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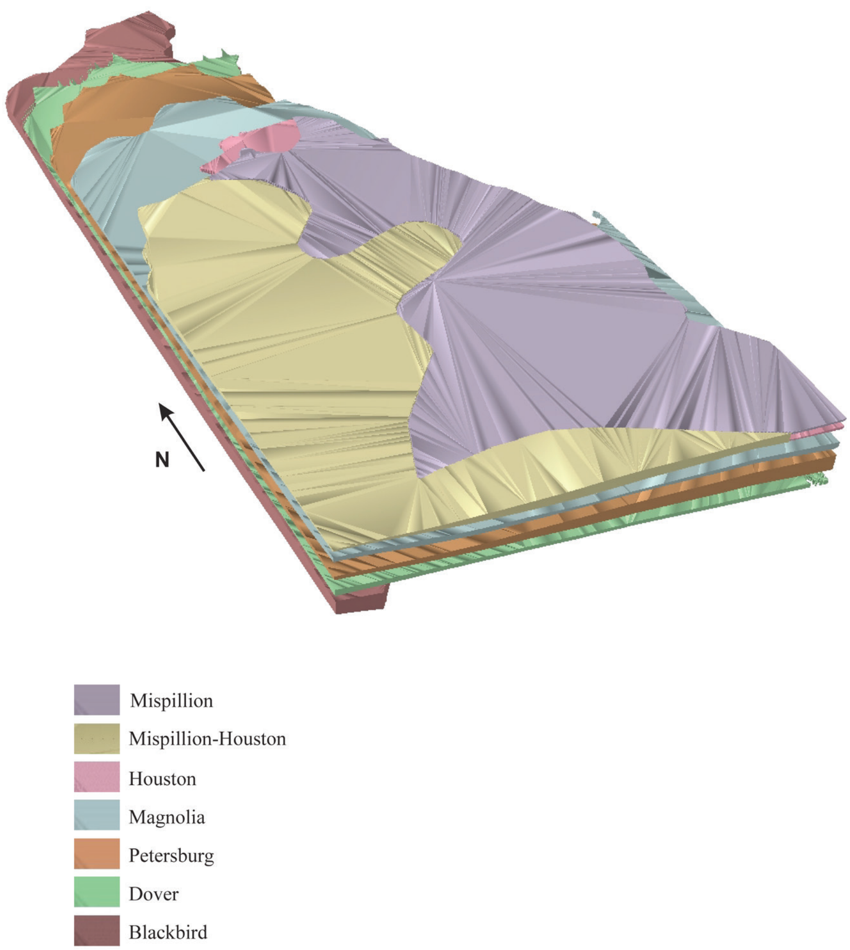
KENT COUNTY GROUNDWATER MONITORING PROJECT: RESULTS OF SUBSURFACE EXPLORATION

By:
A. Scott Andres, Rachel W. McQuiggan, and Changming He



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INTRODUCTION

In 2009, the Delaware General Assembly reauthorized the Delaware Water Supply Coordinating Council (WSCC) plans for preparing water supply and demand estimates through 2030 for Kent and Sussex Counties (Delaware Water Supply Coordinating Council, 2009). The plans were to ensure adequate supplies of water for both public consumption and agricultural irrigation. In order for the WSCC to make informed water-resource recommendations to managers and policymakers, they required the data from a project that incorporated sufficient monitoring infrastructure with systematically collected water samples.

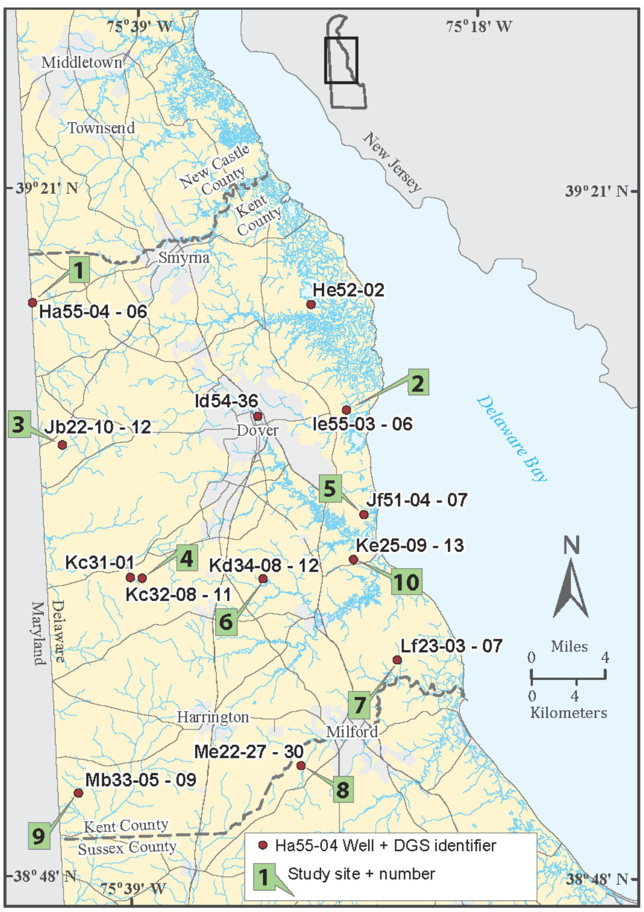

Figure 1. Map of study area.

Through previous research conducted in Kent County by the Delaware Geological Survey (DGS) it was apparent that spatial gaps in monitoring infrastructure and water-resource data existed. As a result, the WSCC recommended that the DGS and the Department of Natural Resources and Environmental Control (DNREC) undertake a project to enhance groundwater-monitoring infrastructure and to collect and analyze data to fill the data void and aid water-resource planning for Kent County. (Fig. 1). The DGS based the project design on the following fundamental concepts:

- Groundwater provides nearly all fresh water for domestic, public, agricultural, and industrial uses in the county.
- Geologic characteristics of the subsurface control the quantity and quality of water availability.
- Groundwater and surface-water resources directly interact on short time scales.

Keeping these concepts in mind while designing water-monitoring infrastructure will result in a monitoring system capable of providing data that will support decision making and applied research on a variety of current and future water quantity and quality issues.

Purpose and Scope

The purpose of this report is to document the methods and results derived from subsurface exploration, monitoring well installation, and hydraulic testing conducted during this study. Selected geologic and hydrologic data and interpretations resulting from previous studies are also discussed in context of the results produced in this study.

The scope of this project was focused on the aquifers in Kent County that supply water to wells for domestic, public, irrigation, and commercial uses as well as provide base flow to local streams. From shallowest to deepest, they are the Columbia, Milford, Frederica, Federalsburg, Cheswold, Piney Point, Rancocas, and Mt. Laurel aquifers. The distribution of these aquifers is dependent on the geology of the area; therefore, their spatial extent and depth below ground surface varies throughout the county. Although the Rancocas and Mt. Laurel aquifers are present throughout Kent County, their depths below the ground surface dip sharply towards the south. Because costs associated with installing wells at depths exceeding 600 feet below ground surface would be prohibitive, wells were installed in the Rancocas and Mt. Laurel aquifers at one site (Site 1; Fig. 1) in northern Kent County.

Acknowledgments

DNREC Water Supply Section managed the financial aspects of the project, issued well permits, and provided other technical assistance. DNREC Division of Fish and Wildlife (William Jones), Delaware Department of Agriculture (DDA) Division of Forestry (Michael Valenti), Town of Smyrna, Polytech High School (Carl "Tad" Jones), Bombay Hook Wildlife Refuge (Oscar Reed) and Abbott's Mill Nature Center (Matthew Babbitt, Elliot Workman) allowed access to their sites for either well or monitoring equipment installation. The Town of Smyrna allowed continued monitoring of

two wells on their property.

The City of Dover (John Sisson, Kate Mills, Jason Lyon) provided water level, water quality and pump-test data for City-operated public supply and test wells and allowed the DGS to install monitoring instrumentation in several of their test wells.

Lifetime Well Drilling, Inc., A.C. Schultes of Delaware, and Somerset Well Drilling, Inc, allowed access to recently completed domestic or production wells for geophysical logging and hydraulic testing.

James Boyle of the New Jersey Geological Survey provided geophysical log and well completion report data for nearby wells in equivalent hydrologic units in New Jersey. David Andreasen and Andrew Staley of the Maryland Geological Survey (MGS) were consulted about monitoring wells in adjacent Maryland. They allowed the DGS to install water-level measurement devices in two Maryland monitoring wells and provided groundwater-level measurements and data from new well installations from their ongoing groundwater monitoring programs. Discussions of similarities and differences of hydrostratigraphy and aquifer hydraulics between Maryland and Delaware were beneficial to both agencies in understanding key water resource issues.

METHODS

Exploratory drilling and well installation operations began at Site 1 (Fig. 1) in April 2017. Drilling and well installations ended in June 2018. Shallow wells were installed at each site (Fig. 1) using the DGS drill rig and hollow-stem augers (HSA). Installation of the deeper aquifer wells was sub-contracted to A.C. Schultes of Delaware. This contract included all drilling, well installation, well development, and site restoration operations. Wells were constructed in the Columbia, Milford, Frederica, Federalsburg, Cheswold, Piney Point, Rancocas, and Mt. Laurel aquifers; however, wells were not constructed in all aquifers at every site (Table 1). Hydraulic testing was conducted at both newly installed and existing monitoring wells and at newly installed domestic wells.

Table 1. List of sites and wells in this study. NAVD88 = North American Vertical Datum of 1988, bgs = below ground surface.

Site ID	Site Name	DGS identifier	DNREC Permit Number	Screen Top (feet bgs)	Screen Bottom (feet bgs)	Land Surface Elevation (NAVD88)	Installation Date	Aquifer
1	Blackiston State Forest	Ha55-04	257526	18	23	65.32	4/5/2017	Columbia
		Ha55-05	259080	440	450	65.55	8/1/2017	Mt. Laurel
		Ha55-06	259057	205	215	65.51	8/2/2017	Rancocas
2	Little Creek Wildlife Area	Ie55-03	257527	18	23	8.23	4/19/2017	Columbia
		Ie55-04	259055	155	165	8.76	8/8/2017	Cheswold
		Ie55-05	259054	115	125	8.45	8/10/2017	Federalsburg
		Ie55-06	259056	335	345	8.15	8/15/2017	Piney Point
3	Tappahanna Wildlife Area – Fortney Tract	Jb22-10	257531	18	23	69.49	4/5/2017	Columbia
		Jb22-11	259053	260	270	69.6	8/21/2017	Piney Point
		Jb22-12	259052	132	142	69.7	8/23/2017	Cheswold
4	Norman G. Wilder Wildlife Area – Petersburg Tract	Kc32-08	257533	13	18	56.72	4/26/2017	Columbia
		Kc32-09	259100	250	260	57.04	8/24/2017	Cheswold
		Kc32-10	259084	115	125	57.01	8/25/2017	Frederica
		Kc32-11	259087	183	193	57.1	8/28/2017	Federalsburg
5	Ted Harvey Wildlife Area	Jf51-04	257532	7	12	8.77	4/19/2017	Columbia
		Jf51-05	259418	250	260	9.3	9/13/2017	Cheswold
		Jf51-06	259417	175	180	9.4	9/14/2017	Federalsburg
		Jf51-07	259403	120	130	9.51	9/15/2017	Frederica
6	McGinnis Pond Wildlife Area	Kd34-08	261998	23	33	41.96	6/26/2018	Columbia
		Kd34-09	261996	444	454	42.3	7/26/2018	Piney Point
		Kd34-10	261993	140	150	42.31	7/27/2018	Frederica
		Kd34-11	261995	280	290	42.05	7/31/2018	Cheswold
		Kd34-12	261994	214	224	42.09	8/1/2018	Federalsburg

Table 1 (continued)

Site ID	Site Name	DGS identifier	DNREC Permit Number	Screen Top (feet bgs)	Screen Bottom (feet bgs)	Land Surface Elevation (NAVD88)	Installation Date	Aquifer
7	Milford Neck Wildlife Area	Lf23-03	257534	7.5	12.5	9.25	4/17/2017	Columbia
		Lf23-04	259372	440	450	9.45	9/28/2017	Cheswold
		Lf23-05	259371	355	365	9.46	10/4/2017	Federalsburg
		Lf23-06	259370	230	240	9.54	10/10/2017	Frederica
		Lf23-07	259369	170	180	9.48	10/11/2017	Milford
8	Abbott's Mill Nature Center	Me22-27	260641	240	250	45.21	1/19/2018	Milford
		Me22-28	260643	320	330	44.94	1/22/2018	Frederica
		Me22-29	260642	430	440	45.59	1/24/2018	Federalsburg
		Me22-30	261997	18	28	45.59	6/26/2018	Columbia
9	Taber State Forest	Mb33-05	257863	13	18	57.8	4/26/2017	Columbia
		Mb33-06	259367	350	360	58.03	9/20/2017	Cheswold
		Mb33-07	259366	285	295	58.02	9/22/2017	Federalsburg
		Mb33-08	259365	194	204	57.86	9/25/2017	Frederica
		Mb33-09	259364	130	140	57.49	9/26/2017	Milford
10	Ted Harvey Wildlife Area – Buckaloo Tract	Ke25-09	257669	4	14	10	4/17/2017	Columbia
		Ke25-10	259399	469	479	9.65	11/8/2017	Piney Point
		Ke25-11	259396	150	160	9.8	11/13/2017	Frederica
		Ke25-12	259398	330	340	9.58	11/15/2017	Cheswold
		Ke25-13	259397	215	225	9.63	11/16/2017	Federalsburg

Hollow-stem auger drilling and coring

Shallow test borings and well installations were completed at each site using HSA methods. Continuous-core soil samples were collected during shallow-well installation at each location using a 2-ft split-spoon sampler. Blow counts were recorded for each six-inch interval of linear depth of the core sampler. Core material was placed into core boxes and wooden markers were used to separate each recovered interval. Sample textures and colors were described on site by a geologist using the Udden-Wentworth grain-size scale (Wentworth, 1922) and color chart (Rock Color Chart Committee, 1979). Sample lithologies were described using the Folk (1954) system. Changes in lithostratigraphic units were noted as well as features such as carbonate content, mineralogy, and grain sorting. The well screen interval was determined based on the encountered depth of the water table and depth to the bottom of the unconfined aquifer observed during drilling.

Mud rotary drilling

While drilling the deeper wells by standard mud rotary methods, soil/sediment cutting samples were collected by the on-site geologist at 10-ft intervals and then rinsed with clean water to remove the drilling mud. The geologist described sample composition including texture (Udden-Wentworth scale, Wentworth, 1922), color (Rock Color Chart Committee, 1979), mineralogy, cementation, and fossils. Sample lithologies were described using the Folk (1954) system. Also noted were zones of water loss. Calcium carbonate content was approximated for each sample interval by measuring the material's reaction to a 10% HCl solution and assigning a numerical value from 0 (no reaction) to 3 (strong reaction). Samples were placed into clean bags, and then labelled with the sample location, depth interval, and geologist's initials.

Samples were left to dry in their respective bags in the DGS garage. Each sample was assigned a unique, sequential identifier and recorded in an internal database along with its corresponding location and depth information. Dried and labelled samples were stored in the DGS sample repository for potential future analysis.

