thin (in places <20 ft) confining layer that separates it from stratigraphically higher sands of the Choptank Formation. In most areas, the underlying confining layer is a relatively thick (commonly 30 to 50 ft), brown clayey silt that Ramsey (1997) considered distinctive as the top of the Calvert Formation. However, this underlying interval can be sandy in places, raising questions about its effectiveness as a confining layer everywhere (e.g., Nc43-02; Plate 1, Cross Section W-W′).

Ramsey (1997) considered the base of the Milford aquifer

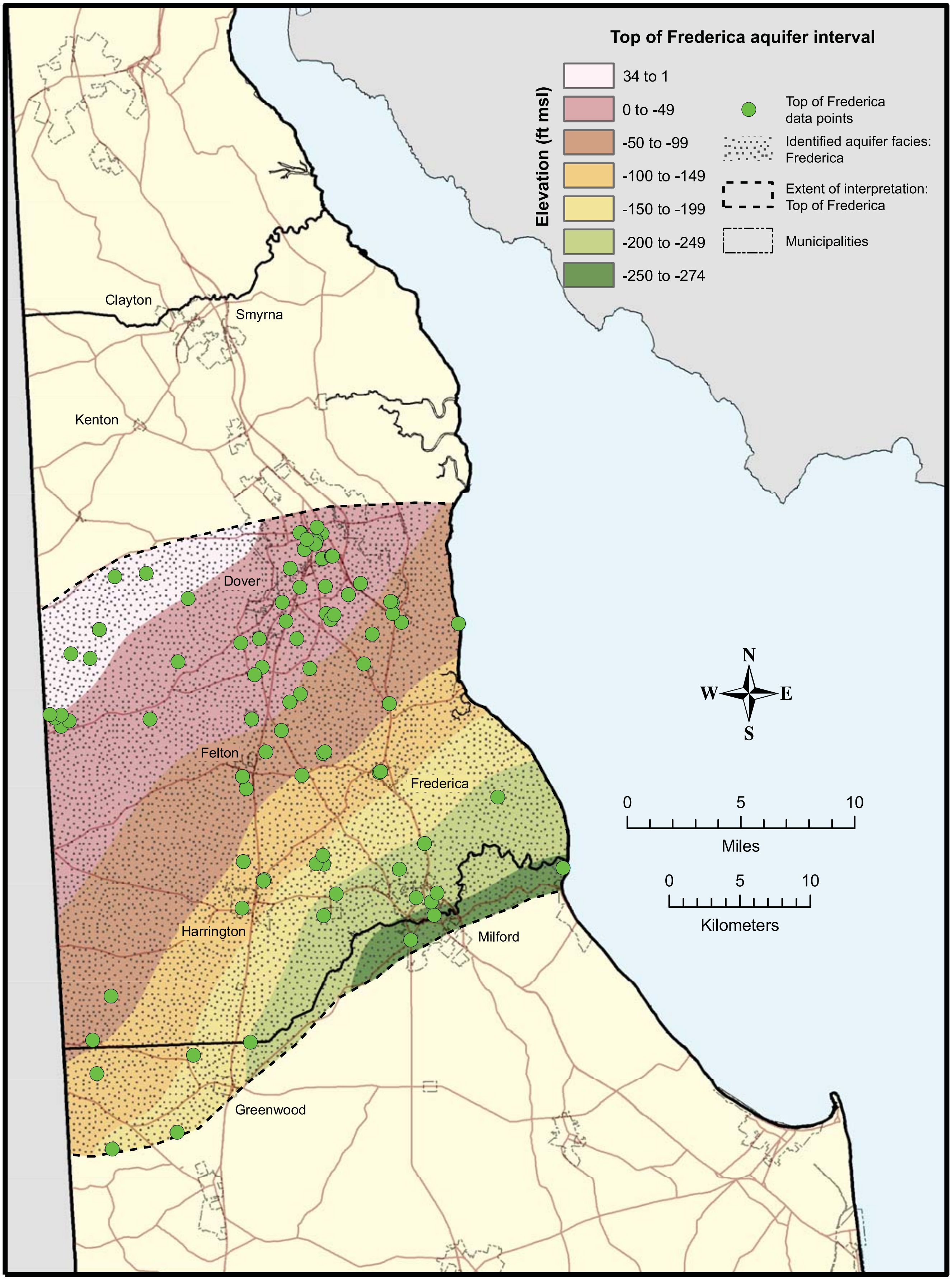

Figure 13. Elevation of the top of the Frederica aquifer and stratigraphic equivalents. The elevation of the top of the Frederica aquifer deepens from just below land surface in central Kent County to approximately 250 ft below sea level in southern Kent County. Well control is densest in the southern half of Kent County where it is an important aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

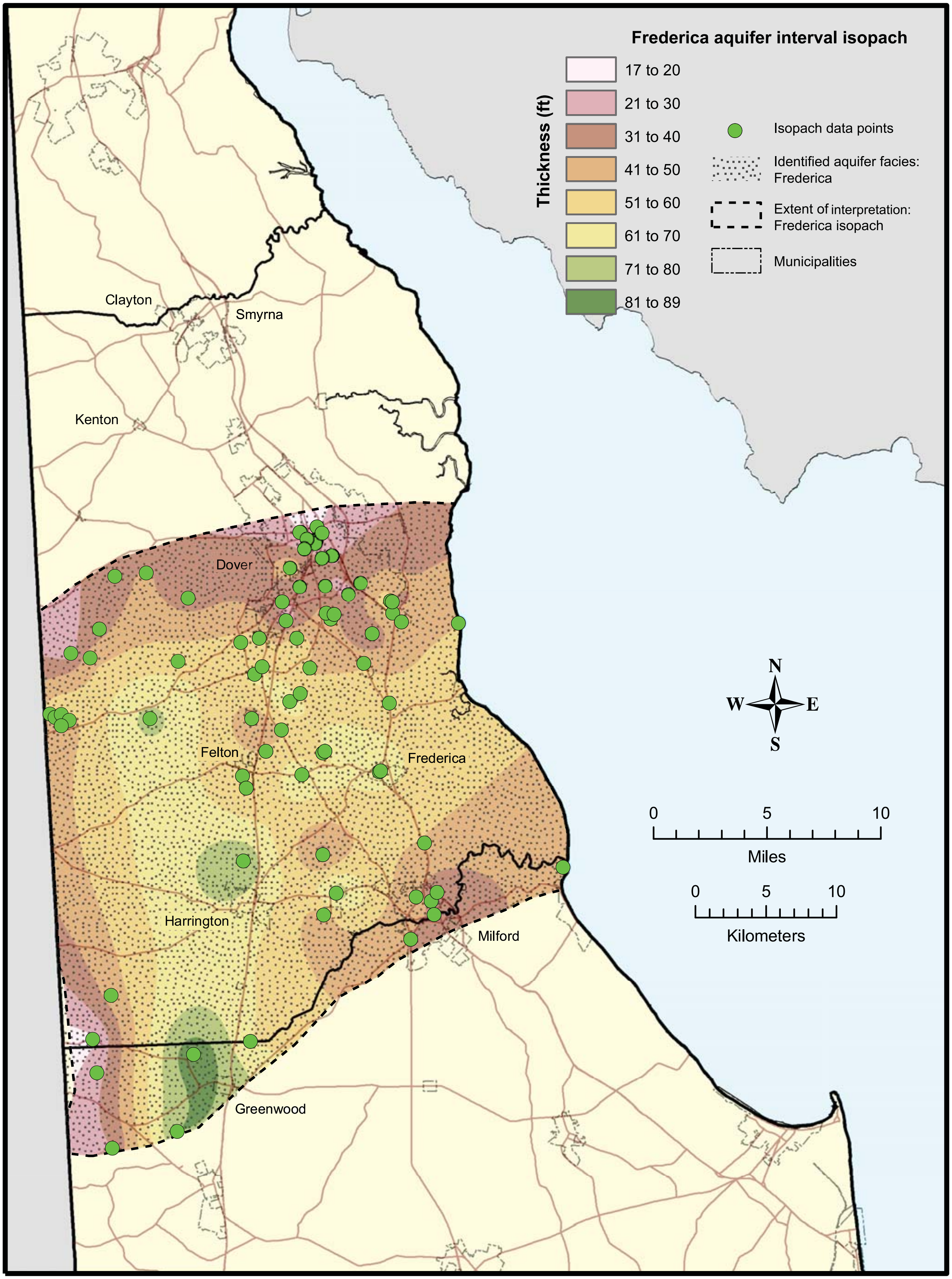

Figure 14. Isopach map of the Frederica aquifer and stratigraphic equivalents. The thickness of the Frederica aquifer ranges from less than 20 ft to more than 70 ft in Kent County. It is composed of clean aquifer-quality sands throughout the county. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

