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HYDROGEOLOGY AT THREE TEST-WELL SITES IN GARRETT COUNTY, MARYLAND

by

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CONTENTS

ILLUSTRATIONS

TABLES

HYDROGEOLOGY AT THREE TEST-WELL SITES IN GARRETT COUNTY, MARYLAND

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KEY RESULTS

Seven test wells were drilled at three sites in Garrett County, in the Appalachian Plateau Physiographic Province of Maryland. The purpose of this study was to (1) provide baseline data on the hydrogeologic characteristics (hydraulic properties, water levels, and water quality) of aquifers at depths typically utilized for water supply, and to (2) investigate the hydraulic connection between the shallow (less than approximately 200 feet) and deep (approximately 500 to 1,000 feet) aquifers and surface water.

Testing indicates that the aquifer system is highly heterogeneous and anisotropic, with distinct differences between sites in fracture orientation (high-angle versus low-angle), fracture density (both transmissive and non-transmissive fractures), hydraulic head gradient, transmissivity, specific yield, water quality, and degree of hydraulic connection to the nearby stream. There are also differences between wells within each site including deep versus shallow aquifer response, hydraulic relation between the wells and stream, head gradient, and water quality. The differences in hydrogeologic characteristics seen in this study illustrates the complexity of the groundwater flow system in the Appalachian Plateau Physiographic Province of Maryland, making prediction of the fate and transport of contaminants in the subsurface very difficult.

At the Buffalo Run test site in northwest Garrett County, open intervals in shallow and deep wells are 40 to 120 ft, and 125 to 230 ft, respectively. Both wells were flowing artesian wells, with hydraulic heads of approximately 87 ft and 5 ft above land surface for the deep and shallow wells, respectively. Flow rates for the deep and shallow wells were 110 and 0.8 gallons per minute, respectively. Most fractures were subhorizontal and associated with bedding. Three transmissive fractures in the deep borehole contributed almost all of the ambient flow. In the shallow borehole, four fractures contributed almost all of the flow. Transmissivities in GA Aa 15 were 710 ft^2 /d during the drawdown phase, and 945 ft^2/d during the recovery phase. The head difference between the two wells suggests that a hydraulic connection between the two zones is unlikely, and the stream gage in Buffalo Run showed no response from the flowing aquifer test of the deep well, indicating little or no hydraulic connection between them. The shallow aquifer responds to rainfall events, indicating a direct hydraulic connection with the surface and suggesting a connection with Buffalo Run. Water quality was similar between the two wells and Buffalo Run, although Buffalo Run had a higher percentage chloride and sulfate, which may reflect input of road salt and other processes.

At the Savage River test site in northeast Garrett County, open intervals in shallow and deep wells are 40 to 120 ft and 500 to 986 ft, respectively. The deep well was essentially a dry hole, indicating a very low permeability; this precluded conducting an aquifer test or collecting a water sample. The water level in the shallow well was 75 ft below land surface. Transmissivity of the shallow well was calculated as 6 and 4 ft^2/d in the drawdown and recovery phases of the pump test, respectively. The specific capacity of the shallow well was 0.06 gpm/ft. Log analysis indicated that the borehole penetrated transmissive bedding and higher-angle fractures. There were virtually no transmissive fractures below 500 ft. A lack of water-level response during aquifer testing indicated no direct hydraulic connection between the deep and shallow aquifers. The relation between shallow groundwater and streamflow in the Savage River could not be evaluated due to lack of proximity (the gage was about 3 miles from the drill site) and the relatively low discharge rate of the test (5 gpm). However, the shallow well and the Savage River stream gage showed similar hydrograph patterns. GA Bf 29 had a mixed-cation, oxygen-rich water type, and had a low dissolved-solids content; Savage River had sodium and chloride as the dominant ions (suggesting an anthropogenic source) and had higher overall dissolved solids.

At the Nydegger test site in southwest Garrett County, open intervals in three wells range from 20 to 32 ft, 40 to 200 ft, and 500 to 985 ft, respectively. Water levels in all three wells were below the level of the adjacent Nydegger Run, indicating that it is a losing stream, and that there is some other control on groundwater flow in the area. The specific capacity in the deep and middle wells was 0.03 and 11.3 gpm/ft, respectively; transmissivity was 2 and 2,300 ft^2/d, respectively. Most fractures were subhorizontal and associated with bedding. The 535-ft fracture zone accounted for more than 90 percent of the total transmissivity in the deep well. Water-level response during aquifer testing indicates a strong hydraulic connection between the deep, middle, and shallow aquifers. The deep, middle, and shallow aquifers respond to rainfall events, indicating a direct hydraulic connection with the surface. The deep well had a sodium-bicarbonate water type, was lower in dissolved solids and had a higher methane concentration compared to the shallow and middle wells, whose water were calcium-chloride or calcium-mixed anion types. Water from both the deep and middle wells differed from the Savage River water samples which were predominantly calcium-sulfate water.

