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David R. Wunsch, Director

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SOUTHERN NEW CASTLE – NORTHERN KENT COUNTIES GROUNDWATER MONITORING PROJECT: RESULTS OF SUBSURFACE EXPLORATION AND HYDROGEOLOGICAL STUDIES

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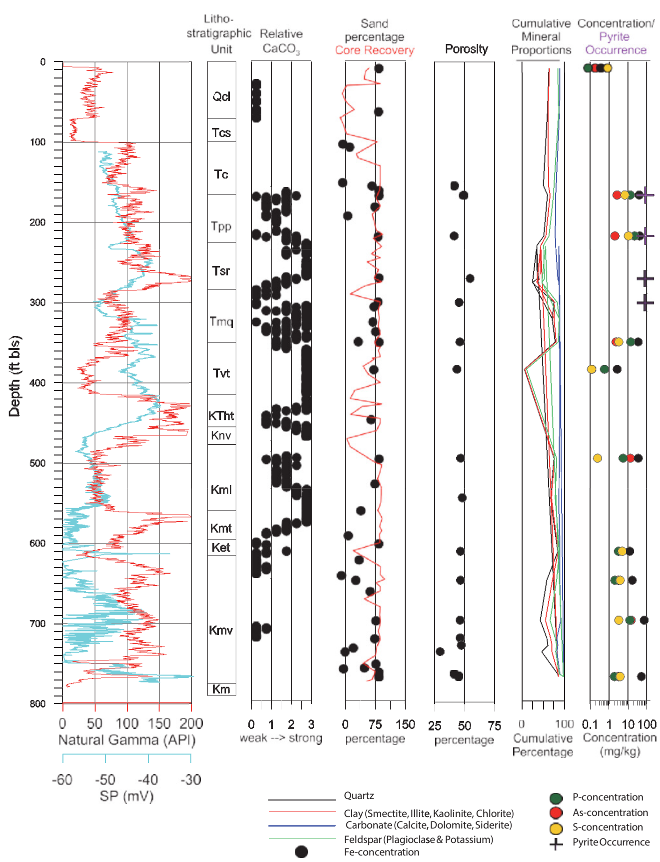

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ABSTRACT

The Delaware Geological Survey, in cooperation with the Department of Natural Resources and Environmental Control, completed a groundwater-monitoring, infrastructure-construction, and data-collection project in southern New Castle and northern Kent Counties, Delaware. This work, recommended by the Governor's Water Supply Coordinating Council and funded by a capital appropriation from the state, addressed data gaps for the shallower aquifers commonly pumped by water-supply wells that serve domestic, public, irrigation, and commercial users and provided additional data to characterize the relationships between the aquifers and streamflow. The aquifers investigated in this study are, from top to bottom, the Columbia, Rancocas, Mt. Laurel, and Magothy. The groundwater-monitoring infrastructure and data created during this project will continue to serve the management and research needs for water resources of Delaware, and lead to additional follow-up projects and technical reports.

Geophysical logs, sediment descriptions, and hydraulic tests of new wells indicate that the Rancocas aquifer is thicker and more permeable than previously thought in the Blackbird State Forest area. Further work is needed to determine the ability of the Rancocas aquifer to support high-capacity water-supply wells and if exploitation of this resource will have significant impacts on overlying streams and wetlands in this area.

Geophysical logs, sediment descriptions, water levels, and hydraulic tests of the Magothy Formation indicate that this unit does not function as an aquifer at many of the sites tested in this study. In the vicinity of Middletown, where the Magothy Formation does function as an aquifer, water levels in the Magothy are similar and exhibit changes similar to water levels observed in the underlying upper Potomac aquifer. This indicates that these aquifers are hydraulically connected and most likely function as a single aquifer in this area.

Hydraulic heads in the Rancocas and Mt. Laurel aquifers are near or below sea level in wells in the eastern third of the study area (east of Route 13). Heads in the Magothy are below sea level in the Middletown area. Automated high-frequency monitoring of water levels will continue in these areas to track trends. Head conditions are due in part to pumping.

Annual minimum flows are decreasing and annual maximum flows are increasing in the more than 50-years of streamflow record at Blackbird Creek. Such trends are consistent with long-term climate trends of more severe droughts and storms. Groundwater levels in the Columbia aquifer and stream baseflows are correlated over time periods of decades but not during the duration of the study period. This highlights a close connection of surface water and groundwater in the Columbia aquifer and underscores the importance of long-term monitoring of both surface water and groundwater.

INTRODUCTION

The Governor's Water Supply Coordinating Council (WSCC) is charged with preparing water supply and demand studies to ensure adequate supplies of good quality water for current and future needs of people and the environment (WSCC, 2006). To fulfill this charge, adequate monitoring infrastructure and systematically collected information on quantity and quality of water are invaluable tools for managers and policy makers in making well-informed decisions on water resources.

Reports by the US Army Corps of Engineers (USACE, 2007) and WSCC (WSCC, 2006) identified gaps in water resources information and monitoring infrastructure for New Castle County, and as a result the WSCC recommended that the Delaware Geological Survey (DGS) undertake a project to enhance groundwater-monitoring infrastructure and to collect and analyze data to aid water-resources planning for southern New Castle County (SNCC) and a portion of northern Kent County (NKC), Delaware (Fig. 1). Project planning and design were based on the following fundamental concepts:

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

Design of water-monitoring infrastructure with these concepts results in a monitoring system capable of providing data to support decision making and applied research on a variety of current, and potential future water quantity and quality issues. The General Assembly and Governor of Delaware agreed to the merits of the DGS project planning and design concepts and provided a capital appropriation to conduct this work.

Purpose and Scope

Construction of monitoring infrastructure (e.g., wells and stream gaging) and data collection conducted during this study address many of the geologic, hydraulic, and hydrologic information gaps identified by USACE (2007), Dugan et al. (2008) and He and Andres (2011). These previous studies created computer-based models of the subsurface hydrogeologic framework, groundwater flow, water budgets, and aquifer response to current and potential future pumping scenarios. These models and their results are state-of-the-practice tools for evaluating groundwater availability and flow conditions. Groundwater-level data collected from the infrastructure installed during this study also serve to test the levels predicted by the groundwater flow model of He and Andres (2011) and will permit extension of the He and Andres (2011) model or other future groundwater flow models to simulate more complex and realistic time-dependent conditions.

The purpose of this technical report is to document the methods, results, and recommendations derived from subsurface exploration, monitoring well installation, hydraulic testing, and groundwater-level and streamflow measurements funded by the capital appropriation. Selected data and interpretations of previous studies are also considered and included in this report in the context of results produced in this study.

The scope of this project is focused on the shallower aquifers commonly pumped by water-supply wells serving domestic, public, irrigation, and commercial users in SNCC and NKC and that provide baseflow to local streams. From top to bottom, they are the Columbia, Rancocas, Mt. Laurel, and Magothy aquifers. Aquifers in the underlying Potomac Formation were not investigated because of the cost of installing wells at depths exceeding 1000 feet (ft) below land surface (bls). Information to assess interactions between streams and shallow aquifers was collected from reactivated and existing streamflow monitoring stations operated by the U.S. Geological Survey (USGS).

Acknowledgments

This work was funded by a fiscal year 2012 capital appropriation from the State of Delaware at the recommendation of the WSCC. The funds were managed by the Delaware Department of Natural Resources and Environmental Control (DNREC), Division of Water, Water Supply Section.

DNREC Division of Fish and Wildlife (Wayne Lehman, Craig Rhoads), Delaware Department of Agriculture (DDA) Division of Forestry (Jim Dobson), Town of Smyrna (Dave Hugg, Darryl Jester, Mark Gede), and New Castle County (NCC) Department of Special Services (John Husband, J. Wayne Merritt, Regis Yurcic, Brian Blackburn) allowed access to their sites. The above mentioned people from the Town of Smyrna provided logistical support for drilling at their site. Steven Curtin of the USGS provided logging support at two sites.

The wireline coring, well installation, and logging operations required assistance from a significant number of people. Eugene Cobbs, Jeff Gray, Andrew Burkhart, and Randy Oehrendorfer of the USGS assisted contracting and conducted wireline coring. Faculty, staff, and students from Rutgers University (K. Miller, J. Browning, R. Baluyot, T. Iscimen, T. Degirmenci, M. Makarova, C. Lombardi) and the University of Delaware (C. Russoniello, M. Christie E. Williamson, N. Spalt, E. Cline) participated in describing and processing the wireline cores. Multiple staff members of the Delaware Geological Survey (P. Stephen McCreary, Peter McLaughlin, Jaime Tomlinson, Kelvin Ramsey) assisted with describing and processing wireline cores, conducting geophysical logging, well installations, miscellaneous field work, and consulting with operational aspects of the drilling. John's Well Drilling, Inc., and Lifetime Well Drilling, Inc. allowed access to recently completed wells for geophysical logging and hydraulic testing.

David Bolton, David Andreasen, and David Drummond of the Maryland Geological Survey (MGS) were consulted routinely. They allowed 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

Core and drill-cutting samples, monitoring wells, and streamflow measurements are essential for characterization and evaluation of geologic and hydrologic conditions. Field operations, in the form of wireline coring, sampling, and geophysical logging commenced in May 2012 and laboratory operations began soon after the first cores were returned to the offices of the DGS. Well installations commenced in July 2012. Coring and well installation sites are shown in Figures 1 and 2 and listed in Tables 1 and 2. Stream gaging commenced in August 2012.

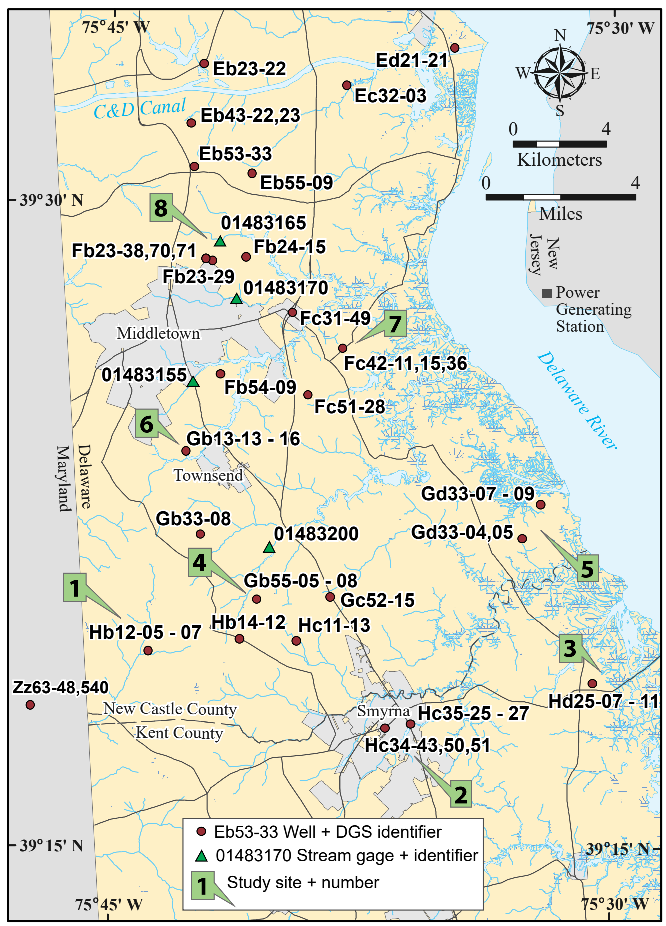

Figure 1. Study area map.

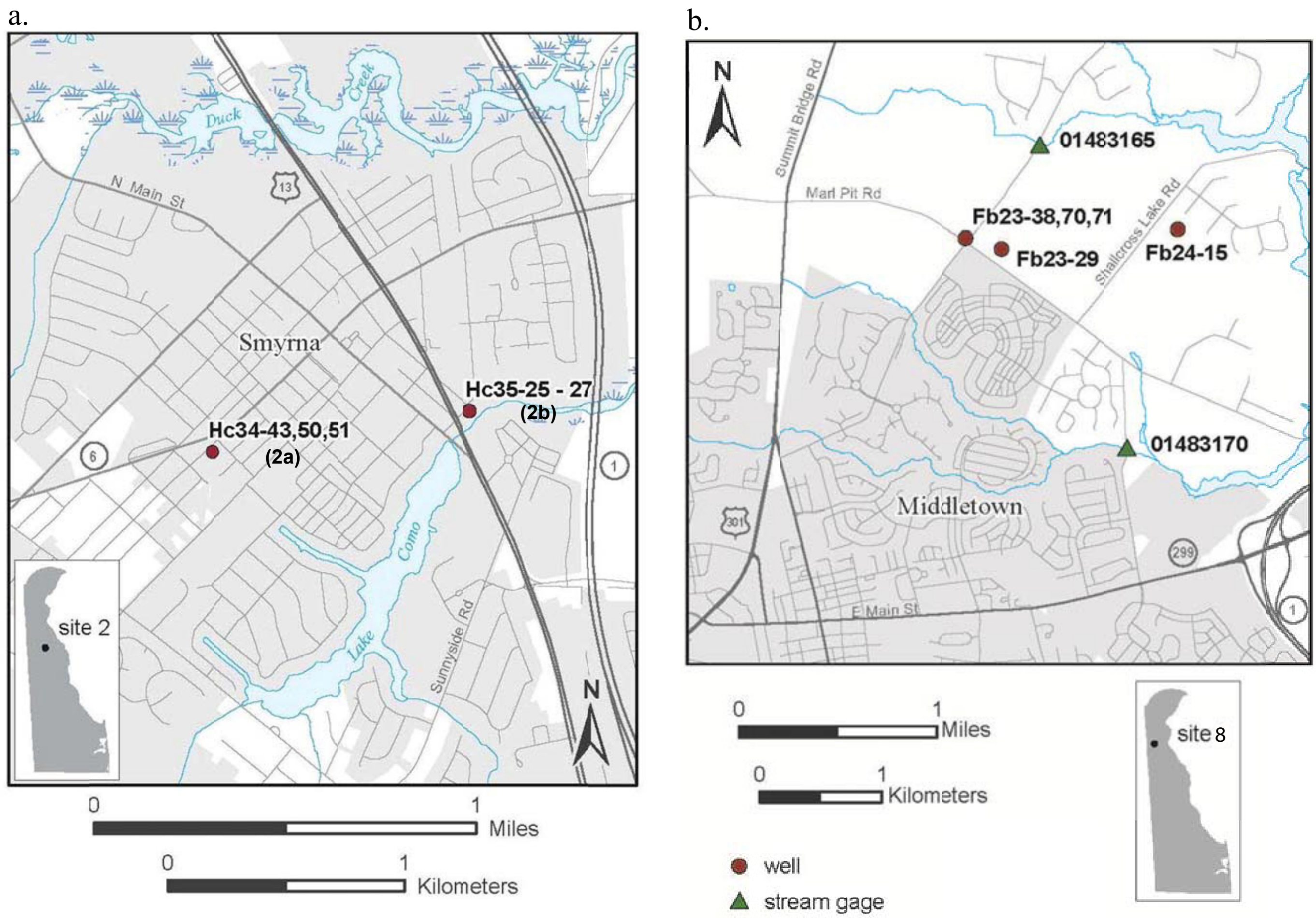

Figure 2. Detail maps for site 2 (a) and site 8 (b).

Table 1. Operational summary of coring and well installation. Aquifer codes: cl–Columbia; pp–Piney Point; rn–Rancocas; ml–Mt. Laurel; m–Magothy. Lithostratigraphic unit codes: Kpt–Potomac Fm.; Km–Magothy Fm.; Kmv–Merchantville Fm.; Ket–Englishtown Fm.; Kmt–Marshalltown Fm. TD-total depth

Site Number and Name	Completion Date (month-year)	DGS Block Identifier	Core Depth (ft)	Maximum Well Depth (ft)	Aquifers	Lithostratigraphic Unit at TD
1-Blackbird Peters Tract	Nov-12	Hb12	22	340	cl, rn, ml	Kmt
2a-Smyrna	Jul-12	Hc34	775	260	cl, rn	Km
2b-Smyrna	Oct-13	Hc35	350	500	rn, ml	Kml
3-Woodland Beach	May-12	Hd25	820	535	cl, pp, ml	Km
4-Blackbird Tybouts	Aug-12	Gb55	24	400	cl, rn (2), ml	Kmv
5-Cedar Creek	Oct-12	Gd33	26	390	cl, rn, ml	Ket
6-Wiggins Mill Park	Jul-13	Gd13	36	325	cl, rn, ml, m	Kpt
7-Water Farm 1	Mar-13	Fc42	--	435	rn, ml, m	Kpt
8-Water Farm 2	Feb-13	Fb23	--	335	cl, rn, ml, m	Kpt

Table 2. Wells installed and/or monitored during this study. NAVD88–North American Vertical Datum of 1988; bls–below land surface.

Site Number	DGS Well Identifier	DNREC Well Identifier	Land Surface Elevation (ft NAVD 88)	Screen Top (ft bls)	Screen Bottom (ft bls)	Aquifer	Water Use	Geophysical Log	Water Level	Aquifer Test
Newly Installed Cores and Wells										
1	Hb12-05	240610	66	14	20	Columbia	monitor		Y	Y
	Hb12-06	240906	66	385	395	Mt. Laurel	monitor	Y	Y	Y
	Hb12-07	240905	66	155	165	Rancocas	monitor		Y	Y
2	Hc34-51	238966	46				core	Y		
	Hc35-25	244254	11.8				core	Y		
	Hc35-26	244611	12.07	485	495	Mt. Laurel	monitor	Y	Y	Y
	Hc35-27	244612	12.08	295	305	Rancocas	monitor		Y	Y
3	Hd25-07	238963	12				core	Y		
	Hd25-09	239967	12	165	175	Piney Point	monitor		Y	Y
	Hd25-10	239975	12	520	530	Mt. Laurel	monitor		Y	Y
	Hd25-11	240607	12	19	24	Columbia	monitor		Y	Y
4	Gb55-05	239977	49	380	390	Mt. Laurel	monitor	Y	Y	Y
	Gb55-06	239966	49	140	150	Rancocas	monitor		Y	Y
	Gb55-07	239976	49	230	240	Rancocas	monitor		Y	Y
	Gb55-08	240611	49	14	19	Columbia	monitor		Y	Y
5	Gd33-07	240596	17.83	15	25	Columbia	monitor		Y	Y
	Gd33-08	240907	17.78	385	395	Mt. Laurel	monitor	Y	Y	Y
	Gd33-09	240904	17.77	155	165	Rancocas	monitor		Y	Y
6	Gb13-13	243697	45.35	23	33	Rancocas	monitor		Y	Y
	Gb13-14	243767	46.16	350	360	Magothy	monitor	Y	Y	Y
	Gb13-15	243771	46.51	200	210	Mt. Laurel	monitor		Y	Y
	Gb13-16	243772	46.41	115	125	Rancocas	monitor		Y	Y
7	Fc42-36	241415	45.26	415	425	Magothy	monitor	Y	Y	Y
8	Fb23-70	241417	62.36	320	330	Magothy	monitor	Y	Y	Y
	Fb23-71	241416	62	135	145	Mt. Laurel	monitor		Y	Y
	Gc52-15	247118	49				core	Y		
Existing Wells										
8	Fb23-29	046613	50.75	12.8	27.8	Columbia	monitor		Y	Y
	Fb23-38	242514	62	49.9	59.4	Columbia-Rancocas	monitor		Y	Y
	Fb24-15	245302	61.2	33.5	48.5	Columbia-Rancocas	monitor		Y	Y
2	Hc34-43	082054	46	280	310	Rancocas	public	Y		Y
	Hc34-50	098123	46	55	65	Columbia	public			Y
7	Fc42-11	Ec3203	52	220	260	Mt. Laurel	monitor		Y	Y
	Fc42-15	176100	52	35	50	Rancocas	monitor		Y	Y
	Eb23-22	186608	60.47	101	105	Magothy	monitor		Y	
	Eb43-22	219665	61	30	60	Mt. Laurel-Englishtown	irrigation	Y		Y
	Eb43-23	186672	60	30	53	Mt. Laurel-Englishtown	irrigation	Y		Y
	Eb53-33	110406	66	69	84	Mt. Laurel-Englishtown	monitor		Y	
	Eb55-09	240519	56	400	420	upper Potomac	monitor		Y	
	Ec32-03	090405	8.16	318	348	lower Potomac	monitor		Y	
	Ed21-21	090407	15	187	197	Magothy	monitor		Y	
	Fb54-09	099009	60.5	34.5	39.5	Columbia	monitor		Y	
	Fc31-49	245977	56	175	185	Mt. Laurel	domestic	Y		Y
	Fc51-28	Gd3304	8.2	97	127	Rancocas	monitor		Y	
	Gb33-08	Gd3305	70.5	140	160	Rancocas	domestic			Y
	Gd33-04	211615	18	395	427	Mt. Laurel	monitor		Y	
	Gd33-05	243249	18	628	660	Magothy	monitor		Y	
	Hb14-12	093154	73	14	19	Columbia	monitor		Y	
	Hc11-13	094975	48.5	110	200	Rancocas	irrigation	Y		Y
Maryland	Zz63-48	Ke Bg 33	65	695	710	upper Potomac	monitor		Y	
Maryland	Zz63-540	Ke Bg 34	65	124	186	Rancocas	monitor		Y	

Coring

Wireline coring was conducted by the USGS drilling rig and crew at Woodland Beach Wildlife Area (Site 7) and at the High Street water plant in Smyrna (site 2a; Figs. 1 and 2, Tables 1 and 2). Additional shallower wireline coreholes were collected by the DGS at Locust Street in Smyrna (site 2b; Figs. 1 and 2, Tables 1 and 2) and at Gc52-15 (Fig. 1). The coring system and sample collecting, describing, and processing were similar to those described by McLaughlin et al. (2008). Split-spoon coring was conducted by the DGS drilling rig and crew at sites 1, 3, 4, 5, and 6 (Fig. 1). Core samples were described, photographed, labeled, and packaged in the field by the team of on-site geologists. Core descriptions and photographs were reviewed in the laboratory and, when appropriate, corrections and additions were added to the records.

