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HYDROGEOLOGY OF THE PORT OF BALTIMORE CONFINED AQUATIC DISPOSAL PILOT PROJECT AREA, MASONVILLE, MARYLAND

by

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KEY RESULTS

The Maryland Port Administration has proposed to install a Confined Aquatic Disposal (CAD) cell at the Masonville vessel berth for the containment of dredge materials from Baltimore Harbor. Construction of the CAD cell requires excavation of predominantly sandy sediment from the Patapsco Formation (Lower Patapsco aquifer) to a depth of approximately 75 feet below sea level. The CAD cell lies within the outcrop area of the Lower Patapsco aquifer system which overlies the Patuxent aquifer system. Both aquifers are important water sources in northern Anne Arundel County. Since the CAD cell may receive contaminated dredge material, a hydrogeologic investigation was undertaken to determine the possibility of migration of potential contaminants towards Anne Arundel County's well fields. Results of the investigation indicate that groundwater in the Lower Patapsco aquifer system in the vicinity of the CAD cell flows from high to low topographic elevations and discharges to the Patapsco River. The direction of flow in the vicinity of the CAD cell is south to north, opposite the direction of Anne Arundel County's well fields. Since the CAD cell is located within the Patapsco River, which is locally an area of groundwater discharge, potential contaminants contained in the fill could not migrate landward. Aquifer testing indicates that the Arundel Clay confining unit, which separates the Lower Patapsco aquifer system from the underlying Patuxent aquifer system, forms a hydraulic barrier which would preclude downward migration of potential contaminants contained in the fill.

INTRODUCTION

The Port of Baltimore shipping channels require periodic maintenance dredging to maintain adequate depths. To increase future storage capacity for dredge material, the Maryland Port Administration (MPA) initiated a pilot study of a confined aquatic disposal (CAD) system. In a CAD system, sand and gravel is excavated from the geologic formation(s) beneath the river or bay bottom and transferred to land storage for some later beneficial use. The remaining cavity (CAD cell) is filled with dredge material consisting mainly of silt and clay. To determine whether any potential contaminants present in the dredge material will affect the groundwater resources, the Maryland Geological Survey (MGS) investigated the hydrogeology (aquifer framework and hydraulics) of the surrounding aquifer system.

PURPOSE AND SCOPE

The purpose of this study is to investigate whether potential contaminants contained in dredge material to be placed in a proposed CAD cell will migrate horizontally in the Lower Patapsco aquifer system and/or vertically to the Patuxent aquifer system and adversely affect well fields operated by the Anne Arundel County Department of Public Works (AADPW).

The report discusses the hydrogeologic framework of the Lower Patapsco and Patuxent aquifer systems underlying the CAD site including the geology, hydraulic properties, water table and potentiometric surfaces, effectiveness of the Arundel Clay confining unit, and water quality.

LOCATION OF STUDY AREA

The study area is the Masonville area of southern Baltimore City, Maryland; however, to adequately characterize the hydrogeology a broader area, including most of southern Baltimore City and a portion of northern Anne Arundel County, was included in the study (fig. 1). Test wells constructed for the study are located at the CAD site adjacent to a MPA vessel berth, at the entrance to the Maryland Environmental Service (MES) Masonville facility (MES Entrance), and at Garrett Park and Bay Brooks Park in Brooklyn, Maryland.

TEST-WELL CONSTRUCTION

During this study, five monitoring wells were constructed—two 4-inch (in.) diameter wells at the CAD site, one 4-in. diameter well at Bay Brooks Park, and one 2-in. diameter well at both the MES Entrance and Garrett Park sites (figs. 1 and 2a-d). Construction information for the monitoring wells is presented in Table 1 and Figures 3a-e. The 4-in. wells were constructed under contract by A.C. Schultes of Maryland, Inc. using a mud rotary rig, and the 2-in. wells were constructed by Findling, Inc. using an auger rig. All wells were constructed using schedule-40 PVC well casing, slotted screen (0.02-in. slot size), and Morie No. 1 well gravel (figs. 3a-e). The CAD and Bay Brooks Park wells were finished with 6-in. steel protective casings, and the MES Entrance and Garrett Park wells were finished with below-grade vaults. For the wells drilled by the mud-rotary method, drill cuttings were collected in the deepest well at the CAD site (BC 4S2E-6) and in the well at Bay Brooks Park (BC 5S2E-26) at 10-foot intervals. The samples were washed, examined, and described using a hand lens (app. A.). In the auger holes, 1.5-in. diameter split-spoon samples were collected at the bottom of each 5-foot auger flight. Typical core recovery ranged from 1 to 1.5 feet (ft), or 50 to 75 percent of the 24-in. core barrel. The outside “rind” on the cores was scraped to expose fresh sediment before making lithologic descriptions (app. A.). Geophysical logs (8-, 16-, 32- and 64-in. normal resistivity, 6-ft lateral resistivity, single-point resistance, spontaneous potential, and gamma radiation) were completed prior to well construction in the deepest hole (well BC 4S2E-6) at the CAD site by Earth Data, Inc. (app. B). Induction and gamma logs were completed by Earth Data, Inc. in the MES Entrance, Garrett Park and Bay Brooks Park wells after the wells were constructed (app. B.). After construction the wells at the CAD and Bay Brooks Park sites were developed using compressed air. At the MES Entrance and Garrett Park sites, the wells were developed by pumping using a 12-volt submersible pump. At the CAD site, 4-hour (hr) constant-rate aquifer tests were run on both wells. A description of the testing is given in the "Transmissivity" section of this report. Altitudes of the top of the well casings at the MES Entrance and Garrett Park sites were determined using a Topcon HiPer SR[1] Global Positioning System (GPS) receiver. Altitudes of the top of the well casings at the CAD and Bay Brooks Park sites were determined using differential GPS.

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HYDROGEOLOGIC FRAMEWORK

The study area is located in Maryland's Coastal Plain Physiographic Province in the outcrop area of the sand facies of the Lower Cretaceous-age Patapsco Formation (Crowley and others, 1976). In the vicinity of the CAD site, the Patapsco Formation is overlain by a thin deposit of Quaternary-age Talbot Formation (Crowley and others, 1976). The hydrogeologic units present beneath the study area consist of, from top to bottom, the Lower Patapsco aquifer system, the Arundel Clay confining unit, and the Patuxent aquifer. The units are correlative with the regional aquifer framework (Andreasen and others, 2013). Hydrogeologic units beneath the CAD site were identified using gamma-radiation logs and, to a lesser extent, lithologic descriptions of drill cuttings. Because of the presence of brackish water in both the Lower Patapsco and Patuxent aquifer systems, the resistivity logs could not be used to differentiate aquifer and confining unit material.

Aquifers and Confining Units

The shallowest hydrogeologic unit in the study area is the Lower Patapsco aquifer system. The unit outcrops in a broad band extending across the northernmost portion of Anne Arundel County into southern Baltimore City and Baltimore County (Andreasen and others, 2013). The Lower Patapsco aquifer system is composed primarily of sand and gravel of the Patapsco Formation but may locally include thin beds of overlying Late Tertiary- to Quaternary-age upland gravel (Crowley and others, 1976). The aquifer system consists of medium to coarse sand with thin gravelly layers interbedded with layers of green, white, and red clay. The depth to the base of the aquifer system at the CAD site is 104 ft below sea level (111 ft below land surface) (fig. 4; app. B). Total saturated sand thickness is about 60 ft at the CAD

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site based on the net sand thickness on the gamma-radiation log. The Lower Patapsco aquifer system forms a continuous, hydraulically connected layer between the CAD site and Anne Arundel County's Dorsey Road well field (fig. 5). Near the Dorsey Road well field, the Lower Patapsco aquifer system is confined by the overlying Patapsco confining unit which separates it from the shallower Upper Patapsco aquifer system (fig. 5) (Wilson and Achmad, 1995; Andreasen and others, 2013).

Underlying the Lower Patapsco aquifer system is the Arundel Clay confining unit, which is composed primarily of the Arundel Clay Formation; however, the confining unit may include clay of the overlying Patapsco Formation and underlying Patuxent Formation if clay-on-clay contacts occur. Differentiating clays of the Patapsco, Arundel Clay, and Patuxent Formations based solely on lithology is difficult, given their similar appearance. The Arundel Clay confining unit consists of very dense, variegated clays with thin interbedded layers of sand and gravel. An indurated layer of iron-cemented sand occurs near the top of the unit. The depth to the top of the confining unit at the CAD site occurs at 106 ft below sea level (113 ft below land surface) (fig. 4; app. B.). At the CAD site, the unit is about 40 ft thick. The Arundel Clay confining unit forms a continuous layer between the CAD site and Anne Arundel County's Dorsey Road well field (fig. 5). The unit thickens to about 120 ft at the Dorsey Road well field.

Underlying the Arundel Clay confining unit is the Patuxent aquifer system, which is composed of sand and gravel of the Patuxent Formation. The unit consists of medium to coarse sand and gravel layers interbedded with tough mottled clay. The top of the Patuxent aquifer system at the CAD site occurs at 147 ft below sea level (154 ft below land surface) (figs. 4 and 6; app. B.). The depth to the base of the aquifer system is approximately 266 ft below sea level (273 ft below land surface) at the CAD site as indicated by the gamma-radiation log; however, sand and gravel was logged in the drill cuttings to a depth of 303 ft below sea level (310 ft below land surface). The relatively high gamma radiation between 273 and 303 ft below sea level suggests that the sands and gravels within that interval have a clayey matrix, possibly composed of saprolite developed on re-worked Pre-Cretaceous basement rock. That interval, therefore, is not likely to function as aquifer material. Total sand thickness of the Patuxent aquifer system is approximately 72 ft thick. The Patuxent aquifer system forms a continuous, hydraulically connected layer between the CAD site and Anne Arundel County's Dorsey Road well field (fig. 5). The altitude of the top of the Patuxent aquifer system ranges from about sea level near its outcrop area to greater than 600 ft below sea level in east-central Anne Arundel County (fig. 6). The aquifer system dips to the southeast at approximately 80 feet per mile (ft/mi). The dip is greater near the outcrop area.

Pre-Cretaceous Basement Rock

Underlying the Patuxent aquifer system is the Pre-Cretaceous basement rock. At the CAD site the basement rock underlies the Patuxent aquifer at 296 ft below sea level (303 ft below land surface) and consists of green, mica-rich saprolite. (figs. 4 and 7; apps. A and B). The altitude of the top of the Pre-Cretaceous basement rock ranges from about sea level just west of Baltimore Harbor to more than 800 ft below sea level in east-central Anne Arundel County (fig. 7). The top of the Pre-Cretaceous basement rock was defined primarily by geologist's or driller's lithologic descriptions that indicated hard rock; however, at one data point (altitude of top of rock of 350 ft below sea level), the contact was described as soft granite and mica (saprolite). The basement rock dips to the southeast at approximately 80 ft/mi.

Transmissivity

Constant-rate aquifer tests were performed on the Lower Patapsco aquifer system and Patuxent aquifer system test wells at the CAD site on October 28th and 25th, 2013, respectively. The tests consisted of a 4-hr pumping phase followed by a maximum of 4 hrs recovery. Discharge was measured periodically using a 55-gallon drum and stopwatch. Water-level measurements were made in both wells during each test using a hand-held electric tape. Water levels were also monitored and recorded in the pumping well in each test using a pressure transducer with a built-in data logger. The pumping rate was 35 gallons per minute (gal/min) in the Lower Patapsco well and 78 gal/min in the Patuxent well.

Transmissivity (T) was calculated using the Cooper-Jacob straight-line method, in which drawdown or residual drawdown data is plotted against elapsed time on semi-logarithmic graphs (figs. 8 and 9) (Cooper and Jacob, 1946). This method assumes that the following conditions are met: (1) the aquifer has infinite extent, and is homogeneous and isotropic; (2) well discharge is at a constant rate; (3) the well screen fully penetrates the confined aquifer, resulting in horizontal flow to the well, and the flow is laminar; (4) the aquifer is of uniform thickness and is horizontal; (5) the potentiometric surface is initially horizontal; and, (6) the aquifer is fully confined and discharge is derived exclusively from storage in the aquifer.

Water levels in both the Lower Patapsco aquifer system and Patuxent aquifer system at the CAD site are affected by tidal fluctuations in the Patapsco River. The tidal effect in the Lower Patapsco aquifer system during the aquifer test was great enough to interfere with the drawdown and recovery responses caused by pumping. In order to use the water-level data to calculate transmissivity, the tidal effects were subtracted from the water-level record. This was accomplished by determining the ratio of tide-level change to groundwater-level change for a period of record unaffected by pumping. Tide levels at the National Oceanic and Atmospheric Administration (NOAA) tide gage (station 8574680) at Baltimore Harbor, plotted along with water levels from the Lower Patapsco test well, indicated a groundwater-level change of 0.83 ft for every 1 ft of tide-level change. This ratio was used to subtract out the tidal influence from the groundwater levels recorded during both drawdown and recovery phases of the aquifer test.

Transmissivity of the Lower Patapsco aquifer system at the CAD site (well BC 4S2E-7) is 2,040 feet squared per day (ft^2/d) calculated from the drawdown phase of the test for the 100-1,000 log cycle (fig. 8). A lower transmissivity value of 1,360 ft^2/d was calculated from the recovery phase for the 1-10 log cycle (fig. 8). The latter part of both the drawdown and recovery phases were used to determine the slope of the drawdown and residual drawdown curves. Use of the latter test data tends to reduce the effects of well-casing storage and partial well penetration of the aquifer. The calculated transmissivity is not reflective of the total transmissivity of the Lower Patapsco aquifer system at the CAD site because only 10 ft of the total saturated aquifer thickness (approximately 60 ft) was screened. The nearest transmissivity data for the Lower Patapsco aquifer system are in the well fields of AADPW in northern Anne Arundel County. Transmissivity values in that area range from 350 to 5,080 ft^2/d, with a median value of 1,695 ft^2/d (Andreasen and others, 2013).

Transmissivity of the Patuxent aquifer system at the CAD site (well BC 4S2E-6) is 808 ft^2/d calculated from the drawdown phase, and 870 ft^2/d calculated from the recovery phase (fig. 9). In both the drawdown and recovery phases, the slope of the drawdown and residual drawdown curves are the same for all log cycles. The calculated transmissivity is not reflective of the total transmissivity of the Patuxent aquifer system at the CAD site because only 20 ft of the total aquifer thickness (approximately 72 ft) was screened. If all of the sands were screened the transmissivity could be significantly greater. The nearest transmissivity values for the Patuxent aquifer system ranges from 238 to 2,160 ft^2/d, with a median value of 1,060 ft^2/d, in an AADPW well field in northern Anne Arundel County (Dorsey Road well field) to 21,950 ft^2/d in an industrial well in southern Baltimore County (Andreasen and others, 2013).

Water-Level Fluctuations

Water levels measured in the CAD, MES Entrance, Garrett Park and Bay Brooks Park test wells from late October, 2013 to early February, 2014 changed less than 1 ft over the time period (fig. 10). Water levels in all of the wells show a flat trend over the period of record.

Water levels in the Lower Patapsco aquifer system at the CAD, MES Entrance, Garrett Park, and Bay Brooks Park sites, and in the Patuxent aquifer system at the CAD site, respond to changes in barometric pressure (fig. 11). Changes in barometric pressure recorded at Baltimore-Washington International

Thurgood Marshall (BWI) Airport, located approximately 6 miles (mi) to the south of the test sites, show an inverse relation to changes in groundwater levels. Water levels in the test wells were recorded at 30-minute intervals using a pressure transducer. Water levels in unconfined aquifers generally show a negligible response to changes in barometric pressure, while water levels in confined aquifers typically fluctuate in response to barometric changes. The presence of a barometric response in the Lower Patapsco aquifer system screened in the test wells, therefore, indicates that the aquifer may be partially confined by overlying clay layers (app. A). The response to barometric effects at the CAD and MES Entrance sites may also be a result of the extensive impervious surfaces in the area surrounding the wells. Impermeable structures, such as parking lots and buildings, of sufficient areal extent may result in barometric efficiencies in unconfined aquifers at levels similar to confined aquifers (Hare and Morse, 1997). This may be the case at the CAD site given the extensive paved area (approximately 100 acres) where the sites are located.

Water levels in the Lower Patapsco and Patuxent aquifer systems at the CAD site and in the Lower Patapsco aquifer system at the MES Entrance site are affected by tides in the nearby Patapsco River. The fluctuations range from about 0.5 to 1.6 ft and 0.1 to 0.5 ft in the Lower Patapsco and Patuxent aquifer systems at the CAD site, respectively, and from 0.03 to 0.12 ft in the Lower Patapsco aquifer system at the MES Entrance site. The CAD and MES Entrance sites are located approximately 20 and 1,600 ft from the Patapsco River, respectively.

Water levels in the Lower Patapsco aquifer system test wells show no noticeable response to precipitation events. In shallow, unconfined aquifers, precipitation typically causes an abrupt rise in groundwater levels followed by a recession curve as the effects of the infiltrating precipitation diminish. The absence of a response suggests that clay layers partially confine the aquifer system, impeding vertical flow. In the MES Entrance and CAD test wells, the extensive area in the vicinity of the sites covered in pavement likely also restricts infiltrating precipitation.

AQUIFER HYDRAULICS

Direction of Groundwater-Flow in the Lower Patapsco and Patuxent Aquifer Systems

The Lower Patapsco aquifer system forms the water-table aquifer in the Masonville-Brooklyn area of Baltimore City. Measured water levels in the fall of 2013 ranged from a high value of approximately 23 ft above sea level at the Bay Brooks Park site to sea level at the CAD site (fig. 12). The direction of groundwater flow is from the higher topographic elevations, where water enters as recharge from precipitation, to lower elevations (fig. 12). Groundwater in the Lower Patapsco aquifer system discharges locally to streams and to the tidal Patapsco River. Since the Lower Patapsco aquifer system is exposed beneath the Patapsco River which allows for denser brackish water to intrude inland along the shoreline, discharge from the Lower Patapsco aquifer system to the Patapsco River likely only occurs at the immediate shoreline boundary. Given the absence of Lower Patapsco production wells in the Masonville-Brooklyn area (Cynthia Latham, Maryland Department of the Environment, personal commun., 2014), the flow regime is not affected by local pumping. South of the outcrop area near BWI Airport water levels are as high as 75 ft above sea level near BWI Airport and decrease eastward to 15 ft above sea level (fig. 12). South of the outcrop area the Lower Patapsco aquifer system is confined or semi-confined by the overlying Patapsco confining unit (Wilson and Achmad, 1995; Andreasen and others, 2013). Withdrawals from Anne Arundel County's Lower Patapsco well field in northern Anne Arundel County do not form significant cones of depression. Approximately 1.3 million gallons per day (Mgal/d) were withdrawn from the Lower Patapsco aquifer system by AADPW in the northern part of the County in 2012 (Cynthia Latham, Maryland Department of the Environment, written commun., 2014). The direction of groundwater flow in the confined portion of the aquifer is from west to east.