INTRODUCTION

The Marcellus Shale has been developed extensively for natural gas in neighboring parts of Pennsylvania and West Virginia, as well as other areas of the eastern United States as a result of advances in directional drilling and hydraulic fracturing. The Marcellus Shale is present in the Appalachian Plateau Physiographic Province in Garrett and western Allegany Counties of Maryland (Brezinski, 2012). The Marcellus Shale is also present in parts of the Valley and Ridge Physiographic Province in eastern Allegany and Washington Counties; however, it is not considered to be a viable drilling target because the intensely folded rocks were heated beyond what is optimal for gas creation (Repetski and others, 2008), and because the folded strata renders directional drilling useless (D. Brezinski, Maryland Geological Survey, oral commun., 2015). Negative impacts may be associated with hydraulic fracturing of the Marcellus Shale, including contamination of shallow groundwater and surface water supplies through spills and improper construction techniques. Potential contaminants include chemicals used in the hydraulic fracturing process, native brine waters, and migration of natural gas (primarily methane) (Soeder and Kappel, 2009). In order to assess the risk of contamination at a given site, a thorough understanding of the hydrogeologic characteristics of each site, including the groundwater-flow system and groundwater-surface water interaction, is necessary.

PURPOSE AND SCOPE

This study was conducted to (1) provide baseline data on hydrogeologic characteristics (hydraulic properties, water levels, and water quality) at depths typically utilized for water supply in Garrett County and western Allegany County at three different sites that are also being monitored for stream flow, chemistry, and biological conditions; and (2) provide a better understanding of the hydraulic connection between the shallow (less than approximately (200 ft) and deep (approximately 500 to 1,000 feet [ft])groundwater regimes and the relation between surface water and groundwater at the sites.

This report documents the methods of investigations used in the study and the hydrogeologic conditions encountered at the three sites. Test-well drilling and completion methods are described, geophysical logging and flow logging data are discussed, and aquifer-test data and groundwater-quality data are presented. These data, along with stream data, are used to compare and contrast hydrogeologic conditions between the three sites.

LOCATION OF STUDY AREA

The study area is located in the Appalachian Plateau Physiographic Province (hereby referred to as the Appalachian Plateau) of Maryland (fig. 1). All test-well sites are in Garrett County. The Appalachian Plateau of Maryland is bordered on the north by Pennsylvania, the west and south by West Virginia, and the east by the Valley and Ridge province of Maryland. The test-well sites are located in areas of relatively low topography near streams.

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(Pennsylvania Geological Survey) and Brandon Fleming and John Williams (both with U.S. Geological Survey). The Maryland Geological Survey is especially grateful to the landowners who allowed us to drill test wells and conduct ongoing monitoring on their property.

HYDROGEOLOGIC SETTING

The Appalachian Plateau in Maryland includes all of Garrett County and the westernmost part of Allegany County (fig. 1). The Appalachian Plateau is underlain by rocks of (youngest to oldest) Permian, Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, Cambrian, and Proterozoic age (tab. 1). These sedimentary rocks include predominantly sandstones, shales, and limestones, with subordinate siltstones, mudstones, and coals. The sedimentary layers are gently folded in a series of anticlines and synclines that generally strike north-northwest and generally dip to the east-southeast and north-northwest (fig. 1). The Devonian-age rocks are exposed on the crests of the anticlines, and the younger Pennsylvanian rocks are exposed in the centers of the synclines. The more resistant sandstones (primarily the Pottsville Formation) form mountain ridges and the less resistant rocks underlie valleys between the ridges.

Commercially valuable coal is present in the Pennsylvanian rocks, and has been mined in underground and surface mines since the early 1800s (Duigon and Smigaj, 1985). The relatively younger Pennsylvanian rocks, which are only present in the synclinal valleys, form five major coal basins in Western Maryland. Natural gas has been extracted from deep gas wells (using conventional extraction techniques) near Accident and Deer Park in Garrett County (Schwarz, 1996). In these areas, high-angle reverse faults have created traps in the Oriskany Sandstone, with the Marcellus Shale as the source rock. The Deer Park gas field is still in production; the Accident field is now used as a gas storage facility, where natural gas is transported by pipeline from other areas and stored for future use (Schwarz, 1996).

METHODS OF INVESTIGATION

Three test-well sites were chosen to collect data necessary to evaluate hydraulic relations between the relatively shallow (less than approximately 200 ft) and deep (approximately 500 to 1,000 ft) groundwater regimes and surface water. The test-well sites are associated with stream Intensive Data Collection sites operated by the Maryland Department of Natural Resources, which were installed to collect flow, chemical, and biological data for three streams in Garrett County. These sites are located at Buffalo Run near Friendsville, Savage River near Avilton, and Nydegger Run at Gorman (figs. 1 and 2). The test-well sites at Buffalo Run and Nydegger Run are within a few hundred yards of the stream gages. It was not possible to locate a test-well site close to the stream gage at Savage River at Avilton (or any of the other Intensive Data Collection sites in Garrett County) so a site was chosen about a mile upstream from the gage.

TEST-WELL DRILLING AND CONSTRUCTION

Construction and yield characteristics of the test wells are given in Table 2. In general, the test wells were drilled and constructed in the manner described below. Construction schematic details are shown in figures 3 through 5. All depths are in feet below land surface. A 14-inch borehole was first drilled to 10 or 20 ft with a rotary tricone bit, and 12-inch temporary surface casing was emplaced, but not grouted. A 12-in. borehole was then drilled to 20 or 40 ft using air percussion and 10-in. steel casing was installed and grouted with a mixture of cement and bentonite. Next, an 8-inch borehole was drilled using air percussion (to 500 ft for the deep well or 40 ft for the shallow well) and 6-in. well casing was installed and grouted. Finally, a 6-in. borehole was drilled using air percussion (to 985 ft for the deep well or 200 ft for the shallow well) and the well was blown out (developed) with compressed air for at least one hour.