to be an unconformity because of the distinct change in grain size. However, in this report, the contact is interpreted to be a normal shift in facies from shallow-offshore muds to erosional estuarine regimes that are filled by tidal channel sands and gravels. Instead, based on regional evidence and sequence stratigraphy, we recognize an unconformity at the top of the Milford sand. In cores from Qj32-27 (Bethany Beach), strontium isotope dates indicate that this is a minor middle Miocene unconformity of approximately 16.5 Ma age (Miller et al., 2003).

DISCUSSION

The confined aquifers of Kent County present a variety of issues in geologic interpretation that have considerable bearing on understanding the availability of ground-water resources. The basic geologic trends are relatively straightforward. All aquifers treated in this report show an overall trend of increasing depth toward the south or southeast. Sedimentary facies changes typically parallel this trend, with more proximal (nearshore) facies to the north or northwest and more distal (offshore) facies to the south of southeast. Although the entire Upper Cretaceous to Quaternary sedimentary section thickens overall to the south-southeast, consistent with this trend, the same does not necessarily hold true for individual aquifers; some thicken in that direction, whereas others show more complex patterns related to sedimentary paleoenvironments.

Some previous reports (Benson and Spoljaric, 1996; Andres and Howard, 1998; Andres, 2001) have postulated northeast-southwest trending faults in northern Kent County that account for much of the southeastward thickening in section. Geophysical log correlation reveals significant increases in depth of key stratigraphic surfaces between some wells used for cross sections in previous studies. However, the maps and cross sections presented herein provide a large amount of additional well data beyond those on the previously published cross sections. These data suggest that the southeastward thickening of the section and the increasing depth of stratigraphic horizons represent a continual trend rather than the previously postulated, fault-controlled, step-wise increases in depth. Therefore, we do not include faults on the cross-sections or maps in this report.

The trend toward more offshore facies to the south-southeast is basically evident at the stratigraphic level of all of the aquifers (with the exception of the Piney Point aquifer, which shows some differences as a result of truncation to the north). The Mount Laurel and Rancocas aquifers change from glauconitic shelf sands in northern Kent County to muddier, deeper-water, non-aquifer facies in central and southern Kent County.

The four Miocene aquifers – the Cheswold, Federalsburg, Frederica, and Milford – are largely similar to one another in their expression of updip-to-downdip facies changes. The Cheswold aquifer serves as a good working model for characterization of these aquifers; log patterns observed in the area can be calibrated to facies types described at the Pollack Farm site by Ramsey (1998). In their more northern, updip locations, these aquifers commonly have a sharp base, above which grain size remains consistent (producing a blocky log pattern) or fines upward. These reflect a shoaling-upward succession from muddy offshore facies (perhaps 30 to 50 ft water depth) to nearshore facies, with estuarine or tidal channels cutting significantly into the underlying beds (which, in a sense, makes this normal facies change appear fairly abrupt). The upward fining reflects a change from tidal channels and deltas to quiet-water estuarine deposits or tidal flats. In some locations, the erosion associated with estuarine/tidal channel deposition appears to cut deeply into the underlying confining unit; this may account for the observations of locally very thin confining layers between the three aquifers in the Calvert Formation, the Cheswold, Federalsburg, and Frederica aquifers. The broader implication of this observation is that the aquifers in the Calvert Formation may behave, in places, as a leaky system of one or two aquifers rather than as three distinct aquifers.

In more medial locations, the Miocene aquifers tend to exhibit 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 it is a bit further offshore; as a result, the development of channels at the top is weaker, and more of the coarsening-upward shoreface package under the cap of estuarine deposits is preserved.

In the more downdip, southern locations, these aquifers exhibit a coarsening-upward pattern that reflects shoaling and shoreline progradation; the facies change upward from offshore muds (as much as 100 ft water depth) to muddy or fine lower shoreface sands to coarser upper shoreface sands (5 to 20 ft water depth).

The shallowing-upward packages that make up these four Miocene aquifers appear, in most cases, to be fairly abruptly overlain by deeper-water deposits that reflect a marine transgression. The contact between the shoaling-upward package and the transgression commonly shows some evidence for an unconformity; in some places, a cemented zone is present (perhaps a marine hardground); in other places, concentrations of authigenic minerals (phosphate) are noted; and, in other places, transgressive lag deposits may be present (see Miller et al., 2003, for examples from cores). As the transgression continues above this level, water depths increase and input of coarse clastics is reduced, resulting in the deposition of offshore mud facies that serve as confining layers.

The aquifer-confining layer alternations in the Miocene section of central Delaware represent cyclic pairs that reflect a transition from deeper-water confining layer facies to shallower-water aquifer facies. This facies change reflects sea-level rise and fall and can be characterized using the concept of sequence stratigraphy. A sequence is a genetically related, unconformity-bound stratigraphic unit. It can be subdivided into smaller packages called systems tracts based on patterns of facies change; each systems tract can generally be related to certain conditions of relative sea-level change. The stratigraphic package most characteristic of the central Delaware Miocene – a shoaling-upward transition from offshore muds and muddy sands facies to nearshore sand deposits that comprise the aquifers – are interpreted as highstand systems tract deposits, taking shape when shoreline progradation rates exceeded a relatively static rate of sea-