Split samples were collected from the wireline cores in the field for determination of gravimetric moisture content. Latitudinal segments approximately two inches (in) long were cut from the core with a steel knife. The sharpened end of a shelby tube was pushed through the center of the core to extract a 1.85 in (47 millimeter (mm)) diameter plug. The plug was then extruded, and if necessary, the length of the plug was trimmed to fit into a pre-weighed (1.87 in (47.5 mm) diameter x 1.42 in (36.1 mm) deep) container (Humboldt Mfg. H-1350.3A). To accurately measure the sample volume, the height of the plug was measured at three points around the plug with a caliper to the nearest 0.04 in (1 mm) and then placed into the container. The container was capped and then weighed in the field on an Ohaus model 4000 digital scale to the nearest 0.1 gram (g) to determine the total sample weight. Capped containers were transported back to the DGS facilities at the end of each day and stored for drying and re-weighing in the laboratory.

Prior to packaging, relative carbonate abundance was determined by applying 10 percent hydrochloric acid (HCl) to the cores in the field at 0.5 ft intervals and ranking the strength of reaction on a four-point scale from none (0) to strong (3). Additional observations were made in the laboratory to supplement and check the field data.

Digital geophysical logs were collected by the DGS using a factory-calibrated Century Geophysical drawworks, tools, and System 6 processing module. Spontaneous potential, single point resistance, short and long-normal resistance, lateral log, natural gamma radiation, and temperature logs were collected with a model 8044 multi-tool in open holes. Core descriptions, photographs, and geophysical logs were used to compile composite descriptive logs. Geophysical and descriptive corehole logs are available in this report and through the DGS web site.

Well Installation

All of the monitoring wells installed during this project that were deeper than 100 ft were constructed under a competitively bid contract by Uni-Tech Drilling, Inc. (UTD) of Franklinville, New Jersey. Drilling sites are shown on Fig. 1. Shallow monitoring wells were installed by the DGS at sites 1, 3, 4, 5, and 6.

At each site, the deepest hole was drilled first to collect the data needed to guide well depths. During drilling of the deepest hole, the geologist on site worked closely with the drill operator to collect representative samples at 10-ft intervals. Samples were washed in fresh water to remove drilling mud and descriptions of composition and color were recorded. Colors were determined by visual comparison to standard Munsell color charts. Washed samples were tested for relative carbonate content with the same method used for cores.

Gamma logs were collected in the drillstem when hole stability was in question or to ensure that the target aquifer had been reached prior to removing drill rods from the hole. Geophysical logs were also collected in the open hole at each site. The sample descriptions and geophysical logs were used to compile a composite descriptive log on site that was used to choose depths for well screens.

Wells installed by UTD were constructed of 2-in inside diameter (ID), solvent-welded, schedule 40 PVC casing and machine-slotted screen installed in holes excavated by standard mud rotary techniques. Wells installed by DGS were constructed of 2-in ID, flush-threaded schedule 40 PVC with holes excavated by standard hollow stem auger (HSA) techniques. Wells were finished with 10 ft of schedule 40 PVC machine-slotted screen.

For wells deeper than 100 ft, gravel pack and grout were emplaced by tremie pipe inserted through the annular space to within 20 to 30 ft of the measured bottom of the hole. The tremie pipe was gradually removed as the hole was backfilled. Neat cement was used as the grouting agent. For wells constructed by HSA methods, gravel pack and granular bentonite were placed through the HSA annulus by gravity, and frequent depth soundings were made to ensure proper placement of gravel and grouting materials.

Following completion, wells were developed by air lift for a minimum of three hours. Wells were scanned with a downhole video camera to ensure that all drill cuttings had been removed from the well. Several wells required additional development to remove suspended material from the water column.

All wells were equipped with protective casings and locking caps. Horizontal positions of wells were determined by Wide Area Augmented Global Positioning System (GPS) and adjusted when necessary using Geographic Information System-based comparisons of GPS-determined well coordinates with high-resolution, geo-referenced aerial photographs. At each site, elevations of well top, water-level measurement points were surveyed from a common site datum to the nearest 0.01 ft by DGS staff using an autolevel. At sites with adequate wireless communications coverage the elevation of the common site datum (Table 2) was determined by survey-grade GPS to the nearest centimeter (cm). Elevations at the remaining sites were determined from Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM) (+/- 15 cm).

Laboratory Operations

Core-sample splits were collected in the laboratory for a variety of tests that characterize a variety of compositional and hydraulic properties. In all cases sample splits were collected from the interior of the cores. Semi-quantitative bulk mineralogy analyses were performed by X-Ray diffraction using automated curve-matching methods by Shawn Butler (Illinois State Geological Survey). Grain-size distribution analyses, sand/clay-silt proportions, and silt/clay proportions were performed in the DGS laboratories following procedures documented in Kramer (1987). Chemical analyses of selected total sorbed metals were analyzed in the University of Delaware Soil Testing Laboratory using method USEPA 3051A (USEPA, 2007a).

Sample density, mineralogy, and moisture content are important data for estimating hydraulic properties. Gravimetric moisture content was determined in the DGS laboratory by calculating the difference between field and oven-dried (80 ^{o}C) weights of field-collected core splits (ASTM D4959-00, 2007). These data formed the bases for calculating bulk wet and dry densities and volumetric water content, which in turn were used to estimate volume of solids, volume of voids, and porosity. For samples with mineralogic analysis, estimates of dry density and porosity were conditioned by the proportions and densities of individual minerals. Mineral densities were taken from Hurlbut and Klein (1977). The difference between the volume of voids and the volume of water provided an indication of whether or not all pores in the sample were completely saturated.

Hydrologic Monitoring and Hydraulic Testing

Groundwater levels were measured in monitoring wells installed during this project, as well as in selected existing monitoring wells to evaluate water pressure conditions in the aquifers. Measurements were made by DGS staff using manual methods similar to Drost (2005) and USEPA (2007b) and automated methods using pressure-temperature-data logger instruments (In-Situ, Inc.) operated on a 15-minute recording interval.

Streamflow monitoring was conducted under a contract with the USGS to evaluate the relationships between aquifers and surface water. Two streamflow-monitoring stations were reactivated for this study and data from two additional existing stations were incorporated into this study (Figs. 1 and 2b). Baseflow separations were conducted on daily mean streamflow data using the Web-based Hydrologic Analysis Tool (Lim et al., 2005, and https://engineering.purdue.edu/~what/). Results from the recursive digital filter (filter parameter 0.98, BFI max 0.8 to 0.9) and local minimum methods were evaluated.

Hydraulic tests provide data to evaluate the water-bearing characteristics of earth materials. Single-well (slug) tests were completed in project monitoring wells and additional newly completed private wells by mechanical and pneumatic methods following the guidelines of Butler (1996). Data from the rising-head parts of the tests were processed in AquiferTest Pro software (SWS, 2013) using the protocols of Bouwer (1989) and Butler (1996). Additional slug test results from Site 8 were obtained from Metcalf & Eddy, Inc. and Duffield Associates, Inc. (2007).

Data Management

All geologic and groundwater data have been archived in DGS internal data systems to ensure long-term, efficient access to data. Geologic, geophysical, and groundwater-level data are available through the DGS web site through the DGIR map interface (maps.dgs.udel.edu/dgir/). Hydraulic data will be available through this portal in the future. Groundwater-level data and related publications are available through links on the DGS home page (http://www.dgs.udel.edu). Streamflow data are maintained by the USGS and are 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, and results of tests of mineralogy, sediment geochemistry, moisture content, density, grain-size, hydraulic conductivity, and groundwater levels. These are discussed in the context of lithostratigraphic and hydrostratigraphic units.

Geology and Hydrogeology

Coring and Well Installation Operations Summary

Exploratory drilling operations began at site 3 in May 2012 with a wireline corehole. Monitoring-well installations began in July 2012 and ended in October 2013. Detailed information about well construction is included in Tables 1 and 2. Wells were monitored at two sites in Smyrna due to access issues at site 2a and to further investigate potential faulting identified in a wireline core collected at site 2a. An additional corehole (Gc52-15, Fig. 1) was completed in June 2014 to explore a potentially thick section of the Rancocas aquifer and the updip limit of the Piney Point aquifer.

Lithostratigraphy and Hydrostratigraphy

Lithostratigraphic units (Fig. 3) penetrated during this work extend from the Potomac Formation (oldest) to the Scotts Corners Formation (youngest). Wells were installed in the Columbia, Piney Point, Rancocas, Mt. Laurel, and Magothy aquifers (Tables 1 and 2). Additional existing wells were used for hydrologic and hydraulic measurements (Table 2). Interpretations of lithostratigraphy and hydrostratigraphy for drillholes installed during this project are summarized in a stratigraphic chart (Fig. 3), logs (Figs. 4-13 Plate 1, Appendix 1), and cross sections (Fig. 14, Plate 2). Interpretations were largely based on analyses of core and cutting samples and geophysical logs collected during this study, correlation to established frameworks drawn from recent publications of the DGS (Benson and Spoljaric, 1996; Andres, 2001; McLaughlin and Velez, 2006; Ramsey, 2005, 2007; Dugan et al, 2008; He and Andres, 2011), MGS (Drummond, 1998, 2001), and discussions with DGS staff members McLaughlin, Ramsey, and Tomlinson.

No new lithostratigraphic or hydrostratigraphic units were discovered during this project. Detailed biostratigraphic and isotope analyses and evaluations needed to more precisely determine biostratigraphy and chronostratigraphy and to further evaluate depositional environments, depositional history, and structural features were beyond the scope of this

Age	Lithostratigraphic Unit (symbol)	Hydrostratigraphic Unit	Avg. Thickness (ft)	Present At Site(s)	Major Lithologies	Hydraulic Function
Miocene	Calvert Fm. (Tc)	Blackbird confining unit	47	2-3	Sandy and muddy facies	Leaky confining unit to aquifer
Eocene	Piney Point Fm. (Tpp)	Piney Point aquifer	58	2-3	Muddy, glauconitic sand	Poor aquifer
	Shark River Fm. (Tsr)	Blackbird confining unit	54	1-7	Muddy to sandy, variably glauconitic	Leaky confining unit
	Manasquan Fm. (Tmq)	Rancocas aquifer	54	1-7	Sandy to muddy, variably shelly, glauconitic	Aquifer to leaky confining unit
Paleocene	Vincentown Fm. (Tvt)	Rancocas aquifer	66	1-8	Sandy to muddy, variably shelly, glauconitic	Aquifer to leaky confining unit
	Hornerstown Fm. (KTht)	Armstrong confining unit	31	1-8	Muddy, variably glauconitic	Leaky confining unit
Cretaceous	Navesink Fm. (Knv)	Armstrong confining unit	24	1-8	Muddy, variably glauconitic	Leaky confining unit
	Mount Laurel Fm. (Kml)	Mt. Laurel aquifer	84	1-8	Sandy variably glauconitic, shelly	Fair to good aquifer
	Marshalltown Fm. (Kmt)	Summit confining unit	28	1-8	Muddy, variably glauconitic	Leaky confining unit
	Englishtown Fm. (Ket)	Englishtown aquifer	24	1-8	Muddy, variably glauconitic	Poor aquifer
	Merchantville Fm. (Kmv)	Summit confining unit	86	1-8	Muddy, variably glauconitic, shelly	Leaky to tight confining unit
	Magothy Fm. (Km)	Magothy aquifer	35	2-3, 6-8	Muddy, charcoal, mud clasts, fine sand	Leaky confining unit to fair aquifer

Figure 3. Lithostratigraphic and hydrostratigraphic units in study area.

study. The samples needed to do these analyses are cataloged and archived in the DGS core and sample repository. Further discussion of the relationships between lithostratigraphy and hydrostratigraphy, structures, hydraulics, and hydrologic functions is contained in later sections.

Readers interested in previous interpretations of litho- and hydrostratigraphy of the region are referred to Jordan, (1962), Owens et al. (1970), Hansen (1992), Marine and Rasmussen (1955), Cushing et al. (1972), Zapecza (1989), Woodruff (1986, 1992), Benson and Spoljaric (1996), and McLaughlin and Velez, (2006).

Data available at this time are not sufficient to identify the northern extent of the Piney Point aquifer or the age-equivalent deposits. We speculate that the Piney Point Formation does extend north of Smyrna (3-3’ on Fig. 14 Plate 2) and that that interval may function as a poor aquifer in that area, potentially yielding a few gallons per minute to a well. It is possible that this interval may be part of the overlying Shark River Formation; however, this would require additional coring and biostratigraphic analysis.

Mineralogy, Geochemistry, and Geotechnical Properties

Results of semi-quantitative, automated x-ray diffraction (XRD) analysis of mineral content (Table 3, Appendix 2) in cores indicate significant variations in mineralogy between geologic units, but the relatively small number of samples per geologic unit (less than 10) indicates that each unit is not well characterized. Quartz is the dominant (greater than 50 percent) mineral component in 90 percent of the samples analyzed. This is consistent with visual descriptions that show sand and silt being dominant (greater than 35 percent, e.g., Sand and/or Silt) or secondary (greater than 10 to less than 35 percent, e.g., Sandy and/or Silty) components in parts of all the geologic units. Comparison of manual-visual descriptions (Appendix 1) with grain-size distribution data indicates that grain-size distribution data tended to over-estimate the sand component in many samples. More aggressive disaggregation treatment of selected samples reduced sand percentages between 20 and 40 percent; however, the grain-size distributions of these treated samples still were sandier than estimated by the manual-visual descriptions. Inspection of the sand fractions of untreated and treated samples by binocular microscope indicated that carbonate-cemented, multi-grain aggregates and concretions are common. Therefore, the use of grain-size distribution data to assess sedimentology or hydraulic characteristics is unreliable.

Carbonate minerals (calcite and siderite) appear as more than a trace component (greater than 10 percent) in about 30 percent of the samples. These minerals are most abundant in the Shark River, Manasquan, Hornerstown, Merchantville, and Magothy Formations. Only a trace of dolomite was detected in a few samples. Carbonate minerals were present as fossils, cements, and concretions at all test drilling sites. The relative abundance of carbonate minerals, determined by the reaction to 10 percent HCl and observations of hard drilling zones, varied significantly between lithostratigraphic units (Figs. 4-13 Plate 1, Appendices 1 and 2). Shell molds and casts, many without the original shell, are common in the muddy beds of the Calvert, Shark River, Manasquan, Vincentown, and Hornerstown Formations. Cemented zones commonly have solution vugs that range in size from less than one mm up to one cm. The presence of molds, casts, and vugs indicates that post-depositional diagenetic alteration dissolved carbonate minerals from fossils and sediments and then moved and re-precipitated secondary calcite, dolomite, and siderite as cemented zones and concretions. Diagenetic processes that result in cementation and concretions can significantly reduce porosity and water-bearing characteristics. Conversely, processes that create solution vugs can significantly increase porosity and water-bearing characteristics.

Feldspar minerals are found as a trace to minor component of most samples. Pyrite and/or marcasite appear as a trace component (greater than 5 to less than 10 percent) in 20 percent of samples, with these minerals most frequently found in the Calvert, Piney Point, Manasquan, and Magothy Formations.

Clay mineral content was assessed only in a gross sense because samples were analyzed in bulk rather than as preparations of clay-sized particles. Automated XRD analysis with this type of sample preparation tends to identify mixed layer illite-smectite, illite, glauconite, and muscovite as illite (S. Butler, personal comm., 2011). This group of minerals is a secondary component (greater than 10 percent) in nearly one-fourth of the samples.

Extractable trace metals (USEPA 3051A) (Table 4, Appendix 3) vary significantly between and within geologic and hydrologic units. Arsenic is of particular interest because naturally occurring elevated concentrations of arsenic (greater than 10 ppb) have been found in the Aquia aquifer in Maryland (Drummond and Bolton, 2010; Haque et al., 2008). The Aquia is correlative to the Rancocas aquifer of Delaware. Naturally occurring arsenic is also found in sediments, groundwater, and surface water in New Jersey (Barringer et al., 2010, 2011) in geologic and hydrologic units correlative to the Rancocas aquifer. Arsenite was the dominant form of dissolved arsenic in both states. Barringer et al. (2010, 2011) and Haque et al. (2008) found that elevated arsenic concentrations in sediment were correlated with elevated concentrations of arsenic in water. Elevated arsenic concentrations in water were associated with elevated concentrations of dissolved organic carbon (DOC) and Fe, and low concentrations of dissolved oxygen (DO), sulfate, and nitrate. Biologically mediated redox reactions for arsenic dissolution were postulated by both Haque et al. (2008) and Barringer et al. (2010).

Extractable arsenic concentrations found in this study are similar to those reported for similar age glauconitic sediments in New Jersey (Barringer et al., 2011) and Maryland (Haque et al., 2008). Goethite, hematite, and other forms of less well-crystallized iron oxyhydroxide minerals are associated with arsenic in New Jersey and Maryland, and visual descriptions of sediment samples collected in this study noted the presence of rusty colored grains typical of oxidized iron-bearing minerals. Clearly the geologic and hydrologic conditions associated with elevated arsenic concentrations in groundwater in New Jersey and Maryland are present in Delaware.

Moisture content, density, and porosity vary significantly between geologic and hydrologic units (Tables 5a, 5b). Most of the samples that were collected for analyzing moisture content, density, and porosity came from muddy, cohesive intervals, that is, intervals that should behave as confining beds. Sample disturbance during collection of core and split samples from sandy intervals precludes analyses of these materials. Because porosity, density, and saturation calculations are dependent on results of semi-quantitative mineralogic analyses, and the precision of these analyses are estimated to be +/- 3 percent (S. Butler, personal comm., 2011) differences of a few percent between samples are considered to be insignificant.

Porosity and density data were collected from too few intervals to determine trends with depth or stratigraphic unit or to estimate overburden pressure. Presumably, density increases and porosity decreases with depth due to burial compaction (Hamilton, 1976), increased amounts of carbonate cemented zones and concretions, and possibly increased abundance of authigenic clay minerals in pore spaces. Many of the calculated water saturations were less than 80 percent, which are consistent with visual observations of core samples that seemed too dry for having been extracted from beneath the water table. Because the Calvert Formation was deposited in a marine environment (Benson and Spoljaric, 1997), the low saturation values imply that these sediments were dewatered, perhaps during glacial periods when sea level was much lower than now. The relative importance of simple gravity drainage or compaction due to lithostatic loading forces to cause dewatering is unknown.

The observation of low saturation in confining beds has hydrologic significance because of the relationship between hydraulic conductivity (K) and saturation. K drops by an order of magnitude or more with even small (less than a few percent) deviations from complete saturation (Freeze and Cherry, 1979). Lower K values result in lower vertical fluxes and velocities of water through confining beds and indicate that recharge to deeper confined aquifers originate from lateral flow from aquifer subcrop areas rather than by vertical leakage.