At the Buffalo Run site, flowing groundwater conditions were encountered while drilling the deep borehole (well GA Aa 15) at 108 ft (about 120 gallons per minute [gpm]) and prevented drilling below 230 ft due to safety concerns (fig. 6). A decision was made to abort the borehole at 230 ft and construct a closed-in flowing well that is open from 125 ft to 230 ft (fig. 3). Six-inch casing was installed to a depth of 125 ft with an 8-in. packer to prevent water flow in the annulus between the 8-in. borehole and 6-in. casing, and grout was emplaced in the annular space. Water was allowed to flow freely from the top of the 6-in. casing for several days to relieve pressure on the grout while it was curing.

In order to close in the flowing well, a wellhead was fabricated, which comprised a steel plate welded to the top of the 6-in. casing with a 2-in. diameter threaded steel pipe, and a 2-in. stainless steel ball valve. The ball valve could be closed to prevent flow and opened to allow water sampling, aquifer testing, and transducer installation. Stainless steel was chosen because it is stronger than a typical brass valve, to prevent rupture in case the wellhead froze. A locking insulated shelter was built around the well, consisting of pressure-treated lumber and 4 inches of rigid foam insulation to further prevent freezing.

The shallow well at Buffalo Run (GA Aa 16) was drilled with a 14-in. borehole and 12-in. temporary casing to 10 ft, a 12-in. borehole and 10-in. casing to 20 ft, 8-in. borehole and 6-in. casing to 40 ft, and 6-in. open hole to 120 ft (fig. 3). It was not flowing while drilling or for several days afterward, apparently because well GA Aa 15 was allowed to flow freely during this time while the grout was curing. After GA Aa 15 was closed, the head in GA Aa 16 recovered, and began flowing by May 30. An expandable, removable well seal was installed on the well head with a 2-in. steel pipe and 2-in. stainless steel ball valve. A locking insulated shelter was built around this well similar to the shelter for GA Aa 15.

At the Savage River site, the deep well (GA Bf 28) was drilled to 985 ft, and cased to 500 ft; and the shallow well was drilled to 200 ft, and cased to 40 ft (fig. 4). However, the deep well had not been completely grouted when the shallow well was drilled, and when the drilling contractor finished grouting the deep well, the grout apparently seeped through a fracture zone to the shallow well, and filled it to a depth of 57 ft. The shallow well was abandoned, and a new well (GA Bf 29) was drilled 15 ft away to a depth of 200 ft. The deep well was essentially a dry hole, with a water level of 919 ft below land surface on June 16, 2014. The water level subsequently rose to about 854 ft on July 7, 2014, and 327 ft on June 22, 2015.

At the Nydegger Run site, test well GA Fb 42 was drilled to 985 ft and cased to 500 ft; and test well GA Fb 43 was drilled to 200 ft and cased to 40 ft (fig. 5). A highly productive fracture zone encountered at 149 to 160 ft produced a blown yield of about 800 gpm in difficult but manageable drilling conditions. A third well GA Fb 44 was drilled to a depth of 32 ft and cased to 20 ft in order to test a fracture zone encountered at about 26 ft. This well was constructed with an 8-in. borehole and 6-in. casing and grouted to 20 ft and a 6-inch borehole to 32 ft (fig. 5). No surface casing was installed for this well. Well GA Fb 42 was grouted with pure bentonite (rather than a mixture of cement and bentonite) to more effectively seal the fracture zone at a depth of 149 to 160 ft.

GEOPHYSICAL AND FLOW LOGGING

Geophysical and flow logs were collected from the test wells by personnel from the U.S. Geological Survey New York Water Science Center (Troy, New York). The logs included natural gamma radiation, electrical resistivity, electromagnetic conductivity, acoustic and optical televiewer, deviation, caliper (diameter of borehole), fluid resistivity and temperature, and vertical flow (app. A). The geophysical and flow logging methods are described by Keys (1990) and Rider and Kennedy (2011). The geophysical logs in electronic format are available from the Maryland Geological Survey upon request.

Not all logs could be collected from all wells. For instance, murky water conditions in GA Bf 28 (Savage River) prevented an acceptable optical televiewer log. “Dry hole” conditions in the Savage River deep well also limited log collection. For the deep wells at the Savage River (GA Bf 28) and Nydegger Run (GA Fb 42) sites, the suite of logs was run first on the open borehole after drilling to 500 ft and again after the well was cased and grouted to 500 ft, and the borehole was drilled to final depth of 985 ft. The deep well at Buffalo Run (GA Aa 15) was logged once, before the casing was installed.

The gamma radiation, electrical resistivity, and electromagnetic conductivity logs provided information on the bedrock lithologies penetrated by the wells. Orientation of bedding planes and fractures was determined from the acoustic and optical televiewer logs. Borehole deviation from vertical was used to correct the orientation of bedding planes and fractures from apparent to true. Fluid-resistivity, temperature, and flow logs were collected under recovery and/or ambient conditions and under low-rate pumped conditions.

Flow-log measurements were made at discrete depths above and below fracture zones and interpreted with the fluid-resistivity and temperature logs to identify transmissive zones and flow between and above them. The ambient and pumped flow logs from selected wells were quantitatively analyzed to estimate fracture-zone transmissivity and hydraulic head by the use of the analytical model FLASH (Flow Log Analysis of Single Holes) developed by Day-Lewis and others (2011). The FLASH model code is based on the Thiem equation, which is a multi-layer, analytical solution for steady-state radial flow to a single well.