The Patuxent aquifer system is a confined aquifer in the Masonville-Brooklyn area. The water level in the aquifer measured in the fall of 2013 was about 2 ft above sea level at the CAD site (fig. 13). A significant cone of depression surrounds Anne Arundel County's Dorsey Road well field, with water levels as deep as 109 ft below sea level (fig. 13). Approximately 4 Mgal/d were withdrawn from the Patuxent aquifer system at the Dorsey Road well field in 2012 (Cynthia Latham, Maryland Department of the Environment, written commun., 2014). There are no production wells withdrawing water from the Patuxent aquifer system in the Masonville-Brooklyn area (Cynthia Latham, Maryland Department of the Environment, personal commun., 2014). The hydraulic gradient is relatively steep within about 2 mi from the deepest part of the cone, and then flattens at greater distances from the pumping center. The influence of the cone of depression surrounding the Dorsey Road well field on groundwater-flow paths appears to diminish northward. As a result, groundwater-flow paths that intersect the CAD site likely trend in a southeastern direction, bypassing the Dorsey Road well field.

The vertical-head gradient between the Lower Patapsco and Patuxent aquifer systems is directed upward at the CAD site. The head in the Patuxent aquifer system is about 1.4 ft higher than in the Lower Patapsco aquifer system.

Effectiveness of the Arundel Clay Confining Unit

At the CAD site, the Arundel Clay confining unit effectively separates the Patuxent aquifer system from the overlying Lower Patapsco aquifer system hydraulically. Water levels observed while the aquifers were pumped indicates that short-term pumping effects do not propagate across the confining unit. Figure 14 shows (A) water levels measured in the Lower Patapsco well while the Patuxent well was pumped for 4 hrs at 78 gal/min; and, (B) water levels in the Patuxent well while the Lower Patapsco well was pumped for 4 hrs at 35 gal/min. Tidal record from the NOAA gage at Baltimore Harbor (station 8574680) is also plotted on the graphs. Water levels in the pumped wells display drawdown curves in response to pumping followed by recovery curves after pumping stopped. Water levels in the unpumped wells during both tests show no response to pumping. The slight decline in water levels in the Lower Patapsco well during the recovery period of the Patuxent well in the first test is likely attributed to the outgoing tide in the Patapsco River.

The effectiveness of the Arundel Clay confining unit is also apparent in the significantly lower chloride concentrations in the Patuxent aquifer system (2,170 mg/L) compared to the Lower Patapsco aquifer system (4,580 mg/L). If a hydraulic connection existed across the confining unit, density-dependent flow would result in increasing chloride concentrations with depth.

WATER QUALITY

Water samples were collected from the Lower Patapsco and Patuxent wells at the CAD site near the end of the 4-hr aquifer tests conducted on October 28th and 25th, 2013, respectively. The samples were collected, filtered, treated, and bottled by MES personnel after pH, specific conductance, dissolved oxygen, turbidity, temperature, and oxidation-reduction potential measurements stabilized. Blank and duplicate samples were also taken. The samples were packed in ice and shipped to three laboratories for analysis. Dissolved aluminum, antimony, arsenic, boron, calcium, cadmium, chromium, cobalt, copper, iron, lead, lithium, mercury, molybdenum, manganese, nickel, selenium, thallium, vanadium, and zinc were analyzed by Brooks Rand Labs of Seattle, Washington[1]. Dissolved magnesium, potassium, sodium, barium, beryllium, silver, strontium, uranium, silica, fluoride, bromide, chloride, sulfate, nitrite, total nitrate plus nitrite, orthophosphorus, total dissolved solids, total organic carbon, phosphorous, and ammonia nitrogen were analyzed by QC Laboratories[1] of Southampton, Pennsylvania. Gross alpha and gross beta particle activity and radon-222 were analyzed by Florida Radiochemistry, Inc.[1] of Orlando, Florida. Results of the water-quality analyses are given in Table 2. The parameters measured in the field

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(pH, specific conductance, dissolved oxygen, turbidity, temperature, and oxidation-reduction potential) are also given in Table 2.

Water from the Lower Patapsco aquifer system is slightly acidic (pH 6.7), low in dissolved oxygen (1.6 milligrams per liter [mg/L]), has high specific conductance (11,600 microsiemens per centimeter at 25 degrees Celsius [μS/cm]), and is a reducing chemical environment (-87 millivolts [mv] oxidation-reduction potential) (tab. 2). Water from the Patuxent aquifer system is acidic (pH 4.2), has no dissolved oxygen, has high specific conductance (6,460 μS/cm), and is an oxidizing chemical environment (281 mv oxidation-reduction potential) (tab. 2).

The general chemical character of groundwater can be classified according to the dominant ions present in the water. Milliequivalent percentages of the major ions in water from the Lower Patapsco and Patuxent aquifers at the CAD site were plotted on a Piper trilinear diagram (Hem, 1985) to show the water type (fig. 15). On this diagram the milliequivalent percentages of cations and anions are plotted on the two triangles at the base. The intersection of these points on the diamond grid represents the water type defined by the dominant ions. The water type of both the Lower Patapsco and Patuxent aquifer systems at the CAD site is sodium chloride. On the graph, sodium and potassium are combined, but in the analyses the milliequivalent percentage of sodium is an order of magnitude greater than potassium in both aquifers. Also plotted on the diagram is pore water from a bottom-sediment core taken in the Chesapeake Bay at the mouth of the Patapsco River. The sample depth was 40 to 42.5 centimeters (cm) below the bottom surface (Tyree and others, 1981). The water type in the sediment core is also sodium chloride.

Chloride concentration in the Lower Patapsco well at the CAD site (BC 4S2E-7) was 4,580 mg/L. The elevated chloride level is a result of a brackish-water wedge extending inland from the Patapsco River. Since the Lower Patapsco aquifer system is exposed beneath the Patapsco River in the vicinity of the CAD site, higher density brackish river water intrudes into the aquifer along the shoreline. The chloride level is likely near the annual average chloride concentration in Patapsco River water. Tyree and others (1981) analyzed chloride concentrations in a bottom-sediment core in the Chesapeake Bay at the mouth of the Patapsco River approximately 12 mi downstream of the CAD site during the fall of 1978. The average chloride concentration in the deeper part of that core (40 to 100 cm below bottom surface) was 4,370 mg/L and likely reflects an annual average concentration. Seasonal variation in chloride concentration dampens out below about 20 cm below the sediment-water interface (Hill, 1988).

Chloride concentration in the Patuxent well at the CAD site (BC 4S2E-6) was 2,170 mg/L. Since the overlying Arundel Clay confining unit effectively confines the Patuxent aquifer system, the likely source of the elevated chloride levels is from the subcrop area of the aquifer system beneath the Patapsco River approximately 2 mi to the west (fig. 13). Brackish water from the Patapsco River may also have entered the Patuxent aquifer system though paleochannels incised through the Arundel Clay confining unit. Chapelle and Kean (1985) present evidence of paleochannels cut through the Arundel Clay confining unit in the Baltimore Harbor area. The presence of brackish water in the Patuxent aquifer system beneath the CAD site is likely a legacy of deep cones of depression formed during earlier water withdrawals for industrial use in the Fairfield area of Baltimore City (Chapelle and Kean, 1985). Figure 13 shows the approximate extent of brackish-water intrusion in the Patuxent aquifer system as last mapped in 1982 (Chapelle and Kean, 1985). Since the head in the aquifer system at the CAD site is now about 2 ft above sea level, the brackish water is likely slowly being flushed out.

Gross alpha-particle activities in the Lower Patapsco and Patuxent wells were 22.3 and 120 picocuries per liter (pCi/L), respectively. Both values exceed the U.S. Environmental Protection Agency's (USEPA's) Primary Drinking Water Standard (Maximum Contaminant Level [MCL]) of 15 pCi/L. Gross beta-particle activities in the Lower Patapsco and Patuxent wells were 67.0 and 87.7 pCi/L, respectively. The USEPA MCL for gross beta-particle activity is 4 millirems per year (mrem/yr), which is a dosage rather than a concentration. A concentration of 50 pCi/L has been used as a screening level for further testing of public water supplies (U.S. Environmental Protection Agency, 2002). It is likely that these levels of radioactivity are due to the presence of naturally-occurring radium isotopes that have been identified in well-water samples in the Patapsco and Patuxent aquifers in Anne Arundel County

(Bolton and Hayes, 1999; Bolton, 2000). Elevated levels of radium in these aquifers are associated with low pH and high dissolved solids. No other MCLs were exceeded. Secondary Maximum Contaminant Levels (SMCLs) (non-enforceable standards established for taste, odor, or other aesthetic considerations) were exceeded in one or both wells for aluminum, chloride, color, iron, manganese, pH, sulfate, and total dissolved solids.

DISCUSSION OF RESULTS

The proposed CAD cell, located in a vessel berth off the Patapsco River, is in a groundwater discharge area of the Lower Patapsco aquifer system, and as such does not pose a threat of contamination to the aquifer system. The Lower Patapsco aquifer system seaward of the freshwater-brackish water interface functions as a hydraulic stagnation zone. On the landward side of the interface, groundwater flows from higher topographic elevations where it is recharged from precipitation to lower elevations where it discharges to streams and to the Patapsco River at the shoreline margin. The flow system in the Lower Patapsco aquifer system in the vicinity of the CAD site is unaffected by well withdrawals. Unless significant withdrawals occur in the area, the overall flow pattern is likely to continue with only naturally-occurring variations in head gradient caused by climatic fluctuations in recharge.

The Arundel Clay confining unit forms an effective hydraulic barrier separating the Lower Patapsco aquifer system from the deeper Patuxent aquifer system. Short-term pumping effects do not propagate across the confining unit at the CAD site. As a result, potential contaminants in dredge material placed in the CAD cell would not migrate vertically to the Patuxent aquifer system. Additionally, an upward vertical head gradient (heads higher in the Patuxent aquifer system compared to the Lower Patapsco aquifer system) at the CAD site would prevent downward migration of contaminants.

Brackish water in the Patuxent aquifer system may pose a long-term threat to groundwater supplies in northern Anne Arundel County, especially if the head gradient steepens southward toward pumping centers. The extent of brackish-water intrusion in the Patuxent aquifer system in southern Baltimore City was last mapped in 1982 (Chapelle and Kean, 1985). To help prevent current and potential future well fields from becoming contaminated by brackish-water intrusion, an updated assessment of the chloride distribution in the Patuxent aquifer system, along with predictions of future groundwater-flow directions and travel times, would be prudent.

SUMMARY

The report discusses the hydrogeologic framework of the Lower Patapsco and Patuxent aquifer systems underlying the CAD site, including the geology, hydraulic properties, water table and potentiometric surfaces, effectiveness of the Arundel Clay confining unit, and water quality. The purpose of this study is to investigate whether potential contaminants contained in dredge material to be placed in a proposed CAD cell will migrate horizontally in the Lower Patapsco aquifer system and/or vertically to the Patuxent aquifer system, and adversely affect well fields operated by AADPW. The study area is the Masonville area of southern Baltimore City. Test wells were constructed in the Lower Patapsco and Patuxent aquifers at the CAD site and in the Lower Patapsco aquifer at the entrance to the MES Masonville facility (MES Entrance), and at Garrett Park and Bay Brooks Park in Brooklyn, Maryland. Geophysical logs were run in the test wells. Aquifer tests were conducted and water samples collected and analyzed from test wells at the CAD site.

The hydrogeologic units present beneath the study area consist of, from top to bottom, the Lower Patapsco aquifer system, the Arundel Clay confining unit, and the Patuxent aquifer. The depth to the base of the Lower Patapsco aquifer system at the CAD site is 104 ft below sea level (111 ft below land surface). Total sand thickness (saturated) is about 60 ft. The depth to the top of the Arundel Clay confining unit at the CAD site occurs at 106 ft below sea level (113 ft below land surface). The unit is about 40 ft thick. The top of the Patuxent aquifer system at the CAD site occurs at 147 ft below sea level (154 ft below land surface). The depth to the base of the aquifer system is approximately 266 ft below sea level (273 ft below land surface) at the CAD site as indicated by the gamma radiation log; however, sand and gravel were logged in the drill cuttings to a depth of 303 ft below sea level (310 ft below land surface). The Pre-Cretaceous basement rock underlies the Patuxent aquifer at the CAD site at 296 ft below sea level (303 ft below land surface) and consists of green, mica-rich saprolite.

Transmissivity of the Lower Patapsco aquifer system at the CAD site (well BC 4S2E-7) is 2,040 ft^2/d calculated from the drawdown phase of the aquifer test for the 100-1,000 log cycle. A lower transmissivity value of 1,360 ft^2/d was calculated from the recovery phase for the 1-10 log cycle. The calculated transmissivity is not reflective of the total transmissivity of the Lower Patapsco aquifer system because only 10 ft of the total saturated aquifer thickness (approximately 60 ft) was screened. Transmissivity of the Patuxent aquifer system at the CAD site (well BC 4S2E-6) is 808 ft^2/d calculated from the drawdown phase, and 870 ft^2/d calculated from the recovery phase. In both the drawdown and recovery phases the slope of the drawdown and residual drawdown curves are the same for all log cycles. The calculated transmissivity is not reflective of the total transmissivity of the Patuxent aquifer system because only 20 ft of the total aquifer thickness (approximately 72 ft) was screened.

Water levels in the Lower Patapsco aquifer system at the CAD, MES Entrance, Garrett Park, and Bay Brooks Park sites, and in the Patuxent aquifer system at the CAD site, respond to changes in barometric pressure. Water levels in the Lower Patapsco and Patuxent aquifer systems at the CAD site and in the Lower Patapsco aquifer system at the MES Entrance site are affected by tides in the nearby Patapsco River. Water levels in the Lower Patapsco aquifer system in the test show no noticeable response to precipitation events.

The Lower Patapsco aquifer system forms the water-table aquifer in the Masonville-Brooklyn area. Measured water levels in the fall of 2013 ranged from a high value of approximately 23 ft above sea level at the Bay Brooks Park site to sea level at the CAD site. The direction of groundwater flow is from the higher topographic elevations, where water enters as recharge from precipitation, to lower elevations. Groundwater in the Lower Patapsco aquifer system discharges locally to streams and to the tidal Patapsco River. The Patuxent aquifer system is a confined aquifer in the Masonville-Brooklyn area. The water level in the aquifer measured in the fall of 2013 was about 2 ft above sea level at the CAD site. A significant cone of depression surrounds Anne Arundel County's Dorsey Road well field, with water levels as deep as 109 ft below sea level. The hydraulic gradient is relatively steep within about 2 mi from the deepest part of the cone, and then flattens at greater distances from the pumping center. The influence of the cone of depression surrounding the Dorsey Road well field on groundwater-flow paths appears to diminish northward. As a result, groundwater-flow paths that intersect the CAD site likely trend in a southeastern direction, bypassing the Dorsey Road well field.

At the CAD site, the Arundel Clay confining unit effectively separates the Patuxent aquifer system from the overlying Lower Patapsco aquifer system hydraulically. Water levels recorded while the aquifers were pumped indicates that short-term pumping effects do not propagate across the confining unit.

Water from the Lower Patapsco aquifer system is slightly acidic (pH 6.7), low in dissolved oxygen (1.6 mg/L), has high specific conductance (11,600 µS/cm), and is a reducing chemical environment (-87 mv oxidation-reduction potential). Water from the Patuxent aquifer system is acidic (pH 4.2), has no dissolved oxygen, has high specific conductance (6,460 µS/cm), and is an oxidizing chemical environment (281 mv oxidation-reduction potential). The water type of both the Lower Patapsco and Patuxent aquifer systems at the CAD site is sodium chloride. Gross alpha-particle activities in the Lower Patapsco and Patuxent wells were 22.3 and 120 pCi/L, respectively. Both values exceed the USEPA MCL of 15 pCi/L. Gross beta-particle activities in the Lower Patapsco and Patuxent wells were 67.0 and 87.7 pCi/L, respectively. The USEPA MCL for gross beta-particle activity is 4 mrem/yr, which is a dosage rather than a concentration; a concentration of 50 pCi/L is used by several states when trying to evaluate risk associated with gross-beta activity levels. SMCLs (non-enforceable standards established for taste, odor, or other aesthetic considerations) were exceeded in one or both wells for aluminum, chloride, color, iron, manganese, pH, sulfate, and total dissolved solids.

Chloride concentration in the Lower Patapsco well at the CAD site (BC 4S2E-7) was 4,580 mg/L. The elevated chloride level is a result of a brackish-water wedge extending inland from the Patapsco River. Chloride concentration in the Patuxent well at the CAD site (BC 4S2E-6) was 2,170 mg/L. Since the overlying Arundel Clay confining unit effectively confines the Patuxent aquifer system at the CAD site, the likely source of the elevated chloride levels is from the subcrop area of the aquifer system beneath the Patapsco River approximately 2 mi to the west or through paleochannels cut through the Arundel Clay confining unit in the Baltimore Harbor area. The presence of brackish water in the Patuxent aquifer system beneath the CAD site is likely a legacy of deep cones of depression formed during earlier water withdrawals for industrial use in the Fairfield area of Baltimore City.

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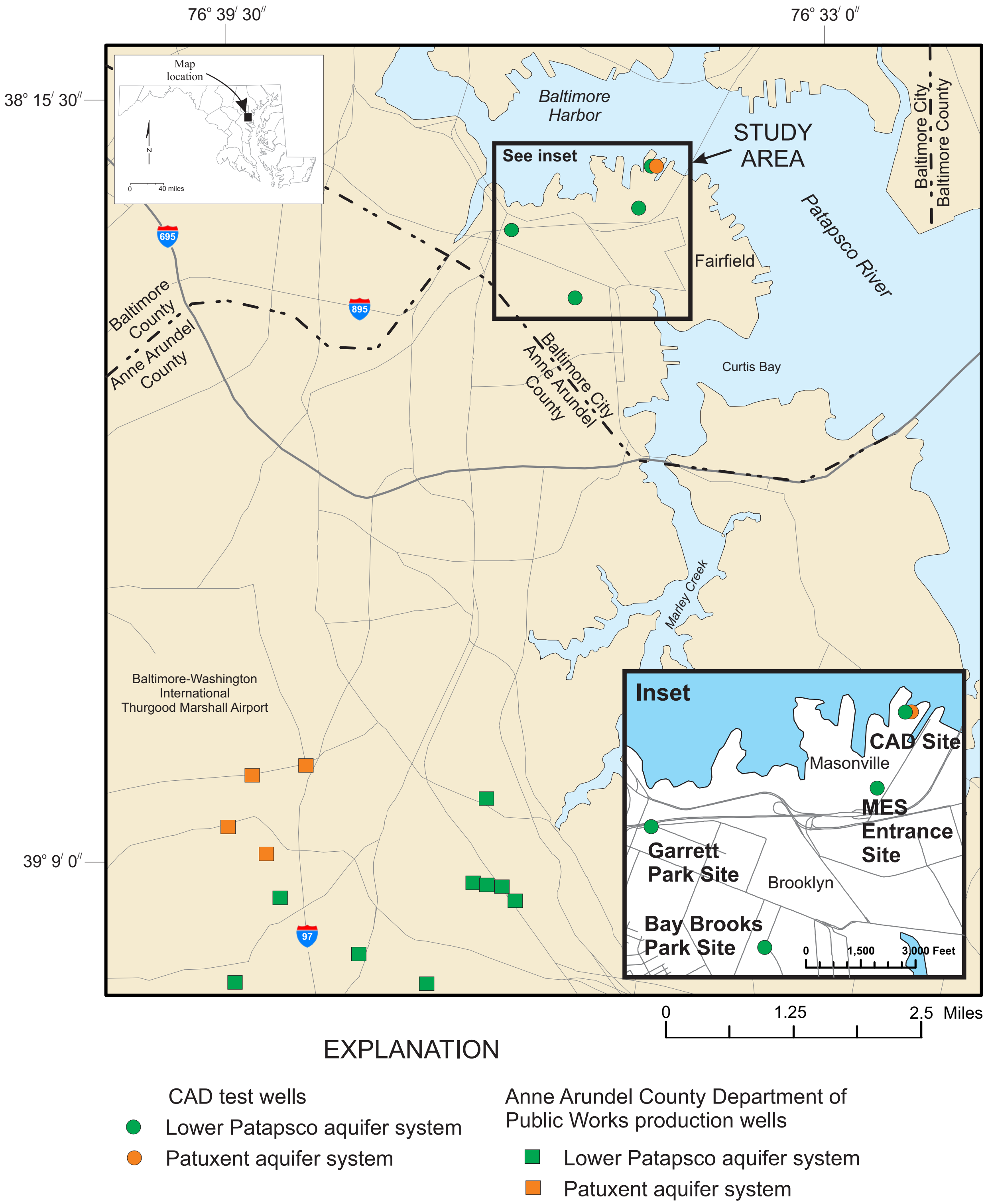


Figure 1. Location of the study area.