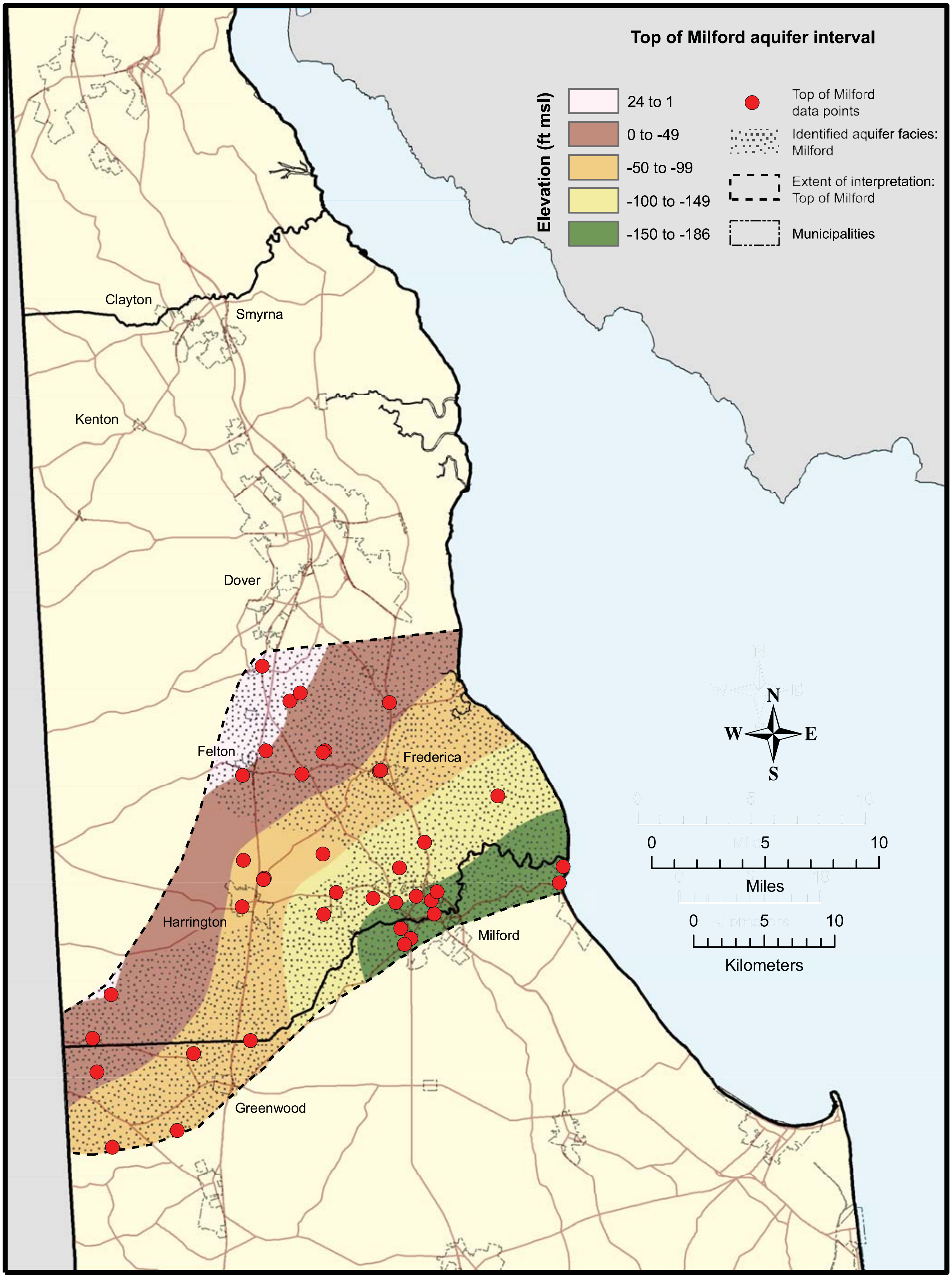

Figure 15. Elevation of the top of the Milford aquifer and stratigraphic equivalents. The elevation of the top of the Milford aquifer deepens from just below land surface in south-central Kent County to more than 150 ft in southern Kent County. Well control is densest in southern Kent County where is locally used as an aquifer. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

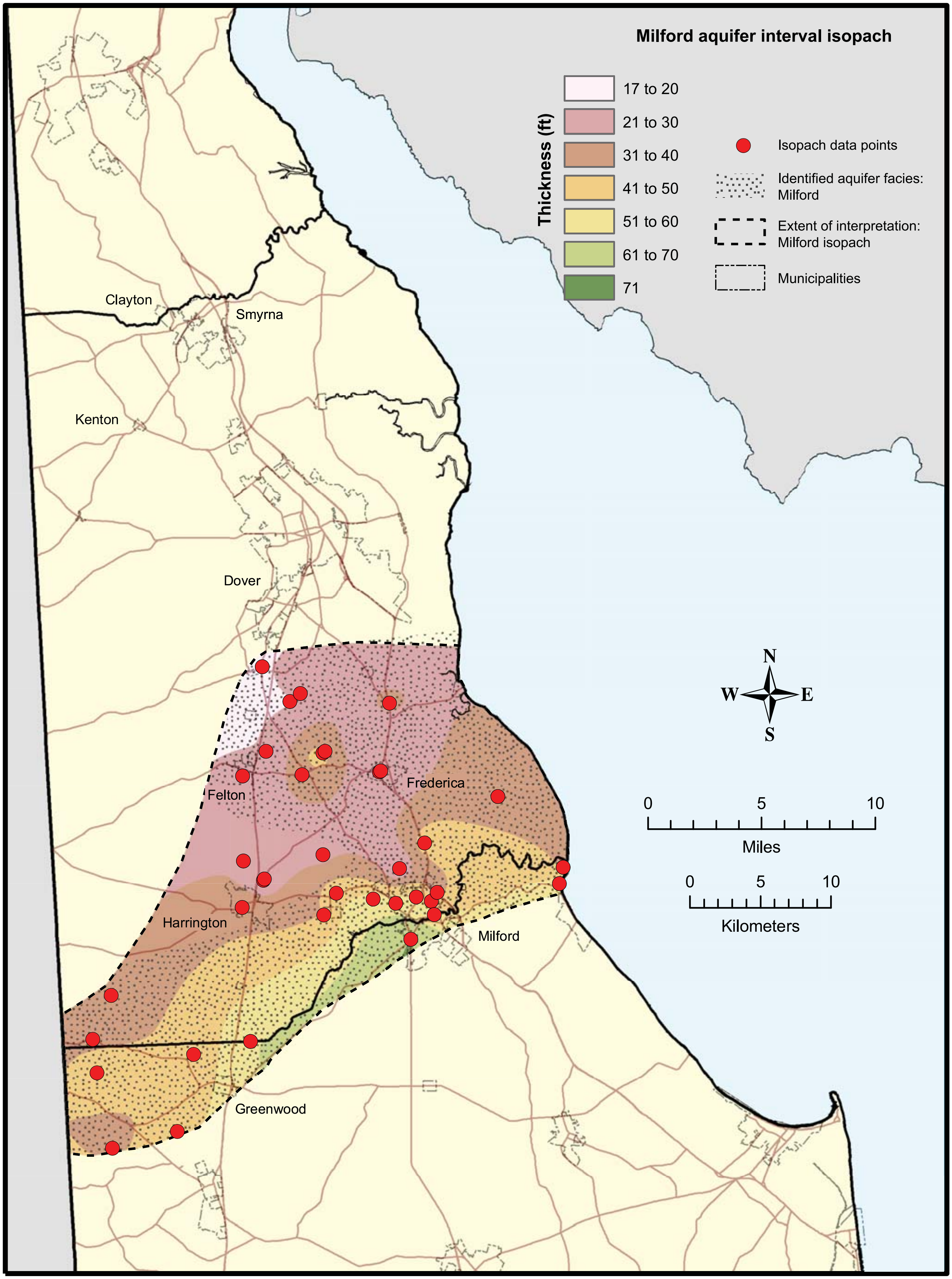

Figure 16. Isopach map of the Milford aquifer and stratigraphic equivalents. The thickness of the Milford aquifer ranges from 15 ft in ear its northern limit in south-central Kent County to more than 60 ft in the Milford area, with an overall southward thickening trend. The aquifer quality of the sands is somewhat variable, with a clean geophysical log signature in most records from southern Kent County but some areas with muddy intervals. The stippled pattern represents sandy facies that are thought to be porous, permeable aquifer-quality lithologies.