AQUIFER TESTING

Aquifer tests were conducted on four of the seven test wells. Constant-discharge tests were performed on wells GA Bf 29, GA Fb 42, and GA Fb 43; a submersible pump was installed in each well and pumped at a constant rate while water-level measurements were made using an electric tape, and also with vented pressure transducers. Water-level measurements for observation wells (non-pumped wells at each site) were also recorded. Water-level measurements were also made on all wells at each site during a recovery period after the pump was shut off. Discharge was measured during the pumping phase of each test with a totalizing flow meter and stopwatch, and adjusted as needed with an in-line gate valve. GA Fb 42 and GA Fb 43 were pumped for 24 hours, and allowed to recover for 24 hours. After 12 hours of pumping well GA Bf 29 (Savage River site) the water level was approaching the pump intake, and the discharge phase of the test was terminated and the recovery phase begun. A preliminary 3-hour step test was performed on each tested well at least one day before the 24-hour test in order to ascertain all equipment was functioning properly, and to determine an optimum discharge rate for each well.

Well GA Aa 15 was flowing with a hydraulic head of approximately 87 ft above land surface, and could not be tested with the submersible pump method described above. Instead, the well was allowed to flow at a constant rate for eight hours while water levels were recorded with a non-vented pressure transducer installed in a specially-constructed chamber (see section on Water-Level Monitoring for further description). Discharge was measured with a 3-in. by 2-in. orifice meter, and was kept constant by adjusting an in-line gate valve. Water levels were also measured in the observation well GA Aa 16 with a non-vented transducer similar to the installation in GA Aa 15. Water-level measurements continued in both wells for a recovery period of 18 hours after the discharge phase of the test.

Well GA Bf 28 at the Savage River site did not produce a significant amount of water, and could not be tested. Well GA Fb 44 at the Nydegger Run site had only about 13 ft of water (well depth 32 ft, water level about 19 ft) so it would have been impossible to install a submersible pump large enough to adequately stress the aquifer. Well GA Aa 16 at the Buffalo Run site was flowing with a head approximately 4 ft above land surface, and so could not be tested with a typical pumping test. The flow was not great enough to conduct a flowing well test as was done with GA Aa 15.

Transmissivity for the four tested wells was calculated using the Cooper-Jacob semi-logarithmic straight line method for discharge and recovery phases of each test (Cooper and Jacob, 1946). For the discharge phase of the test, time in minutes is plotted on the logarithmic x-axis and drawdown is plotted on the arithmetic y-axis. For the recovery phase of the test, time since discharge started, divided by time since discharge stopped, is plotted on the logarithmic x-axis and residual drawdown is plotted on the arithmetic y-axis. If the assumptions of the method are met, the values plot on a straight line (after contribution from well storage becomes negligible), the slope of which is used to calculate transmissivity. Assumptions include a homogeneous aquifer of infinite extent and constant thickness, with no leakage, and no recharge or discharge boundaries within the area of influence. The Cooper-Jacob straight-line method assumes that the aquifer is a porous medium (i.e. unconsolidated porous sediment such as sand and gravel); however, in the consolidated rock aquifers considered in this report, fractures are fundamental to the flow of water. Applying the Cooper-Jacob straight-line method to fractured rocks assumes that the rocks are sufficiently homogeneously fractured and interconnected such that the rock behaves similar to porous medium (Belcher and others, 2001).

WATER-LEVEL MONITORING

Following the aquifer testing, water levels were measured in all seven test wells using pressure transducers and recorded at 15-minute intervals. Installations at most wells included a vented transducer deployed on a cable locked inside the well. These vented transducers were open to the atmosphere through a very small tube in the cable, and automatically corrected the water-level record for barometric (atmospheric) fluctuation. The transducer recorded water levels on internal memory, which was downloaded every one to two months to a field device and transferred to a computer at the office for plotting and analysis. Water-level measurements were collected using an electric tape during site visits, and transducer data were corrected if necessary.

Flowing conditions at the two wells at the Buffalo Run site (GA Aa 15 and GA Aa 16) necessitated a different transducer deployment than described above. Because the wells were shut-in, vented transducers could not be hung on cables in these wells. Instead, unvented transducers were installed in specially built chambers constructed from PVC pipe fittings that were attached to the 2-in. ball valves. Atmospheric pressure was measured during site visits using a pressure gage in open air at the height of the shut-in measuring point to correct pressure measurements to the measuring point datum. After each transducer was programmed and installed in the chamber, air was bled from the system through a brass valve at the end of the device. The shut-in transducer arrangement was not open to the atmosphere, so barometric-fluctuation corrections were not required. Because these two wells were shut-in, there was no actual water level to measure. The transducer recorded total (absolute) water pressure, which was converted to a theoretical water level (if a standpipe were installed to allow water to rise to its equilibrium level) using the following equation:

$$WL = (P_t - P_a) * 2.31$$

where

WL = water level in feet above the measuring point

P_t = total pressure recorded, in pounds per square inch, and

P_a = atmospheric pressure at the measuring point, in pounds per square inch.

GROUNDWATER SAMPLING

Water samples were collected from six of the seven test wells. One well at the Savage River site and three wells at the Nydegger Run site were sampled during the pumping phases of each aquifer test. At the Buffalo Run site, water samples were collected directly from the flowing wells. Samples were analyzed for major ions, nutrients, trace elements, methane, radioactivity, and other constituents and indicators. All samples except methane were analyzed by the U.S. Geological Survey National Water Quality Laboratory in Denver, Colorado and their subcontracted laboratories. Methane analyses were performed by ALS Environmental in Middletown Pennsylvania. Wellwater-quality data were compared with stream-water quality data provided by Maryland Department of Natural Resources Monitoring and Non-Tidal Assessment (M. Kashiwagi, Maryland Department of Natural Resources, written commun., 2015).