Geophysical logging

Prior to drilling, the digital elevation models (DEMs) of McLaughlin et al. (2009) were used to estimate aquifer depths at each site. At each site, the deepest hole was drilled, sampled, and logged in order to select the well-screen intervals for the confined aquifers. Digital geophysical logs were collected by the DGS using a factory-calibrated Century Geophysical drawworks, tools, and System 6 processing module. Natural gamma radiation, spontaneous potential, single-point resistivity, short-normal resistivity, long-normal resistivity and lateral resistivity were measured in open boreholes with a Century 8144A multi-parameter electric (MPE) wireline geophysical multi-tool. A Century 9512 electrical induction and gamma tool was used to measure natural gamma radiation and bulk formation conductivity in several PVC-cased wells installed during this project.

Monitoring-well installation

Forty-two (42) monitoring wells were installed at ten sites between April 2017 and July 2018, totaling over 8,600 linear feet. At each site, a shallow well was drilled and installed in the unconfined aquifer (Columbia) using the DGS

HSA drill rig. Well screens were set in the coarsest sediment that was observed in the core samples. A minimum of two additional wells were drilled and installed at each site in deeper, confined aquifers using mud-rotary methods. Well-screen depths were chosen based on an evaluation of down-hole geophysical logs and cutting samples. Table 1 provides a summary of monitoring wells installed during this project and the associated aquifers at each site.

Monitoring wells were constructed using 2-inch inner diameter, schedule 40 PVC threaded casing or solvent-welded casing and either a 5- or 10-ft slotted well screen at the bottom, depending on the thickness of the unconfined aquifer at a particular location. Wells deeper than 100 ft included a 5-ft sump, consisting of non-slotted casing pipe, attached to the bottom of the screened interval. The purpose of the sump is to allow for potential sediment accumulation over time without interfering with the screened interval. For shallow wells, a gravel pack was emplaced through the augers into in the annular space between the well screen and borehole as the augers were removed. Two to three feet of bentonite pellets were emplaced on top of the gravel pack, again through the augers. Depth to the top of the gravel pack and bentonite was sounded periodically to ensure the material was settling to the bottom and not creating any voids. The remaining annular space was filled with chipped bentonite after the augers were removed. For deeper wells, tremie pipe was lowered to approximately 20 ft above the bottom depth and incrementally pulled out of the drillhole. Annular space was filled with #2 gravel pack up to 10 ft above the screen top and was grouted with cement to the ground surface using a tremie pipe system.

Following installation, wells were developed by air-lift pumping. Shallow wells were pumped for a minimum of one hour and deeper wells were pumped overnight for a minimum of six hours, or until the water appeared to be clear and free of suspended material. Wells were finished approximately 2½ feet above the ground surface, and furnished with a locking steel protective casing and concrete pad. Metal tags with DNREC permit numbers were affixed to the steel protective casing and the DGS well identifier was inscribed on the inside of the protective cap.

Horizontal coordinates (NAD83) for each monitoring well were determined with a global positioning system (GPS) with real-time kinematic corrections using the Leica SmartNet Network. The elevation (NAVD88) was measured at the top of one well at each site using the same GPS system. Relative elevation differences between the GPS-surveyed well and remaining wells at each site were surveyed using a Sokkisha B2A auto level.

Aquifer and Confining Unit Mapping

The DEMs of Kent County aquifers from McLaughlin et al. (2009) were used to calculate the thicknesses of confining units encountered during this investigation. Thicknesses were calculated by grid-to-grid math operations in ArcMap v. 10.6 (ESRI, 2018). Given an upper aquifer with basal elevation BE1, an underlying aquifer with top elevation TE1, and an intervening confining unit, the confining unit thickness was calculated as BE1 minus TE1 (Fig. 2a). Resulting grids have a 100-m horizontal resolution and a 1-ft vertical resolution.

The confining unit thickness maps will provide a visual reference for potential areas where two aquifers interact with one another. The horizontal extent of each confining unit layer was clipped based on the distribution of data points from the overlying aquifer base-elevation model and does not necessarily represent the actual limits of the existence of each unit (Fig. 2b).

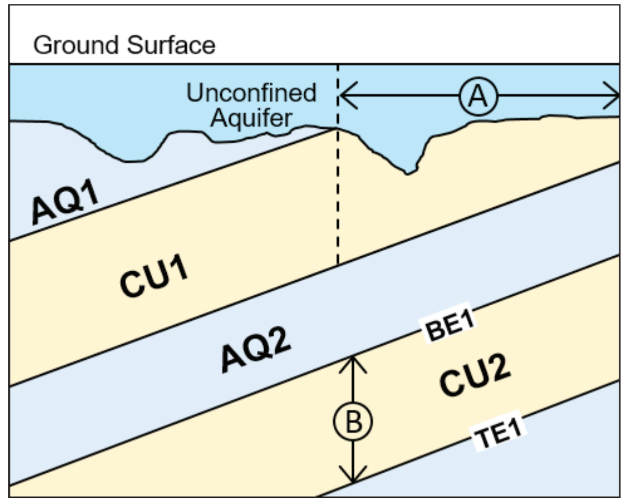

Figure 2a. Illustration of process used to map confining unit thickness. Not to scale. A) Area where confining unit CU1 is present, but is not mapped. B) Calculated thickness of confining unit CU2.

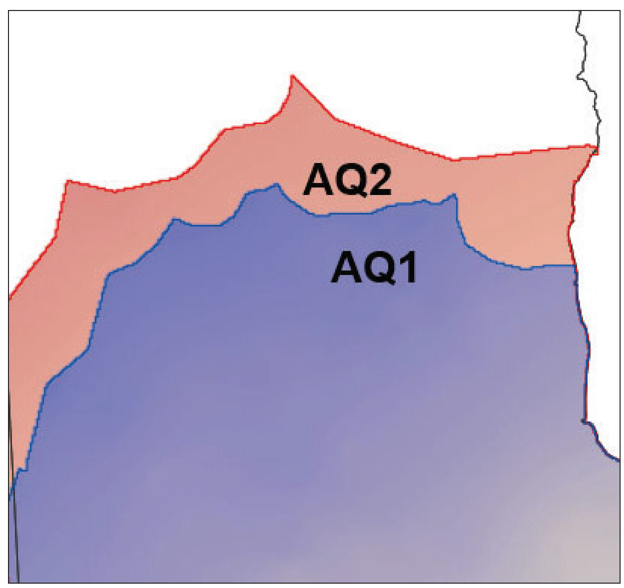

Figure 2b. Plan view 2-D example of situation "A" described in Figure 2a. Not to scale. Boundary limits of the Frederica (blue) and Federalsburg (red) aquifers. The red color represents the area where the confining unit between these two aquifers is likely present, but has not been mapped.

Aquifer Testing

Hydraulic conductivity (K) and relative permeability were determined by performing single-well slug tests on all new monitoring wells and several newly constructed domestic wells. The tests and resulting analyses were performed with a mechanical slug following procedures suggested by Butler (1998). Prior to conducting each test, static water levels were established by recording a depth-to-water measurement collected with an electric tape indicator. An In-Situ Level Troll 700 pressure transducer/logger was then installed and attached to a laptop computer via a vented, direct-read cable and programmed to measure and transmit water-level data at 0.25- to 0.50- second intervals. Data were evaluated in real time to evaluate test progress and ensure that the test was not compromised by installation of the pressure transducer or slug. Two-inch diameter slugs were used in four-inch diameter wells, 0.75 inch diameter slugs were used in two-inch diameter wells.

Data were pre-processed using Microsoft Excel and evaluated with AquiferTest Pro (Waterloo Hydrogeologic, Inc., 2016). In most cases, data collected from unconfined aquifers were analyzed using the solution of Bouwer and Rice (1976). Data collected from confined aquifers were analyzed using both the Bouwer and Rice (1976) and Hvorslev (1951) solutions for comparison. Following recommendations made by Butler (1998) on processing slug-test data with a slightly overdamped (concave upward) response, normalized level data between 0.15 and 0.25 (corresponding with 15 to 25 percent of recovery to static) were used along with the Hvorslev (1951) method, and normalized level data between 0.20 and 0.30 (corresponding with 20 to 30 percent of recovery to static) were used along with the Bouwer and Rice (1976) method. For all confined aquifers exhibiting a near-linear pressure response to the slug test on a semi-log plot, K results using the Hvorslev (1951) method were chosen to be included in this report. This method was selected based on the relative small standard deviation between replicate tests. Reported values are the mathematical mean of three rising-head tests. Several of the confined aquifers exhibited non-linear/oscillating slug test responses. These data were analyzed following Butler's method for high-K aquifers (Butler et al., 2003) using an iterative curve-matching process.

Transmissivities (T) in each aquifer at a site were calculated based on the following formula:

$$T\ (ft^2/day) = K\ (ft/day) * \text{Aquifer Thickness (ft)}$$

Slug tests characterize only the limited volume of aquifer affected by the slug test; therefore, T values estimated from slug tests at a given site are useful to compare with larger datasets that include T values from pumping tests and slug tests at multiple sites.

Published and unpublished hydraulic data (T, K, and specific capacity [SC]) from DGS files were tabulated and evaluated in this report. The unpublished hydraulic data were extracted from prior unpublished DGS studies, consultant reports, and pumping test records provided by owners of large capacity irrigation wells. The vast majority of unpublished data were sufficient only for computing SC (pumping rate divided by drawdown). Because many pumping tests included only a pumping well and did not evaluate well efficiency, those data may impart a bias toward under-predicting aquifer hydraulic properties. For wells with only SC tests, data were included from wells greater than 4 inches in diameter with tests of at least 4 hours in duration, and a pumping rate of at least 100 gallons per minute to avoid influence of well construction, short test length, and low pumping rates.

Data Management and Public Access

All geologic and hydrologic data were archived in the DGS internal database to ensure long-term, efficient management of and access to data. Lithologic and geophysical data are available through the DGIR map interface (maps.dgs.udel.edu/dgir/). Hydraulic data are available on the data pages of DGS web site (https://www.dgs.udel.edu/data). Streamflow data are maintained by the USGS and available from the National Water Information System (http://waterdata.usgs.gov/de/nwis/sw).

RESULTS AND DISCUSSION

Geologic and hydrologic data discussed in this report include geophysical and descriptive logs, determinations of aquifer tops and bottoms, K test results, and estimates of transmissivity (T). Wells were constructed in the unconfined portion of the Columbia, Milford, Frederica, Federalsburg, Cheswold, Piney Point, Rancocas, and Mt. Laurel aquifers; however, wells were not constructed in all aquifers at every site (Table 1). These data are discussed in the context of lithostratigraphic and hydrostratigraphic units.

Lithostratigraphy and Hydrostratigraphy

Lithologic analysis and mapping by McLaughlin and Velez (2006) and McLaughlin et al. (2009) found that aquifers and confining units dip to the southeast, and their tops, in most cases, are truncated by erosional unconformities in updip areas and overlain by the younger, Quaternary-age Beaverdam or Columbia Formations, or the Lynch Heights and Scotts Corners members of the Delaware Bay Group. The Piney Point (Formation and aquifer) is an exception to these trends. The top of the Piney Point Formation is truncated by an erosional unconformity, and overlain by the Calvert Formation (McLaughlin et al., 2009). Leahy (1976, 1979) first reported that the stratigraphic relationship between the Piney Point and Calvert Formations restricts recharge to the Piney Point aquifer by diffuse leakage through its bounding confining units. Discussion of the processes of recharge to the Piney Point aquifer is beyond the scope of this report. In downdip areas, lithostratigraphic units occur deeper in the subsurface and have spatially variable thicknesses, but appear to be relatively continuous over Kent County. Individual hydrostratigraphic units also follow the depth trend; however, there are some exceptions to this, including the Piney Point (Formation and aquifer) and the Middle Choptank aquifer (McLaughlin et al., 2009).

No new lithostratigraphic or hydrostratigraphic units were discovered during this project. Lithologies encountered during drilling and logging are consistent with those of McLaughlin et al. (2009). Lithostratigraphic units (Fig. 3) penetrated during this work extend from the Mt. Laurel Formation (oldest) to the Scotts Corners Formation (youngest). Interpretations of lithostratigraphy and hydrostratigraphy for drillholes installed during this project are summarized in a stratigraphic chart (Fig. 3). Hydrostratigraphy based on geophysical and descriptive log data from individual sites is displayed in Figures 4-13 and Appendix 1. Core and cutting samples and geophysical logs collected during this study are the primary data for hydrostratigraphic correlation to established frameworks (McLaughlin and Velez, 2006; McLaughlin et al., 2009; Ramsey, 2007; Andres, 2001; Andres et al., 2018). Discussions of lithologic and geophysical data with DGS staff members McLaughlin, Ramsey, and Tomlinson supplemented our work.

Age	Geologic Units	Hydrogeologic Units
Pleistocene	Unnamed alluvial, swamp, marsh, eolian deposits Delaware Bay Group Columbia Fm.	Columbia aquifer and unnamed confining beds
?	Beaverdam Fm.	
middle Miocene	St. Marys Fm.	St. Marys confining unit
	Choptank Fm.	upper Choptank aquifer
		Mispillion confining unit
		middle Choptank aquifer
		Houston confining unit
		Milford aquifer
	Calvert Fm.	Magnolia confining unit
lower Miocene		Frederica aquifer
		Petersburg confining unit
		Federalsburg aquifer
		Dover confining unit
		Cheswold aquifer
		Blackbird confining unit
Eocene	Piney Point Fm.	Piney Point aquifer
	Shark River Fm.	Blackbird confining unit
	Manasquan Fm.	Rancocas aquifer
Paleo-cene	Vincentown Fm.	
	Hornerstown Fm.	Armstrong confining unit
upper Cretaceous	Navesink Fm.	
	Mt. Laurel Fm.	Mt. Laurel aquifer

Figure 3. Lithostratigraphic and hydrostratigraphic units.

Detailed biostratigraphic and isotope analyses and evaluations needed to more precisely determine biostratigraphy and chronostratigraphy and to further evaluate depositional environments and depositional history were beyond the scope of this study. Core sampling needed to identify lithostratigraphic boundaries and structural features (e.g., Andres et al.,2018) was not performed in this study. Further discussion of the relationships between hydrostratigraphy, hydraulics, and hydrologic functions is contained in later sections.

Overall, the aquifer DEMs of McLaughlin et al. (2009) successfully predict the elevations of aquifer tops and bottoms at our study sites, with relatively small mean differences for individual aquifers (Table 2a) indicating that the aquifer DEMs are useful for general, large-scale planning and modeling purposes. However, the range of differences between aquifer top and bottom elevations in individual boreholes and from DEMs is five to ten times larger than the range of mean differences (Tables 2a, 2b), indicating that site-specific data from drilling and logging are better tools than the DEMs for site-specific tasks such as picking a well depth and designing the well screen. The reduced goodness-of-fit between site-specific observations and regional estimates is typical (e.g., Dugan et al., 2008), and is due to smoothing inherent in the gridding algorithms that generate the regional estimates (Davis, 2002).

Confining Units

Dugan et al. (2008) named confining units in New Castle County to allow more efficient description of the spatial distribution, continuity, geometry, hydraulic properties, and hydrologic functions of confining units. The confining units were named in much the same way that many Delaware aquifers were named, that is, a name is taken from a place where a drillhole penetrates the confining unit. Two of these units, the Armstrong and Blackbird confining units (Fig. 3), were penetrated by drillholes installed for this study. Other investigators have similarly named confining units. For example, the St. Marys confining unit (Andres and Klingbeil, 2006; McLaughlin et al., 2009; Sanford et al., 2012; Andreason et al., 2013) is named for the St. Marys Formation, a fine-grained, regionally extensive lithostratigraphic unit that forms the confining unit. Similarly, new names for several confining (hydrostratigraphic) units are defined for dominantly fine-grained, spatially continuous beds in the Calvert and Choptank Formations (Fig. 3).

