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

By Alex R. Fiore

Prepared in cooperation with the U.S. Air Force

Open-File Report 2019–1134

U.S. Department of the Interior
U.S. Geological Survey
U.S. Department of the Interior
DAVID BERNHARD, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2020

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Fiore, A.R., 2020, 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: U.S. Geological Survey Open-File Report 2019–1134, 42 p., https://doi.org/10.3133/ofr20181134.

ISSN 2331-1258 (online)
Acknowledgments

The author would like to acknowledge the staff of the Air Force Civil Engineer Center for support and cooperation, as well as colleagues from HydroGeoLogic, Inc.; Burns & McDonnell; and Tehama, LLC, working at Joint Base McGuire-Dix-Lakehurst. Technical reviews of this manuscript were provided by Stephen Cauller (U.S. Geological Survey [USGS]), Emmanuel Charles (USGS), and Peter Sugarman (New Jersey Geological and Water Survey). USGS interns Michael DeBonis, Orion Farr, Matthew Pronschinske, and Morgan Torstenson assisted in the preparation of the data used in this report.
Contents

Acknowledgments..........................................................................................................................iii
Abstract........................................................................................................................................1
Introduction...................................................................................................................................1
  Purpose and Scope .....................................................................................................................3
  Area of Investigation ..................................................................................................................4
  Previous Investigations .............................................................................................................4
  Well Numbering System ...........................................................................................................4
Data and Methods .....................................................................................................................4
Hydrostratigraphic Framework ...................................................................................................6
  Kirkwood-Cohansey Aquifer System .......................................................................................6
    Semiconfining Subunits Within the Kirkwood-Cohansey Aquifer System .........................7
  Piney Point Aquifer ...................................................................................................................8
  Manasquan-Shark River Confining Unit ....................................................................................8
  Confined Portion of the Vincentown Aquifer .........................................................................9
    Downdip Limit of the Confined Portion of the Vincentown Aquifer ....................................9
  Unconfined Portion of the Vincentown Aquifer .....................................................................12
  Navesink-Hornerstown Confining Unit ....................................................................................15
Summary.....................................................................................................................................15
References Cited............................................................................................................................16
Appendix 1 Lithologic Logs and Drillers' Logs for Selected Wells ............................................19

Figures

1. Map showing location of Joint Base McGuire-Dix-Lakehurst and
   reconnaissance areas, New Jersey ..........................................................................................2
2. Map showing downdip limit of the confined portion of the Vincentown aquifer
   in the vicinity of Joint Base McGuire-Dix-Lakehurst, New Jersey, from various
   publications ..................................................................................................................................11
3. Map showing location of wells 051250 / 08-MW-52 and 051251 / 08-MW-102,
   Joint Base McGuire-Dix-Lakehurst, New Jersey ..................................................................13
4. Log interpretation of wells 051250 / 08-MW-52 and 051251 / 08-MW-102, Joint
   Base McGuire-Dix-Lakehurst, New Jersey .........................................................................14
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 ...............14

Tables

1. Stratigraphic relations between selected hydrogeologic units and geologic
   formations in the vicinity of Joint Base McGuire-Dix-Lakehurst, New Jersey ..............3
2. Identifiers for wells on Joint Base McGuire-Dix-Lakehurst, New Jersey ..............................5
3. Wells used to develop a hydrostratigraphic framework, and interpreted aquifer
   structure points, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey ..............5
Plates

Plate 1  Map of well locations and outcrop areas of hydrostratigraphic units, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 2  Map of the bottom of the Kirkwood-Cohansey aquifer system, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 3  Map of the top of semiconfining subunits within the Kirkwood-Cohansey aquifer system, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 4  Map of the thickness of semiconfining subunits within the Kirkwood-Cohansey aquifer system, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 5  Map of the top of the Piney Point aquifer, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 6  Map of the top of the confined portion of the Vincentown aquifer, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 7  Map of the thickness of the confined portion of the Vincentown aquifer, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 8  Map of the bottom of the unconfined portion of the Vincentown aquifer, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 9  Map of the bottom of the Navesink-Hornerstown confining unit, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 10 Sections A-A’ through E-E’, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 11 Sections F-F’ through I-I’, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey