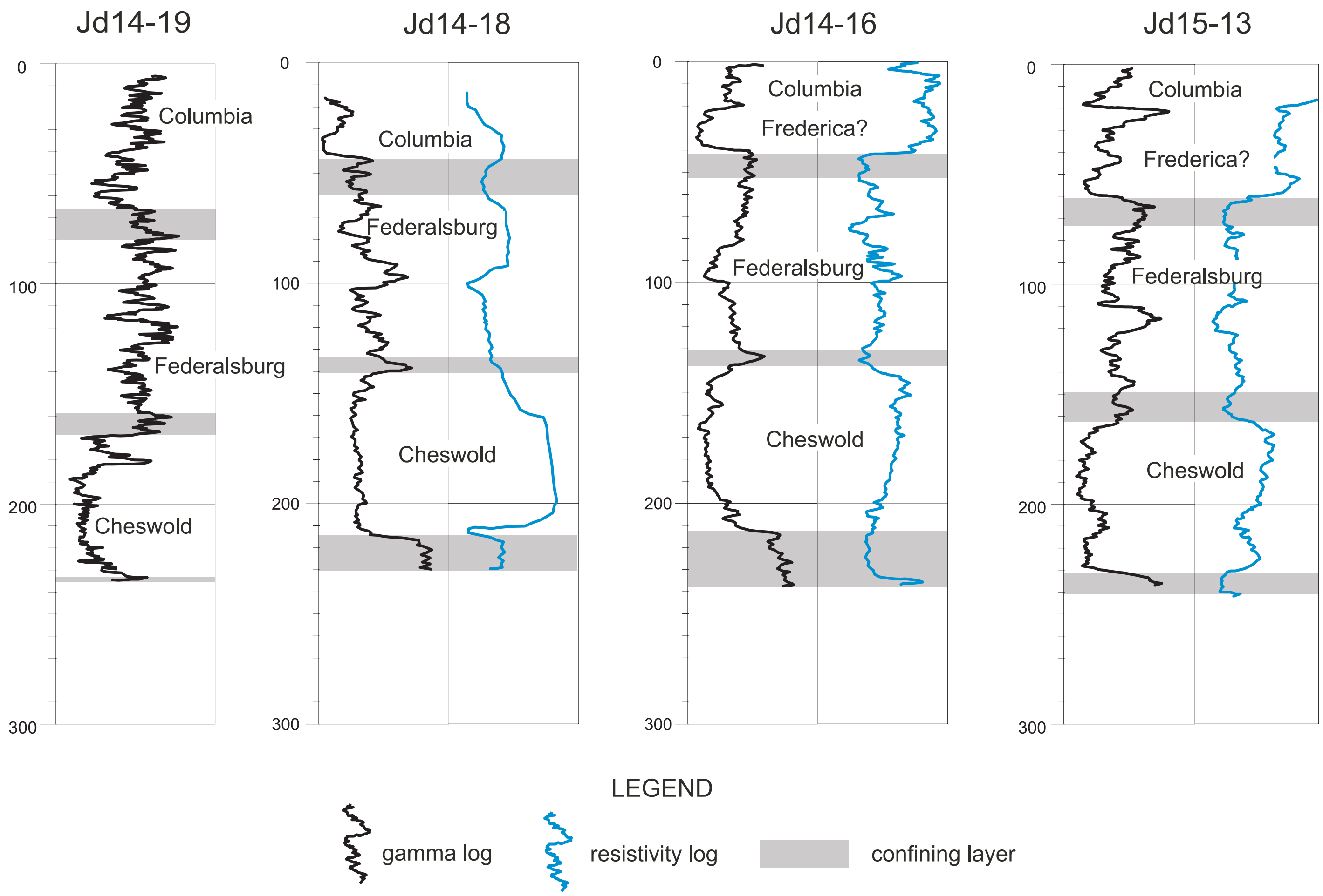

Figure 17. Geophysical logs showing the character of the stratigraphic interval between the Columbia and Cheswold aquifers, Dover, with special attention to potential confining layers.

level change. 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 lag deposits and muds are interpreted as transgressive systems tract deposits produced by the subsequent rise of sea level. Miller (2002) has estimated that the amplitude of some early and middle Miocene sea-level changes may be as much as 100 ft or more based on Ocean Drilling Program records, so Miocene locations in Delaware would have experienced significant changes in shoreline position through time.

The question of geologic controls on possible aquifer leakage has also been an issue of interest in Kent County. Johnston (1977) identified an area in the middle of Dover (near the Division Street bridge over the St. Jones River) where he computed substantial vertical leakage from the Columbia aquifer into the Cheswold aquifer due to heavy pumping of the Cheswold aquifer. Geophysical logs are available for a hole at this location (Jd14-18) and nearby sites (Fig. 17). Our examination of the geology of this area does not exclude the possibility of leakage from the Columbia aquifer into the Cheswold aquifer, but it does not show a clear pathway, either. This site is located in the general subcrop area of the Frederica aquifer, where the Frederica aquifer is commonly in direct contact with the Columbia aquifer (i.e., Jd14-16, Fig. 17); this provides a potential flow pathway downward. The confining layer under the Columbia/Frederica sand appears to be around 10 to 20 ft thick in this area and does not appear to be especially fine-grained based on gamma and resistivity logs; therefore, it may be leaky. The Federalsburg aquifer is present below the Frederica aquifer in this area, but it hardly qualifies as an aquifer; it is generally a muddy sand facies and in some wells has a distinct mud break within it (Fig. 9, Jd15-05; Fig. 17, Jd14-18 and Jd15-13). In at least one site (Jd14-18, Fig. 17), it appears that the Columbia aquifer may be nearly in contact with the top of the Federalsburg aquifer, with only a slightly muddy confining layer in between. The possible leakiness of the confining layer between the Columbia/Frederica and the Federalsburg sand may allow further downward groundwater flow. The final barrier is the confining layer between the Cheswold sand and the Federalsburg sand; although this zone exhibits some of the higher (muddier) gamma values in the geophysical log records near this location (Fig. 17), it is very thin – in places less than 10 ft – so it may allow leakage. Is the geology of the interval between these aquifers notably more “leaky” at this site than in other parts of Kent

County? A comparison of the local geophysical logs (Fig. 17) to the cross-sections (Plate 1, Cross Sections N3-N3′, S3-S3′, E-E′, and W-W′) suggests it has several aspects that might contribute to leakiness – possible local proximity of the base of the Columbia aquifer to the top of the Federalsburg sand, and a locally thin confining layer between the Cheswold and Frederica sands – but it does not have exceptionally open flow pathways, either. Heavy pumping at nearby wells may be the explanation for Johnston's (1977) finding; however, there are probably other areas around Dover where the geology would similarly allow leakage with equivalent pumping.

We expect that the results of this study, when combined with the results of ongoing surficial geological mapping, will allow the subcrop areas of each aquifer to be delineated. The relationship between the confined aquifers and the surficial aquifer was not included in the scope of this study because it would require detailed analysis of the surficial geology of the county. Where Columbia sands rest directly on sands of the Cheswold, Federalsburg, Frederica, or Milford aquifers, the exact level of the contacts may be difficult to identify because of the similarity of the lithologies. We expect that this will be adddressed in a future study of the unconfined aquifer of Kent County.

SUMMARY

New subsurface geological data combined with new stratigraphic approaches allow improved delineation of the distribution and geological characteristics of seven confined aquifers in Kent County. The lowest of the units treated here, the Mount Laurel aquifer, is a Late Cretaceous (Campanian) unit that occurs at around 300 ft below sea level in the Smyrna-Clayton area and is locally used as a ground-water source. In northern Kent County, it is typically composed of just under 100 ft of glauconitic quartz sands deposited in a shelf setting that pass southward into age-equivalent, finer-grained, non-aquifer facies. Two Paleogene-age aquifers lie above the Mount Laurel aquifer. The Rancocas aquifer is a glauconite-rich Paleocene-Eocene shelf sand used as a ground-water source in northern Kent County. It occurs as high as 100 ft below sea level in northwestern Kent County and becomes deeper southeastward; it rapidly changes facies to finer-grained, non-aquifer lithologies in the same direction. Above these units lies the Piney Point aquifer, an important ground-water source in central and southern Kent County. This middle Eocene unit is a coarsening-upward, shelly, glauconitic, quartz sand deposited in a shelf environment. The top of the Piney Point aquifer ranges from around 250 ft below sea level in the Dover area to more than 700 ft below sea level in southeastern Kent County. To the north-northwest of Dover, the Piney Point aquifer thins and becomes finer grained, eventually disappearing in the Smyrna area, reflecting its truncation by a basal Miocene unconformity.