Hydraulic Characteristics

Dugan et al. (2008) and Metcalf & Eddy et al. (2007) provided the most current compilation and review of hydraulic testing results for the aquifers evaluated in this study. Results of hydraulic tests (Appendix 4) in new wells conducted during the current study are generally consistent with those in previous studies and show that K varies more than four orders of magnitude between hydrostratigraphic units and within individual hydrostratigraphic units between sites. Transmissivity (T), which is the product of K and aquifer thickness, follows similar variability to K.

Table 3. Summary of mineralogic analyses by x-ray diffraction. Reported as percentage.

		Calvert Fm	Piney Point Fm	Manasquan Fm	Vincent-town Fm	Horners-town Fm	Navesink Fm	Mt. Laurel Fm	Marshall-town Fm	Merchant-ville Fm	Magothy Fm
# of Observations		3	4	8	3	1	2	2	2	10	4
Mineral											
Illite-Smectite	min	1.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0
	mean	1.3	0.8	0.3	0.5	0.0	3.0	0.5	0.5	1.9	0.5
	max	2.0	2.0	1.0	1.0	0.0	3.0	1.0	1.0	5.0	2.0
Illite	min	4.0	0.0	0.0	0.0	1.0	13.0	1.0	1.0	0.0	0.0
	mean	5.7	3.0	7.0	2.0	1.0	21.0	3.0	1.5	10.2	2.3
	max	7.0	7.0	11.0	4.0	1.0	29.0	5.0	2.0	22.0	9.0
Glauconite	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mean	0.0	2.5	1.3	2.5	0.0	0.0	0.0	0.0	0.0	3.5
	max	0.0	6.0	4.0	5.0	0.0	0.0	0.0	0.0	0.0	14.0
Kaolinite	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mean	0.7	2.5	1.3	2.5	0.0	0.0	0.0	0.0	0.0	0.3
	max	2.0	6.0	4.0	5.0	0.0	0.0	0.0	0.0	0.0	1.0
Chlorite	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mean	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.3
	max	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0
Quartz	min	76.0	61.0	36.0	47.0	17.0	30.0	57.0	61.0	35.0	69.0
	mean	81.7	65.0	48.0	64.5	17.0	41.5	71.5	69.5	64.2	85.5
	max	85.0	71.0	62.0	82.0	17.0	53.0	86.0	78.0	95.0	96.0
Potassium-Feldspar	min	0.0	4.0	5.0	4.0	2.0	0.0	0.0	3.0	2.0	0.0
	mean	1.3	4.8	5.7	6.0	2.0	0.0	1.5	4.5	6.0	2.5
	max	4.0	5.0	6.0	8.0	2.0	0.0	3.0	6.0	8.0	7.0
Plagioclase-Feldspar	min	0.0	2.0	2.0	2.0	2.0	0.0	0.0	0.0	1.0	0.0
	mean	0.0	3.5	4.3	3.0	2.0	0.0	1.0	1.5	5.3	2.0
	max	0.0	7.0	6.0	4.0	2.0	0.0	2.0	3.0	9.0	6.0
Calcite	min	0.0	1.0	4.0	2.0	76.0	17.0	1.0	8.0	0.0	0.0
	mean	0.0	4.3	7.3	2.5	76.0	21.0	19.5	20.0	4.4	0.0
	max	0.0	10.0	12.0	3.0	76.0	25.0	38.0	32.0	14.0	0.0
Dolomite	min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mean	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.2	0.0
	max	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
Siderite	min	0.0	3.0	11.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0
	mean	0.0	7.3	20.3	15.0	2.0	0.0	3.0	0.0	3.0	0.5
	max	0.0	12.0	34.0	30.0	2.0	0.0	6.0	0.0	13.0	1.0
Pyrite+Marcasite	min	7.0	0.0	3.0	0.0	1.0	6.0	0.0	1.0	0.0	0.0
	mean	8.3	4.0	3.7	4.0	1.0	13.0	0.0	1.0	1.8	1.3
	max	10.0	10.0	4.0	8.0	1.0	20.0	0.0	1.0	9.0	4.0
Muscovite	min	0.0	0.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mean	0.0	5.0	7.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0
	max	0.0	8.0	7.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0

Table 4. Summary of total extractable metal (USEPA 3051) concentrations from Hc34-51 and Hd25-07. Additional data are presented in Appendix 3.

		Columbia Fm	Calvert Fm	Piney Point Fm	Manasquan Fm	Vincent-town Fm	Mt. Laurel Fm	Marshall-town Fm	Merchant-ville Fm	English-town Fm	Magothy Fm
Count		1	2	2	2	2	2	1	5	2	2
Element											
Arsenic	min	0.34	8.62	3.59	3.67	0.22	20.48	10.67	5.57	8.72	5.61
	mean	0.34	10.10	4.10	3.91	1.18	22.13	10.67	20.72	9.72	6.75
	max	0.34	11.58	4.62	4.15	2.15	23.78	10.67	43.45	10.71	7.90
Cadmium	min	0.09	0.33	0.06	0.19	0.07	0.04	0.22	0.05	0.06	0.02
	mean	0.09	0.43	0.09	0.25	0.15	0.49	0.22	0.12	0.07	0.08
	max	0.09	0.54	0.12	0.30	0.24	0.93	0.22	0.22	0.08	0.13
Chromium	min	2.31	14.77	55.53	55.37	5.05	194.76	33.98	21.38	19.05	11.07
	mean	2.31	15.46	68.19	111.08	19.88	196.49	33.98	48.36	32.66	17.51
	max	2.31	16.14	80.85	166.80	34.72	198.21	33.98	115.72	46.27	23.95
Copper	min	7.44	23.64	3.45	7.53	7.09	12.53	19.28	8.83	6.88	12.05
	mean	7.44	27.10	4.92	15.85	13.49	26.64	19.28	21.09	17.36	23.81
	max	7.44	30.57	6.38	24.16	19.89	40.74	19.28	38.93	27.84	35.58
Nickel	min	1.46	13.26	9.93	8.52	4.56	21.48	17.56	9.78	3.42	10.59
	mean	1.46	15.79	10.64	21.39	12.48	22.97	17.56	20.06	7.36	15.65
	max	1.46	18.32	11.36	34.27	20.40	24.46	17.56	37.59	11.31	20.72
Lead	min	1.61	10.30	8.48	7.29	3.47	10.18	7.86	4.86	4.34	6.19
	mean	1.61	12.52	9	7.68	5.18	10.45	4.86	11.45	6.50	11.02
	max	1.61	14.73	9.52	8.08	6.89	10.73	4.86	20.58	8.66	15.84
Silicon	min	207.04	530.43	1075.53	800.02	603.98	572.87	1650.90	420.38	940.74	691.29
	mean	207.04	590.13	1194.94	907.39	1018.84	695.34	1650.90	1002.90	1054.80	693.32
	max	207.04	649.84	1314.35	1014.80	1433.71	817.81	1650.90	1650.90	1168.90	695.35
Zinc	min	0.91	60.84	31.72	48.21	10.18	54.62	35.86	35.86	16.82	54.28
	mean	0.91	61.10	43.57	67.24	30.77	131.36	35.86	67.68	34.53	54.33
	max	0.91	61.36	55.42	86.26	51.36	208.11	35.86	90.20	52.25	54.37

Many of the wells in Dugan et al. (2008) and Metcalf & Eddy et al. (2007) have screens longer than 10 ft and are open to both the Columbia Formation and the immediately underlying lithostratigraphic unit (Mt. Laurel, Manasquan, or Vincentown Formations). In general, wells screened in the typically coarse-grained sediments of the Columbia aquifer and wells with screens open to the Columbia and one additional hydrostratigraphic unit (Mt. Laurel or Rancocas aquifers) generally have the largest average K values among the wells examined in this study. Wells screened in finer-grained sediments of the Columbia Formation, and wells with longer screens open to the Columbia and non-aquifer lithostratigraphic units tend to have smaller K values. K values vary more than one order of magnitude over relatively short distances (less than a few hundred feet). For wells constructed and/or tested during this study, K values much greater than the median (Appendix 4) were observed in the Columbia aquifer at sites 3 and 5.

Hydraulic properties of the Rancocas aquifer vary horizontally and vertically due to lithostratigraphic and sedimentologic factors (Table 6). Thickness varies significantly with location (McLaughlin and Velez, 2006; Dugan et al., 2008) because of the association of the aquifer with two lithostratigraphic units, the Vincentown Formation (lower) and Manasquan Formation (upper). These lithostratigraphic units have spatially variable compositions and thicknesses in the study area.

At site 2 (Fig. 2a), K values were smaller than the median in two wells in the Manasquan Formation sediments of the Rancocas aquifer. Sediments from this interval are muddy and cemented with carbonate. The underlying Vincentown Formation also is sandier than the Manasquan but has many carbonate-cemented intervals. Further testing that would help determine the water-bearing properties of the Vincentown Formation were not possible due to access problems that prevented installation of a well at the site of Hc34-51 (Fig. 2a), and the presence of thick, very hard, cemented zones precluded well construction at the site of Hc35-26 (Fig. 2a) due to cost concerns. Core samples of the Manasquan and Vincentown Formations were also very mud- and carbonate-rich at site 3,

Table 5a. Results of moisture, density, and porosity testing for Hc34-51. Vsam–sample volume; Vw–water volume; Vv–void volume; cm^3–cubic centimeter; g–gram; (1) assume quartz density; (2) assume mineral compensated density.

Site	Depth (ft bls)	Sample Identifier	Vsam (cm^3)	Vw/Vsam	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Porosity (1)	Vv-Vw (1)	Porosity (2)	Vv-Vw (2)
Hc34-51	61.9	110630-01	5.95	0.34	1.69	1.37	0.48	0.15	0.50	0.17
Hc34-51	102	110637-01	6.12	0.54	1.81	1.28	0.52	-0.02	0.54	0.00
Hc34-51	105.7	110639-01	6.06	0.53	1.76	1.23	0.54	0.01	0.55	0.03
Hc34-51	137.5	110648-01	5.95	0.34	1.68	1.35	0.49	0.15	0.51	0.17
Hc34-51	150	110655-01	6.12	0.57	1.30	0.72	0.73	0.15	0.74	0.16
Hc34-51	154	110657-01	6.12	0.33	1.64	1.32	0.50	0.17	0.52	0.19
Hc34-51	159.8	110660-01	6.23	0.32	1.61	1.29	0.51	0.19	0.53	0.21
Hc34-51	166	110664-01	6.17	0.32	1.62	1.29	0.51	0.19	0.53	0.21
Hc34-51	180.1	110672-01	5.95	0.34	1.73	1.38	0.48	0.13	0.50	0.15
Hc34-51	191	110676-01	6.06	0.42	2.00	1.58	0.40	-0.02	0.43	0.00
Hc34-51	217	110686-01	6.06	0.33	1.65	1.57	0.41	0.08	0.43	0.10
Hc34-51	269	110713-01	6.01	0.33	1.67	1.27	0.52	0.19	0.54	0.20
Hc34-51	299	110725-01	5.95	0.34	1.69	1.58	0.40	0.07	0.43	0.09
Hc34-51	305	110728-01	6.12	0.39	1.90	1.51	0.43	0.04	0.45	0.06
Hc34-51	324	110738-01	6.06	0.43	1.97	1.54	0.42	-0.01	0.44	0.01
Hc34-51	336	110744-01	6.12	0.37	1.76	1.39	0.48	0.10	0.49	0.12
Hc34-51	348.5	110750-01	6.01	0.46	2.10	1.64	0.38	-0.08	0.40	-0.05
Hc34-51	349	110751-01	6.01	0.33	1.68	1.33	0.50	0.16	0.51	0.18
Hc34-51	383.5	110769-01	5.95	0.34	1.69	1.36	0.49	0.15	0.51	0.17
Hc34-51	426	110783-01	5.95	0.34	1.70	1.36	0.49	0.15	0.51	0.17
Hc34-51	430	110785-01	6.12	0.33	1.79	1.46	0.45	0.12	0.47	0.14
Hc34-51	445.5	110789-01	6.17	0.36	2.21	1.86	0.30	-0.06	0.33	-0.03
Hc34-51	494.5	110809-01	5.95	0.34	1.69	1.34	0.49	0.15	0.51	0.17
Hc34-51	525.5	110827-01	6.12	0.33	1.90	1.57	0.41	0.08	0.43	0.10
Hc34-51	543	110838-01	6.23	0.32	1.62	1.43	0.46	0.14	0.48	0.16
Hc34-51	559.5	110846-01	6.12	0.37	2.02	1.66	0.37	0.01	0.40	0.03
Hc34-51	590.5	110863-01	6.12	0.31	1.90	1.59	0.40	0.09	0.42	0.11
Hc34-51	600.6	110870-01	6.12	0.33	1.64	1.35	0.49	0.16	0.51	0.18
Hc34-51	620.8	110875-01	6.06	0.37	2.00	1.64	0.38	0.02	0.40	0.04
Hc34-51	640	110887-01	6.06	0.42	1.94	1.53	0.42	0.01	0.44	0.03
Hc34-51	646	110891-01	6.17	0.32	1.63	1.35	0.49	0.17	0.51	0.19
Hc34-51	660	110899-01	6.12	0.42	1.83	1.41	0.47	0.05	0.49	0.07
Hc34-51	696.3	110917-01	6.06	0.34	1.69	1.39	0.48	0.14	0.49	0.16
Hc34-51	718.6	110930-01	6.12	0.33	1.67	1.34	0.49	0.16	0.51	0.18
Hc34-51	726.9	110934-01	6.12	0.33	1.64	1.32	0.50	0.18	0.52	0.19
Hc34-51	730	110936-01	5.95	0.40	1.90	1.49	0.44	0.03	0.46	0.05
Hc34-51	734.9	110938-01	5.95	0.34	1.68	1.76	0.34	0.00	0.36	0.02
Hc34-51	750	110944-01	6.01	0.39	1.97	1.59	0.40	0.01	0.42	0.04
Hc34-51	754.9	110946-01	6.01	0.34	1.67	1.33	0.50	0.16	0.52	0.18
Hc34-51	756	110947-01	6.01	0.79	2.51	1.72	0.35	-0.44	0.38	-0.42
Hc34-51	760	110949-01	6.06	0.36	1.83	1.47	0.45	0.09	0.47	0.11
Hc34-51	763.3	110950-01	5.95	0.34	1.70	1.46	0.45	0.11	0.47	0.13
Hc34-51	766.4	110952-01	5.95	0.34	1.68	1.36	0.49	0.15	0.51	0.17

Table 5b. Results of moisture, density, and porosity testing for Hd25-07. Vsam–sample volume; Vw–water volume; Vv–void volume; cm^3–cubic centimeter; g–gram; (1) assume quartz density; (2) assume mineral compensated density.

Site	Depth (ft bls)	Sample Identifier	Vsam (cm^3)	Vw/Vsam	Wet Density (g/cm^3)	Dry Density (g/cm^3)	Porosity (1)	Vv-Vw (1)	Porosity (2)	Vv-Vw (2)
Hd25-07	69.5	110112-01	6.20	0.59	1.70	1.11	0.58	-0.01	0.60	0.00
Hd25-07	71.4	110113-01	5.90	0.54	1.77	1.23	0.54	-0.01	0.55	0.01
Hd25-07	101.3	110127-01	6.20	0.55	1.66	1.11	0.58	0.03	0.60	0.05
Hd25-07	103.3	110128-01	5.90	0.56	1.59	1.03	0.61	0.05	0.62	0.07
Hd25-07	375.9	110255-02	5.90	0.50	2.01	1.51	0.43	-0.07	0.45	-0.05
Hd25-07	376.7	110255-01	6.20	0.48	1.94	1.46	0.45	-0.03	0.47	-0.01
Hd25-07	377.2	110256-01	6.10	0.47	1.89	1.42	0.46	0.00	0.48	0.02
Hd25-07	394.7	110266-01	6.20	0.46	1.94	1.47	0.44	-0.02	0.47	0.00
Hd25-07	424.2	110282-01	5.88	0.44	1.98	1.54	0.42	-0.02	0.44	0.00
Hd25-07	444	110290-01	5.97	0.44	1.94	1.50	0.44	-0.01	0.46	0.01
Hd25-07	446.5	110291-01	5.90	0.43	1.87	1.44	0.46	0.03	0.47	0.05
Hd25-07	449.4	110293-01	5.90	0.43	1.90	1.47	0.45	0.01	0.47	0.03
Hd25-07	484.7	110315-01	5.90	0.36	2.03	1.67	0.37	0.01	0.39	0.04
Hd25-07	490	110318-01	5.95	0.31	1.82	1.51	0.43	0.12	0.45	0.14
Hd25-07	516	110332-01	5.95	0.32	1.94	1.61	0.39	0.07	0.41	0.09
Hd25-07	613	110385-01	5.95	0.29	1.83	1.54	0.42	0.13	0.44	0.15
Hd25-07	661.1	110408-01	6.06	0.36	2.00	1.63	0.38	0.02	0.41	0.04
Hd25-07	662.2	110408-02	6.01	0.36	1.99	1.64	0.38	0.02	0.41	0.05
Hd25-07	678	110415-01	5.95	0.38	2.07	1.69	0.36	-0.02	0.39	0.01
Hd25-07	686	110420-01	6.01	0.39	2.03	1.64	0.38	-0.01	0.40	0.01
Hd25-07	707.2	110430-01	5.95	0.45	1.98	1.53	0.42	-0.03	0.44	-0.01
Hd25-07	723	110436-01	5.95	0.39	1.92	1.53	0.42	0.03	0.44	0.05
Hd25-07	742	110442-01	5.95	0.42	2.01	1.58	0.40	-0.02	0.42	0.00
Hd25-07	751.6	110448-01	6.23	0.40	2.12	1.72	0.35	-0.05	0.37	-0.02
Hd25-07	809.75	110480-01	6.12	0.37	1.92	1.55	0.42	0.04	0.44	0.07

and led to the decision not to install a well into the Vincentown at this site.

Core samples and geophysical logs at Gc52-15 show that much of the Rancocas aquifer (lower half of the Manasquan Formation and all of the Vincentown Formation) is very sandy but contains many intervals where carbonate cement and concretions are ubiquitous. Millimeter- to centimeter-size solution cavities are present in some samples, and some of the cavities contain sparry carbonate indicating that precipitation of carbonate occurred after formation of the cavities. Cement and concretions could limit the water-bearing properties of the aquifer unless solution cavities or other more porous zones are connected between cemented intervals. Hydraulic fracturing techniques also may improve well yields in cemented zones of the aquifer.

Geologic heterogeneity also can impart hydraulic characteristics that are favorable for high-yielding wells in the Rancocas aquifer. The Rancocas at site 4 is much thicker than other sites because sandy beds of the Manasquan Formation are stacked on sandy beds of the Vincentown Formation. Cemented beds are less common at site 4 and are much less common than at sites 2 and 3 and Gc52-15. The combination of a high K value and large aquifer thickness at site 4 indicates that the Rancocas aquifer may yield many hundreds of gallons per minute to a properly constructed well. Greater than average K also occurs at sites 1 and 6 (Fig. 1) and at well Hc11-13. Stacking of sandy beds most likely accounts for the higher than average specific capacity of public water-supply wells in the Rancocas aquifer at Townsend (Dugan et al., 2008). Available drillhole, corehole, and hydraulic data generally show that a zone capable of supporting high-yielding wells is restricted to areas north of Smyrna and west of Route 1. More precise definition of this zone would require additional test drilling and hydraulic testing.

Results of slug tests in six new wells constructed in the Mt. Laurel aquifer for this study and one existing well that was redeveloped and retested for this study supplement core observations from this study and hydraulic testing data compiled in Dugan et al. (2008). K and transmissivity (T) values estimated for the Mt. Laurel aquifer range from poor to excellent for K and T (Table 6, Appendix 4) and vary horizontally and vertically due to geologic heterogeneities within the Mt. Laurel Formation.

Causes for variability of K values in the Mt. Laurel aquifer are well illustrated by comparison of data from sites 3 and 5 and McLaughlin and Velez's (2006) maps of the distribution of aquifer-quality sands. At both sites natural gamma radiation and electric geophysical logs are consistent with an interpretation of aquifer-quality sand in the Mt.

Table 6. Estimated water-bearing properties at sites 1 through 8. Transmissivity is estimated from results of hydraulic tests and aquifer thickness.