Plate 12 Sections J-J’ through L-L’, Joint Base McGuire-Dix-Lakehurst and vicinity, New Jersey
## 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 (m²) |
| acre                | 0.4047    | hectare (ha)     |
| acre                | 0.4047    | square hectometer (hm²) |
| acre                | 0.004047  | square kilometer (km²) |
| square mile (mi²)   | 259.0     | hectare (ha)     |
| square mile (mi²)   | 2.590     | square kilometer (km²) |
| **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 (in³)    | 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.
| Abbreviation | Description                                      |
|--------------|--------------------------------------------------|
| 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

By Alex R. Fiore

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)]

| Geologic Epoch | Formation name | Hydrogeologic unit |
|----------------|----------------|--------------------|
| Holocene       | Surficial units | Kirkwood-Cohansey aquifer system |
| Pleistocene    |                |                    |
| Pliocene       |                |                    |
| Miocene        | Kirkwood Formation | Manasquan-Shark River confining unit |
|                | Cohansey Formation | Piney Point aquifer |
| Eocene         | Shark River Formation | Vincentown aquifer |
|                | Manasquan Formation | Composite confining unit |
| Paleocene      | Vincentown Formation | Navesink-Hornerstown confining unit |
|                | Hornerstown Formation |                |
| Late Cretaceous| Tinton Sand<sup>2</sup> | Wenonah-Mount Laurel aquifer |
|                | Red Bank Sand<sup>2</sup> |                |
|                | Navesink Formation |                |
|                | Mount Laurel Formation |                |
|                | Wenonah Formation |                |

<sup>1</sup>Oligocene units are not present in the study area and are not included on this chart.

<sup>2</sup>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)      |
| 40000074351701   | 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/ofr2019134]
**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, and 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 Zapecka (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 finely 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 perfluorohexanesulfonic 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 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 JBM DL 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 JBM DL 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 JBM DL (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 updip, 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 (Zapecka, 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 except 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 290440 on section L–L’, where the altitude is approximately 104 ft. The lowest altitude occurs at the aquifer’s updip limit either near well 290440, where top of the Vincentown aquifer is approximately 235 ft, or updip 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 updip 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 updip 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 updip 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 updip 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 updip 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 undefined 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
EXPLANATION

- **Kirkwood Formation and Cohasey Formation**
- **Manasquan Formation**
- **Vincentown Formation**
- **Navesink Formation, Red Bank Sand, and Hornerstown Formation**
- **Wenonah Formation and Mount Laurel Formation**
- **Base boundary**
  - Downdip limit of the confined portion of the Vincentown aquifer, this study
  - Downdip limit of the confined portion of the Vincentown aquifer, Sugarman and others (2013, 2018a)
  - Downdip limit of the confined portion of the Vincentown aquifer, Cauller and others (2016)
  - Downdip limit of the confined portion of the Vincentown aquifer, Zapecza (1989)

**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
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; Cuiller 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.

References Cited

AECOM, 2010, Conceptual site model for Joint Base McGuire-Dix-Lakehurst: Philadelphia, Pa., AECOM, 85 p.

Anderson, H.R., and Appel, C.A., 1969, Geology and groundwater resources of Ocean County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 29, 74 p., 2 maps, accessed March 9, 2018, at https://pubs.er.usgs.gov/publication/70047881.

Cauller, S.J., Voronin, L.M., and Chepiga, M.M., 2016, Simulated effects of groundwater withdrawals from aquifers in Ocean County and vicinity, New Jersey: U.S. Geological Survey Scientific Investigations Report 2016–5035, 77 p. [Also available at https://doi.org/10.3133/sir20165035.]

DePaul, V.T., and Rosman, R., 2015, Water-level conditions in the confined aquifers of the New Jersey Coastal Plain, 2008: U.S. Geological Survey Scientific Investigations Report 2013–5232, 107 p., 9 pl. [Also available at https://doi.org/10.3133/sir20135232.]

Esri, 2018, How topo to raster works: Redlands, Calif., Esri, accessed April 12, 2019, at https://pro.arcgis.com/en/app/tool-reference/3d-analyst/how-topo-to-raster-works.htm.

Fiore, A.R., 2016, Hydrogeologic barriers to the infiltration of treated wastewater at the Joint Base McGuire-Dix-Lakehurst Land Application Site, Burlington County, New Jersey: U.S. Geological Survey Scientific Investigations Report 2016–5065, 83 p. [Also available at https://doi.org/10.3133/sir20165065.]

