Prepared in cooperation with the U.S. Air Force

Regional Hydrostratigraphic Framework of Joint Base McGuire-Dix-Lakehurst and Vicinity, New Jersey, in the Context of Perfluoroalkyl Substances Contamination of Groundwater and Surface Water

Open-File Report 2019–1134

U.S. Department of the Interior
U.S. Geological Survey

Cover. Clay-sand facies of the Cohansey Formation exposed in a gully, Manchester Township, New Jersey. Notebook for scale.

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DAVID BERNHARD, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
cubic inch (in^3)	0.01639	liter (L)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

AFFF	aqueous film forming foam
AFCEC	U.S. Air Force Civil Engineer Center
CSM	conceptual site model
DWPS	drinking water protection study
EPA	U.S. Environmental Protection Agency
JBMDL	Joint Base McGuire-Dix-Lakehurst
NJDEP	New Jersey Department of Environmental Protection
PFAS	per- and polyfluoroalkyl substances
PFHxS	perfluorohexanesulphonic acid
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
USGS	U.S. Geological Survey

Regional Hydrostratigraphic Framework of Joint Base McGuire-Dix-Lakehurst and Vicinity, New Jersey, in the Context of Perfluoroalkyl Substances Contamination of Groundwater and Surface Water

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Abstract

A study was conducted by the U.S. Geological Survey, in cooperation with the U.S. Air Force, to describe the regional hydrostratigraphy of shallow aquifers and confining units underlying Joint Base McGuire-Dix-Lakehurst (JBMDL) and vicinity, New Jersey, in the context of contamination of groundwater and surface water by per- and polyfluoroalkyl substances (PFAS) potentially originating from JBMDL sources. The aquifers studied are two that crop out within JBMDL boundaries—the Kirkwood-Cohansey aquifer system and the Vincentown aquifer—and another aquifer near JBMDL that does not crop out at land surface—the Piney Point aquifer. The unconfined portion of the Vincentown aquifer and portions of the Kirkwood-Cohansey aquifer system that overlie the unconfined portion of the Vincentown aquifer are consolidated into, and described as, a single, separate unconfined aquifer system. Regionally extensive clay subunits that potentially create semiconfined hydrologic conditions within the mostly unconfined Kirkwood-Cohansey aquifer system also are identified. Two confining units were studied—the Manasquan-Shark River confining unit underlying the Kirkwood-Cohansey aquifer system, which includes the basal confining sediment in the Kirkwood Formation, and the Navesink-Hornerstown confining unit underlying the Vincentown aquifer. The hydrostratigraphic units are defined using available borehole geophysical logs, lithologic logs, and (or) drillers' logs from 131 wells and are presented in a series of 8 aquifer structure maps and 12 cross sections. The framework positions JBMDL into a regional hydrostratigraphic structure for which higher-resolution delineation of the shallow aquifers can be constructed to determine potential pathways of PFAS contamination in groundwater to off-site drinking water wells in areas adjacent to JBMDL.

Introduction

Joint Base McGuire-Dix-Lakehurst (JBMDL) is a triservice military installation composed of McGuire Air Force Base, Army post Fort Dix, and Naval Air Engineering Station Lakehurst and covers about 42,000 contiguous acres (66 square miles) in Burlington and Ocean Counties in New Jersey (fig. 1). The U.S. Air Force Civil Engineer Center (AFCEC) is evaluating groundwater contamination issues associated with per- and polyfluoroalkyl substances (PFAS) at JBMDL, including perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), and perfluorononanoic acid (PFNA). Most of the PFAS have been introduced by fire-suppressing aqueous film forming foam (AFFF), which originated at multiple fire training areas, AFFF storage or disposal areas, or past aircraft, vehicle, or fuel fires on the base. Concerns that PFAS have migrated to civilian domestic wells in areas adjacent to JBMDL has prompted AFCEC to initiate a Drinking Water Protection Study (DWPS) to investigate the multiple releases of PFAS within the hydrologic system and provide a higher-resolution update to the hydrogeologic conceptual site model (CSM) previously developed by AECOM (2010). Five reconnaissance areas have been delineated by the Air Force in neighborhoods adjacent to the JBMDL boundary (fig. 1) where off-base civilian domestic wells are potentially at risk for PFAS contamination by on-base sources (HGL, 2011).

New Jersey, through the New Jersey Department of Environmental Protection (NJDEP), became the first State to adopt a maximum contaminant level and water-quality standard for any PFAS. In 2018, a groundwater quality standard of 13 parts per trillion (ppt; 13 nanograms per liter) was adopted by the State for PFNA. NJDEP announced an interim groundwater quality criterion of 10 ppt for PFOA and PFOS in

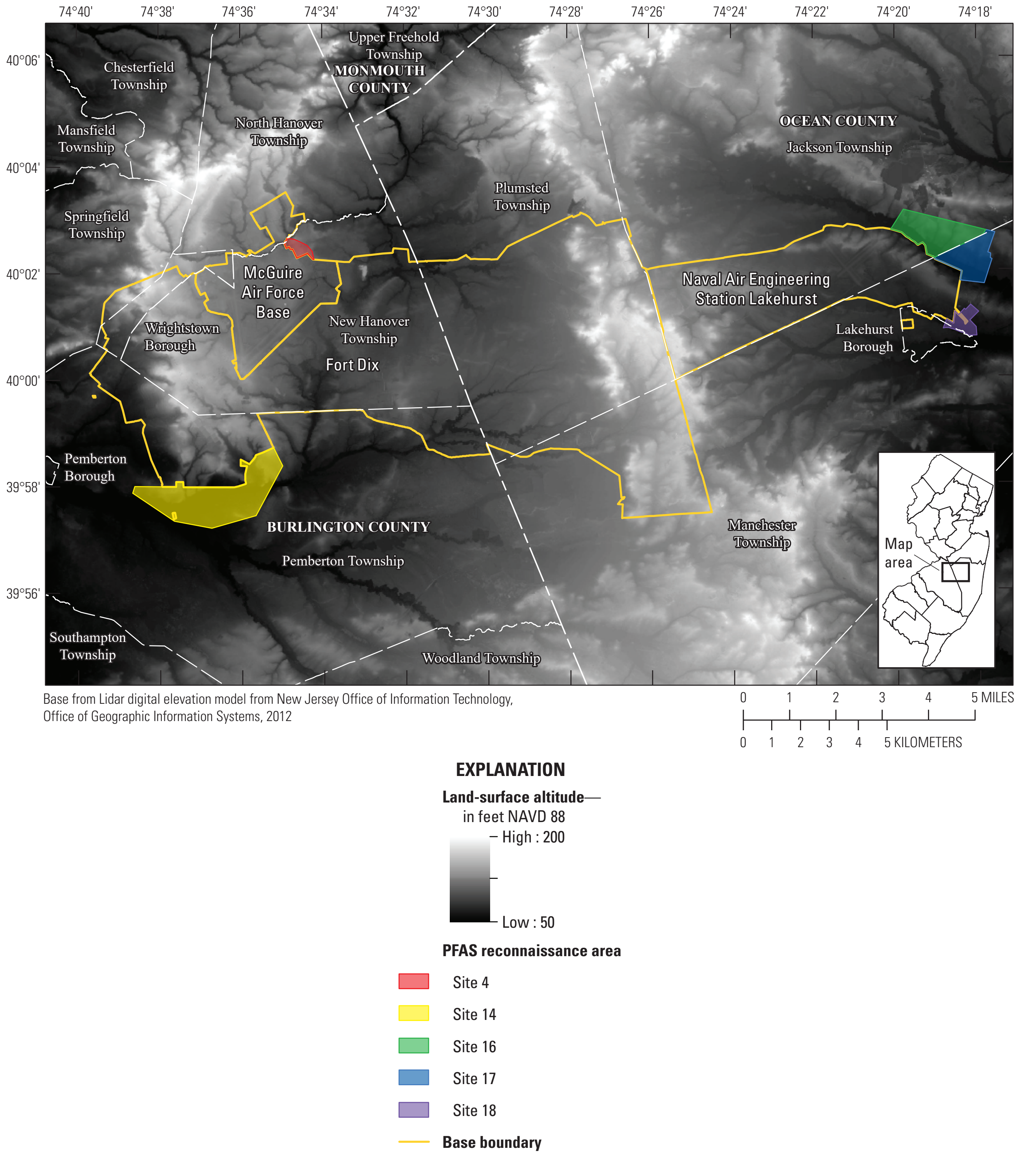

Figure 1. Location of Joint Base McGuire-Dix-Lakehurst and reconnaissance areas, New Jersey. (NAVD 88, North American Vertical Datum of 1988; PFAS, per- and polyfluoroalkyl substances)

a press release on January 18, 2019 (NJDEP, 2019). In 2016, the U.S. Environmental Protection Agency (EPA) issued a non-regulatory lifetime Health Advisory of 70 ppt for individual and combined PFOA and PFOS in drinking water (EPA, 2019). Studies indicate that exposure to PFOA and PFOS at greater than certain levels may result in adverse health effects (EPA, 2019).

The U.S. Geological Survey (USGS), in cooperation with the U.S. Air Force, conducted a study of the regional-scale hydrostratigraphic framework of shallow aquifers underlying JBMDL and vicinity and provided data for use in the ongoing DWPS in the updating of the CSM being performed by contractors of the U.S. Army Corps of Engineers. The framework includes the two aquifers that crop out within JBMDL boundaries—the Kirkwood-Cohansey aquifer system and the Vincentown aquifer, another shallow aquifer in the vicinity of the JBMDL—the Piney Point aquifer, and two interlying confining units amongst these aquifers—the Manasquan-Shark River and Navesink-Hornerstown (table 1). Assessing the structure of these aquifers and confining units at a regional scale provides a better understanding of the overall hydrostratigraphic context into which the higher-resolution CSM hydrogeology can be situated. Positioning the CSM regionally is essential given the large geographic area of JBMDL, the multiple source areas of PFAS, and the groundwater flow distances the PFAS can potentially travel to civilian drinking water wells outside the boundaries of JBMDL.

Purpose and Scope

This report describes the extent and configuration of the Kirkwood-Cohansey aquifer system, Piney Point aquifer, confined portion of the Vincentown aquifer, and unconfined portion of the Vincentown aquifer that includes overlying portions of the Kirkwood-Cohansey aquifer system in the vicinity of JBMDL. The extent and configuration of the Manasquan-Shark River and Navesink-Hornerstown confining units and potential regional confining or semiconfining subunits within the Kirkwood-Cohansey aquifer system also are described. The hydrostratigraphic framework is presented in a series of 12 cross sections and 8 maps developed primarily through correlations of borehole geophysical logs, lithologic logs, and drillers' logs collected from 131 wells during previous investigations. The framework will provide the regional hydrostratigraphic context to the U.S. Army Corps of Engineers contractors who are updating the CSM of JBMDL and provide the overall setting for concurrent PFAS-related studies at JBMDL and vicinity. The hydrostratigraphy also can serve as

Table 1. Stratigraphic relations between selected hydrogeologic units and geologic formations in the vicinity of Joint Base McGuire-Dix-Lakehurst, New Jersey.

[Modified from Sugarman and others (2013, 2018a, b), Rea (2017), and Zapecza (1989)]

<table>
<tr><th>Geologic Epoch[1]</th><th>Formation name</th><th colspan="2">Hydrogeologic unit</th></tr>
<tr><td>Holocene
Pleistocene
Pliocene</td><td>Surficial units</td><td colspan="2" rowspan="2">Kirkwood-Cohansey aquifer system</td></tr>
<tr><td rowspan="2">Miocene</td><td>Cohansey Formation</td></tr>
<tr><td>Kirkwood Formation</td><td rowspan="3">Manasquan-Shark River confining unit</td><td></td></tr>
<tr><td rowspan="2">Eocene</td><td>Shark River Formation</td><td>Piney Point aquifer</td></tr>
<tr><td>Manasquan Formation</td><td rowspan="6">Composite confining unit</td></tr>
<tr><td rowspan="2">Paleocene</td><td>Vincentown Formation</td><td>Vincentown aquifer</td></tr>
<tr><td>Hornerstown Formation</td><td rowspan="4">Navesink-Hornerstown confining unit</td></tr>
<tr><td rowspan="5">Late Cretaceous</td><td>Tinton Sand[2]</td></tr>
<tr><td>Red Bank Sand[2]</td></tr>
<tr><td>Navesink Formation</td></tr>
<tr><td>Mount Laurel Formation</td><td colspan="2" rowspan="2">Wenonah-Mount Laurel aquifer</td></tr>
<tr><td>Wenonah Formation</td></tr>
</table>

[1]Oligocene units are not present in the study area and are not included on this chart.

[2]The Red Bank Sand and Tinton Sand are minor aquifers in Monmouth County, New Jersey, but are not mapped in Burlington and Ocean Counties.

the basis for the subsurface hydrogeologic structure for inclusion in a USGS-developed groundwater flow simulation model of JBMDL.

Area of Investigation

The JBMDL regional study area, as delineated in this report, is defined by the outcrop area of the Navesink-Hornerstown confining unit in the northwest, the presumed groundwater flow boundary created by the Toms River and its tributaries in the northeast and southeast, and the presumed groundwater flow boundary created by the North Branch Rancocas Creek and its tributaries in the southwest (pl. 1). These boundaries were chosen to represent the overall unconfined groundwater flow domain for JBMDL and vicinity.

The study area spans northern Burlington and Ocean County, and a small area of southern Monmouth County (fig. 1; pl. 1). Municipalities in close proximity to JBMDL include Springfield Township, North Hanover Township, New Hanover Township, Wrightstown Borough, and Pemberton Township in Burlington County, and Plumsted Township, Jackson Township, Lakehurst Borough, and Manchester Township in Ocean County (fig. 1)

Previous Investigations

The hydrogeology of the area encompassed by JBMDL is discussed in the preliminary CSM by AECOM (2010). Work on the hydrostratigraphy of McGuire Air Force Base and portions of Fort Dix was completed in 1996 (O. Zapecza, U.S. Geological Survey, written commun., 1996). Fiore (2016), Szabo and others (2005), and Jacobsen (2000) provided site-scale hydrogeologic information for shallow portions of the Kirkwood-Cohansey aquifer system for small geographic areas in Fort Dix but provide limited hydrostratigraphic context. Walker and others (2008) developed a Kirkwood-Cohansey aquifer system framework for a drainage basin close to the southwestern border of JBMDL.