Aquifer	Site	Site Name	Thickness (ft)	Estimated Transmissivity (ft^2/day)
Columbia	1	Blackbird State Forest - Peters Tract	22	130
	2	Smyrna	43	4300
	3	Woodland Beach	40	13000
	4	Blackbird State Forest - Tybouts Tract	36	8600
	5	Cedar Swamp Wildlife Area	26	550
	6	Wiggins Mill Park	18	950
	7	Water Farm 1	20	760
	8	Water Farm 2	38	2700
		Median	31	1825
Piney Point	3	Woodland Beach	139	74
Rancocas	1	Blackbird State Forest - Peters Tract	107	7100
	2	Smyrna	97	120
	3	Woodland Beach	71	85
	4	Blackbird State Forest - Tybouts Tract	170	13900
	5	Cedar Swamp Wildlife Area	121	1300
	6	Wiggins Mill Park	120	6700
	7	Water Farm 1	115	2800
	8	Water Farm 2	51	2600
		Median	111	2700
Mt. Laurel	1	Blackbird State Forest - Peters Tract	81	290
	2	Smyrna	63	140
	3	Woodland Beach	106	1400
	4	Blackbird State Forest - Tybouts Tract	80	4500
	5	Cedar Swamp Wildlife Area	95	22000
	6	Wiggins Mill Park	68	5200
	7	Water Farm 1	81	2200
	8	Water Farm 2	61	610
		Median	81	1800
Magothy	2	Smyrna	*35*	4
	3	Woodland Beach	30	3
	6	Wiggins Mill Park	17	0.05
	7	Water Farm 1	27	0.08
	8	Water Farm 2	43	1200
		Median	30	3

Laurel Formation. The measured K at site 3 is consistent with a moderately permeable aquifer; however, T is more than an order of magnitude greater at site 5 (Table 6). Sands in the Mt. Laurel Formation at site 3 are extensively bioturbated with clay-lined and clay-filled burrows and contain a relatively high proportion of carbonate. Neither bioturbation or cementation can be unequivocally interpreted from the cutting samples and geophysical logs available to McLaughlin and Velez (2006) or to this study at site 5. Both bioturbation and cementation are expected to reduce porosity and a probable cause of the less permeable K values commonly observed in the Mt. Laurel aquifer. The greater than average K observed in the Mt. Laurel aquifer at site 5 is inferred to be due to the coarser grained, less silty and less cemented character of sediments at that site.

Information on the hydraulic and hydrologic characteristics of the Magothy Formation in Delaware is generally lacking, and previous workers (USACE, 2007; He and Andres, 2011) have interpreted that the Magothy Formation and upper Potomac aquifer function as a single hydrologic unit. Much of the previously known information about the Magothy aquifer as a viable water source in Delaware comes from wells in the Town of Middletown. Hydraulic data (Dugan et al., 2008) and water-use data (He and Andres, 2011) indicate the presence of an aquifer capable of supporting moderate capacity wells (approximately 432,000 gallons per day (kgpd) or 300 gallons per minute). A few additional public-supply wells located between Middletown and the Chesapeake and Delaware Canal are allocated to pump less quantities (36 to 244 kgpd) from the Magothy aquifer (WSCC, 2006), although reported water use from these wells is much smaller than the allocated use (He and Andres, 2011).

McKenna et al. (2004) postulated that the Magothy Formation functions as an aquifer only over a limited geographic extent, likely only in areas where post-Potomac Formation erosion created conditions where sands of the Magothy Formation could accumulate and be preserved. The present study supports this interpretation. Only at site 8, generally located within the area where the Magothy aquifer is pumped for water supply, did sediment samples and K testing (Table 6, Appendix 4) indicate the presence of water-

Table 7. Watershed and streamflow statistics. mi²–square miles; cfs–cubic feet per second.

Station Name	Station Identifier	Watershed Area (mi^2)	Period of Record	Minimum Flow (cfs)	Average Flow (cfs)	Maximum Flow (cfs)	Minimum Baseflow (cfs)	Average Baseflow (cfs)	Maximum Baseflow (cfs)	Unit Flow (cfs/mi^2)	Unit Baseflow (cfs/mi^2)	Baseflow/ Total Flow
Blackbird Creek	1483200	4.06	Oct 1956 to present	0	4.97	397	0	3.05	35.15	1.22	0.75	0.61
Dove Nest Branch	1483170	4.68	Oct 1978 to Sept 1980 Oct 2003 to Sept 2004 Apr 2012 to June 2014	1.6	5.26	120	1.77	3.65	19.49	1.12	0.78	0.69
Spring Mill Branch	1483165	1.79	Oct 2000 to Sept 2004 Apr 2012 to June 2014	0.2	2.93	100	0.19	2.18	9.38	1.64	1.22	0.74
Tributary to Silver Lake	1483155	2	Apr 2001 to present	0.63	2.94	117	0.55	2.12	16.4	1.47	1.06	0.72

Figure 15. Simple planar fracture from Calvert Formation, 61.7 ft bls at Gc52-15. Core oriented with down toward right.

bearing sands in the Magothy Formation. Sandy beds in the Magothy Formation at site 8 were about 15-ft thick and indicate that the aquifer is transmissive enough to support a moderate (less than 432 kgpd) yielding well. K values at sites 6 and 7 (Table 7) are inconsistent with interpretation of the presence of aquifer materials at those locations. Core samples from sites 2 and 3 also exposed fine-grained and carbonate-cemented sediments that would be expected to result in very low K and T at these sites, probably similar to K values observed at sites 6 and 7. The lack of aquifer materials and the significant expense of installing wells to a depth greater than 700 ft precluded the installation of wells in the Magothy Formation at sites 2 and 3. Similarly, an expectation of a lack of aquifer-quality sediments and projected well depths near 600 ft led to the decision not to install wells in the Magothy Formation at sites 1, 4, and 5.

The interpretation that the Magothy Formation functions as an aquifer over a limited geographic extent is also consistent with observations of well drillers and previous unpublished DGS interpretations of geophysical logs. In many cases, well permits indicate that well drillers plan to install wells in the Magothy aquifer; however, drillers will instead complete wells in an underlying aquifer in the Potomac Formation because drill cuttings and geophysical logs indicate that the Magothy Formation is not sandy and thick enough to support a well with the desired capacity. T values are likely to be more than an order of magnitude smaller than those reported by Dugan et al. (2008) over a substantial portion of the study area. As a result, the Magothy Formation would not be capable of supporting water-supply wells over a large portion of the study area and the Groot et al. (1983) estimate of 3 million gallons per day water availability from the Magothy aquifer is likely a gross overestimate.

Deformation Features

Deformation features were noted in muddy sediments in the four wireline cores installed in this study. Using terminology of Shultz and Fossen (2008), the features are discontinuities that can be classified as joints and fractures. The intensity (density) of joints and fractures varies from single thin (less than few mm) planar features (Figs. 15-17), which fit the definition of a sharp discontinuity, to intersecting, thin planar to curving features, to thicker (15-30 cm) brecciated zones (Fig. 18), which fit the definition of a tabular discontinuity. Fracture lengths range from less than 1 mm (microfractures) to sizes larger than the core (6-8 cm). Deformation features that suggest drilling-induced deformation or rotation around a vertical axis and intrusion of drilling fluids are not present (Lundberg and Moore, 1986; Leggette, 1982).

The orientation of joint and fracture surfaces range from near horizontal to approximately 75 degrees from horizontal (Figs. 15-18). Surface textures on joint and fracture surfaces vary from hackly and plumose, to shiny and waxy with risers and steps associated with microfractures (Blenkinsop, 2000), to slickenlines that can be traced over the entire fracture surface. The slickenlines typically are oriented sub-parallel to the core axis. Many of the slickenlines have step-like terminations that indicate normal offset, but others have no features that indicate sense of motion.

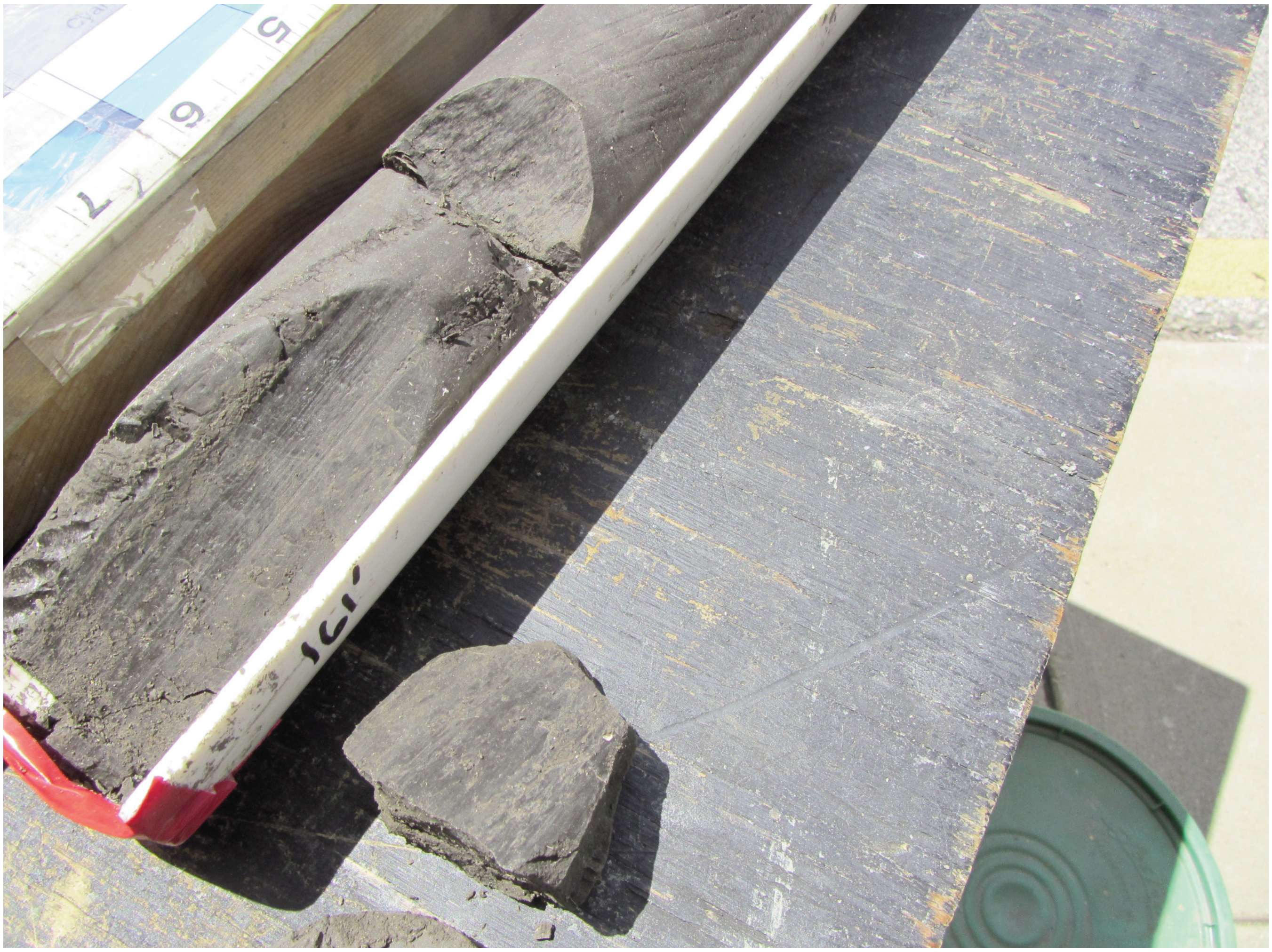

Figure 16a. Slickenlines in sample from 161 feet bls at site 3 (Hd25-07). a) Two fault surfaces are present in this photo. The chunk of sediment located to the right of the core was flipped over from its original position in the core sample just to the left. Numbers on scale are showing tenths of feet, sub-divisions are hundredths of ft.

The combination of fracturing, waxy surfaces, and slickenlines has been observed in fault (shear) zones and surrounding damaged zones in mud-rich sediments and sedimentary rocks from faulted, semi-consolidated sediments in California (Schleicher et al., 2006; Schleicher et al., 2010; Carpenter et al., 2011) and in ocean-bottom cores (Expedition 333 Scientists, 2012; Vannucchi et al., 2012). Miller et al. (1990, Fig. 1) note a microfault in a core from Coastal Plain sediments in New Jersey but the deformation fabrics in the fault zone were not described. Andres and Howard (1998) noted displacements on the order of 0.1 to 0.3 ft of bedding and diagenetic features in sandy sediments of the Calvert Formation at depths greater than 30-ft bls in an excavation (Id11-a) approximately 4.3 miles south of Hc35-25.

Deformation features in sandy sediments are probably present, but poor core recovery in sand intervals prevented their detection. Multiple studies (Owen, 1987, 1996; Bense et al., 2003; Sverdrup and Bjorlykke, 1999; Heynekamp et al., 1999) of outcrop exposures of fault zones have documented that deformation styles in faulted, unconsolidated sandy sediments differ from those in muddy sediments. The lack of cohesiveness of sandy sediments does not permit the formation of striae. Liquefaction and fluidization in response to stresses during faulting tend to reorganize sand grains (Owen, 1996). These processes also tend to erase depositional structures and diagenetic features typically used to infer the presence of a fault and sense of fault motion in small diameter cores. Liquefaction is a common problem when wireline coring in sandy sediments, leading to poor recovery of cored sections and difficulty in preserving sedimentary, diagenetic, and structural features for observation. Acoustic televiewer and micro-resistivity logging techniques have the potential to image bedding, fractures, cementation, and other features in the corehole wall that could be used to infer the presence of structural fabrics in unconsolidated sandy sediments.

There are no markers in our cores that indicate fault offset. Detailed biostratigraphic, magnetostratigraphic, and chronostratigraphic analyses could be used to estimate offset, although the faults are in a part of the stratigraphic record that regionally has produced few fossils suitable to resolve the offset question (Kenneth Miller, oral communication, 2012).

In Hc34-51 (site 2a), one zone between 157 and 162 feet below land surface (bls) in the Calvert Formation shows

Figure 16b. Reflected light photomicrograph of slickenlines and perpendicular fractures on footwall. Down towards bottom of photo. Scale is in mm.

multiple fracture surfaces and breccia and another zone at about 251 feet bls in the Shark River Formation has a single fracture. Multiple cores from Hd25-07 (site 3) have brecciated material and fracture surfaces between about 137 and 162 feet bls in the Calvert Formation. Multiple fractures were also found in cores from Hc35-25, at 90-95, 115-120, and 130-135 ft bls in the Calvert Formation, and at 260-270 ft bls in the Shark River Formation. The zones at 130-135 and 260-270 ft bls were partially brecciated by an intersecting pair of fractures, one near horizontal and the other cutting the core at about 60 degrees.

Deformation features at all three sites occur within muddy sediments of the Calvert Formation just above the contact with Piney Point Formation. At Hc35-25 (site 2b), the shallowest fracture zone occurs just below coarse sands and fine gravels of the Cheswold sand. The coring process partially liquefied the coarse-grained material obliterating any faults or fractures that may have been present. In the future, acoustic televiewer logging techniques could be used to image bedding, fractures, cementation, and other features in the corehole wall and could show structural fabrics in the Cheswold sands and other loose, unconsolidated sandy sediments.

The association of carbonate cemented zones in the Vincentown Formation near structural features in the overlying units at sites 2 and 3 could indicate that circulation of hypogene or diagenetic fluids through faults had a role in cementation. Carbonate cementation associated with fault zones is present in many sedimentary basins and, in cases where carbon in the cement is isotopically light, has been interpreted as evidence for upward migration of deep groundwater (Sverdrup and Bjorlykke,1999; Eichhubul et al, 2009; Rawling et al., 2001; Appold et al., 2007; Boles et al, 2004). The association of carbonate dissolution features in the Manasquan and Vincentown Formations and faults in the overlying units could also indicate that dissolution has been significant enough to thin the Manasquan and Vincentown Formations, and subsequently cause fractures and faults in the overlying units. This process has occurred on a much larger scale in similar age sediments in Florida (Cunningham, 2014, 2015; Reese and Cunningham, 2014)

The association of structural features, cemented zones, and solution cavities is relevant to evaluation of water resources in Delaware Coastal Plain aquifers because it likely influences the water-bearing characteristics of

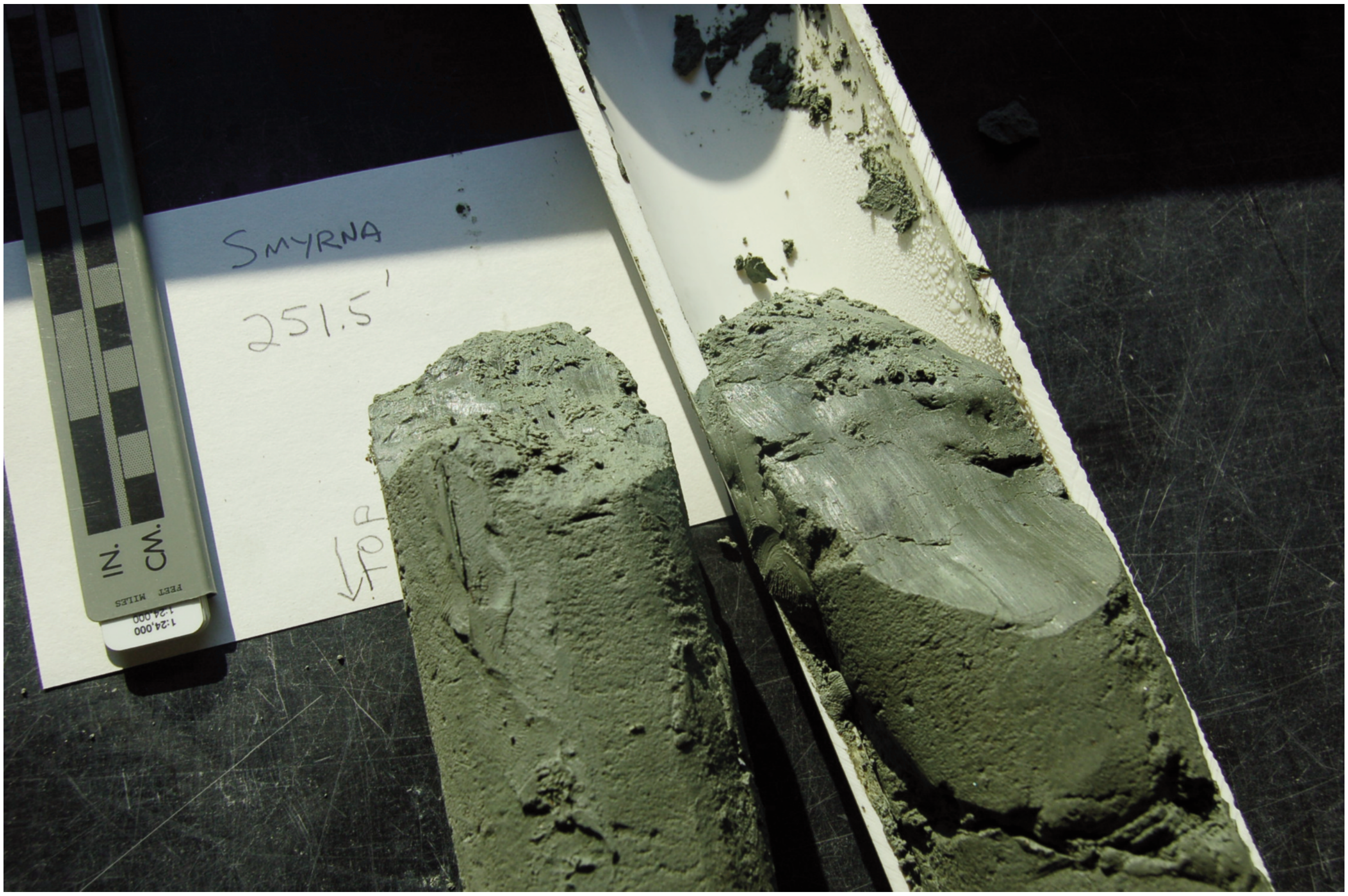

Figure 17. Slickenlines in sample from 251 feet bls, at site 2a (Hc34-51). The fault occurs in muddy sediment of the Shark River Formation. This photo was taken just after cleaning the core following its removal from the ground. Scale bar is showing inches and centimeters.

aquifers. K and T of the Rancocas and Mt. Laurel aquifers range from moderately to highly permeable and transmissive north of Smyrna to less permeable and transmissive south of Smyrna (Dugan et al., 2008, this study). The degree to which structures and cementation affect hydraulic properties relative to sedimentology cannot be determined from available information.