Fiore, A.R., Voronin, L.M., and Wieben, C.M., 2018, Hydrogeology of, simulation of groundwater flow in, and potential effects of sea-level rise on the Kirkwood-Cohansey aquifer system in the vicinity of Edwin B. Forsythe National Wildlife Refuge, New Jersey: U.S. Geological Survey Scientific Investigations Report 2017–5135, 59 p. [Also available at https://doi.org/10.3133/sir20175135.]

Goodrow, S.M., Ruppel, B., Lippincott, L., and Post, G.B., 2018, Investigation of levels of perfluorinated compounds in New Jersey fish, surface water, and sediment: New Jersey Department of Environmental Protection, Division of Science, Research, and Environmental Health Publication SR15-010, 46 p, accessed April 10, 2019, at https://nj.gov/dep/dsr/publications/Investigation%20of%20Levels%20of%20Perfluorinated%20Compounds%20in%20New%20Jersey%20Fish,%20Surface%20Water,%20and%20Sediment.pdf.

HGL, 2011, PFC site maps: Joint Base McGuire-Dix-Lakehurst web page, accessed March 15, 2019, at https://www.jbmdl.jb.mil/Portals/47/documents/PFC%20figs%20Feb%202013.pdf?ver=2017-02-23-081812-310.

Jacobsen, E., 2000, Ground-water quality, water levels, and precipitation at the biosolids study site, Lakehurst Naval Air Engineering Station, New Jersey, 1995-97: U.S Geological Survey Open-File Report 2000-197, 62 p., accessed April 9, 2019, at https://doi.org/10.3133/ofr00197.

Keys, W.S., 1990, Borehole geophysics applied to groundwater investigations: U.S. Geological Survey Techniques of Water-Resources Investigation, book 2, chap. E2, 150 p., accessed March 9, 2018, at https://pubs.er.usgs.gov/publication/twri02E2.

Minard, J.P., 1964, Geology of the Roosevelt quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-340, scale 1:24,000, accessed April 8, 2019, at https://doi.org/10.3133/gq340.

Minard, J.P., and Owens, J.P., 1962, Geologic map of the New Egypt quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-161, scale 1:24,000, accessed April 22, 2019, at https://doi.org/10.3133/gq161.

Minard, J.P., and Owens, J.P., 1963, Pre-Quaternary geology of the Browns Mills quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-264, scale 1:24,000, accessed April 22, 2019, at https://doi.org/10.3133/gq264.
Mullikin, L., 2011, Expansion of monitoring well network in confined aquifers of the NJ coastal plain, 1996–1997: New Jersey Geological Survey Open-File Report 11–1, 61 p., accessed April 9, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofreport/ofr11-1.pdf.

New Jersey Department of Environmental Protection (NJDEP), 2019, DEP requests input on proposed ground water quality criteria for chemicals of emerging concern: New Jersey Department of Environmental Protection News Release 19/P006, accessed April 22, 2019, at https://www.nj.gov/dep/newsrel/2019/19_0006.htm.

New Jersey Office of Information Technology, Office of Geographic Information Systems, 2012, New Jersey 10 foot resolution lidar derived digital elevation model (DEM), non-hydro-flattened: New Jersey Office of Information Technology, accessed November 8, 2019, at https://njogis-newjersey.opendata.arcgis.com/datasets/new-jersey-10-foot-dem?geometry=~83.436%2C38.666%2C-66.023%2C41.605.

New Jersey Office of Information Technology, Office of Geographic Information Systems, 2016, NJ 2015 natural color orthophoto cached tile base map service, 1 foot, accessed November 8, 2019, at https://geodata.state.nj.us/arcgis/rest/services/Basemap/Orthos_Natural_2015_NJ.

Owens, J.P., and Minard, J.P., 1962, Geologic map of the Columbus quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-160, scale 1:24,000, accessed April 22, 2019, at https://doi.org/10.3133/gq160.

Owens, J.P., and Minard, J.P., 1964, Pre-Quaternary geology of the Pemberton Quadrangle, New Jersey: U.S. Geological Survey Geologic Quadrangle Map GQ-262, scale 1:24,000, accessed April 22, 2019, at https://doi.org/10.3133/gq262.