Zapecza (1989) provided a regional-scale hydrostratigraphic framework for the entire New Jersey Coastal Plain. County-specific aquifer maps and sections, and other hydrologic information, are available for Ocean County (Sugarman and others, 2013; Anderson and Appel, 1969) and Burlington County (Sugarman and others, 2018a; Rush, 1968). The hydrostratigraphy of large portions of Ocean County has been delineated in other groundwater studies (Mullikin, 2011; Cauller and others, 2016; Fiore and others, 2018).

Bedrock and (or) surficial 1:24,000-scale geologic maps of USGS 7.5-minute quadrangles that contain parts of JBMDL are available in reports by Minard and Owens (1962), Owens and Minard (1962), Minard and Owens (1963), Owens and Minard (1964), Stanford (2016), and Sugarman and others (2016). Other 1:24,000-scale geologic maps of the study area, but not containing parts of JBMDL, are available in reports by Minard (1964), Sugarman and others (1991, 2018b), Stanford (2000a, b), and Stanford and Sugarman (2017).

Well Numbering System

This report utilizes a well-numbering system used by USGS in New Jersey since 1978. The unique well number consists of a numerical two-digit county code followed by a four-digit sequence number. In this report, the county codes used are 05, Burlington County; 25, Monmouth County; and 29, Ocean County. For example, well 050330 is the 330th well inventoried in Burlington County. With this method, each well has a unique identifier. Table 2 includes the unique identifiers for wells located on JBMDL that are used in this report, along with the names used locally at JBMDL.

Data and Methods

The correlations used in this hydrostratigraphic framework are primarily based on existing borehole geophysical logs and (or) detailed lithologic descriptions by the USGS, New Jersey Geological and Water Survey, or others from 131 wells in or near the study area (table 3, in a separate file on the web page). Some wells outside the study area were used to fill data gaps where no wells were present in the study area. No new data were collected by the USGS for hydrostratigraphic analysis in this study. All logs used in this report are accessible in the online USGS GeoLog Locator database (U.S. Geological Survey, 2019a).

Borehole geophysical logs allow for the delineation of aquifers and confining units in the subsurface. Two types of borehole geophysical logs were used in this study, natural gamma logs and resistivity logs. Fine-grained, low permeability sediments generally have larger quantities of gamma-emitting radioisotopes, such as potassium-40, and are less resistive to the flow of electrical current than other sediments; thus, inflections to the right on a natural gamma log and inflections to the left on a resistivity log generally correspond to clays and silts (Keys, 1990).

Drillers' logs were used in areas where no other data sources were available. Given that drillers' logs are inherently less consistent in terms of descriptions and accuracy of depths and sediment textures compared to coring and descriptions by geologists, the structure of the units is considered approximate and not necessarily an exact representation; depths of actual subsurface conditions are also approximate.

Topographic contouring of the top and bottom altitudes and thicknesses of hydrostratigraphic units was performed manually. The contour lines were then rasterized electronically using an iterative finite-difference interpolation process in the geographic information system (Esri, 2018). Some wells, particularly those in close proximity to others but for which aquifer structure depths and altitudes may differ, may not appear to be perfectly within the contours illustrated on the maps as a result of this technique.

Table 2. Identifiers for wells on Joint Base McGuire-Dix-Lakehurst, New Jersey.

[NWIS, U.S. Geological Survey National Water Information System database]

NWIS site number	Unique identifier	Local name
395949074365501	050330	Fort Dix 4
400034074362101	050331	Fort Dix 1
400105074352101	050332	Fort Dix 5
400129074365601	050333	Fort Dix 2
400138074375301	050334	Fort Dix 3
400141074352501	050335	McGuire D
400216074360701	050337	McGuire A (old)
400300074351701	050340	McGuire B
395938074374201	050388	Fort Dix 6
395941074325001	050754	Range HQ 7
400148074352001	051250	08-MW-52
400148074352101	051251	08-MW-102
400057074382301	051319	MAG-71
400056074382801	051326	MAG-69
400154074381901	051365	DXGB-4
395953074332601	051416	R&G Club Range 14
400156074342401	051795	McGuire C
400048074341701	051901	ASP-1
395851074365501	051938	MW-3D
400210074354201	051992	McGuire A-R
400055074382501	052018	MAG-106C
400101074354001	052019	00-PZ-102
400115074375701	052020	GTG-02
400144074352601	052021	00-PZ-103
400146074340201	052022	00-PZ-104
400217074360901	052023	00-PZ-101
400218074343901	052024	BGMW-6D
400105074224401	290118	Lakehurst 32
400101074224301	291265	Lakehurst 45
400144074192801	291577	Lakehurst 48
400207074303201	291578	Fort Dix Brindle Lake
400148074313001	292196	ARDEC-1
395736074255001	292238	COL Liberty PW-2

Table 3. Wells used to develop a hydrostratigraphic framework, and interpreted aquifer structure points, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey.

[NWIS, USGS National Water Information System database; lidar, light detection and ranging; ft, feet; NAVD 88, North American Vertical Datum of 1988; --, not applicable; G, natural gamma log; R, resistivity log; L, lithologic log; D, driller log. Table 3 is downloadable as a CSV file from https://doi.org/10.3133/ofr20191134]

Hydrostratigraphic Framework

The hydrostratigraphic framework and the geometry of the aquifer units are presented in a series of 8 maps (pls. 2–9) and 12 cross sections (pls. 10–12). Maps delineate the structural contours for the bottom of the Kirkwood-Cohansey aquifer system, the top of the regional semiconfining subunits within the Kirkwood-Cohansey aquifer system, the thickness of these subunits, the top of the Piney Point aquifer, the top of the confined portion of the Vincentown aquifer, the thickness of the confined portion of the Vincentown aquifer, the bottom of the unconfined portion of the Vincentown aquifer, and the bottom of the Navesink-Hornerstown confining unit. Altitudes for each aquifer and confining unit are given on the associated map and in table 3; wells without an altitude value either do not penetrate the given aquifer or the log quality was deemed too poor to determine a value for that particular unit at that site. Lines of section A–A′ through L–L′ are aligned roughly subparallel to the northwest–southeast direction of dip, and each extends to an altitude of -300 feet (ft) to encompass each of the aquifers included in the study area.

Surficial deposits commonly overlie the Coastal Plain formations at land surface and can be up to 100 ft thick (Stanford and others, 2007). Where present, the surficial deposits are assumed to be part of the aquifer over which they reside. Thus, the altitude of the top of each hydrologic unit in its outcrop area would equate to land-surface altitude. A similar treatment is given to the outcrop areas in Sugarman and others (2013, 2018b), but Zapecza (1989) does not consider outcrop areas part of that hydrostratigraphic unit.

Borehole geophysical logs used in developing the framework are shown directly on the cross sections. The wells with borehole geophysical logs used for the framework are listed in table 3. For wells with gamma logs and resistivity logs available for the same well, only gamma logs are shown on the cross section for ease of viewing. Drillers' logs and lithologic logs discussed in this report are provided in appendix 1.

Kirkwood-Cohansey Aquifer System

The Kirkwood-Cohansey aquifer system consists of the Miocene-age Kirkwood Formation and Cohansey Formation, as well as younger surficial formations such as the Beacon Hill Gravel (not shown in a figure) in some locations. The Kirkwood-Cohansey aquifer system primarily consists of fine- to coarse-grained sand with interbedded lenses of clay-silt and locally prevalent gravel lenses (Sugarman and others, 2013). The sediments in the Kirkwood-Cohansey aquifer system typically are in shades of brown, red, yellow, gray, and white (Stanford, 2013, 2016). The Cohansey Formation may be cemented with iron oxide in some locations, and the Kirkwood Formation contains some mica (Stanford, 2013, 2016); these features can reasonably be used as identifying characteristics of the Kirkwood-Cohansey aquifer system in drillers' logs.

The bottom of the Kirkwood-Cohansey aquifer system is equivalent to the top of the Manasquan-Shark River confining unit. The basal portion of the Kirkwood-Formation is primarily composed of silt and clay (Sugarman and others, 2016) and is included with the underlying confining unit (Manasquan-Shark River) rather than the Kirkwood-Cohansey aquifer system. Outliers of the Kirkwood Formation and Cohansey Formation are present in topographically high, updip areas (Sugarman and others, 2013, 2018b). These outliers are isolated occurrences of Kirkwood Formation or Cohansey Formation not hydraulically connected to the Kirkwood-Cohansey aquifer system and thus not considered part of the aquifer system in this report. Instead the outliers are regarded as surficial deposits overlying other hydrostratigraphic units.

Contours of the altitude of the bottom of the Kirkwood-Cohansey aquifer system are depicted in plate 2. In the study area, the altitude of the bottom of the Kirkwood-Cohansey aquifer system ranges from more than 135 ft to less than -145 ft. Within JBMDL, the bottom of the Kirkwood-Cohansey aquifer system is shallowest at an altitude of about 124 ft at well 051365 on section C–C′ where it is mapped as overlying the unconfined portion of the Vincentown aquifer, described below. The altitude of the bottom of the aquifer system may reach 140 ft farther updip from well 050340 on section F–F′. The Kirkwood-Cohansey aquifer system is deepest at JBMDL at an altitude of about -53 ft at well 292238 on section G–G′ (pl. 2) but may reach as deep or deeper at the southeasternmost corner of Lakehurst between wells 291577 and 290429 on section J–J′. Given the higher altitude at well 292238, that location is where the Kirkwood-Cohansey aquifer system is thickest at JBMDL. The Kirkwood-Cohansey aquifer system is thinnest updip along the outcrop areas and is particularly thin at JBMDL near the Site 4 reconnaissance area (pl. 11) and updip from well 052021 on section E–E′ where the aquifer is generally less than 20 ft thick (pl. 10).

Contours of the bottom of the aquifer system indicate an undulating topography that appears to plateau or level off in some areas owing to a slightly higher altitude of the Kirkwood-Cohansey indicated at some wells compared to others along the strike direction. The most noticeable of these plateaus is the large zone of 0- to 20-ft altitude south of the Site 14 reconnaissance area. On JBMDL, the bottom of the Kirkwood-Cohansey aquifer system appears to plateau around 100–120 ft on the western side of McGuire Air Force Base and part of Fort Dix, as indicated by wells on sections C–C′ and D–D′. Much of this leveling off is caused by the interpreted 108-ft altitude at well 050331 on section C–C′. The lithologic log for this well describes a yellow fine-grained sand from the 0- to 26-ft depth below land surface, underlain by a yellow very fine-grained clayey sand from 26 to 58 ft; no sample was collected from 58 to 65 ft, and a greenish-grey sandy clay and glauconite was present at 65 to 174 ft (app. 1). The bottom of the Kirkwood-Cohansey aquifer system, the entire Manasquan-Shark River confining unit, and the top of the Vincentown aquifer are not clear in this log, primarily owing to the unknown lithology from the 58- to 65-ft depth and the lack of detailed lithology from the 65- to 174-ft depth. The upper 26 ft was assumed to be the Kirkwood-Cohansey aquifer system, which corresponds to a bottom altitude of 108 ft, but the clayey sand from 26 to 58 ft may also be Kirkwood-Cohansey aquifer system, in which case the bottom altitude would occur at 76 ft, which is also reasonable. The 26-ft depth was used because the 65-ft depth indicates a reasonable approximation for the top of the Vincentown aquifer and because the other wells farther downdip on section C–C′ also indicate shallower Kirkwood-Cohansey aquifer system bottom altitudes compared to the wells around it.

Because the Kirkwood-Cohansey aquifer system is the largest unconfined aquifer system at JBMDL by area, it seems likely that the Kirkwood-Cohansey aquifer system would contain most of the PFAS contamination in groundwater on JBMDL. The hydrogeologic heterogeneity and complexity in the Kirkwood-Cohansey aquifer system need to be considered when interpreting potential groundwater flow paths and PFAS migration pathways.

Semiconfining Subunits Within the Kirkwood-Cohansey Aquifer System

Despite being categorized as an unconfined aquifer, the low-permeability clay subunits in the Kirkwood-Cohansey aquifer system create high vertical and horizontal heterogeneity and can cause semiconfined conditions and perched water tables within the aquifer (Zapecza, 1989; Sugarman and others, 2013; Fiore and others, 2018). The subunits of interbedded clays can be continuous over several miles (Stanford, 2016). Clays in the Kirkwood-Cohansey aquifer system can be rich in organic carbon when deposited in back-bay settings, making them black in color (Stanford, 2013; Stanford, 2016). These areas of high organic carbon have high sorption potential for PFAS compounds in the subsurface, which would pose an important consideration in assessing the fate, transport, and remediation of PFAS. Thus, mapping the extent and configuration of these subunits within the Kirkwood-Cohansey aquifer system that extend regionally across large portions of the study area is important for full characterization of the aquifer.

The top altitudes and thicknesses of the subunits within the Kirkwood-Cohansey aquifer system that may cause semiconfined conditions within the aquifer are shown in plates 3 and 4, respectively. Six subunits were substantial enough to be identified in the study area. Another subunit was identified at well 051390 on section A–A′, but it did not correlate well with others around it and is assumed to be part of another subunit outside the study area. The top surface of each of these identified subunits strikes parallel to the general strike of the Kirkwood-Cohansey aquifer system and is thicker in the middle and thinner around the edges. The top surfaces of 4 of the 6 subunits share the same general southeastern dip direction of the Kirkwood-Cohansey aquifer system. The top surfaces of the subunit spanning from well 050683 on section A–A′ to 290425 on section G–G′ and the subunit from well 051597 on section B–B′ to wells 051600 and 050357 on section F–F′ dip generally toward the northwest. This inconsistency likely stems from the composition of these subunits; they may be composed of a series of interbedded clays and sands rather than a single large clay lens. Although mapped as one subunit, it may in reality consist of multiple small subunits whose geometry is obscured by the resolution of this mapping and is susceptible to subjective interpretations. For example, Walker and others (2008) consider the subunit at wells 051556 and 051560 on section C–C′ to extend to well 051597 on section B–B′, but for this study it is considered to be two separate subunits. Therefore, the geometry of these units is considered a general conceptualization of regional importance and is not assumed to be local ground truth without further testing and data. Similarly, other clay lenses may be present within the Kirkwood-Cohansey aquifer system besides those mapped here, but additional data and higher resolution mapping are required to fully locate their presence.

