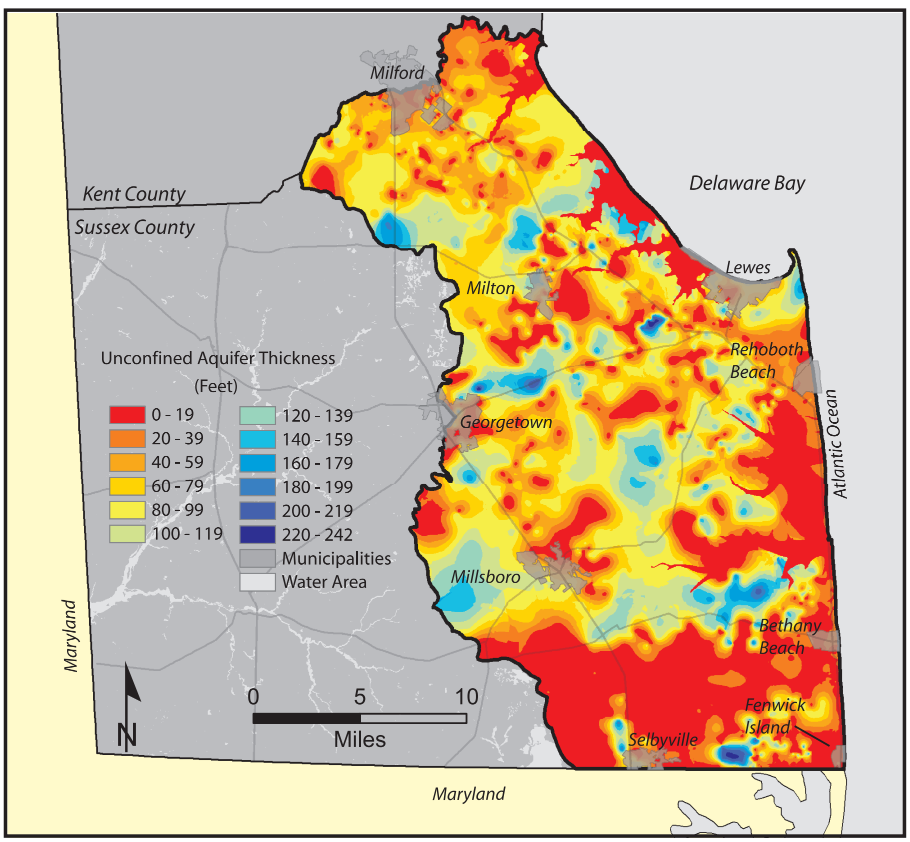
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

REPORT OF INVESTIGATIONS NO. 70

THICKNESS AND TRANSMISSIVITY OF THE UNCONFINED AQUIFER OF EASTERN SUSSEX COUNTY, DELAWARE

By

A. Scott Andres and Andrew D. Klingbeil



University of Delaware
Newark, Delaware
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CONTENTS

ILLUSTRATIONS

TABLES

PLATE

THICKNESS AND TRANSMISSIVITY OF THE UNCONFINED AQUIFER OF EASTERN SUSSEX COUNTY, DELAWARE

A. Scott Andres and Andrew D. Klingbeil

ABSTRACT

The unconfined portion of the Columbia aquifer is a key hydrologic unit in Delaware, supplying water to many agricultural, domestic, industrial, public, and irrigation wells. The aquifer is recharged through infiltration of precipitation and is the source of fair-weather stream flow and water in deeper confined aquifers. The aquifer occurs in permeable sediments ranging in age from Miocene to Recent. Over most of Delaware, the top of the unconfined or water-table portion of the Columbia aquifer occurs at depths less than 10 feet below land surface. Because of the permeable character of the aquifer and its near-surface location, the unconfined aquifer is highly susceptible to contamination.

Eastern Sussex County is experiencing rapid residential and commercial growth. Ground water is the sole source of fresh water for all uses, and land-based wastewater disposal systems such as rapid-infiltration basins, domestic and community septic systems, and spray irrigation facilities are common means of wastewater disposal. As a result, there are growing concerns about the impacts development has on the quality and quantity of water in the unconfined aquifer. Informed management of the quantity and quality of water from this important natural resource requires adequate information about the thickness and water-transmitting properties of the aquifer materials.

The Beaverdam Formation is the primary geologic unit forming the Columbia aquifer in the study area. Significant water-bearing beds that function as part of the aquifer also occur in the Cat Hill, Bethany, Lynch Heights, Scotts Corners, and Cypress Swamp Formations. The basal confining unit is primarily formed by fine-grained beds in the Choptank, St. Marys, Cat Hill, Bethany, Omar, and Cypress Swamp Formations. These units also contain minor water-bearing beds and transmit quantities of water that are likely to be significant on a regional scale but are not likely to transmit significant quantities of water on a local scale.

The geometry and transmissivity of the unconfined aquifer of eastern Sussex County, Delaware, were mapped using a rules-based method based on sediment properties and spatial continuity of sedimentary deposits. Observations at more than 2,600 locations were classified, interpreted, and mapped. The resultant thickness and elevation maps were produced in grids with 30-m horizontal resolution. The transmissivity maps were produced in grids with 90-m horizontal resolution.

The unconfined aquifer is absent where confining units are present at land surface and ranges in thickness up to 250 feet in some locations where sands of the Bethany and Cat Hill Formations are in contact with sands of the Beaverdam Formation. The median thickness is 64 feet. Transmissivity ranges from zero feet-squared per day to nearly 16,000 feet-squared per day, with a median of 3,700 feet-squared per day.

INTRODUCTION

The Columbia aquifer is the shallowest aquifer in Delaware. This aquifer is the source of water for thousands of domestic, public, agricultural, irrigation, and industrial wells. The Columbia aquifer is the primary source of water supporting fair-weather flow in streams (baseflow) and supplies water to deeper confined aquifers. The aquifer is also the receiving water body for all land-based wastewater disposal methods. The Columbia aquifer has been named in publications as the unconfined, water table, and Pleistocene. It is noteworthy that in many locations the Columbia aquifer is neither an unconfined nor a water-table aquifer, and it does not occur in Pleistocene sediments.

Thickness and water-transmitting (transmissivity) characteristics of the Columbia aquifer are important elements in many engineering, hydrogeologic, and environmental management decisions. A thick aquifer with high transmissivity will support high capacity water supply wells that are used for irrigation, industrial, and public supply purposes. Therefore, the water-transmitting properties of the unconfined portion of the Columbia aquifer are significant to many processes that occur near land surface. Wastewater disposal through subsurface (i.e., septic) and surface (spray irrigation and rapid infiltration) wastewater disposal systems will not function properly in an area that has a very thin aquifer with low transmissivity. Aquifer recharge, storm-water infiltration, and runoff are also influenced by the thickness and transmissivity of the Columbia aquifer.

Previous Mapping and Modern Data Needs

In recognition of the importance of the Columbia aquifer to Delaware's water resources, maps of the base of the Columbia aquifer have been prepared by many investigators of the Delaware Geological Survey (DGS) and U. S. Geological Survey (USGS), including Sundstrom and Pickett (1969, 1970), Johnston (1973, 1977), Talley (1982, 1988), Denver (1983), and Andres (1987). Similar maps of the Columbia aquifer were produced for Maryland by Bachman and Wilson (1984). In addition, ground-water recharge potential mapping (Andres 2003, 2004a) characterized areas by their ability to transmit water into the unconfined portion of the Columbia aquifer. These maps were produced at a variety of scales and with a variety of supporting documentation of data and methods.

In recent years, the increasing usage of geographic information systems (GIS) in environmental management and land-use decision making has created the need for technically competent, GIS-ready maps of the unconfined aquifer. Because data sets and mapping tools are vastly improved since the last county- and state-wide maps were compiled in the 1970s, DGS and Delaware Department of Natural Resources and Environmental Control (DNREC) staff decided that the state would be better served by redoing the mapping work rather than by attempting to put the older maps into digital format. For example, the scales of the existing county- and state-wide maps are on the order of about 1:250,000 to 1:500,000, which are not appropriate for many applications in source-water protection, modeling, and watershed and site studies. Available data now support county-wide mapping at a scale of 1:24,000.

One of the key technical reasons for updating the mapping is that the mapping efforts listed in a preceding paragraph relied on a few hundred data points and on stratigraphic columns and depositional models that have since been revised. Recently, the stratigraphic column and depositional models of Jordan (1962, 1964) have been significantly revised (Ramsey, 1993, 2001, 2003; Benson and Spoljaric, 1996; Andres and Ramsey, 1995; Andres and Howard, 2000). In addition, thousands of new data points have become available through ground-water recharge potential mapping (Andres, 2003, 2004a) and geologic mapping (Ramsey, 1993, 1999, 2001, 2003; Andres and Howard, 2002) efforts. These studies have indicated that the concept of a single Columbia aquifer inaccurately describes field conditions at many locations.

Purpose and Scope

This report documents the methods and results of a pilot project done to map the thickness of the water-table or unconfined portion of the Columbia aquifer in eastern Sussex County, Delaware (Fig. 1). The goals of the project were to establish appropriate methodologies and procedures for producing new maps of the elevation of the aquifer base, aquifer thickness, and aquifer transmissivity, to determine if the method can be used to map the entire county in a cost effective and timely way, and to make the resultant spatial data available. In addition, because of the importance of geologic interpretations to the mapping effort and because 1:24,000-scale surficial geologic maps are lacking for a large portion of the study area a significant effort of this project was to describe and map the geologic units that form the aquifer and underlying confining units.

The study area (including bodies of surface water) is approximately 1,460 square kilometers (560 square miles) in size and includes locations that drain to the Delaware Bay and the Atlantic Ocean. The study area was chosen by the DGS and the DNREC Water Supply Section (WSS) because the area is identified as a high priority area for a number of regulatory and environmental restoration efforts that can use the information. Moreover, a significant amount of existing data collected during previous ground-water studies is available.

One of the uses of the output of this project is for delineation of wellhead protection areas (WHPA). Under current policies of the Source Water Assessment and Protection Program (SWAPP) in Delaware, public drinking water supply wells in the unconfined aquifer require

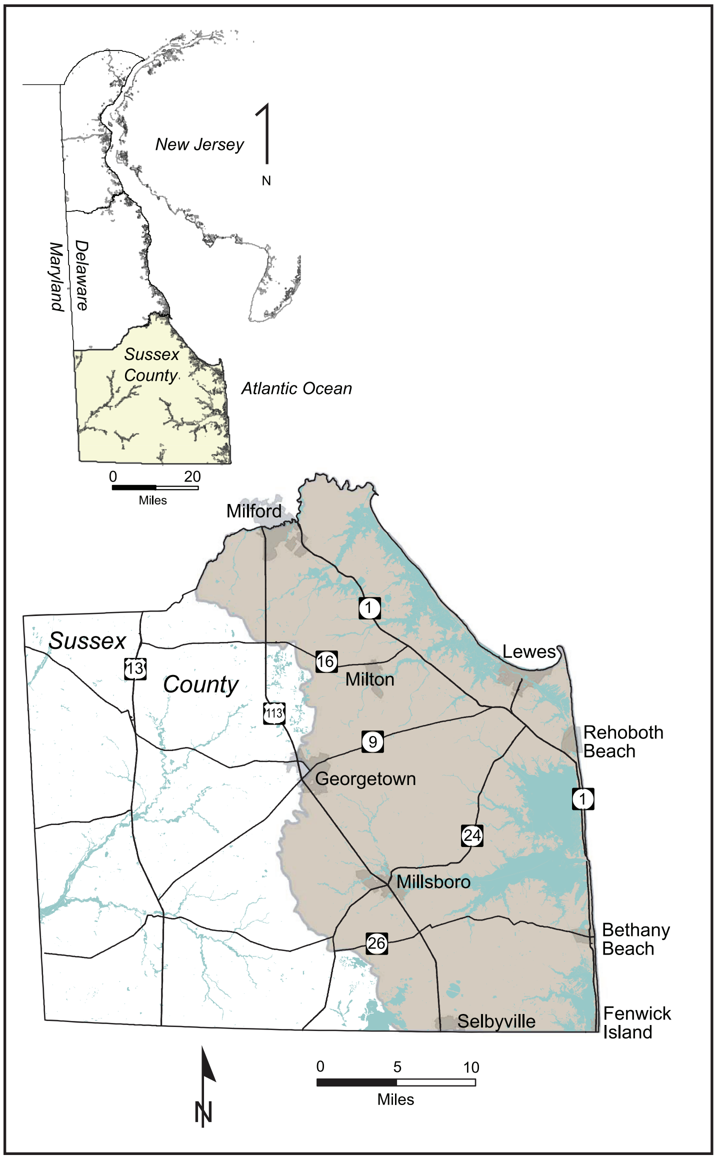


Figure 1. Location map showing the study area (shaded gray in lower figure.) The drainage divide, separating streams that flow into the Chesapeake and Delaware Bays, defines the western boundary of the study area.