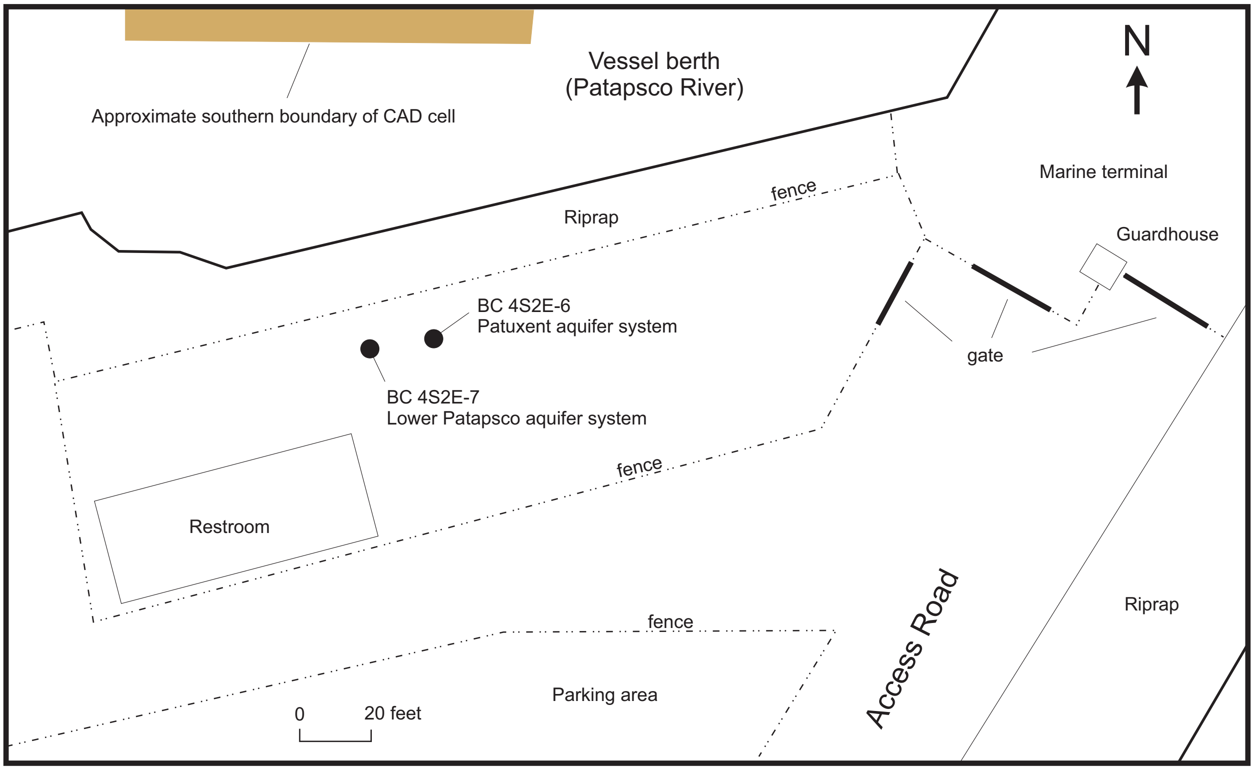


Figure 2a. Location of test wells at the CAD site.

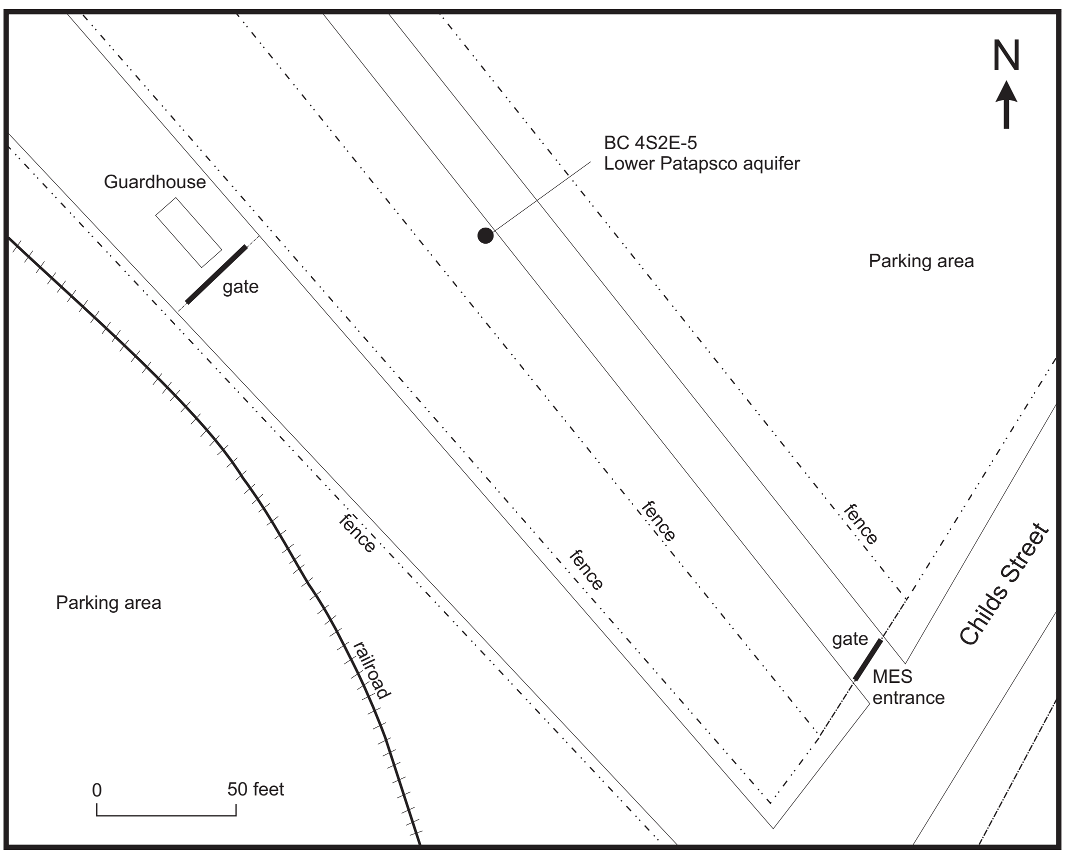


Figure 2b. Location of test well at the MES Entrance site.

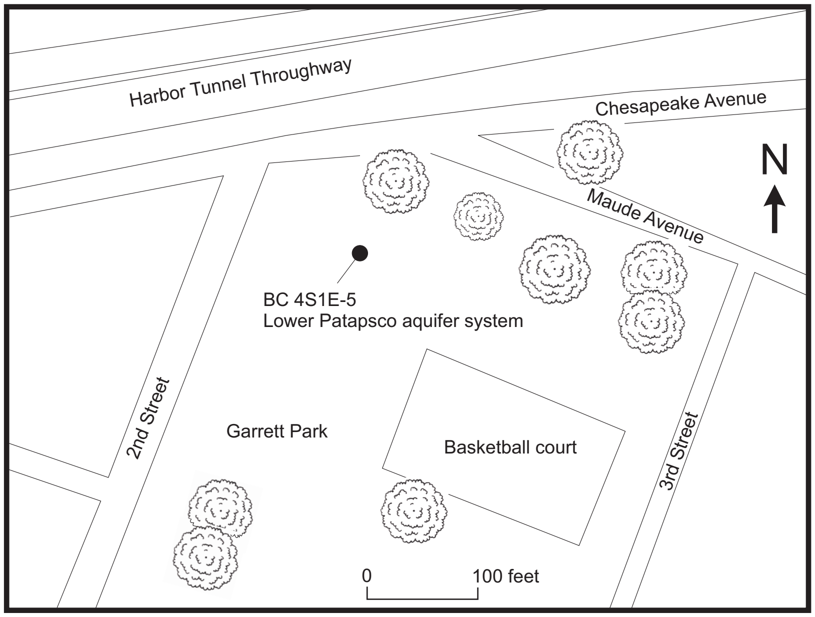


Figure 2c. Location of test well at the Garrett Park site.

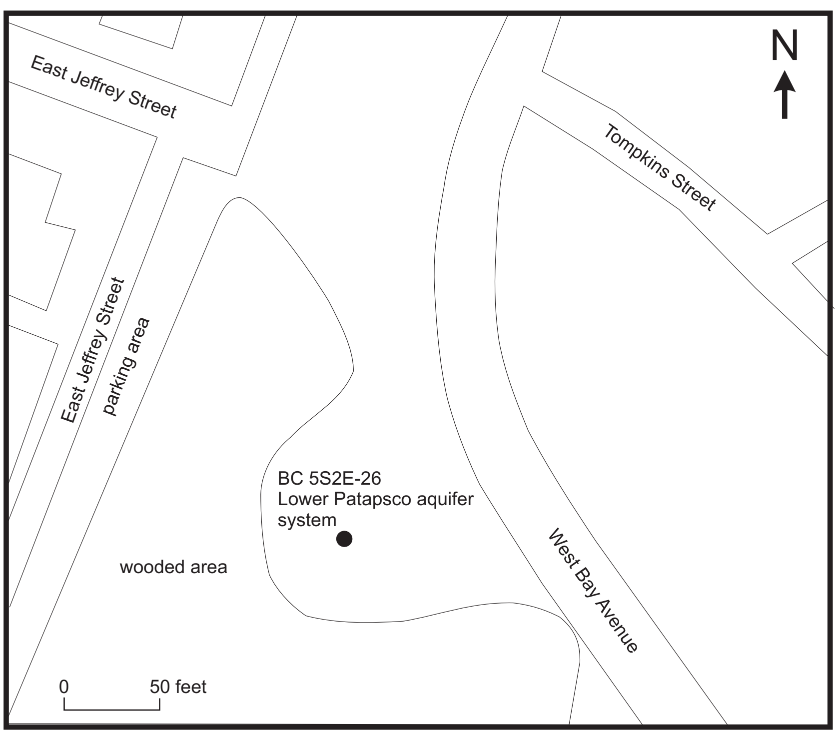


Figure 2d. Location of test well at the Bay Brooks Park site.

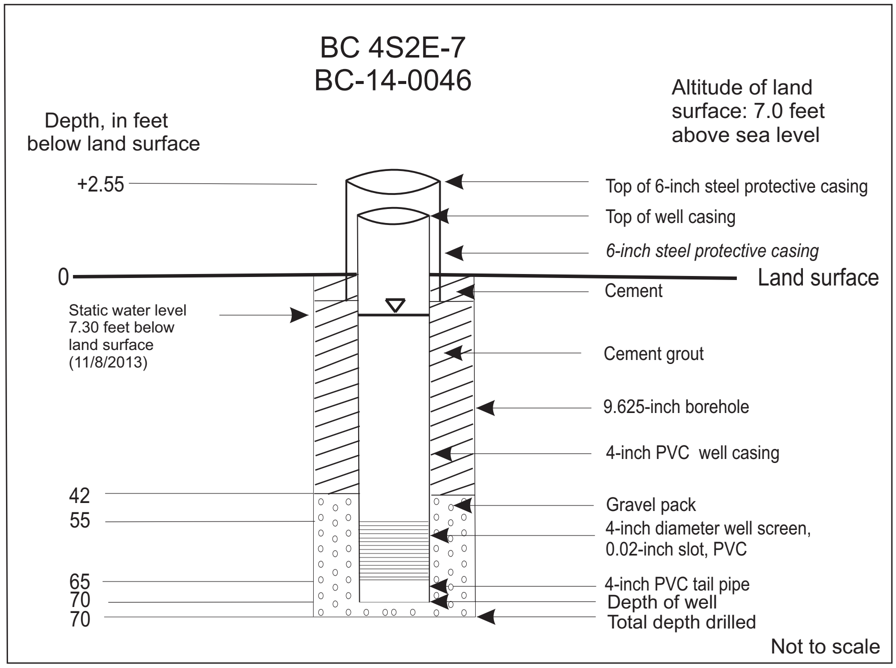


Figure 3a. Test-well construction schematic for the CAD site (Lower Patapsco aquifer system well).

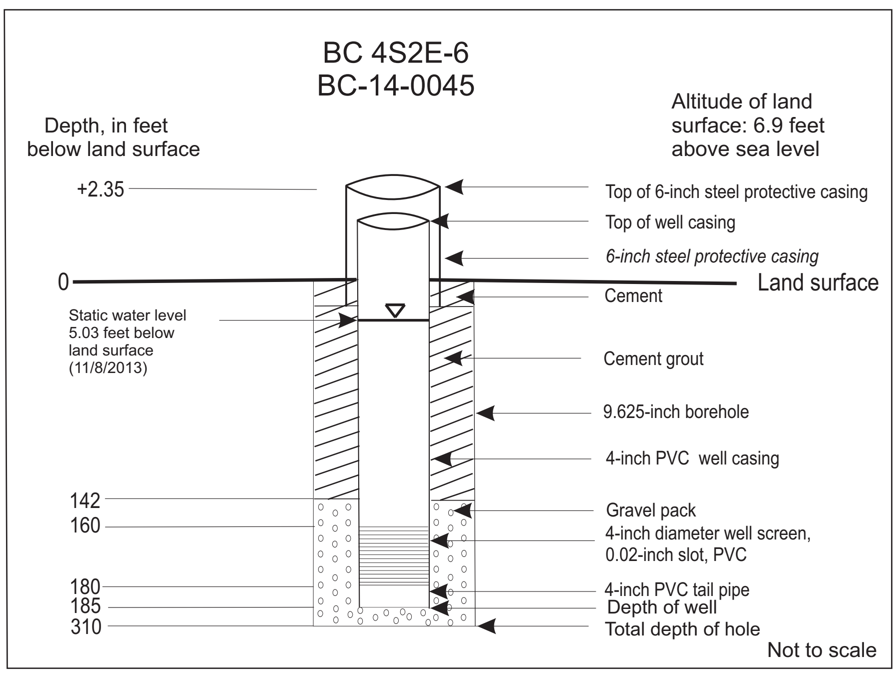


Figure 3b. Test-well construction schematic for the CAD site (Patuxent aquifer system well).

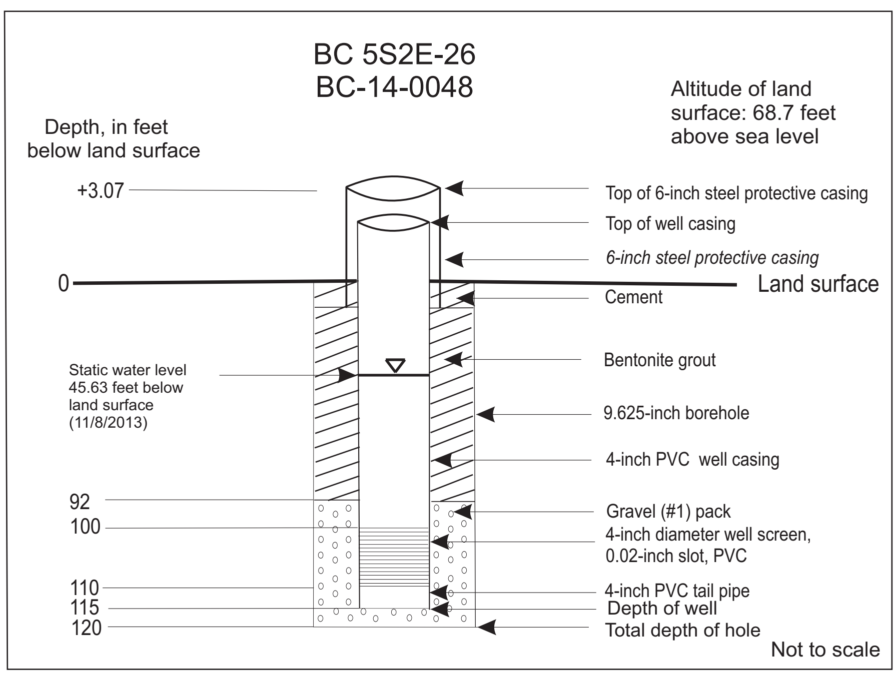


Figure 3c. Test-well construction schematic for the Bay Brooks Park site.

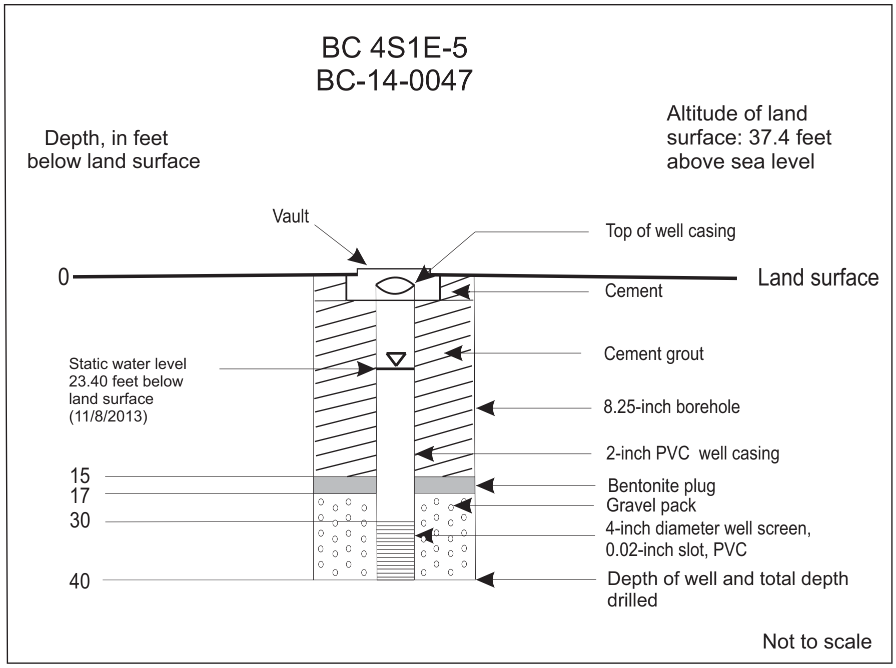


Figure 3d. Test-well construction schematic for the Garrett Park site.