Two regional subunits are mapped in proximity to a PFAS reconnaissance area. Notably, a subunit based on wells 291265, 291380, 291577, and 292043 spans a large portion of the Lakehurst installation of JBMDL, from section H–H′ through off-site well 292043 on section L–L′. This subunit underlies PFAS reconnaissance areas sites 16, 17, and 18, where the bottom of the Kirkwood-Cohansey aquifer system is deeper than at the other reconnaissance areas. Many domestic wells in these reconnaissance areas are screened in the Kirkwood-Cohansey aquifer system, so hydrologic heterogeneity caused by this subunit could have an effect on the groundwater flow system around those wells. The presence of a low-permeability subunit at well 291265 is based on the high gamma intensities for that well from about 40 to 20 ft in altitude (pl. 11), which falls into an interval on the drillers' log described as "brown clay and sand" (app. 1). Nearby well 290118 has only a drillers' log that does not indicate a clay at this location (app. 1). However, that drillers' log is less detailed, and it is assumed this subunit was missed.

Well 291380 on section I–I′ has high gamma intensity from about 25 to 15 ft in altitude (pl. 11), which correlates into a "clay, brown" interval on a low-resolution drillers' log (app. 1). On section J–J′, a "brown sand and clay" described on the drillers' log for well 291577 at Lakehurst (app. 1), correlated to high gamma intensity from altitudes of 20 to -5 ft, is also assumed to be part of this subunit (pl. 12). The next downdip well, 290429, indicates no subunit at this depth, so this subunit likely pinches out between 291577 and 290429 beneath Site 18 reconnaissance area. Likewise, no subunit is indicated at wells 290132 and 290134 updip from well 291577 on section J–J′, so the updip pinch out of the subunit likely occurs somewhere beneath Site 16 and Site 17 reconnaissance areas. A 10-ft-thick clay was described on the drillers' log of well 292043 on section L–L′ (app. 1), which is assumed to be near the easternmost extent of this subunit.

Another subunit is present near PFAS Site 14 reconnaissance area on the southwestern side of Fort Dix. This subunit may overlap Site 14, based on its identification in wells 051769 on section B–B′ and 050737 on section C–C′. The drillers' log for well 051769 indicates a "silty grey clay" at a large interval from about the 21- to 76-ft depth (app. 1). The 21-ft depth is assumed to be the top of the subunit at an altitude of 59 ft, and the bottom of this subunit is assumed to extend to near the bottom of the Kirkwood-Cohansey aquifer system. If so, the location near this well would be the thickest part of the subunit, but there is low likelihood that there is enough aquifer material underlying this subunit at this location from which a domestic well could be pumping groundwater. The subunit is thinner at well 050737 on section C–C′, which has a gamma log indicating elevated gamma intensity from about 62 to 72 ft in altitude (pl. 10), and indicates the subunit pinches out updip from this well before reaching updip wells 050796, 050380, and 050714, which are in Site 14 reconnaissance area.

The northeastern extent of the subunit may extend to well 051179 on section E–E′, based on elevated gamma intensity from about 53 to 45 ft in altitude (pl. 10) that correlates with a "silty, sandy brown clay" described on the drillers' log (app. 1). The presence of this subunit near well 051179 is noteworthy because of the detection of high levels of PFAS, predominantly PFOS and perfluorohexanesulphonic acid (PFHxS), in surface water, sediment, and fish tissue in this area (Goodrow and others, 2018) and the presence of domestic wells screened in the Kirkwood-Cohansey aquifer system in the surrounding neighborhood that may be exposed to the contaminants. If these domestic wells are screened below this subunit and above the regional bottom of the Kirkwood-Cohansey aquifer system, then the subunit may semiconfine, or perhaps fully confine, the groundwater that is pumped to these wells and limit flow and transport pathways of PFAS from potential surficial sources. However, more data and a higher density of well logs in this area are needed to fully characterize the hydrogeology of this area.

Piney Point Aquifer

The Piney Point aquifer is within the Shark River Formation and consists of fine-to-very coarse glauconitic quartz sand that grades into finer sediments downdip (Sugarman and others, 2013, 2018b). The entirety of the Piney Point aquifer is confined, so nowhere does it crop out at land surface. Plate 5 depicts the altitude of the top of the Piney Point aquifer. The closest proximity of JBMDL to the updip limit of the Piney Point occurs approximately 9,500 ft downdip from well 292238 along section G–G′.

The Piney Point aquifer is shallowest in the study area near well 290085 on section K–K′, where the altitude of the top of the aquifer is about -150 ft. At this location, the top of the Piney Point aquifer is approximately 75 ft deeper than the bottom of the Kirkwood-Cohansey aquifer system. The Piney Point is deepest at well 292183 along section I–I′ where the top altitude is -270 ft.

Cauller and others (2016) suggest that groundwater in the Piney Point aquifer near the updip limit might have hydraulic connection with the Kirkwood-Cohansey aquifer system. However, groundwater withdrawals from the Piney Point aquifer are primarily east and south of the study area (DePaul and Rosman, 2015), so the likelihood of receptors in the Piney Point aquifer to potential PFAS contamination from JBMDL is small.

Manasquan-Shark River Confining Unit

The Manasquan-Shark River confining unit underlies the Kirkwood-Cohansey aquifer system and consists of the Eocene-age Manasquan Formation and Shark River Formation. For this report, the lowermost portion of the Kirkwood Formation, which is clayey and silty (Sugarman and others, 2016), is considered to be part of this confining unit rather than the overlying Kirkwood-Cohansey aquifer system, similar to that assumed by Sugarman and others (2018a). The Manasquan Formation is primarily a green, yellow, olive, or gray calcareous clay-silt with glauconite sand in the clayey matrix that coarsens upward into a very fine quartz sand (Sugarman and others, 2016). Some drillers' logs mention a "blue clay" (U.S. Geological Survey, 2019a) that is assumed to be the Manasquan Formation in this report. The Shark River Formation is a gray, olive, green, or brown calcareous clay-silt that coarsens upward into a quartz sand with minor glauconite (Sugarman and others, 2016).

The Manasquan Formation portion of the Manasquan-Shark River confining unit crops out in JBMDL (pl. 1), but the Shark River Formation portion does not crop out in the study area (Sugarman and others, 2013, 2018a). In some areas, the Kirkwood Formation directly overlies the Vincentown Formation updip from the subcrop of the Manasquan Formation, such as in the updip portions of sections B–B′ through F–F′ (pl. 1). The clay-silt facies of the Kirkwood Formation is the only portion of the confining unit between the Kirkwood-Cohansey aquifer system and Vincentown aquifer in these areas, and is as little as 1 ft thick at some locations. In such cases, the confining unit may be semiconfining or not confining at all, even where the Manasquan Formation is present.

Further downdip, the underlying Vincentown Formation grades into low permeability silts and clays that are hydraulically similar to the overlying Manasquan-Shark River confining unit; thus, the Vincentown Formation is no longer considered an aquifer (Zapecza, 1989; Sugarman and others, 2013, 2018a). The Manasquan-Shark River confining unit is therefore considered to be merged with the clays and silts of the Vincentown Formation, the clays and silts of the lowermost Kirkwood Formation overlying the Piney Point aquifer, and the Navesink-Hornerstown confining unit. This amalgam of confining sediment is referred to as the “composite confining unit” (table 1; Zapecza, 1989; DePaul and Rosman, 2015; Cauller and others, 2016; Rea, 2017).

No maps were created for the Manasquan-Shark River confining unit. The top of this unit is equivalent to the bottom of the Kirkwood-Cohansey aquifer system. The bottom of this unit is equivalent to the top of the confined portion of the Vincentown aquifer, where present, or the bottom of the Navesink-Hornerstown confining unit where the Vincentown aquifer grades into the composite confining unit.

Confined Portion of the Vincentown Aquifer

The Vincentown aquifer is a sparsely fossiliferous and glauconitic quartz sand composed of the Vincentown Formation of Paleocene age that grades into finer-grained silts and clays and becomes a confining unit downdip (Zapecza, 1989; Sugarman and others, 2013, 2018a). Zapecza (1989) describes the Vincentown aquifer as more calcareous than glauconitic in Burlington County and more glauconitic than calcareous in Ocean County. Other than direct infiltration in its outcrop area, the Vincentown aquifer receives recharge from the Kirkwood-Cohansey aquifer system where the overlying confining unit is thin or leaky (DePaul and Rosman, 2015; O. Zapecza, U.S. Geological Survey, written commun., 1996). The Vincentown aquifer is unconfined near its outcrop area and becomes confined where overlain by the thick Manasquan-Shark River confining unit. The confined portion of the Vincentown aquifer is discussed in this section; the unconfined portion is described in the section entitled “Unconfined Portion of the Vincentown Aquifer.” The altitude of the top of the confined portion of the Vincentown aquifer is shown in plate 6.

Most groundwater withdrawals from the Vincentown aquifer are made in northern Ocean County where the aquifer is more productive than in Burlington County (DePaul and Rosman, 2015) where it is thinner and less extensive (Sugarman and others, 2018a). The confined portion of the Vincentown aquifer is approximately 12,000 ft wide along dip in the southwest portion of the study area, increasing to approximately 57,000 ft wide along dip in the east and northeast extent of the study area. Few groundwater withdrawals occur from the Vincentown aquifer in Burlington County expect for a few instances of domestic and irrigation well uses (DePaul and Rosman, 2015), so despite the lower water use, there is still potential for Vincentown aquifer wells in Burlington County to be exposed to PFAS.

The highest altitude of the top of the confined Vincentown aquifer is updip from well 290699 on section L–L′, where the altitude is approximately 104 ft. The lowest altitude occurs at the aquifer’s downdip limit either near well 290440, where top of the Vincentown aquifer is approximately -235 ft, or downdip from well 292043 on section L–L′. In JBMDL, the highest altitude of the confined portion of the Vincentown aquifer is near well 050332 at approximately 75 ft on section C–C′, and the lowest altitude is at the aquifer’s downdip extent in the area updip from well 291577 on section J–J′. The map of the altitude of the top of the confined portion of the Vincentown aquifer depicts a plateau occurring near well 050331 on section C–C′ similar to that described previously in the Kirkwood-Cohansey. Because of this discrepancy, less emphasis was assigned to the 69-ft altitude at well 050331 when contouring compared to other wells.

The thickness of the confined portion of the Vincentown aquifer is depicted on plate 7. The thickness was determined by subtracting the altitude of the top of the Vincentown aquifer at a well from the altitude of the bottom of the Vincentown aquifer at that well. The Vincentown aquifer is thickest in the area spanning well 291316 on section K–K′, where the thickness is about 80 ft, to well 290784 on section L–L′, where the Vincentown aquifer is approximately 105 ft thick. The Vincentown aquifer is thinnest at the downdip limit of the aquifer and the updip limit of the outcrop area. The Vincentown aquifer is generally thicker in the Ocean County portion (eastern) of the study area compared to Burlington County (western).

Sugarman and others (2013) denote the overall thickness of the Vincentown aquifer as variable, and this is evident in thickness changes between the eastern McGuire Air Force Base and the western Fort Dix parts of JBMDL. A zone of high thickness is present in the westernmost part of JBMDL around wells 051633 on section A–A′ and 050332 on section C–C′, with thicknesses of about 40 ft and 45 ft, respectively. Another zone of thickness is present around well 051901 on section E–E′ to well 292196 on section G–G′, with thicknesses of about 45 and 42 ft, respectively. Roughly along the strike direction between these two zones, the Vincentown aquifer becomes thinner, decreasing to a thickness of 29 ft and less near well 050333 on section D–D′. Other than the plateau near well 050331, the top of the Vincentown aquifer remains fairly consistent along this strike-parallel band spanning these two areas, which indicates the thickness change is caused by some combination of beveling at the top of the aquifer, variation in the bottom altitude of the aquifer (or top of the underlying Navesink-Hornerstown confining unit), and (or) general facies changes within the Vincentown Formation.

Downdip Limit of the Confined Portion of the Vincentown Aquifer

As stated previously, the Vincentown aquifer grades downdip into a confining unit. Owing to the possibility of PFAS contamination in the Vincentown aquifer and the potential for domestic wells to be screened in the aquifer in or near PFAS reconnaissance areas Site 4 and Site 14, the downdip limit of the Vincentown aquifer is given extra attention and discussion in this report to justify the placement of the aquifer’s extent in the study area.

On section A–A′, the downdip limit of the confined portion of the Vincentown aquifer occurs near well 051613 (pls. 6, 7, and 10). At well 052029, the Vincentown aquifer was interpreted to be from the -68 to -103 ft altitude, based on black sand and shells described in the drillers' log from the 150- to 184-ft depth (app. 1). The presence of the Vincentown aquifer is difficult to determine at the next well to the southeast on section A–A′, 052028, as the drillers' log describes "clayey sands, sand clay mixtures" from depths of 10–160 ft (app. 1) without providing much detail other than sediment color. A "fine black sand and grey clay" is described on the drillers' log for well 051613 at the 140-ft depth (app. 1), which equates to an altitude of approximately -91 ft, which is a reasonable approximation for the top of the aquifer at this location. No bottom altitude of the aquifer was estimated for this well. Logs from the next well on section A–A′, 052026, did not indicate the presence of the Vincentown aquifer, indicating that sediments grade to finer-grained and lower permeability sediments updip from well 052026. Because the only sources of information for all wells from 052029 to 052026 on section A–A′ used to determine the Vincentown aquifer structure are drillers' logs, these estimates are meant to be considered unrefined approximations.

Section C–C′ also has wells near the downdip limit of the Vincentown aquifer: 050714, 050796, and 050380. Wells 050714 and 050796 are about 200 ft apart. The drillers' log for well 050714 describes a sand with streaks of clay from the 182- to 197-ft depth and a black medium sand from the 197- to 219-ft depth (app. 1). These sand zones are assumed to be the Vincentown aquifer, which would place the aquifer from -70 to -104 ft in altitude at well 050714. The drillers' log for well 050796 denotes a "sandy green marl with streaks of sand and gravel" at the 168- to 203-ft depth (app. 1) that may be the Vincentown aquifer, but these depths would correspond to altitudes of -51 to -86 ft, about 20 ft shallower than well 050714 despite the proximity. Therefore, the top of the Vincentown aquifer was assumed to be approximately -60 ft at this location. Notably, the thicknesses of the Vincentown aquifer, based on drillers' logs at these wells, are similar, about 37 ft at well 050714 and 35 ft at well 050796, which allows for more confidence in the approximate thickness of the aquifer at this location compared to the altitude. The Vincentown aquifer at well 050380 on section C–C′ was interpreted to be present from -88 to -102 ft altitude, based on a glauconitic sand-clay identified on the lithologic log and green "marl" on the drillers' log, which was encountered from the 178- to 196-ft depth (app. 1). Many drillers' logs use the term "marl," but such a term may not be the most accurate description, and the drillers' logs are assumed to be referring to glauconitic units in those instances. The Vincentown aquifer is not present on the gamma log of well 050737 (pl. 10), the next well downdip along section C–C′, so the downdip limit of the confined portion of the Vincentown aquifer is present between wells 050380 and 050737.