Weathering features such as oxidized iron on joint, fracture, and fault surfaces varies with depth and location. A distinct lack of weathering on many surfaces indicates that these fractures are not open to flow of oxidizing fluids. Small (less than 1mm) yellow- to orange-brown, plumose, irregularly shaped to elongated features suggestive of secondary iron oxides were observed on fracture surfaces of some samples from the Calvert Formation. Sample 112889 (61 ft bls in core Gc52-15) displays a simple fracture oriented 60 degrees from vertical but shows no slickenlines (Fig. 18). The features in this sample are three-dimensional, indicating that the secondary minerals formed after fracturing. The long axes of some of the features are oriented parallel to the fracture dip, indicating that mineral growth occurred in the presence of the stress field that caused the fracture.

Early groundwater and geologic investigations noted changes in slopes of contacts and thicknesses of post-Hornerstown Formation lithostratigraphic units (e.g., Marine and Rasmussen, 1955; Jordan, 1962). These trends have been confirmed and more recent studies have refined the location of the area where the thickening occurs to the vicinity of Smyrna. Benson and Spoljaric (1997) and Andres (2001) interpreted these thickening trends as evidence of growth-style faulting and noted the associations between these trends and the occurrences of aquifers and confining beds. Conversely, McLaughlin and Velez (2006) rejected the fault hypothesis and attributed the slope and thickness trends to the configuration of the shallow ocean basin during deposition of the Deal and Shark River Formations and to erosion of the Piney Point, Shark River, Deal, and Manasquan Formations prior to deposition of the Calvert Formation. Data collected during this project clearly show the presence of faulting but are not sufficient to determine the degree to which geologic structures control the observed thickening trends.

Groundwater Levels and Weather

Long-term precipitation stations near the study area are operated by the Delaware Environmental Observation System (DEOS) and the National Weather Service (NWS) at Dover (DEOS-DDFS) and Wilmington, Delaware (NWS-ILG). Several additional stations operated by the DEOS are located within or close to the study area but have shorter records. Precipitation amounts at NWS-ILG and DEOS-DDFS from May 2012 – April 2014 did not indicate extremely wet or dry conditions, with precipitation at NWS-ILG nearly 6.4 inches above the long-term annual normal, and just 0.1 inch below annual normal at DEOS-DDFS. Some months were wetter than normal. In late October 2012 (Hurricane Sandy) and

Figure 18. Breccia and slickenlines in sample from 141 feet bls at site 3 (Hd25-07). The chunk of sediment was flipped over from its original position in the core marked by the red pen. Numbers on scale bar are showing tenths of ft, sub-divisions are hundredths of ft.

June 2013 measured precipitation was more than six inches above normal at DEOS-DDFS and nearly 10 inches above normal at NWS-ILG.

Groundwater Hydrograph and Temperature Response to Weather and Tides

Hydrographs illustrate relationships between recharge and flow. Further, the term hydraulic diffusivity (D), which is the ratio between K and specific storage (Ss), and Ss being positively correlated to the compressibility of geologic materials (Freeze and Cherry, 1979) explains how the amplitudes of hydrograph response typically decay with time and with distance from the point of recharge. In the Coastal Plain of Delaware, the range of water-level fluctuations in deeper confined parts of an aquifer is usually less than those in the unconfined recharge area of that same aquifer. A time lag usually exists between the maximum water level in the deeper confined part of the aquifer compared to the recharge area. Aquifers with higher D will show more rapid and greater responses to recharge events than aquifers with lower D in the same event. In practice, the interpretation of D of an aquifer is highly complex because the terms K and Ss are each dependent on many additional terms that describe the poro-mechanical properties of a material (Merritt, 2004; Knudby and Carrera, 2006).

Unless noted otherwise this discussion refers to wells not affected by pumping. A majority of the sites in this study were located in areas where head fluctuations were controlled by weather and/or tidal forces. Head fluctuations in confined-aquifer wells at site 5 (Gd33-08 Rancocas and 09 Mt. Laurel; Fig. 19) and site 3 (Hd25-09 Piney Point; Fig. 19) are near bodies of tidally affected surface water that reflect the diurnal tide of Delaware Bay and tidal tributaries. The amplitudes of head fluctuations range from a few hundredths of a foot to a few tenths of a foot, much less than the amplitude of the diurnal tide in Delaware Bay. At site 5, there is a change in amplitude and phase lag in the tidal fluctuations between the Rancocas and Mt. Laurel aquifers. The shallower Rancocas aquifer responds to bay tides before the Mt. Laurel, and is thought to be a result of the shallower depth. Interestingly, the tidal amplitude is greater in the Mt. Laurel aquifer than the Rancocas. We believe that this is due to the more transmissive character of the Mt. Laurel at this site. At site 3, the Piney Point aquifer at a depth of 165-175 ft bls shows a tidal fluctuation, but the Mt. Laurel aquifer does not. It is likely that the presence of several hundred feet of confining unit between the aquifer and surface water at that site dampen the tidal signal of the bay. Delaware Bay tidal data are not collected near sites 3 and 5 and thus not adequate to compute tidal efficiency and other aquifer hydraulic parameters at these wells. Simulation of tidal data is beyond the scope of this study.

Monthly mean water levels and the annual range of mean monthly water levels observed in the Columbia aquifer in well Hb14-12 (Fig. 20) during the study period (July 1, 2012 through February 28, 2014) are slightly below the median (average 0.82 ft less, range 0.1 ft less) for the period of record (1957-present). Seasonal head changes in other wells screened in the Columbia aquifer (Table 2, Figs. 21a-b) have similar ranges (2.1 to nearly 4.9 ft) during the current study. No detectable trends during the period of record are evident in annual mean and minimum water levels in well Hb14-12. Annual maximum water levels in this well have a significant (alpha-0.01) upward trend as determined by a Mann-Kendall test.

The response of the Columbia aquifer to seasonal recharge patterns seems to be dependent on depth to water table (DTW). Wells with depths to water of less than 15 ft (Gb55-08, Hb12-05, Hb14-12, Hd25-11, Figs. 20, 21b) show water-level fluctuations that are generally consistent with expected trends of seasonal recharge in winter and early spring followed by slowly declining water levels during the growing season (Andres, 2001; Talley, 1998). Water levels in wells with DTWs greater than 15 ft (Fb23-29, Fb24-15, Fb54-09) show smaller annual ranges and a delayed rise several months later than wells with shallower depths to water. Water-level fluctuations in wells with greater depths to water also appear to have much lower frequencies. The smoother water-level response indicates that recharge is slower in areas with DTWs greater than 15 ft than in areas with DTW less than 15 ft, almost certainly due to the diffusive effects of the greater thickness of the vadose zone.

The timing and magnitude of recharge responses to storm events also are associated with DTW (Fig. 22). Significant increases in water elevations (1.5 to 2.7 ft in a few days) indicate groundwater recharge occurred in wells Gb55-08, Hb12-05, and Hd25-11 following Hurricane Sandy (October 29-31, 2012) as well as following multiple consecutive months of above normal precipitation from June-August 2013. The responses of Fb23-38, Fb24-15 and Fb54-09 to Sandy, having much greater DTW, are less than 0.5 ft.

Fluctuations in mean daily water levels in the Columbia aquifer at site 3 (Hd25-11, Fig. 21a) are more pronounced than in most other wells in the unconfined aquifer and correspond to fluctuations in mean daily tide levels at the Reedy Point, Delaware tide station (NOAA 8551910). Hd25-11 is approximately 1200 ft from the tidal marsh indicating that tidal fluctuations are affecting groundwater levels in the unconfined aquifer at considerable distances from Delaware Bay (nearly 2 miles to the east).

Groundwater temperature and temperature fluctuations have been used to identify recharge periods, the degree of aquifer confinement, and to trace movement of water masses (Anderson, 2005). In this study, groundwater temperatures in wells screened in the Columbia aquifer, with DTWs greater than 15 ft (Fb23-29, Fb24-15, Fb54-09), showed smaller annual ranges than wells with shallower DTWs and showed no significant responses to individual storm events. This provides further confirmation that recharge to the water table is slower in areas with DTWs greater than 15 ft, an effect that is almost certainly due to the greater thermal diffusivity of the vadose zone.

Head Response in the Mt. Laurel and Rancocas Aquifers

Seasonal head changes in wells in the Rancocas aquifer (Fig. 21c) are generally larger than head changes in the Mt. Laurel aquifer (Fig. 21d). The expected trend of decreasing range of head change with increasing aquifer depth (associated with decreasing water elevation and increasing distance from the recharge area) was not observed at sites 2 (Hc34-43, Hc35-26, 27) and 8 (Fb23-71) and is likely due to a combination of effects of pumping, spatially variable recharge, and spatially variable patterns of D. Seasonal head changes in the Rancocas aquifer are similar to those observed in the Columbia aquifer at all sites except 5 (Gd33-09). Seasonal

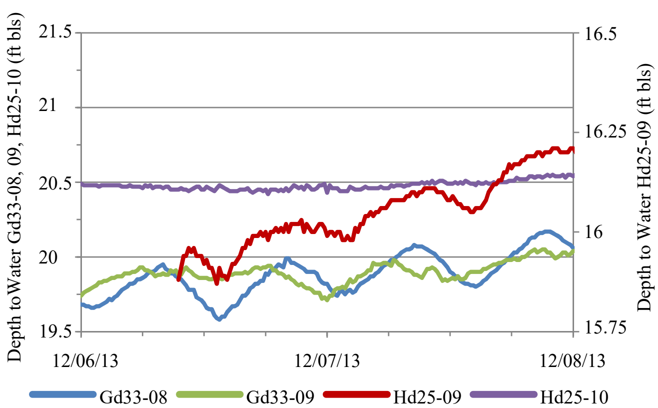

Figure 19. Hydrograph showing tidal fluctuations at site 3 (Hd25-09 and 10) and site 5 (Gd33-08 and 09).

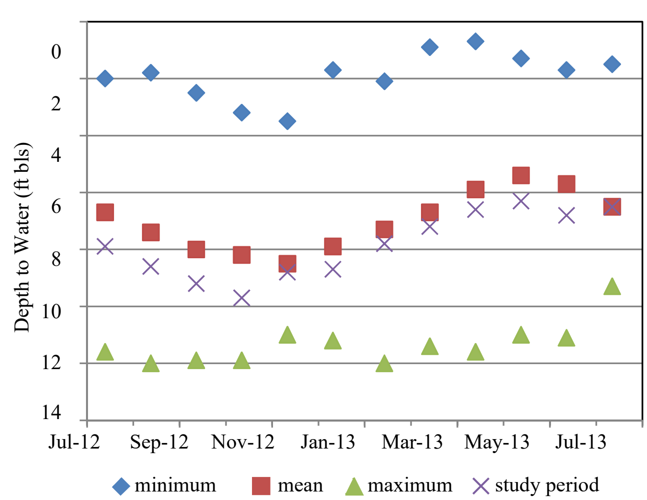

Figure 20. Hydrograph of historical monthly minimum, mean, and maximum water levels, and monthly mean water levels from well Hb14-12.

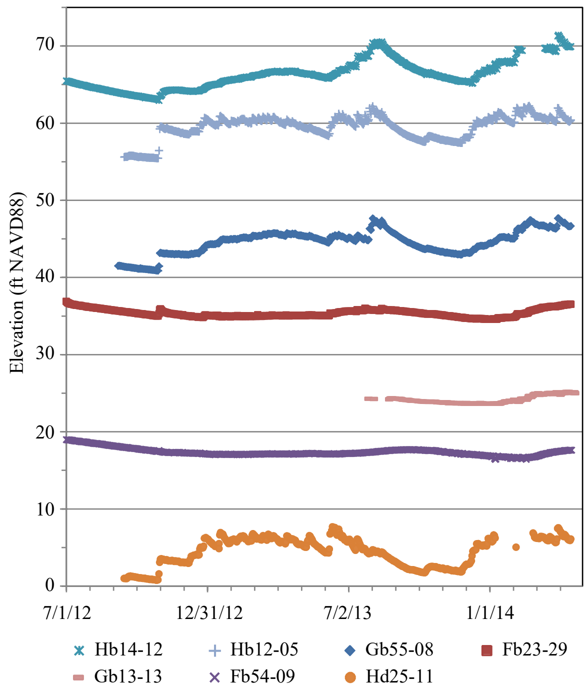

Figure 21a. Hydrographs for wells in the Columbia aquifer (elevation).

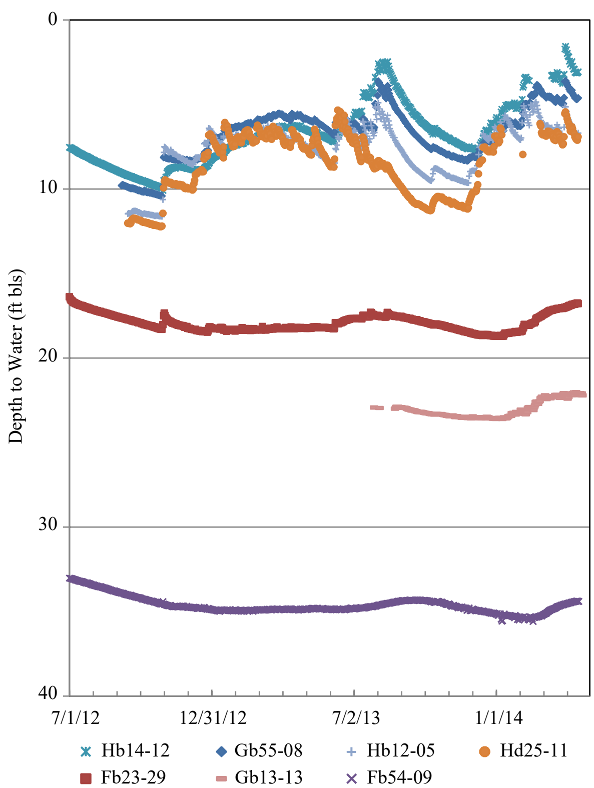

Figure 21b. Hydrographs for wells in the Columbia aquifer (depth to water).

and annual head changes in wells in the Mt. Laurel aquifer are similar to those observed in the Columbia aquifer at all sites except 3 (Hd25-10) and 5 (Gd33-08).

Except for sites 3 (Hd25-10) and 5 (Gd33-08, 09), the Rancocas and Mt. Laurel aquifers exhibit higher frequency (e.g., less than 1 month) water-level fluctuations similar to wells in the Columbia aquifer where DTWs are greater than 15 ft. Water levels in these aquifers also respond to storm events that cause recharge in the Columbia aquifer. However, the magnitudes of the water-level responses to storms are on the order of hundredths to a few tenths of a foot in the Rancocas and Mt. Laurel aquifers. Additional analysis is needed to determine if this phenomenon is related to spatial variability of D, or to hydrostatic loading by additional water in the Columbia aquifer.

Spatial variability of head responses in the Rancocas and Mt. Laurel aquifers provide further indication of spatial heterogeneity in hydraulic properties (e.g., K, Storage (S), and D) of these aquifers. For example, there are no consistent associations between the timing and magnitude of water level responses and location of the well with respect to distance from updip recharge areas, aquifer elevation, aquifer thickness, K at an individual well, and groundwater elevation. In a homogeneous aquifer, wells exhibiting larger seasonal and annual head-change amplitudes would typically be located in parts of the aquifer that are spatially closer to the recharge area. The case where wells at greater depths and distances from the recharge area are showing faster and larger water-level responses implies that there is a better hydraulic connection between the wells and a recharge area, possibly through zones of greater D. It is not certain if the high D zones are oriented vertically or horizontally. If the zones of high D are oriented vertically, it is likely that they are associated with structural features (i.e., faults and joints) that have increased K and/or decreased Ss, as drillholes have not detected large sedimentary features that cut across confining beds and aquifers. Horizontal orientation of high D zones would imply that there are large-scale sedimentologic features that connect updip recharge zones to downdip portions of the aquifer.

Pumping Effects

Water-level fluctuations in wells Fb23-70 (Magothy aquifer, site 8), Fc42-11 (Mt. Laurel aquifer, site 7), Hc34-50 (Columbia aquifer, site 2), and Zz63-540 (Rancocas aquifer) are likely influenced by nearby pumping wells (Figs. 21a, 21c, 21d, and 21e). Wells Hc34-50 and Fc42-11 are near public water-supply wells and have day-to-day head fluctuations in excess of 5 ft. Water-supply wells in the Magothy aquifer are located in Middletown about 2 mi (3.3 km) from Fb23-70 (site 8). In addition, Fb23-70 is in a large regional zone of drawdown (dePaul et al., 2008) and is likely responding to multiple wells that pump the Magothy and the upper Potomac aquifers (USACE, 2007). Well Zz63-540 is in an area where irrigation is significant (D. Drummond, Maryland Geological Survey, oral communication). The hydrograph for well Zz63-540 shows daily variations of as much as 2.6 ft daily during the irrigation season in 2012, while fluctuations of a few hundredths of a foot are observed

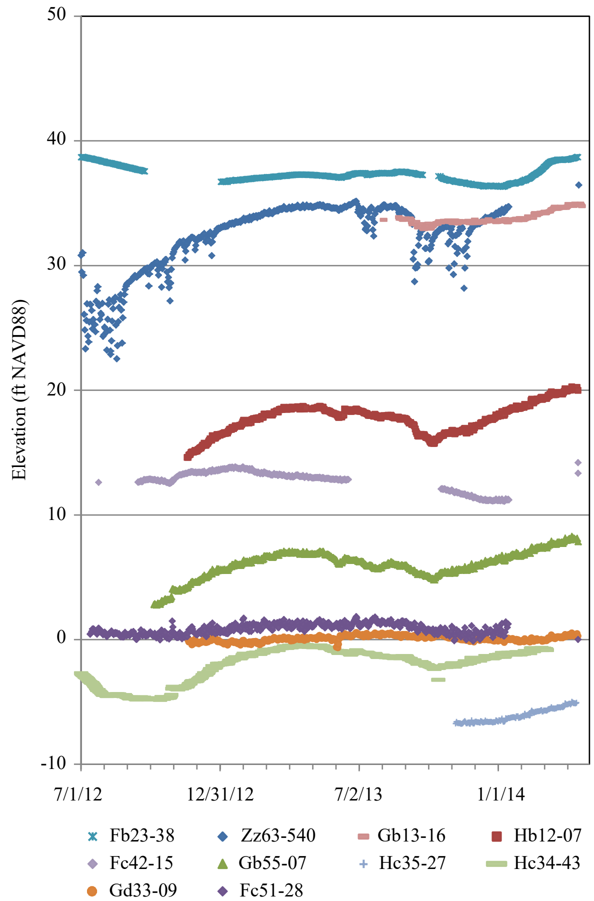

Figure 21c. Hydrographs for wells in the Rancocas aquifer.

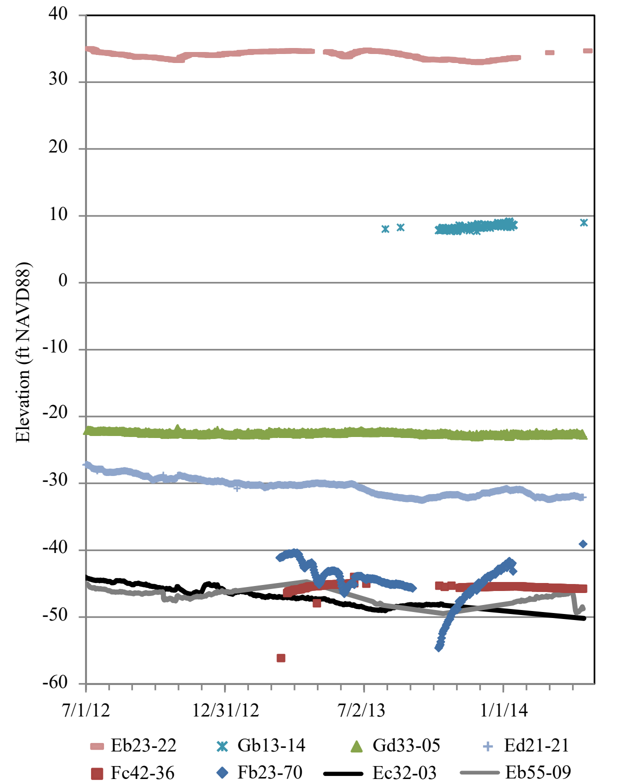

Figure 21e. Hydrographs for wells in the Magothy and Potomac aquifers.