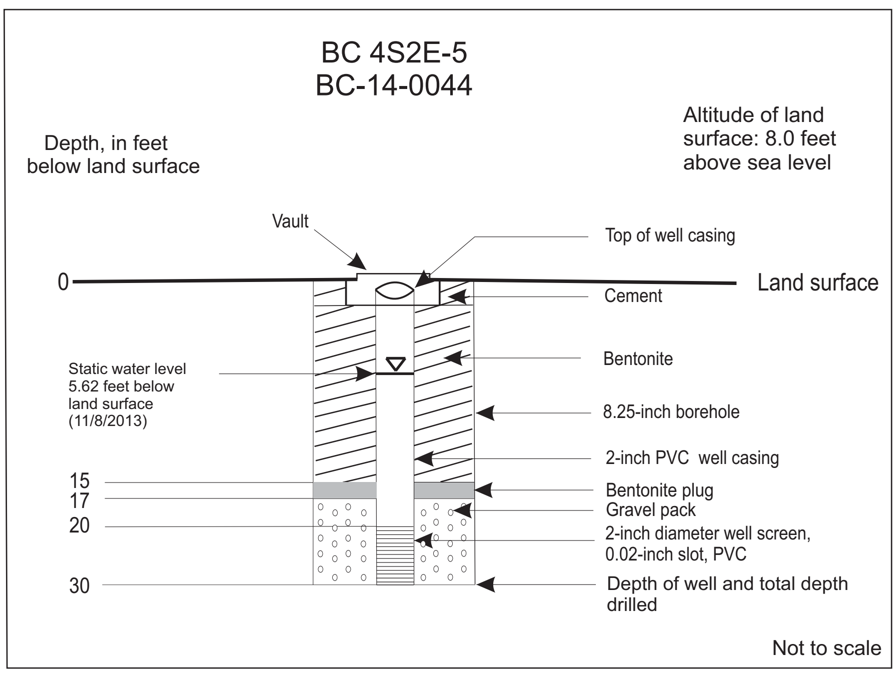


Figure 3e. Test-well construction schematic for the MES Entrance site.

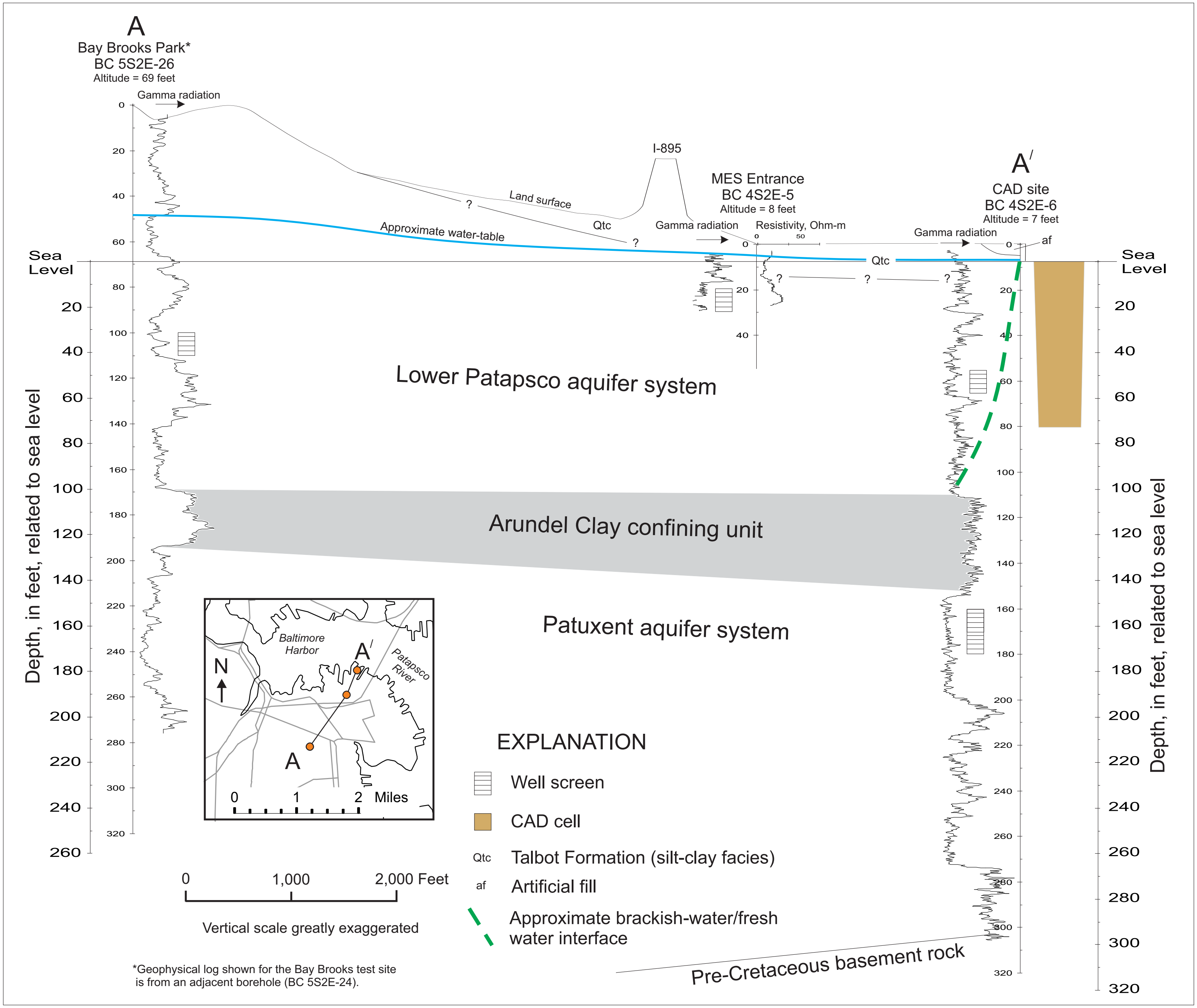


Figure 4. Hydrogeologic cross section from Bay Brooks Park to the CAD site.

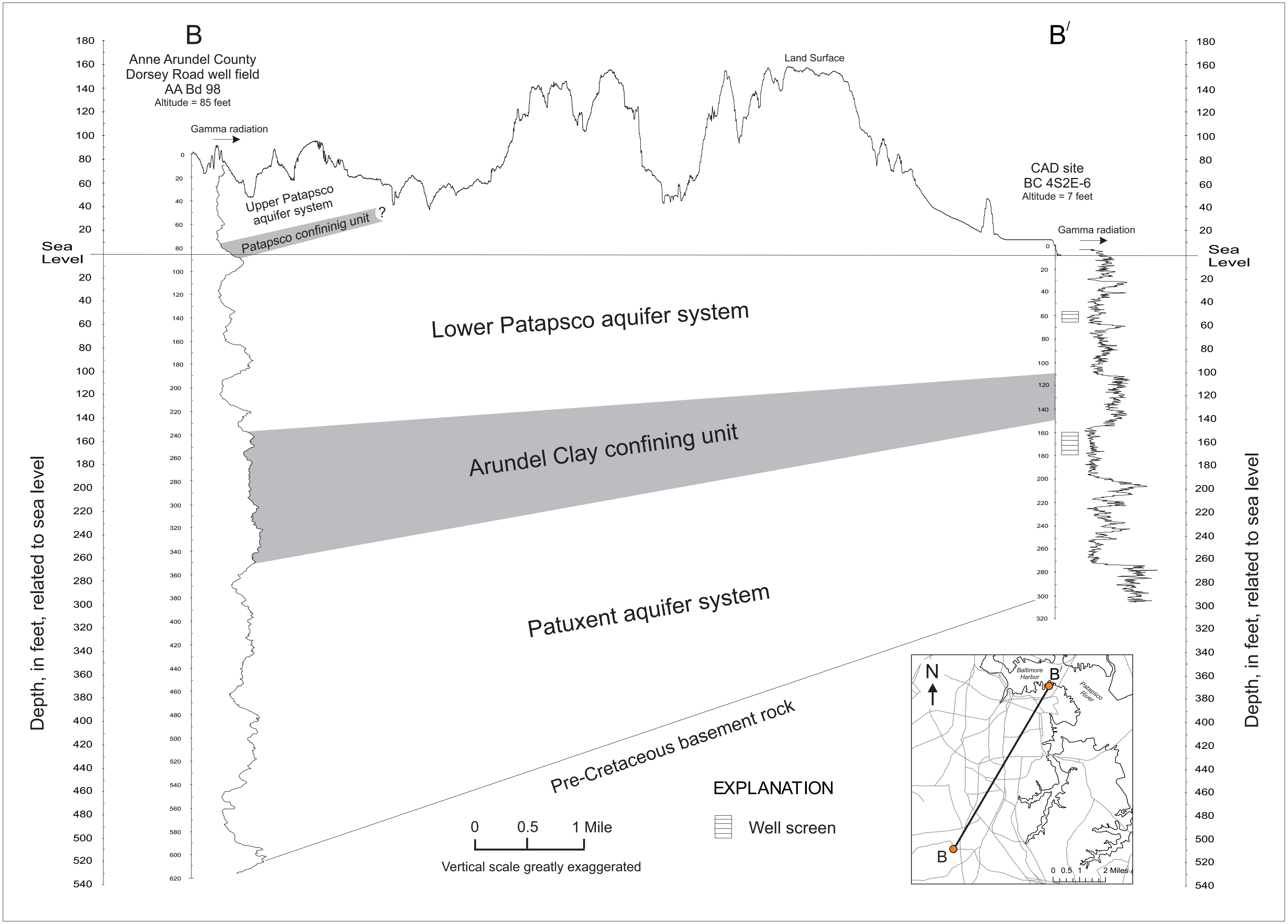
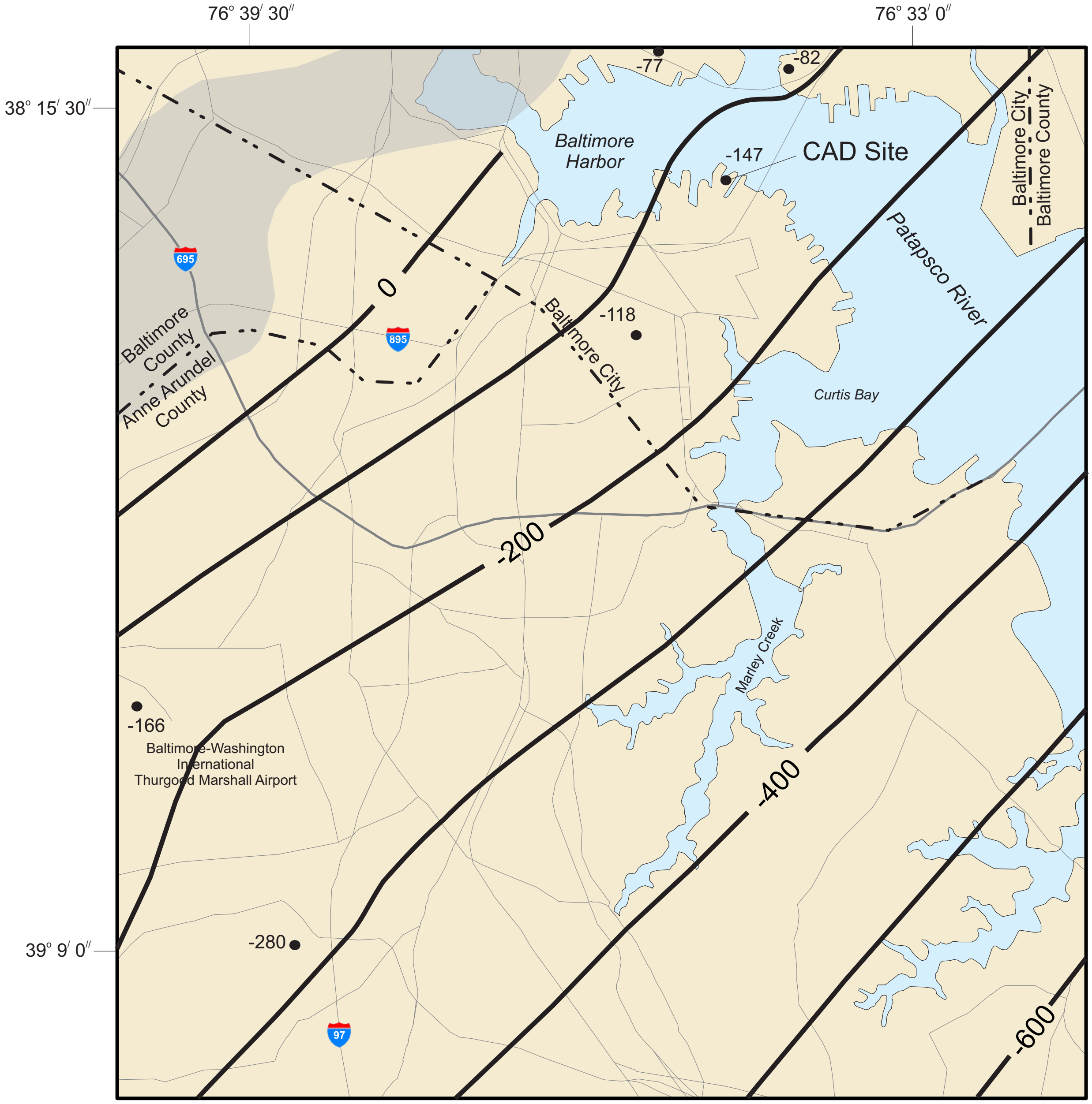


Figure 5. Hydrogeologic cross section from Anne Arundel County Dorsey Road well field to the CAD site.



0 1.25 2.5 Miles

EXPLANATION

-280 • Data point. Number is altitude of the top of the Patuxent aquifer system, in feet relative to sea level.

— -200 — Contour showing the altitude of the top of the Patuxent aquifer system, in feet related to sea level. Contour interval is 100 feet.

Approximate outcrop area of the Patuxent aquifer system.

Figure 6. Top of the Patuxent aquifer system.

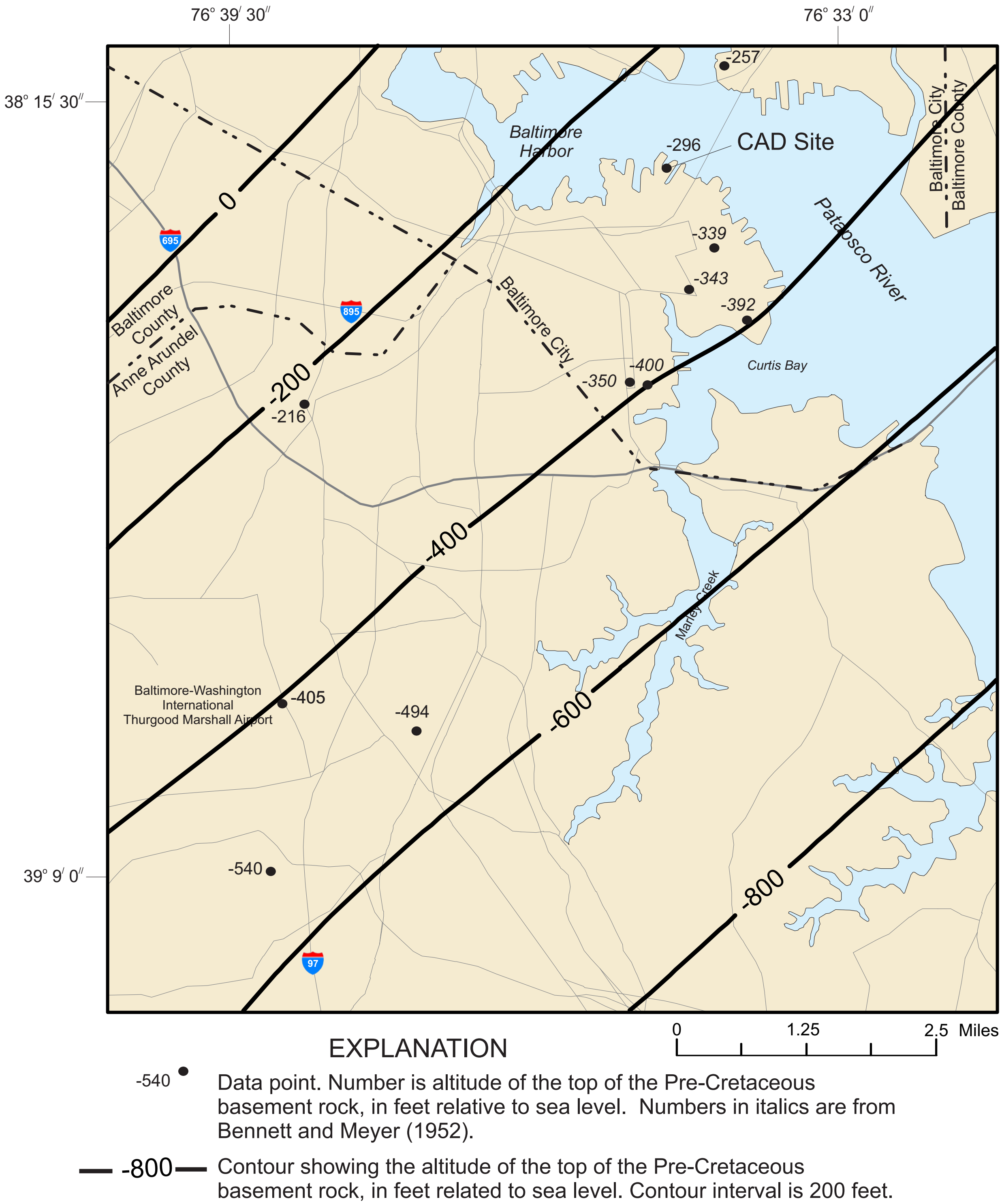
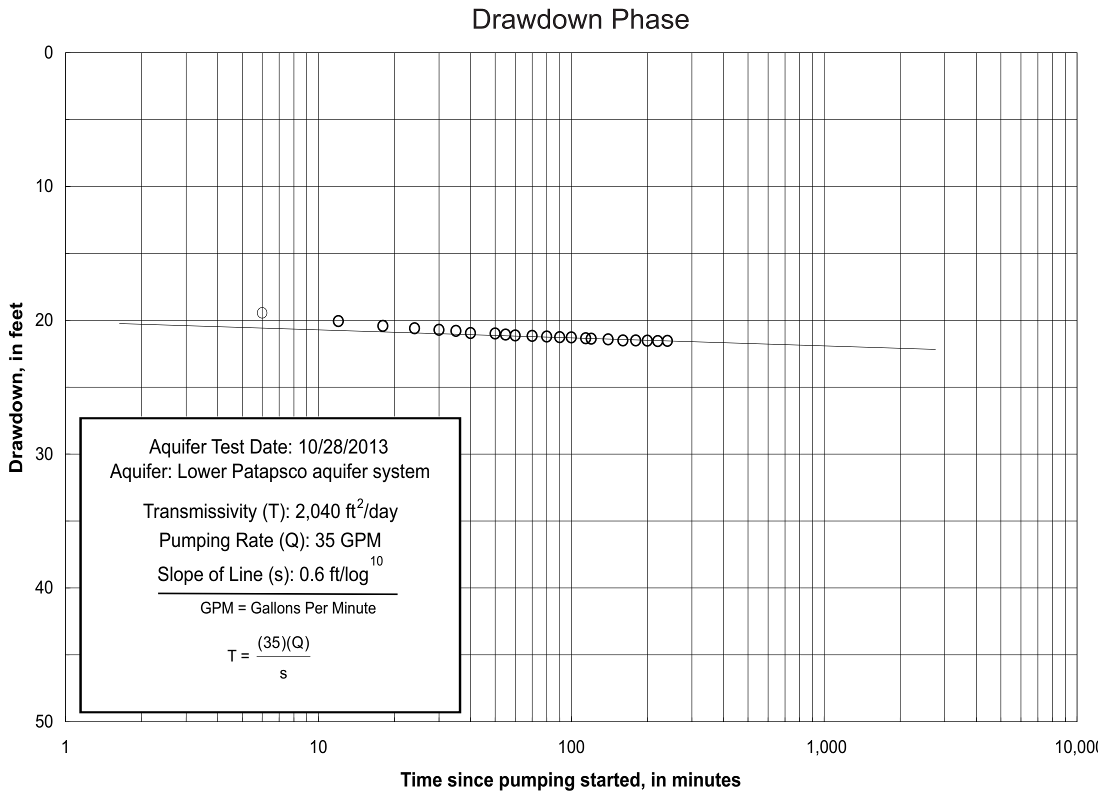


Figure 7. Top of the Pre-Cretaceous basement rock.