HYDROGEOLOGY AT TEST SITES

BUFFALO RUN SITE

Geology

The geology at the Buffalo Run site was mapped as Conemaugh Group by Brezinski and Conkwright (2013) (fig. 7). The lithologic log for well GA Aa 15 (app. B) indicates about 20 ft of alluvium, comprising brown to gray sand, mixed with boulders of Conemaugh bedrock. The Conemaugh Group extends from 20 to 88 ft, and consists of gray and brown sandstone. A coal interbedded with black shale was encountered from 88 to 100 ft, which is interpreted as the Upper Freeport Coal at the top of the Allegheny Formation. The Allegheny Formation extends to the bottom of the hole at 230 ft, and includes gray and brown shale to 180 ft and gray sandstone to 230 ft.

Geophysical and flow logging

Geophysical and flow logs were collected from the Buffalo Run deep test-well site (GA Aa 15) on May 13, 2014 under ambient flowing conditions after drilling to 230 ft and before the 6-inch diameter casing and packer were installed (fig. 3). The borehole was an 8-inch diameter open hole from 20 to 230 ft and had an ambient shut-in head of about 87 ft above sea level (fig. 3). The borehole penetrated sandstone intervals with high resistivity and low gamma counts at 45 to 65 and 78 to 87 ft. Carbonaceous intervals were penetrated at 87 to 110 and 159 to 186 ft. The upper carbonaceous interval displayed an upward increase in gamma counts indicating an upward increase in shale content. Coals present in the carbonaceous intervals were delineated by their low conductivity and low gamma counts at 106-109, 165 to 167, and 184 to 186 ft. Bedding delineated on the OTV and ATV logs had an average dip of less than 4 degrees. Most fractures were subhorizontal and associated with bedding. Log analysis indicated that the borehole penetrated transmissive fractures at 106-111, 216, 222, and 229 ft. Ambient borehole flow was upward from the deep transmissive zones discharging to the surface at an estimated rate of 110 gpm. Fractures below 200 ft deep contributed almost all of the upward flow.

Geophysical and flow logs were collected on June 16, 2014 under ambient flowing and low-rate pumped conditions from the Buffalo Run shallow well (GA Aa 16) (app. A2). The well was a 6-inch diameter open hole from 40 to 120 ft and had an ambient shut-in head of about five feet above land surface (fig. 3). The borehole penetrated the two sandstone intervals and the upper carbonaceous interval with the basal coal as was penetrated by deep well GA Aa 15. Log analysis indicated that the well penetrated transmissive bedding fractures at 102,110, 114, and 117 ft. The 114-ft zone contributed more 40 percent of the pumped flow with the other three zones each contributing about 20 percent. This transmissive fractured interval appears to be the same interval penetrated by and subsequently cased off in deep well GA Aa 15. Ambient borehole flow in shallow well GA Aa 16 was upward from the transmissive zones discharging to the surface at a rate of 0.8 gpm. Pumping the well at 4.1 gpm resulted in more than 9 ft of drawdown and increased the upward flow from the transmissive zones.

Aquifer testing

A flowing-well aquifer test was conducted on well GA Aa 15 on October 2-3, 2014. The well was allowed to flow at a constant rate of 110 gpm for eight hours while water levels were recorded with an unvented transducer at one-minute intervals (fig. 8). Total drawdown in the flowing well was about 35 ft. The specific capacity at the end test was 3.1 gallons per minute per foot (gpm/ft) of drawdown. Water levels were also monitored in test well GA Aa 16 with an unvented transducer at one-minute intervals. Stage (stream water level) was monitored in Buffalo Run at 15-minute intervals by the U.S. Geological Survey. The stream gage was located approximately 200 ft from the test wells (fig. 2).

Transmissivity values calculated from the drawdown and recovery phases of the test were 710 and 945 feet squared per day (ft^2/d), respectively. The slope of the semi-logarithmic drawdown and recovery plots both show a gradual steepening with later time, which indicates a reduction in transmissivity with distance that may indicate a limit to the areal extent of the fracture zone.

The shallow well GA Aa 16, showed a significant response during the drawdown and recovery phases of the test on GA Aa 15 (fig. 9). Drawdown in GA Aa 16 was about 1.4 ft and recovery was about 0.5 ft in the 14 hours after flow ceased in GA Aa 15. This would appear to indicate that there is a significant hydraulic connection between the fracture zones open in the shallow (40 to 120 ft) and deep (125 to 230 ft) wells. However, the hydraulic head difference between the two wells of about 83 ft does not corroborate this notion. The response of water levels in the shallow well is probably caused by unloading of pressure in the deeper fracture zone propagated upward into the shallow fracture zone. This is similar to a tidal fluctuation propagated from an estuary downward into a confined aquifer, even though there is no actual flow of water from the estuary to the confined aquifer. The stage in Buffalo Run did not show a response to the flowing aquifer test of GA Aa 15 (fig. 9).