Thicknesses and lithologies of confining units are spatially variable (Figs. 4-13, Appendices 1 and 2). Displays of confining unit thicknesses (Fig. 14, Appendix 2) include Sussex County because the supporting grid data from McLaughlin et al. (2009) included those areas. Where confining units are thicker and composed of predominately muddy sediment, it is likely that the units will impede the flow of water between the overlying and underlying aquifers. Conversely, where confining units are thinner and composed of coarser-grained sediments, it is likely that the units will transmit water between overlying and underlying aquifers. Groundwater flow modeling in New Castle County found that flow of water from

Table 2a. Comparison of aquifer surface elevations from this study and predicted by McLaughlin et al. (2009). Notes: (1) negative number indicates observed elevation deeper than modeled elevation; positive number indicates observed elevation shallower than modeled elevation; (2) bottom elevation and thickness left blank when bottom of aquifer was not encountered during drilling; all elevations are North American Vertical Datum of 1988 in feet.

Aquifer	Site ID	DGSID	LS Altitude (NAVD88)	Geologic Unit at Screen	Observed Aquifer Top (elev)	Observed Aquifer Bottom (elev)	Difference in Top Elevation from DEM [1] (ft)	Difference in Bottom Elevation from DEM [1] (ft)	Difference in Thickness (ft)
Columbia	1	Ha55-04	65.3	Tc	65.9	32.9	0.0	1.0	1.0
Columbia	2	Ie55-03	8.2	Tbd	8.7	-4.3	0.0	36.0	36.0
Columbia	3	Jb22-10	69.5	Tbd	69.4	25.4	0.0	-1.0	-1.0
Columbia	4	Kc32-08	56.4	Tbd	57.1	-3.9	0.0	-26.0	-26.0
Columbia	5	Jf51-04	8.8	Qsc	9.0	-29.0	0.0	33.0	33.0
Columbia	6	Kd34-08	37.3	Qlh	37.3	-4.7	0.0	0.0	0.0
Columbia	7	Lf23-03	9.3	Qsc	8.8	-5.2	0.0	17.0	17.0
Columbia	8	Me22-30	45.6	Tbd	45.6	-44.4	0.0	-9.0	-9.0
Columbia	9	Mb33-05	58.0	Tbd	58.1	13.1	0.0	2.0	2.0
Columbia	10	Ke25-09	10.0	Tbd	10.2	-21.8	0.0	3.0	3.0
Milford	7	Lf23-07	9.5	Tch	-122.2	-175.2	9.4	0.0	-9.4
Milford	8	Me22-27	47.2	Tch	-179.8	-227.8	-25.0	-13.6	11.4
Milford	9	Mb33-09	57.5	Tch	-63.9	-104.9	3.8	0.5	-3.4
Frederica	4	Kc32-10	56.8	Tc	-35.9	-96.9	1.0	8.3	7.3
Frederica	5	Jf51-07	11.5	Tc	-92.0	-141.0	0.1	0.7	0.7
Frederica	7	Lf23-06	9.5	Tc	-209.2	-274.2	-1.5	0.7	2.2
Frederica	8	Me22-28	46.9	Tc	-259.8	-292.8	-6.2	13.3	19.5
Frederica	9	Mb33-08	57.9	Tc	-133.9	-182.9	-8.4	8.9	17.3
Frederica	10	Ke25-11	9.8	Tc	-131.8	-164.8	-9.9	3.7	13.6
Federalsburg	2	Ie55-05	8.4	Tc	-79.6	-119.6	-7.7	-13.6	-5.9
Federalsburg	4	Kc32-11	56.8	Tc	-109.9	-164.9	5.5	2.4	-3.1
Federalsburg	5	Jf51-06	9.4	Tc	-165.0	-190.0	4.5	24.3	19.7
Federalsburg	6	Kd34-12	37.3	Tc	-172.7	-227.7	-22.2	-7.4	14.8
Federalsburg	7	Lf23-05	9.5	Tc	-302.2	-361.2	18.3	18.3	0.0
Federalsburg	8	Me22-29	47.6	Tc	-324.8	-399.8	28.4	-1.0	-29.4
Federalsburg	9	Mb33-07	58.0	Tc	-209.9	-276.9	0.4	-36.7	-37.1
Federalsburg	10	Ke25-13	9.6	Tc	-194.8	-232.8	2.2	13.7	11.5
Cheswold	2	Ie55-04	8.8	Tc	-129.3	-194.3	-12.7	4.3	17.0
Cheswold	3	Jb22-12	69.7	Tc	-26.6	-76.6	-0.7	-5.1	-4.4
Cheswold	4	Kc32-09	56.8	Tc	-176.1	-206.1	0.1	28.8	28.7
Cheswold	5	Jf51-05	9.3	Tc	-239.0	-276.0	-12.1	26.0	38.1
Cheswold	6	Kd34-11	37.3	Tc	-240.7	-306.7	-7.4	-24.1	-16.8
Cheswold	7	Lf23-04	9.4	Tc	-400.2		11.3		
Cheswold	9	Mb33-06	58.0	Tc	-280.9	-305.9	-34.2	0.1	34.3
Cheswold	10	Ke25-12	9.6	Tc	-263.8	-338.8	8.1	-0.6	-8.7
Piney Point	2	Ie55-06	8.2	Tpp	-314.6		0.4		
Piney Point	3	Jb22-11	69.6	Tpp	-166.4		0.8		
Piney Point	6	Kd34-09	37.3	Tpp	-403.7		-29.8		
Piney Point	10	Ke25-10	9.7	Tpp	-432.8		-5.3		
Rancocas	1	Ha55-06	65.5	Tvt	-79.2	-317.2	16.8	-19.5	-36.3
Mt. Laurel	1	Ha55-05	65.5	Kml	-365.4		-30.1		

Table 2b. Summary statistics of observed versus modeled elevations by aquifer. Negative number indicates observed elevation deeper than modeled elevation. Cells marked with "n/a" where there are insufficient data points to calculate standard deviation or bottom depth of aquifer was not encountered during drilling. Blank cells indicate where the top of the aquifer was at land surface.

	Top							
	Columbia	**Milford**	**Frederica**	**Federalsburg**	**Cheswold**	**Piney Point**	**Rancocas**	**Mt. Laurel**
MIN		-25.0	-9.9	-22.2	-34.2	-29.8	16.8	-30.1
MEAN		-3.9	-4.2	3.7	-5.9	-8.5	16.8	-30.1
MAX		9.4	1.0	28.4	11.3	0.8	16.8	-30.1
MEDIAN		3.8	-3.8	3.4	-4.0	-2.5	16.8	-30.1
STDEV		18.4	4.6	15.3	14.4	14.5	n/a	n/a
COUNT	10	3	6	8	8	4	1	1

	Bottom							
	Columbia	**Milford**	**Frederica**	**Federalsburg**	**Cheswold**	**Piney Point**	**Rancocas**	**Mt. Laurel**
MIN	-26.0	-13.6	0.7	-36.7	-24.1	n/a	-19.5	n/a
MEAN	5.6	-4.4	5.9	0.0	4.2	n/a	-19.5	n/a
MAX	36.0	0.5	13.3	24.3	28.8	n/a	-19.5	n/a
MEDIAN	1.5	0.0	6.0	0.7	0.1	n/a	-19.5	n/a
STDEV	18.7	8.0	5.1	19.7	18.3	n/a	n/a	n/a
COUNT	10	3	6	8	7	n/a	1	n/a

the Columbia aquifer to underlying aquifers is likely to be the primary source of recharge to confined aquifers (He and Andres, 2011). Flow of water between the Columbia aquifer and underlying aquifers or between confined aquifers is likely to be greater when confining units are thin to absent and water use in one of the aquifers causes differences in water levels (i.e., hydraulic head) between the aquifers. Monitoring water levels in wells constructed for this project will provide the data needed to evaluate relationships between confining unit thicknesses, lithologies, and hydraulic head differences.

The following subsections describe the lithology and hydrological function of the confining units named during this investigation. Descriptions of the Armstrong and Blackbird confining units can be found in Dugan et al. (2008). Descriptions of the St. Marys Formation and confining unit can be found in Andres and Klingbeil (2006) and Andreason et al. (2013). The Armstrong confining unit was penetrated only at Site 1. The Blackbird confining unit was encountered at sites 1, 2, 3, 5, 6, 8 and 10. The St. Marys confining unit was not penetrated in any project drillholes but is identified in other drillholes in southernmost Kent County by McLaughlin et al. (2009).

Dover confining unit (dcu)

The Dover confining unit separates the Federalsburg aquifer (where present) and the Cheswold aquifer and has variable thickness and composition over the study area (Appendices 1 and 2). At site 7 (Fig. 10), logs show that the Dover confining unit is only slightly finer grained than the intervals identified as the overlying Federalsburg and underlying Cheswold aquifers. At sites 6, 9, and 10 (Figs. 9, 12, and 13, respectively), the base of the Dover confining unit is a compact, cemented layer of greyish-brown sand and shells slightly below the top of the Cheswold aquifer. Where the Dover confining unit is thicker, at site 5, it consists of a fining upward sequence from the Cheswold aquifer then a coarsening upward sequence into the fine-grained aquifer sands of the Federalsburg (Fig. 8).

Petersburg confining unit (pcu)

The Petersburg confining unit separates the Frederica and Federalsburg aquifers and was noted at all sites, except for sites 1 and 3 (Figs. 5 and 7 – 13). The Petersburg confining unit is composed of moderate-brown to dusky reddish-brown silty clay interbedded with greyish-brown shelly clay and silt layers. The confining layer is generally between 25 and 45-ft thick, increasing in thickness to the south/southeast (Appendices 1 and 2). A spike in gamma ray readings commonly occurs at or near the bottom of the Petersburg.

Abbreviations used in Figures 4 through 13.

Aquifers

cl	Columbia
uchop	Upper Chopatnk
mchop	Middle Choptank
mil	Milford
fred	Frederica
fed	Federalsburg
chs	Cheswold
pp	Piney Point
rn	Rancocas
ml	Mount Laurel

Confining Units

bcu	Blackbird
acu	Armstrong
mscu	Mispillion
hcu	Houston
mcu	Magnolia
pcu	Petersburg
dcu	Dover

Other

API	American Petroleum Institute
mV	millivolts
m	meters
ft	feet
SP	spontaneous potential
Bls	below land surface

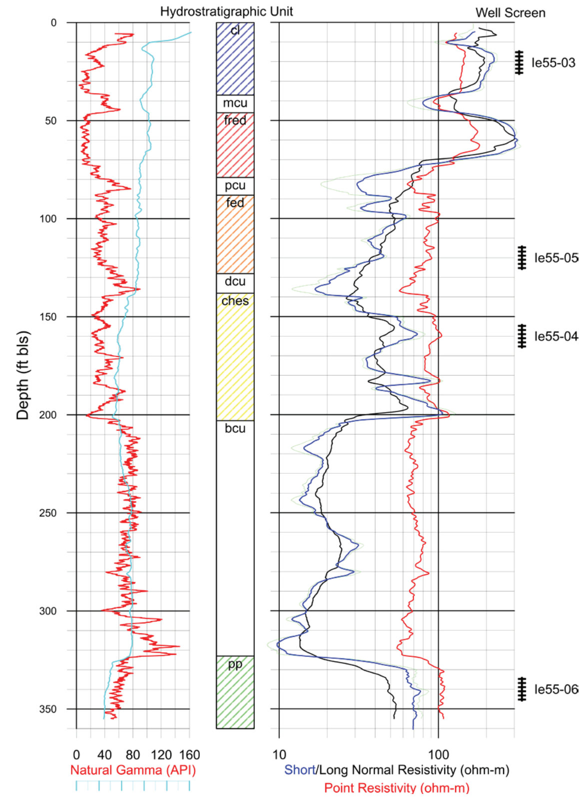

Figure 5. Geophysical log, hydrostratigraphy, and well-screen information at Site 2.

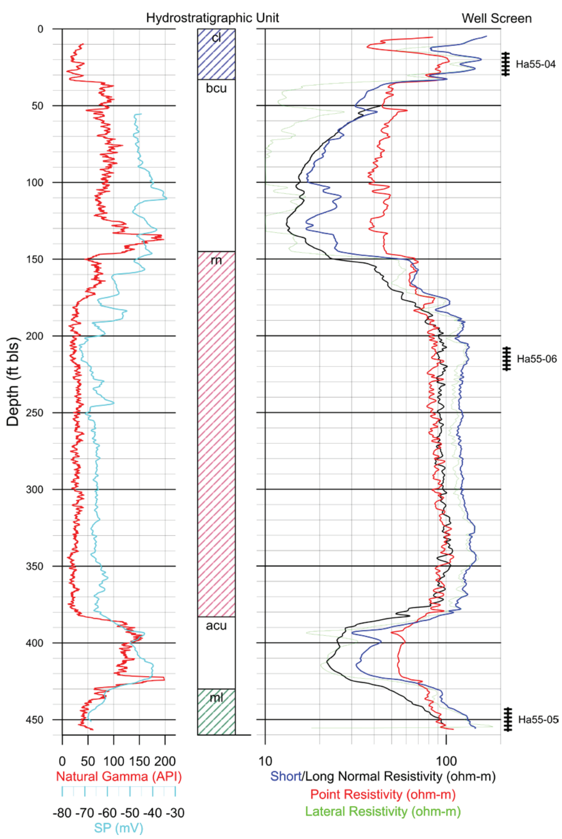

Figure 4. Geophysical log, hydrostratigraphy, and well-screen information at Site 1.

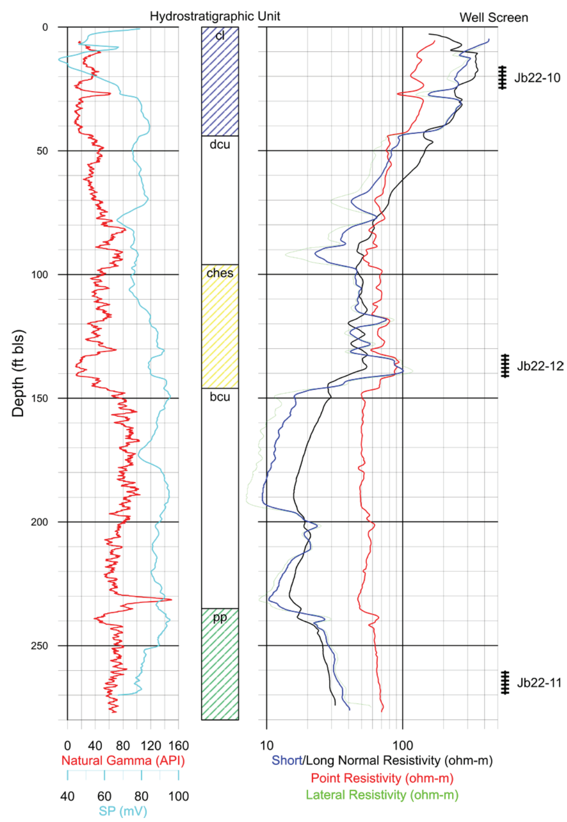

Figure 6. Geophysical log, hydrostratigraphy, and well-screen information at Site 3.