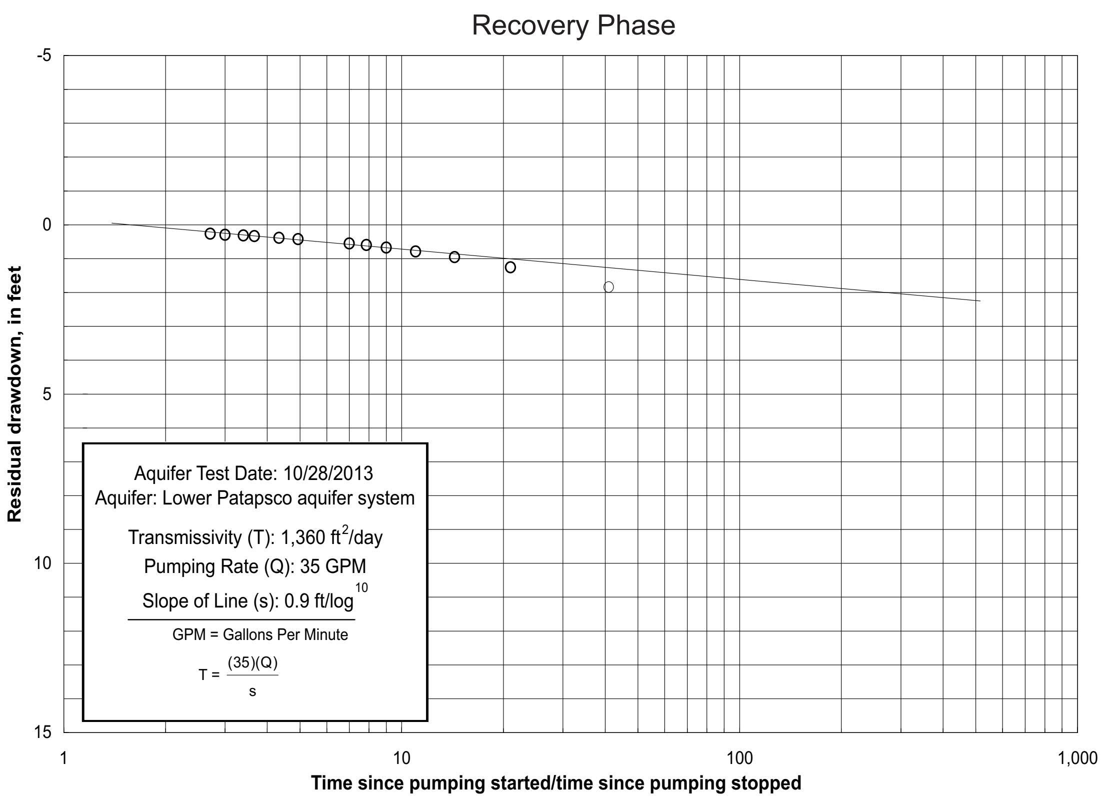
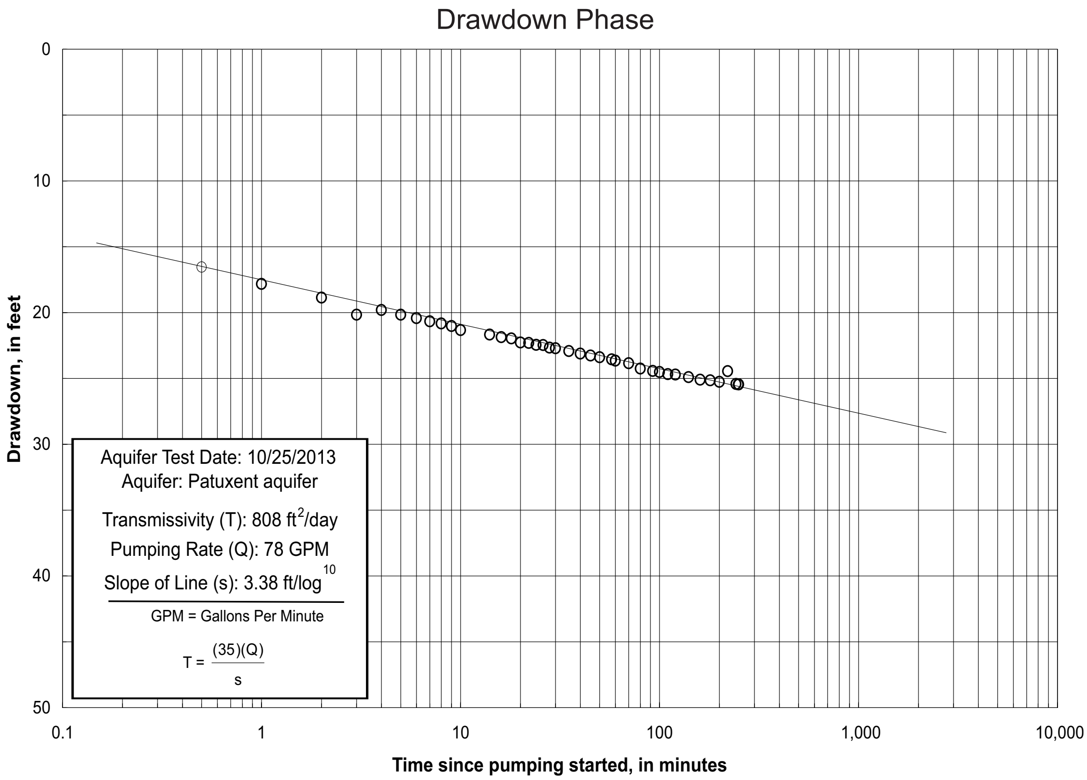


Figure 8. Drawdown and recovery data and transmissivity calculations for CAD test well BC 4S2E-7 (Lower Patapsco aquifer system).



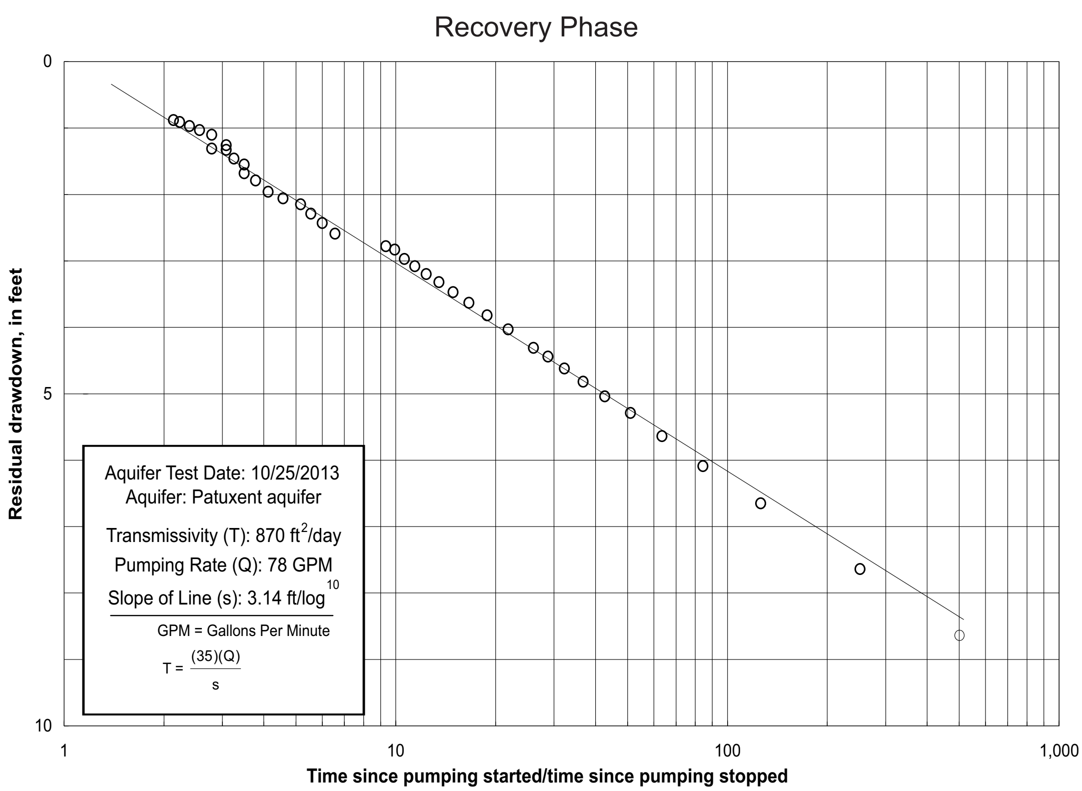


Figure 9. Drawdown and recovery data and transmissivity calculations for CAD test well BC 4S2E-6 (Patuxent aquifer system).

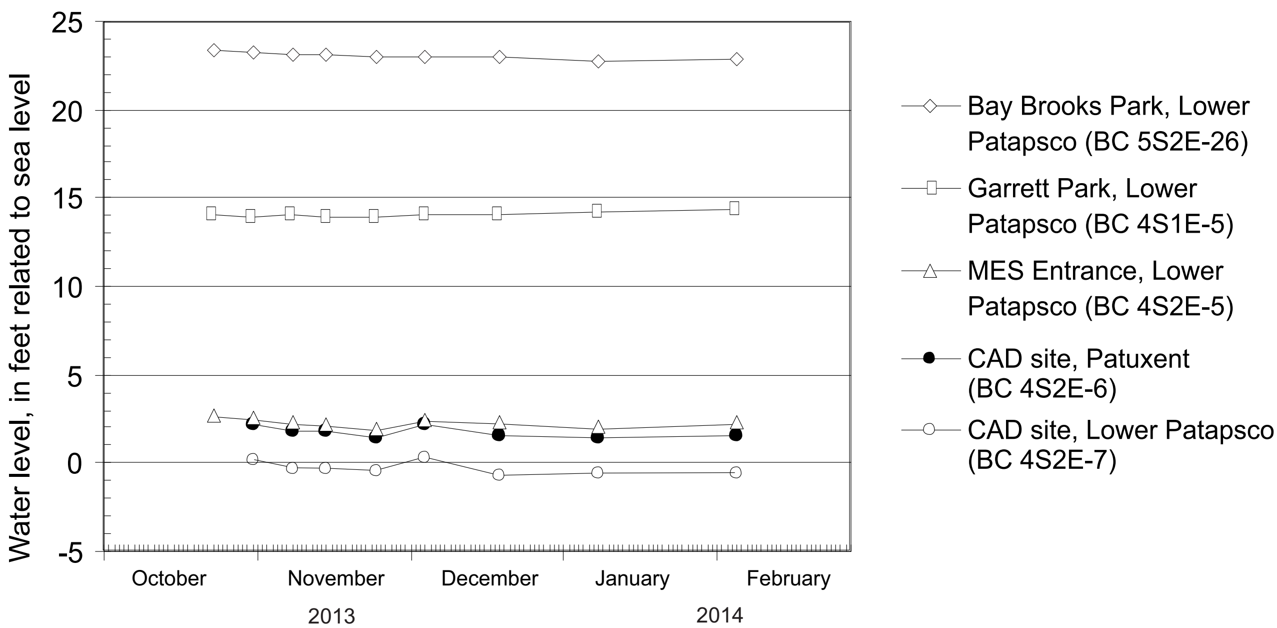


Figure 10. Hydrograph showing water levels in test wells from October 2013 to February 2014.

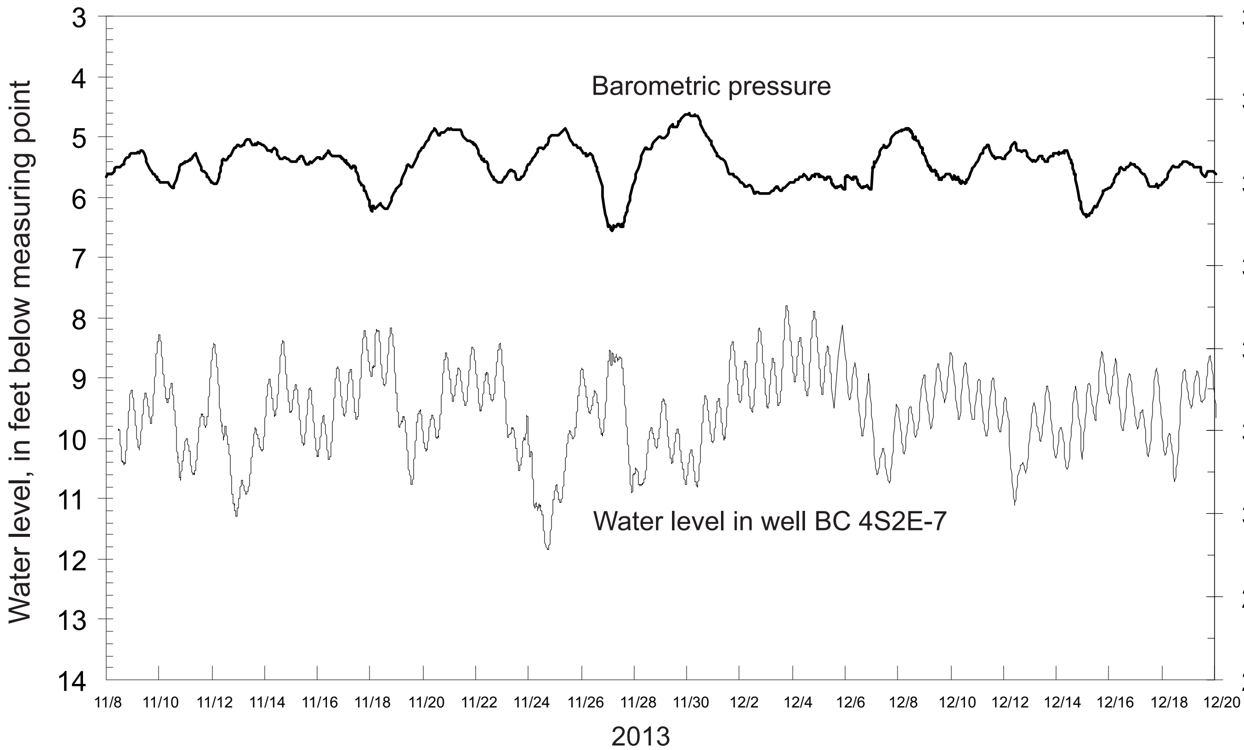


Figure 11a. Hydrograph showing water-level fluctuations in the CAD Lower Patapsco aquifer system test well.

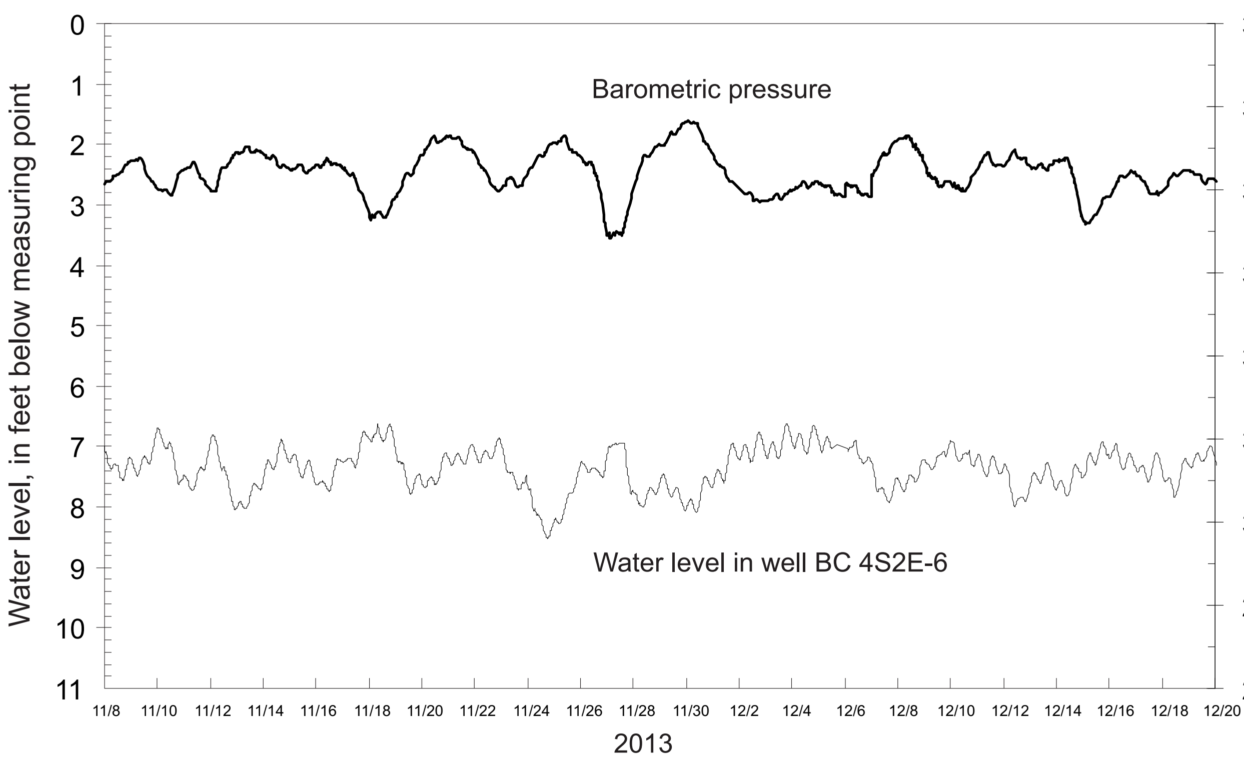


Figure 11b. Hydrograph showing water-level fluctuations in the CAD Patuxent aquifer system test well.