Rea, F., 2017, Generalized stratigraphic table for New Jersey: New Jersey Geological and Water Survey Information Circular, 5 p., accessed April 8, 2019, at https://www.state.nj.us/dep/njgs/enviroed/infocirc/njstratcol.pdf.

Rush, F.E., 1968, Geology and ground-water resources of Burlington County, New Jersey: New Jersey Department of Conservation and Economic Development Special Report 26, 45 p., accessed April 22, 2019, at https://pubs.er.usgs.gov/publication/70159222.

Stanford, S.D., 2000a, Surficial geology of the Adelphia Quadrangle, Monmouth and Ocean Counties, New Jersey: New Jersey Geological and Water Survey Open-File Map 37, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm37.pdf.

Stanford, S.D., 2000b, Surficial geology of the Roosevelt Quadrangle, Mercer, Monmouth and Ocean Counties, New Jersey: New Jersey Geological and Water Survey Open-File Map 36, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm36.pdf.

Stanford, S.D., 2013, Geology of the Keswick Grove quadrangle, Ocean County, New Jersey: New Jersey Geological and Water Survey Open-File Map 100, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm100.pdf.

Stanford, S.D., 2016, Geology of the Whiting quadrangle, Ocean and Burlington Counties, New Jersey: New Jersey Geological and Water Survey Open-File Map 113, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm113.pdf.

Stanford, S.D., Pristas, R.S., and Witte, R.W., 2007, Surficial geology of New Jersey: New Jersey Geological Survey Digital Geodata Series 07–2, scale 1:100,000, accessed April 22, 2019, at https://www.nj.gov/dep/njgs/geodata/dgs07-2.htm.

Stanford, S.D., and Sugarman, P.J., 2017, Geology of the Toms River and Seaside Park quadrangles, Ocean County, New Jersey: New Jersey Geological and Water Survey Open-File Map 116, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm116.pdf.

Sugarman, P.J., Carone, A.R., Stroiteleva, Yelena, Pristas, R.S., Monteverde, D.H., Domber, S.E., Filo, R.M., Rea, F.A., and Schagrin, Z.C., 2018a, Framework and properties of aquifers in Burlington County, New Jersey: New Jersey Geological and Water Survey Geologic Map Series GMS 18-3, scale 1:100,00, accessed April 9, 2019, at https://www.nj.gov/dep/njgs/pricelst/gmseries/gms18-3.pdf.

Sugarman, P.J., Carone, A., Malerba, N.L., and Lyons, Scott, 2018b, Bedrock geologic map of the Lakewood quadrangle, Ocean County, New Jersey: New Jersey Geological and Water Survey Open-File Map 121, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm121.pdf.

Sugarman, P.J., Castelli, M.V., Dalton, R.F., and Melerba, N.L., 2016, Bedrock geologic map of the Lakehurst quadrangle, Ocean County, New Jersey: New Jersey Geological and Water Survey Open-File Map 113, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/ofmap/ofm113.pdf.

Sugarman, P.J., Monteverde, D.H., Boyle, J.T., and Domber, S.E., 2013, Aquifer correlation map of Monmouth and Ocean Counties, New Jersey: New Jersey Geological and Water Survey Geologic Map Series 13-1, scale 1:100,000, accessed April 9, 2019, at https://www.state.nj.us/dep/njgs/pricelst/gmseries/gms13-1.pdf.
Sugarman, O.J., Owens, J.P., and Bybell, L.M., 1991, Geologic map of the Adelphia and Farmingdale quadrangles, Monmouth and Ocean Counties, New Jersey: New Jersey Geological and Water Survey Geologic Map Series GMS 91-1, scale 1:24,000, accessed April 22, 2019, at https://www.state.nj.us/dep/njgs/pricelst/gmseries/gms91-1.pdf.

Szabo, Z., Zapecza, O.S., Oden, J.H., and Rice, D.E., 2005, Radiochemical sampling and analysis of shallow ground water and sediment at the BOMARC missile facility, east-central New Jersey, 1999-2000: U.S. Geological Survey Scientific Investigations Report 2005–5062, 87 p., accessed April 9, 2019, at https://pubs.usgs.gov/sir/2005/5062/.