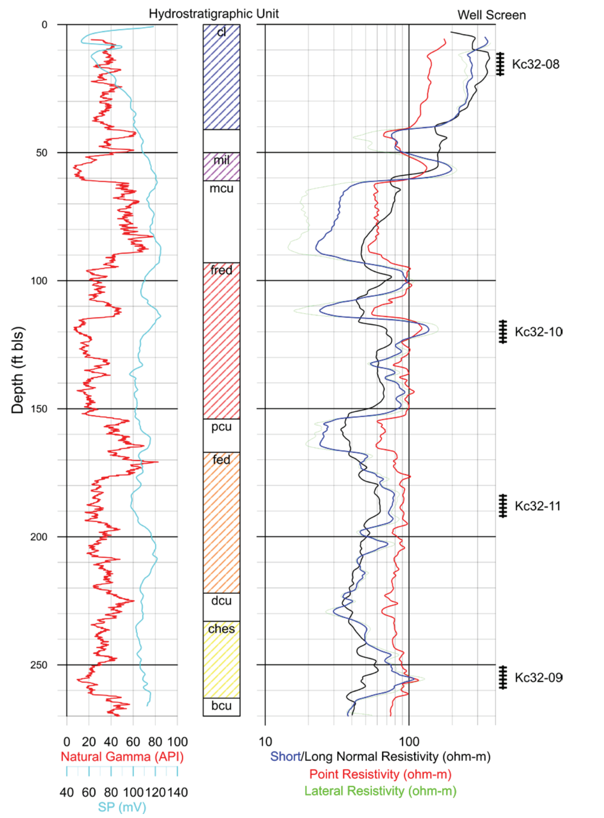

Figure 7. Geophysical log, hydrostratigraphy, and well-screen information at Site 4.

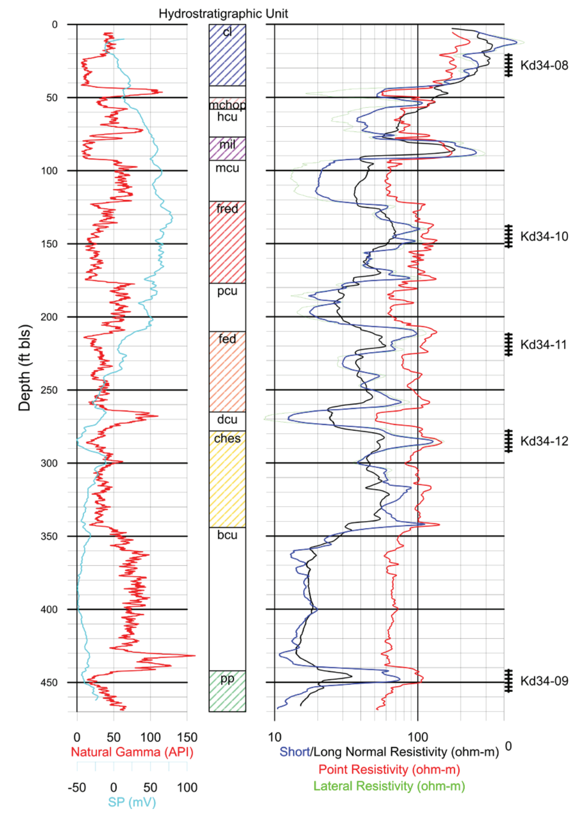

Figure 9. Geophysical log, hydrostratigraphy, and well-screen information at Site 6.

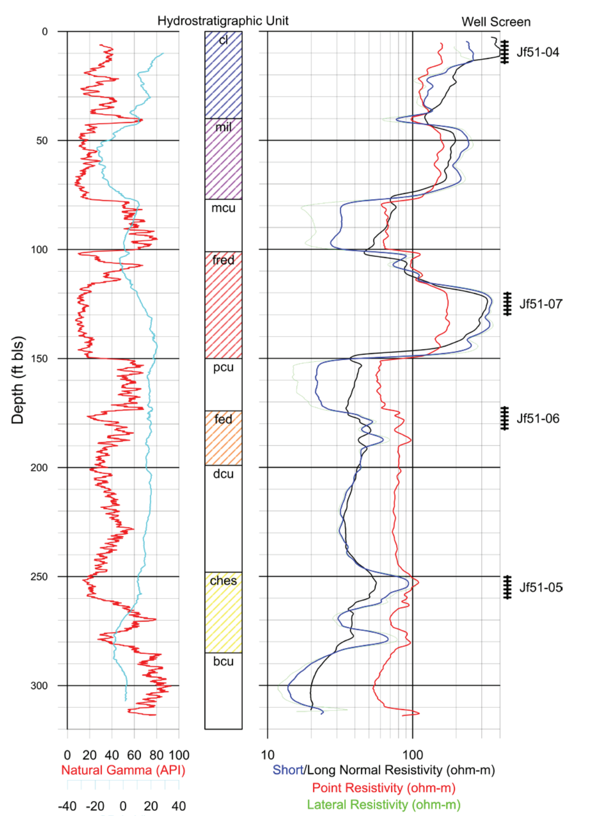

Figure 8. Geophysical log, hydrostratigraphy, and well-screen information at Site 5.

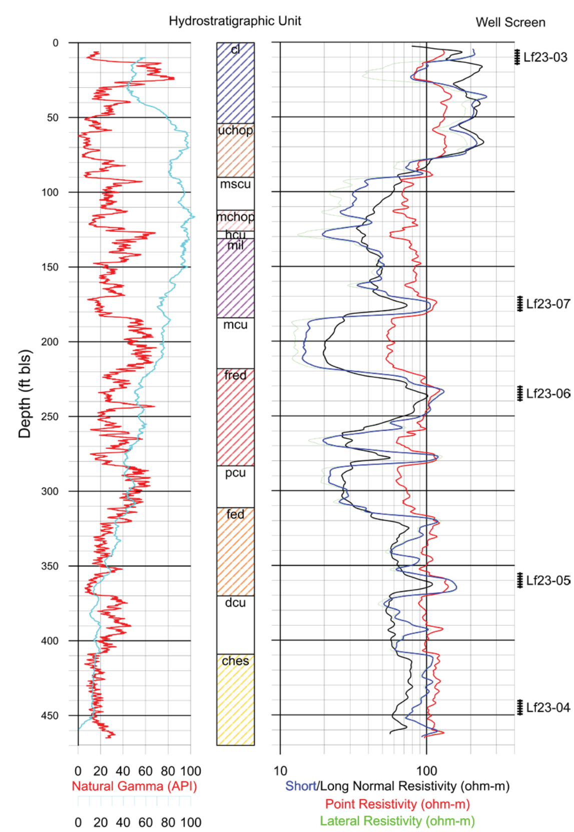

Figure 10. Geophysical log, hydrostratigraphy, and well-screen information at Site 7.

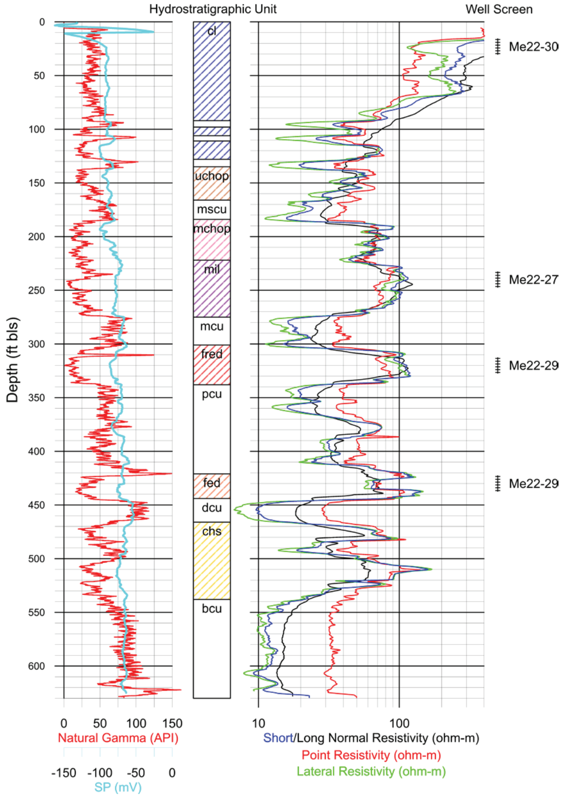

Figure 11. Geophysical log, hydrostratigraphy, and well-screen information at Site 8.

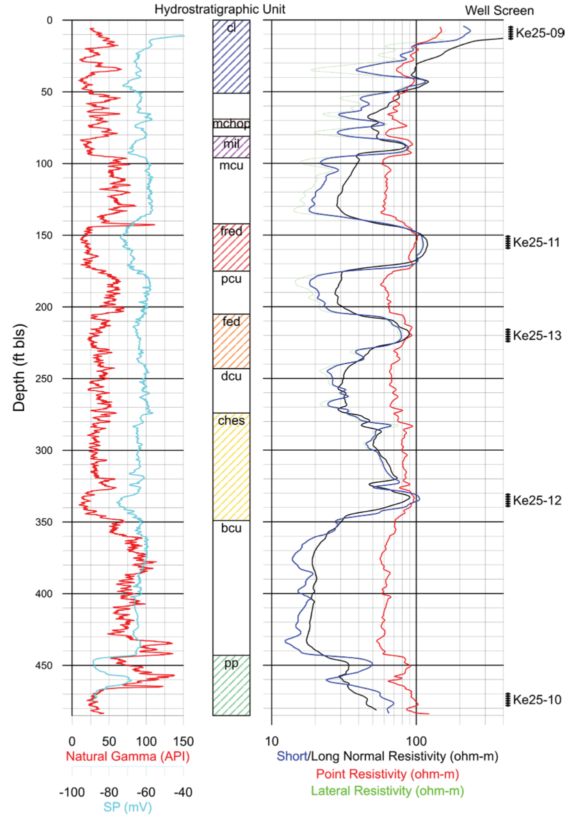

Figure 13. Geophysical log, hydrostratigraphy, and well-screen information at Site 10.

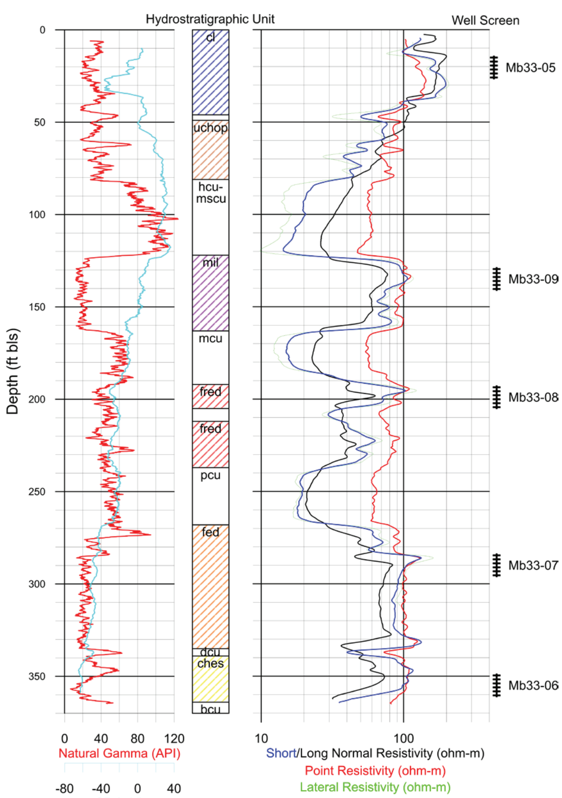

Figure 12. Geophysical log, hydrostratigraphy, and well-screen information at Site 9.

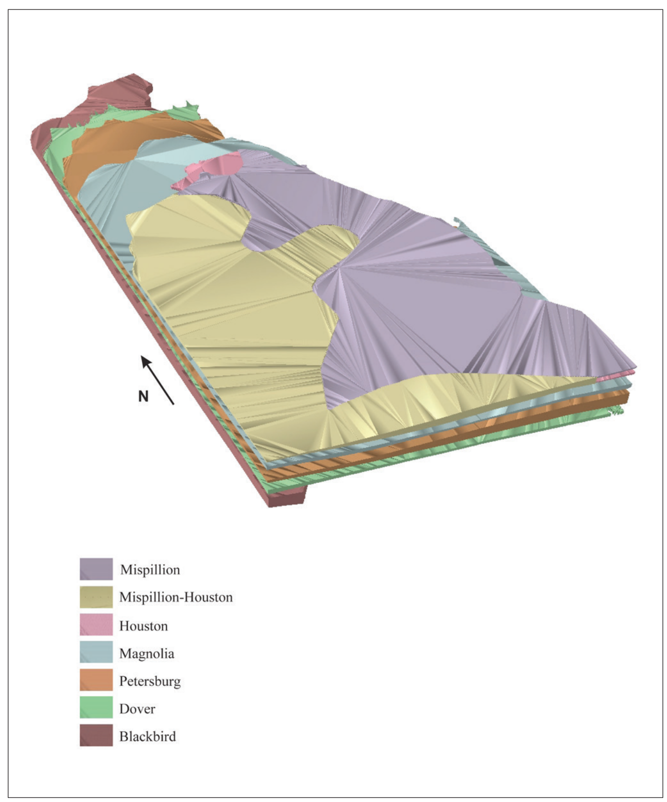

Figure 14. Three-dimensional view of confining units in Kent and Sussex County.

Magnolia confining unit (mcu)

The Magnolia confining unit occurs at the top of the Calvert Formation and separates the Frederica aquifer (Calvert Formation) from the Milford aquifer (Choptank Formation). Where the Frederica aquifer exists just below the Columbia aquifer, near its up-dip locations in central Kent County, the Magnolia confining unit may be present, such as at site 2 (Fig. 5). Overall, the Magnolia confining unit thickens to the southeast (down-dip) and is truncated to the northwest (up-dip) locations (Appendices 1 and 2). The Magnolia confining unit was noted at sites 2, 4, 5, 6, 7, 8, 9, and 10 (Figs. 5, and 7 – 13 respectively). This confining unit consists of laminated to interbedded brown, occasionally reddish-brown, clay and green/olive-grey silty clay with scattered shell beds. In down-dip locations (south and southeast), a spike in gamma ray values was observed either at or near the bottom of this unit.

Houston confining unit (hcu)

The Houston confining unit occurs within the Choptank Formation and separates the Milford and Middle Choptank aquifers. In Kent County, the middle Choptank aquifer exists only in the east-southeast. West of the lateral extent of the middle Choptank aquifer (approximately Frederica, Delaware in Kent County), the Houston confining unit is directly overlain by the Mispillion confining unit. While the Milford aquifer was noted at sites 4 – 10, the Houston confining unit was present at only sites 6, 7 and 9 (Figs. 9, 10, and 12, respectively). Lithology consists of medium-brown to reddish-grey, medium to thinly-bedded layers of silt and clay, clayey silt and fine-grained sandy silt and clay, and rare shell beds.

Mispillion confining unit (mscu)

The Mispillion confining unit lies within the Choptank Formation and, where the middle Choptank aquifer exists, separates it from the overlying upper Choptank aquifer. As described above, this unit exists westward beyond the lateral extent of the middle Choptank aquifer, where the Mispillion confining unit contacts the Houston confining unit (Fig. 14). The Mispillion confining unit was observed at sites 7, 8 and 9 (Figs. 10, 11, and 12, respectively), which are located in southern and southeastern Kent County. Where encountered, thickness ranged from 2 to 19 ft. It is composed of blueish-grey to medium grey, clayey silts and shelly, clayey, fine to medium-grained sands. Due to its thickness and variable composition, the Mispillion confining unit is not effective as a hydrological barrier and functions as a leaky confining unit to poor aquifer.