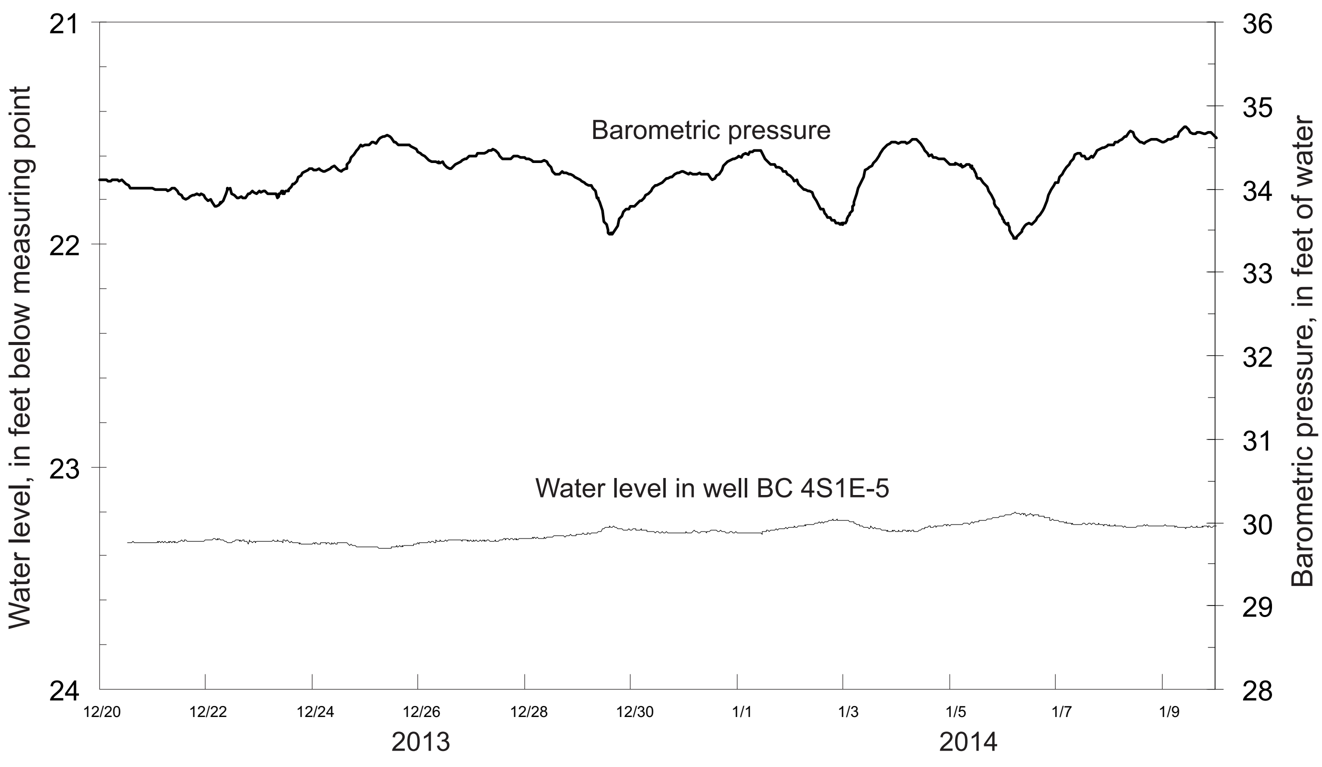


Figure 11c. Hydrograph showing water-level fluctuations in the Garrett Park test well.

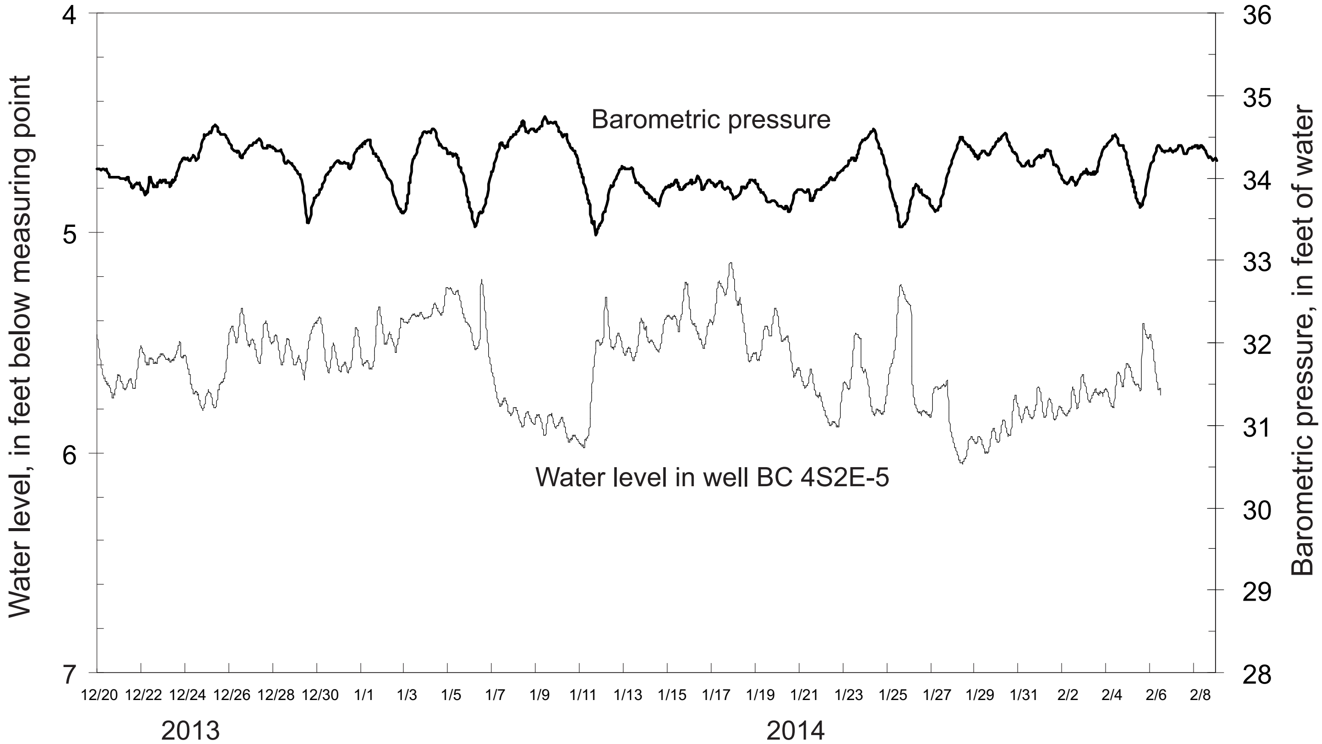


Figure 11d. Hydrograph showing water-level fluctuations in the MES Entrance test well.

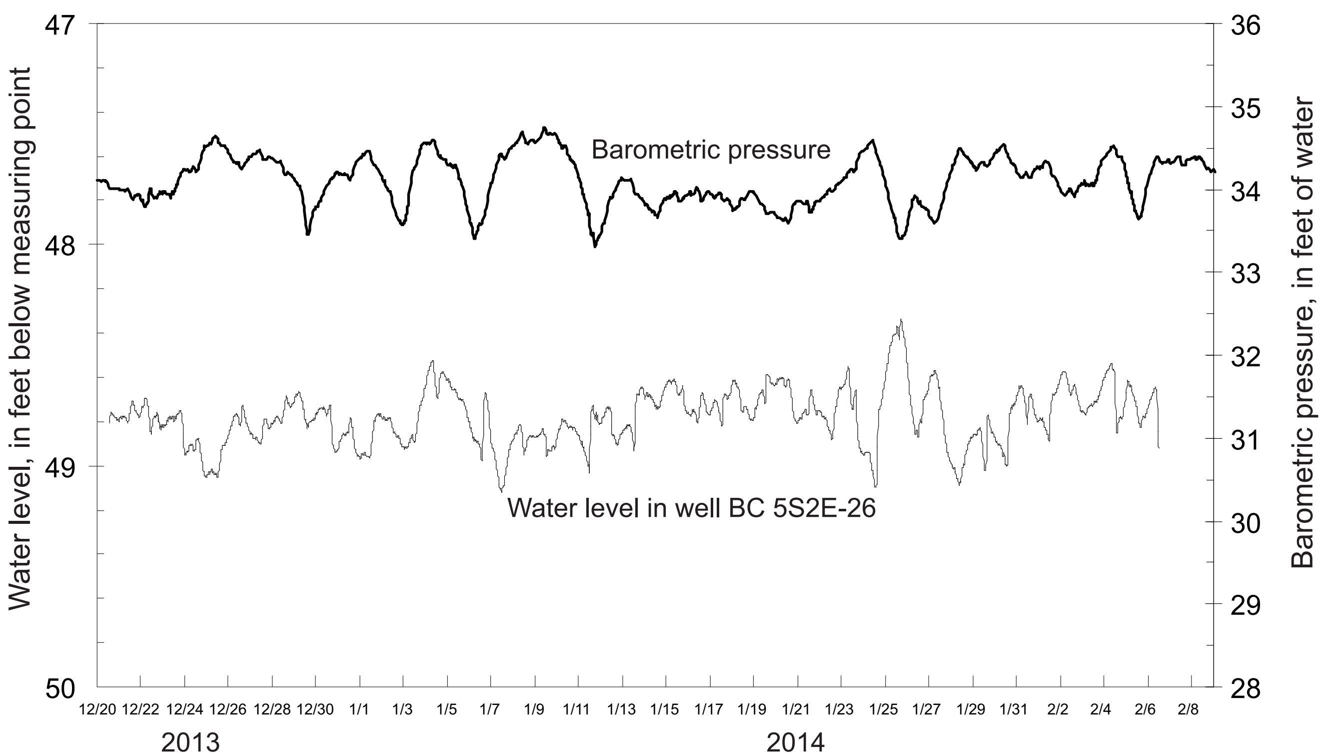
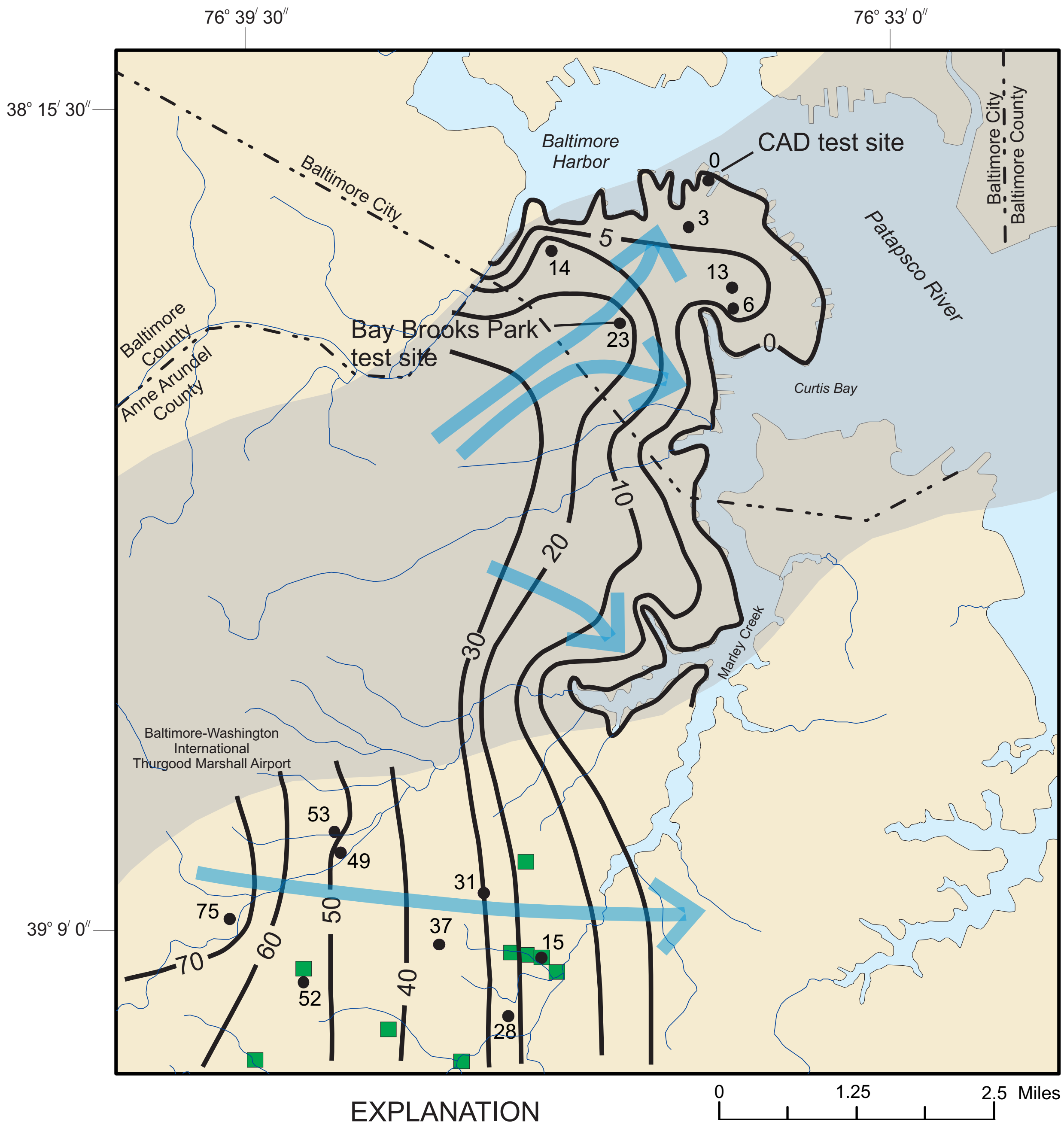


Figure 11e. Hydrograph showing water-level fluctuations in the Bay Brooks Park test well.



EXPLANATION

52 Data point. Number is altitude of the water level in feet related to sea level.

60 Contour showing the altitude of the water table or potentiometric surface, in feet related to sea level. Contour interval is 5 feet (0 - 10 feet) and 10 feet (10 - 70 feet).

Generalized direction of groundwater flow.

Approximate outcrop area of the Lower Patapsco aquifer system.

Anne Arundel County Department of Public Works Lower Patapsco aquifer system production wells

Figure 12. Altitude of the water table and potentiometric surface of the Lower Patapsco aquifer system in the fall of 2013.

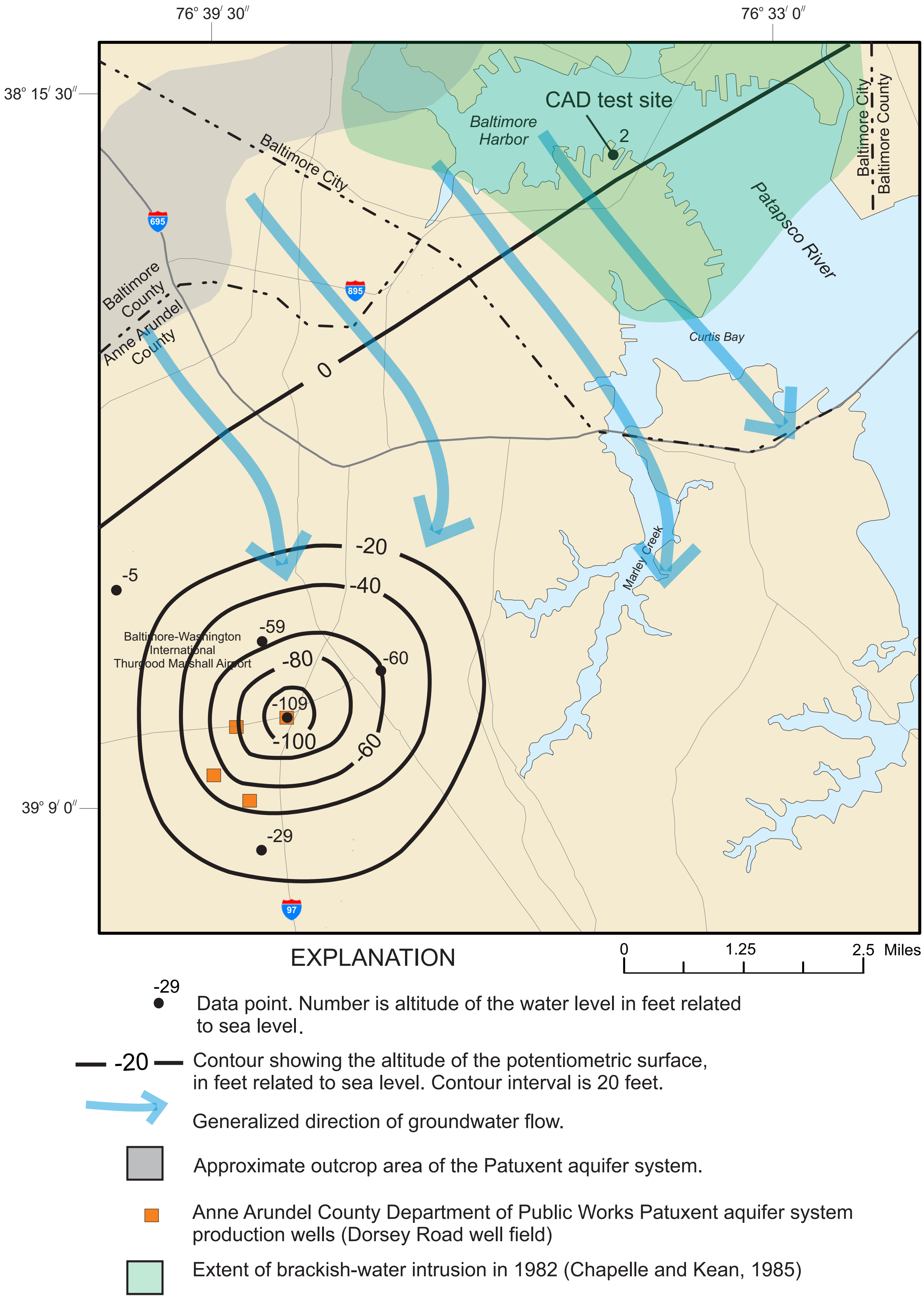


Figure 13. Altitude of the potentiometric surface of the Patuxent aquifer system in the fall of 2013.