Section E–E′ terminates at well 051179. The Vincentown aquifer is not present at this well, an interpretation also posited by O. Zapecza (U.S. Geological Survey, written commun., 1996), or at an adjacent well included in Sugarman and others (2018a). If the Vincentown aquifer continued along section E–E′ to well 051179, the top of the aquifer would be present at about the -75 ft altitude, or a depth of 165 ft. This depth would fall in the high intensity zone on the gamma log (pl. 10) and a 124-ft-thick clay zone on the drillers' log (app. 1), which is unlikely to have permeable aquifer material. The Vincentown aquifer is difficult to interpret from a drillers' log at well 050754 on section F–F′. A "clayish" fine sand from 179- to 228-ft depths identified on the drillers' log (app. 1) was assumed to be the Vincentown aquifer, corresponding to altitudes of -80 to -129 ft. Clayey fine sand is often considered part of confining units in the New Jersey Coastal Plain aquifers (Sugarman and others, 2018a), but the assumption that the clayey fine sand is part of the aquifer is reasonable given the ambiguity of the drillers' log, the presence of clay within the sands of the Vincentown aquifer elsewhere in the study area, and the location of well 050754 updip from the downdip limit of the Vincentown aquifer from various studies (fig. 2). Because well 051179 on section E–E′ does not include the Vincentown aquifer, the downdip limit of the aquifer likely occurs between wells 050754 and 051179.

The estimates of the downdip limit of the Vincentown aquifer from various studies in the area are shown in figure 2. The studies include Zapecza (1989), Sugarman and others (2013) in Ocean County, Cauller and others (2016) in Ocean County, Sugarman and others (2018a) in Burlington County, and this study. In Burlington County, the interpreted approximate downdip limits are all fairly close, but the downdip limit in Ocean County is more varied.

Much of this variation of interpretations is caused by well 290134 and well 290132 on section J–J′, which are less than 200 ft apart, and well 290440 east of the study area. Zapecza (1989) does not consider the Vincentown aquifer to be present at well 290134, but Sugarman and others (2013) include the aquifer at adjacent well 290132 (identified as well 29-52272 in that report). Both studies include only 1 of those 2 wells. Gamma intensities on the natural gamma log for well 290132 are intermediate relative to the entire log and lower for the Vincentown portion of the log (pl. 12). The interpreted Vincentown aquifer altitudes, based on the gamma log, are -161 to -200 ft, which equate to depths of 263 to 302 ft. The lithologic log for well 290132 describes a glauconitic and calcareous mixed sand and clay at these depths (app. 1), which is similar to other descriptions of the Vincentown aquifer near the downdip limit. Therefore, for this study the Vincentown aquifer is considered to be present near wells 290132 and 290134. Well 290134 has only a drillers' log, and depths of 262 to 302 ft on this log are within a described green silty marl (app. 1).

The downdip limit of the confined portion of the Vincentown aquifer also occurs between wells 290440 and 290588 east of the study area. Sugarman and others (2013) consider the Vincentown aquifer to be present at well 290440 (identified as well 29-06549 in that study) and to pinch out between wells 290440 and 290588 (identified as well 29-09259 in that study). Cauller and others (2016) do not mention well 290440, but the downdip limit from that study

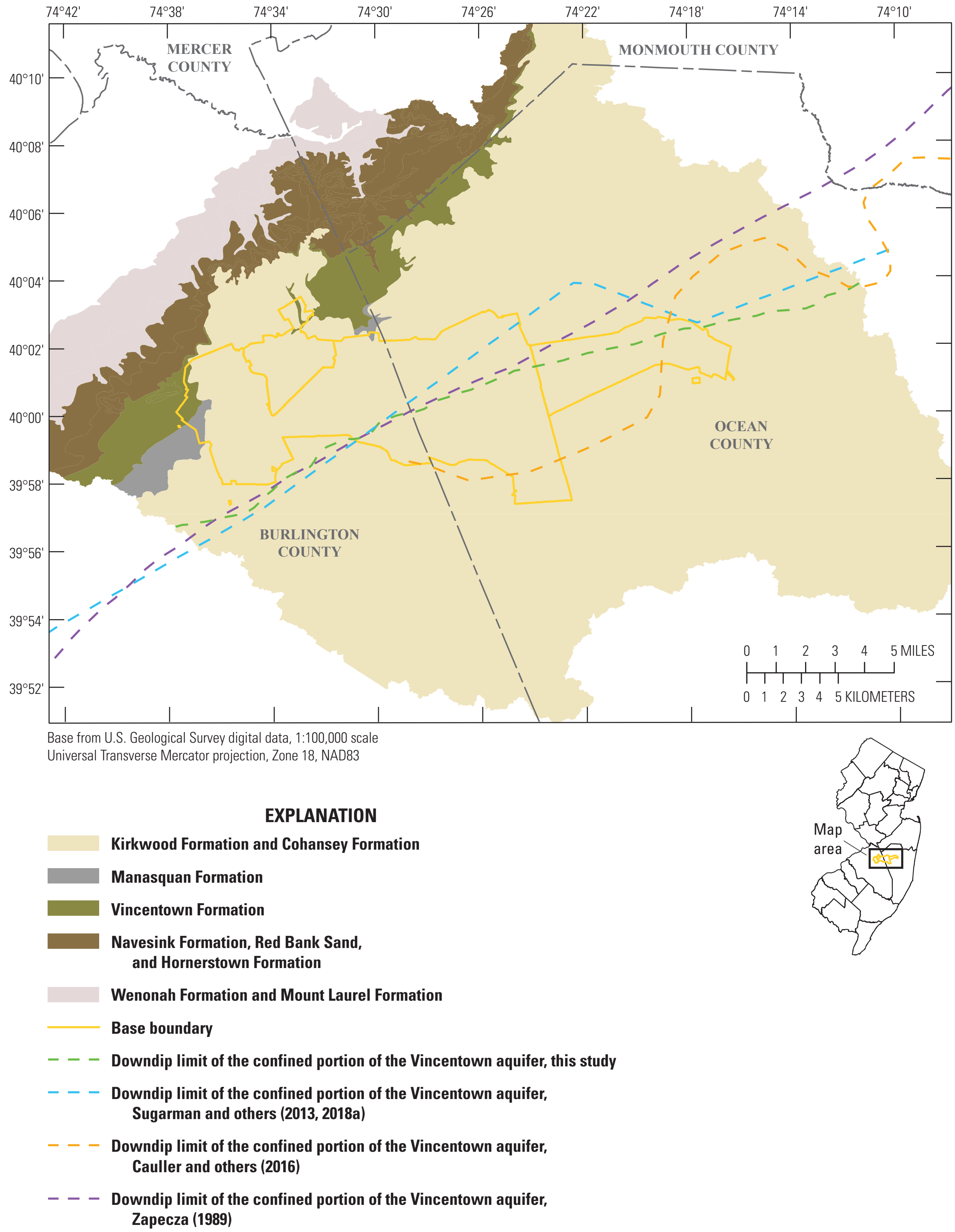

Figure 2. Downdip limit of the confined portion of the Vincentown aquifer in the vicinity of Joint Base McGuire-Dix-Lakehurst, New Jersey, from various publications.

extends to the same location as in Sugarman and others (2013), between wells 290440 and 290588. Zapecza (1989) does not include the Vincentown aquifer at well 290440. Based on the gamma log, the Vincentown aquifer at well 290440 is present between altitudes of -235 to -270 ft (table 3; U.S. Geological Survey, 2019a) or from 302 to 337 ft in depth. Similar to well 290132, the gamma log for well 290440 indicates intermediate intensities in a relatively lower intensity zone at this interval compared to the intensities of the zones above and below, and these depths are situated in a green marl, as described on the drillers' log (app. 1). Well 290588 is entirely clay in this interval, so the well likely does not encounter the Vincentown aquifer at that location.

The downdip limit of the confined portion of the Vincentown aquifer occurs along section L–L′ downdip from well 292043. Zapecza (1989), Sugarman and others (2013), and Cauller and others (2016) do not consider the Vincentown aquifer to be present at this location but did not include well 292043 in their studies. The drillers' log for well 292043 describes a "dark green marl and black sand" from the 295- to 320-ft depth (app. 1), which is assumed to be Vincentown aquifer. These depths equate to aquifer altitudes of approximately -228 to -253 ft at this location, which is reasonable given that the top of the Vincentown aquifer along the strike direction at well 290440 is at an altitude of -235 ft. The drillers' log mentions a "Vincentown shell" about 50 ft shallower (app. 1), but this interval is likely too shallow and likely falls within the Shark River Formation or Manasquan Formation.

Unconfined Portion of the Vincentown Aquifer

The USGS maintains two wells on McGuire Air Force Base in which groundwater levels are continuously monitored: well 051251 (local name 08-MW-102) and well 051250 (local name 08-MW-52) (fig. 3). Well 051251 is screened in the Kirkwood-Cohansey aquifer system, and well 051250 is screened in the Vincentown aquifer (fig. 4; pls. 1 and 7). The wells are approximately 250 ft apart (fig. 3). Hydrographs from these wells indicate a hydraulic connection between the Kirkwood-Cohansey aquifer system and the Vincentown aquifer at this location (O. Zapecza, U.S. Geological Survey, written commun., 1996). A hydraulic connection is also indicated using 2018 groundwater-level data (U.S. Geological Survey, 2019b) because both wells show similar fluctuations of groundwater levels in response to factors such as precipitation (fig. 5). The lithologic log for well 051250 describes a silt unit at depths from about 15 to 25 ft below land surface with sands above and below (app. 1). This interval correlates well with the gamma log, which indicates a 14-ft-thick unit is present at that depth (fig. 4). This silt unit is likely either the Manasquan Formation or the basal portion of the Kirkwood Formation, which is included with the Manasquan-Shark River confining unit.

The hydraulic connection between these aquifers indicates the 14-ft-thick silt unit is not a confining unit of the Vincentown aquifer at this location; thus, the Vincentown aquifer is presumed to be unconfined at this location and at all locations in the study area where a fine-grained silt or clay layer between the Kirkwood-Cohansey aquifer system and Vincentown aquifer is 14 ft thick or less. This 14-ft thickness threshold was arbitrarily doubled to 28 ft to delineate the locations in the study area where the Vincentown aquifer is most likely to have hydraulic connection with the Kirkwood-Cohansey aquifer system. Therefore, where the thickness of the silt unit is 28 ft or less, the Vincentown aquifer is assumed to be more unconfined than confined, and where the thickness is greater than 28 ft, the Vincentown aquifer is assumed to be more confined than unconfined.

Because no additional continuous water levels were measured in other Kirkwood-Cohansey aquifer system and Vincentown aquifer well pairs, it is unknown whether the fine-grained unit is leaky only at this particular location or throughout the study area and at what point the Manasquan-Shark River confining unit thickens enough to minimize leakance and confine the Vincentown aquifer. More monitoring of groundwater levels, aquifer tests, and a higher density of well logs are needed to fully delineate the area where the Vincentown aquifer ceases to be unconfined and becomes confined, a boundary that is realistically gradational with varying degrees of semiconfined conditions in between rather than a line adequately represented by a single isopach.

In this report, the Kirkwood-Cohansey aquifer system and the unconfined portion of the Vincentown aquifer are considered to be a single, separate unconfined aquifer system, similar to past assumptions (O. Zapecza, U.S. Geological Survey, written commun., 1996). The downdip limit of this unconfined aquifer system is therefore mapped as the downdip limit of the unconfined portion of Vincentown aquifer. This boundary represents the 28-ft isopach for the fine-grained units (Manasquan Formation and (or) basal Kirkwood Formation) between the sands of the Vincentown Formation and sands of the Kirkwood and Cohansey Formations. The downdip limit bisects the outcrop area of the Manasquan Formation and includes the entire Vincentown Formation outcrop. The unconfined portion of the Vincentown aquifer is delineated on the cross sections along with the extrapolated updip correlations of the bottom of the Kirkwood-Cohansey aquifer system and the top of the Vincentown aquifer where the interlying silt unit (probably basal Kirkwood Formation) is less than 28 feet thick.

Altitudes of the bottom of the unconfined portion of the Vincentown aquifer are shown in plate 9. Areas where the Cohansey and (or) Kirkwood Formations directly overlie the Hornerstown Formation (pl. 1), such as the area between wells 050442 and 051979, are also included in this aquifer system extent without distinction from the updip limit of the

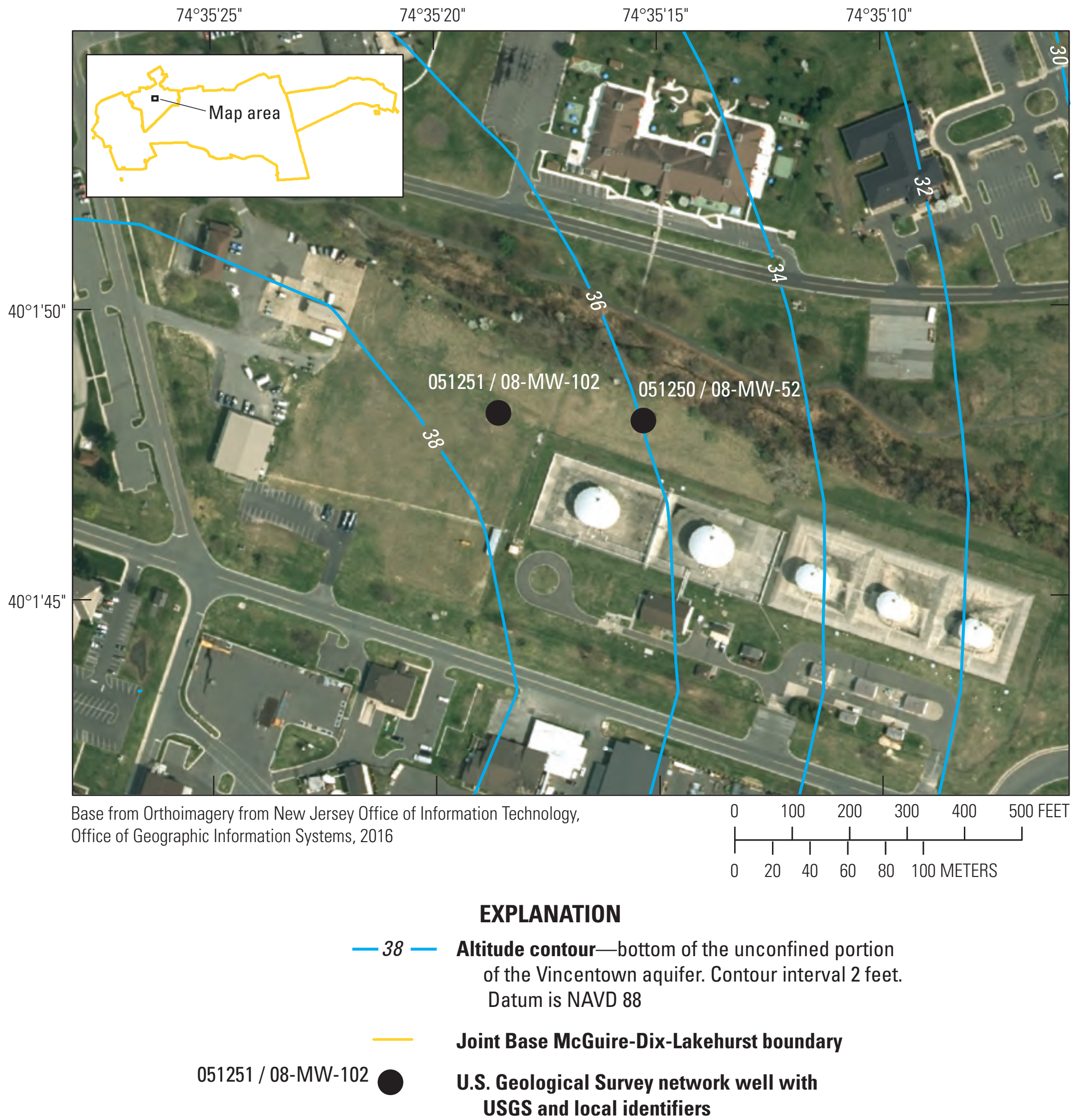

Figure 3. Location of wells 051250 / 08-MW-52 and 051251 / 08-MW-102, Joint Base McGuire-Dix-Lakehurst, New Jersey. (USGS, U.S. Geological Survey; NAVD 88, North American Vertical Datum of 1988)