Houston-Mispillion (undifferentiated) confining unit (hcu-mscu)

In the southwestern portion of Kent County, the Houston and Mispillion confining units are in direct contact and are "stacked". The best example of this stacked confining unit was observed at site 9 (Fig. 12), where it consists of approximately 39 ft of interbedded silt and clay and separates the Milford aquifer from the upper Choptank aquifer. At this location, a distinct coarsening upward sequence is observed in samples as well as the natural gamma radiation log, decreasing from about 120 to about 60 API units. The combined lithologies also becomes less compact (easier drilling) with the trend in grain size. At locations in central Delaware, the two units are difficult to differentiate in the field.

Hydraulic Characteristics

Results of hydraulic (slug) tests (Table 4a, Table 3) conducted during this study show that K varies from one to more than two orders of magnitude within individual hydrostratigraphic units. Mean K values of aquifers show only a factor of about 4 variability between aquifers. As expected, higher K values are observed at sites where aquifers are composed of coarser-grained sediments in comparison to sites where aquifers are composed of finer-grained sediments (Appendices 1 and 3).

Because this study generated a relatively small sample set, results from aquifer testing conducted prior to this study were incorporated into the analysis (Table 4b, Appendix 3). Some of the additional data were derived from slug tests and some from pumping tests. K values were calculated from T values divided by aquifer thickness, with thickness determined from site-specific logs where available, or the DEMs of McLaughlin et al. (2009) where a log penetrating the entire aquifer was not available. There were no significant differences between the populations of K or logK values determined by these two methods. Many of the tests (31 of 125 total) were completed at the Central Solid Waste Management Facility in western Kent County and may impart some bias to the overall county-wide statistics. The Milford (3 tests), Rancocas (9 tests), and Mt. Laurel aquifers (4 tests) do not have enough test data to warrant additional analysis. For the Columbia, Frederica, Cheswold, and Piney Point aquifers, the expanded dataset shows that K ranges of each aquifer are generally wider than for the wells constructed for this study (Table 4b). Mean aquifer K of the Frederica is largest followed by Cheswold, Columbia and essentially equivalent values for the Federalsburg and Piney Point.

Table 3. Results of hydraulic tests completed in this study. BR = Bouwer and Rice (1976), HV = Hvorslev (1951), BU = Butler high-K (1998), ft = feet.

Aquifer	Site No.	WellID	No. of Tests (Rising Head)	Standard Deviation	Mean Hydraulic Conductivity (ft/day)	Analysis Method	Aquifer Thickness (ft)	Transmissivity (ft2/day)
Columbia	1	Ha55-04	3	1.5	14.0	BR	33	450
	2	Ie55-03	3	3.4	22.0	BR	13	280
	3	Jb22-10	3	0.5	13.0	BR	44	590
	4	Kc32-08	3	1.6	19.0	BR	61	1200
	5	Ke25-09	3	2.4	18.0	BR	30	540
	6	Kd34-08	3	19.9	50.0	BR	42	2100
	7	Lf23-03	3	2.4	63.0	BR	14	880
	8	Me22-30	3	0.3	7.1	BR	90	640
	9	Mb33-05	3	5.7	82.0	BR	45	3700
	10	Jf51-04	3	1.0	12.0	BR	39	480
Milford	7	Lf23-07	3	1.1	14.0	HV	53	750
	8	Me22-27	4	26.0	85.0	BU	48	4100
	9	Mb33-09	3	11.9	76.0	HV	41	3100
Frederica	4	Kc32-10	5	36.2	140.0	HV	61	8500
	5	Ke25-11	3	5.4	100.0	BU	33	3400
	6	Kd34-10	3	0.5	7.3	HV	53	380
	7	Lf23-06	3	0.5	6.5	HV	65	420
	8	Me22-28	4	16.9	95.0	BU	33	3100
	9	Mb33-08	3	0.0	1.5	HV	49	75
	10	Jf51-07	5	8.1	110.0	BU	49	5400
Federalsburg	2	Ie55-05	3	0.0	0.2	HV	40	7.5
	4	Kc32-11	5	0.1	0.7	HV	55	37
	5	Ke25-13	4	0.4	8.2	HV	38	310
	6	Kd34-12	3	0.2	1.6	HV	55	89
	7	Lf23-05	4	2.7	49.0	BU	59	2900
	8	Me22-29	3	0.1	3.3	HV	75	250
	9	Mb33-07	3	0.2	3.4	HV	67	230
	10	Jf51-06	5	0.7	6.3	HV	25	160
Cheswold	2	Ie55-04	4	0.3	4.5	HV	65	290
	3	Jb22-12	5	10.7	95.0	HV	50	4800
	4	Kc32-09	5	0.3	0.6	HV	30	19
	5	Ke25-12	3	10.5	110.0	BU	78	8500
	6	Kd34-11	3	0.3	2.8	HV	66	180
	7	Lf23-04	3	1.1	43.0	HV	61	2600
	9	Mb33-06	3	4.6	26.0	HV	25	640
	10	Jf51-05	5	0.2	1.0	HV	37	36
		Id24-11	3	5.2	38.0	HV	75	2800
		Id54-36	3	4.0	170.0	BU	103	18000
Piney Point	2	Ie55-06	4	12.1	70.0	BU	212	15000
	3	Jb22-11	4	0.1	1.7	HV	130	220
	5	Ke25-10	3	1.9	2.7	HV	238	640
	6	Kd34-09	3	0.8	25.0	HV	14	350
		Kb34-12	1	-	0.7	HV	165	110
		Lb42-12	3	0.8	14.0	HV	183	2600
		Id45-08	3	0.2	2.6	HV	153	400
		He52-05	3	1.0	3.5	HV	156	550

Table 4a. Summary statistics of hydraulic conductivity (K) from tests conducted during this study. K values in ft/day.

AQUIFER	COUNT	MIN K	MEAN K	MAX K	MEDIAN K	STDEV
Columbia	10	7	30	82	18	26
Milford	3	1	13	26	12	13
Frederica	7	2	66	140	95	59
Federalsburg	8	0	9	49	3	16
Cheswold	8	1	35	109	15	44
Piney Point	7	1	17	70	3	25

Table 4b. Summary statistics of hydraulic tests in DGS internal database. K values in ft/day. This data includes new K values from Table 4a.

AQUIFER	COUNT	MIN K	MEAN K	MAX K	MEDIAN K	STDEV
Columbia	47	0.8	63	330	42	81
Milford	3	15	58	85	74	37
Frederica	14	1.5	78	160	81	48
Federalsburg	9	0.2	9	49	4	15
Cheswold	18	0.6	40	170	28	45
Piney Point	21	0.2	19	92	17	22
Rancocas	9	0.9	30	110	13	38
Mt. Laurel	4	2.3	12	30	8	13
All	125	0.2	39	330	22	n/a

We tested the relationship between aquifer thickness and K to learn if thicker aquifers tended to host highly permeable layers in comparison to thinner aquifers. No significant relationships were found between aquifer thickness and K or log(K) for any of the aquifers indicating that high permeability sands are associated with both thin and thick aquifer sections. We hypothesize that the relatively smaller variability of aquifer thickness (up to a factor of 4) in comparison the large variability of K (more than 2 orders of magnitude) is a key factor in this relationship.

Mean aquifer T values estimated from slug test K values and aquifer thicknesses (Table 3) are generally consistent with T values in Table 4c. Larger differences between T values at individual sites and values determined from pumping tests are due to the smaller aquifer volumes characterized by slug tests. In addition, there are inherent differences between the populations of wells that are slug tested and those that are tested by a pumping test. Some smaller slug-test determined K values are from monitoring wells that were screened in poor quality aquifers where large capacity wells would not be installed.

Table 4c. Summary statistics of transmissivity (T) values in DGS internal database. T values in ft^2/day

AQUIFER	COUNT	MIN T	MEAN T	MAX T	MEDIAN T	STDEV	GEOMETRIC AVERAGE
Columbia	2	1700	1715	1730	1715	21	1715
Frederica	11	58	2124	6690	1500	2267	1031
Federalsburg	2	564	1552	2540	1552	1397	1197
Cheswold	35	50	2469	13200	1570	2900	1304
Piney Point	24	26	2644	7350	2550	1901	1717
Rancocas	3	530	1182	2240	775	925	973
Mt. Laurel	2	468	3034	5600	3034	3629	1619
All	80	26	2416	13200	1680	2385	1389

Table 4d. Summary statistics of specific capacity (SC) values in DGS internal database. SC values in gallons/minute-ft.

AQUIFER	COUNT	MIN SC	MEAN SC	MAX SC	MEDIAN SC	STDEV	GEOMETRIC AVERAGE
Columbia	108	1.1	20	71	15.3	14	16
Upper Choptank	3	9.0	16	20	18.0	6	15
Middle Choptank	7	4.1	18	64	6.0	22	11
Milford	3	1.3	8.6	14	10.2	6.6	5.7
Frederica	27	2.4	13	75	6.4	17	8.2
Federalsburg	11	1.6	9.9	20	10.0	5.8	7.9
Cheswold	43	1.8	18	59	17.0	12	13
Piney Point	9	3.1	11	33	8.3	9.2	8.7
Rancocas	5	1.4	7.3	22	4.6	8.5	4.6
Mt. Laurel	2	0.3	1.0	1.7	1.0	1.0	0.7
All	219	0.3	17	75	13.0	14	12

Pumping Tests

Similar to K values, T values determined from pumping tests range over more than two orders of magnitude (Table 4c). Only the Piney Point, Cheswold, and Frederica aquifers have enough tests to compute meaningful statistics. Two-tailed t-tests of normal and log-transformed data from these aquifers show that average T values are not different (alpha=0.05). The similarities in average T values are not unexpected given the generally similar compositions and marine depositional environments of the three aquifers.

Results of F-tests of normal and log-transformed variances show slightly different characteristics. Variance of normal T data from the Cheswold aquifer is significantly different from those of the Piney Point and Frederica aquifers, but the Frederica and Piney Point have similar variances. F-tests of log-transformed T data show the Cheswold and Frederica variances are different, but those of the other aquifer pairings (Cheswold-Piney Point and Frederica-Piney Point) are not different. Similar to a comparison of average T values, the difference in variances of the Cheswold and Piney Point are not unexpected given the differences in lithologies and depositional settings of the materials forming those aquifers. The difference in variances of normal data from the Cheswold and Frederica aquifers is somewhat unexpected given the generally similar lithologies and depositional settings of the materials forming those aquifers. However, the lack of difference in variance of log-transformed T data from these aquifers indicates that T data from these aquifers come from the same log-normally distributed population.

Evaluation of pumping tests having both T and SC results (Fig. 15) finds statistically significant (alpha=0.05) relationships between those variables for tests in all aquifers and for tests completed in the Cheswold, Federalsburg, and Frederica aquifers (Calvert Formation). Because there are many more wells with SC test data than wells with T data (Table 4d), the empirical relationships will be useful for providing aquifer hydraulic property data (e.g., Mace, 2001; Rotzoll and El-Kadi, 2008) to map spatial distribution of T for future groundwater-flow modeling studies. There are not enough data from other Kent County aquifers to calculate relationships for the other aquifers (Mace, 2001). Additional tests will likely become available in the future and provide enough data to evaluate these aquifers.

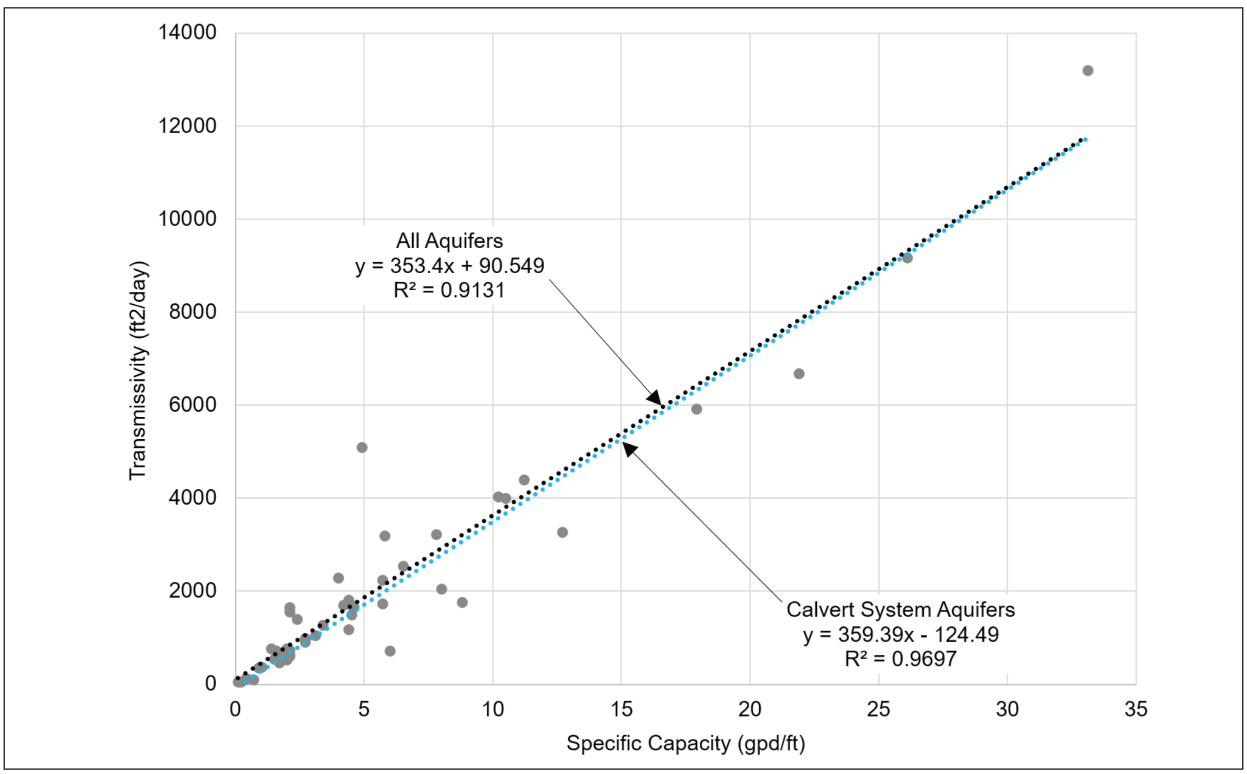

Figure 15. Specific capacity and transmissivity correlation. Black trend line indicates analysis includes all aquifers. Blue trend line indicated analysis only includes Calvert system aquifers

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APPENDICES

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ha55-05 DNREC Permit No: 259080
Site No: 1 Site Name: Blackiston WMA