The glauconitic aquifers of the pre-Miocene section are overlain by four Miocene-age aquifers used in central and southern Kent County: Cheswold, Federalsburg, Frederica, and Milford. All four of these nearshore aquifer sands represent shallowing-upward coastal successions, with estuarine facies more typical in the northern extent of each aquifer, and shoreface facies more typical in the southern part of the county. The Cheswold aquifer is a lower Miocene quartz sand, shelly in places, that is most commonly used in northern and central Kent County. From near-surface occurrences in northern Kent County, it deepens to more than 400 ft below sea level in southeastern Kent County. It ranges from 30 to 120 ft thick, with an overall trend of thickening to the southeast as well as some locally significant thickness variations. The overlying Federalsburg aquifer is a similar lower Miocene quartz sand, in places more than 60 ft thick, but it more commonly includes thinner or muddier, lower aquifer quality sands than do the other Miocene aquifers. It occurs as far north as the north side of Dover and descends to more than 350 ft below sea level in southeastern Kent County. The next aquifer upward, the Frederica aquifer, is an important ground-water source in much of Kent County south of Dover. From its northern occurrences in the Dover area, it deepens to more than 250 ft below sea level in the Milford area; it is commonly around 50 ft thick. The highest of the Miocene sands, the Milford aquifer, is locally used as for shallow, domestic water supplies in southernmost Kent County. Its northernmost extent is along a general trend from west of Harrington to southeast of Dover. It is typically around 50 ft thick and is found at approximately 200 ft below sea level in the Milford area. In some older studies, the Milford aquifer was mistakenly identified as the Frederica aquifer. The confining layers between the Miocene aquifers are thin in some areas, likely creating a locally leaky system where adjacent aquifers may be in hydrologic communication.

This study exclusively examined confined aquifers. The nature of the relationships of the confined aquifers in their subcrop areas to the unconfined aquifer has not been treated in this report. Surficial geological mapping underway in Kent County should provide data to address the nature of these relationships in future work.

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APPENDIX 1: Wells used for cross sections and their respective depths in feet below sea level.

Section W-W'

Well ID	Depth
Gc55-04	-480
Hc14-17	-470
Hc13-02	-297
Hc32-23	-312
Hc31-07	-650
Ib14-32	-550
Ic21-06	-219
Ib55-06	-240
Jc12-16	-394
Jc31-01	-294
Jc43-06	-400
Kc13-06	-406
Jd51-06	-375
Kd12-07	-370
Kd24-05	-449
Kd23-02	-270
Kd33-04	-288
Kd42-06	-277
Kd51-05	-579
Kd45-28	-505
Kd54-03	-470
Ld41-16	-621
Ld42-16	-192
Ld51-07	-208
Nc13-03	-1443
Nc43-02	-960
Nc53-07	-341

Section N1-N1'

Zz63-48	-2120
Ib14-32	-550
Hc31-07	-650
Hc42-12	-421
Hc34-20	-280
Hc24-04	-547
Hd11-05	-385
Hd25-05	-607

Section N2-N2'

Well ID	Depth
Ia33-01	-360
Zz63-196	-415
Ib41-03	-265
Ib32-03	-258
Ib25-06	-332
Ic21-06	-219
Ic44-06	-310
Ic25-12	-399
Hd51-02	-276
Hd42-01	-195
Hd44-01	-249

Section N3-N3'

Zz63-186	-225
Jb41-09	-377
Jb35-06	-288
Jc31-01	-294
Jc12-16	-394
Ic55-01	-343
Id45-01	-429
He52-02	-254

Section S3-S3'

Kb12-04	-308
Kb13-01	-327
Jb54-01	-383
Kc13-06	-406
Jd51-06	-375
Jd43-05	-485
Jd34-01	-496
Jd23-01	-481
Jd25-09	-558
Je12-03	-537

Section S2-S2'

Zz63-187	-259
Kb32-01	-812
Kc31-01	-330
Kd11-07	-556
Kd12-07	-370
Jd45-06	-695
Je32-04	-1398
If42-01	-399

Section S1-S1'

Well ID	Depth
Zz63-191	-524
Mb44-02	-360
Mb54-01	-279
Nb24-04	-340
Nc13-03	-1443
Md51-01	-280
Md15-24	-390
Ld55-28	-390
Le52-02	-214
Le53-03	-238
Le54-04	-452
Me15-29	-948
Lg42-02	-302

Section E-E'

Gd31-02	-729
Gd32-05	-1347
Gd33-05	-2295
Hd25-05	-607
Hc44-08	-380
Hc45-21	-458
Ic25-12	-399
Id31-26	-1158
Id45-01	-429
Id53-04	-492
Jd14-12	-573
Jd15-05	-546
Je12-03	-537
Je32-04	-1398
Je43-03	-577
Je43-02	-1000
Ke12-16	-228
Ke23-05	-542
Kd45-28	-505
Ke53-06	-197
Ke52-02	-179
Le35-36	-445
Le55-12	-451
Me15-29	-948
Me14-20	-474

APPENDIX 2: Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses are given in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Mount Laurel aquifer interval

Well ID	Top	Base	Thickness
Gc55-04	-315	-420	105
Gd31-02	-265	-375	110
Gd32-05	-295	-400	105
Gd33-05	-320	-425	105
Hc14-17	-330	-430	100
Hc24-04	-365	-469	104
Hc31-07	-381	-474	93
Hc34-20	-430	-520	90
Hc42-12	-410	-500	90
Hd11-05	-377		
Hd25-05	-510	-595	85
Ib14-32	-450	-540	90
Id31-26	-705	-800	95
Je32-04	-950	-1050	100
Kb32-01	-792		
Nc13-03	-1260	-1355	95
Zz63-195	-742	-838	96
Zz63-48	-225	-310	85

Rancocas aquifer interval

Well ID	Top	Base	Thickness
Gc54-02	-110		
Gc54-03	-115		
Gc55-04	-95	-280	185
Gd31-02	-50	-230	180
Gd32-05	-80	-255	175
Gd33-05	-150	-275	125
Gd53-02	-239		
Hc13-02	-105		
Hc14-03	-124		
Hc14-16	-122		
Hc14-17	-110	-290	180
Hc23-10	-150		
Hc24-04	-175	-320	145
Hc31-07	-146	-330	184
Hc32-23	-155		
Hc33-10	-192		
Hc34-20	-220	-395	175
Hc34-20	-222		
Hc42-12	-197	-375	178
Hc42-13	-194	-370	176
Hc42-14	-186	-370	184
Hc44-08	-325		
Hc45-21	-360		
Hd11-04	-177		
Hd11-05	-180	-328	148

Rancocas aquifer interval (cont.)

Well ID	Top	Base	Thickness
Hd25-05	-350	-460	110
Ia33-01	-135		
Ib14-32	-200	-398	198
Ib32-03	-215		
Ib41-03	-205		
Id31-26	-555	-660	105
Je32-04	-815	-920	105
Je43-02	-860		
Kb32-01	-568	-758	190
Nc13-03	-1040	-1180	140
Zz63-195	-484	-675	191
Zz63-196	-195		
Zz63-48	-5	-170	165

Piney Point aquifer interval

Well ID	Top	Base	Thickness
Gd53-02	-91	-161	70
Hc44-08	-135	-240	105
Hc45-04	-134		
Hc45-21	-139	-280	141
Hd25-05	-148	-290	142
Hd42-01	-154		
Hd44-01	-188		
Hd51-02	-169		
He52-02	-227		
Ib55-06	-168		
Ic25-12	-176	-345	169
Ic44-06	-210	-265	55
Ic54-06	-250	-340	90
Ic55-01	-259		
Ic55-02	-254		
Ic55-03	-252		
Id31-01	-234		
Id31-26	-234	-395	161
Id45-01	-262	-410	148
Id53-02	-260		
Id53-03	-264		
Id53-04	-257	-440	183
If42-01	-326		
Jb34-02	-222		
Jb35-06	-226	-360	134
Jb41-06	-192		
Jb41-09	-173	-310	137
Jb42-01	-188		
Jb54-01	-240	-350	110
Jc12-16	-220	-340	120

APPENDIX 2 (cont.): Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Piney Point aquifer interval (cont.)