WHPAs be delineated by analytic or numerical models if the pumping rate exceeds 50,000 gallons per day (DNREC, 1990, 1999). In addition, all public water supply wells in confined aquifers have WHPAs set to a minimum 150-ft radius; hence, the classification of the aquifer as confined or unconfined is critical to the proper definition of the WHPA. Input to WHPA models for wells in unconfined aquifers include aquifer thickness, water-table elevation, and transmissivity.

The products of this study will also have applications in evaluations of sites for land-based wastewater disposal systems. In this application, the thickness and transmissivity of the unconfined portion of the Columbia aquifer directly affect the maximum rate of water discharge that the aquifer can support without raising the water table to land surface and, in part, determine the rate of transport of contaminants from a disposal site to nearby wells.

In general, map products generated by this work will be used in support of a number of public environmental programs and private site reviews that need to assess hydrologic conditions. While the map products and spatial data are an important part of the assessment process, they depict estimates of the configuration and water-bearing characteristics of the aquifer. As a result, the map products and spatial data must be considered on the bases of the methods by which they were produced and the specific application for which they are being employed. There will be some applications and projects where use of these map products and spatial data is not appropriate. In these cases, the mapping method can be employed using data from site-specific investigations.

Acknowledgments

This project was funded by the DNREC through a grant from the U.S. Environmental Protection Agency. Bailey L. Dugan, Elizabeth C. Wolff, Matthew J. Martin, Mark A. Neimeister, and P. Stephen McCreary assisted with data collection. Thomas E. McKenna, Robert Canace, and Douglas E. Rambo critically reviewed the manuscript.

METHODS

Previous studies of the Columbia aquifer have led to complex and sometimes confusing naming conventions for the Columbia aquifer. In most cases, the base of the Columbia aquifer has been defined as the top of the underlying older Tertiary or Cretaceous units beneath the Columbia Formation or Columbia Group. Johnston (1973) noted that this definition often led to arbitrary distinction of the base of the aquifer, especially at many locations in Sussex County where sandier beds of the underlying units could be designated as part of the Columbia aquifer or as part of underlying aquifers, solely on the basis of sediment color. Compound aquifer names (i.e., Columbia-Pocomoke, Columbia-Cheswold) have been used to identify areas where investigators have found that the Columbia aquifer is in direct hydraulic connection with underlying aquifers (Talley and Windish, 1984; Andres, 1986a; Talley, 1988).

Because of the complexity of near-surface geology, many investigators have reported that the Columbia aquifer is a very heterogeneous hydrologic unit (Sundstrom and Pickett, 1969; Johnston, 1973; Bachman and Wilson, 1984; Hamilton et al., 1993; Andres, 2004a). These studies have noted that in some areas the Columbia functions as an unconfined aquifer; however, in other areas, the aquifer may be vertically stratified into unconfined and confined units. The complexities caused by vertical stratification and lateral heterogeneity are problematic in ground-water management regulations and policies because regulations and policies have different requirements depending on whether the shallowest aquifer is confined or unconfined.

In addition to the compound aquifer names described in the previous paragraph, the heterogeneous character of the Columbia aquifer has led to other geomorphologic and soil-based classifications of the aquifer (Hamilton et al., 1993). One of the categories of the Hamilton et al. (1993) hydrogeomorphic classification, "surficial confined," was applied to a large area of southern Sussex County, Delaware, and adjacent Worcester and Wicomico counties in Maryland. This name accurately describes the confined nature of the water-bearing beds used by many water supply wells in the area, but the name is inaccurate in that it is not the aquifer closest to land surface. Instead, there is a thin unconfined surficial aquifer above the confining bed (Andres and Howard, 2002). This surficial aquifer is directly connected to the surface drainage system and as such is an integral part of the movement of water and pollutants from land surface to surface water and eventually to the Inland Bays and Chesapeake Bay (Andres and Howard, 2002; Ator et al., 2004).

In recognition that hydrologic criteria—e.g., hydraulic properties, aquifer boundaries, grain-size distribution, cementation, and areal continuity of sedimentary units—are more appropriate criteria than sediment color or geologic age for characterizing aquifer behavior and ground-water flow, we have developed a materials- and rules-based method to interpret and map the near-surface, unconfined, or water-table portion of the Columbia aquifer. This method provides a system for evaluating and incorporating new data into regional and site-specific studies. The system is based upon evaluation of hydraulic properties of geologic materials at individual observation locations and uses techniques of geologic mapping and geostatistics to interpret conditions between observation locations. The rationale for this method is similar to that used for the ground-water recharge potential mapping (Andres, 2004a).

We will be using the terms "unconfined" and "water-table aquifer" instead of Columbia aquifer in recognition of the mapping methods. The definition of an unconfined aquifer is one in which the pressure of water in the aquifer is equal to atmospheric pressure (Freeze and Cherry, 1979). In the study area, this condition is recognized when the static water level observed in a shallow well is coincident with the top of the aquifer. In this case, the top of the aquifer is the water table. The fit of pumping test data to theoretical models sometimes is a criteria used to evaluate whether an aquifer is confined or unconfined (Freeze and Cherry, 1979), although many of the assumptions inherent in the theoretical models render their applicability to complex hydrologic settings questionable. From a practical standpoint, pumping test data needed to prove the extent of confined aquifer conditions beneath every confining unit in the study area are not available and would be prohibitively expensive to collect.

In this discussion, we are using the term "confining bed" interchangeably with the term "aquitard." Freeze and Cherry (1979 p. 47) describe an aquitard as "the less permeable beds in a stratigraphic sequence." Aquitards transmit much smaller quantities of water than aquifers do, but they may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow (Bear, 1979). However, permeabilities of confining beds are not sufficient to yield useful quantities of water to wells. As such, the confining beds would be classified as leaky confining beds.

Data and Rules Used for Evaluating Hydrogeologic Framework and for Determining Base of Unconfined Aquifer

Data used in this study are descriptive and geophysical logs of drillholes and boreholes obtained from the records of the DGS and the DNREC. The term "borehole" will be used for both the drillholes and boreholes in this discussion. An additional 27 boreholes and geophysical logs were completed by the DGS as part of this study. Water-well completion reports submitted by drilling contractors provide the largest number of logs. Logs were selected using criteria developed in the Ground-Water Recharge Potential Mapping program (Andres, 2004a). The methods used for determining borehole locations are documented in Andres (2004a).

Three basic rules were established to ensure that a systematic process was used to determine the thickness and hydraulic properties of the unconfined aquifer (Fig. 2). The first mapping rule is that land surface is the top of the aquifer. The second rule is that the top of the first confining bed greater than 10 ft thick encountered below land surface is the base of the unconfined aquifer. The third rule is that the confining bed forming the base of the unconfined aquifer must be detected in other nearby borehole records. If the confining bed can be identified in other boreholes within a search radius of 2,500 to 5,000 ft, then the choice or "pick" of the base of the aquifer is assigned a high confidence rating (see discussion of confidence ratings in following section). If the confining bed does not extend more than 2,500 to 5,000 ft, then either the pick is given a confidence rating of uncertain, or the top of the next shallowest 10-ft thick confining bed is picked as the base of the unconfined aquifer. This last rule prevents relatively discontinuous confining beds from being mapped as the base of the unconfined aquifer. There is no geologic unit criterion for defining the unconfined aquifer.

Data recorded while evaluating borehole records

The data gathering process estimates and collects a variety of information on the stratigraphic units encountered in borehole records. In many borehole records (geophysical, geologist, and driller logs) it is not possible to definitively identify the stratigraphic units and the contacts. Thus while evaluating a borehole record, the stratigraphic units and the depths to the top of the units are picked, and an assessment of the confidence in the picks is made. The stratigraphic horizons picked in individual borehole records include the stratigraphic unit forming the base of the aquifer, depth to that unit and its thickness, and depths to the top of stratigraphic units within the unconfined aquifer. This process captures additional data useful for evaluating the geologic framework of the unconfined aquifer. Where possible, the tops of older units occurring beneath the unconfined aquifer were identified. Data on the depths to the tops of stratigraphic units will be useful for future mapping of deeper confined aquifers.

Method for estimating transmissivity

There are only limited data on hydraulic characteristics of the unconfined aquifer in the study area. The number of transmissivity (T) values determined from aquifer pumping tests is very limited (6 observations) and are too sparsely

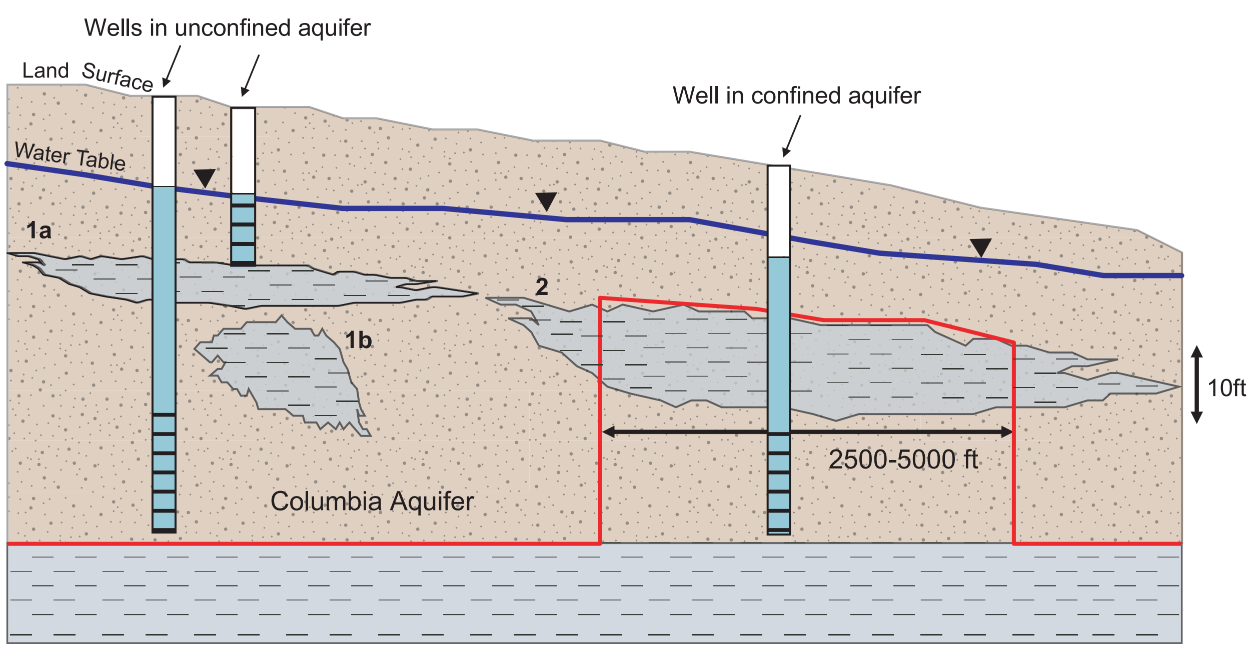


Figure 2. Illustration of rules for determining the base of the unconfined aquifer. Red line in the figure defines the base of the unconfined aquifer. A basal confining bed must be ≥ 10 feet thick, be spacially significant, and be defined by multiple picks. Beds 1a and 1b are too thin and not laterally extensive enough, respectively, to be mapped as confining units. Bed 2 meets the qualifications of a confining unit in both thickness and lateral extent.

distributed to use for estimating aquifer transmissivity over the entire study area. Specific capacity (95 observations) and slug test-derived hydraulic conductivities (131 observations) are the most numerous and widely distributed types of aquifer test data for the Columbia aquifer. Johnston (1977), in a modeling study, used specific capacity data as a first cut to estimate aquifer T for the model input data, but found that this indirect method is prone to large uncertainties.