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
Debris - plants, animal carcass, roots, with SILTY MATRIX	0	0.2
SILT, slightly Sandy, f-m, medium orange brown, dark orange yellow.	0.2	6
SAND, m-c, Gravelly, f-m, slightly Silty, trace Clay, medium yellow-orange, red-orange, medium grey brown, light grey, common chalky white and multi-colored grains, trace mica.	6	16
Bedded and laminated: SAND, f-m, trace Silt, red-orange; SILT + SAND, f, medium yellow-grey, yellow-orange; SAND, f, Silty, medium yellow-grey, yellow-orange; SILT, Clayey, medium yellow grey, yellow orange; SAND, m-vc, Silty, trace Clay, pale yellow brown (10YR6/2)(sd), greyish orange pink (5YR7/2)(sd), light brown (5YR5/6)(slt), orangey red (slt), laminations and bedding increase with depth, sand grains coarsen with depth.	16	33
CLAY, Gravelly, f, trace Sand, c-vc, medium black grey (N3)(cl), moderate orange pink (5Y8/4)(cl), dark yellow orange (10YR6/6)(gravel), angular gravel and granules mixed in with clay, some orange-pink clay.	33	52
CLAY, Silty, medium dark grey (N4), brownish black (5YR2/1), very compact, coarsening upwards- percentage of silt decreasing w/depth.	52	122
CLAY + SILT, trace Sand, f-m, medium dark grey (N4)(cl,slt), greyish brown (5YR3/2)(cl,slt), brownish black (5YR2/1)(sd), sand and some silt compacted in 5-10mm clumps of low moisture content.	122	134
SAND, f-c, Clayey, olive grey (5Y4/1)(sd), black (N1)(sd), dark grey (N3)(cl), glauconite 40%, quartz 60%, CaCO3 2% (95% <2mm), weak acid reaction (1).	134	147
SAND, f-vc, Shelly, trace Silt, olive grey (5Y4/1), black (N1), glauconite increasing with depth from 40% to 75%, quartz decreasing with depth from 60% to 25%, CaCO3 increasing with depth from 3% to 15% (5% >2mm), strong acid reaction (3), thick (~10') shell bedding, overall fining upwards, cemented zones approx. 5' thick.	147	205
SAND, f-m, trace Shells, trace Silt, dark green grey (5GY4/1), olive grey (5Y4/1), glauconite 10%, quartz 90%, CaCO3 2-10%, moderate to strong acid reaction (2-3), slight coarsening upward correlates with slight decrease of amount of shell fragments with depth.	205	252
SAND, f-c, Silty, Shelly, dark green grey (5GY4/1), olive grey (5Y4/1), black (N1), glauconite 50-80%, quartz 50-20%, CaCO3 4-50%, glauconite fraction greatest in the middle of this interval, slight coarsening downwards, moderately thick (5-10') shell beds towards the bottom of the unit, larger shell fragments (>2mm) around 340' and 60', moderate to strong acid reaction, cemented zones increasing with depth.	252	383

A1-1

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ha55-05 (continued)   DNREC Permit No: 259080
Site No: 1   Site Name: Blackiston WMA

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
Bedded: SAND, f-m, trace Shells, greenish black (5GY2/1),glauconite 70%, quartz 30%, CaCO3 50-75% (70-80% >2mm); SILT + CLAY, grey black (N2), clay and silt are mostly stuck together in granule-sized pellets and a little bit shaley, shell size increases slightly with depth up to 8mm, strong acid reaction.	383	420
SAND, m, trace Sand, f, trace Silt, greenish black (5G2/1), grey black (N2), glauconite 95%, quartz 5%, CaCO3 2-5% (95% >2mm), weak acid reaction.	420	427
SAND, f-m, Silty, moderate brown (5YR3/4), duskey yellow brown (10YR2/2), glauconite 20%, quartz 80%, CaCO3 1%, weak acid reaction, sub-rounded, well sorted.	427	460
Log by: R. W. McQuiggan		

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ie55-06
Site No: 2

DNREC Permit No: 259056
Site Name: Little Creek Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, trace Organic debris, Dark Brown	0	2
SAND, f-m, slightly Silty, trace Granules, dark brown, medium red brown, yellow brown, mottled; GRAVEL, f-m, Sandy, c, medium brown, bed at the base of this interval.	2	6
CLAY + SILT, trace Granules, few laminae SAND, f-m, Silty, scattered Fe-Stone concretions, light grey brown, light yellow-grey, yellow-orange mottled.	6	12
SAND, f-vc, Gravely, trace Silt, pale yellowish brown (10YR6/2), brownish grey (5YR4/1), dark yellow orange (10YR6/6)(gr), overall fining upward, larger grains are angular, medium yellow-orange beds, opaque heavy mineral laminae, rare Silty laminae, layers of light grey and yellow-orange laminae to 24'.	12	35
SAND, f-m + SILT, pale yellowish brown (10YR6/6), well sorted, confining layer between sand intervals.	35	47
SAND, m-vc, trace Granules, light brown (5YR5/6); common laminae SAND, f-m, very Silty, brownish grey (5YR4/1).	47	79
CLAY + SILT, slightly Sandy, f-c, trace Shells, duskey yellow brown (10YR2/2), <10% shell fragments (<1mm), weak acid reaction.	79	88
Bedded: SAND, f-c, Shelly, trace Silt, dusky yellow brown (10YR2/2), olive grey (5Y6/1), majority of shell size ranging from 2-7mm; SILT + CLAY, Sandy, f, Shelley, olive grey (5Y6/1), less shells 10%, majority of shell size <2mm; SHELLS, Sandy, f-c, olive grey (5Y6/1), shell fragments up to 80%; zones approx. 5-10' containing more sand and more, larger shell fragments separated by muddy zones with smaller shell fragments at 94-98', 99-103'.	88	128
SILT + CLAY, Shelly, trace Sand, f, olive grey (5Y6/1), shell fragments <2mm.	128	138
Bedded: SHELLS + SAND, m-c, slightly Silty, trace Clay, olive grey (5Y4/1), light olive grey (5Y6/1), shell beds containing 30-40%, coarsest shell fragments and sand at 176-185' and 193-203'; SAND, f-m, Silty, trace Shells, olive grey (5Y4/1), light olive grey (5Y6/1), at approx. 169-176' and 185-192', well sorted, moderate acid reaction, beds approx. 8' thick.	138	203
CLAY, Silty, trace Shells, moderate brown (5YR3/4), brownish grey (5YR4/1), overall fining downwards, shell bed tapering off with depth, slightly less compact lens from 221-237'.	203	244

A1-3

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ie55-06 (continued) DNREC Permit No: 259056
Site No: 2 Site Name: Little Creek Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, Clayey, slightly Shelly, trace Sand, f-c, moderate brown (5YR3/4), brown grey (5YR4/1), pale yellow brown (10YR6/2), increasingly more dry-feeling, compact, Clayey chips, slightly less compact material 310-315', no acid reaction.	244	302
Interbedded: SILT, Clayey, slightly Shelly, moderate brownish grey (5YR4/1), moderate yellowish brown (10YR4/2); CLAY, slightly Silty, trace Shells, moderate yellowish brown (10YR4/2), shaley pellets; overall fining downwards, increasingly more compact with depth.	302	325
SAND, f-m, Silty, trace Shells, trace Sand, c, olive grey (5Y3/2), green black (5G2/1), glauconite 20-50%, quartz 80-50%, shell fragments <2mm, well sorted, moderate acid reaction.	325	360
Log by: R. W. McQuiggan		

A1-4

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Jb22-11 DNREC Permit No: 259053
Site No: 3 Site Name: Fortney Tract

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT + CLAY, Sandy, f, medium brown-grey, light brown-grey, mottled.	0	4
SAND, f-c, trace Silt, light grey-orange, medium yellow-brown.	4	6.7
Laminated and thinly bedded: SILT + SAND, f, AND SAND, f-m, Silty, light grey, yellow-orange, yellow-brown.	6.7	10
CLAY + SILT, Sandy, f, common lamina SAND, f-m, Silty, light yellow orange, light grey-brown, medium olive grey, trace plant debris around 12'.	10	16.8
SAND, f-c, Gravelly, f, trace silt + clay, dark yellow brown (10YR6/6), yellow-orange, moderate yellow brown (10YR5/4), light brown (5YR6/4), coarser grains are yellow-orange and white, cuttings indicate coarsening downward, poorly sorted.	16.8	26
Finer interval not observed in cuttings. Log suggests SAND,f, Silty.	26	28
SAND, m-vc, Gravelly, f, trace sand, f, dark yellow brown (10YR6/6), moderate yellow brown (10YR5/4), light brown (5YR6/4), coarser grains are yellow-orange and white, angular, fining downwards.	28	44
SAND, m-c, Silty, trace granules, pale yellow brown (10YR6/2), dark yellow brown (10YR4/2); laminae of SILT + SAND, f, brown grey (5YR4/1), poorly sorted.	44	55
Bedded: SILT, Sandy, f-c, Shelly, Clayey, olive grey (5Y4/1), brownish black (5YR2/1); interbeds SHELLS, Sandy, f-c, olive grey (5Y4/1), brownish black (5YR2/1); CLAY + SILT, Shelly, dusky yellow brown (10YR2/2), fining downwards, increasingly more compact with depth, cemented beds at 73-79' and 87-89', shell fraction increasing with depth, most shell fragments >2mm, moderate acid reaction.	55	96
SILT, Clayey, Shelly, trace sand, f, olive grey (5Y4/1), about 60% of shell frag >2mm), moderate acid reaction, cemented beds from 97-100' and 106'.	96	115
SHELLS, Silty, Sandy, f-m, trace sand, c, olive green (5Y4/1); interbeds SILT + CLAY, Shelly, olive grey (5Y6/1); thicker shell beds from 115-122' and 127-129', separated by muddy zones between, 10% of shell fragments >2mm, strong acid reaction.	115	131
SHELLS, Sandy, f-c, trace silt, olive grey (5Y3/2), shell fraction 70-80% (75% >2mm), cemented zone around 145', strong acid reaction.	131	146
SILT + CLAY, trace shells, olive grey (5Y4/1), shell fragments 1% (<2mm), Clayey/shaley chips, weak acid reaction.	146	194

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Jb22-11 (continued)
Site No: 3

DNREC Permit No: 259053
Site Name: Fortney Tract

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, Clayey, trace sand, f-m, trace shells, olive grey (5Y4/1), slightly less Clayey/shaley chips at 194', fining/more compact downwards, weak acid reaction.	194	229
SILT + CLAY, trace sand, f-m, trace shells, olive grey (5Y4/1), 5-15mm Clayey/shaley chips, only 1-3% shells, no acid reaction.	229	235
SAND, f-vc, trace Silt, trace clay, greenish black (5G2/1), olive black (5Y2/1), brownish black (5YR2/1), glauconite 30%, quartz 70%, slight coarsening downwards.	235	280
Log by: R. W. McQuiggan		

A1-6

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Kc32-09 DNREC Permit No: 259100

Site No: 4 Site Name: Norman G. Wilder Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, Clayey, Sandy, f, trace organics in top 0.5', dark brown, light brown-grey.	0	1.2
SAND, f-c, Silty, Slightly Clayey, trace Granules, light brown-grey, medium yellow-brown with red-orange mottles	1.2	3.4
Thinly bedded: SAND, f-m, Silty, trace Clay, trace OHM; SAND, m-c, trace Silt, medium yellow-brown, yellow-gray, yellow orange	3.4	24
SAND, f-c, trace granules, pale yellow brown (10YR6/2), angular larger grains.	24	41
Interbedded: SAND, f-c, trace Silt, pale brown (5YR5/2), greyish red (10Y4/2), dark yellow orange (10YR6/6), coarser grains and predominantly white and yellow orange, angular; SILT, Sandy, f, trace clay, brownish black (5YR2/1), brownish grey (5YR4/1), finer beds 42-45' and 48-50', overall coarsening downwards.	41	51
SAND, f-c, Silty, trace granules, brownish grey (5YR4/1).	51	61
SILT + CLAY, trace sand, m-c, trace gravel, f-m, greyish brown (5YR3/2), dusky yellow brown (10YR2/2), trace silty laminae, clay/silt chips 5-15mm, less pebbles/coarse material with depth, increasingly clayier with depth.	61	93
Bedded: SAND, f-m, Shelly; SAND, f-m + SHELLS; greyish brown (5YR3/2), brown grey (5YR4/1), beds approx 3' thick, moderate to strong acid reaction.	93	109
SILT, very Clayey, trace Shells, greyish brown (5YR3/2).	109	115
SHELLS, Sandy, f-m, trace pebbles, grey brown (5YR4/1), shell bed 115-123', strong acid reaction.	115	154
Interbedded: CLAY, Silty, trace shells, pale brown (5YR5/2), very dusky red (10R2/2); SILT + CLAY, Shelly, grey brown (5YR3/2), increasing less shells (10% to less), beds approx. 5' thick, weak acid reaction.	154	176
SAND, f-c, + SHELLS, trace silt, trace clay, pale brown (5YR5/2), grey brown (5YR3/2), shell fraction consistently around 40-50%; laminae/thin beds SILT, sl Clayey, Shelly, trace Sand, f, dark brown, weak acid reaction.	176	183
SILT + SAND, f, very Shelly, pale brown (5YR5/2), grey brown (5YR3/2), weak acid reaction.	183	195
SILT, Sandy, f, trace shells, pale brown (5YR5/2), grey brown (5YR3/2); beds SILT, Shelly, slightly Clayey, cemented at 203-206' and 220-222'; majority of shell fragments <2mm, weak acid reaction.	195	222
SILT, Clayey, sl Sandy, f, trace shells, olive grey (5Y4/1), shells fragments <2mm, weak acid reaction.	222	233

A1-7

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Kc32-09 (continued)
Site No: 4

DNREC Permit No: 259100
Site Name: Norman G. Wilder Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SAND, f-m, very Silty, trace shells, dark brown, olive grey (5Y4/1), weak acid reaction.	233	245
SHELLS + SAND, f-c, olive grey (5Y4/1), increasingly more shells and concretions, cemented zones around 247' and 250-260', concretions between 250-260', shell fraction greatest between 250 and 260' (60-80%) (90%>2mm), moderate to strong acid reaction.	245	263
CLAY, Silty, Shelly, dark brown, olive grey (5Y4/1), silty concretions, moderate acid reaction.	263	275
Log by: R. W. McQuiggan		

A1-8

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Jf51-05
DNREC Permit No: 259418
Site No: 5
Site Name: Ted Harvey Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, slightly Clayey, trace organics, dark red-brown, yellow-brown.	0	4.3
Thinly bedded: SAND, f-m, Silty; SAND, m-c, Gravelly, f-m, light to medium yellow-brown, yellow-orange, yellow-grey.	4.3	16
Bedded: SAND, f-vc, trace Silt, pale yellow brown (10YR6/2), light brown (5YR6/4); SAND, m-vc, Silty, trace clay, pale yellow brown (10YR6/2), light brown (5YR6/4), chalky white silt matrix, larger grains are angular; SAND, f-m, Silty, trace clay, dark brown, bedding <10' thick.	16	32
SAND, m-c, Gravelly, f, light brown (5YR6/4), dark yellow orange (10YR6/6), very pale orange (10YR8/2), opaque minerals, quartz and feldspar, Fe, silt and finer grains appear orange, angular, well sorted.	32	38
CLAY, very Silty, trace sand m-vc, brown grey (5YR4/1), dark yellow orange (10YR6/6)(s), clay "chips"/pellet approx. 1-2cm, chips appear dry inside.	38	42
SAND, vf-m, Sandy, c, trace Gravel, f-m, brown grey (5YR4/1), olive grey (5Y3/2).	42	77
Bedded: CLAY, trace Silt, trace Sand, f-m; CLAY, Silty, trace Sand, f-m; brown grey (5YR4/1), olive grey (5Y3/2), clay chips are moist, fining downwards.	77	101
SAND, f-c, trace Sand, vc, trace Gravel, f, olive grey (5Y3/2), dark yellow brown (10YR2/2).	101	107
CLAY + SILT, slightly Sandy, f-vc, olive grey (5Y3/2), dark yellow brown (10YR2/2), clay chips, coarsening down.	107	113
SAND, f-vc, trace Granules, olive grey (5Y3/2), dark yellow brown (10YR2/2), slightly fining downward, well sorted, three approx 10' thick beds of coarser to slightly less coarse sand.	113	150
Interbedded: SILT + CLAY, trace Sand, f; SILT,Clayey, Sandy, f-m, grey brown (5YR3/2), dusky yellow brown (5YR2/2), dark yellow brown (10YR2/2), clay/shaley pellets, bedding generally 2-3' thick.	150	174
SHELLS + SAND, f-m, trace Silt, grey brown (5YR3/2), duskey yellow brown (5YR2/2), overall fining downward, 40% shells, moderate acid reaction.	174	185
SAND, vf-m, Silty, trace shells, grey brown (5YR3/2), duskey yellow brown (5YR2/2), cemented bed 185-188', 10% shells, coarsening downwards, weak acid reaction.	185	199
SILT, Clayey, trace sand, f, trace shells, grey brown (5YR3/2), duskey yellow brown (5YR2/2), fining downward, increasingly more clay content.	199	228