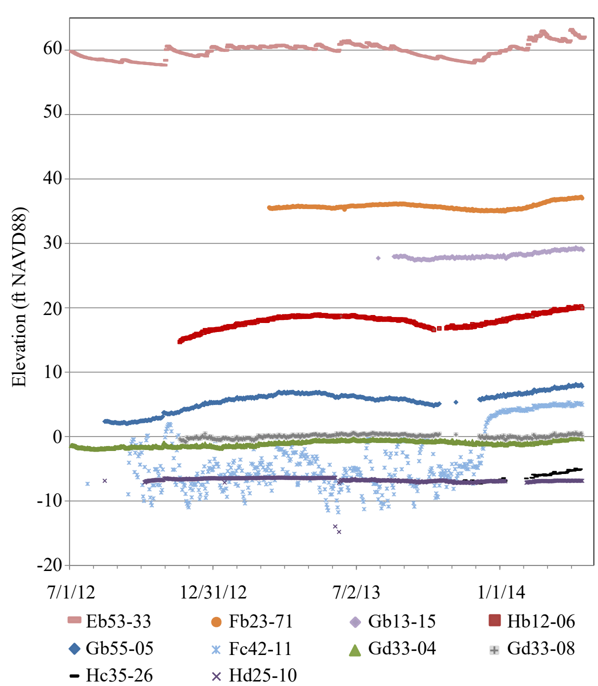

Figure 21d. Hydrographs for wells in the Mt. Laurel aquifer.

during the winter and spring when irrigation pumping is minimal.

Annual maximum water elevations in well Zz63-540 (Rancocas aquifer, Fig. 21c) show a small decline between 1977 and present. However, the frequency of measurement in this well varies from year to year and water levels recorded by instrumentation during this study show that water levels are affected by pumping. As a result, the water-level record from this well is not adequate to determine if the observed trend is significant.

Average heads in the Rancocas aquifer at sites 2 and 5 (Fig. 21c), Mt. Laurel aquifer at sites 2, 3, and 5 (Fig. 21d), and in the Magothy Formation at sites 5 and 7 (Fig. 21e) are below sea level. Under non-pumping conditions groundwater elevations are expected to be greater than the local minimum elevations of bodies of surface water, in this case current sea level approximated by the North American Vertical Datum of 1988 (NAVD88). At these sites head fluctuations do not indicate the effects of nearby pumping wells but rather that long-term pumping has caused a regional drawdown of heads in these aquifers.

Recharge to Confined Aquifers

Results of the groundwater-flow model study by He and Andres (2011) indicate that groundwater-flow directions in the Rancocas and Mt. Laurel aquifers are dominantly horizontal, controlled by topography in the recharge areas, and parallel the regional slope of these units where they are

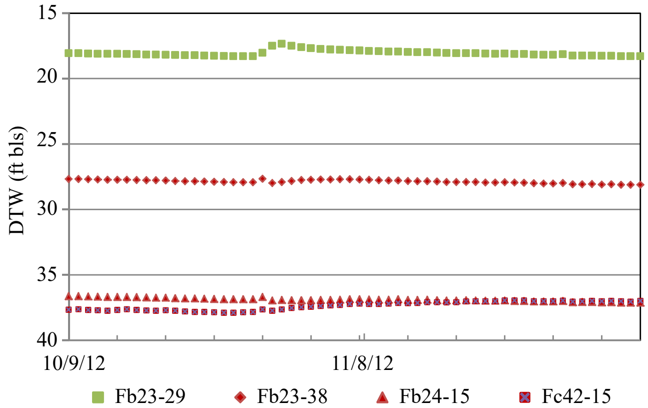

Figure 22a. Response of daily mean water levels in the Columbia aquifer to Hurricane Sandy.

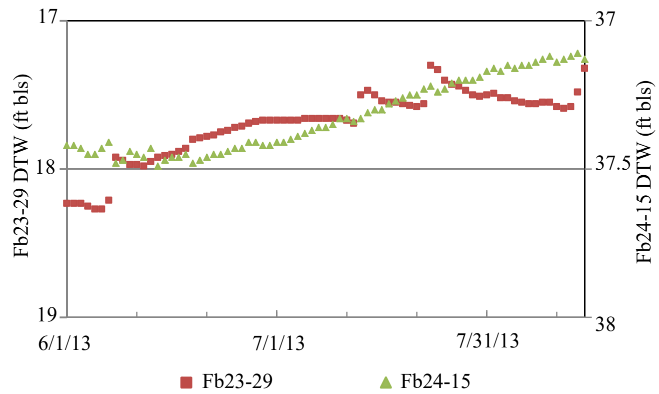

Figure 22b. Response of daily mean water levels in the Columbia aquifer to wet weather in June-July 2013.

confined. As a result, recharge to these aquifers should be greatest in their subcrop areas where the aquifers are in direct contact with the overlying Columbia aquifer or separated only by thin, leaky confining beds.

Recharge to the subcrop area of the Rancocas aquifer, illustrated by the hydrograph from Fb23-38 (site 8) responds to seasonal weather patterns and storms. The amplitude of water-elevation variations due to seasonal and short-term weather events is greater in well Fb23-29, which is screened across the water table in the Columbia aquifer, than in wells Fb23-38 and Fb24-15, which are screened several tens of feet below the water table in both the Columbia and Rancocas aquifers (Fig. 22a and b). Water levels in the shallower well also respond earlier to recharge events than the deeper wells. In the case of an individual large storm such as Hurricane Sandy in October 2012, (Fig. 22a), water elevations in the shallow well (Fb23-29) increase by nearly 0.4 ft following the storm, while there is no response deeper in the aquifer (Fb23-38, Fb24-15). Water elevations in both shallow and deep parts of the aquifer respond to longer duration recharge events such as the above normal precipitation in June 2013 (Fig. 22b) although the amplitude of head response is smaller deeper in the aquifer. The lesser response is thought to be due to preferential lateral flow of water in the shallow part of the aquifer.

Water elevations in well Eb53-33 (Fig. 21d),which is the farthest updip observation well in the Mt. Laurel aquifer, are consistently greater than 50 ft and are similar to water-table elevations estimated by Martin and Andres (2005). The hydrograph shows a close temporal association with seasonal and short-term weather events and indicates that this well is in close hydraulic communication with the water table.

Long-Term Trends

No long-term records of groundwater levels exist for the Rancocas aquifer in Delaware. This aquifer (Aquia aquifer in Maryland) is heavily used in adjacent areas of Maryland, where by the late 1990s, pumping had reduced groundwater elevations to less than 60 ft below sea level (Drummond, 2001) in some areas. However, Drummond (1998, 2001) shows that the effects of pumping in Maryland do not extend into Delaware; however, the effects of localized irrigation withdrawals may extend into Delaware. Groundwater elevations in the Rancocas are below sea level in Hc34-43 and Hc35-27 (site 2). The nearest significant users of groundwater to this site are the Town of Clayton and the J.T. Vaughn Correctional Center located just northeast of Smyrna. Average water elevation at Fc51-28 is slightly above sea level, although there are periods when the elevation is below sea level. Drawdown in the area just across the Delaware River in New Jersey is not observed (dePaul et al., 2008).

Long-term groundwater-level observations of the Mt. Laurel aquifer (well Gd33-04, Fig. 23a) show the regional effects of water use where levels have declined at an average rate of about 0.15 ft/yr since the 1960s. The rate of decline appears to be less during the past 10 years. A greater than 10-ft decline also appears to have occurred between the early 1990s and present at Fc42-11 (site 7), although a nearby production well complicates the interpretation. Regional effects of pumping also occur in wells installed in this project, as shown by water elevations in the Mt. Laurel aquifer at Hd25-10 (site 3), Gd33-08 (site 5), and Hc35-26 (site 2) near or just below sea level. Regionally, potentiometric surface maps (Drummond, 1998; dePaul et al., 2008; He and Andres, 2011) do not show drawdown below sea level in the Mt. Laurel extending from Delaware into adjacent states. Water-level data are not sufficient to evaluate the long-term, regional effects of water use from the Mt. Laurel aquifer at the nearby power-generating station in New Jersey.

Despite the fact that estimated water production from the Magothy aquifer is fairly small (2.3 million gallons per day, WSCC, 2006), long-term observations of groundwater levels (Fig. 23b) at Gd33-05 (Site 5) show levels have declined more than 20 ft (average rate of 0.62 ft/yr) since the mid 1960s. Wells Gd33-05 and Ec32-03 (Potomac aquifer) show a striking similarity in the slope of water-level decline. In addition, groundwater elevations in the Magothy aquifer at Ed21-21, Fb23-70 and Magothy Formation (confining bed) at Fc42-36 are below sea level and very similar in magnitude to elevations observed in the upper Potomac aquifer at wells Eb55-09 and Ec32-03. USACE (2007) hypothesized there was a good hydraulic connection between

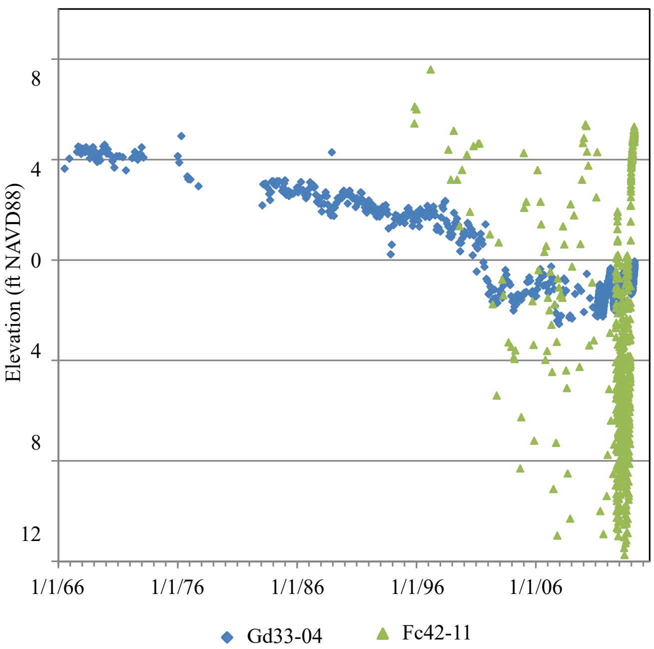

Figure 23a. Long-term hydrographs for wells in the Mt. Laurel aquifer.

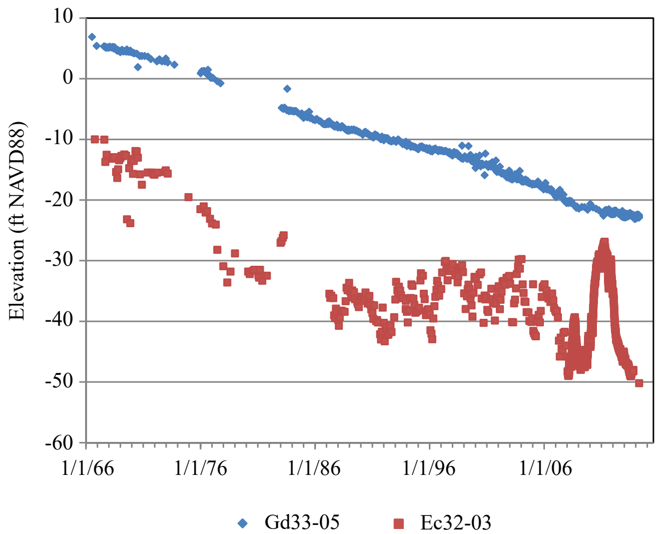

Figure 23b. Long-term hydrographs for wells in the Magothy, and Potomac aquifers.

the Magothy and heavily pumped aquifers in the Potomac Formation to explain both the similarities in long-term decline in water levels in both aquifers and elevations in the Magothy Formation. Interestingly, groundwater elevations in wells Eb23-22 and Gb13-14 (site 6) are above sea level, despite being in an area where regional potentiometric surface maps (dePaul et al., 2008) would indicate that heads should be well below sea level. This difference indicates a poor hydraulic connection between the Magothy Formation at these locations and the underlying upper Potomac aquifer as well as to the Magothy at sites 7 and 8 and well Ed21-21.

Vertical Head Differences

Comparison of groundwater elevations (heads) over time between wells at individual sites shows variable differences between aquifers. At sites 1, 3, 4, 5, and 7 the difference is greater than 10 ft, indicating that confining beds between aquifers have very low permeability and that little vertical transfer of water from shallow aquifers to deep confined aquifers takes place. Without significant vertical transfer of water, the deep confined aquifers are primarily being recharged by lateral flow from updip areas. At site 6, heads in the Rancocas are greater than heads in the Columbia indicating that the recharge area of the Rancocas for that site is located at a higher elevation than the elevation of the water table at that site. Very small (less than 0.1 ft) differences in mean daily water elevations and no difference in mean water levels in two wells that were finished at different depths (150 and 280 ft bls) in the Rancocas aquifer at site 4 indicate that vertical head differences equilibrate rapidly at this site.

Comparison to Model-Predicted Heads and Previous Regional Studies

The groundwater flow model (He and Andres, 2011) predicted that groundwater levels would decline several tens of feet in multiple aquifers in response to future increased pumping rates. Model-estimated water-level declines did not reach the tops of the aquifers; however, the model predicted that increased pumping was at least partially offset by reductions in the discharge of groundwater to local streams. He and Andres (2011) emphasized that the predictive power of the model was limited by sparse information on the hydraulic properties of the aquifers, groundwater levels, and streamflows needed to calibrate and validate the model.

Groundwater levels measured in this study provide a check for levels predicted by the He and Andres (2011) model (Fig. 24). In general, model-predicted water levels fit the water levels observed in newly constructed wells within the error tolerances used in calibrating the model, indicating that the boundary conditions and aquifer characteristics used in that model are reasonable for predicting water levels. Observed water levels indicate that potentiometric surfaces predicted by the He and Andres model (He and Andres 2011) reasonably represent field conditions and can be used as an analysis tool for groundwater-flow directions and velocities. Differences between predicted and observed water levels are greatest for the Magothy aquifer, where little head information was available to He and Andres (2011). The Magothy and upper Potomac units also were depicted as a single model layer, which limits the ability of the model to resolve head differences between these units.

Results of this study and the He and Andres (2011) model differ from regional head-estimate maps prepared by dePaul et al. (2008). Equipotential maps from dePaul et al. (2008) for the Vincentown (plate 4, our Rancocas aquifer) and Mt. Laurel-Wenonah aquifers, (plate 5, our Mt. Laurel aquifer) tend to highlight drawdown around the measurement points. Water-level data from site 7, located near pumping wells, confirm localized drawdown, but the magnitude of drawdown is not as significant as indicated by dePaul et al. (2008). In addition, data from monitoring wells not strongly impacted by pumping at sites 1, 4, 6, and 8 demonstrate that heads in the Rancocas and Mt. Laurel aquifers are tens of feet higher than those depicted by dePaul et al. (2008), and

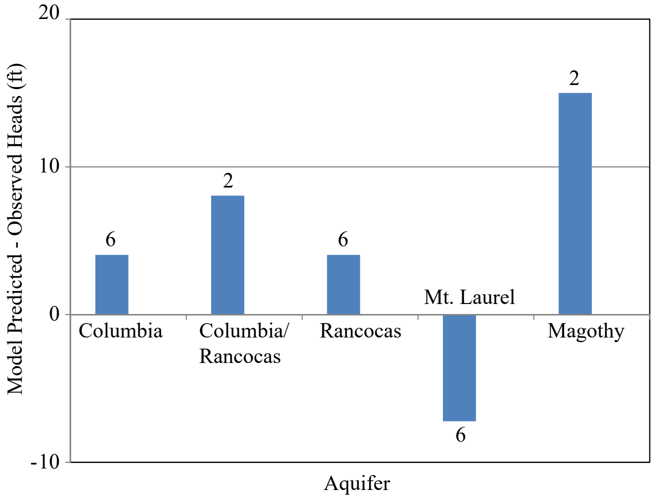

Figure 24. Comparison of observed and model-simulated heads by aquifer. Numbers next to bars represent number of observations.

are consistent with He and Andres (2011) results. These findings indicate that future regional efforts to map heads should not rely solely on measurements in production wells as was done in dePaul et al. (2008), and interpretation of spatially sparse head data should use high-frequency water-level measurements and spatially dense flow model results.

Most of the Delaware data in the dePaul et al. (2008) report were measured in production wells and the number and distribution of wells were rather sparse. They argue that their use of production wells for water-level measurements was not ideal, but that their measurement protocols of waiting hours after pumping ceased and then making multiple measurements over short time periods provided data useful for their interpretation of regional conditions. The wells in this study are dedicated observation sites but also are rather sparsely distributed. However, the addition of high-frequency measurements over many months provides for a more informed interpretation of the effects of pumping on water levels. Furthermore, the incorporation of model results of He and Andres (2011) fills in spatial data gaps.

Future Monitoring of Groundwater Levels

Viability of observations wells is routinely reviewed by DGS staff members. Several of the long-term wells used by DGS to track water conditions have had to be replaced, repaired, and abandoned due to encroachment by roads, age, damage by vehicular traffic, snow removal, and farming. Hb14-12 replaced Hb14-01, which was damaged by traffic, within the right-of-way of a roadway intersection. Hb14-12 is still located very close to the roadway and, although constructed with a protective cover, is still vulnerable to damage by snow removal and loss due to encroachment by roadway intersection improvements. The location also presents a safety hazard to employees that conduct water-level measurements and instrument maintenance. Overall, water-level responses of Gb55-08 and Hb12-05 are similar to those of long-term observation well Hb14-12, indicating that these two wells are good candidates to replace Hb14-12. These two wells are also co-located with wells constructed in deeper aquifers, thus providing data to compare shallow and deep aquifers.

A video inspection and slug test of well Gd33-04, which was installed in the mid 1960s, indicate that this well may have a fouled well screen. This well was installed at the edge of a farm field but has since been fully surrounded by mature trees. Mobilization of equipment to rehabilitate this well would be difficult and expensive. Well Gd33-09, installed during this project, will replace Gd33-04.

Streamflow, Weather, and Groundwater Levels

Cushing et al. (1972) and Johnston (1973, 1976) noted the close link between weather, shallow groundwater levels, generally permeable sediments, and streamflow in Delaware. Similarly, the association between land use, shallow groundwater, and stream water quality have been noted by many investigators (McKenzie, 1979; Ritter and Chirnside, 1984; Denver, et al., 2004) prompting state regulations and programs to protect groundwater to preserve quality and quantity of surface water.

Only one gaging station at Blackbird Creek (USGS 01483200, Fig. 1) has a long period of record (greater than 50 years) and was in operation during the study period. The remaining three stations (Figs. 1 and 2a) have been in operation for fewer than 15 years.

Because baseflow (groundwater discharge) typically dominates the groundwater budget (Johnston, 1976) and groundwater-level monitoring is much less expensive than streamflow gaging, correlations between monthly mean total stream discharge, baseflow, and monthly mean groundwater levels in nearby wells that are screened in the Columbia aquifer were evaluated to determine if groundwater levels could be used as predictors of total flow or baseflow. In addition, evaluation of unit discharge, the ratio of flow to watershed area, provides insight into the relationships between the shallow aquifer and streams in a watershed.

Use of the recursive digital filter option of the Web-based Hydrologic Analysis Tool (Lim et al., 2005) yielded baseflows and water budgets (Table 7) that were most consistent with manual baseflow separations reported by Johnston (1976) and Cushing et al. (1973). The local minimum option yielded unrealistic water budgets having larger baseflow proportions (greater than 85 percent). Comparison of long-term monthly mean total discharge from Blackbird Creek (01483200) with a combined dataset of monthly manual measured groundwater levels (prior to 2002) and monthly mean groundwater levels (post 2001) from well Hb14-12 from 1963-2013 are significantly correlated at the 5 percent confidence level but are not well fit (r-square 0.35). Monthly mean baseflow correlates better with groundwater levels (r-square 0.55). These results indicate the value of conducting long-term paired observations of stream flow and groundwater levels in the same watershed. In contrast, when only the study period is considered, results show insignificant correlations between groundwater levels and total flow and baseflow, an indication that short periods of observation reduce the predictive power of groundwater levels.