Well ID	Top	Base	Thickness
Jc31-01	-230		
Jc43-06	-258		
Jd12-03	-268	-362	94
Jd14-12	-283	-450	167
Jd14-14	-295	-458	163
Jd14-15	-291	-453	162
Jd15-05	-300	-490	190
Jd23-01	-288	-465	177
Jd25-04	-293	-495	202
Jd25-09	-290	-490	200
Jd34-01	-302		
Jd43-05	-298	-460	162
Jd45-05	-314	-580	266
Jd45-06	-314	-530	216
Jd45-10	-307		
Jd51-06	-298		
Je12-03	-300	-530	230
Je32-04	-312	-565	253
Je32-05	-312	-533	221
Je43-02	-370	-635	265
Je43-03	-353		
Je43-04	-348		
Kb12-04	-228	-300	72
Kb13-01	-249		
Kb32-01	-264	-405	141
Kc13-06	-285		
Kc31-01	-303	-500	197
Kd11-07	-315	-535	220
Kd24-05	-347		
Kd45-04	-395		
Kd45-28	-400		
Kd51-05	-375		
Ke23-05	-405		
Ld41-16	-415	-620	205
Ld55-28			
Md51-01			
Me15-29	-640		
Nc13-03	-509	-750	241
Nc43-02	-575	-800	225
Zz63-186	-130		
Zz63-187	-225		
Zz63-188	-260		
Zz63-189	-235		
Zz63-191	-316		
Zz63-195	-212		

Cheswold aquifer interval

Well ID	Top	Base	Thickness
Hc14-03		16	
Hc24-04		-5	
Hc31-07	25	-29	54
Hc32-23		-20	
Hc33-10		-22	
Hc34-20		-17	
Hc34-20		-18	
Hc42-12		-69	
Hc42-13		-66	
Hc42-14		-59	
Hc44-08		-80	
Hc45-04		-44	
Hc45-21		-66	
Hd11-04		-18	
Hd11-05		-11	
Hd25-05		-30	
Hd42-01		-54	
Hd44-01		-81	
Hd51-02		-84	
He24-01		-98	
He52-02	-42	-131.5	89.5
Ia33-01		0	
Ib14-32	35	-40	75
Ib25-06	4	-64	68
Ib32-03		-1	
Ib41-03		-10	
Ib55-06	0	-71	71
Ic21-06	10	-55	65
Ic25-12	-1	-75	74
Ic35-02		-47	
Ic42-05		-52	
Ic44-06		-90	
Ic44-07		-90	
Ic54-06	-80	-128	48
Ic54-07	-80	-126	46
Ic55-01	-76	-158	82
Ic55-02	-82	-136	54
Ic55-03	-78	-128	50
Id31-01	-57	-130	73
Id31-26	-49	-132	83
Id45-01	-71.5	-137	65.5
Id51-07	-113	-173	60
Id52-01	-86	-158	72
Id53-02	-107	-164	57
Id53-03	-112	-174	62

APPENDIX 2 (cont.): Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses are given in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Cheswold aquifer interval (cont.)

Well ID	Top	Base	Thickness
Id53-04	-105	-165	60
If42-01	-130	-199	69
Jb34-02	-57	-124	67
Jb35-06	-57	-129	72
Jb41-06		-114	
Jb41-09	-19	-93	74
Jb42-01	-8	-104	96
Jb54-01	-110	-160	50
Jc12-16	-30	-115	85
Jc31-01	-78	-135	57
Jc43-06	-103	-156.5	53.5
Jd12-03	-102	-153	51
Jd14-12	-130	-198	68
Jd14-14	-140	-216	76
Jd14-15	-139	-213	74
Jd14-16	-128	-204	76
Jd14-17	-122	-188	66
Jd14-18	-130	-204	74
Jd14-19	-134	-198	64
Jd14-22	-138		
Jd15-05	-150	-199	49
Jd15-13	-136	-201	65
Jd23-01	-122	-203	81
Jd24-15	-133	-207	74
Jd25-04	-152	-200	48
Jd25-07	-143	-204	61
Jd25-08	-156	-202	46
Jd25-09	-154	-221	67
Jd32-01	-133	-192	59
Jd34-01	-138	-222	84
Jd35-07	-160		
Jd43-05	-121	-194	73
Jd43-13	-147	-178	31
Jd44-28	-139	-222	83
Jd45-05	-182	-234	52
Jd45-06	-178	-244	66
Jd45-10	-169	-217	48
Jd51-06	-158	-205	47
Jd53-04	-170		
Je12-03	-155	-200	45
Je31-05	-164	-212	48
Je32-04	-176	-219	43
Je32-05	-170	-212	42
Je43-02	-230	-272.5	42.5
Je43-03	-212	-264	52

Cheswold aquifer interval (cont.)

Well ID	Top	Base	Thickness
Je43-04	-223	-257	34
Je44-04	-198	-253	55
Je52-05	-210	-260	50
Kb12-04	-110	-160	50
Kb13-01	-137	-180	43
Kb32-01	-155	-195	40
Kb32-02	-152		
Kc13-06	-153	-210	57
Kc31-01	-175	-232.5	57.5
Kd11-07	-165	-228	63
Kd12-07	-172	-229	57
Kd23-02	-190	-250	60
Kd24-05	-195	-250	55
Kd31-10	-175	-230	55
Kd33-04	-203	-285	82
Kd42-06	-230		
Kd45-04	-224	-300	76
Kd45-28	-230	-300	70
Kd51-05	-215	-295	80
Kd54-03	-232	-312	80
Ke23-05	-260	-320	60
Ld41-16	-250	-315	65
Ld55-28	-356		
Le35-36	-403		
Le54-04	-398		
Le55-12	-440		
Mb44-02	-234	-320	86
Mb54-01	-246		
Me14-20	-445		
Me15-29	-430	-533	103
Nc13-03	-311	-401	90
Nc43-02	-306	-425	119
Nc53-07	-308		
Zz63-186	35	-53	88
Zz63-187	-110	-165	55
Zz63-188	-160	-200	40
Zz63-189	-135	-172	37
Zz63-191	-140	-210	70
Zz63-195	-140	-180	40
Zz63-196		-25	
Zz63-197	-275		

APPENDIX 2 (cont.): Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses are given in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Federalsburg aquifer interval

Well ID	Top	Base	Thickness
He52-02	-6	-32	26
Ib55-06	40	15	25
Ic54-06	-38	-69	31
Ic54-07	-34	-66	32
Ic55-01	-27	-65.5	38.5
Ic55-02	-16	-70	54
Ic55-03	0	-62	62
Id31-01	-2	-46	44
Id31-26	-5	-36	31
Id45-01	-25	-53	28
Id52-01	-37	-70	33
Id53-02	-69	-92	23
Id53-03	-74	-97	23
Id53-04	-50	-95	45
If42-01	-50	-115	65
Jb34-02	-22	-34	12
Jb35-06	-22	-39	17
Jb41-09	20.5	-14	34.5
Jb54-01	-47	-90	43
Jc12-16	29	-3	32
Jc31-01	-35	-60	25
Jc43-06	-62	-86.5	24.5
Jd12-03	-64	-92	28
Jd14-12	-70	-120	50
Jd14-14	-86	-114	28
Jd14-15	-85	-111	26
Jd14-16	-74	-98	24
Jd14-17	-68	-98	30
Jd14-18	-62	-122	60
Jd15-05	-70	-140	70
Jd15-13	-48	-118	70
Jd23-01	-74	-94	20
Jd24-15	-84	-105	21
Jd25-04	-61	-139	78
Jd25-07	-62	-138	76
Jd25-08	-64	-147	83
Jd25-09	-72	-148	76
Jd32-01		-120	
Jd34-01	-76	-118	42
Jd43-05	-72	-111	39
Jd43-13	-85		
Jd45-05	-99	-164	65
Jd45-06	-91	-165	74
Jd45-10	-91	-157	66
Jd51-06	-100	-142	42
Jd53-04	-91	-167	76

Federalsburg aquifer interval (cont.)