A1-9

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Jf51-05 (continued)
Site No: 5

DNREC Permit No: 259418
Site Name: Ted Harvey Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SILT, Clayey, trace sand, f; to SILT, Clayey, Sandy, f-m, grey brown (5YR3/2), duskey yellow brown (5YR2/2), coarsening downward.	228	248
SAND, f-c, trace Granules, trace shells, grey brown (5YR3/2), duskey yellow brown (5YR2/2), sandy and shelley concretions, 5% shells, cemented zones.	248	263
SAND, f-c, Gravelly, f, trace silt, trace shells, olive grey (5Y3/2), shells ~8%, CEMENTED, weak acid reaction.	263	275
SAND, f-m, Shelly, slightly silty, olive grey (5Y3/2), shells 25% (most <2mm), cemented zone 278-280', moderate acid reaction.	275	285
Thinly bedded: SILT + CLAY, trace sand, f-m; SILT, Clayey, slightly Sandy, f-m, dark greyish brown, olive grey (5Y3/2), beds approximately 1-3' thick.	285	320
Log by: R. W. McQuiggan		

A1-10

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Kd34-09 DNREC Permit No: 261996
Site No: 6 Site Name: McGinnis Pond Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
(Topsoil) SAND, vf-f, v Silty, tr Organics, mottled pale brown (5YR5/2) and darker grey brown (5YR3/2), more reddish color with depth, slightly coarser (less silt) with depth	0	1.8
SAND, vf-f, sl Silty, tr mica, opaque white minerals, moderate brown (5YR4/4) to yellowish-reddish brown, compact	1.8	3
SAND, vf-f, Sandy, m, tr Gravel, greyish orange (10YR7/4) to yellow grey (5Y7/2), colors mottled with layers (1 cm) dark yellowish orange (10YR6/6), common angular opaque minerals, rare laminae dark brown/ grey silt	3	8.9
SAND, f-c, tr Gravel, light brown (5YR5/6) mottled with dusky red (5R3/4), sub-rounded grains, rare tan SILT, Clayey layers (0.5-1.5cm), rare dark brown Silt laminae, reddish-grey CLAY, Silty thin beds (<1cm)	8.9	19
SAND, m-vc, gravelly, loose, bedded with SAND, f-c, sl Gravelly, rare dark brown SILT laminae, common reddish grey CLAY, Silty thin beds (0.5cm), colors layered light brown (5YR5/6), dark yellow orange (10YR6/6), and grey, whitish grey SILT, pinkish-tan CLAY and SILT, mottled black SAND, F-M throughout, rare thin (1mm) black laminae SILT, (water at 19')	19	25
SAND, m-c, dark red-brown, partially cemented, hard	25	26
SAND, m-vc, slightly gravelly, trace Silt, bedded medium yellow orange, medium red brown, and medium gray, some Fe-rich concretions, trace opaque minerals, with few thin beds SAND, f-m, Silty, light yellow gray to light yellow brown	26	44
CLAY, medium blue grey (5B5/1), medium light grey (N6), dark yellowish orange (10YR6/6), mottled colors	44	50
SAND, c-vc, gravelly, f, brownish grey (5YR4/1), light brown grey (5YR6/1), very angular grains	50	57
CLAY, medium blue grey (5B5/1), medium light grey (N6), dark yellowish orange (10YR6/6), mottled colors, very compact layer 71-75'	57	75
SAND, c + GRAVEL, dark yellow orange (10YR6/6), pink grey (5YR8/1), thin beds SAND, f-m, slightly Sandy, c, brownish grey (5YR4/1), pale brown (5YR5/2), silty and f-sand clumps, thin (<1ft) CLAY bed at 79'	75	91
Thinly bedded SAND, f, Silty, brownish grey (5YR4/1), black grains; SILT, Clayey, reddish brown, greyish red (5YR4/2), dry; SAND, f + SILT, greyish black, slight coarsening downward	91	121
SAND, c, Shelley (15%), slightly Gravelly, f, greyish black (N2), brownish black (5YR2/1)	121	127

A1-11

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Kd34-09 (continued) DNREC Permit No: 261996
Site No: 6 Site Name: McGinnis Pond Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SAND, vf-m, Silty, Shelley (15-40%), dark grey (N3), brownish black, shell content increasing with depth, coarsening downward, hard layer 138-142’, medium to strong HCl reaction, thin beds SILT, Clayey, dry, compact	127	176
CLAY, v Silty, trace shells, medium dark grey (N4), dark reddish brown (10R3/4), moderate brown (5YR3/4), coarsening downward	176	211
SHELLS, Sandy, vf-f, slightly Silty, dark yellowish brown (10YR), strong HCl reaction, concretions throughout, trace CLAY layers	211	264
SILT + CLAY, trace sand, f, greyish olive	264	273
SAND, vf-f, Silty, trace shells, dark greenish grey (5GY4/1), olive green (5Y4/1), lighter tan/pale brown silty concretions, coarsening down to 285’ then fining down to 300’, weak HCl reaction	273	300
SHELLS + SAND, f-m, olive grey (5Y3/2), strong HCl reaction	300	344
CLAY, slightly Silty, olive grey (5Y3/2), greyish red (5R4/2), thin bed SAND, f, around 425’	344	439
SAND, f-m, trace shells, olive grey with beds CLAY, slightly Silty, greyish red (5R4/2), very hard, cemented	439	443
SAND, f-c, Shelley, trace gravel, olive grey (5Y3/2), ~10% glauconite, weak HCl reaction	443	457
CLAY, reddish brown, thin beds SAND, f-m, olive grey, trace glauconite in sand fraction, fining downwards, hard layer at 470’	457	470
Log by: R. W. McQuiggan		

A1-12

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Lf23-04
Site No: 7

DNREC Permit No: 259372
Site Name: Milford Neck Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
Topsoil: SILT, trace Sand, f, dark brown.	0	0.6
SILT + CLAY, Sandy, f-m, trace Organics, light brown, yellow-brown, yellow-orange, mottled.	0.6	2.8
SAND, f-c, slightly Clayey, trace Sand, vc, orange-brown, light yellow-grey, brown, coarsening downward.	2.8	5
SAND, m-vc, Gravelly f-m, light yellow-gray, gray, trace opaque heavy minerals.	5	8.5
SAND, c-vc, Gravelly, f, pale brown (5YR5/2), light brown grey (5YR6/1), poorly sorted; few laminae SAND, f-m, Silty, light grey, blue-grey; SILT+SAND f, brownish black (5YR2/1).	8.5	14
SILT, trace Sand, f, trace Clay, trace organics, moderate brown (5YR3/4), dark reddish brown (10R3/4), mottled; common v thin beds CLAY + SILT, medium dark grey (N4); fining downward.	14	25
SAND, f-m, trace Sand, c, brownish grey (5YR4/1), medium dark grey (N4); trace laminae SILT, Sandy, f, brownish black (5YR2/1).	25	40
SAND, f-m, Silty, trace Sand, c, brownish grey (5YR4/1), pale yellow brown (10YR6/2).	40	48
SAND, f-m, trace Silt, brownish grey (5YR4/1), pale yellow brown (10YR6/2).	48	59
SAND, f-c, Gravelly, f, greyish orange (10YR7/4), light brown (5YR6/4).	59	78
Laminated: SAND, f-m, Silty, light brown (5YR6/4), grey orange (10YR7/6); orange-y SILT + SAND, f, Fe concretions, slight coarsening downward.	78	85
SAND, f-c, trace Silt, moderate yellow brown (10YR5/4), pale yellow brown (10YR6/2).	85	93
SAND, f-c, Shelly, trace Silt, brown grey (5YR4/1), moderate yellow brown (10YR5/4), majority of shell fragments <2mm, moderate acid reaction.	93	112
GRAVEL, f, Shelly, Sandy, m-c; trace laminae CLAY, Silty, brownish grey (5YR4/1), light olive brown (5Y5/6), moderate acid reaction.	112	126
SILT, Clayey, brownish grey (5YR4/1), no acid reaction.	126	131

A1-13

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Lf23-04 (continued)
Site No: 7

DNREC Permit No: 259372
Site Name: Milford Neck Wildlife Area

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
Bedded: SAND, f-c, Silty, Shelly, olive grey (5Y4/1), weak acid reaction; SILT, trace Clay, medium dark grey (N4), thin beds; SAND, f + SHELLS, Silty, olive grey (5Y4/1), strong acid reaction; SAND, f, Shelly, brownish grey (5YR4/1), olive grey (5Y4/1), fine grained concretions, cemented zone 142', overall coarsening downward, beds generally less than 5' thick.	131	169
SHELLS, Sandy, f-m, brownish grey (5YR4/1), olive grey (5Y4/1), shell fraction 75%, strong acid reaction.	169	184
Bedded and laminated: CLAY, very Silty, trace shells, moderate brown (5YR3/4); CLAY, trace Silt, trace shells, grey brown (5YR3/2).	184	218
Bedded: SHELLS, Sandy, m-vc; SAND, f-c + SHELLS; duskey yellow brown (10YR3/2), brownish grey (5YR4/1), majority of shells >2mm, beds 8-10' thick, strong acid reaction.	218	243
Thinly bedded: SAND, f-m + SHELLS, trace Silt, dark greyish brown; CLAY, Silty, moderate brown (5YR3/4), greyish brown (5YR3/2), beds generally <5' thick.	243	261
Bedded: CLAY, trace Silt, moderate brown (5YR3/4), greyish brown (5YR3/2); SAND, f-m + SHELLS, duskey yellow brown (10YR3/2), brownish grey (5YR4/1), shell fragments <2mm, acting as confining layer between sand + shell layers of aquifer, beds approximately 2-3' thick.	261	274
SAND, f-m + SHELLS, trace silt, dark greyish brown, greyish brown (5YR3/2).	274	283
Bedded: CLAY + SILT, trace Sand, f, trace Shells, moderate brown (5YR3/4); SILT, Clayey, trace Shells, greyish brown (5YR3/2), olive grey (5Y4/1), weak acid reaction.	283	311
SAND, vf-m + SHELLS, Silty, brownish grey (5YR4/1), olive grey (5Y4/1); coarsening downward, scattered shell beds, cemented zone 353-356'.	311	370
SILT + SAND, vf-f, Shelly, brownish grey (5YR4/1), olive grey (5Y4/1), shell fraction 30%, cemented zone 386-392', weak acid reaction.	370	409
SAND, F-M, Silty, trace Shells, medium dark grey (N4), slightly fining downward, trace shells with depth, cemented zone 463-465'.	409	470
Log by: R. W. McQuiggan		

A1-14

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Mb33-06 | DNREC Permit No: 259367
Site No: 9 | Site Name: Taber State Forest

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
Topsoil: SAND, f-m, Silty, trace organics, dark brown.	0	0.5
SAND, f-m, Silty, medium yellow-brown, medium yellow-orange, fining downward.	0.5	2.2
SAND, f-m, trace Silt + Granules, medium yellow-orange, few lite yellow-gray laminae.	2.2	5
CLAY, Silty to SILT, Clayey, trace Granules, few laminae SAND, F-C, mottled Lite gray and medium gray, pebble layer at base.	5	9.4
SILT, Clayey, Sandy f-c, trace Gravel, f-m, medium gray-brown, light gray.	9.4	11.2
Thinly bedded: SAND, m-c, Gravelly f-m, trace Silt; SAND, f-m, slightly Silty; SAND, m-c, Gravelly, f-m, Silty, layered light grey (N7), medium red-orange, light yellow-grey, dark yellow-orange (10YR6/6), larger grains angular to sub-angular.	11.2	34
Driller noted thin clay layer, did not appear in cuttings/samples	34	38
SAND, m-vc, trace Gravel, f-m, reddish-orange.	38	45
CLAY, Silty, trace Sand, f, olive grey (5Y4/1), brownish grey (5YR4/1).	45	49
SAND, f-m, Shelly, Silty, trace Sand, c, olive grey (5YR4/1), medium grey (N5), slight fining downwards; very thin beds of SILT, Sandy, vf-f, Shelly; rough/hard (shell?) beds containing larger (1cm+) shell and bone fragments at 65' and 74', moderate acid reaction.	49	83
Thinly bedded: SILT + CLAY; SILT, Clayey, trace Shells; mottled medium dark grey (N4), greyish red (5R4/2), pale yellowish brown (10YR6/4), fining downward, no acid reaction, beds generally between 1-3' thick.	83	122
SAND, f-m, Silty, Shelly, medium dark grey (N4), brownish black (5YR2/1), shells 30%, (most 3-4 mm), moderate acid reaction.	122	140
SAND, vf-f, Silty, trace shells, medium dark grey (N4), brownish black (5YR2/1).	140	163
Thinly bedded: SILT, Clayey, trace Sand, f, greyish red (5R4/2), greyish brown (5YR3/2); SILT, Sandy, f, moderate grey (N5), brownish grey (5YR4/1), bed approximately 1-2' thick.	163	192
SAND, f-m, + SHELLS, trace Silt, medium dark grey (N4).	192	205
SILT, Clayey, trace Shells, greyish brown (5YR3/2), moderate brown (5YR3/4), shells >2mm, scattered shell beds with shell content increasing from 3-10%.	205	241
SILT, very Clayey, greyish brown (5YR3/2), moderate brown (5YR3/4), fining downwards, increasingly more clay content with depth.	241	273

A1-14

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Mb33-06 (continued)
Site No: 9

DNREC Permit No: 259367
Site Name: Taber State Forest

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SAND, f-c, Shelly, sl Clayey, olive grey (5Y4/1), brownish grey (5YR4/1).	273	284
SAND, f-m, Silty, trace Shells, olive grey (5Y4/1), cemented beds at 284-287' and 300-305', weak acid reaction.	284	335
SHELLS, Sandy, f-m, olive grey (5Y4/1), brownish grey (5YR4/1), CEMENTED, strong acid reaction.	335	339
SAND, f-m + SHELLS, medium dark grey (N4), brownish black (5YR2/1), olive black (5Y2/1), shells <2mm, sandy concretions, strong acid reaction.	339	364
Log by: R. W. McQuiggan		