Unit flow and unit baseflow values (Table 7), which are ratios of flow to watershed area, and ratios of unit flows to unit baseflows show significant variations between watersheds. These measures of watershed hydrology are influenced by the local physiography and hydrogeology. The greatest potential for recharge of the Rancocas aquifer is in the Dove Nest Branch, Spring Mill Branch, and Silver Lake Tributary watersheds where sands of the Columbia aquifer are greater than 50 ft thick and are in connection with, or separated by thin confining beds from the Rancocas (Dugan et al, 2008). The ratio of baseflow to total flow in these streams is larger than in Blackbird Creek, which does not overlie a subcrop area of a deeper aquifer and where the Columbia aquifer is considerably thinner. The small number of watersheds does not allow meaningful statistical comparison of unit total and base flows.

The long-term record for Blackbird Creek does allow an assessment of long-term trends in streamflow. Mann-Kendall trend analysis of annual data reveals a significant (alpha=0.05) decline in annual minimum streamflow and a significant increase in annual maximum streamflow. These trends are consistent with more severe dry periods and storm events that have occurred more recently (Delaware Division of Energy and Climate, 2014). The increased annual maximum flow trend could potentially be correlated with increased impervious surface area in the watershed. Increased impervious cover would cause larger peak storm flows but this is unsubstantiated by historical land cover data.

CONCLUSIONS

The groundwater-monitoring, infrastructure-construction, and data-collection project in southern New Castle and northern Kent Counties, Delaware, addressed gaps in water-level, hydraulics, and water-quality data for the shallower aquifers commonly pumped by water-supply wells serving domestic, public, irrigation, and commercial users. From top to bottom, these are the Columbia, Rancocas, Mt. Laurel, and Magothy aquifers. A major accomplishment of this project was the construction of 22 new monitoring wells and five wireline coreholes at eight sites. Other major data-collection tasks included automated measurement and logging of groundwater levels in the new wells and seven existing wells, geophysical logging and hydraulic testing of new and existing wells, water sampling at monitoring and domestic wells, re-establishment and operation of two streamflow stations, and physical, mineralogic, and chemical testing of sediment samples. This report focuses on the initial assessment of physical hydrogeologic characteristics of geologic materials, aquifers, and confining beds and interpretations of groundwater-level and streamflow measurements. The groundwater-monitoring infrastructure and data created during this project will continue to serve the management and research needs for water resources of Delaware, and lead to additional follow-up projects and technical reports.

In the Blackbird State Forest area, geophysical logs, sediment descriptions, and hydraulic tests of new wells indicate that the Rancocas aquifer is thicker and more permeable than previously thought. Prior to this project, the Rancocas aquifer in this area had not been tested and had been partially penetrated by only a few water-supply wells. Further work is needed to determine the ability of the Rancocas to support high-capacity water-supply wells in this area and if exploitation of this resource will have significant impacts on overlying streams and wetlands.

Geophysical logs, sediment descriptions, water levels, and hydraulic tests of the Magothy Formation indicate that this unit does not function as an aquifer at all but one of the test sites. This is supported by anecdotal information from well drillers and well completion reports. Previous estimates of water availability from the Magothy were grossly overstated. In the vicinity of Middletown where the Magothy Formation does function as an aquifer, water levels exhibit characteristics similar to water levels observed in the underlying upper Potomac aquifer. This supports previous work that considered water-bearing beds in the Upper Potomac and Magothy Formations to be part of a single connected aquifer unit.

Evidence of faulting was observed in core samples collected from the Calvert Formation at all five coreholes as well as in the Manasquan and Shark River Formations in coreholes located in Smyrna. These features are located near the northern, updip limit of the Piney Point aquifer, a major source of water for the Dover area. Within individual coreholes, spatial proximity of the faults with zones of carbonate cement in the Manasquan and Vincentown Formations indicate that deep, carbonate-rich waters may be the source of the cement.

Groundwater-level data measured in new monitoring wells compare well with the model predictions of He and Andres (2011). Maximum heads in the Rancocas and Mt. Laurel aquifers observed in monitoring wells and predicted by the model are tens of feet greater than indicated by a USGS regional water-level study that largely relied on measurements made in production wells (dePaul et al., 2008). These findings highlight the importance of using monitoring wells and groundwater-flow models for water-resource assessment.

Regional and local pumping influences were evident at multiple sites. Heads in the Rancocas and Mt. Laurel aquifers are near or below sea level in wells in the eastern third of the study area (east of Route 13). Heads in the Magothy are below sea level in the Middletown area. Heads are below sea level in the only monitoring well completed for this project in the Piney Point aquifer. A combination of automated high-frequency and quarterly manual monitoring of water levels will continue in these areas to track trends.

More than 50 years of streamflow records at Blackbird Creek indicate long-term declining annual minimum flow and increasing annual maximum flow which are consistent with long-term climate trends of increasingly severe droughts and storms. Groundwater levels in the Columbia aquifer are a good predictor of stream baseflows over time periods of decades but not over shorter time periods (several years or less). Surface waters and the Columbia aquifer are closely connected in the local hydrologic system and the continuation of long-term monitoring is critical to help protect both water supply and streamflow for the long term.

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APPENDICES

Appendix 1. Descriptive Logs

DGS Site Identifier: Hb12-06

Site 1

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND, m-c, vc, trace Gravel, f+ Clay, STRONG BRN	0	10
SAND, m-c-vc, slightly Clayey, STRONG BRN	10	22
CLAY, soft, slightly Silty, trace Gravel, f, GRN-GRY	22	40
SAND, f-m-c, trace Gravel, f+Clay, RD-BRN	40	46
CLAY, soft, trace Sand, f-m, + Gravel, f, GRN-GRY	46	80
CLAY, soft, Sand, m-c, Gravel, f, DK GRN-GRY	80	86
CLAY, soft, Sandy, f-m-c, trace Gravel, f, DK GRN-GRY	86	96
SAND, f-m-c, Gravel, f, trace Shell, Clay, DK GRN-GRY	96	116
SAND, f-m-c-vc, slightly Gravelly, f, trace Clay+Shell, OLV	116	141
SAND, f-m-c, slightly Gravelly, f, trace Shell, Glauconite (10-15%), OLV	141	146
SAND, m-c, slightly Gravelly, f + Shelly, trace Clay, Glauconite (10-15%), OLV	146	236
SAND, f-m-c, Shelly, trace Clay, Glauconite (5%), OLV	236	246
SAND, f-m-c, Shelly, trace Clay, Glauconite (10-15%), OLV	246	256
SAND, m-c, Gravel, f, slightly Shelly, Glauconite (5-10%), OLV	256	263
SAND, f-m-c, Glauconite (10%), GRN-GRY	263	276
CLAY, Sandy, f-m-c, Shelly, Glauconite (15%), DK GRN-GRY	276	296
SAND, m-f-c, slightly Silty, Clayey, trace Shell, DK GRN-GRY	296	310
SAND, m-f-c, Clayey, slightly Silty, trace Shell, DK GRN-GRY	310	336
CLAY, Silty, Sandy, f-m, trace Shell, Glauconite (15%), PL GRN	336	346
SAND, m-c-f, slightly Silty, trace Shell, few thin beds, CLAY, Silty, Glauconite (15 - 25%), OLV, LT GRN-GRY to PL GRN	346	376
SAND, f-m, slightly Silty, trace Shell+Clay, OLV, LT GRN-GRY to PL GRN	376	399
SAND, f-m, v Silty, Clayey, trace Shell, DK GRN-GRY TO LT GRN-GRY	399	416
SAND, f, Silty, slightly Clayey, LT GRY	416	426
SAND, f-m, very Silty, Clayey, glauconitic, GRY	426	432
SILT+SAND f, Clayey, slightly glauconitic, LT GRY to GRY-BRN	432	443
SAND, f-m, very Silty, Slightly Clayey, trace Granules, glauconitic, GRY	443	450
SAND, f-m, Silty, LT BRN	450	466

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Hc34-51

Site 2a

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
Topsoil, SAND, f-c, Silty, trace Granules, LT BRN	0	1
SAND, f-c, trace Silt, LT BROWN to LT Y-OR	1	3
SAND, m-c, slightly Silty, trace Granules, BRN-Y	3	9
SAND, m-c-f, trace Silt+Granules, BRN-Y	9	20
SAND, c-m, Slightly Gravelly, f, trace Silt, RD-Y	20	29
SAND, c-m + GRAVEL, f-m, trace Silt, RD-Y	29	42
SAND, c-m, Gravelly, f-m, trace Silt, RD-Y	42	60
Same but BRN	60	99
CLAY, Silty, LT to DK GRN-GRY, slightly micaceous	99	138
CLAY, Silty, Slightly Shelly, DK GRN-GRY, trace mica	138	161
as above with few thin beds SAND, f-m, Silty, OLV-GRY, Glauconitic	161	170
SAND, f-c, Silty, trace Shell, DK GRN-GRY, v. glauconitic, moderately calcareous	161	204
SAND, f + SILT, DK GRN-GRY, v. glauconitic, slightly calcareous	204	216
SAND, f + SILT, Clayey, LT OLV-GRY, v. glauconitic, slightly calcareous	216	236
CLAY, Silty, trace Sand, f to SILT, Clayey, Sandy f, GRN-GRY, moderately calcareous	236	270
SAND, Silty, Clayey, DK OLV-GRY, very glauconitic, slightly calcareous	270	289
SAND, f, Silty, trace Clay, Shell, Granules, DK GRN-GRY to GRN-GRY very calcareous, trace Glauconite, few cemented zones 0.5-2 ft thick	289	340
SAND, f, Silty, trace Clay, Shell, Granules, DK GRN-GRY to GRN-GRY, moderately Glauconitic+ calcareous	340	359
SAND, f, Silty, trace Granules+Shell to SILT+SAND, f-m, Slightly Clayey GRN-GRY, common cemented zones 0.5-4 ft thick	359	420
SILT+SAND, f, Clayey, trace Shell to Shelly, very Glauconitic, few beds CLAY, Silty DK GRN-GRY to GRN-GRY, moderately calcareous, few cemented zones 1-4 ft thick	420	465
SAND, m-f-c, Silty, trace Granules, Shell, Clay, OLV-BRN TO OLV, moderately - very calcareous, moderately Glauconitic, common cemented zones 1-4 ft thick	465	550
SAND, f-c, Silty, Clayey, Shelly, very glauconitic, many beds CLAY, Silty, Shelly, DK GRN-GRY	550	580
SAND, f-c, Silty, Clayey, Shelly, DK GRN-GRY to GRN-BLK, DK OLV-BRN, moderately glauconitic, calcareous, common cemented zones 1-4 ft thick	580	615
SILT, Sandy, f, slightly Shelly, DK GRN-GRY, DK OLV-BRN, micaceous	615	639
CLAY, Silty, Slightly Shelly, trace Sand, f, GRN-BLK, micaceous	639	654
SAND, f-m, Slightly Silty, Shelly, DK GRN-GRY, micaceous	654	659
CLAY, Silty, Slightly Shelly, trace Sand, f, micaceous, To SILT, Clayey, Slightly Sandy, f, Shelly, DK GRN-GRY, micaceous, slightly glauconitic	659	699
SAND, f-m, Slightly Silty, Shelly, micaceous, DK GRN-GRY, calcareous very hard	699	738
CLAY, slightly Silty, trace Sand, f-c, GRN-BLK	738	745
SAND, f-c, trace Silt, OLV	745	749
CLAY, slightly Silty, trace Sand, f-c, micaceous, GRN-BLK to BLK	749	764
SAND, f-m, Slightly Silty, GRN-GRY	764	779

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Hc35-26

Site 2b

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
Fill, SAND, f-m, Silty, Pebbly LT BRN	0	4.5
TRASH, cinders, glass, DK GRY	4.5	16.5
SAND, f-m, Gravelly, LT GRN-GRY to RD to Y-RD	16.5	25
SAND, c-m, slightly Silty, Y-RD, Y-BRN to DK RD-GRY	25	75
SAND, f-c, Silty, trace Gravel, f, laminated LT OLV-BRN, DK GRY-BRN, OLV-Y	75	80
SAND, c-m, Gravelly, f, trace Pebble+Silt, Y-BRN	80	85
SILT, slightly Clayey + SILT, Sandy, f, LT GRN-GRY	85	146
SAND, f-m, Silty, Glauconite (50%), calcareous, DK GRN-GRY	146	150
SILT+SAND, f, Clayey, trace Shell, Glauconite (50%), calcareous, GRN-BLK to DK GRN-GRY	150	160
SAND, f-c, slightly Clayey, Glauconite (50%), partly cemented, trace mica, calcareous, DK GRN-GRY	160	200
SAND, f-c, Clayey, tr Silt, Glauconite (50%), trace Wood, calcareous, VRY DK GRY to DK GRN-GRY	200	230
SAND, f-c, slightly Silty+Clayey, calcareous, DK GRN-GRY	230	240
CLAY + SAND, vf, Glauconite, calcareous, trace mica, GRN-GRY to GRY-GRN	240	272
SAND, c-vc, Silty, Clayey, Glauconite (>50%), calcareous, cemented, GRN-GRY to GRY-GRN	272	291
SILT, Sandy, f-m, Glauconite (50%), cemented, calcareous, VRY DK GRY-BRN	291	320
SAND f-c, Clayey, slightly Silty, trace Sand f-m, slightly calcareous, VRY DK GRY-BRN	320	336
SAND, f-c, slightly Clayey+Silty, VRY DK GRY-BRN	336	360
SAND, f-c, Shelly, trace Clay, VRY DK GRY-BRN	360	370
SHELL+SAND, f-vc, slightly Clayey, Glauconite (10%), DK GRN-GRY to GRY-GRN	370	380
SAND, f-vc, Clayey, trace Shell, GL DK GRN-GRY to GRY-GRN	380	392
SAND, f-vc, Clayey, trace Shell, DK GRN-GRY to GRY-GRN	392	423
SAND, f-vc, Shelly, Silty, Clayey, Glauconite, DK GRN-GRY to GRY-GRN	423	441
CLAY, SAND, f-m-c, slightly Silty, Shelly, Glauconite, DK GRN-GRY to DK GRY-GRN	441	450
SAND, c-vc, slightly Clayey+Shelly, Glauconite, OLV to DK GRY-GRN	450	510

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Hb25-07

Site 3

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
Topsoil, SAND, f, Silty, LT BROWN	0	1
SAND, f-m, Silty, MTLD LT BROWN+LT Y-OR, fines upward	1	4
SAND, m-c, slightly Silty, trace Granule, MOD BRN-Y	4	6
few thin beds SILT, Sandy, f, Cly, LT BRN-GRY+RD-OR	6	15
SAND, m-c-f, trace Gravel f-m, Silt PALE BRN,	15	28
SAND, c, Gravelly, f-m trace Silt, bedded YELLOW+LT GRY	28	34
SAND, f-m, Silty, with laminae SD f, and SILT, LT GRN-GRY	34	39
SAND, c-m, + Gravel f-m, trace Silt, LT GRN-GRY, with thin beds CLAY and SILT, GRN-GRY	39	52
SILT, Clayey, Sandy, f, slightly micaceous, DK GRN-GRY	52	99
SILT, Clayey, Shelly, with beds SILT, Clayey, trace Shell, DK GRN-GRY	99	144
SILT, Sandy, f, to SILT and SAND f, DK GRN-GRY	144	165
SAND, f-m, Silty, trace Clay+Granules, glauconitic, very calcareous, GRN-GRY	165	199
SAND, f-c, Shelly, Silty, glauconitic, very calcareous, DK GRN-GRY with LT OLV-GRY mottles	199	248
SAND, f-m, Shelly, Silty, trace Clay, glauconitic, very calcareous, LT GRN-GRY	248	295
SAND, f-vf, + SILT, Clayey, trace Shell, glauconitic, very calcareous, OLV-GRY to GRN-GRY	295	358
CLAY, Silty, trace Sand, f + Shell, trace Glauconite, moderately calcareous, DK GRN-GRY to DK BL-GRY	358	401
CLAY, Silty, Sandy, f, trace Shell, trace Glauconite to SILT, Clayey, trace Sand f, micaceous, phosphate nodules, slightly calcareous, Dk GRN-GRY to DK BL-GRY	401	454
SILT, Sandy, f, trace Clay + Shell, micaceous slightly glauconitic+calcareous, DK GRN-GRY to BRN-GRY	454	468
SILT, Sandy, f, trace Clay + Shell with common beds SAND, f, Silty, trace Clay + Shell, micaceous, glauconitic, calcareous, DK GRN-GRY TO BRN-GRY	468	480
SILT. Clayey, Sandy f, trace Shell, glauconitic, calcareous, MOD OLV-GRY	480	512
SAND, f-c, Shelly, Silty, trace Clay + Granules, with few interbeds with SILT and SAND, f-c, Shelly, trace clay; SILT + CLAY, Sandy f-m; GRY with DK Y-BRN mottles glauconitic, calcareous	512	618
SAND, f-m,+SILT, Clayey, Shelly, glauconitic, calcareous, LT GRY to DK OLV-BRN	618	647
SILT+CLAY, Shelly, Sandy, f-m, glauconitic, slightly calcareous, GRY-GRN	647	660
SAND, f, Silty, trace Clay + Shell, with beds SAND, f, + SILT, trace Clay and Shell; glauconitic, slightly calcareous, DK GRN-GRY	660	682
SILT+CLAY, Sandy, f-m, trace Shell, glauconitic, micaceous, GRY-GRN	682	698
CLAY, CLAY+SILT, Sandy f, micaceous, glauconitic, DK GRN-GRY	698	715
SILT, Clayey, trace Sand f, + Shell, micaceous, moderately calcareous, DK GRY to GRN-GRY	715	739
CLAY, Silty, trace Shell + Sand f,glauconitic, lignitic, DK GRY	739	760
SILT+SAND, f,. Clayey, Shelly, glauconitic, slightly calcareous, DK GRY to GRN-GRY	760	789
SAND, f-m, very Silty, Clayey, trace granules, micaceous, lignitic, trace Glauconite, DK GRY	789	820

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Gb55-05

Site 4

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND, f, + SILT, Clayey, LT BRN	0	3
SAND, m-c-f, trace Silt, LT Y-OR	3	7
SAND, c-m, slightly Gravelly, f-m, trace Silt, LT Y-OR	7	17
SAND, c-m, Gravelly, f-m, trace Silt, RD-OR	17	36
CLAY, Silty, to SILT, Clayey, LT GRY	36	55
CLAY, Silty, to SILT, Clayey, LT GRN-GRY	55	69
CLAY+SILT, DK GRN-GRY, hard	69	84
CLAY+SILT, trace Shell+Pebble, OLV	84	91
SILT, Sandy, f, Silty, trace Shell to SAND, f-m, Silty, Shelly, hard, calcareous cement, trace Glauconite, GRN-GRY	91	100
SAND, f-vf, Silty, trace Sand, c + Shell, hard, calcareous cement, slightly glauconitic, LT GRN-GRY	100	114
SHELL, Sandy, f-c, Slightly Silty, glauconitic, few thin cemented layers, LT GRN-GRY	114	126
SAND, m-f-c, Shelly, Slightly Silty, trace Granules, glauconitic, LT GRN-GRY	126	138
SAND, m-f-c, Slightly Shelly+ Silty, trace Clay, glauconitic few thin cemented layers, LT GRN-GRY	138	162
SAND, m-f-c, Slightly Shelly+ Silty, trace Clay+Granules, very glauconitic, calcareous, LT GRN-GRY	162	181
SAND, m-f-c, Silty, Slightly Clayey+Shelly, trace Granules, glauconitic, very calcareous, GRN-GRY	181	199
SAND, m-f-c, Slightly Shelly+Silty trace Granules, to SAND, m-c-f, Slightly Gravelly, f, trace Silt, LT GRN-GRY very calcareous, glauconitic, LT GRN-GRY	199	265
SAND, f-m, Silty, Shelly, Slightly Clayey, few thin cemented zones, glauconitic, LT GRN-GRY TO DK GRN-GRY	265	270
SAND, f-m, Silty, Shelly, Clayey, few thin cemented zones, very glauconitic, calcareous, DK GRN-GRY to OLV	270	295
SILT, Clayey, Sandy, f, to SILT+CLAY, glauconitic few thin Shelly beds, cemented zones, slightly calcareous, OLV	295	308
SAND, m-c-f, Silty, trace Shell+Granules, glauconitic, OLV	308	330
SAND, m-c-f, Slightly Gravelly, f, trace Shell+Silt, glauconitic few thin beds SAND, f +SILT, OLV	330	400
SAND, f, Silty, Clayey, glauconitic, OLV	400	426
SAND, f-c, trace Silt+Shells, to SAND, f, Silty, glauconitic, GRN-GRY	426	442
CLAY, Silty to CLAY, trace mica, DK GRN-GRY	442	496
CLAY, Silty to CLAY, micaceous, DK GRN-GRY	496	536