The data gathered in this study also included lithologies encountered in each borehole. Lithologies encountered in each borehole were classified as sand, sand and gravel, silty sand, interbedded sand and mud, or mud, and their thicknesses were tabulated. For interbedded materials, the percentage of each material type is estimated. From statistical relationships between these lithologic categories and hydraulic conductivity (K) data from slug tests developed by Andres (1991, 2004a), it is possible to estimate a T of the unconfined aquifer as the sum of the products of material thicknesses (b) and hydraulic conductivities from equation 1. Use of median K values will provide a reasonable representation of T over the entire study area but will underestimate or overestimate T values in some areas. The K values associated with material types and an example calculation are shown in Figure 3.

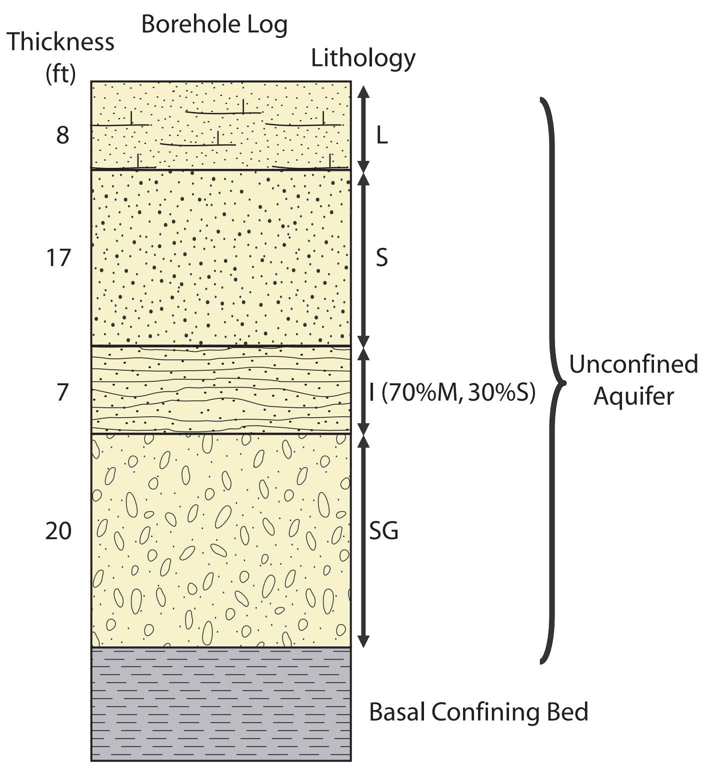
$$T = (K1 \times b1) + (K2 \times b2) + ... + (Kn \times bn) \quad \text{[equation 1]}$$

Many boreholes penetrate more than 80 percent of the thickness of the water-table aquifer, but do not reach the base of the aquifer. In these cases, a K value that is the local average of all materials is assigned to the interval between the bottom of the borehole and the estimated base of the aquifer; then, the product of the interval thickness and the average K value is added to the estimated transmissivity for that borehole.

Gridding procedures

Because of the need for GIS-ready quantitative data products of the unconfined aquifer, grids of the elevation of the base of the aquifer, depth to the base of the aquifer, and aquifer T were computed using a combination of Surfer (Golden Software, 2004) and ArcMap Geostatistical Analyst (ESRI, 2003). The elevation and depth grids have 30-m horizontal and 1-ft vertical resolutions. The T grids have a 90-m horizontal resolution. In statistical evaluations, the T values are rounded to two significant digits.

An inverse-distance-squared algorithm was used for computing structure maps of contacts between geologic units, and a kriging algorithm was used for computing the elevation of the base of the aquifer and T (Table 1). The thickness of the aquifer was computed as the difference between land-surface elevation and elevation of the base of the aquifer. Experience gained during this study indicates that efforts made to minimize the differences, or fit, between observed data and grid-estimated values provided better fit-



Lithology	Typical K (ft/day)
Sand and Gravel (SG)	125
Sand (S)	71
Silty Sand (L)	11
Interbedded (I)	split to M and S
Mud (M)	0.5

Figure 3. Illustration of method used to estimate transmissivity (T) from lithologic data. Hydraulic conductivity (K) values for lithologies are from Andres (1991, 2004). In this example, T = 3,947 ft^2/day or (11ft/day x 8ft) + (71ft/day x 17ft) + ((0.7 x 7ft) x 0.5ft/day) + ((0.3 x 7ft) x 71ft/day) + (125ft/day x 20ft).

Table 1 Gridding parameters used in quantitative analysis of elevation of the base of the aquifer, depth to the base of the aquifer, and transmissivity of the unconfined aquifer of eastern Sussex County, Delaware.

Grid	Algorithm	Equation Type	Search Type	Search Radius (km)	No. of Sectors	Max. No. from All Sectors	Max. No. from Each Sector	Min. No. from All Sectors*	Max. Allowable Empty Sectors**
Structure Contour	Inverse Distance Squared	N/A	Sector	16	4	16	4	1	3
Elevation of Base of Aquifer	Kriging (point)	Linear Variogram S = 1 A = 1,0	Sector	3	4	32	8	1	3
Transmissivity	Kriging (point)	Linear Variogram S = 1 A = 1,0	Sector	38.9	4	64	16	8	3

* Node blanked if fewer; ** Node blanked if greater; S = Slope; A = Anisotropy

ting grids than detailed work on developing semi-variograms for input to the kriging equations. In this quality assurance process, the residuals, or differences between elevations picked at individual locations and the estimated elevations, were computed, and the locations where the residuals were greater than the specified threshold were reinterpreted. The entire gridding and residual comparison process was repeated with successively smaller residual thresholds until the mean residual was less than 1 ft and

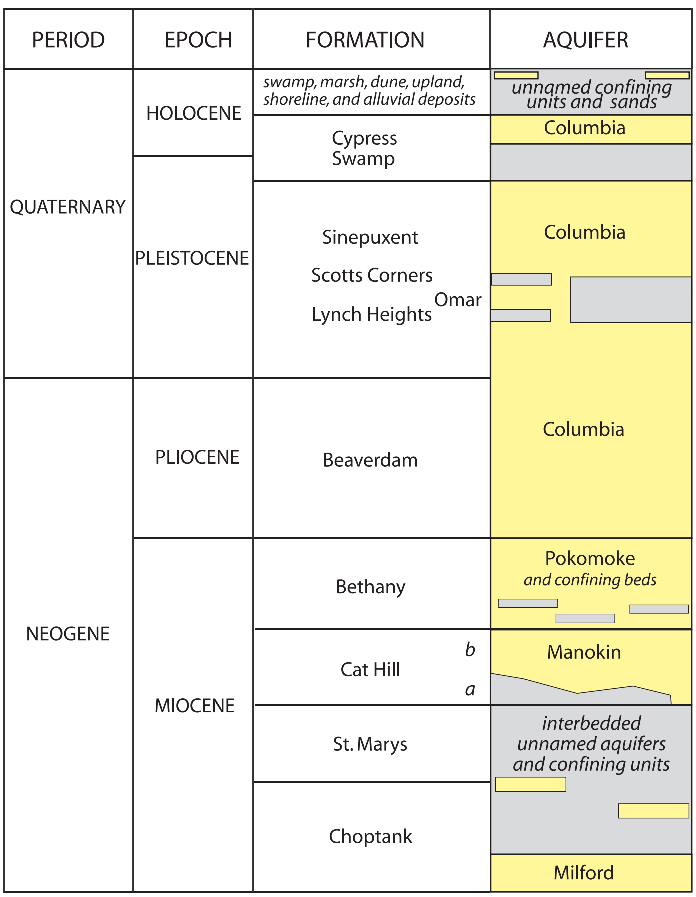


Figure 4. Lithostratigraphy and hydrostratigraphy for the study area. This chart summarizes the names of the aquifers, the formations in which they occur, and their chronostratigraphic position. Areas shaded yellow are aquifers and areas shaded gray are confining beds.

the absolute value of more than 90 percent of the residuals was less than 5 ft. Readers may contact the DGS if they are interested in more detailed information on the estimation procedures and results.

GEOLOGIC UNITS AND THEIR HYDROLOGIC FUNCTIONS

Our interpretations of lithostratigraphy and hydrostratigraphy (Fig. 4) are derived from the geologic mapping models and lithostratigraphic columns of Benson (1990), Ramsey (1993, 1997, 2001, 2003), and Andres and Howard (2000), and from the materials mapping model of Andres (2004a) applied to observations at more than 2,700 locations in and adjacent to the study area. One of the geologic units of Owens and Denny (1979a), the Sinepuxent Formation, is extended from adjacent Maryland into the southeastern portion of the study area. Discussions of previously published geologic mapping models and lithostratigraphic columns are available in Rasmussen et al. (1960), Jordan (1962, 1964) Sundstrom and Pickett (1969), Owens and Denny (1979b), and Benson (1990).

Results are presented as a series of maps and cross sections (Figs. 5-9, Plate 1). The surficial geologic map (Fig. 9) was developed during the course of this study and is used to identify the lithostratigraphic units that form the near surface portion of the unconfined aquifer and near surface confining beds. Portions of the map will likely be revised in two to three years when 1:100,000 scale geologic mapping progresses into Sussex County.

From oldest to youngest, the Choptank, St. Marys, Cat Hill, Bethany, Beaverdam, Lynch Heights, Scotts Corners, Omar, Sinepuxent, and Cypress Swamp Formations are the near-surface geologic units of primary interest in this study. Fill materials, placed by human activities, occur in restricted locations. Upland deposits (Ramsey, 2001)—swamp, marsh, dune, shoreline, and alluvial deposits—occur in geographically restricted portions of the study area. The bulk of our discussion concentrates on the compositions and surficial expressions of units that form the unconfined aquifer: the Cat Hill, Bethany, Beaverdam, Lynch Heights, Scotts Corners, Sinepuxent, and Cypress Swamp Formations. A limited discussion of the composition and stratigraphic relationships of units that typically function as the base of the unconfined aquifer—the Choptank, St. Marys, and Omar Formations—are included to complete the subsurface hydrogeologic framework.

Because fossils have been recovered from only scattered locations within the study area and many of the units have similar compositions, determinations of formation boundaries in many drillhole and geophysical logs are based on interpretations of composition and, therefore, are not well constrained

Choptank Formation

The Choptank Formation is a Miocene lithostratigraphic unit (Benson, 1990; Ramsey, 2001; Miller et al., 2003). The Choptank Formation is interpreted to have been deposited in middle neritic to estuarine environments (Miller et al., 2003).

In the study area, the Choptank is a heterogeneous unit composed of stacked sequences of beds of predominantly muddy sediment (mixtures of silt and clay), beds of mixtures of mud, sand, and shells, and beds that are predominantly sand and shell. Cemented zones are reported in many drillers' logs. Where unoxidized, colors typically are shades of blue, gray, and brown, and yellow to red where oxidized. In the northern part of the study area, the uppermost beds of the Choptank are almost everywhere composed of the sandy muds and muddy sands, and as such they function as confining units. Beds that are predominantly sand and shell function as minor aquifers. We have not identified locations within the study area where aquifer sands of the Choptank Formation are in contact with the overlying unconfined aquifer.

The stratigraphic contact between the Choptank and St. Marys Formations appears to be an unconformity (Hansen, 1981; Andres, 1986b; Miller et al., 2003). In locations north of the updip extent of the St. Marys Formation, the Choptank is unconformably overlain by younger units (Ramsey, 1993). Limited data indicate that this contact dips to the southeast (Fig. 5).

St. Marys Formation

The St. Marys Formation is a Miocene lithostratigraphic unit (Benson, 1990; Ramsey, 2001). The St. Marys Formation is interpreted to have been deposited in middle to upper neritic marine environments (Miller et al., 2003).

In the study area, the St. Marys is dominantly composed of mud, sandy mud, and shelly mud, with minor thin beds of fine to medium quartzose sand, silty fine sand, and rare thin beds of sandy fine gravel. Mica, lignite, phosphatic grains, and glauconite are rare accessory components. Thin cemented zones are reported in many drillers' logs. Where unoxidized, colors typically are shades of blue, gray, and brown, and yellow to red where oxidized. In areas near the updip limit of this unit, it appears that the St. Marys may contain more sand. Because of its areally consistent fine-grained character, the St. Marys functions as the basal confining unit of the unconfined aquifer where the aquifer is not confined by younger units.

The stratigraphic contact between the St. Marys Formation and the overlying Cat Hill Formation typically is gradational from mud to sand, although a rapid vertical change from mud to sand is observed in a few geophysical logs (Hansen 1981; Andres, 1986b, 2004b; Achmad and Wilson, 1993; Andres and Ramsey, 1995; Ramsey, 2001, 2003). Limited data indicate that this contact dips to the southeast (Fig. 6). In locations north of the updip extent of the Cat Hill Formation, the St. Marys Formation is unconformably overlain by younger units (Ramsey, 1993).