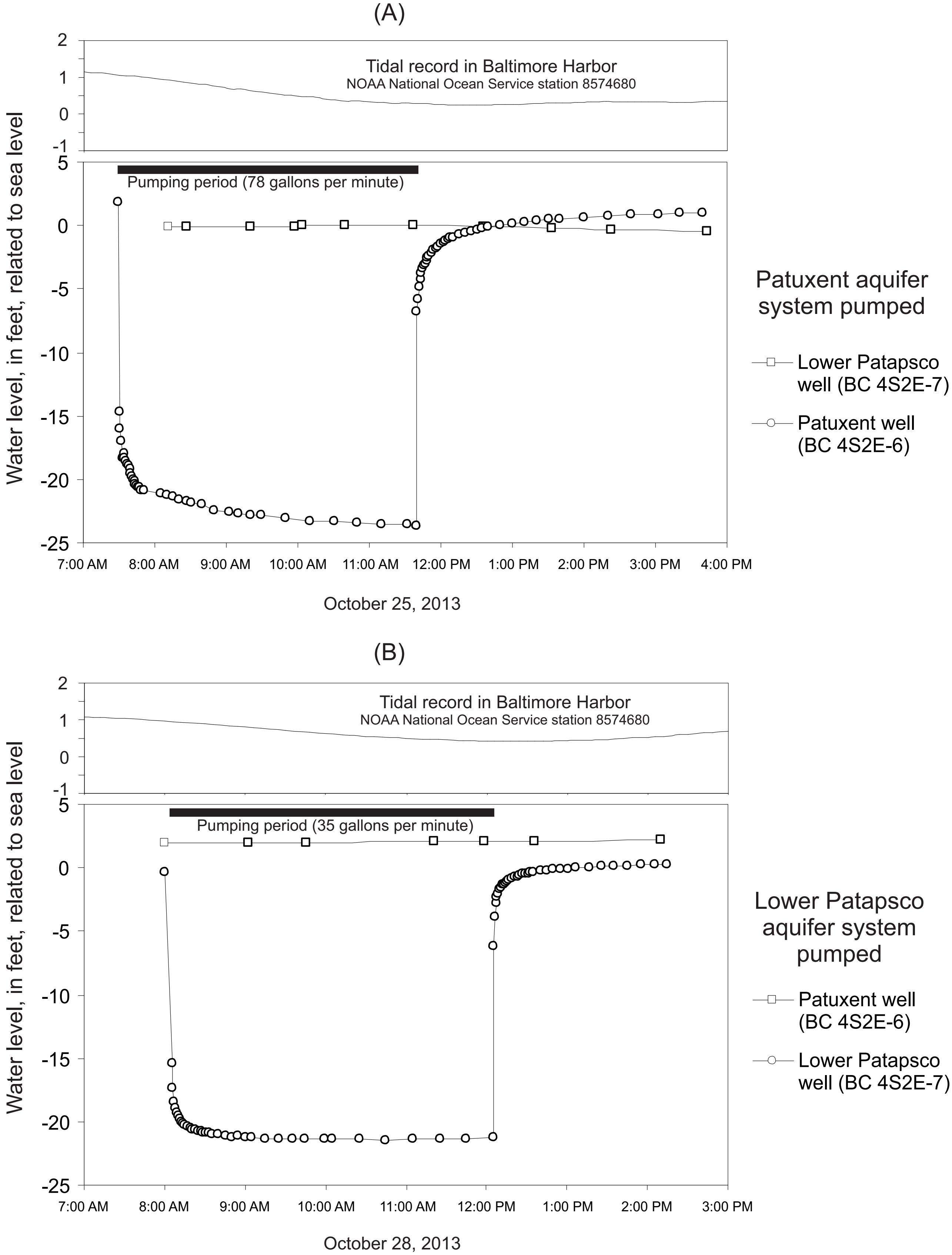


Figure 14. Water-level observations (A) in the Lower Patapsco well when the Patuxent well is pumped, and (B) in the Patuxent well when the Lower Patapsco well is pumped at the CAD site.

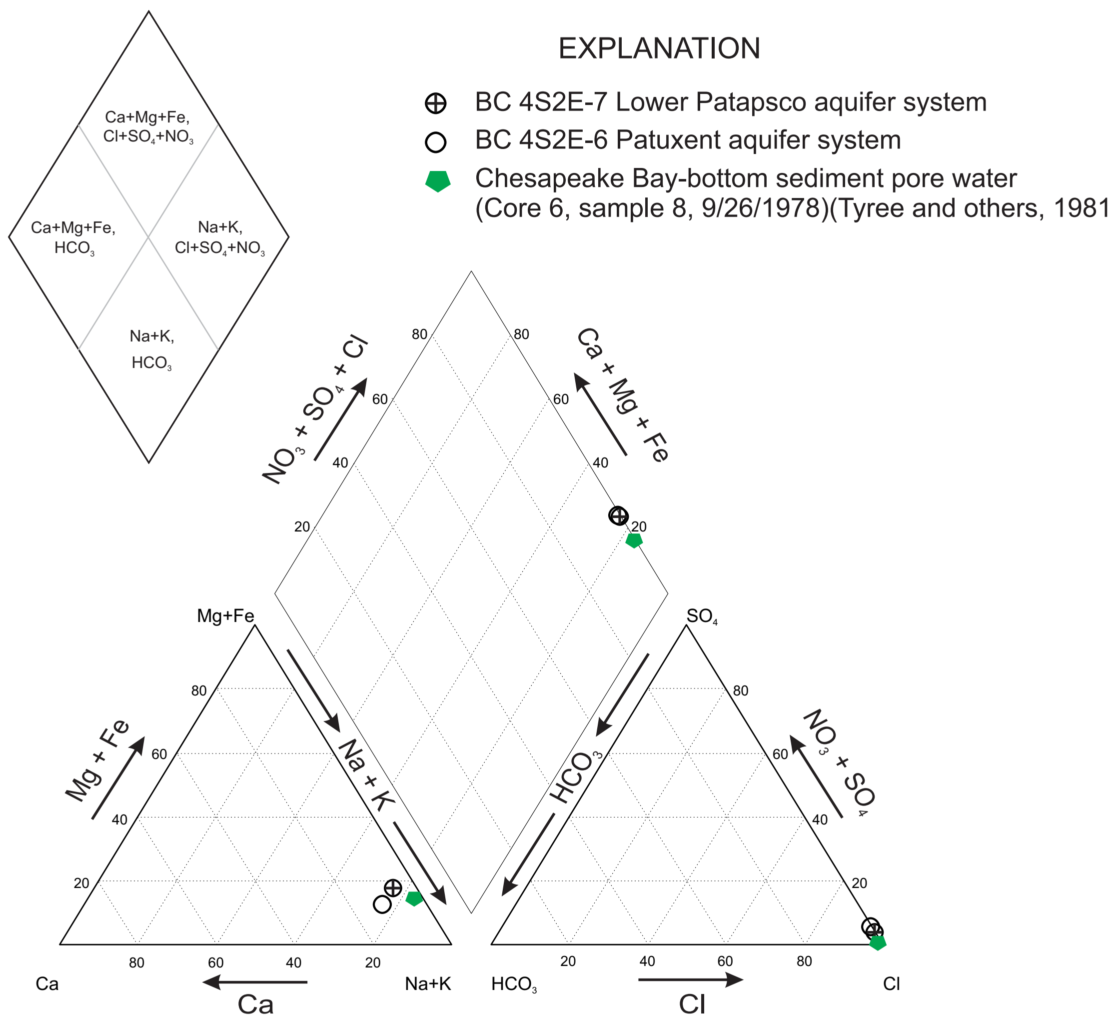


Figure 15. Piper diagram showing milliequivalent percentages of major ions in water samples taken from the CAD test wells in 2013.

Table 1. Construction data for the test wells.

[NAD, North American Datum; dd-mm-ss, degrees-minutes-seconds; ft, feet; in., inches;]

Well number	Well location/ aquifer	Permit number	Latitude, NAD 83 dd-mm-ss	Longitude, NAD 83 dd-mm-ss	Land surface altitude, ft	Drilling method	Depth drilled, ft	Bottom of well, ft	Screen, top, ft	Screen, bottom, ft	Casing and screen diameter, in.	Top of gravel pack, ft	Grout material
BC 4S1E-5	Garrett Park, Lower Patapsco	BC-14-0047	39-14-23.7	76-36-25.8	37.4	Auger	40	40	30	40	2	17	cement
BC 4S2E-5	MES Entrance, Lower Patapsco	BC-14-0044	39-14-34.7	76-35-02.6	8.0	Auger	30	30	20	30	2	17	cement
BC 4S2E-6	CAD site, Patuxent	BC-14-0045	39-14-56.1	76-34-50.7	6.9	Mud rotary	310	185	160	180	4	142	cement
BC 4S2E-7	CAD site, Lower Patapsco	BC-14-0046	39-14-56.2	76-34-50.5	7.0	Mud rotary	70	70	55	65	4	42	cement
BC 5S2E-26	Bay Brooks Park, Lower Patapsco	BC-14-0048	39-13-49.3	76-35-44.6	68.7	Mud rotary	120	115	100	110	4	92	bentonite

Table 2. Water-quality data for the Lower Patapsco and Patuxent aquifer systems at the CAD site.

[µg/L, micrograms per liter; <, less than; mg/L, milligrams per liter; E, estimated; pCi/L, picocuries per liter; ng/L, nanograms per liter; N, nitrogen; P, phosphorus; mv, millivolts; µS/cm microsiemens per centimeter at 25 degrees Celsius; NTU, nephelometric turbidity units]

Parameter	BC 4S2E-7 Lower Patapsco aquifer system	BC 4S2E-6 Patuxent aquifer system
Aluminum, µg/L	<75.8	4,680[1]
Ammonia nitrogen as N, mg/L	4.00	1.38
Antimony, µg/L	<2.02	<2.02
Arsenic, µg/L	3.13	0.220
Barium, dissolved, mg/L	0.271	0.0892
Beryllium, dissolved, mg/L	<0.00200	0.00940
Boron, µg/L	649	84.4E
Bromide, mg/L	17.7	6.51
Calcium, mg/L	148	121
Cadmium, µg/L	<1.01	1.3
Chloride, mg/L	4,580[1]	2,170[1]
Chromium, µg/L	0.110E	0.769
Cobalt, µg/L	30.5	242
Color, apparent, units	350[1]	<5
Copper, µg/L	126	75.1
Fluoride, mg/L	<0.100	0.853
Gross Alpha particle activity, pCi/L	22.3[2]	120[2]
Gross Beta particle activity, pCi/L	67.0	87.7
Iron, µg/L	123,000[1]	257
Lead, µg/L	<1.26	2.61
Lithium, µg/L	19.2	79.8
Magnesium dissolved, mg/L	212	82.8
Manganese, µg/L	3,630[1]	6,610[1]
Mercury, ng/L	116	258
Molybdenum, µg/L	0.866E	<1.52
Nickel, µg/L	<10.1	203
Nitrite (as N), mg/L	<0.0500	<0.0500
Orthophosphate as P, mg/L	<0.0100	<0.0100
Oxygen, dissolved, mg/L, field	1.56	0
Oxidation-reduction potential, mv, field	-87	281
pH, field	6.7	4.2[1]
Phosphorus total, mg/L	0.0618	<0.0500
Potassium dissolved, mg/L	51.0	10.7
Radon-222, pCi/L	130	<39.2
Selenium, µg/L	0.294	6.91
Silica dissolved, mg/L	19.2	10.6
Silver dissolved, mg/L	<0.0100	<0.0100
Sodium dissolved, mg/L	2,080	924
Specific conductance, µS/cm, field	11,600	6,460
Strontium dissolved, mg/L	1.71	0.833
Sulfate, mg/L	288[1]	191
Temperature, water, degrees Celsius, field	15.0	14.8
Thallium, µg/L	0.267E	0.481E
Total dissolved solids, mg/L	6,090[1]	2,950[1]
Total nitrate/nitrite as N, mg/L	<0.500	<0.500
Total organic carbon, mg/L	0.642	M0.500
Turbidity, NTU, field	11	0.1
Uranium dissolved, mg/L	<0.00200	0.0119
Vanadium, µg/L	25.3	32.7
Zinc, µg/L	576	1,710

[1] Exceeds U.S. Environmental Protection Agency's Secondary Maximum Contaminant Level for drinking water

[2] Exceeds U.S. Environmental Protection Agency's Primary Maximum Contaminant Level for drinking water

Appendix A. Lithologic logs of drill cuttings and split-spoon samples for Garrett Park, MES Entrance, Bay Brooks Park, and CAD test wells.

Garrett Park test well (BC 4S1E-5)

Split-spoon core samples			
Hydrologic unit	**Core depth[1] (feet below land surface)**	**Primary lithology**	**Secondary description**
Lower Patapsco aquifer system	0-1.5	Sand, with minor clay	Sand, mostly angular to sub-angular quartz; micaceous soil (fill?); color grades downward darker to lighter **Top**: Dark grey (7.5YR, 4/1) **Bottom**: Strong brown (7.5YR, 5/6)
	5-6.5	**Top**: Sand **Bottom**: Sand, with minor clay	**Top**: Micaceous sandy soil (fill?); strong brown (7.5YR, 5/6); very fine to gravelly sand, mostly angular quartz **Bottom**: Sand, as above; reddish yellow (7.5YR, 7/6) clay
	10-11.5	Clay	Pale yellow (2.5Y, 8/4) and red (2.5YR, 5/6-5/8); clay concretions reddish brown to dark reddish brown (2.5YR, 4/3 – 3/3)
	15-16.5	Clay	Pale yellow (2.5Y, 8/4), red (2.5YR, 4/6 - 5/6), and white to pinkish white (2.5YR, 8/1 to 8/2)
	20-21.5	Sand, with very minor clay globules	Very fine to medium sand, mostly quartz, sub-angular to sub-rounded; clay globules, pale yellow (2.5Y, 8/4) and reddish black (2.5YR, 2.5/1)
	25-26.5	**Top**: Sand, with very minor clay **Bottom**: Clay	**Top**: Fine to coarse quartz, sub-rounded to rounded **Bottom**: White (5Y, 8/1)
	30-31.5	**Top**: Sand, with minor clay **Bottom**: Clayey sand	**Top**: Fine to med sand, mostly quartz, sub-rounded; pinkish white to pink (2.5YR, 8/2 – 8/3) clay; approximately 1 inch at top is gravel with sand **Middle**: Black particles—possible concretion **Bottom**: Fine to medium granules, mostly quartz, sub-rounded; white (5Y, 8/1) and pinkish white to pink (2.5YR, 8/2 – 8/3) clay globules
	35-36.5	**Top**: Clay **Middle**: Sand, with minor clay **Bottom**: Clay	**Top**: 1 to 4 inches of white (5Y, 8/1) and dark reddish brown (2.5YR, 2.5/3) clay **Middle**: 4 to 5 inches of fine to medium sub-rounded quartz sand in reddish brown clay matrix **Bottom**: White (5Y, 8/1) and dark reddish brown (2.5YR, 2.5/3) clay
	40-41.5	**Top**: Clay **Bottom**: Sandy clay	**Top**: 1 to 4 inches of white (5Y, 8/1) clay **Bottom**: White (5Y, 8/1) clay; fine to medium, rounded, mostly quartz sand

[1] Core recovery typically ranged from 1 to 1.5 feet.

Appendix A. Continued.

MES Entrance test well (BC 4S2E-5)

Split-spoon core samples			
Hydrologic unit	**Core depth[1] (feet below land surface)**	**Primary lithology**	**Secondary description**
Lower Patapsco aquifer system	0-1.5	Sand with very minor silt	Very fine to very coarse, sub-rounded, mostly quartz, minor muscovite, lightly iron-stained, reddish yellow to strong brown (7.5YR, 6/6 - 5/6)
	5-6.5	Sand with very minor clay	Very fine to coarse, sub-rounded to rounded, mostly quartz, minor muscovite, lightly iron-stained, strong brown (7.5YR, 5/6) light gray (7.5YR, 7/1) and red (2.5YR, 5/6)
	10-11.5	Clay	Light bluish gray to bluish gray (5PB, 7/1 – 6/1) with black to dark red mottling
	15-16.5	Clay	Bluish gray (10B, 5/1)
	20-21.5	Clay	Dark gray (4/N)
	25-26.5	**Top:** Clay contact **Remainder of core:** Sand and gravel with minor clay	**Top:** Dark gray (4/N) **Remainder of core:** Medium to very coarse to cobbles, not well sorted, mostly quartz and very minor dark minerals, sub-rounded to rounded red (2.5YR, 4/8) and very light brown (10YR, 8/4) clay
	30-31.5	Clay	Greenish black (10Y, 2.5/1)

Appendix A. Continued.

Bay Brooks Park test well (BC 5S2E-26)

Mud-rotary ditch samples			
Hydrologic unit	**Depth (feet below land surface)**	**Primary lithology**	**Secondary description**
Lower Patapsco aquifer system	0-10	Sand	Fine to medium grains, quartz, sub-rounded, organic fill and minor clay
	10-20	Sand	Medium to very fine granules, quartz, sub-rounded
	20-30	Sand	Medium to coarse grains, minor very fine granules, quartz, sub-angular to sub-rounded
	30-40	Sand with very minor silt and clay	Fine to very coarse grains, quartz, sub-angular to sub-rounded
	40-50	Sand with minor silt and clay	Medium to fine granules, mostly clear quartz, very minor rose quartz and rock fragments (meta-sandstone/conglomerate?), sub-angular to sub-rounded; white clay
	50-60	Gravel with moderate amount of silty clay and very minor sand	Fine granules, quartz (some rose), sub-rounded to rounded white clay very minor fine to medium grains, quartz, sub-rounded
	60-70	Gravel, as above	As above
	70-80	Gravel, as above except with significant amount of clay	As above
	80-90	Clay with very minor gravel and sand	White clay, medium to fine granule grains, sub-angular, mostly quartz
	90-100	Clay, as above (driller reported last 2 feet in sand)	As above
	100-110	Clay, as above except with moderate amount of gravel and sand	As above, larger grains from above?
	110-120	Sand with moderate amount of clay	Medium to fine granules, mostly quartz (some rose), rounded white clay

Appendix A. Continued.