Water-level monitoring

The long-term hydrographs of the wells at the Buffalo Run test site show some interesting trends that are difficult to explain (fig. 10). The water level in GA Aa 15 (deep well) shows a rise after the preliminary aquifer test on September 10-11, 2014 and the aquifer test on October 2-3, 2014 that exceeds the water levels before the tests, followed by a decrease a week or so later. The head prior to the preliminary aquifer test on September 10 was about 1,607.6 ft and recovered to about 1,609.0 ft a few days after the test. The head prior to the aquifer test on October 2 was about 1,608.4 ft and recovered to about 1,611.6 ft a few days after the test. This may be part of a background rising trend separated by downward spikes caused by the aquifer tests, although fluctuations of this magnitude are not exhibited in the subsequent part of the hydrograph from November, 2014 through April, 2015.

The hydrograph for GA Aa 16 (shallow well) shows a general rise in water level from August through November 2014 with downward spikes during the tests of GA Aa 15 (fig. 10). It rose to 1,529.7 ft on December 7 then dropped to 1,526.4 ft on December 16, then rose back to 1,528.0 on

December 22, when it continued a steady increase. The owner of the only nearby pumping well (domestic well) did not report any unusual water use during that period. It is possible that a rock fracture opened up temporarily when water pressure reached a critical level (1,529.7 ft head), allowed drainage to a lower pressure area, then sealed again when the pressure reached a critical low point (1,526.4 ft head). This curious trend is not exhibited in the deep well or the stage in Buffalo Run. Several water-level peaks in well GA Aa 16 correspond to peaks in stream stage in Buffalo Run following rain events, suggesting a direct hydraulic connection of the shallow aquifer with the surface.

The stage in Buffalo Run shows a similar pattern to the water level in the shallow well (GA Aa 16), except for the upward and downward spikes described above. The stream stage shows a slight general increase from August 2014 through April 2015 with upward spikes of about 0.5 to 1 ft caused by precipitation events (fig. 10). A larger spike is seen on March 4, 2015 of about 3 ft, which corresponds to an increase in temperature above freezing and ensuing snowmelt.

Relative hydraulic heads in the wells and stream indicate a significant upward head gradient. Average heads in the deep and shallow wells and stream are about 1,610, 1,528, and 1,516 ft above sea level, respectively (fig. 10). The natural 82-ft head difference over the 107 ft separating the water-bearing zones in the deep and shallow wells indicates a very low permeability for the rock in this interval. This rock is predominantly greenish-gray shale and siltstone with some greenish-gray sandstone and minor coal beds (app. B).

Water quality

Water quality in GA Aa 15 and 16 is similar (tab. 3). Both wells have low total dissolved solids (TDS), are slightly alkaline, and show little indication of anthropogenic contamination, based on chloride and nitrogen levels. Sodium is the major cation in both wells (45 to 55 percent milliequivalent percent) with lesser percentages of calcium (30 to 40 percent) and magnesium (10 to 15 percent) (fig. 11). Bicarbonate is the dominant anion type for both wells. The cation chemistry for Buffalo Run is similar to that of the wells, but has a slightly wider range in composition. The anion type for Buffalo Run has a higher percentage of chloride and sulfate than the wells, likely reflecting an input of road salt runoff (chloride and sodium both peak in December), and possibly oxidation of sulfide minerals associated with coal beds within the watershed. In terms of absolute concentrations, the wells had higher pH, alkalinity, ammonium, calcium, sodium, barium, and strontium, which likely reflect longer rock-water contact time than Buffalo Run. Groundwater is under reducing conditions at the wellsite (dissolved oxygen was less than 1 milligrams per liter [mg/L]), in contrast to the well-oxygenated water of Buffalo Run. This is reflected in generally higher concentrations of iron and ammonium and lower concentrations of sulfate in wellwater compared with stream water.

SAVAGE RIVER SITE

Geology

The geology at the Savage River test site was mapped as Hampshire Formation by Brezinski and Conkwright (2013) (fig. 12). The site is on the eastern limb of a broad anticline between the Georges Creek coal basin to the east, and the Castleman coal basin to the west. The highly resistant Pottsville Formation forms Big Savage Mountain just to the east of the site. High-angle reverse faults are indicated near the center of the anticline, west of the Savage River test site.

The lithologic log for test well GA Bf 28 indicates 30 ft of alluvium, which includes brown to red sand, silt, and pebbles (app. C). The rest of the drilled interval from 30 to 985 ft is the Hampshire Formation, which is predominantly reddish brown and greenish gray sandstone interbedded with subordinate greenish gray and reddish gray shale and siltstone.

Geophysical and flow logging

Geophysical and flow logs were collected on May 22, 2014 under recovery, ambient, and low-rate pumped conditions from the Savage River deep test-well site (GA Bf 28) after drilling to 500 ft and before the 6-inch diameter casing was installed. The borehole was an 8-inch diameter open hole from 40 to 500 ft and had an ambient water level of 78.4 ft. Log analysis indicated that the borehole penetrated transmissive bedding and higher-angle fractures at 55, 72, 98,139, 201, and 397 ft. Measured ambient and pumped flows were not consistent or repeatable due to significant leakage between the flowmeter diverter and the borehole wall. However, analysis of the fluid resistivity, specific conductance, and temperature logs suggests that the ambient borehole flow was downward from the shallow higher-head zones to the lower-head deep zone. The rate of the downward flow was estimated from the fluid logs to be at least 0.8 gpm. Pumping the borehole at 2 gpm resulted in 4.2 ft of drawdown. The fluid logs indicated that the shallow fractures contributed 100 percent of the low-rate pumped flow, and the downward flow below the 72-ft fracture was not reversed by the pumping.