Well ID	Top	Base	Thickness
Je12-03	-76	-145	69
Je31-05	-84	-156	72
Je32-04	-91	-165	74
Je32-05	-96	-162	66
Je43-02	-145	-220	75
Je43-03	-135	-202	67
Je43-04	-130	-193	63
Je44-04	-157	-191	34
Je52-05	-128	-168	40
Jf41-06	-165	-205	40
Kb12-04	-41	-79	38
Kb13-01	-60	-95	35
Kb31-01	-80	-155	75
Kb32-01	-77	-145	68
Kb32-02	-72	-144	72
Kb32-05	-80		
Kb32-13	-78		
Kc13-06	-90	-137	47
Kc31-01	-120	-165	45
Kd11-07	-109.5	-144.5	35
Kd12-07	-110	-159.5	49.5
Kd14-05	-119		
Kd23-02	-132	-175	43
Kd24-05	-133.5	-188	54.5
Kd31-10	-115	-145	30
Kd33-04	-140	-197.5	57.5
Kd42-06	-155	-220	65
Kd45-04	-167	-200	33
Kd45-28	-178	-218	40
Kd51-05	-165	-200	35
Kd54-03	-192	-222	30
Ke12-16	-150	-220	70
Ke23-05	-170	-235	65
Ld11-01	-158	-190	32
Ld41-16	-218	-242	24
Ld55-28	-300	-340	40
Le35-36	-300	-375	75
Le54-04	-330	-386	56
Le55-12	-340	-420	80
Mb44-02	-150	-215	65
Mb54-01	-140	-220	80
Md15-24	-283		
Me14-20	-375	-435	60
Me15-29	-365	-418	53
Nb24-04	-157	-230	73
Nb55-02	-221		

APPENDIX 2 (cont.): Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses are given in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Federalsburg aquifer interval (cont.)

Well ID	Top	Base	Thickness
Nc13-03	-275	-299	24
Nc43-02	-246	-290	44
Nc53-07	-252	-295	43
Ob25-05	-240		
Ob45-02	-255	-335	80
Zz63-187	-50	-100	50
Zz63-188	-105		
Zz63-189	-75		
Zz63-191	-30	-125	95
Zz63-197	-185	-265	80

Frederica aquifer interval

Well ID	Top	Base	Thickness
Ic54-06		-6	
Ic54-07		-4	
Ic55-01		-12	
Id45-01		-9	
Id53-02		-24	
Jb34-02	29	-9	38
Jb35-06		-10	
Jb54-01	10	-27	37
Jc12-16			
Jc31-01	19	-23	42
Jc43-06	0	-36	36
Jd12-03		-30	
Jd14-12	-4	-30	26
Jd14-14	-2	-42	40
Jd14-15		-39	
Jd14-16	-12	-30	18
Jd14-17	-6	-26	20
Jd14-18	-15	-34	19
Jd14-19	-10	-30	20
Jd14-22	-10	-31	21
Jd15-05		-29	
Jd15-13	0	-31	31
Jd23-01	-1	-50	49
Jd24-15	-10	-40	30
Jd25-04	-20	-50	30
Jd25-07	-23	-52	29
Jd25-08	-24	-45	21
Jd25-09	-1	-37	36
Jd34-01	-21	-51	30
Jd35-07	-16	-47	31
Jd43-05	-15	-48	33
Jd43-13	-22	-48	26

Frederica aquifer interval (cont.)

Well ID	Top	Base	Thickness
Jd45-05	-24	-66	42
Jd45-06	-22	-68	46
Jd45-10	-19	-62	43
Jd51-06	-31	-85	54
Jd52-02	-23	-77	54
Jd53-04	-20	-75	55
Je12-03		-54	
Je31-05	-34	-62	28
Je32-04	-30	-68	38
Je43-02	-65	-120	55
Je43-03	-60	-120	60
Je43-04	-76	-106	30
Je44-04	-70	-121	51
Je52-05	-72	-102	30
Jf41-06	-80	-131	51
Kb12-04	27	0	27
Kb13-01	12	-35	47
Kb31-01	2	-52	54
Kb32-01	-5	-48	43
Kb32-02	1	-57	58
Kb32-05	-8	-56	48
Kb32-13	-9	-55	46
Kc13-06	-25	-82	57
Kc31-01	-35	-110	75
Kd11-07	-28	-91	63
Kd12-07	-32	-91	59
Kd14-05	-53	-103	50
Kd23-02	-49	-121.5	72.5
Kd24-05	-52.5	-109	56.5
Kd31-10	-42	-86	44
Kd33-04	-60.5	-110	49.5
Kd42-06	-70	-122	52
Kd45-04	-89	-141	52
Kd45-28	-81	-146	65
Kd51-05	-75	-130	55
Kd54-03	-105	-177	72
Ke12-16	-75	-125	50
Ke23-05	-95	-150	55
Ke52-02	-130	-195	65
Ke53-06	-130	-195	65
Ld11-01	-88	-136	48
Ld35-01	-154	-190	36
Ld41-16	-105	-185	80
Ld42-16	-130		
Ld42-17	-139		
Ld44-01	-154		

APPENDIX 2 (cont.): Stratigraphic picks used for isopach and tops of aquifer maps. Depths are given in feet below sea level and thicknesses are given in feet. Missing data indicates top/base of aquifer interval was not able to be picked.

Frederica aquifer interval (cont.)

Well ID	Top	Base	Thickness
Ld45-01	-167		
Ld51-07	-125		
Ld55-28	-210	-290	80
Le35-36	-205	-255	50
Le44-06	-219		
Le54-04	-230	-273	43
Le55-07	-247	-287	40
Le55-12	-230	-265	35
Lf13-06	-221		
Lg42-02	-255	-300	45
Mb44-02	-80	-125	45
Mb54-01	-93	-112	19
Md15-24	-220	-265	45
Md51-01	-204	-265	61
Me14-20	-270	-310	40
Me15-29	-265	-305	40
Nb24-04	-121	-148	27
Nb55-02	-159	-190	31
Nc13-03	-155	-245	90
Nc43-02	-160	-241	81
Nc53-07	-175	-243	68
Ob25-05	-171	-230	59
Ob45-02	-190	-240	50
Zz63-191		-4	
Zz63-197	-120	-155	35

Milford aquifer interval

Well ID	Top	Base	Thickness
Jd45-06		-11	
Kd11-07		9	
Kd12-07	22	2	20
Kd23-02	0	-20	20
Kd24-05	2	-25	27
Kd33-04		-15	
Kd42-06	2	-20	22
Kd45-04	-6	-55	49
Kd45-28	-15	-50	35
Kd51-05	0	-25	25
Kd54-03	-35	-70	35
Ke12-16		-40	
Ke23-05	-40	-72	32
Ke52-02	-65	-85	20
Ke53-06	-65	-85	20
Ld11-01		-26	
Ld35-01	-88	-116	28
Ld41-16	-60	-90	30
Ld42-16	-75	-100	25
Ld42-17	-78	-106	28
Ld51-07	-63	-100	37
Ld55-28	-125	-174	49
Le35-36	-120	-167	47
Le44-06	-147	-167	20
Le52-02	-145	-200	55
Le53-03	-150	-205	55
Le54-04	-145	-200	55
Le55-07	-173	-214	41
Le55-12	-155	-194	39
Lf13-06	-128	-166	38
Lg41-08	-185	-241	56
Lg42-02	-185	-225	40
Mb44-02	2	-34	36
Mb54-01	-20	-58	38
Md15-24	-135	-176	41
Md51-01	-70	-130	60
Me14-20	-151	-222	71
Me14-23	-166		
Me15-29	-168	-222	54
Me24-12	-165		
Nb24-04	-43	-90	47
Nb55-02	-82	-119	37
Nc13-03	-65	-109	44
Nc43-02	-75	-120	45
Nc53-07	-90	-145	55
Ob25-05	-105	-165	60
Ob45-02	-110	-170	60
Zz63-197		-85	

APPENDIX 3: Locations of wells used in this study. Maryland identifiers are provided in italics for wells located in Maryland. Elevations are provided in feet ablove sea level; northings and eastings are provided in meters (UTM Zone 18).