Cat Hill Formation

The Cat Hill Formation (Andres, 2004b) is a late middle Miocene (Owens and Denny, 1979b; Hansen, 1981; Benson, 1990) to perhaps Pliocene (Miller et al., 2003) lithostratigraphic unit, though the age estimates are poorly constrained because of a general lack

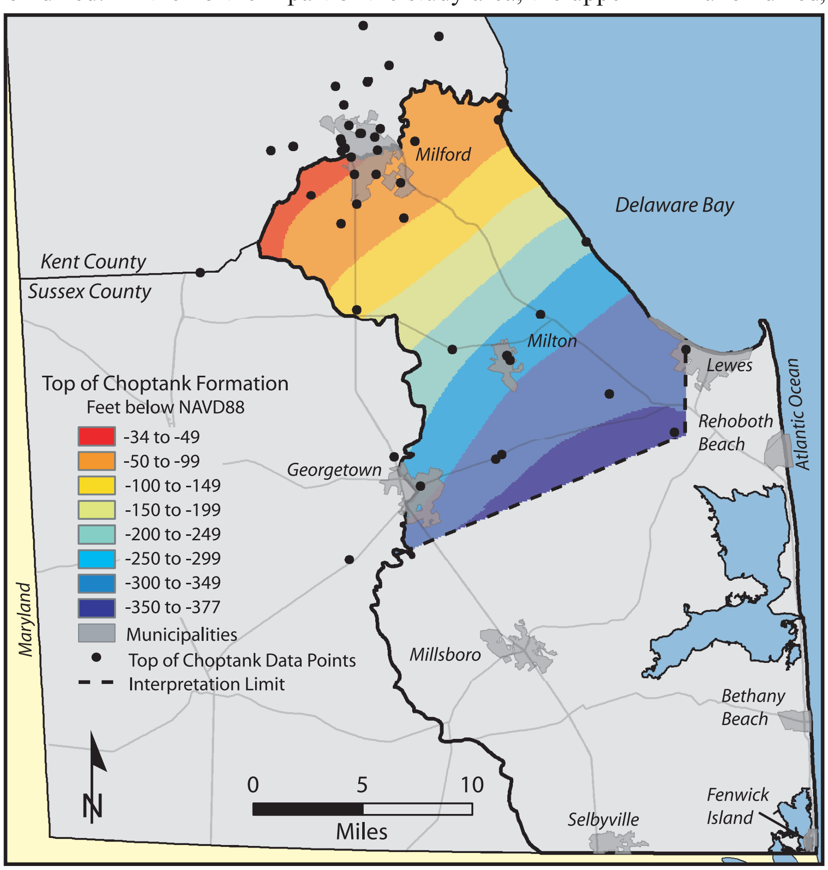


Figure 5. Structure contour map of the elevation of the top of the Choptank Formation. Modeling grid has been clipped to the study area boundary (heavy black line). All data points shown on the figure were used in the interpretation.

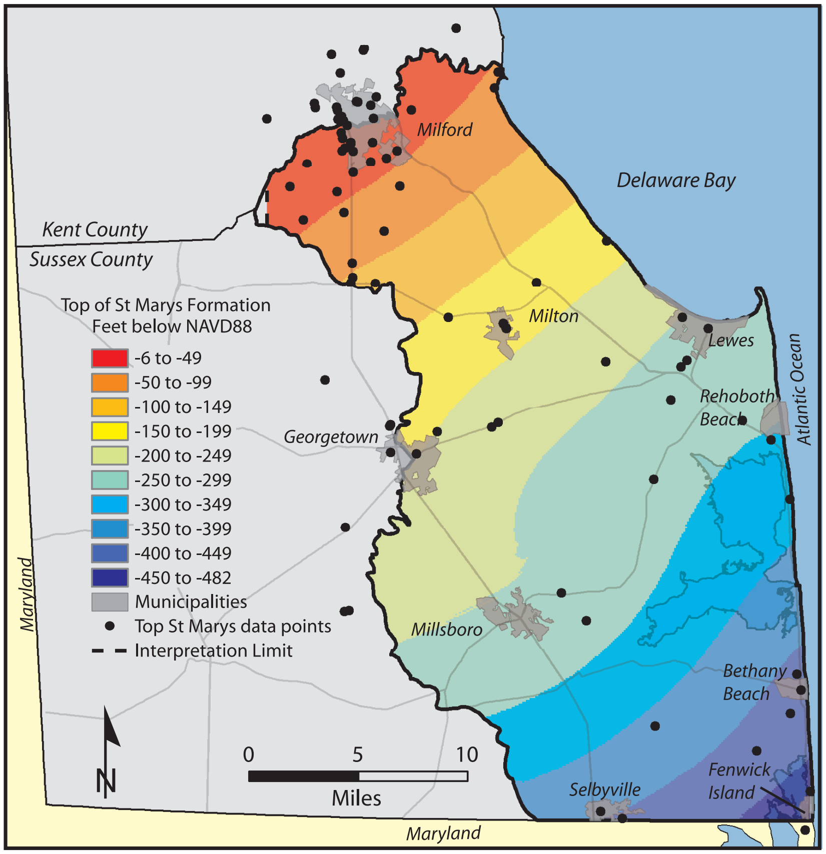


Figure 6. Structure contour map of the elevation of the top of the St. Marys Formation. Modeling grid has been clipped to the study area boundary (heavy black line). All data points shown on the figure were used in the interpretation.

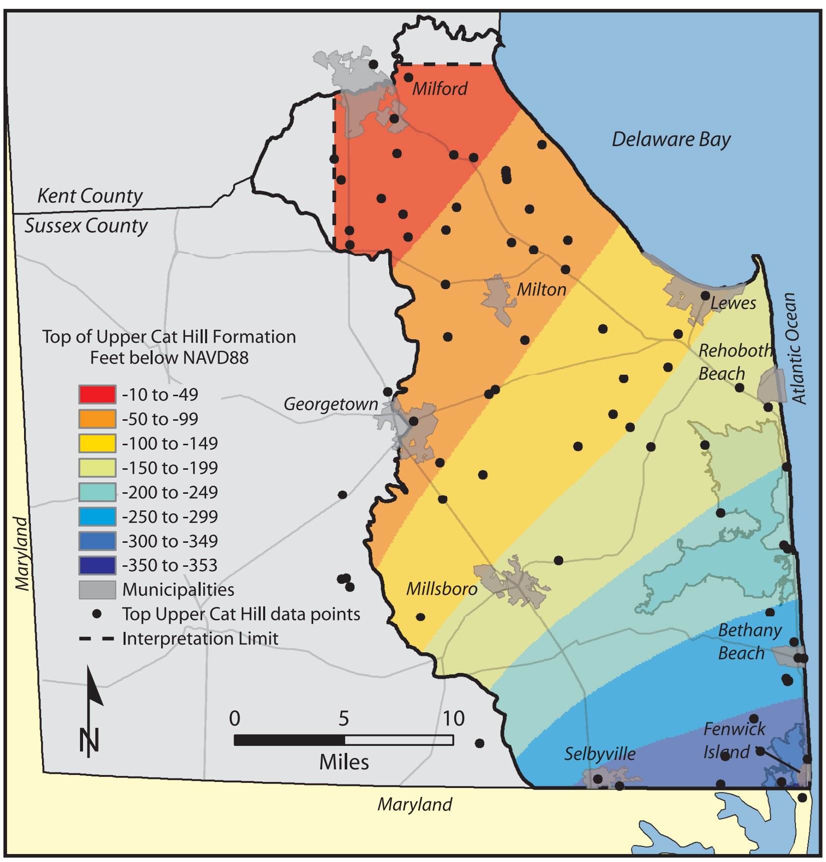


Figure 7. Structure contour map of the elevation of the top of the Cat Hill Formation. Modeling grid has been clipped to the study area boundary (heavy black line). All data points shown on the figure were used in the interpretation.

of diagnostic fossils or other materials that can be age dated. The Cat Hill Formation is interpreted to have been deposited in shallow marine environments (Miller et al., 2003). Sandier intervals of the Cat Hill function as the Manokin aquifer. There are locations where aquifer sands of the Cat Hill Formation are in direct contact with aquifer sands of the overlying Beaverdam Formation and likely function as part of the unconfined aquifer.

The Cat Hill Formation is dominantly composed of sand with minor beds of mud and is informally subdivided into two subunits. The lower subunit (a) is a coarsening upward fine to medium silty quartzose sand and clayey fine sand; the upper subunit (b) is a medium to coarse gray quartzose sand with beds of gravelly coarse sand. Macrofossils, typically described as shells or shell hash on drillers' logs, are reported in scattered locations. Mica, lignite, phosphatic grains, and glauconite are rare accessory components. Where unoxidized, colors typically are described as white to shades of gray and blue, and yellow to brown where oxidized.

Miller et al. (2003) interpreted the sandier beds of the Cat Hill b subunit to have been deposited in upper shoreface/foreshore to lower estuarine environments. The finer-grained beds of the Cat Hill (a) subunit are interpreted as having been deposited in quiet offshore/middle neritic to lower shoreface environments.

All available data show that the Cat Hill Formation occurs only in the subsurface. As a result, a precise identification of lateral boundaries is problematic. Variations in thickness reflect spatial changes in depositional environments during filling of the sedimentary basin and post-deposition erosional truncation (Andres, 1986b; 2004b).

The stratigraphic relationships between the Cat Hill and overlying units vary with location. Because the contact between the Cat Hill Formation and overlying Bethany Formation occurs only in the subsurface and is typically observed on geophysical and drillers' logs, it is difficult to characterize. In many locations it is marked by an abrupt change from sand to mud indicating either a disconformable erosional surface or a change in the depositional environment (Andres, 1986b, 2004b; Miller et al., 2003) that represents a paraconformity. Where the Bethany Formation is absent, the Cat Hill Formation is unconformably overlain by the Beaverdam Formation or younger units. As noted by

Andres (1986b, 2004b), in locations where beds above and below the contact between the Cat Hill and Bethany Formations are predominately sand and in the absence of core samples, the distinction between the Cat Hill and Bethany Formations and interpretation of the nature of the contact is difficult. The upper contact between the Cat Hill Formation and younger units is a complex surface that generally dips to the southeast (Fig. 7).

Bethany Formation

The Bethany Formation (Andres, 2004b) is a late middle Miocene (Owens and Denny, 1979b; Hansen, 1981; Benson, 1990) to perhaps Pliocene (Miller et al., 2003) lithostratigraphic unit, though the age estimates are poorly constrained because of a general lack of diagnostic fossils or other materials that can be age dated. The Bethany Formation is interpreted to have been deposited in lower shoreface to estuarine environments (Miller et al., 2003). Sandier intervals in the Bethany Formation function as the Pocomoke aquifer. Muddier intervals function as confining beds and in many locations in eastern Sussex County form the base of the unconfined aquifer. Because individual muddy beds are laterally discontinuous, there are locations where aquifer sands of the Bethany Formation are in direct contact with aquifer sands of the overlying Beaverdam Formation and likely function as part of the unconfined aquifer.

Descriptive logs of the Bethany Formation typically show it to be composed of a sequence of clayey and silty beds with discontinuous lenses of fine to coarse quartzose sand. The most common lithologies are lignitic, silty, clayey, pebbly, fine quartzose sand; sandy, silty, clay; fine to medium quartzose sand; sandy, clayey, silt; and medium to coarse quartzose sand with granule zones (Miller et al., 2003). In a few areas, the Bethany is predominately composed of sand, silty sand, and gravelly sand. Thin gravel layers occur most frequently in updip areas and are rarer in downdip areas. Laminations of heavy minerals are common in the fine to medium sands, and thin layers of gravel and coarse sand are rarer (Miller et al., 2003). Where unoxidized, colors typically are described as white to shades of gray and blue, and yellow to brown where oxidized.

Available data indicate that the Bethany Formation occurs only in the subsurface, and most observations and descriptions are limited to drillers' and geophysical logs and geologists' descriptions of samples of borehole cuttings. As a result, precise identification of lateral boundaries is problematic. Variations in thickness reflect spatial changes in depositional environments during filling of the sedimentary basin and post-deposition erosional truncation (Andres, 1986b; 2004b).