Aquifer testing

Near dry-hole conditions in well GA Bf 28 (deep) indicate very low permeability in the lower part (500 to 985 ft) of the Hampshire Formation that is open in this well. Primary porosity of the cemented sandstones and shales is probably very low, and any fractures and joints present that would contribute to secondary porosity are closed too tightly to allow significant groundwater flow. A small amount of water is entering the well, probably from numerous minor fractures, or from primary porosity of the sandstone. The water level in GA Bf 28 rose 474 ft from early-July 2014 to mid-April 2015 (fig. 13), equating to approximately 3 gallons per day, or 0.002 gpm. The water-level rise has slowly been leveling off, indicating that it will reach equilibrium conditions at about 2,270 ft above sea level (320 ft). The lack of a sharp break in slope of the water-level curve indicates that water is entering the borehole somewhat evenly throughout the open section, not from a discrete fracture or fracture zone. A slug test performed on July 9, 2014 (fig. 14) also indicated low-permeability conditions of the Hampshire Formation. Fifteen gallons of water were poured into the top of the well, and within a few minutes the water level rose 9 ft, indicating that about 13 gallons made it to the bottom of the well. The remaining 3 gallons probably adhered to the inside of the casing and borehole. The water level recorded by the transducer did not recover to the previous water level, but instead showed a continued rise at the same rate observed prior to the test.

Well GA Bf 29, the shallow well at the Savage River test site, yielded 5 gpm during a 12-hour aquifer test with about 87 ft of total drawdown (tab. 2; fig. 15). The specific capacity at the end test was 0.06 gpm/ft. The test duration was limited to 12 hours to maintain the water level above the submersible pump intake. Transmissivities calculated from the drawdown and recovery phases of the test were 6 and 4 ft^2/d, respectively (fig. 15). The slope of the semi-logarithmic drawdown plot shows a steepening at about 150 minutes, which indicates a limit to the areal extent of the fracture zone. This could have been caused by the inadvertent partial grouting of the fractures in constructing well GA Bf 28, about 40 ft to the northeast, but probably indicates that the fractures naturally have a limited extent, within the zone of influence of this test.

The hydrograph for well GA Bf 28 shows no response to the aquifer test on GA Bf 29 (fig. 14), most likely due to the low permeability of the rocks contributing water to the deep well, and the low pumping rate which was not great enough to significantly stress the aquifer. The stage in the Savage River also showed no response to the aquifer test of GA Bf 29, which is expected owing to the intervening distance (nearly three miles) (fig. 2) and the relatively low discharge rate of the test (5 gpm).

Water-level monitoring

The long-term hydrographs for test well GA Bf 29 and Savage River show similar patterns, but do not necessarily indicate a direct hydraulic connection between the shallow groundwater regime and the river (fig. 13). Both hydrographs show water-level rises after rainstorms, indicating rapid groundwater recharge, and a typical storm-water response in the river. The lack of a significant barometric fluctuation in the well indicates water-table conditions, and, in conjunction with the rapid recharge, the absence of significant confining material above the open section. The slow, nearly constant rise in water level in well GA Bf 28 also indicates a very low hydraulic connection between the deep and shallow groundwater regimes.

Water quality

The water sample from GA Bf 29 is predominantly a calcium-magnesium bicarbonate type (as defined by Back [1966]) with low total dissolved solids (TDS) (86 mg/L) (fig. 16; tab.3). Well GA Bf 28 was not sampled because of its very deep water level, low yield, and the likelihood that the water in the well bore would not be representative of ambient groundwater. Water chemistry in the Savage River differs greatly from water chemistry in well GA Bf 29 (fig. 16). Water from Savage River is a sodium-chloride type, with higher TDS ranging from 100 to 1,038 mg/L. Savage River chemistry appears to be dominated by runoff of road salt, likely coming from Interstate 68, which is about four miles upstream of the sampling site on Savage River. Chloride concentrations and TDS in the Savage River vary seasonally, with highest values in February. However, both remain high throughout the year relative to expected background levels, indicating migration of salty water into the shallow groundwater flow system, and gradual release throughout the year from storage. Well GA Bf 29 is not affected by road salt.

NYDEGGER RUN SITE

Geology

The geology at the Nydegger Run site was mapped as Conemaugh Group (undivided) by Brezinski and Conkwright (2013) (fig. 17). The site is within the Upper Potomac coal basin, which is formed by a broad syncline with coal-bearing Pennsylvanian-age rocks in its core. The Upper Potomac coal basin is bounded to the northwest by Backbone Mountain, and extends southwestward into West Virginia. Backbone Mountain is formed primarily by the Pottsville Formation, and is the same ridge as Big Savage Mountain to the northeast.

The lithologic log for test well GA Fb 42 indicates 10 ft of alluvium, which comprises olive brown clay, sand, and rounded pebbles (app. D). The Conemaugh Group extends from 10 ft to 198 ft and is predominantly greenish gray to black sandstone, interbedded with lesser amounts of greenish gray siltstone and shale. Coal seams (with minor pyrite) were encountered from 17 to 20 ft and 90 to 92 ft. Large (up to 1½ ft long) fragments of calcite-cemented sandstone were recovered from 149 to 160 ft that had rounded edges, indicating dissolution-enhanced fractures.

Pyritized coal was encountered from 198 to 235 ft, interbedded with dark gray to black shale and siltstone. This interval is interpreted to be the Upper Freeport Coal, and the top of the Allegheny Formation. Brezinski (1998) mapped the top of the Upper Freeport Coal at about 2,120 ft elevation, which fits with this description. The contact between the Conemaugh Group and Allegheny Formations is difficult to delineate due to the lithologic similarity of the two units (Duigon and Smigaj, 1985). The remainder of the Allegheny Formation, down to 468 ft, consists predominantly of dark greenish gray to black sandstone, with subordinate amounts of siltstone and shale.