A1-15

Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ke25-10
Site No: 10

DNREC Permit No: 259399
Site Name: Ted Harvey Wildlife Area – Buckaloo Tract

Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
TOPSOIL, SILT, Clayey, dark brown, trace roots and organics	0	2.8
SAND, f-m, sligthly Silty + Clayey, Gravelly, f-m, with depth, light grey, yellow-brown, red brown, rare red-yellow mottles	2.8	6
Thinly bedded: SAND, f-c, trace Silt, light grey, yellow grey; SILT, Sandy, f, Clayey, trace organics, red-brown	6	7.8
SAND, f-c, trace Silt, trace Gravel, yellow-brown, light brown, brown grey; common laminae SAND, f-c, Silty, light brown.	7.8	11.8
Thinly bedded: SAND, f-c, trace Silt, light grey, yellow grey; SILT, Sandy, f, Clayey, trace organics, red-brown	11.8	12.2
SILT + CLAY, trace Sand, f, Lite Gray with common laminae SILT, Sandy, f; SAND, f-m Silty, Red-yellow and brown-yellow, fining downward.	12.2	18
SAND, m-c, Gravelly, f, light brown (5YR5/6), dark yellowish orange (10YR6/6); very thin beds SAND, f, very Silty, Fe-rich, orange.	18	30
CLAY, dark greenish grey (5GY4/1), pale yellow (10YR8/6), orange, colors are thinly (1mm) laminated and mottled.	30	36
SAND, f-c, brownish grey (5YR4/1), trace dusky green (5G3/2), trace black, sub-angular grains.	36	51
Bedded: CLAY, Silty, pale brown (5YR5/2), dusky yellow brown (10YR2/2), mottled grey orange (10YR7/4); trace laminae SAND, f, pale brown (5YR5/2), laminae within clay beds; SAND, f-c, brownish grey (5YR4/1), trace dusky green (5G3/2), trace black, sub-angular grains, beds between 2-5' thick.	51	81
GRAVEL, f, Sandy, c-vc, brownish grey (5YR5/2).	81	95
Bedded: CLAY + SILT, moderate brown (5YR3/4), SAND, f-m, Silty, slightly Clayey, brownish grey (5YR5/2); beds between 3-9' thick.	95	133
CLAY, Silty, trace shells, moderate brown (5YR3/4).	133	142
SAND, f-c, Shelly to trace Shells, trace Sand, vc, brownish grey (5YR4/1), black green (5Y2/1), shell fraction decreases with depth from 20% to 2%.	142	175
CLAY, Silty, sandy, f, trace shells (10%), moderate brown (5YR3/4), greyish red (5R4/2).	175	203

A1-16

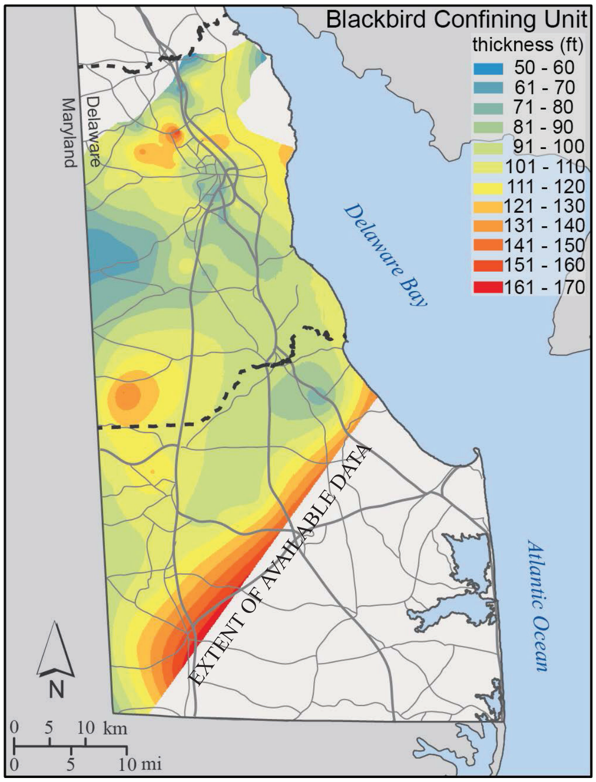
Appendix 1. Descriptive logs of wells drilled in this study.

DGS Site Identifier: Ke25-10 (continued) DNREC Permit No: 259399
Site No: 10 Site Name: Ted Harvey Wildlife Area – Buckaloo Tract

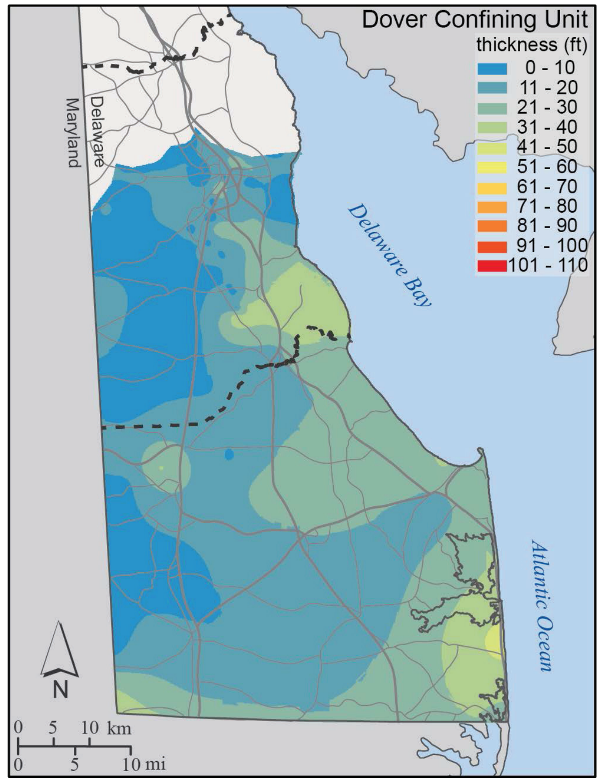
Material Description	Depth to Top of Strata (ft)	Depth to Bottom of Strata (ft)
SHELLS + SAND, vf-f, olive grey (5Y4/1), slight fining downward, decrease in size of shell fragments, weak to moderate acid reaction.	203	241
SILT, Clayey, trace shells, dark greenish grey (5GY4/1), grey, greyish brown (5YR3/2).	241	271
SAND, f-m, Silty, Shelley, olive grey (5Y4/1), greyish brown (5YR3/2), sandy concretions, shell fraction ranging from 10-25%, cemented zones at 271-273', 281-285'.	271	320
SAND, vf, trace Clay + Silt, trace shells, olive grey (5Y4/1), greyish brown (5YR3/2).	320	327
SAND, f-c, trace shells (8-10%), brownish grey (5YR4/1).	327	349
SAND, vf, Shelly, slightly Silty, olive grey (5Y4/1).	349	360
CLAY, trace Sand, vf, trace shells, moderate brown (5YR3/4), increasingly less sand content.	360	385
CLAY, Shelly (20%), trace sand, f + silt, moderate brown (5YR3/4).	385	408
CLAY, Silty, trace shells, brownish grey (5YR4/1).	408	433
Bedded: SAND, f, brownish grey (5YR4/1); CLAY + SILT, trace shells, olive grey (5YR3/2), beds generally 2-3' thick.	433	442
Fining downward: SAND, f-m, trace sand, c, trace shells, greyish olive (10Y4/2), glauconite 30%, quartz 70%.	442	457
SHELLS + SAND, f, greyish olive (10Y4/2), glauconite 30%, quartz 70%, shell fragments <2mm, moderate acid reaction, cemented zone 457-460'.	457	465
SHELLS, Sandy, f-m, greyish olive (10Y4/2), greenish black, glauconite 40%, quartz 60%, slight coarsening downward, strong acid reaction.	465	495
Log by: R. W. McQuiggan		

A1-17

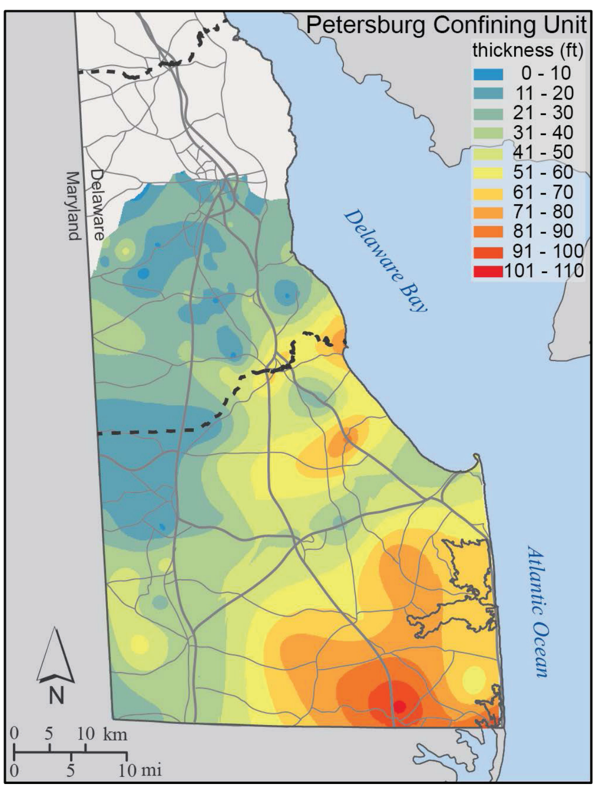
Appendix 2. Thickness maps of select named confining units in Kent County.



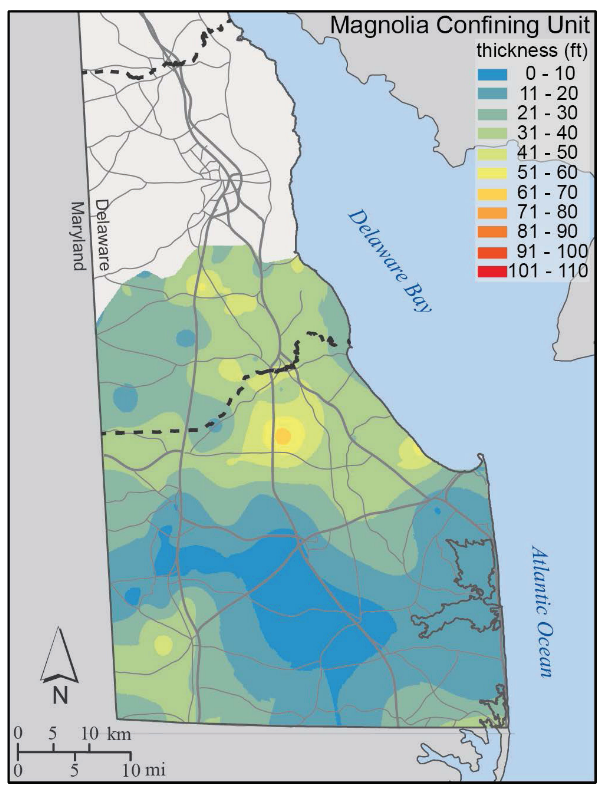
Thickness of the Blackbird confining unit.



Thickness of the Dover confining unit.

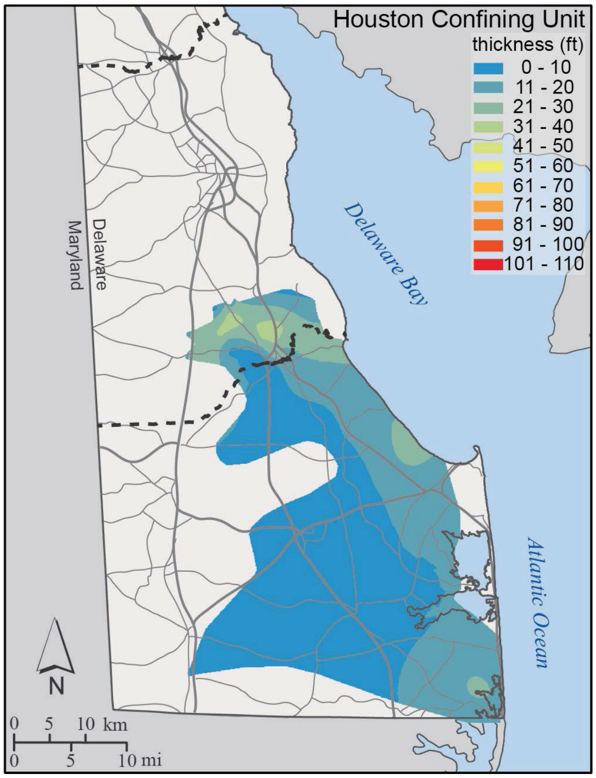


Thickness of the Petersburg confining unit.

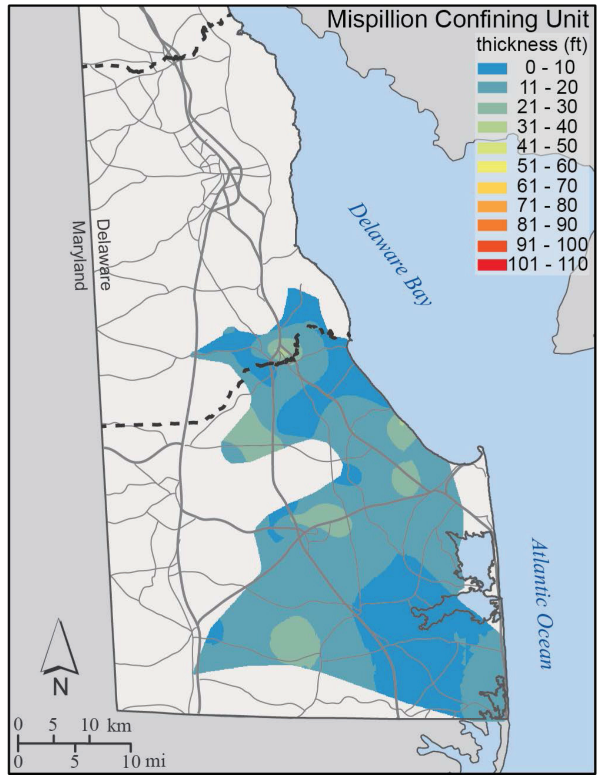


Thickness of the Magnolia confining unit.

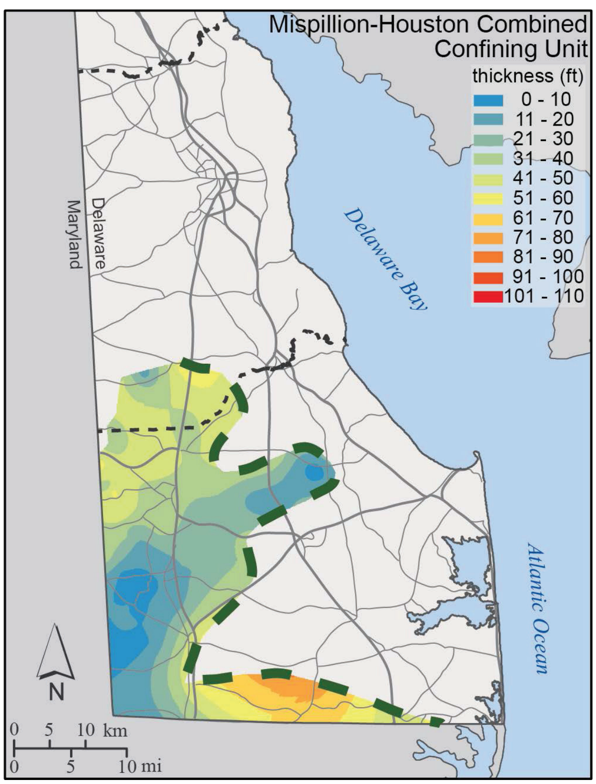
Appendix 2. Thickness maps of select named confining units in Kent County.



Thickness of the Houston confining unit.



Thickness of the Mispillion confining unit.



Thickness of the Houston-Mispillion combined confining unit. Green dashed line indicates the approximate limit of the stacked Houston-Mispillion confining unit, based on extent of Middle Choptank aquifer.

Delaware Geological Survey
University of Delaware
Newark, Delaware 19716