U.S. Air Force, 2016, Site inspection (SI) of fire fighting foam usage at various air force bases in the eastern United States—Validated SI results; Joint Base McGuire-Dix-Lakehurst, New Jersey: U.S. Air Force, accessed April 10, 2019, at https://www.jbmdl.jb.mil/Portals/47/documents/JB%20MDL%20Verified%20Results.pdf?ver=2016-11-29-081655-927.

U.S. Environmental Protection Agency (EPA), 2019, EPA’s per- and polyfluoroalkyl substances (PFAS) action plan: U.S Environmental Protection Agency 823R18004, 72 p., accessed April 22, 2019, at https://www.epa.gov/pfas/epas-pfas-action-plan.

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

U.S. Geological Survey, 2019b, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed April 9, 2019, at https://doi.org/10.5066/F7P55KJN.

Walker, R.L., Reilly, P.A., and Watson, K.M., 2008, Hydrogeologic framework in three drainage basins in the New Jersey Pinelands, 2004–2006: U.S. Geological Survey Scientific Investigations Report 2008–5061, 147 p., accessed April 9, 2019, at https://pubs.usgs.gov/sir/2008/5061/.

Zapecza, O.S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain, regional aquifer-system analysis—Northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404–B, 49 p., 24 pls. [Also available at https://pubs.er.usgs.gov/publication/pp1404B.]
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.
### Log of Well No. 1
as determined from well samples
by R. E. Johnson, State Geologist

| Depth (ft) | Description |
|-----------|-------------|
| 0 - 23    | Fine-grained, yellow sand |
| 23 - 25   | Fine-grained yellow sand with small pebbles |
| 25 - 38   | Very fine-grained, clayey yellow sand |
| 38 - 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 - 350 | 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 Grey clay |
|           | and 474 Grey, fossiliferous clay |
| 503 - 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 |
| 925 - 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.                         |      |
| 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 quartz 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    | As 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

| Depth (ft) | Description                       |
|-----------|-----------------------------------|
| 0         | Sand                              |
| 1         | 19' White sandy clay              |
| 37        | 37' Yellow sandy clay             |
| 58        | 58' Yellow sandy clay             |
| 74        | 74' White sand                    |
| 78        | 78' Black marl                    |
| 98        | 98' Green marl                    |
| 122       | 122' Green sandy marl             |
| 178       | 178' Green hard marl              |
| 196       | 196' Green sandy marl             |
| 210       | 210' Green sandy marl             |
| 275       | 275' Green sandy marl and oyster shells |
| 375       | 375' Hard sand                    |
| 393       | 393' Hard sand marl and oyster shells |

Figure 1.3. Drillers' log of well 050380.
Figure 1.4. Drillers’ log of well 050714.
| Well Log                  | Feet From Ground Surface (0 to 3) |
|--------------------------|-----------------------------------|
| White Sand               |                                   |
| Yellow Sand              | 3 - 6                             |
| Clayish Orange Sand      | 6 - 11                            |
| Stones-Dark Yellow Sand  | 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.
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)

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
Figure 1.9. Drillers' log of well 051613.

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 1.10. Drillers' log of well 051769.

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 GLAUCONITE
241-256 SILTY BROWN CLAY WITH SOME SAND
256-265 SILTY GRAY CLAY WITH GLAUCONITE SHELLS
265-312 MEDIUM GRAY TO GREEN SAND WITH SHELL FRAGMENTS

Figure 1.11. Drillers' log of well 052026.

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
|          | Description                                                                 |
|----------|-----------------------------------------------------------------------------|
| 0 - 10:  | Brown/Yellow GW - Well-graded gravels and gravel-sand mixtures, little or no |
| 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.
Figure 1.14. Drillers' log of well 290118.
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, thinly micaceous somewhat fossiliferous quartzose and glauconitic clay.

503 - 533° Greenish grey, mixte slightly fossiliferous lignitic glauconite and fine quartz sand.

533 - 603° Grey to greenish grey mixture of glauconite and sand and very local fossils.

603 - 653° Grey to greenish grey moderately fossiliferous clay slightly glauconitic fine to coarse quartz sand.

653 - 713° Olive grey, highly fossiliferous somewhat dirty moderately glauconitic fine to medium quartz sand.

713 - 733° Olive 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° Olive, finely micaceous slightly glauconitic silt to very fine sand.