Vincentown Formation subcrop. The unconfined portion of the Vincentown aquifer is shallowest around well 251259 on section L–L′, where it is more than 200 ft in altitude, and deepest around well 292049 on section H–H′, where it is less than -5 ft in altitude. At JBMDL, the unconfined portion of the Vincentown aquifer ranges from about 124 ft in altitude at well 051365 on section C–C′ to deeper than about 5 ft in altitude at well 051795 on section F–F′.

The hydraulic connection between the Kirkwood-Cohansey aquifer system and Vincentown aquifer has important implications for studying PFAS at JBMDL because PFAS contamination originating at the sources in the Kirkwood-Cohansey aquifer system may enter the unconfined portion of the Vincentown aquifer. The hydraulic heads in well 051251 were about 2 ft higher than in well 051250 throughout 2018 (fig. 5), which indicates a downward, vertical hydraulic gradient from the Kirkwood-Cohansey aquifer system into the unconfined portion of the Vincentown aquifer. Well 051251 was sampled in 2016 and found to have high levels of PFAS (2,580 nanograms per liter [ng/L]), which included a combination of PFOA and PFOS at 280 and 2,300 ng/L, respectively (U.S. Air Force, 2016). Because of their hydraulic connection, it is likely that well 051250 also has high levels of PFOA and PFOS. The PFAS may potentially migrate into the confined portion of the aquifer, posing additional challenges for remediation, and consequently migrate to off-base domestic wells screened in the Vincentown aquifer. The Site 4 PFAS reconnaissance area is of particular concern because that area is

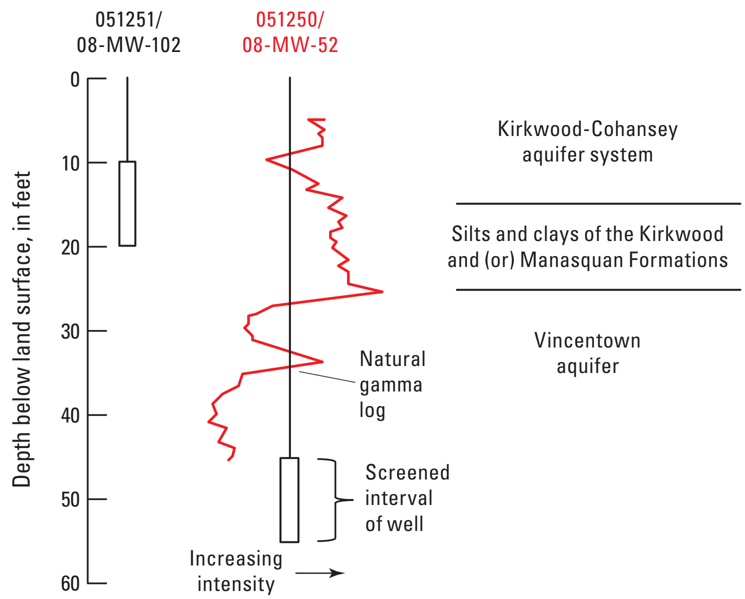

Figure 4. Log interpretation of wells 051250 / 08-MW-52 and 051251 / 08-MW-102, Joint Base McGuire-Dix-Lakehurst, New Jersey.

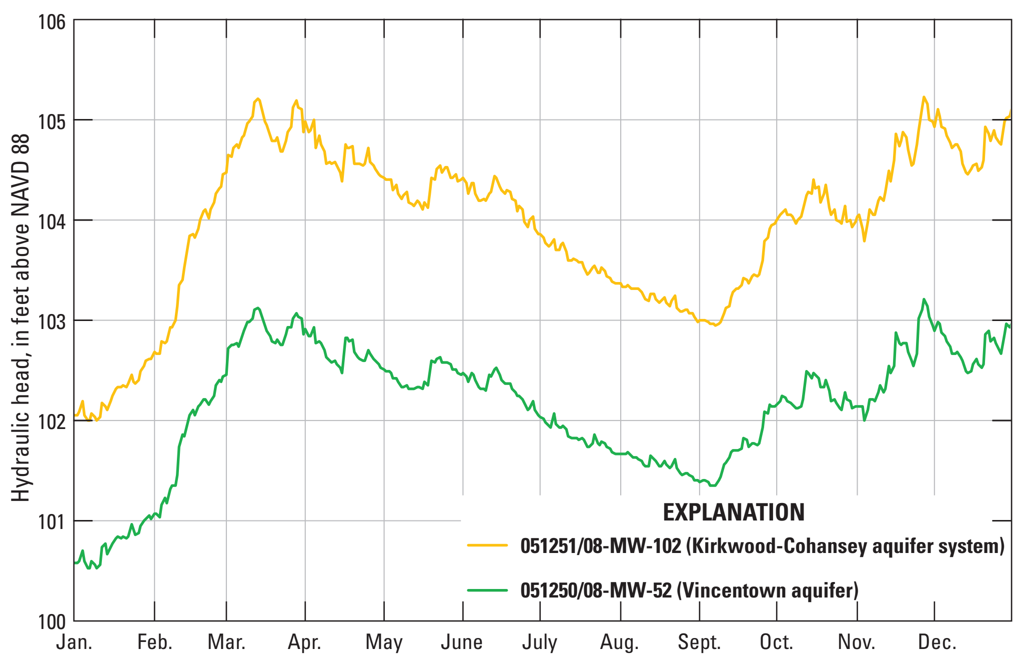

Figure 5. Hydrographs of continuous groundwater levels at wells 051250 / 08-MW-52 and 051251 / 08-MW-102, Joint Base McGuire-Dix-Lakehurst, New Jersey, 2018.

most likely to have domestic wells screened in the Vincentown aquifer given that the aquifer is relatively shallow and relatively thick compared to other areas.

PFAS migration may also occur in the Site 14 reconnaissance area and the area spanning Site 14 to around well 051179 on section E–E′ where PFOS and PFHxS have been identified at high levels in surface water, sediment, and fish tissue (Goodrow and others, 2018). However, the thinning of the Vincentown aquifer at these locations indicates there is less of a possibility that wells are screened in the Vincentown aquifer in that area. Similarly, Site 16, despite being partially underlain by the Vincentown aquifer, is less likely to have domestic wells screened in the Vincentown aquifer given the greater depth and the smaller thickness of the aquifer at that location.

Navesink-Hornerstown Confining Unit

The Navesink-Hornerstown confining unit consists of the Navesink Formation and Red Bank Sand of Cretaceous age and Hornerstown Formation of lower Paleocene age. The Navesink Formation is a gray, dark green, or brown clayey or silty glauconitic sand that may contain large shells in areas (Sugarman and others, 1991, 2018a). The Red Bank Sand is divided into an upper Shrewsbury Member, primarily an orange, brown, gray, or pink medium-to-coarse sand, and a lower Sandy Hook Member, a gray or olive silty sand (Sugarman and others, 1991, 2016). The Hornerstown Formation primarily consists of yellow, green, or black clayey glauconite sand (Sugarman and others, 2016; Sugarman and others, 2018a). The Navesink Formation and Hornerstown Formation are present throughout the study area (Sugarman and others, 2013, 2018a), but the Red Bank Sand does not crop out in Burlington County other than in a small area updip from sections F–F′ and G–G′ (Minard and Owens, 1963; Sugarman and others, 2013). The Shrewsbury Member of the Red Bank Sand is a minor aquifer in Monmouth County but is typically considered part of the confining unit (Zapecza, 1989; Cauller and others, 2016) or is not mapped as an aquifer owing to its negligible thickness in Burlington and Ocean Counties (Sugarman and others, 2013, 2018a).

Plate 8 shows the altitude of the bottom of the Navesink-Hornerstown confining unit. The top of the Navesink-Hornerstown confining unit is equivalent to the bottom of the Vincentown aquifer, where present. The Navesink-Hornerstown confining unit becomes part of the composite confining unit when merged with the confining unit overlying the Piney Point aquifer, the Manasquan-Shark River confining unit, and the transition of the Vincentown aquifer into a confining unit (table 3). The bottom of the Navesink-Hornerstown is also the bottom of the composite confining unit and is equivalent to the top of the Wenonah-Mount Laurel aquifer, which is not described in this report. The contact between the bottom of the Navesink-Hornerstown confining unit and the top of the underlying Wenonah-Mount Laurel aquifer is generally well recognized on geophysical logs as a sharp decrease in gamma intensity and increase in resistivity (pls. 10–12).

In the study area, the altitude of the bottom of the Navesink-Hornerstown confining unit is highest near well 251259 on section L–L′ at about 90 ft and lowest near well 292183 on section I–I′ at about -810 ft, the steepest downdip gradient of all the units described in this report. In JBMDL, the bottom of the Navesink-Hornerstown confining unit is recorded as highest near well 050340 on section F–F′ at an altitude of about 6 ft but may also be higher around well 051365 on section C–C′. The Navesink-Hornerstown confining unit is lowest on JBMDL between wells 291577 and 290429 on section J–J′, where the altitudes are approximately -415 and -433 ft, respectively.

Summary

The hydrostratigraphic framework of the Kirkwood-Cohansey aquifer system, Piney Point aquifer, the confined portion of the Vincentown aquifer, and the unconfined portion of the Vincentown aquifer was developed from borehole geophysical logs from 131 wells at the Joint Base McGuire-Dix-Lakehurst (JBMDL) and vicinity in a study conducted by the U.S. Geological Survey in cooperation with the U.S. Air Force. The extent and configuration of these hydrostratigraphic units as well as the interlying confining units are presented in a series of 8 maps and 12 cross sections.

The Kirkwood-Cohansey aquifer system is the largest unconfined water-table aquifer in the study area. The Kirkwood-Cohansey aquifer system is highest in the northwest part of the study area and dips about 300 feet (ft) toward the southeast. Despite being primarily composed of sand, the Kirkwood-Cohansey aquifer system also contains subunits of low permeability clay and silt that create high hydrogeologic heterogeneity that include semiconfined conditions, perched water tables, and zones of high potential for sorption of per- and polyfluoroalkyl substances (PFAS) in the aquifer system. Six of these subunits are substantial enough that their extents and configurations are presented in the maps and cross sections. In particular, two subunits are present that may affect groundwater flow complexity to PFAS reconnaissance areas, notably to the Site 14 reconnaissance area and to Sites 16, 17, and 18, as well as provide sites for sorption of PFAS on organic carbon that would impose challenges to remediate.

The Piney Point aquifer subcrops in the southeast portion of the study area and does not underlie any portion of JBMDL. The Piney Point receives recharge from the Kirkwood-Cohansey aquifer system, but owing to the great depths of this aquifer and negligible quantities of water withdrawn from the aquifer in the study area, groundwater in the Piney Point is unlikely to be vulnerable to PFAS contamination.

The Vincentown aquifer crops out in JBMDL and continues downdip until it grades into a low permeability confining unit. The Vincentown aquifer is generally thicker in Ocean County than in Burlington County, up to about 100 ft thick, and is more extensive in Ocean County. Continuously monitored groundwater levels from a well in the Vincentown aquifer indicate a response to precipitation and a 2-ft downward hydraulic head gradient from the Kirkwood-Cohansey aquifer system, indicating the Vincentown aquifer is also unconfined where the overlying Manasquan-Shark River confining unit is thin and leaky. Natural gamma logs from this well indicate a 14-ft-thick silt layer overlies the unconfined portion of the Vincentown aquifer, and a 28-ft isopach is assumed to be the boundary between the unconfined portion of the Vincentown aquifer and the confined portion. The unconfined portion was consolidated with the overlying portions of the Kirkwood-Cohansey aquifer system into a separate unconfined aquifer system. Recharge of the Vincentown aquifer through the Kirkwood-Cohansey aquifer system indicates the possibility of PFAS contamination of the unconfined and confined Vincentown groundwater, which affect potential receptors in Site 4 reconnaissance area and to a lesser extent Site 14 reconnaissance area.

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Appendix 1 Lithologic Logs and Drillers' Logs for Selected Wells

This appendix contains clipped images of the original lithologic logs and (or) drillers' logs (figs. 1.1–1.22), including scans of paper logs, for wells cited in the report. All other well logs are available in U.S. Geological Survey (2019). Clips of the log are provided rather than digitized transcribed versions to preserve the original data without assuming interpretation of the abbreviations, handwriting, or other notations therein. Annotations on original logs such as choices for contacts of geologic formations are not assumed to be consistent with the interpretations in this report.