Within the study area, data indicate that the Bethany Formation is overlain by the Beaverdam Formation. Limited data indicate that the upper contact between the Bethany Formation and Beaverdam Formation is a complex surface that generally dips to the southeast (Fig. 8). Interpretation of the stratigraphic relationships between the Bethany Formation and the overlying Beaverdam Formation is hindered by the fact that the contact occurs only in the subsurface, where it is typically observed only in geophysical and drillers' logs or in samples of cuttings from boreholes. Adding to the difficulties, in some locations lithologies above and below the contact are similar, and there is a general lack of diagnostic fossils and materials that can be age dated.

Along the coast, the Bethany and Beaverdam Formations can contain significant amounts of muddy sediments and multiple sand-on-mud contacts, indicating multiple erosional contacts. In contrast, in locations to the north and west of the type locality, where the Beaverdam Formation is predominately composed of coarse-grained sand, the contact is more clearly interpreted as an erosional surface at an abrupt change from a blue gray to olive gray mud bed to an overlying gravelly sand. At many locations, the top few inches of the mud bed is cemented with limonitic cement, suggest-

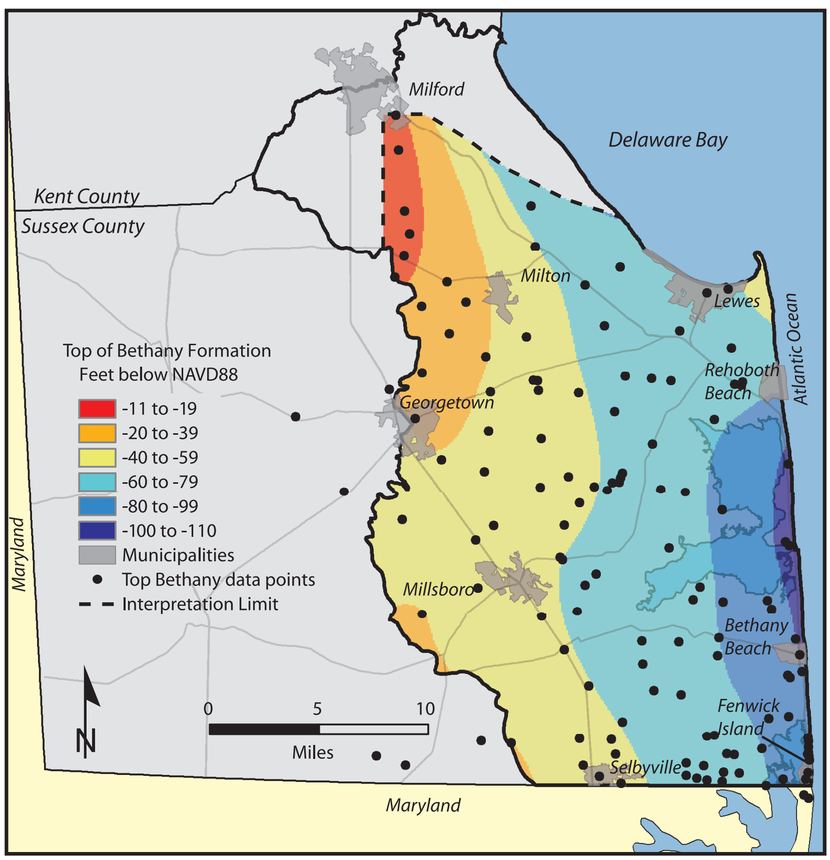


Figure 8. Structure contour map of the elevation of the top of the Bethany Formation. Modeling grid has been clipped to the study area boundary (heavy black line). All data points shown on the figure were used in the interpretation.

ing the presence of a paleosol or erosional surface and further supporting the interpretation of an erosional contact. Less commonly in updip areas, where the top of the Bethany Formation is a fine to medium sand, or pebbly, medium to coarse sand, the contact with the overlying Beaverdam Formation may be difficult to distinguish on drillers' or geologists' logs. In the case of a sand on sand contact, the gamma log signature of the Bethany Formation typically shows lower values than the Beaverdam Formation.

Beaverdam Formation

The Beaverdam Formation is a Pliocene lithostratigraphic unit (Groot et al., 1990). The Beaverdam is the main lithostratigraphic unit comprising the unconfined aquifer in the study area. The Beaverdam crops out along the western boundary of the study area (Fig. 9). Lithologically, the Beaverdam is heterogeneous and consists of multiple facies. Three distinct facies are present in the Beaverdam Formation in eastern Sussex County.

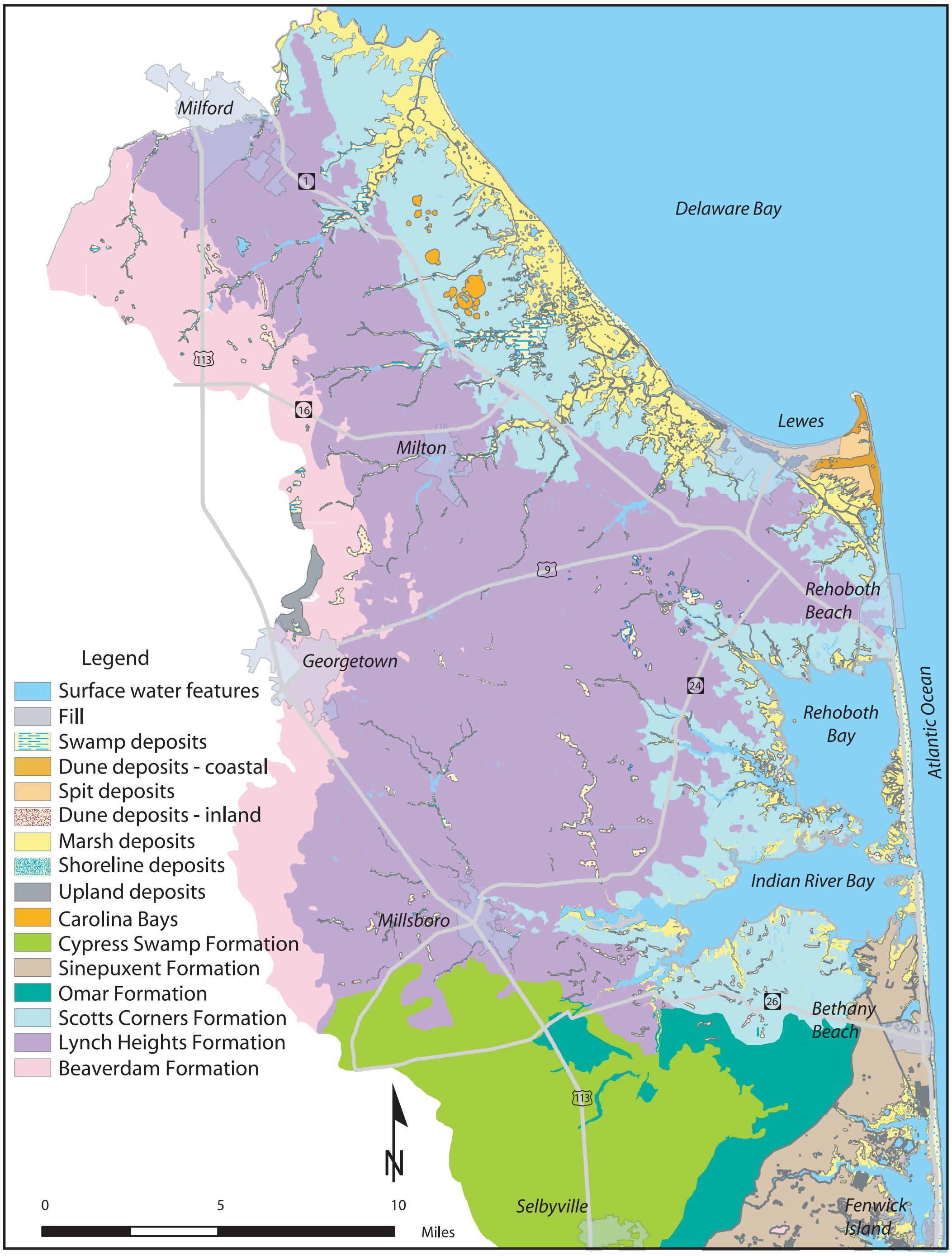


Figure 9. Map of surficial geologic units in the study area. Lithologic characteristics of the units are discussed in the text. Refer to Figure 4 for stratigraphic relationships of units. Portions of the map are taken from Ramsey (1993, 2001, 2003).

1. Sand, medium to coarse, trace silt and granules; sand, medium to coarse, gravelly fine to medium; gravel, fine to medium, sandy coarse to medium, with fine gravel-sized mud rip-up clasts. Individual gravel beds are typically less than 1 ft thick although gravelly intervals can be as much as 35 ft thick. Coarse to medium sand-size multi-colored quartz grains, and white, soft grains are very common and impart a distinctive appearance that has been described as "oatmeal." This assemblage is thought to have been deposited in high energy conditions in channel, beach, and shallow nearshore environments. This assemblage functions as an aquifer.
2. Sand, fine to coarse, trace silt and granules; sand, fine to medium, silty; sand, fine, and silt. A clayey matrix occurs in some sand beds. In almost all of these occurrences, beds are grain supported not matrix supported. The finer-grained lithologies tend to occur in thin (<1-ft thick) beds and are not areally extensive. As in lithologic assemblage one, multicolored quartz and white, soft sand-size mud clasts are very common. This assemblage is thought to have been deposited in moderate energy environments such as smaller tributary tidal channels, levees, tidal deltas, and subtidal flats. The coarser-grained lithologies in this assemblage function as an aquifer. The finer-grained beds influence local ground-water flow, but because they are areally discontinuous, they do not function as confining beds.
3. Laminated to thinly bedded silt, clayey, sandy, fine to medium; clay and silt, trace sand, fine; sand, fine to coarse, silty. A clayey matrix commonly occurs in some sand beds. Typically, there are equal occurrences of matrix and grain supported beds. Beds of fine-grained materials are commonly stacked in sequences that are 2 to 10 ft thick. The thicker sequences can be correlated between boreholes over hundreds to thousands of feet. Sand-size quartz that occurs in multiple colors and white, soft sand-size mud clasts are very common. This assemblage is thought to have been deposited in low energy conditions in distal subtidal to intertidal flat, open-water bay bottom, and tidal creek environments. The finer-grained beds influence local ground-water flow and function as confining beds where they have sufficient areal extent.

Individual assemblages of lithologies 1 and 2 are usually arranged in fining upward sequences that range from a few feet thick to about 10 ft thick. Sequences typically have sharp (erosional) bottom contacts. Sequences of assemblage 1 are stacked or can grade upward into assemblage 2. Lithologic assemblages 1 and 2 also alternate in vertical succession. Sequences of assemblage 2 are stacked or can grade upward into assemblage 3. Lithologic assemblages 2 and 3 also alternate in vertical succession. The Beaverdam Formation generally fines upward with the occurrences of lithologic assemblage 3 being more common in the upper half and assemblage 1 being more common in the lower half of the unit. Colors typically are described as yellow, orange, and brown reflecting generally oxidizing geochemical conditions. In locations and at depths where geochemical conditions in the Beaverdam Formation sediments are more reduced, colors are described as white, light to dark gray, and light blue.

The sediment composition and bedding styles observed in the Beaverdam are typical of deposits of freshwater and saltwater environments. The interpretation of estuarine and lagoonal environments is supported by palynologic data (Groot et al., 1990) that show saltwater tolerant plant species.

Lynch Heights Formation

The Lynch Heights Formation is a Quaternary lithostratigraphic unit (Ramsey, 1993, 1997). The Lynch Heights Formation crops out (Fig. 9) at land surface elevations between about 15 and 40 ft over much of the study area. A scarp occurring between elevations of 15 to 20 ft is the surficial expression of the contact between the Lynch Heights and younger Scotts Corners. A less distinct break in slope at land surface elevations between 40 and 45 ft marks the contact between the Lynch Heights and Beaverdam Formations. Sediments of the Lynch Heights function as either part of the unconfined aquifer or as confining beds.

The Lynch Heights consists of several distinct lithologies: sand, fine to coarse, trace silt, granules, pebbles; sand, fine to medium, silty, trace granules; clay, silty, trace sand, fine; and, silt, clayey, sandy, fine. Coarse-grained beds function as part of the unconfined aquifer. Thicker, areally extensive fine-grained beds function as confining units. Colors typically are described as yellow, orange, and brown, reflecting generally oxidizing geochemical conditions. In locations where geochemical conditions in the Lynch Heights Formation sediments are more reduced, colors are described as white, light to dark gray, and light blue.