872 - 930° Olive to olive grey, fairly clean mixture of glauconitic and fine quartz sand.

930 - 983° Olive, somewhat dirty slightly glauconitic fine to very coarse quartz sand with scattered pebbles of various sizes.

983 - 1023° Light grey, clean, glauconitic slightly micaceous silt to sand.

1023 - 1063° Grey, finely micaceous almost glauconitic, fossiliferous silt.
1063 - 1103' Cre white fossiliferous slightly glauconitic silty micaceous silt with scattered qtz grains.

1103 - 1133' Grey with slight olive tint highly fossiliferous lightly micaceous glauconitic fine to medium sand.

1133 - 1364' Grey to light olive grey lightly fossiliferous fairly clean slightly micaceous and glauconitic fine quartz sand.

1073 - 1083' Washed and sieved - fine-medium quartz glauconite mainly rounded types, some accordion shapes many broken shell fragments coiled forams, all calcareous se a siderite nodules.

1113 - 1123' Washed and sieved - fine-medium quartz sand fresh green accordion shaped glauconite many shell fragments noted small number broken small immature type accoronds. These have been noted by F. J. M. Previously in the downip woodburn peotony formations - few coiled calcareous forams - few siderite nodules.

Note: to 113 to 123' some very coarse quartz shins which can be St. Laurel.
**Figure 1.16.** Drillers' log of well 290134.
**Figure 1.17.** Drillers' log of well 290440.
### Figure 1.18
Drillers' log of well 290588.

| Depth (ft) | Lithology |
|-----------|-----------|
| 0         | Original ground |
| 60        | Clay, sandy clay |
| 68        | Fine, gray sand |
| 117       | Clay, mixed clay |
| 132       | Clay, soft, sand clay |
| 111       | Grey clay |
| 115       | Clay, very hard clay |
| 218       | Clay, black, sand |
| 255       | Sand clay, gravel, clay |
| 252       | Hard streaks |
| 428       | Grey, thin clay |
| 438       | Sand, clay |
| 510       | Clay, black, sand, gravel |
| 531       | Grey, sand, gravel |
| 533       | Sand, clay, gravel |
| 623       | Hard streaks |
| 650       | Grey, clay, sand, gravel |
| 728       | Clays, sand, gravel |
| 734       | Hard streaks |
| 893       | Sand, thin clay |
| 924       | Sand, gravel |
| 926       | Hard streaks |
| 576       | Er, clay, black, sandy sand |
| 589       | Hard streaks |
| 1221      | Clay, black, sand, gravel |
| 1248      | Filt. sand, gravel, clay |
| 1316      | Vitr. fl, clay, gravel, sand |
| 1037      | Sand, and clay, streaks |
| 1107      | Bedded, yellow, clay |
| 1183      | Red, manganese, clay, streaks |
| 1179      | Red, fine sand, dark sand |
| 1236      | Clay, and clay, streaks |
| 1242      | Clay, and, hard, streaks |
| 1295      | Clay, and, hard, streaks |
| 1319      | Clay, clay, hard, streaks |
| 1325      | Concreted, pavement, hard, streaks |
| 1329      | Hard streaks |
| 1362      | Hard, clay |
| 1347      | Concreted, pavement, hard, streaks |
| 1348      | Clay, hard, streaks |
| 1398      | Red, sand, clay, streaks |
| 1433      | Clay, and, hard, streaks |
| 1435      | Sand, and, hard, streaks |
| 1516      | Liithic, sand, clay, and, clay |
| 1560      | Sand, and, clay, streaks |
| 1571      | Sand, and, clay, streaks |
| 1575      | Clay, and, clay, streaks |
| 1584      | Clay, and, clay, streaks |
| 1594      | Clay, and, clay, streaks |
| 1620      | Clay, red, clay, and, clay |
| 1624      | Clay, red, clay, and, clay |
| 1641      | Clay, red, clay, and, clay |
| 1642      | Clay, red, clay, and, clay |

"Appendix 1 Lithologic Logs and Drillers' Logs for Selected Wells"
| Formation                  | Depth  |
|---------------------------|--------|
| 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.) | Description |
|----------------|------------|-------------|
| 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              | 1222-1230  | 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.
## Appendix 1  Lithologic Logs and Drillers' Logs for Selected Wells

| 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              |
| 694-706           | 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.
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.