CAD deep test well (BC 4S2E-6)

Mud-rotary samples			
Hydrologic unit	**Depth (feet below land surface)**	**Primary lithology**	**Secondary description**
Lower Patapsco aquifer system	0-10	Clay with moderate amount of sand, wood and shell fragments	Dark greenish gray (5GY, 4/1) clay, very micaceous fine to very coarse grains, mostly quartz, sub-rounded (very strong hydrocarbon smell, oily sheen[2])
	10-20	Clay, as above except no wood and shell fragments	As above, except for hydrocarbon smell
	20-30	Sand with minor clay	Medium sand to fine pebbles, smaller grains mostly quartz, larger grains rock fragments, fill (?), angular to sub-angular, minor wood and shell fragments, minor greenish gray (5GY, 5/1) clay (organic mucky smell, cobble-sized coal chunk[2])
	30-40	Sand	As above, except minor mica flakes (oily sheen[2])
	40-50	Clay with moderate amount of sand	Light and dark greenish gray (5GY, 8/1 and 4/1) clay fine to medium sand, mostly quartz, sub-angular (more sandy at interval base[2])
	50-60	Sand with very minor clay	Fine to very coarse sand, mostly medium, sub-angular quartz grains; medium dark gray clay
	60-70	Sand	Medium sand to medium pebbles, mostly quartz and rock fragments, angular to sub-angular
	70-80	Sand with very minor clay and silt	Fine sand to fine pebbles, mostly quartz, minor rock fragments and mica, sub-angular (red and white clay washed out?[2])
	80-90	Gravel with very minor clay and silt	Very fine sand and fine to medium pebbles, mostly quartz, sub-angular to rounded (red clay washed out?[2])
	90-100	Gravel with minor clay	As above, except for more apparent red clay
	100-110	Gravel with minor clay	As above
	110-111	Very hard layer[2]	Very slow drilling[2]; likely iron-cemented sandstone
Arundel Clay confining unit	111-120	Gravel with clay and minor sand	Fine to medium pebbles, angular and very fine to medium sand, sub-rounded red, dark gray, and yellow clays; frequent lignite/peat fragments
	120-130	Clay with very minor sand and gravel	Red and very dark greenish gray; very minor coarse sand to fine pebbles, angular to sub-angular, mostly quartz
	130-140	Clay with minor sand and gravel	As above, except fine to medium sand grains
	140-150	Clay with minor gravel	Red, brown and white clay; very coarse sand to fine pebbles, angular, mostly quartz, rare rock fragments and minor lignite/peat
	150-160	Clay with minor gravel	As above

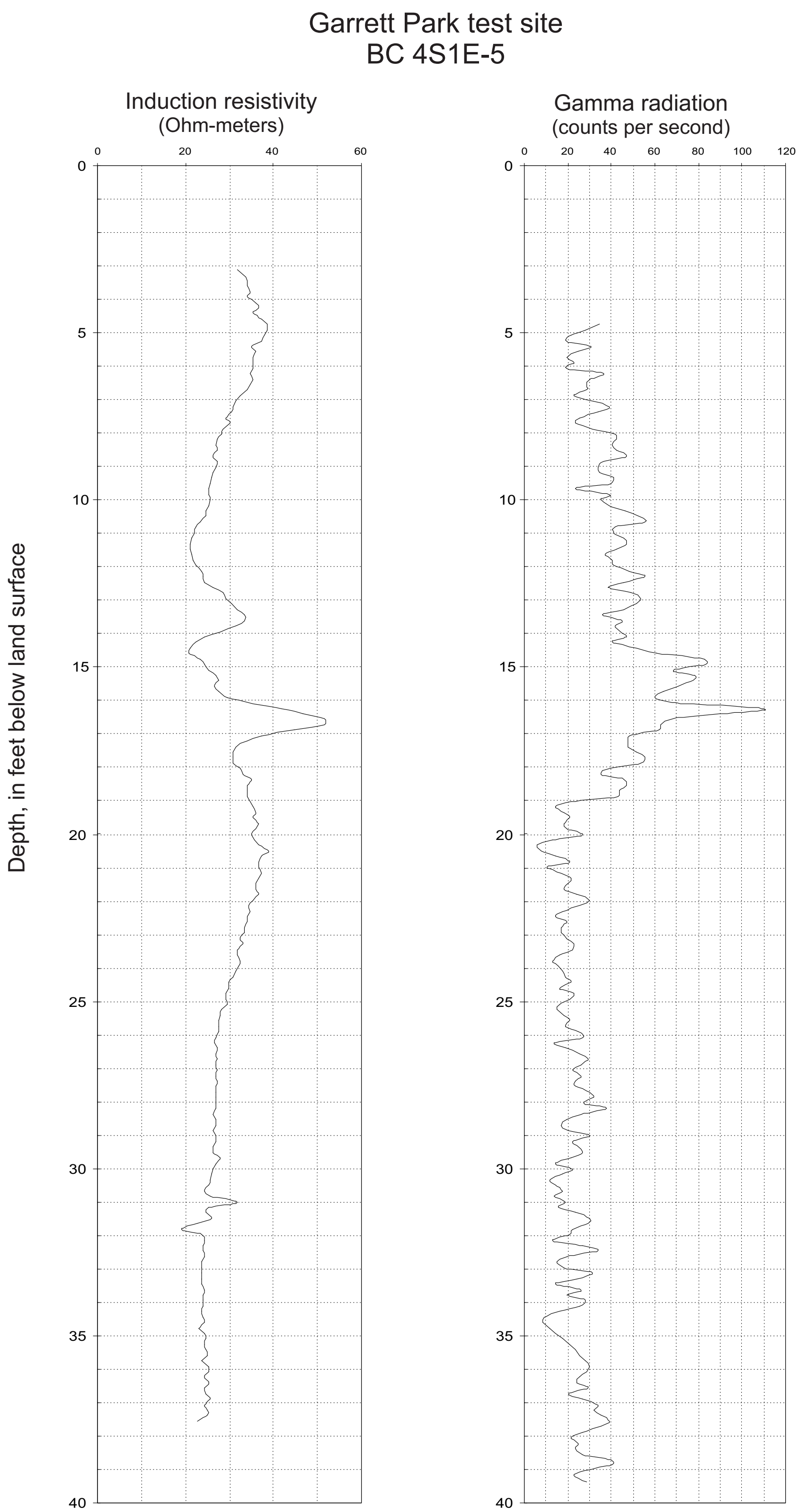
[2] Field notes

Appendix A. Continued.

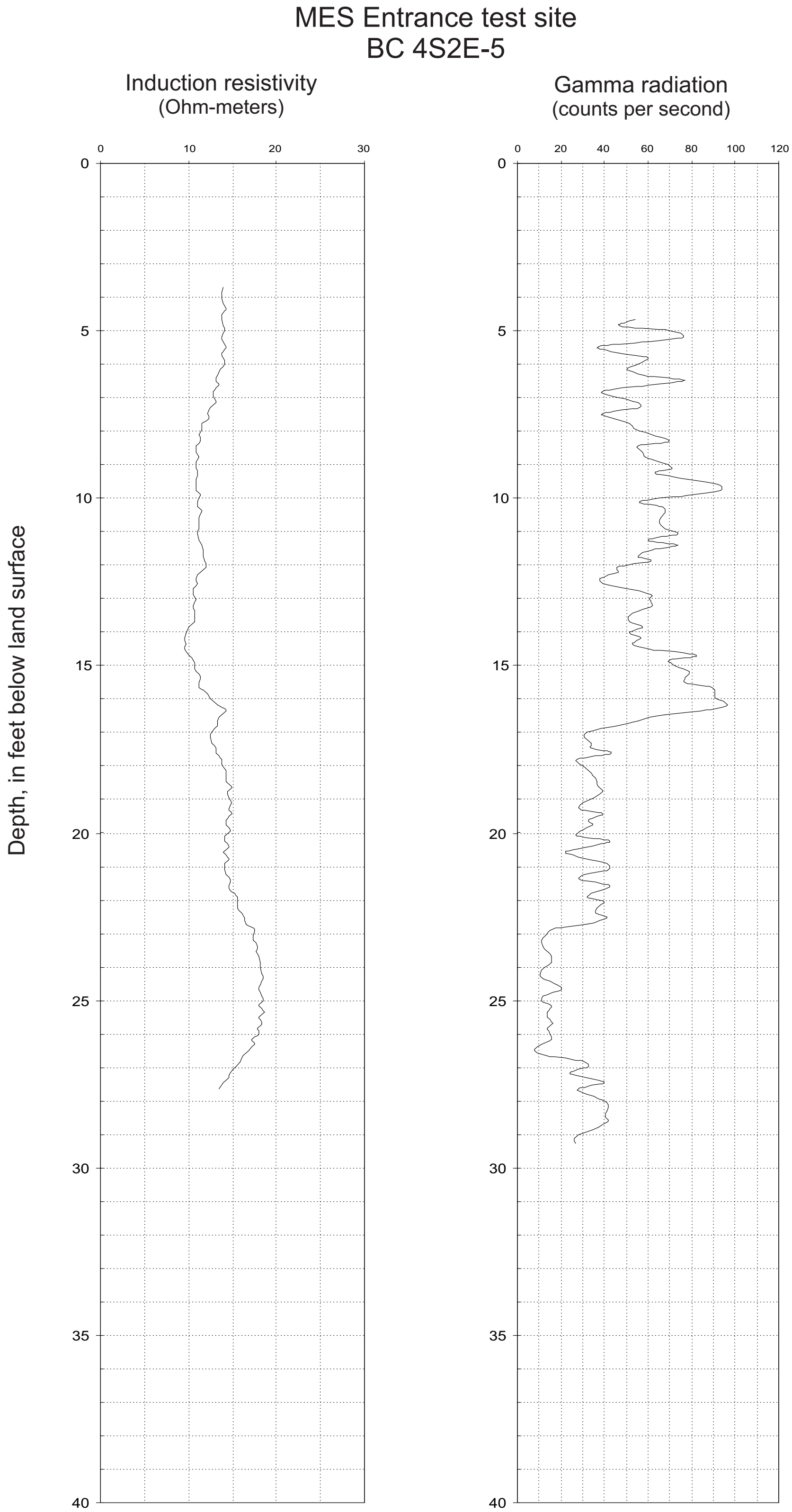
CAD deep test well (BC 4S2E-6)—Continued

Mud-rotary samples—Continued			
Hydrologic unit	**Depth (feet below land surface)**	**Primary lithology**	**Secondary description**
Patuxent aquifer system	160-170	Clay with minor gravel	As above
	170-180	Clay with minor gravel	As above
	180-190	Sandy clay	Clay as above; fine to very coarse sand and fine pebbles, mostly quartz, rare mica, sub-rounded to rounded
	190-200	Sandy clay	As above
	200-210	Clay with minor gravel and sand	Mottled clay, red, purple and white; coarse sand to fine pebbles, mostly quartz, sub-rounded
	210-220	Clay with minor gravel and sand	Clay, as above, except greater amount of sand gravel
	220-230	Clay with minor gravel and sand	As above
	230-240	Clay with minor gravel	Mostly white clay fine pebbles, mostly quartz, sub-rounded
	240-250	Clay with minor gravel	As above
	250-260	Clay with minor gravel	As above
	260-270	Gravel with moderate amount of clay	Very fine to fine pebbles, fine to very coarse sand, mostly quartz, angular to sub-rounded white clay
	270-280	Gravel with moderate amount of clay	Medium sand to fine pebbles, mostly quartz and rare mica, angular to sub-angular; white and red clay
	280-290	Gravel with minor clay	Medium sand to fine pebbles, mostly quartz and rare mica, angular to sub-angular greasy green clay
	290-300	Gravel and sand with moderate amount of clay	Medium sand to medium pebbles, quartz, rock fragments (schist?) and mica, angular, dark red clay globules with medium to coarse sand, mostly quartz and yellow clay
Pre-Cretaceous basement rock	300-310	Gravel and sand with moderate amount of clay and saprolite	As above, except with saprolite and no yellow clay
	Drill bit sample at 309.8	Saprolite	Green, mica rich clay

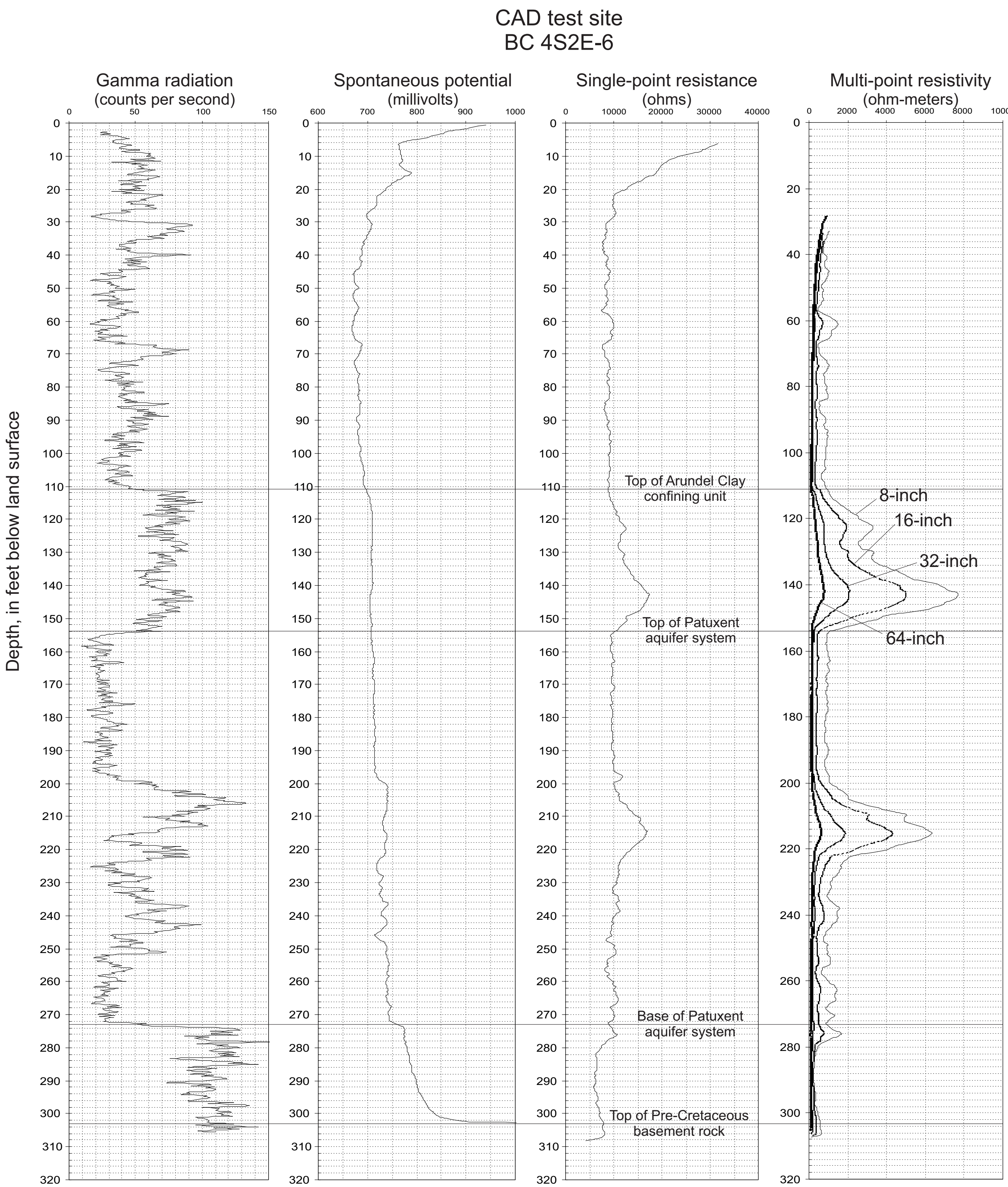
Appendix B. Geophysical logs run in test wells.



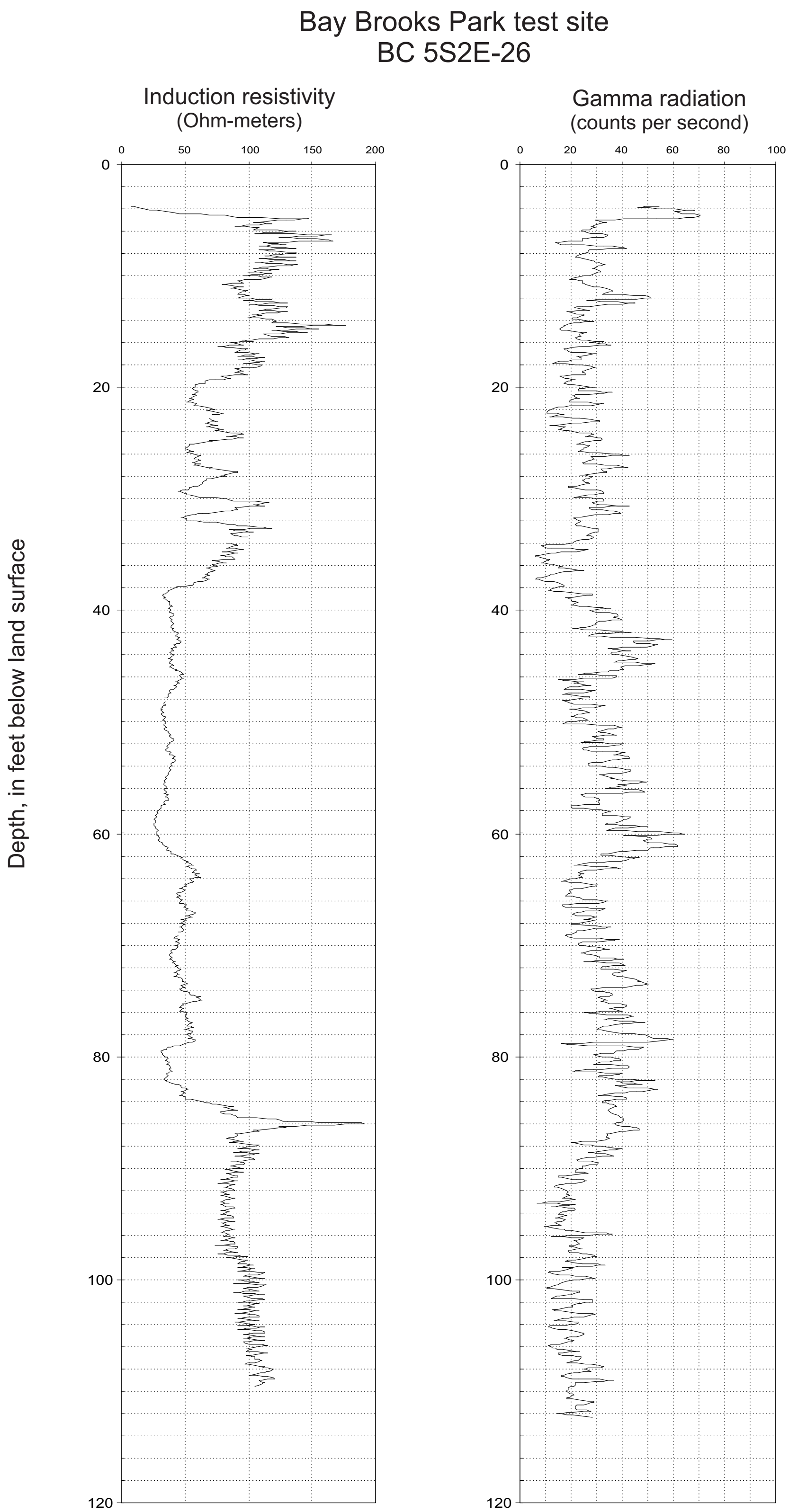
Appendix B. Continued.



Appendix B. Continued.



Appendix B. Continued.



Appendix C. Abbreviations used in this report

AADPW	Anne Arundel County Department of Public Works
af	artificial fill
BWI	Baltimore-Washington International Thurgood Marshall Airport
CAD	confined aquatic disposal
cm	centimeter
commun.	communication
E	estimated
ft	feet
ft^2/d	feet squared per day
ft/mi	feet per mile
gal/min	gallons per minute
gpm	gallons per minute (figs. 8 and 9)
GPS	global positioning system
hr(s)	hour(s)
in.	inch
MCL	Maximum Contaminant Level
MES	Maryland Environmental Service
Mgal/d	million gallons per day
mg/L	milligrams per liter
MGS	Maryland Geological Survey
mi	mile
MPA	Maryland Port Administration
mrem/yr	millirems per year
mv	millivolts
N	nitrogen
NOAA	National Oceanic and Atmospheric Administration
ng/L	nanograms per liter
NTU	nephelometric turbidity unit
P	phosphorus
pCi/L	picocuries per liter
PVC	polyvinyl chloride
Q	pumping rate
Qtc	Talbot Formation (silt-clay facies)
s	slope of line per log cycle
SMCL	Secondary Maximum Contaminant Level
T	transmissivity
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius
$<$	less than

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A message to Maryland's citizens

The Maryland Department of Natural Resources (DNR) seeks to balance the preservation and enhancement of the living and physical resources of the state with prudent extraction and utilization policies that benefit the citizens of Maryland. This publication provides information that will increase your understanding of how DNR strives to reach that goal through the earth science assessments conducted by the Maryland Geological Survey.

Martin O'Malley
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