The Lynch Heights Formation rests unconformably on the Beaverdam Formation in many boreholes. The thickness of the Lynch Heights Formation in the area varies from 0 to about 15 ft.

Fine-grained layers are interpreted to be low energy subtidal flats and bay bottom deposits. Sandier layers are higher energy tidal channels, bay beaches, and nearshore bay deposits. The interpretation of estuarine and lagoonal environments is supported by sediment composition, observations of marsh grasses, burrows and burrow mottling, and palynologic fossils of saltwater tolerant plant species from many locations (Groot et al., 1990; Groot and Jordan, 1999; Ramsey, 1997).

Scotts Corners Formation

The Scotts Corners Formation is a Quaternary lithostratigraphic unit (Ramsey, 1993, 1997) that crops out along Delaware Bay and the Rehoboth and Indian River Bays (Fig. 9). The Scotts Corners contains several distinct lithologies that are very similar to those observed in the Lynch Heights Formation, but overall it tends to be finer grained than the Lynch Heights. The Scotts Corners consists of sand, fine to medium, silty, trace granules; clay, silty, trace sand, fine; silt, clayey, sandy, fine; and sand fine to coarse, trace silt, granules, and pebbles. Coarse-grained beds function as part of the unconfined aquifer. Thicker, areally extensive fine-grained units function as confining units. Colors typically are described as yellow, orange, and brown reflecting generally oxidizing geochemical conditions. In locations and at depth where geochemical conditions in the Scotts Corners Formation sediments are more reduced, colors are described as white, light to dark gray, and light blue.

The Scotts Corners Formation is the surficial geologic unit at land surface elevations below 15 ft. A scarp occurring between land surface elevations of 15 to 20 ft separates the Scotts Corners from the older Lynch Heights Formation. The thickness of the Scotts Corners Formation in the area varies from 0 to about 15 ft. Where the Lynch Heights Formation is absent, the Scotts Corners Formation rests unconformably on the Beaverdam Formation.

Fine-grained layers are interpreted to be low energy subtidal flats and bay bottom deposits. Sandier layers are higher energy tidal channels, bay beaches, and nearshore bay deposits. The interpretation of estuarine and lagoonal environments is supported by sediment composition, observations of burrow mottling in outcrop, and palynologic data from many locations (Groot et al., 1990; Groot and Jordan, 1999; Ramsey, 1997) that show saltwater tolerant plant species.

Omar Formation

The Omar Formation (Jordan, 1962) is a surficial unit in the southern portion of the study area (Fig. 9). It was originally described as a Quaternary heterogeneous unit of gray quartz sands interbedded with clayey silts and silty clays that commonly contain abundant plant debris. The Omar is recognized in logs and exposures as a fine-grained deposit with common beds of shells. Beds of medium to fine sand with admixtures of silt and clay matrix and beds of gravelly coarse sand are less common. There are several distinct thick (> 30 ft) units of blue/dark gray clay at the base of the Omar. Muddier beds of the Omar form the base of the unconfined aquifer over a large area in the southeastern portion of the study area and in adjacent Maryland (Achmad and Wilson, 1993). The Omar Formation was deposited in estuarine, lagoonal, pond, and swamp environments.

Jordan (1964) originally assigned a thin (<15 ft) surficial sandier interval to the Omar Formation. Andres and Howard (2000) argued that because the sandier interval is much younger than the underlying muddy beds and unconformably overlies them, the sandier interval is part of the Cypress Swamp Formation. Groot and Jordan (1999) also included late Tertiary beds in the Omar. However, other recent publications (Andres and Howard, 2000; Ramsey, 1999) identify the Omar as a Quaternary unit. It is most likely that the Tertiary beds are part of the Beaverdam Formation.

Sinepuxent Formation

The Sinepuxent Formation is a Quaternary marine to marginal marine sedimentary deposit (Owens and Denny, 1979a). It is a heterogeneous unit consisting of gray silty fine sand to medium sand with thin beds of clay and peat and light-colored fine to medium sand with scattered gravel. The sandier beds function as part of the unconfined aquifer, and the muddier beds function as confining units. The Sinepuxent Formation unconformably overlies the Omar Formation and is unconformably overlain by Holocene marsh, swamp, and shoreline deposits.

The Sinepuxent is the surficial geologic unit in the southeastern portion of the study area (Fig. 9) at land surface elevations below 20 ft. A scarp occurring between land surface elevations of 15 to 20 ft separates the Sinepuxent from the Omar. Coarse-grained beds function as part of the unconfined aquifer. Thicker, areally extensive fine-grained units function as confining units.

Cypress Swamp Formation

The Cypress Swamp Formation (Andres and Howard, 2000) crops out in the southern portion of the map area (Fig. 9). The Cypress Swamp is recognized in logs and exposures as interbedded fine sand, silty fine sand, fine sandy silt, silts, clays, and organic silts and peats. A late Pleistocene (< 23,000 years before present) to Holocene unit, the Cypress Swamp unconformably overlies either the Beaverdam Formation or the Omar Formation and was deposited in fresh water swamp, pond, marsh, dune, and stream environments.

Sandier beds of the Cypress Swamp form a thin, typically less than 15 ft thick, moderately permeable, unconfined aquifer (Andres and Howard, 2002). Depth to water in this aquifer is generally less than 3 ft below land surface (Martin and Andres, 2005). The water table is at land surface in many locations during the winter and spring (Andres and Howard, 2002). As a result, areas underlain by the Cypress Swamp Formation are intensively ditched. The combination of the ditching and shallow depth to the water table causes contaminants introduced at land surface to move relatively quickly through the aquifer into the ditches (Ator et al., 2004). Because of its near surface position and minor thickness, this aquifer is not used for potable water supply.

Unnamed Units

So-called unnamed units are typically thin or occur in areas of active deposition in geographically restricted portions of the study area. They form only a small volume of the materials that make up the unconfined aquifer. Because of their limited spatial distribution and volume, they have only local influences on the hydrology of the study area.

Upland and dune deposits - Upland and dune deposits, up to 15 ft thick, are found at higher elevations in the western portion of the study area. Upland deposits consist of fine to very fine sand, with some beds of clayey silt and clayey sand where located near swamp deposits, and rare beds of medium to coarse sand. Dune deposits are composed of fine to coarse sand. These units unconformably overlie either the Beaverdam or Lynch Heights Formations.

Shoreline and bay deposits - Shoreline and bay deposits are found along the bay and ocean coastlines and beneath Delaware and coastal bays. These sediments range from fine-grained clays and silts and abundant plant remains to sand and gravel that were deposited in beach, dune, washover, marsh, lagoon, and estuarine environments along Delaware Bay, Rehoboth Bay, Indian River Bay and Little Assawoman Bay during the Holocene sea level rise (Ramsey, 1999). They have variable thicknesses, from a featheredge to as much as 100 ft. Thicker units are associated with paleodrainage systems that have filled in during the Holocene. These units unconformably overlie the Beaverdam, Lynch Heights, Omar, Sinepuxent, and Scotts Corners Formations. Thicker deposits form confining layers that affect the location and rate of ground-water discharge into the coastal environment. In some locations, these deposits have notable local ecologic significance such as in the area of Cape Henlopen where ground-water flow that recharges through the very permeable sand dunes has created rare coastal freshwater wetlands where it discharges into the adjacent marshes and swamps.

Swamp and alluvial deposits - Swamp and alluvial deposits occur in the riparian zones of modern streams. These sediments range from fine-grained clays and silts with abundant plant remains to sand. Some upland swamp deposits occur along the western boundary of the study area. Swamp deposits differ from marsh deposits in that there is forested cover on swamp deposits. Swamp and alluvial deposits unconformably overlie the Beaverdam, Lynch Heights, Omar, Sinepuxent, and Scotts Corners Formations. These deposits affect the location and rate of ground-water discharge into the streams and riparian zones.

Man-made deposits - There are some land areas that are underlain by dredge spoils, such as along the Lewes and Rehoboth Canal, Assawoman Canal, and the western side of Fenwick Island. Dredge spoil composition is highly heterogeneous and reflects the composition of the dredged areas. These areas are identified as "Fill" on the map (Fig. 9).

RESULTS AND DISCUSSION

Our investigation of the unconfined aquifer and underlying confining unit used map, cross-section, and statistical tools to evaluate areal, cross-sectional, and volumetric aspects of its geologic, geometric, and hydraulic characteristics. In total, more than 4,000 records of test borings, water wells, and outcrops were reviewed. Of these, records of more than 2,650 locations were used to evaluate thickness of the unconfined aquifer, and another approximately 1,100 records provided data to evaluate the occurrence and geometry of geologic units, aquifer lithologies, and aquifer hydraulic properties (Fig. 10).

Selected Hydrologic Characteristics of the Unconfined Aquifer

Similar to what was found in previous studies (Sundstrom and Pickett, 1970; Denver, 1983; Talley, 1982, 1988; Andres, 1986a, 1987), this study has found that the unconfined aquifer is made up of multiple lithostratigraphic units and that the specific units forming the aquifer vary with location. In contrast to the aforementioned studies, we have mapped the unconfined portion of the Columbia aquifer. As a result, this study has confirmed that there are some areas where the unconfined aquifer is thin to absent because there is a thick confining layer at land surface or at shallow depths below land surface.

The Cat Hill, Bethany, Beaverdam, Lynch Heights, Scotts Corners, Omar, Sinepuxent, and Cypress Swamp Formations as well as upland, shoreline, marine, and dune deposits form the unconfined aquifer in the study area (Fig. 9, Plate 1). Of these, sandy deposits of the Beaverdam Formation form the largest portion of the vol-

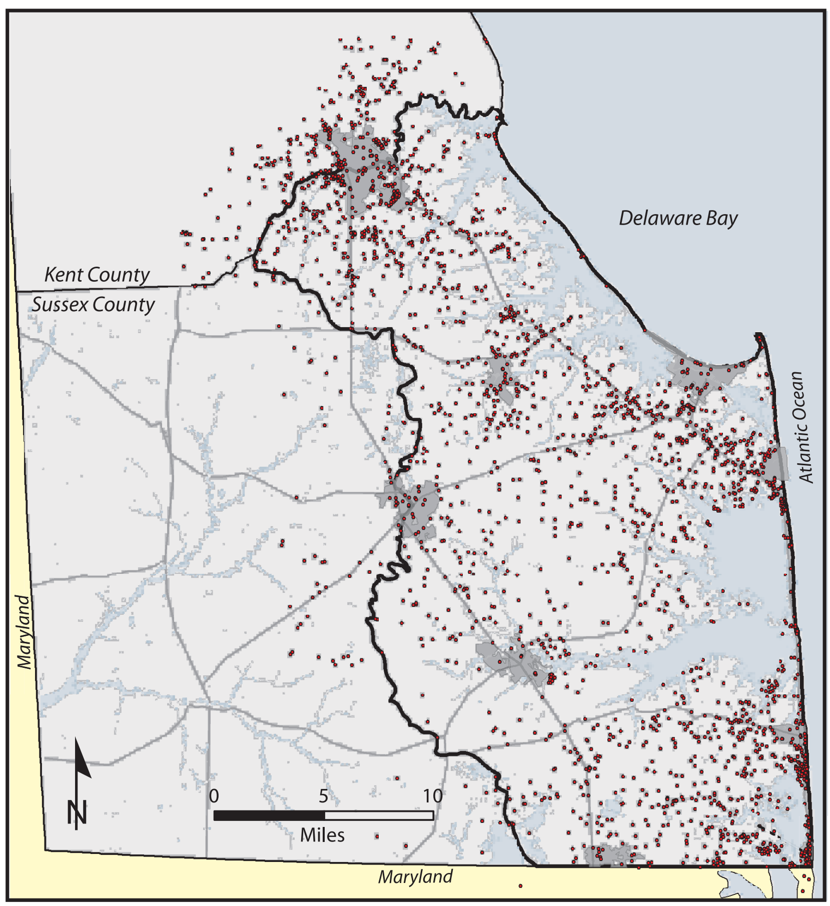


Figure 10. Map showing locations of more than 2,650 data points that were used to evaluate the thickness of the unconfined aquifer. Study area boundary is outlined with heavy black line.

ume of the aquifer, and most wells that pump water from the unconfined aquifer are finished in the Beaverdam Formation. In map view (Fig. 9) however, younger units that overly the Beaverdam form the top of the aquifer over most of the study area. Cross sections (Plate 1) show that the younger units are relatively thin and that sandy beds of the Beaverdam Formation form the bulk of the unconfined aquifer.