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AUG 6 1941
STATE WATER POLIC
COMMISSION

Log of Well No. 1

as determined from well samples

by M. E. Johnson, State Geologist

0 - 23'	fine-grained, yellow sand
23 - 26	Fine-grained yellow sand with small pebbles
26 - 58	Very fine-grained, clayey yellow sand
58 - 65	No sample
65 - 174	Greenish-grey, sandy clay and glauconite
at 174	Grey, glauconitic, fossiliferous clay
at 230	Very fine-grained, grey clayey and micaceous sand
at 282	Same as last but glauconitic
at 320	Grey clay
332 - 336	Fine to coarse glauconitic sand with pyrite nodules
340 - 350	Fine to coarse grey glauconitic sand with a little lignite and a few small pebbles
at 356	Medium to coarse light-brown sand
358 - 366	Light brownish grey sand and gravel
at 369	Lignitic, fine to medium-grained, light brownish-grey sand
370 - 407	Fine to medium-grained, fossiliferous, light-brownish-grey sand
at 407	Dark-grey fossiliferous clay
at 452	Grey, silty, fossiliferous clay
at 464 and 474	Grey clay
at 503	Grey, fossiliferous clay
505 - 577	Greenish-grey glauconitic clay
at 577	Glauconitic, speckled, grey fine to medium-grained sand with a few coarse grains and small pebbles
577 to 920	Thin, alternating beds of sand and clay
at 920	Mixture of red clay and sand
935 - 963	Fine to coarse sand with a few small pebbles in lower part
963 - 980	Chiefly fine to medium-grained sand but some clay

Figure 1.1. Lithologic log of well 050331.

Depth in Feet	Description	Form
0 - 12	Buff, fine to medium, angular quartz, sand, with some granules present. Few graus glauconite.	
12 - 19	Light grey, fine to very fine, angular quartz sand with a few coarse, rounded grains and a few mica flakes.	
19 - 29	As above, but slightly yellowish, and with a higher percentage of coarse grains, some of which are granule size.	
29 - 37	Yellow-brown, fine, angular, well-sorted qutz. sand with many mica flakes. Few coarse grains	
37 - 49	As above	
49 - 59	As above	
59 - 69	Light, grey-brown, fine, angular sand with some mica and glauconite.	
69 - 74	Same as 29-59.	
74 - 84	Dark, olive-black, slightly silty clay with many minute flakes of mica.	
84 - 94	As above	
94 - 104	Medium greyish-green, plastic clay with some very small grains of glauconite.	
104 - 114	A s above	
114 - 122	As above	
122 - 132	Light olive-grey, plastic "pepper" clay with many small grains of glauconite; more sand than in samples above or below.	
132 - 142	As above, but more clayey.	
142 - 152	Same as 132-142.	
152 - 162	As Above.	
162 - 172	As Above.	
172 - 178	As Above.	
178 - 188	As Above; but containing more glauconite.	
188 - 196	As above.	
196 - 210	Dark greyish-olive clay with much fine to medium grained glauconite	
210 - 220	Olive-black slightly clayey sand consisting entirely of medium sized, well-rounded glauconite grains, with many shell fragments.	
220 - 230	As above, but lacking shells.	
230 - 240	Same as preceding.	
240 - 250	Dark, greenish-grey clay, with a little mica and glauconite	
250 - 260	As above	
260 - 270	Somewhat more glauconitic and sandy clay, otherwise like above and containing some small shell fragments.	
270 - 275	As above.	

Figure 1.2. Lithologic log of well 050380.

STRATIFICATION

0'	-	12'	Sand
12'	-	19'	White sandy clay
19'	-	37'	Yellow sandy clay
37'	-	59'	Yellow sandy clay
59'	-	74'	White sand
74'	-	98'	Black marl
98'	-	122'	Green marl
122'	-	178'	Green sandy marl
178'	-	196'	Green hard marl
196'	-	210'	Green sandy marl
210'	-	275'	Green sandy marl and oyster shells
275'	-	302'	Hard sand
302'	-	303'	Hard sand marl and oyster shells

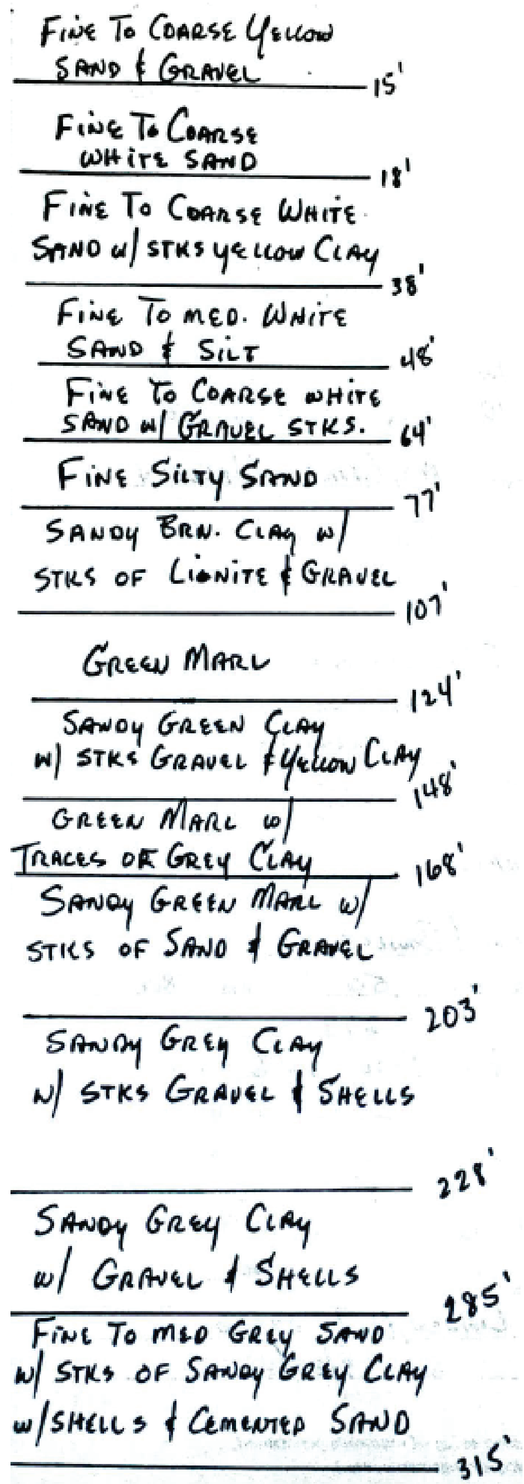
Figure 1.3. Drillers' log of well 050380.

0'-5'	HARD BROWN SOIL
5'-19'	MEDIUM BROWN SAND
19'-24'	COARSE SAND & GRAVEL
24'-37'	COARSE SAND & GRAVEL - CLAY STREAKS
37'-49'	SANDY CLAY
49'-76'	COARSE SAND & GRAVEL
76'-89'	CLAY,
89'-110'	HARD CLAY
110'-122'	STKS OF SAND & CLAY
122'-131'	BLACK SAND WITH STK'S OF CLAY
131'-139'	HARD PACKED SAND
139'-151'	MEDIUM BLACK SAND
151'-163'	HARD CLAY
163'-171'	BLACK SAND
171'-182'	PYRITES AND CLAY
182'-197'	SAND, STREAKS OF CLAY
197'-219	MEDIUM BLACK SAND
219'-223'	PYRITE-CLAY SHELLS
223'-228'	MEDIUM SAND
228'-236'	PYRITE- CLAY SHELLS
236'-249'	SOFT CLAY
249'-272'	MEDIUM SAND
272'-289'	SAND- STREAKS OF CLAY
289'-305'	MEDIUM SAND

Figure 1.4. Drillers' log of well 050714.

WELL LOG	FEET FROM GROUND SURFACE
White Sand	0 TO 3
Yellow Sand	3 - 6
Clayish Orange Sand	6 - 11
Stones-Dark Yellow Snd.	11 - 17
Black Clay	17 - 23
Gray Sandish Clay	23 - 86
Green Clay	86 - 120
Fine Sand	120 - 128
Clay Silty - Marl	128 - 165
Marl	165 - 179
Fine Sand, Clayish	179 - 228
Marl	228 - 240
Fine Sand, Silty	240 - 248
Marl-Fine Sandish Clay	248 - 297
Sand	297 - 303
Silty Sand	303 - 395
Hardpan	395 - 396
Fine Gray Sand-Silty	396 - 420
Sand, Thin Streaks of Clay	420 - 446
Hardpan	446 - 447
Fine Gray Sand	447 - 458
Silty Sand	458 - 469
Sand, Fine	469 - 471
Clay, Sandish	471 - 500
Sandish Clay, Silty	500 - 518
Clay, Lenses of Sand	518 - 545

Figure 1.5. Drillers' log of well 050754.



FINE TO COARSE YELLOW SAND & GRAVEL — 15'
FINE TO COARSE WHITE SAND — 18'
FINE TO COARSE WHITE SAND W/ STKS YELLOW CLAY — 38'
FINE TO MED. WHITE SAND & SILT — 48'
FINE TO COARSE WHITE SAND W/ GRAVEL STKS. — 64'
FINE SILTY SAND — 77'
SANDY BRN. CLAY W/ STKS OF LIGNITE & GRAVEL — 107'
GREEN MARL — 124'
SANDY GREEN CLAY W/ STKS GRAVEL & YELLOW CLAY — 148'
GREEN MARL W/ TRACES OF GREY CLAY — 168'
SANDY GREEN MARL W/ STKS OF SAND & GRAVEL — 203'
SANDY GREY CLAY W/ STKS GRAVEL & SHELLS — 228'
SANDY GREY CLAY W/ GRAVEL & SHELLS — 285'
FINE TO MED GREY SAND W/ STKS OF SANDY GREY CLAY W/SHELLS & CEMENTED SAND — 315'

Figure 1.6. Drillers' log of well 050796.

LOG:	0-1	Topsoil
	1-6	Silty and clayey yellow sand
	6-24	Slightly silty coarse white sand
	24-37	Coarse yellow sand to light gravel (silty and clayey)
	37-70	Silty, sandy brown clay
	70-82	Very fine and very clayey gray quartz sand (Kirkwood)
	82-103	Dense green clay
	103-104	Hardpan
	104-110	Sandy green glauconitic clay
	110-112	Hardpan
	112-123	Sandy green glauconitic clay
	123-125	Hardpan
	125-145	Sandy green clay with interbedded lenses of fine gray sand
	145-157	Green clay
	157-159	Hardpan
	159-195	Green clay
	195-197	Hardpan
	197-268	Gray clay with glauconite & shell fragments
	268-269	Hardpan
	269-283	Fine to medium gray/green moderately glauconitic sand
	283-284	Hardpan
	284-300	Fine grayish-green sand
	300-302	Gray clay
	302-310	Fine grayish-green sand
	310-313	Gray clay
	313-336	Fine grayish-green sand
	336-345	Gray sandy clay, sand and glauconite (slow drilling, less chatter, fluid color changed)

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32-15753
32-03-138

345-350	Gray clay with thin interbedded sand lenses (each less than 1/2 foot thick)
350-	Gray clay

Figure 1.7. Drillers' log of well 051179.

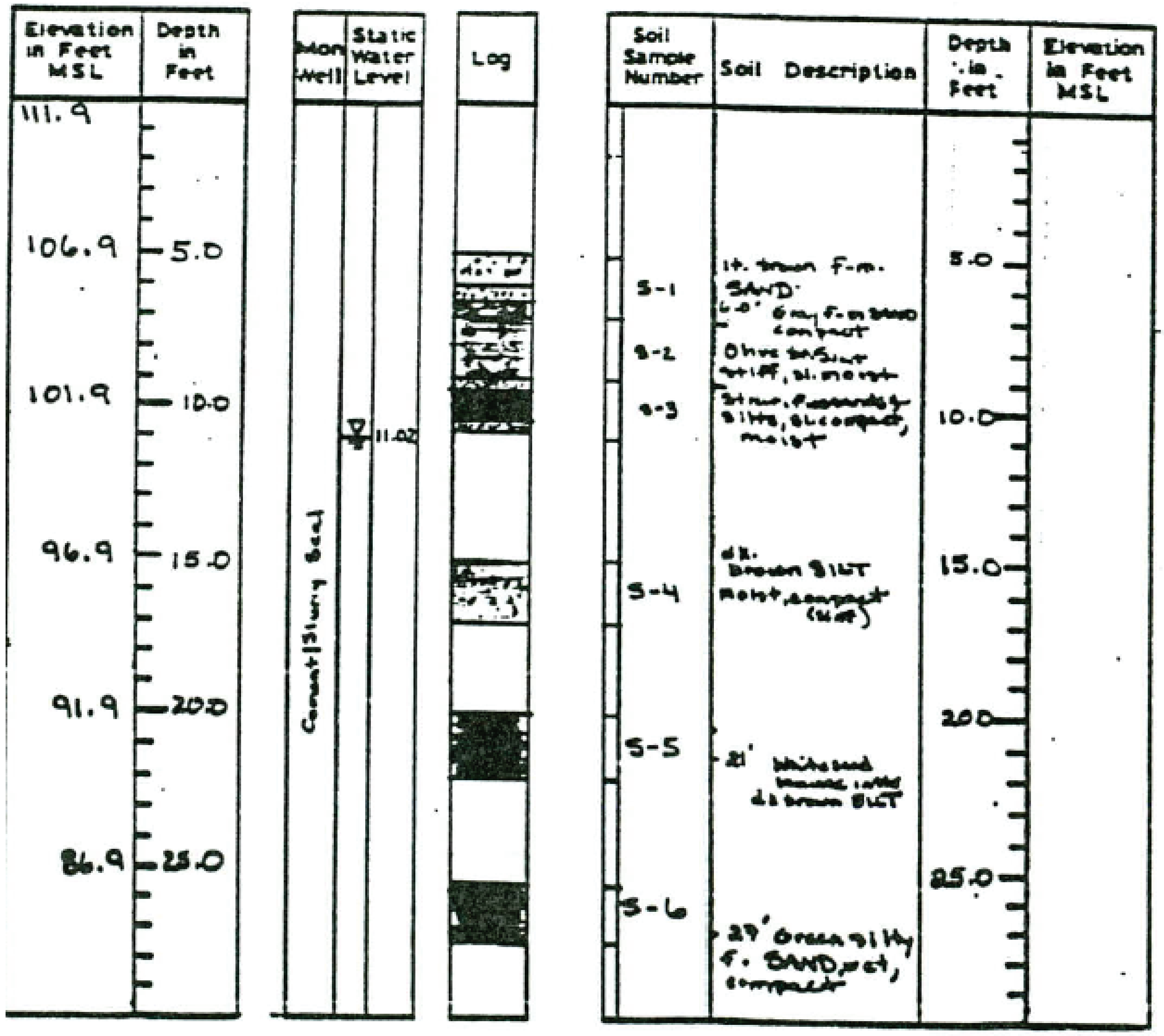

Figure 1.8. Lithologic log of well 051250.