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Gd33-08

Site 5

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SILT, Clayey, DK BRN to GRY BRN	0	10
SAND, f-c, Pebbly, slightly Silty, LT BRN, with common beds	10	
CLAY, Silty, Pebbly, iron staining, pebbly, LT BRN		17
SAND, f-c, trace Silt to Silty, LT to DK GRY	17	26
CLAY, Sandy, f-m, LT GRY	26	76
CLAY, Silty, slightly Sandy, f-c, trace Shell, DK OLV BRN	76	90
CLAY, Silty, Shelly, slightly Sandy, f-c, DK OLV BRN, cemented at 90'	90	114
CLAY, Sandy, f-c, MOD OLV BRN	114	125
SAND, f-c, Slightly Silty, Clayey, cemented at 125, 132, DK GRY	125	140
SAND, m-f-c, Slightly Silty, trace Granules, DK GRY	140	152
SAND, m-f, Silty, Slightly Clayey, DK GRY	152	208
SAND, f-m, and CLAY, Silty, trace Granules, DK GRY	208	233
SAND, f-c, very Shelly, slightly Silty, trace Clay+Gravel, f, MD GRY, glauconitic	233	268
SAND, f-m, very Silty, Clayey, trace Shell, MD GRY, slightly glauconitic	268	
common beds SILT+CLAY, Sandy f, glauconitic		323
SAND, f-m, Silty, Shelly, MD GRY, glauconitc, common cemented zones	323	345
SAND, f-m, Shelly, Slightly Silty, trace Granules and Clay, MD GRY, very	345	
glauconitic, common cemented zones		425
SAND, f-m, very Silty, Clayey, MD GRY, glauconitic	425	432
SILT+SAND f, Clayey, LT GRY to GRY-BRN, slightly glauconitic	432	442
SAND, f-m, very Silty, Slightly Clayey, trace Granules, MD GRY, glauconitic	442	450
SAND, f-m, Silty, LT BRN	450	466

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Gb13-14

Site 6

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND f-c, slightly Clayey, poorly sorted, DK Y-BRN	0	18
SILT, Clayey, trace Sand, f, DK Y-BRN	18	21
SAND f-c, poorly sorted, glauconitic, Fe concretions, DK Y-BRN	21	32
SAND f-m, glauconitic Fe concretions, LT BRN-GRY	32	40
SAND f-m, Shelly, very calcareous, LT BRN-GRY		
SAND f-m, Shelly, slightly Silty, trace Fe concretions,	40	77
very calcareous DK Y-BRN		
SILT, Clayey, trace Sand and Shell, f-m, calcareous, DK Y-BRN	77	87
SHELL, trace Sand+Silt, Glauconite (5%), Y	87	97
CLAY, Sandy, f, trace Silt, DK Y-BRN	97	127
SAND, m-c-vc, poorly sorted, trace Silt + Clay, DK OLV-GRY	127	140
CLAY, Sandy, f-m-c, trace Silt, Glauconite (10%),	140	
DK GRN-GRY to GRY-GRN		170
CLAY, Sandy f-m-c, Shelly, trace Fe concretions,	170	187
DK GRY-GRN to LT GRN-GRY		
SAND, Clayey, f-m-c, slightly Silty,	187	
Glauconite (5%), phosphate nodules, OLV-GRY to OLV		249
CLAY, Sandy f-m, trace Silt+Shell, Glauconite (5%),	249	
VRY DK BL-GRY		271
SAND, f, + SILT, Clayey, trace Shell, VRY DK BL-GRY	271	286
CLAY, trace Silt, DK GRN-GRY to GRY-GRN	286	317
CLAY, trace Silt, trace Shell+Sand, f-m,	317	
trace mica, DK GRN-GRY to GRY-GRN		350
CLAY+SAND f, trace Silt + Wood, DK GRN-GRY to GRY-GRN	350	357

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Fc42-36

Site 7

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND, m-vc, Sligthly Gravelly, f, trace Silt+Clay, Y-BRN	0	20
CLAY, Sandy, f-c, LT Y-BRN	20	30
SAND, f-vc, RD	30	40
SAND, f, slightly Silty, trace Clay, Glauconite (15%), GRN-GRY to GRY	96	106
SILT, Clayey, Sandy, f, trace Shell, Glauconite (35%), slightly calcareous,	106	126
SHELL, Silty, Sandy, f, trace clay, Glauconite (20%), calcareous, GRY	126	136
SILT + SHELL, Sandy, f, trace Clay, calcareous, LT GRN-GRY - GRY	136	146
SAND, f-m, Silty, trace Clay+Shell, Glauconite (40%), slightly calcareous, GRY to LT GRY	146	156
SILT, Sandy f, Clayey, trace Shell, Glauconite (25%), thin beds SAND, f-c, Clayey, trace Shell, Glauconite (25-35%), GRY	156	176
SAND, f-m, Silty, Shelly, trace Clay, Glauconite (20%), calcareous, DK GRN-GRY	176	186
CLAY, slightly Sandy, f-m, trace Shell, Glauconite (5%), GRN-GRY	186	196
CLAY, sand, f-c, slightly silty, trace shell, Glauconite (15%), slightly calcareous, GRN-GRY	196	236
CLAY, Sandy, f-m, Silty, trace shell, Glauconite (15%), GRN-GRY	236	266
CLAY, Sandy, f-m, trace Shell, Glauconite (15%), slightly calcareous, GRN-GRY	266	276
CLAY, Sandy, f-m, trace Shell, Glauconite (20-25%), iron oxide and phosphate nodules, slightly calcareous, GRN-GRY	276	286
CLAY + SAND, f-m-c, Shelly, Glauconite (20%), calcareous, GRY	286	306
CLAY, Sandy, f-m, Shelly, Glauconite (20%), calcareous, VRY DK GRY	306	316
CLAY, slightly Silty+Shelly, Glauconite (10%), VRY DK GRY	316	396
CLAY, Sandy, f, slightly Silty, Glauconite (5%), VRY DK GRY	396	416
CLAY and SAND, f-vc, slightly Silty, trace wood + shell, slightly calcareous, GRN-GRY	416	426
CLAY, Sandy, f-m, trace wood, GRN-GRY	426	436

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Fb23-70

Site 8

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND, f-c, slightly Gravelly, f, STRONG BRN	0	40
SAND, vc, Gravelly f, STRONG BRN	46	56
SAND, m-c, Gravelly, f, trace Fe concretion+mica, Glauconite (10%) LT Y-BRN	56	66
CLAY, Sandy, f-m-c, trace Shell+Mica, Glauconite (15%), DK GRN-GRY	66	96
CLAY, Sandy, f-m-c, trace Shell+Mica, Glauconite (%15), slightly calcareous, DK GRN-GRY	96	126
CLAY, Sandy, f-m, trace Shell, slightly calcareous, DK GRN-GRY	126	136
CLAY, Sandy, f-m, trace Shell, Glauconite (5%), slightly calcareous, DK GRN-GRY	136	156
CLAY, Sandy, f-m+Shelly, Glauconite (10%), slightly calcareous, DK GRN-GRY	156	176
CLAY, Sandy, f-m + Shelly, Glauconite (10%), slightly calcareous, DK GRN-GRY	176	196
CLAY, Sandy, f, Slightly Shelly, trace Gravel, f, slightly calcareous, DK GRN-GRY	196	206
CLAY, slightly Sandy, f, DK GRN-GRY	206	216
CLAY, slightly Sandy f + Shelly, slightly calcareous, DK GRN-GRY	216	246
SILT+SAND f-m, trace Shell, slightly calcareous, GRY	246	256
SILT+SAND f-m, trace Shell, Glauconite (15%), slightly calcareous, GRY	256	266
SILT+SAND, f-m, slightly Clayey, trace shell, Glauconite (10%), slightly calcareous, GRY	266	276
SILT, slightly Sandy, f, trace Clay, Glauconite (5%), DK GRN-GRY	276	286
SILT, Sandy, f, trace Clay, Glauconite, DK GRN-GRY	286	296
SILT, Sandy, shelly, trace Clay, Glauconite (5%), slightly calcareous, GRN-GRY	296	306
SILT, Sandy, f, 10GY 6/1, few thin beds CLAY, Silty, Sandy f, trace Wood, DK GRN-GRY	306	316
SILT, Sandy, f, trace clay, shell, Glauconite (5%), slightly calcareous, DK GRN-GRY	316	326
SAND, f-m, Sandy, trace Shell, Clay+Wood, GRN-GRY	326	336
SILT + CLAY, Sandy, f-m, trace Wood, PK	336	346
SILT, Clayey, slightly Sandy, f, trace Wood, LT GRN-GRY TO PK-GRY	346	366

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 1. Descriptive Logs

DGS Site Identifier: Gc52-15

Land surface datum

Material Description	Depth top (ft)	Depth bottom (ft)
SAND, vf-c, Silty, trace Pebbles, Y to Y-BRN	0	7
SAND, f-m, Silty, with beds SAND f and SILT, and SILT, Sandy, f, Y to Y-BRN	7	27
SAND, c-m, Gravelly, f-m, Cobbly, LT Y to Y-BRN	27	29
CLAY, Silty, few laminae of SILT, OLV-GRY	29	46
SILT, Clayey, GRN-GRY	46	90
SILT, Clayey, Slightly Shelly, DK OLV-GRY	90	97
SAND, vf-c, Shelly, trace Gravel, f, Glauconite (60-70%), very calcareous, GRN-GRY	97	154
SAND, vf-c, Shelly, Silty, very calcareous, Glauconite (10%), cemented, LT GRN-GRY	154	210
LIMESTONE with beds SAND, vf-c, Silty, Glauconite (10 %), LT GRY to LT GRN-GRY	210	265
SAND, vf-c, Silty, Shelly, Glauconite (50%), calcareous, cemented, DK GRN-GRY	265	273
SAND, vf-f, Shelly, Silty, Glauconite (90%), DK GRN-GRY	273	310
SAND, vf-c, Silty, Slightly Shelly, Glauconite (50-70%), DK GRY to OLV-GRY	310	325
SAND, m-vc, Silty, Slightly Shelly+Clayey, trace Granules, calcareous, Glauconite (<10%), OLV-GRY to OLV-BRN	325	345

Color and textural modifier abbreviations

DK	Dark	**BLK**	Black	**vf**	very fine
LT	Light	**BRN**	Brown	**f**	fine
PL	Pale	**GRN**	Green	**m**	medium
MOD	Moderate	**GRY**	Gray	**c**	coarse
VRY	Very	**OLV**	Olive	**vc**	very coarse
		OR	Orange		
		PK	Pink		
		RD	Red		
		Y	Yellow		

Appendix 2. Results of bulk mineralogic analysis by x-ray diffractometry

DGS Identifier	Sample Identifier	Depth (ft bls)	Litho-stratigraphic Unit	Mixed Layer Illite Smectite	Illite	Glauconite	Kaolinite	Chlorite	Quartz	K-Feldspar	Plagioclase-Feldspar	Calcite	Dolomite	Siderite	Pyrite + Marcasite	Muscovite
Hc34-51	110618-01	8	Columbia	0	0	0	0	0	74	15	5	0	2	3	0	0
Hc34-51	110630-01	61.9	Columbia	0	0	0	0	0	71	14	11	0	1	1	0	0
Hc34-51	110657-01	154	Piney Point	2	7	0	0	2	61	5	7	1	1	3	10	0
Hc34-51	110664-01	166	Piney Point	0	0	6	6	0	71	5	3	2	0	3	2	8
Hc34-51	110686-01	217	Piney Point	1	0	4	4	0	62	5	2	4	0	11	4	7
Hc34-51	110713-01	269	Manasquan	1	0	5	5	0	47	4	2	2	0	30	8	0
Hc34-51	110725-01	299	Vincentown	0	1	0	0	0	86	4	2	4	0	1	1	0
Hc34-51	110751-01	349	Manasquan	0	1	0	0	0	89	3	2	1	0	2	1	0
Hc34-51	110769-01	383.5	Hornerstown	0	1	0	0	0	17	2	2	76	0	2	1	0
Hc34-51	110809-01	494.5	Mt. Laurel	0	1	0	0	0	86	3	2	1	0	6	0	0
Hc34-51	110838-01	543	Marshalltown	0	2	0	0	0	78	6	3	8	0	0	1	0
Hc34-51	110870-01	600.6	Merchantville	0	0	0	0	0	95	2	1	0	0	1	0	0
Hc34-51	110891-01	646	Merchantville	1	9	0	0	1	69	5	5	0	0	8	0	0
Hc34-51	110917-01	696.3	Merchantville	2	9	0	0	0	54	7	4	11	1	13	0	0
Hc34-51	110930-01	718.6	Merchantville	1	7	0	0	0	69	7	4	1	0	3	1	6
Hc34-51	110934-01	726.9	Merchantville	2	6	0	0	0	72	6	5	0	0	3	1	4
Hc34-51	110938-01	734.9	Merchantville	1	22	0	0	1	57	5	4	0	1	2	1	6
Hc34-51	110950-01	763.3	Magothy	0	0	0	0	0	95	2	1	0	0	1	1	0
Hc34-51	110952-01	766.4	Magothy	0	0	0	0	0	96	1	1	0	0	1	0	0
Hd25-07	110112-01	69.5	Calvert	1	7	0	2	0	76	4	0	0	0	0	10	0
Hd25-07	110113-01	71.4	Calvert	1	4	0	0	1	85	0	0	0	0	0	8	0
Hd25-07	110128-01	103.3	Calvert	2	6	0	0	2	84	0	0	0	0	0	7	0
Hd25-07	110255-01	376.7	Manasquan	2	2	0	0	0	62	7	5	19	0	0	4	0
Hd25-07	110255-02	375.9	Manasquan	3	2	0	1	0	65	4	0	22	0	0	3	0
Hd25-07	110256-01	377.2	Manasquan	1	1	0	0	0	62	0	0	22	0	10	3	0
Hd25-07	110266-01	394.7	Manasquan	3	2	0	0	1	70	0	0	24	0	0	0	0
Hd25-07	110290-01	444	Vincentown	1	5	0	0	0	80	7	5	1	0	0	0	0
Hd25-07	110291-01	446.5	Vincentown	1	4	0	0	0	86	8	0	1	0	0	0	0
Hd25-07	110293-01	449.4	Vincentown	1	6	0	0	0	79	8	4	1	0	0	0	0
Hd25-07	110315-01	484.7	Navesink	3	13	0	0	0	53	0	0	25	0	0	6	0
Hd25-07	110318-01	490	Navesink	3	29	0	0	0	30	0	0	17	0	0	20	0
Hd25-07	110332-01	516	Mt. Laurel	1	5	0	0	0	57	0	0	38	0	0	0	0
Hd25-07	110385-01	613	Merchantville	1	1	0	0	0	61	3	0	32	0	0	1	0
Hd25-07	110408-02	662.2	Englishtown	1	4	0	0	0	86	5	0	3	0	0	1	0
Hd25-07	110430-01	707.2	Merchantville	2	11	0	0	1	71	7	6	2	0	0	0	0
Hd25-07	110436-01	723	Merchantville	1	10	0	0	1	65	8	8	6	0	0	1	0
Hd25-07	110442-01	742	Merchantville	4	12	0	0	2	55	5	7	10	0	0	5	0
Hd25-07	110448-01	751.6	Merchantville	5	16	0	0	3	35	8	9	14	0	0	9	0
Hd25-07	110480-01	809.75	Magothy	2	9	0	0	3	82	0	0	0	0	0	4	0

Appendix 3. Results of total extractable elemental testing. Values reported in mg/kg.

DGS Identifier	Sample Identifier	Depth (ft bls)	Litho-stratigraphic Unit	As	Cd	Cr	Cu	Ni	Pb	Si	Zn
Hc34-51	110618-01	8	Columbia	0.34	0.09	2.31	7.44	1.46	1.61	207.04	0.91
Hc34-51	110664-01	166	Piney Point	4.62	0.12	80.85	6.38	11.36	9.52	1314.35	55.42
Hc34-51	110686-01	217	Piney Point	3.59	0.06	55.53	3.45	9.93	8.48	1075.53	31.72
Hc34-51	110751-01	349	Manasquan	4.15	0.19	166.80	7.53	8.52	7.29	1014.75	48.21
Hc34-51	110769-01	383.5	Vincentown	0.22	0.24	5.05	7.09	4.56	3.47	603.98	10.18
Hc34-51	110809-01	494.5	Mt. Laurel	23.78	0.04	198.21	12.53	21.48	10.73	817.81	54.62
Hc34-51	110870-01	600.6	Englishtown	8.72	0.08	19.05	6.88	3.42	4.34	1168.92	16.82
Hc34-51	110891-01	646	Merchantville	5.57	0.07	21.38	11.38	9.78	5.88	1176.46	48.56
Hc34-51	110917-01	696.3	Merchantville	25.57	0.10	115.72	8.83	18.22	20.58	420.38	84.68
Hc34-51	110952-01	766.4	Magothy	5.61	0.13	23.95	12.05	10.59	6.19	695.35	54.37
Hd25-07	110113-01	71.4	Calvert	8.62	0.33	16.14	23.64	13.26	10.30	649.84	60.84
Hd25-07	110128-01	103.3	Calvert	11.58	0.54	14.77	30.57	18.32	14.73	530.43	61.36
Hd25-07	110255-01	376.7	Manasquan	3.67	0.30	55.37	24.16	34.27	8.08	800.02	86.26
Hd25-07	110290-01	444	Vincentown	2.15	0.07	34.72	19.89	20.40	6.89	1433.71	51.36
Hd25-07	110315-01	484.7	Navesink	4.12	0.29	87.98	23.56	22.35	5.38	552.32	69.67
Hd25-07	110332-01	516	Mt. Laurel	20.48	0.93	194.76	40.74	24.46	10.18	572.87	208.11
Hd25-07	110385-01	613	Marshalltown	10.67	0.22	33.98	19.28	17.56	4.86	1650.90	35.86
Hd25-07	110408-02	662.2	Englishtown	10.71	0.06	46.27	27.84	11.31	8.66	940.74	52.25
Hd25-07	110430-01	707.2	Merchantville	18.33	0.05	26.84	27.03	17.13	9.19	907.20	90.20
Hd25-07	110448-01	751.6	Merchantville	43.45	0.16	43.87	38.93	37.59	16.72	859.41	79.09
Hd25-07	110480-01	809.75	Magothy	7.90	0.02	11.07	35.58	20.72	15.84	691.29	54.28

Appendix 4. Results of hydraulic tests. *Unit does not function as an aquifer at this location.

DGS Well Identifier	Aquifer	K (ft/d)
Eb43-22	Englishtown/Mt. Laurel	15
Eb43-23	Englishtown/Mt. Laurel	21
Fb23-29	Columbia/Rancocas	80
Fb23-38	Columbia	110
Fb23-70	Magothy	29
Fb23-71	Mt. Laurel	27
Fb24-15	Columbia/Rancocas	11
Fc31-49	Mt. Laurel	2
Fc42-11	Mt. Laurel	4
Fc42-11	Mt. Laurel	10
Fc42-15	Rancocas	24
Fc42-36	Magothy*	0.0033
Gb13-13	Rancocas	53
Gb13-14	Magothy*	0.0032
Gb13-15	Mt. Laurel	77
Gb13-16	Rancocas	58
Gb33-08	Rancocas	18
Gb55-05	Mt. Laurel	56
Gb55-06	Rancocas	105
Gb55-08	Columbia	237
Gb55-08	Columbia	240
Gd33-07	Columbia	21
Gd33-08	Mt. Laurel	230
Gd33-09	Rancocas	11
Hb12-05	Columbia	6.1
Hb12-06	Mt. Laurel	3.6
Hb12-07	Rancocas	66
Hc11-13	Rancocas	53
Hc34-43	Rancocas	0.91
Hc35-26	Mt. Laurel	2.3
Hc35-27	Rancocas	1.6
Hd25-09	Piney Point	0.53
Hd25-10	Mt. Laurel	13
Hd25-11	Columbia	330

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