DGS ID	Elevation	Northing	Easting
Gc54-02	49	4354138.5	448057.4
Gc54-03	40	4354168.5	448201.6
Gc55-04	35	4354240.3	448444.4
Gd31-02	20	4359267	451154.6
Gd32-05	21	4358060.5	451816.7
Gd33-05	18	4357978	453113
Gd53-02	6	4355446.7	453756.3
Hc13-02	43	4352822.5	446612.3
Hc14-03	50	4353768.5	448079.3
Hc14-16	35	4352420	447560
Hc14-17	45	4353894.5	447721.1
Hc23-10	20	4351158	446576.5
Hc24-04	40	4351765.5	447898.2
Hc31-07	48	4348630.8	443705
Hc32-23	40	4349688.5	445153.2
Hc33-10	38	4349529	445942.9
Hc34-20	40	4349920.5	447191.1
Hc34-20	40	4349920.5	447191.1
Hc42-12	40	4348209.5	444974.9
Hc42-13	40	4348148	445022.6
Hc42-14	46	4348179	444951
Hc44-08	30	4348156.5	448257.1
Hc45-04	39	4347382	448851.5
Hc45-21	42	4347255	448817
Hd11-04	15	4352700	450401.2
Hd11-05	15	4352816.5	450548.1
Hd25-05	15	4351794	456091
Hd42-01	20	4347365	451583
Hd44-01	21	4347379	454363
Hd51-02	14	4344944	451041
He24-01	6	4351007.5	461688.5
He52-02	8	4345613.5	459376.6
Ia33-01	70	4340034	431740
Ib14-32	70	4344100	440450
Ib25-06	68	4342249	442200
Ib32-03	65	4340988.5	437729.8
Ib41-03	63	4339107	435353
Ib55-06	70	4335867.5	441218.9
Ic21-06	61	4342339	442512
Ic25-12	47	4342661	449491.7
Ic35-02	45	4339258.5	448423
Ic42-05	50	4337910	443958.9
Ic44-06	50	4338814	446864
Ic44-07	50	4338813.7	446863.7
Ic54-06	52	4335704	447956
Ic54-07	52	4335672.9	447979.3

DGS ID	Elevation	Northing	Easting
Ic55-01	55	4336190	449470.2
Ic55-02	50	4336127.5	449233.3
Ic55-03	50	4336127.5	449233.3
Id31-01	42	4339446.5	450790.5
Id31-26	42	4339476.5	450910.6
Id45-01	25	4338278	455460.7
Id51-07	45	4335516.5	449772.5
Id52-01	40	4336971.5	452238
Id53-02	40	4336289	452929.8
Id53-03	40	4336196	453001.8
Id53-04	38	4336444	452810.8
If42-01	5	4337795	465606.3
Jb34-02	68	4331530.5	440919.8
Jb35-06	67	4331441	441036
Jb41-06	40	4329907.5	435676.5
Jb41-09	60	4329925.9	435603.6
Jb42-01	66	4329863.5	437233
Jb54-01	60	4327777.5	439810.8
Jc12-16	66	4334410	444252
Jc31-01	66	4331761	443130.8
Jc43-06	60	4329976	446103
Jd12-03	50	4334563.5	451314
Jd14-12	35	4334617.5	454072.1
Jd14-14	20	4334118	455173.4
Jd14-15	21	4334087.5	455173.2
Jd14-16	10	4333995	455148.3
Jd14-17	20	4333841	455099.9
Jd14-18	10	4335011.5	455226.6
Jd14-19	35	4334618	454000.2
Jd14-22	26.3	4334152.5	454501.2
Jd15-05	32	4334202	456661.8
Jd15-13	29	4334575.5	455586.3
Jd23-01	35	4332125	453337.4
Jd24-15	35	4333453.7	454316.6
Jd25-04	25	4332971	456318.7
Jd25-07	20	4332971.5	456246.8
Jd25-08	20	4332971.5	456246.8
Jd25-09	25	4332780	455582
Jd32-01	20	4330529	452175
Jd34-01	20	4330764.5	454001
Jd35-07	30	4330847	455803
Jd43-05	40	4329723.5	452770.3
Jd43-13	40	4328380	453040
Jd44-28	40	4329344	454449.5
Jd45-05	34	4328501.5	456198.2
Jd45-06	25	4328904	455864

APPENDIX 3 (cont.): Locations of wells used in this study. Maryland identifiers are provided in italics for wells located in Maryland. Elevations are provided in feet above sea level; northings and eastings are provided in meters (UTM Zone 18).

DGS ID	Elevation	Northing	Easting
Jd45-10	35	4328808.5	456440
Jd51-06	55	4326823	449826
Jd52-02	45	4327144.5	451121.8
Jd53-04	35	4327128	453811.8
Je12-03	22	4334162.5	458293.8
Je31-05	10	4330252	457432.8
Je32-04	24	4331048.5	458301
Je32-05	22	4331048.5	458349.2
Je43-02	20	4328907	460576.7
Je43-03	23	4329765.5	460439.3
Je43-04	27	4329711.5	460551.8
Je44-04	11	4328290.5	461193.2
Je52-05	10	4327458.8	459134.4
Jf41-06	5	4328210	465252.2
Kb12-04	55	4326067	437792
Kb13-01	55	4325748	439170.2
Kb31-01	35	4321766	436319.9
Kb32-01	55	4321544.5	436661.5
Kb32-02	45.7	4321749	437101.7
Kb32-05	57.2	4321332	437688.7
Kb32-13	58.8	4320950.5	437116.8
Kc13-06	55	4325516	445377
Kc31-01	55	4321431.5	443392.8
Kd11-07	60	4324587.5	450817.4
Kd12-07	50	4325108.5	451324.9
Kd14-05	52	4325026.5	454712.9
Kd23-02	50	4322661.5	453281.2
Kd24-05	51	4323220	454020
Kd31-10	58	4321432.5	450601.7
Kd33-04	52	4320653.7	452703.5
Kd42-06	53	4319120	451590
Kd45-04	40	4319010.5	455640
Kd45-28	35	4319144	455790
Kd51-05	50	4317379.5	449930
Kd54-03	50	4317462.5	454156.4
Ke12-16	12	4325354	458553
Ke23-05	18	4322543	460350
Ke52-02	8	4317450.5	459023
Ke53-06	12	4317724.5	459722.1
Ld11-01	54	4316515	450213.3
Ld35-01	29.9	4311820	455623
Ld41-16	55	4311366.8	450007
Ld42-16	50	4309993	451425
Ld42-17	51	4310082	451493
Ld44-01	51.8	4311222	455155
Ld45-01	49.5	4311174	455701

DGS ID	Elevation	Northing	Easting
Ld51-07	59	4308070	449920
Ld55-28	50	4309089	456593
Le35-36	25	4312653.4	462848.9
Le44-06	37	4310843.5	461058.9
Le52-02	46	4308667	459181
Le53-03	44	4308378.5	460806
Le54-04	41	4308803	462252.5
Le55-07	21	4308511	463309.6
Le55-12	35	4309150.5	463717.2
Lf13-06	9	4315929	468036.6
Lg41-08	5	4309778.5	472393.9
Lg42-02	2	4310918	472638.6
Mb44-02	45	4301837	440634
Mb54-01	45	4298742	439347.9
Md15-24	50	4307542.5	455695.9
Md51-01	56	4298602.5	450510.3
Me14-20	30	4305814.5	461853.2
Me14-23	30	4306527.5	461134.2
Me15-29	7.3	4307564	463523.3
Me24-12	35	4305416.5	461417.9
Nb24-04	40	4296378	439622
Nb55-02	45	4291044.5	440712.9
Nc13-03	62.7	4297673.5	446477.6
Nc43-02	50	4292225	445330.7
Nc53-07	51	4290034	445629.2
Ob25-05	46	4286653	441007
Ob45-02	45	4282939.5	441957
Zz63-48 *Ke Bg 33*	65	4350840	431987
Zz63-186 *CO Ad 19*	75	4329634	431467
Zz63-187 *CO Bd 53*	60	4321613	432190
Zz63-188 *CO Cc 102*	30	4311250	422616
Zz63-189 *CO Cd 48*	50	4314823	429509
Zz63-191 *CO Dd 46*	40	4303450	428230
Zz63-195 *QA Ef 29*	60	4309027	416814
Zz63-196 *QA 73 3751*	65	4338800	433800
Zz63-197 *DO Ah 3*	35	4280921	435828

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