The coarser-grained, most permeable beds of the Beaverdam Formation (facies 1) are thought to have been deposited in high energy conditions in channel, beach, and shallow nearshore environments. The thickest and, therefore, more transmissive sections of the aquifer occur where these beds are vertically stacked. The coarse-grained beds of facies 2, deposited in moderate energy environments such as smaller tributary tidal channels, levee, tidal delta, and subtidal flats also are likely to form a highly transmissive aquifer in locations where the coarse-grained beds are vertically stacked.

Because of the amount of new data available and different methods employed in our study when compared to previous studies, our maps of the elevation of the base (Fig. 11) and thickness (Fig. 12) of the unconfined aquifer depict a much more complex aquifer geometry than previous maps. Of particular note are the large areas along Delaware Bay and south of Indian River Bay where the aquifer is less than 20 ft thick because fine-grained beds of Quaternary units occur at shallow depths. The complex geometries of the areas of thicker unconfined aquifer are also noteworthy. These areas occur where sandy beds of the Cat Hill (e.g., Manokin aquifer) and Bethany Formations (e.g., Pocomoke aquifer) are in direct contact with the Beaverdam Formation. Sundstrom and Pickett (1969) and Pickett (1976) depicted these aquifer subcrop areas as simple southwest to northeast trending arcuate shapes, whereas our maps show that the areas have much more complex geometries.

The range of aquifer thickness spans more than two orders of magnitude, though slightly more than half the area has a thickness between 50 and 100 ft (Fig. 13). Also of note is that the unconfined aquifer is less than 10 ft thick over nearly 11 percent of the study area. Deviations of predicted elevations of the base of the aquifer from observed values (e.g., residuals) fall within a narrow range (Table 2). All of the larger magnitude deviations are associated with data points that occur near the edges of shallow confining units, which is due to a combination of grid resolution and smoothing by the gridding process.

The gridding process tends to smooth the spatial distribution and reduce the maximum range of thickness values compared to the borehole-estimated thickness values. It is interesting to note that the mean and median borehole thicknesses are smaller than the corresponding grid values. This is a result of the increased likelihood of an individual borehole penetrating the basal confining unit when the basal confining unit is present at a shallow depth than when the basal confining unit is at a greater depth.

The most numerous and spatially distributed data on hydraulic characteristics of the unconfined aquifer are K values determined from slug tests. As a result, this study uses a method that estimates T from statistical relationships between aquifer materials and slug-test determined K values (equation 1). Using this method, T values were determined at more than 2,700 locations. In turn, these data are input to a gridding process that computes T on a 90-m grid (Fig. 14).

The range of aquifer T values spans more than four orders of magnitude. More than 80 percent of the area has transmissivity values between 1,000 and 10,000 ft^2/day (Fig. 15). Because of the relationship between aquifer thickness and T (equation 1), T is equal to zero in areas where there is no unconfined aquifer. The results of linear regression of aquifer thicknesses and logarithms of non-zero values of borehole estimated T values (Fig. 16) show that thickness accounts for more than 70 percent of the variation in T. Though this is a significant correlation (r = 0.8386), cross-sectional views of the T and base of aquifer

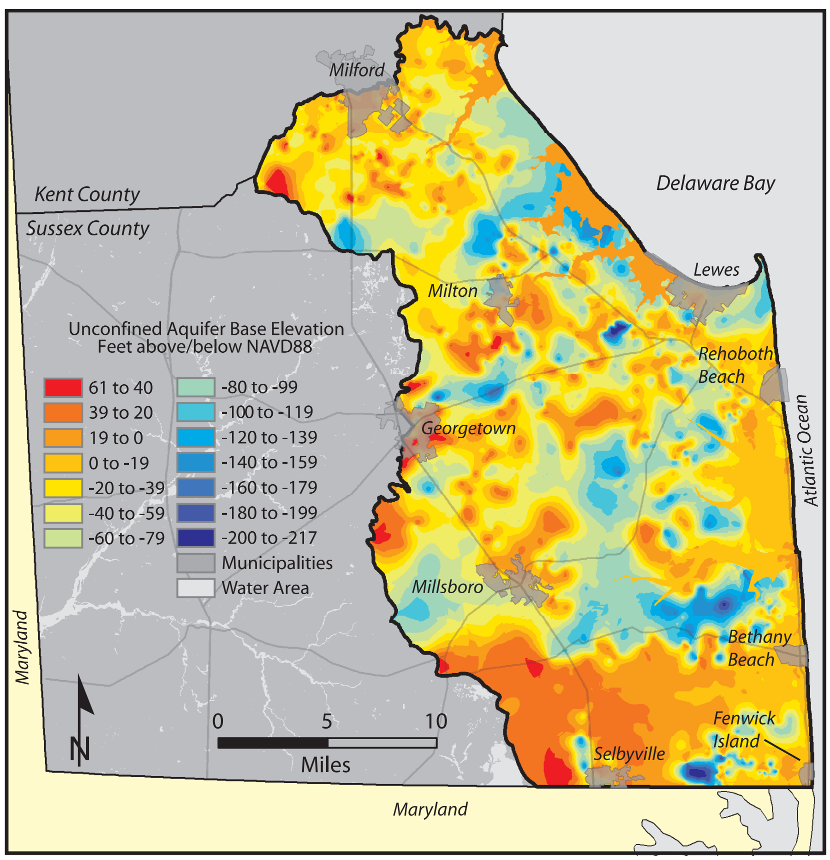


Figure 11. Map of elevation of the base of the unconfined aquifer. Elevation is relative to NAVD 1988. Elevation grid has a 30-m horizontal resolution. Data point location map is shown in Figure 10.

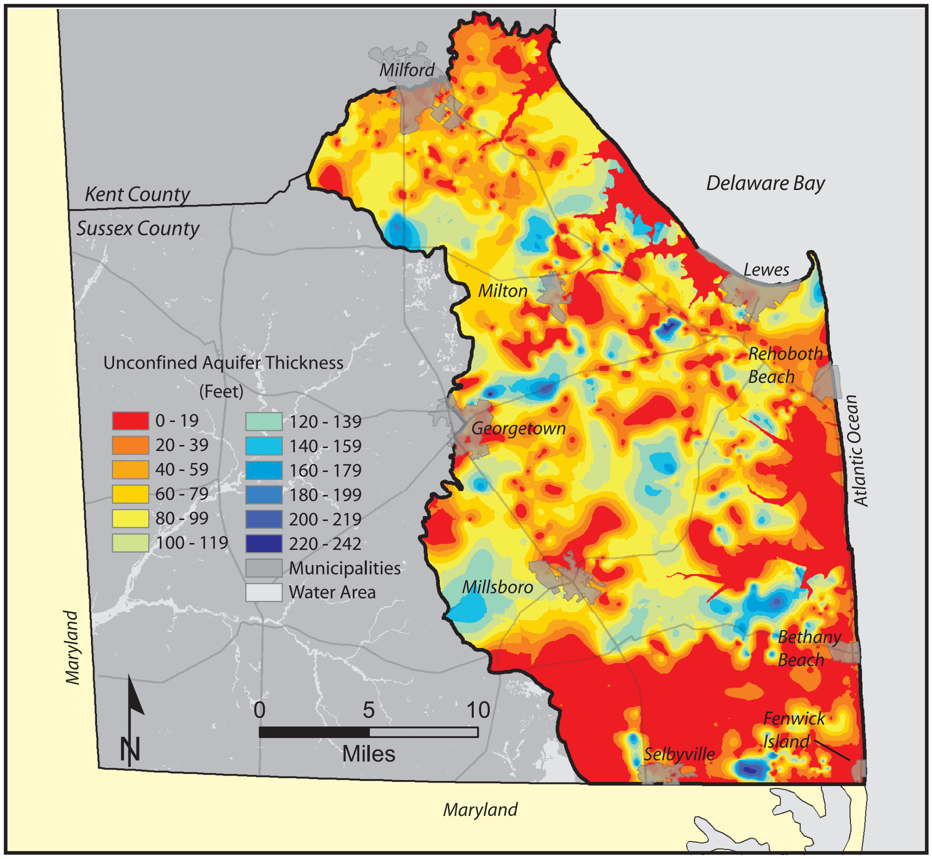


Figure 12. Map of thickness of the unconfined aquifer. Thickness is in feet. Thickness grid has a 30-m horizontal resolution. Data point location map is shown in Figure 10.

elevation grids (Plate 1) show that the thickest sections of the aquifer do not always correspond to the most transmissive sections of the aquifer.

The vast majority of residuals of grid-estimated aquifer T values compared to values estimated from boreholes fall within a narrow range (Table 3). The gridding process tends to smooth the spatial distribution and to reduce the maximum range of T values compared to the borehole-estimated T values. This is due to spatial averaging inherent in any gridding process, and this averaging is further evidenced by the correspondence of the central tendencies (e.g., mean and median) of the grid- and borehole-estimated T values.

Of the six T values determined by pumping tests, four were obtained from the confined portion of the Columbia aquifer and cannot be directly compared to the grid estimates of the unconfined portion of the aquifer. Comparison of the borehole- and grid-estimated T values with T values determined from pumping tests shows that the former methods produce smaller values than the latter method (Table 4). Because the borehole- and grid-estimated T values are largely determined by aquifer thickness, the differences are due to using average K values. Back calculation (equation 1) of the K values needed to match the pumping-test T values indicates that K values would have to be about two times larger than those used. These K values fall within the range of K values reported by Andres (1991, 2003, 2004a). The borehole descriptive logs used to estimate T could also have been in error as a result of under reporting the thicknesses of high permeability sand and gravel.

The methods used in this regional study are readily adaptable to site-specific studies where T and b values are needed to design wastewater disposal or water-supply systems. In these cases, site-specific T values can be computed for the disposal or supply zones from descriptive logs and pumping-test or slug-test-determined aquifer K or T values.

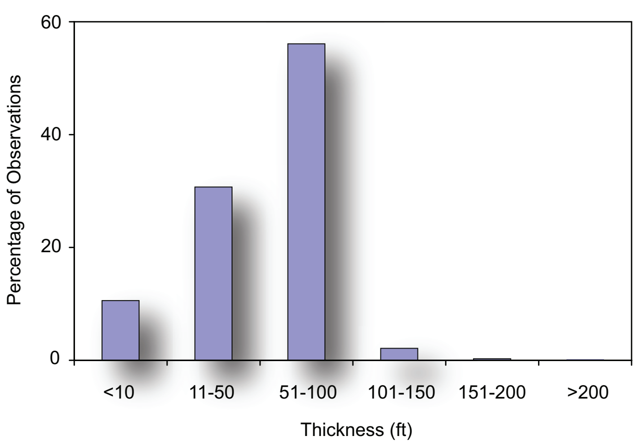


Figure 13. Distribution of observed aquifer thicknessess. Summary statistics are shown in Table 2.

Table 2. Statistics of predicted and observed thicknesses of the base of the unconfined aquifer. Residuals are computed as the difference between borehole and grid values at the location of each borehole.