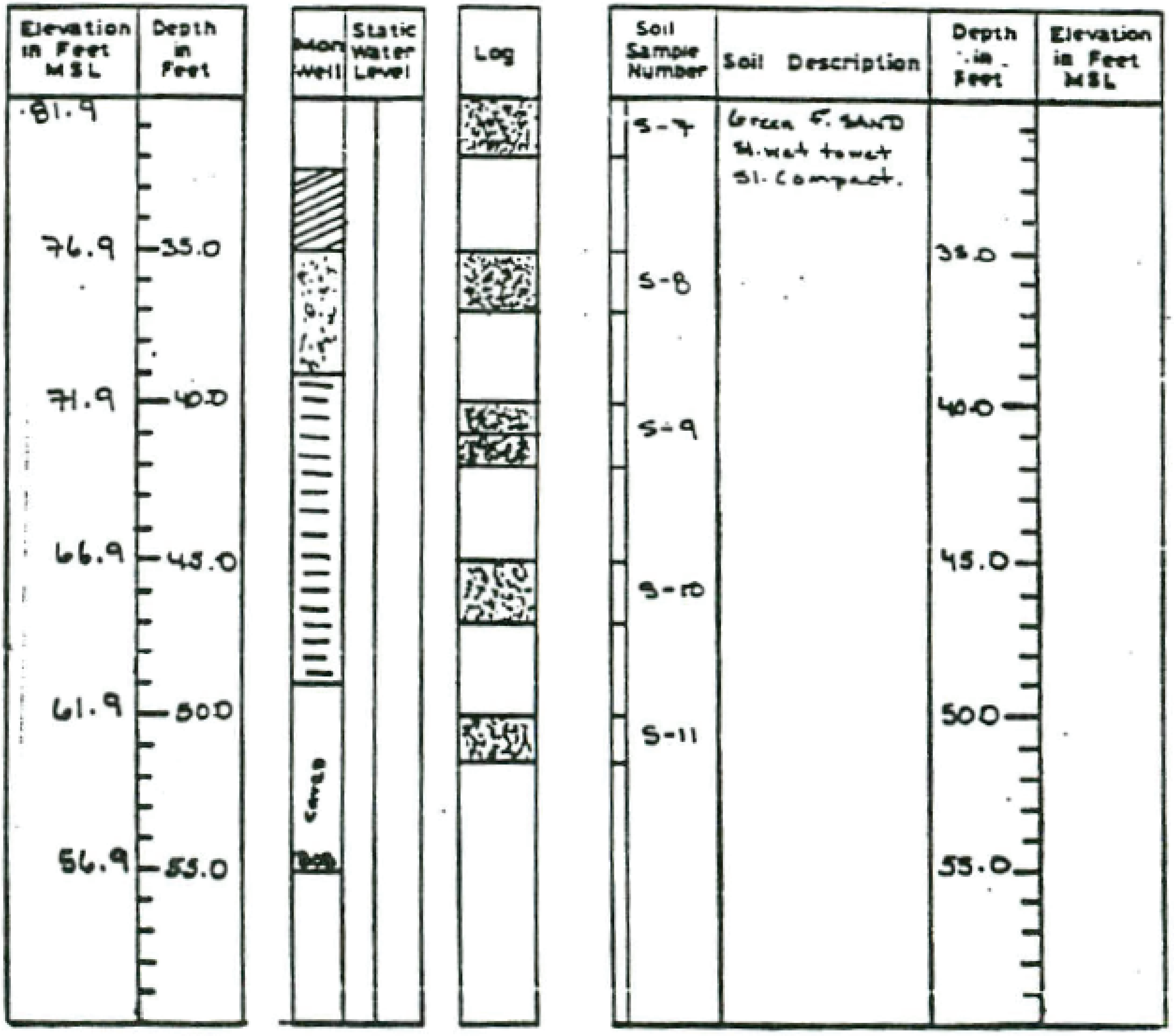

Figure 1.8. —Continued

0-7	F-C GREY/WHITE SAND
7-12	F-C BROWN SAND
12-32	FINE GREY SAND & MICA
32-40	FINE GREY SAND & CLAY
40-60	GREY/GREEN CLAYS
60-140	FINE BLACK SAND &
	GREEN CLAY
140-200	FINE BLACK SAND &
	GREY CLAY
200-230	FINE GREY SAND & CLAY
230-240	FINE BLACK & SHELLS
240-280	F-C GREY/GREEN/SHELLS

Figure 1.9. Drillers' log of well 051613.

0-3	TOPSOIL, ROOTS ETC
3-21	COARSE ROCKS, TAN MED COARSE
	SAND
21-76	SILTY GREY CLAYS
76-230	DENSE BRIGHT GREEN CLAYS
230-241	SILTY GRAY CLAY GLAMCONTIC
241-256	SILTY BROWN CLAY WITH SOME
	SAND
256-265	SILTY GRAY CLAY WITH GLAUCONITE
	SHELLS
265-312	MED GRAY TO GREEN SAND WITH
	SHELL FRAGMENTS

Figure 1.10. Drillers' log of well 051769.

0 - 16: Tan SW - Well-graded sands and gravelly sands, little or no fines
16 - 60: Brown SC - Clayey sands, sand-clay mixtures
60 - 180: Green OL - Organic silts and organic silty clays of low plasticity
180 - 240: Grey OH - Organic clays of medium to high plasticity
240 - 280: Grey/ Green SW - Well-graded sands and gravelly sands, little or no fines Shells

Figure 1.11. Drillers' log of well 052026.

0 - 10: Brown/ Yellow GW - Well-graded gravels and gravel-sand mixtures, little or no fines
10 - 20: Brown/Yellow/Grey SC - Clayey sands, sand-clay mixtures
20 - 40: Grey SC - Clayey sands, sand-clay mixtures
40 - 60: Green SC - Clayey sands, sand-clay mixtures
60 - 160: Black/ Green SC - Clayey sands, sand-clay mixtures shell traces
160 - 200: Grey OH - Organic clays of medium to high plasticity
200 - 240: Black/Grey/Green SW - Well-graded sands and gravelly sands, little or no fines shells

Figure 1.12. Drillers' log of well 052028.

0 - 2: black OT - Other top soil
2 - 14: orange OT - Other medium sand
14 - 28: yellow OT - Other clay
28 - 57: brown OT - Other clay
57 - 80: green OT - Other clay
80 - 150: dark green OT - Other clay
150 - 185: black OT - Other sand and shells
185 - 215: dark grey OT - Other clay
215 - 265: green black OT - Other coarse sand

Figure 1.13. Drillers' log of well 052029.

Well Log	Ft. from Ground Surface	Well Log	Ft. from Gr. Surface
Sand	0 - 53'	Clay (hard)	1043 - 1113'
Brown Sandy Clay	53 - 56'	Sand	1113 - 1120'
Sand	56 - 87'	Hard Pan	1120 - 1122'
Clay	87 - 100'	Clay (hard spots)	1122 - 1136'
Sand	100 - 105'	Sand	1136 - 1144'
Sandish Clay	105 - 131'	Clay	1144 - 1151'
Clay (hard)	131 - 142'	Sand	1151 - 1156'
Hard Pan	142 - 144'	Hard Pan	1156 - 1157'
Clay	144 - 147'	Sand	1157 - 1160'
Hard Pan	147 - 148'	Hard Pan	1160 - 1161'
Clay	148 - 153'	Clay	1161 - 1164'
Sand	153 - 156'	Sand	1164 - 1169'
Hard Pan	156 - 162'	Clay	1169 - 1179'
Clay	162 - 187'	Hard Pan	1179 - 1180'
Clay(Hard spots)	187 - 237'	Clay	1180 - 1227'
Clay (Green)	237 - 257'	Sand	1227 - 1237'
Hard Pan	257 - 271'	Clay	1237 - 1242'
Clay	271 - 327'	Sand	1242 - 1261'
Sand	327 - 333'	Hard Pan	1261 - 1263'
Clay	333 - 378'	Clay	1263 - 1267'
Clay (silty)	378 - 428'	Sand	1267 - 1290'
Sand	428 - 440'	Clay	1290 - 1296'
Clay (sandish)	440 - 480'	Sand	1296 - 1305'
Sand	480 - 516'	Hard Pan	1305 - 1309'
Clay	516 - 524'	Sand	1309 - 1337'
Sand	524 - 529'	Clay	1337 - 1369'
Hard Pan	529 - 532'	Clay (hard)	1369 - 1392'
Hard packed Sand	532 - 541'	Sand	1392 - 1399'
Hard Pan	541 - 547'	Clay	1399 - 1405'
Clay	547 - 564'	Sand	1405 - 1462'
Sand	564 - 583'	Sand	1462 - 1474'
Hard Pan	583 - 585'	Clay	1474 - 1482'
Sand	585 - 606'	Hard Pan	1482 - 1485'
Clay	606 - 637'	Clay	1485 - 1497'
Clay (sandish)	637 - 642'	Hard Pan	1497 - 1499'
Hard Pan	642 - 643'	Clay	1499 - 1502'
Clay (silty)	643 - 660'	Sand (silty)	1502 - 1518'
Clay (hard black)	660 - 745'	Clay	1518 - 1537'
Clay (silty)	745 - 757'	Hard Packe Sand	1537 - 1547'
Clay (hard)	757 - 852'	Sand	1547 - 1558'
Sand	852 - 869'	Clay	1558 - 1560'
Clay	869 - 872'	Sand	1560 - 1563'
Sand	872 - 911'	Clay	1563 - 1564'
Clay	911 - 922'	Sand	1564 - 1566'
Sand (silty)	922 - 935'	Clay	1566 - 1569'
Clay (hard)	935 - 965'	Sand	1569 - 1586'
Hard Pan	965 - 966'	Clay	1586 - 1594'
Clay (hard)	966 - 1019'	Sand (hard packed)	1594 - 1613'
Hard Pan	1019 - 1019'6	Sand	1613 - 1619'
Clay	1019'6" - 1022'	Clay	1619 - 1620'
Hard packed Sand	1022 - 1025'	Sand	1620 - 1634'
Clay	1025 - 1043'		

Figure 1.14. Drillers' log of well 290118.

3 - 13'	Light pinkish grey green, fine to coarse quartz sand with moderate percentage heavy minerals.
13 - 23'	Same
23 -33'	Light yellowish grey, fine to very coarse clean quartz sand with some heavy minerals.
33 - 43'	Light pinkish grey, fine to medium green quartz sand - some heavy minerals.
43 - 53'	Same
53 - 93'	Light yellowish grey green medium to coarse qts sand.
93 - 113'	Light grey green coarse to very coarse qtz sand.
113 - 123'	Medium grey fine to medium slightly dirty quartz sand.
123 - 143'	Light olive grey moderately glauconitic slightly micaceous fairly clean fine quartz sand.
143 - 173'	Olive grey slightly clay glauconitic lightly fossiliferous fine quartz sand.
173 - 183'	Grey slightly micaceous somewhat dirty glauconitic fine quartz sand.
183 - 233'	Light grey to olive grey glauconitic somewhat clay and fossiliferous fine to medium qts sand.
233 - 263'	Light sea green glauconitic and sandy - probably fossiliferous clay.
263 - 293'	Grey clay lightly micaceous glauconitic - probably fossiliferous fine sand and clay.
293 - 323'	Olive grey slightly micaceous clay quartzose - probably fossiliferous glauconite sand.
323 - 403'	Greenish grey lightly fossiliferous slightly quartzose fine glauconite sand.

Figure 1.15. Lithologic log of well 290132.

413 - 473'	Grey with greenish tinge, somewhat fossiliferous slightly clay highly glauconitic fine to coarse quartzose sand.
473 - 503'	Grey finely micaceous somewhat fossiliferous quartzose and glauconitic clay.
503 - 533'	Greenish grey mixture slightly fossiliferous lignitic glauconite and fine quartz sand.
533 - 603'	Grey to greenish grey mixture of glauconite and quartz sand with local fossils.
603 - 653'	Grey to greenish grey moderately fossiliferous clay highly glauconitic fine to medium quartz sand.
653 - 713'	Olive grey highly fossiliferous somewhat dirt moderately glauconitic fine to medium quartz sand.
713 - 733'	Grey finely micaceous fossiliferous slightly glauconitic silt to very coarse quartz sand.
733 - 763'	Grey to olive grey moderately micaceous and glauconitic fine quartz sand.
763 - 823'	Grey to olive grey finely micaceous somewhat fossiliferous and glauconitic silt to fine sand with scattered coarse to very coarse quartz grains.
823 - 863'	Grey finely micaceous slightly glauconitic silt to very fine sand.
872 - 930'	Grey to olive grey fairly clean mixture of glauconitic and fine quartz sand.
944 - 983'	Grey somewhat dirty slightly glauconitic ? fine to very coarse quartz sand with scattered pebbles [illegible]".
983 - 1013'	Grey fairly clean glauconitic slightly micaceous [illegible] sand.
1013 - 1063'	Grey finely micaceous slightly glauconitic fossiliferous silt.

Figure 1.15. —Continued

escription	Corre

1063 - 1103' Gre ..i,hl foss_liferous slightly lauconitic inel ..icaceous silt with scattered qtz grains.

1103 - 1133' rey with slight olive tinge highly fossiliferous lightly micaceous gla..onitic fine to medium sand.

1133 - 1364' rey to light olive grey lightly foss.lifer ous fairly clean slightly micaceous and glauconitic fine quartz sand.

1073 - 1083' ashed and sieved - fine-medium quartz lauconite mainly ro.nded types, some accordion shapes many broken shell fragments coiled forams, all cal- careous so.e siderite nodules.

1113 - 1123' ashed and sieved - fine-medium quartz sand fresh and acc.rdion sha.ed gla.conite many shell frag- ments noted small number broken small immature type astro.ods. hese have been noted by F.+.M. reviously in the downdip Woodbury . .arotny formations - few coiled calcareous forams - few siderite nod.les.

ot : .+ 113 to 123' some very coarse quartz rains which ma be Mt. La.rel.