Statistical Measure	Residuals	Borehole Values	Grid Values
Minimum	-29.9	0	0
5th percentile	-4.42	0	5
First quartile	-0.926	10	25
Mean	0.00414	48.5	65
Median	-0.0115	32	64
Third quartile	0.748	80	95
95th percentile	4.51	140	136
Maximum	45.24	250	242

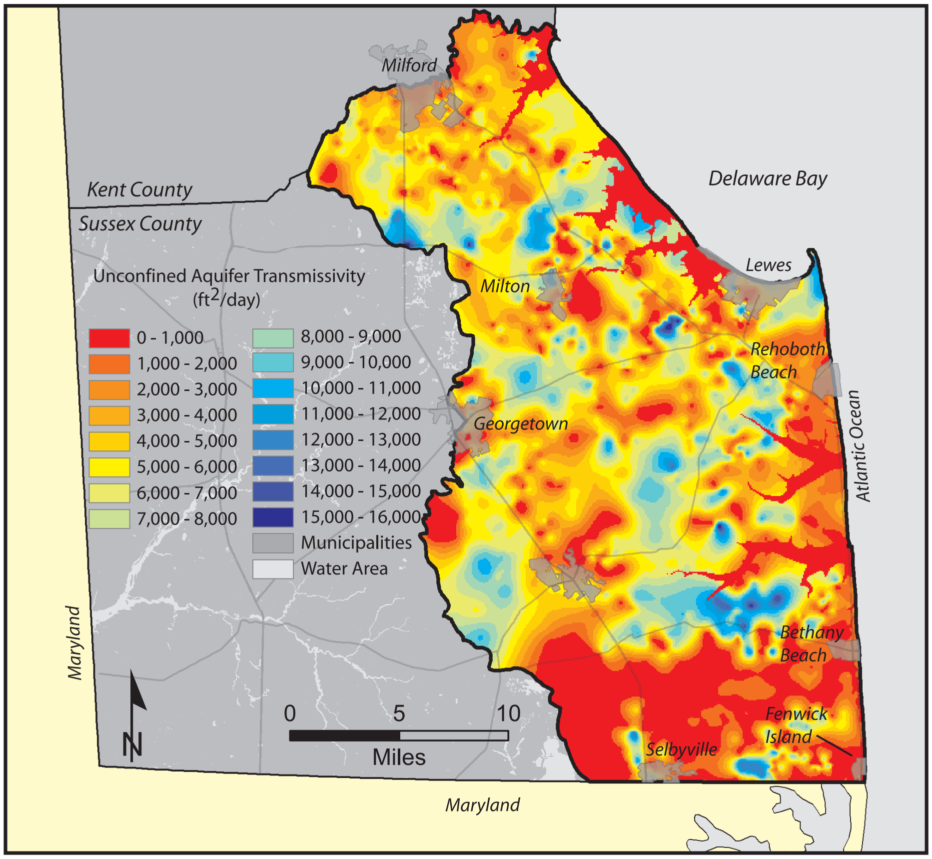


Figure 14. Map of transmissivity (T) of the unconfined aquifer. T grid has a 90-m horizontal resolution.

Selected Hydrologic Characteristics of the Underlying Confining Units

Similar to what was found in previous studies (Sundstrom and Pickett, 1970; Denver, 1983; Talley, 1982, 1988; Andres, 1986a, 1987), this study has found that the confining layer forming the base of the unconfined aquifer is made up of multiple lithostratigraphic units, and that the specific unit or units forming the confining layer vary with location (Fig. 17). Only the St. Marys and Choptank Formations have enough lateral continuity to function as confining units beneath the entire study area. The Omar and Cypress Swamp Formations form a shallow (< 20 ft) relatively areally extensive confining unit over much of the area south of Indian River Bay in the southern portion of the study area. In portions of this area, thick, fine-grained beds of the Omar Formation occur at land surface, and there is no unconfined aquifer.

Because we have mapped the unconfined portion of the Columbia aquifer, this study has found that the same geologic units that form the aquifer in one location function as the confining layer in other locations. For example, the Beaverdam Formation, which is the primary water-bearing geologic unit forming the unconfined aquifer, and the Lynch Heights and Scotts Corners Formations, which are the surficial units over a significant portion of the study area, also contain laterally extensive fine-grained beds that function as the basal confining unit (Fig. 17). Available information indicates that these beds were likely deposited in low energy conditions in distal subtidal to intertidal flat, open-water bay bottom, and tidal creek environments. These confining beds do not form a regionally continuous confining unit, as do confining beds in the Choptank and St. Marys Formations. However, the thickness and lateral continuity of confining beds in the Beaverdam, Lynch Heights, and Scotts Corners Formations are significant for local-scale hydrology.

A distinct difference between this study and previous studies is that we identified Holocene fine-grained marsh and swamp deposits as the confining layer where these deposits meet the thickness and lateral continuity requirements for confining layers. These conditions are commonly met in large areas along Delaware Bay. We have also mapped confining layers where thick, laterally extensive

Table 3. Statistics of predicted and observed transmissivities of the unconfined aquifer. Residuals are computed as the difference between borehole and grid values at the location of each borehole.

Statistical Measure	Residuals	Borehole Values	Grid Values
Minimum	-5,910	0	17
5th percentile	-727	71	289
First quartile	-166	920	1,200
Mean	2.40	4,200	4,200
Median	-12	3,600	3,700
Third quartile	139	6,500	6,400
95th percentile	813	11,000	10,000
Maximum	8,960	18,000	16,000
Standard error	11.07	67.45	63.06

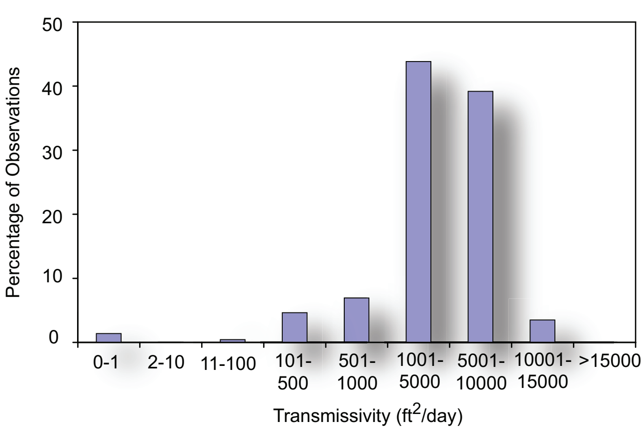


Figure 15. Distribution of transmissivities estimated from lithologies. Summary statistics are shown in Table 3.

Table 4. Comparison of transmissivities estimated by various methods. Transmissivities (T) reported in feet-squared per day. Borehole T estimates are from nearest boreholes. Grid T estimates are from grid cell that contains the well with the pumping test data.

DGS Well Identifier	Well Type	Duration (hours)	Analysis Method	Pumping Test T	Borehole T Estimate	Grid T Estimate
Ph13-32	Observation	48	Bolton	18,000	6,000 - 7,800	6,400
Qh11-04	Observation	48	Theis	16,000	6,800 - 10,000	8,400

fine-grained lagoonal and estuarine deposits occur beneath portions of Rehoboth and Indian River Bays (Chrzastowski, 1986). We interpret the unconfined aquifer as having no thickness in these areas.

The lithologies of the geologic units forming the confining unit are typically dominated by clay and silt, but in some locations contain thin beds and mixtures of sand and even gravel. These units were deposited in a variety of terrestrial, marginal marine, and shallow-water marine environments. Inter- and intra-formational unconformities truncate the fine-grained beds. Because of the lithologies and the spatial discontinuities of individual beds and geologic units, the confining unit is expected to be leaky. As a result, the confining unit may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow. However, because of the contrast in permeability between aquifers and confining units, the quantities of water transmitted by confining units on a local scale are relatively insignificant, and the confining units will significantly alter the rates and directions of ground-water flow. These characteristics of confining units are important to project designs for land-based wastewater disposal systems and for wellhead protection area delineations.

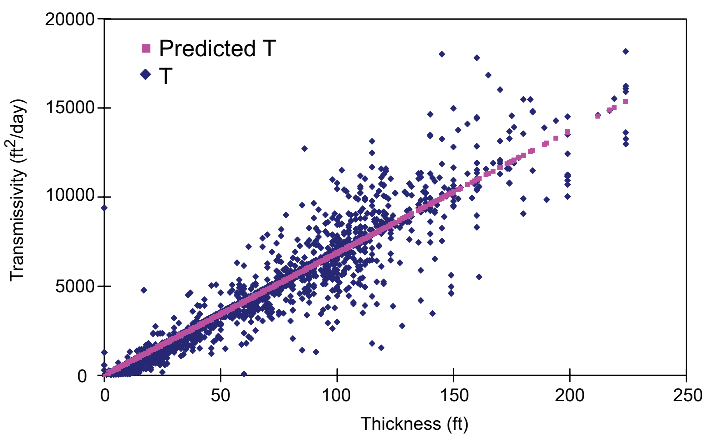


Figure 16. Plot of predicted transmissivities and transmissivities estimated from lithologies.

CONCLUSIONS

The unconfined portion of the Columbia aquifer is a key hydrologic unit in Delaware that supplies water to many agricultural, domestic, industrial, public, and irrigation wells. The aquifer is the source of fair-weather stream flow, and is the aquifer that receives recharge from precipitation. It is also the primary receiving water body for all land-based wastewater disposal. Informed management of this important natural resource requires adequate information about the thickness and water-bearing properties of the aquifer materials.

The primary geologic unit forming the unconfined portion of the Columbia aquifer is the Beaverdam Formation. The Cat Hill, Bethany, Lynch Heights, Scotts Corners, and Cypress Swamp Formations also contain significant water-bearing beds that function as part of the aquifer. The primary geologic units forming the basal confining unit are the Choptank, St. Marys, Bethany, Omar, and Cypress Swamp Formations. These units also contain minor water-bearing beds.

A rules-based method has been developed for mapping the geometry and transmissivity of the unconfined aquifer of eastern Sussex County, Delaware. The primary criteria for characterizing and mapping the unconfined aquifer are based on sediment properties and spatial continuity of sedimentary deposits. Observations at more than 2,600 locations were classified, interpreted, and mapped. The resultant thickness and elevation maps were produced in grids with 30-m horizontal resolution. The transmissivity maps were produced in grids with 90-m horizontal resolution.

The aquifer is less than 50 ft thick over approximately 41 percent of the study area and less than 100 ft thick over more than 97 percent of the map area. Median aquifer thickness is 64 ft. The aquifer is capable of transmitting large quantities of water, with more than 85 percent of the study area having transmissivity in excess of 1,000 ft^2/day. Thickness trends reflect the compositions and spatial distributions of the geologic units and the environments in which they were deposited.

The distribution of grid-estimated transmissivity values tends to be smoother than the borehole-estimated transmissivity values due to the spatial averaging inherent in the gridding process and the use of median hydraulic conductivity values in the process used to estimate transmissivity values at boreholes. However, the application of the study method to individual site studies can be adapted to use site-specific hydraulic conductivity data to estimate transmissivity values at boreholes.

Laterally extensive, fine-grained beds of multiple geologic units form the basal confining unit beneath the unconfined aquifer. The available information indicates that these beds were deposited in low energy conditions in mid-

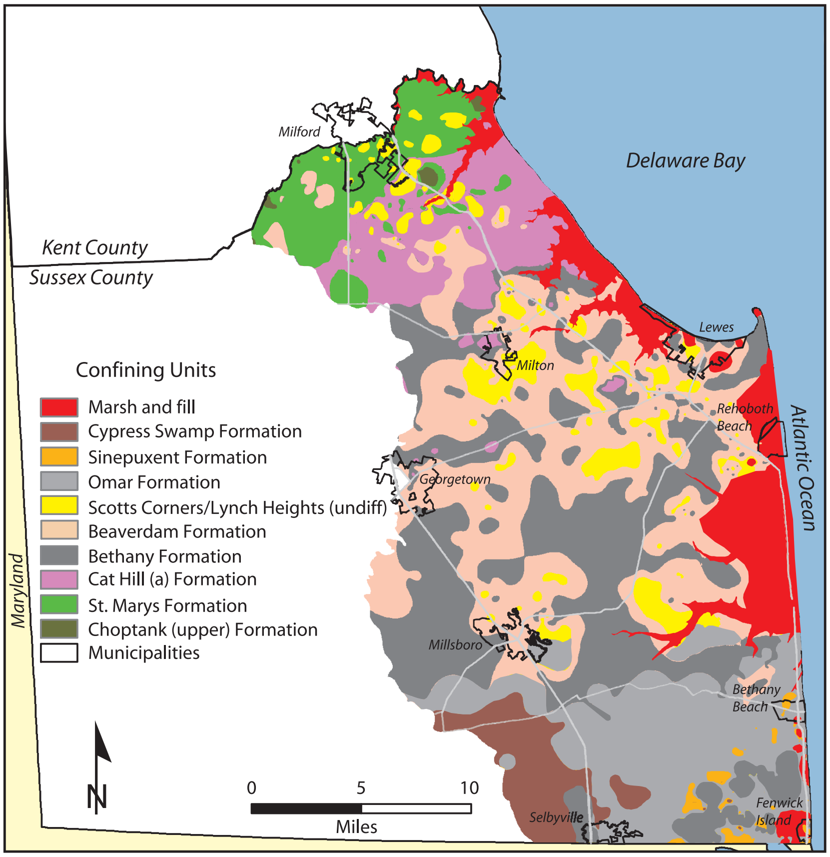


Figure 17. Map of confining units at the base of the unconfined aquifer.

dle to inner neritic marine, to distal subtidal to intertidal flat, open-water bay bottom, and tidal creek environments. The same geologic units that form the aquifer in one location function as the confining layer in other locations.

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