Figure 1.15. —Continued

DRILLERS LOG

Well Log	Ft. from Ground Surface
Yellow Brown Sand	0 to 75
Yellow Br.Sandy Clay	75 - 78
Med. Sand & Stones	78 - 90
Black Clay	90- 111
Sand	111 - 117
Bl. Clay & Gr. Marl	117 - 206
Hard Pan	206 - 207
Bl. Clay & Gr. Marl	207 - 213
Hard Pan	213 - 228
Clay, Black	228 - 230
Hard Pan	230 - 233
Clay	233 - 242
Hard Pan	242 - 243
Green Marl silty	243 - 318
Silty Sand	318 - 324
Marl	324 - 328
Sand Silty	328 - 339
Marl	339 - 346
Sand Silty	346 - 349
Soft Clay Sandy	349 - 382
Silt	382 - 421
Clay	421 - 424
Sand Hard Packed	424 - 451
Clay, Silty	451 - 510
Sand	510 - 516
Clay Silty	516 - 519
Sand	519 - 521
Clay Silty & Soft	521 - 531
Sand	531 - 537
Hard Pan & Sand Lamina	537 - 560
Sand	560 - 566
Clay	566 - 598
Clay Soft Sandy	598 - 648
Hard Pan	648 - 656
Sand	656 - 678
Clay Hard Sandy	678 - 800
Sand Fine Silty	800 - 873
Sand Fine to Med.	873 - 911
Clay & Hard Spots	911 - 921
Sand Fine	921 - 927
Clay	927 - 929
Hard Pan	929 - 930
Clay	930 - 936
Sand	936 - 946
Hard Spot of Clay	946 - 947
Sand Med. to Coarse	947 - 980
Clay	980 - 1009
Clay Silty	1009 - 1011
Hard Pan	1011 - 1012
Soft Silty Clay&Shells	1012 - 1016

Well Log	Ft. from Ground Surface
Fine Silty Sand	1016 - 1029
Hard Pan	1029 - 1030
Sand Fine Silty	1030 - 1037
Clay Soft	1037 - 1056
Fine S lty Sand	1056 - 1065
Clay Soft Silty	1065 - 1088
Sand	1088 - 1092
Clay Soft Silty	1092 - 1131
Hard Pan	1131 - 1134'-6"
Clay	1134'6" @ 1136
Hard Pan	1136 - 1136'6"
Clay	1136'6"-1140
Hard Pan	1140 - 1141
Clay	1141 - 1148
Hard Pan	1148 - 1161

242
90
152

850 Kmr

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Figure 1.16. Drillers' log of well 290134.

WELL LOG	FEET FROM GROUND SURFACE 0 TO 1
Brown Sand	0 - 64
Black Clay	64 -106
Sand	106 -113
Clay	113 -172
Hard Packed Sand	172 -184
Clay	184 -223
Clay & Streaks of Sand	223 -246
Clay & Shells	246 -267
Green Marl	267 -357
Hard Packed Sand	357 -367
Clay - Sandish	367 -435
Sand & Hard Pan	435 -443
Clay	443 -457
Sand	457 -487
Clay Silty	487 -571
Sand, Shells & Hard Pan	571 -654
Clay	654 -667
Sand.	667 -712
Green Marl	712 -719
Hard Packed Sand	719 -757
Black Clay	757 -827
Black Marl & Shells	827 -870
Clay Silty	870 -899
Clay & Hard Pan	899 -917
Clay	917 -944
Clay & Hard Pan	944 -957
Hard Clay	957 -968

WELL LOG	FEET FROM GROUND SURFACE 0 TO
Sand	968-1000
Clay	1000-1003
Sand	1003-1009
Clay	1009-1021
Clay & Streaks of Sand	1021-1077
Sand	1077-1087
Clay & Hard Pan	1087-1101
Clay	1101-1105
Sand	1105-1116
Clay & Hard Pan	1116-1247
Sand	1247-1255
Clay & Hard Pan	1255-1329
Hard Packed Sand	1329-1342
Sand & Hard Spots	1342-1383
Clay Silty & Hard Pan	1383-1424
Sand & Clay Laminates	1424-1440
Sand	1440-1484
Clay	1484-1510
Sand	1510-1530
Sand Clay & Hard Pan	1530-1556
Sand	1556-1595
Fine Sand	1595-1604
Sand Clay & Hard Pan	1604-1615
Sand & Hard Pan	1615-1628

Figure 1.17. Drillers' log of well 290440.

ORIGINAL GROUND LEVEL	0'
FILL	3'
COAR. YELLOW SANDY GRAV.	60'
FINE GRAY SAND	68'
CLAY W/ MIXED GRAV.	117'
CLAY. STK'S SOFT SR.+GRA.	132'
GREY CLAY	171'
CLAY. VERY HARD STRK	175'
CLAY W/ STRK'S OF SAND	218'
GRN CLAY - STK'S OF CLAY	255'
HARD STREAKS	262'
GREEN TOUGH CLAY	420'
SANDY CLAY	436'
GRN CLAY W/ STRK'S FINE SND	510'
BLK + WHITE SAND - CLAY + SILT	567'
SANDY CLAY W/ LIGNITE	632'
SANDY CLAY	668'
HARD STREAK'S	670'
GREY CLAY W/ LIGNITE	720'
CLAY, STKS SAND + LIGNITE	734'
CLAY, HD. STK'S - LIGN. - SHELLS	736'
HARD STREAKS	791'
GR. SANDY CLAY - SHELLS - STKS	853'
GREY SANDY CLAY	934'
HARD STREAKS	936'
GR. CLAY + BLK SILTY SAND	976'
HARD STREAKS	992'
GR. CLAY. STK'S BLK FI. SAND	1021'
FI. BLK SAND. W/ STK'S CLAY	1049'
HD. GR. CLAY W/ SAND STK'S	1066'
SAND AND CLAY STRK'S	1087'
HARD SAND FACED W/ CLAY	1107'
MED. FINE SAND. CLAY STK'S	1153'
MED-FINE SAND. STKS CLAY	1175'
MED. FINE SAND. CLAY STK'S	1206'
CLAY WITH HARD STRK'S	1218'
CLAY WITH HARD STRK'S	1242'
HARD CLAY	1319'
CEMENTED FORMATION	1325'
HARD STREAKS	1329'
SAND. CLAY STK'S + HD STK'S	1362'
TOUGH CLAY	1367'
SANDY CLAY + SAND STK'S	1398'
HD. SAND. CLAY STK'S. [illegible]	1433'
CLAY WITH SAND STRK'S	1495'
SAND WITH HARD STRK'S	1506'
MED TO COARSE SAND + CLAY	1566'
SAND AND CLAY STRK'S	1571'
SANDY CLAY + SAND STRK'S	1579'
TOUGH CLAY	1594'
SAND. SOME CLAY STRK'S	1620'
CLAY - RED WHITE + GREY	1624'
TOUGH, RED, WHITE, GREY CLAY	1647'
CLAY	1684'
ROCK	1692'

Figure 1.18. Drillers' log of well 290588.

formations.

Sand	0-16
White Clay	16-27
Brown Clay & Sand	27-86
Green Marl	86-196
Sand	196-205
Green Marl	205-230
Clay Silty Sand Streaks	230-265
Hard Green Clay	265-280
Silty Clay	280-286
Hard Clay w/Sand Streaks	286-296
Soft Green Clay w/Tan Clay	296-317
Silty Sand w/Dk. Brown Clay	317-340
Silty Dk. Brown Clay	340-389
Sand	389-425
Dk. Brown Clay w/Sand	425-472
Clay w/Sand Spots	472-565
Sand and Hard Spots	565-605
Silty Clay w/ Sand Streaks	605-664
Please See Attached	

Figure 1.19. Drillers' log of well 291265.

*continued	
664-691	Silty Sand
691-782	Clay
782-904	Silty Clay and Sand
904-920	Hard Whitish-Gray Clay
920-934	Very Hard Red Clay
934-945	Clay with Sand Laminations
945-955	Sand
955-955 ½	Hard Pan
955 ½-962	Clay with Hard Pan Laminations
962-1000	Hard Dark Gray Clay
1000-1048	Silty Clay with Hard Pan Laminations
1048-1135	Sand & Hard Pan, Streaks of Clay
1135-1154	Clay
1154-1163	Clay with Sand Streaks
1163-1167	Silty Sand
1167-1185	Clay and Hard Spots
1185-1220	Hard White and Red Clay
1220-1240	Clay with Silty Spots
1240-1265	Silty Sand
1265-1270	Clay
1270-1294	Sand
1294-1296	Hard Clay
1296-1309	Clay with Silty Spots
1309-1337	Sand
1337-1398	Sand with Streaks of Clay
1398-1470	Sand and Hard Spots
1470-1495	Hard Red Clay
1495-1509	Clay and Hard Pan
1509-1554	Sand and Fine Gray Clay
1554-1563	Silty Clay
1563-1588	Sand
1588-1605	Silty Sand with Clay Laminations
1605-1627	Silty Sand - Hard Drilling with Clay Laminations
1627-1651	Clay with Hard Laminations

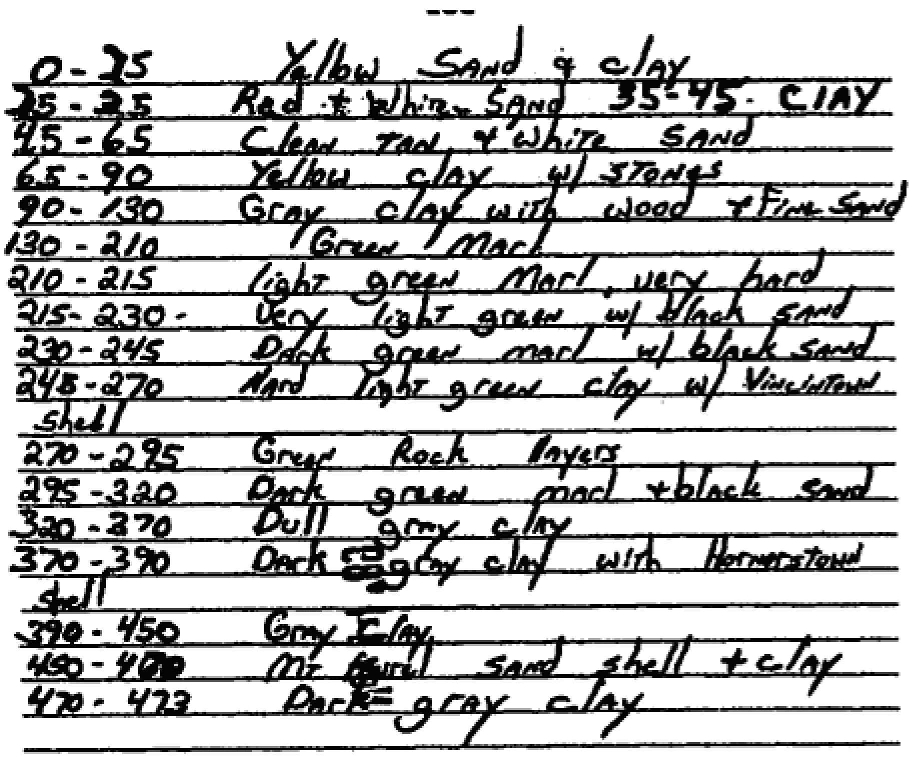
Figure 1.19. —Continued

Thickness (ft.)	Depth (ft.)	
36	0-36	Sand and clay
45	36-81	Clay, brown
109	81-190	Marl (clay, greenish)
222	190-412	Silty clay, black, sandy
36	412-448	Marl (clay, greenish)
28	448-476	Sand
109	476-585	Silty clay
3	585-588	Hardpan
27	588-615	Sand; shells
104	615-719	Clay
23	719-742	Silty clay; shells at 719-730 ft.
43	742-785	Silty sand
49	785-834	Clay, hard
34	834-868	Silty sand
74	868-942	Clay; sand streaks
43	942-985	Sand; hardpan streaks
17	985-1002	Clay, hard
4	1002-1006	Sand; hardpan streaks
3	1006-1009	Clay
25	1009-1034	Sand; hardpan streaks
19	1034-1053	Clay
15	1053-1068	Sand; hardpan streaks
6	1068-1074	Clay
32	1074-1106	Sand; hardpan streaks
11	1106-1117	Silty clay
3	1117-1120	Hardpan
12	1120-1132	Silty sand
19	1132-1151	Clay
9	1151-1160	Hardpan
6	1160-1166	Sand
2	1166-1168	Clay, hard
26	1168-1194	Sand; hardpan streaks
28	1194-1222	Clay, hard
8	1122-1130	Sand
106	1130-1336	Clay; sand streaks at 1230-1248 ft.; red, hard, hardpan streaks at 1248-1286 ft.; less hard at 1286-1290 ft.; very hard at 1290-1336 ft.
6	1336-1342	Sand; shells
40	1342-1382	Clay, hard; shells at 1345-1382 ft.
6	1382-1388	Silty clay
24	1388-1412	Silty sand; clay streaks
5	1412-1419	Silty clay
29	1419-1448	Clay, red, very hard
19	1448-1467	Sand
2	1467-1469	Clay
4	1469-1473	Sand

Figure 1.20. Drillers' log of well 291380.

Depth From Ground	Well Log
0-41	Yellow Sand & Gravel
41-43	Clay
43-91	Brown Sand & Clay
91-126	Silty Sand & Clay
126-146	Brown Clay
146-169	Hard Clay
169-302	Green Clay
302-406	Silty Clay
406-426	Silty Sand & Clay
426-481	Black Sand
481-554	Clay
554-568	Sand
568-568.5	Hard Pan
568.5-581	Silty Clay
581-694	Silty Gray Clay
694-708	Sand
708-843	Silty Clay
843-889	Clay
889-911	Silty Clay w/ Sand streaks
911-916	Hard Clay
916-989	White Sand
989-1015	Sand w/ Clay laminating
1015-1022	Silty Clay
1022-1041	Clay

Figure 1.21. Drillers' log of well 291577.



0-25	Yellow Sand & clay
25-35	Red & White Sand 35-45 CLAY
45-65	Clean tan & white sand
65-90	Yellow clay w/ stones
90-130	Gray clay with wood & Fine Sand
130-210	Green Marl
210-215	light green Marl, very hard
215-230 -	very light green w/ black sand
230-245	Dark green marl w/ black sand
245-270	Hard light green clay w/ Vincentown shell
270-295	Green Rock layers
295-320	Dark green marl + black sand
320-370	Dull gray clay
370-390	Dark gray clay with Hornerstown shell
390-450	Gray clay
450-470	Mt Laurel sand shell + clay
470-473	Dark gray clay

Figure 1.22. Drillers' log of well 292043.

Reference Cited

U.S. Geological Survey, 2019, USGS GeoLog locator database: U.S. Geological Survey data release, accessed April 9, 2019, at https://doi.org/10.5066/F7X63KT0.

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