The Pottsville Formation, of Pennsylvanian age, extends from 468 to 837 ft, and is mostly medium- to coarse-grained greenish gray sandstone. Black shale and siltstone was encountered from 628 to 664 ft, which included small amounts of coal. The lower part of the borehole (837 to 985 ft) was the Mississippian-age Mauch Chunk Formation, which consists of shale and siltstone, mottled dusky red and greenish gray. The contact between the Pottsville and Mauch Chunk Formations was distinct and easily recognizable. The thicknesses of all the geologic units logged in this borehole are substantially greater than noted in the descriptions of Brezinski and Conkwright (2013).

The Steyer #2 Mine, an underground coal mine in the Lower Bakerstown coal seam, extends to within about 800 ft northwest of the site, and the Mettiki mine, in the Upper Freeport coal extends to within about one-half mile southeast of the site. Undocumented abandoned coal mines may also exist in the area. It is unclear what, if any, effect these mines could have on the hydrogeology of the site.

Geophysical and flow logging

Geophysical and flow logs were collected on June 9-10, 2014 under recovery and low-rate pumped conditions from the Nydegger Run deep-well site (GA Fb 42) after drilling to 500 ft and before the 6-inch diameter casing was installed. The borehole was an 8- to 10-inch diameter open hole from 40 to 500 ft (fig. 5). During logging, the water level in the borehole was recovering from the drilling operation and ranged from 25 to 19 ft. The borehole penetrated sandstone intervals with high resistivity and low gamma counts at 180 to 193, 266 to 288, and 391 to 443 ft. A high-conductivity anomaly at 218 to 219 ft may be associated with a highly pyritized coal bed. Thirty-one of the 38 fractures identified on the OTV and ATV logs were penetrated above 250 ft. Most fractures were subhorizontal and associated with bedding. Log analysis indicated that the borehole penetrated transmissive fractures at 52, 66, 95, 101, 150, and 407 ft. Measured ambient and pumped flows were not consistent or repeatable due to significant leakage between the flowmeter diverter and the borehole wall. However, analysis of the fluid resistivity, specific conductance, and temperature logs suggests that the borehole flow was downward from the shallow higher-head zones to the lower-head zone at 150 ft (similar to that was determined for well GA Fb 43). In addition, borehole flow appeared to be upward from the higher-head 407-ft zone to the lower-head 150-ft zone. Based on analysis of the fluid logs, the rate of this upward flow was about 0.05 gpm. Pumping the borehole at 5.5 gpm resulted in minimal drawdown. The effect of pumping on borehole flow was unclear because the borehole-water column had not reached a steady ambient condition before pumping started, but it is assumed that the shallow pumped flow was similar to that measured in well GA Fb 43.

Geophysical and flow logs were collected on June 17, 2014 under ambient and low-rate pumped conditions from the Nydegger Run middle well (GA Fb 43). The well is a 6-inch diameter open hole from 40 to 200 ft and had an ambient water level of 19.4 ft. The borehole penetrated the uppermost interval of high resistivity and low gamma counts associated with relatively clean sandstones at 181 to 193 ft. The distribution and orientation of bedding and fractures was similar to that described above. Log analysis indicated that the well penetrated transmissive bedding fractures at 54, 65, 82, 94, 102, and 152 ft. These transmissive zones appear to be the same zones as those cased off in the upper part of deep well GA Fb 42. In middle well GA Fb 43, the 54-ft and 65-ft zones were highly transmissive and accounted for an estimated 27 and 65 percent, respectively, of the total well transmissivity. The 152-ft zone accounted for an estimated 7 percent of the total well transmissivity. Ambient borehole flow was downward from the shallow higher-head fractured zones to the deep lower-head fractured zone. The maximum measured rate of ambient downward flow was 2 gpm. The estimated head difference between the shallow zones and the deeper zone was 2.5 ft. Pumping the well at 5 gpm resulted in minimal drawdown that reversed flow from downward to upward above the 65-ft zone but only slightly reduced the downward flow below it. The 54- and 65-ft zones contributed 100 percent of the low-rate pumped flow.

Geophysical and flow logs were collected on June 18, 2014 under ambient and low-rate pumped conditions from the deep section of the Nydegger Run deep well (GA Fb 42), which is a 6-inch diameter open hole from 500 to 985 ft and had an ambient water level of 17.9 ft. Log analysis indicated that the well penetrated transmissive bedding fractures at 535, 627, 735, 768, 792, and 841 ft. The 535-ft zone accounted for more than 90 percent of the total well transmissivity. Ambient borehole flow was upward from the higher-head zones between 735 and 841 ft to a lower-head zone at 535 ft. The maximum measured rate of ambient upward flow was 0.3 gal/min. The estimated head difference between the 535-ft zone and 735- to 841-ft zones was more than 50 ft. Pumping the well at 0.7 gpm resulted in 13.1 ft of drawdown that only slightly increased the upward flow from the deeper zones. More than 60 percent of the low-rate pumped flow was contributed by the 535-ft zone.

Aquifer testing

An aquifer test was conducted on the deep well at the Nydegger Run test site (GA Fb 42) on June 23 - 25, 2014. The well was pumped for 24 hours at a constant rate of 4 gpm, then allowed to recover for 24 hours. The specific capacity at the end of the test was 0.03 gpm/ft. Water levels were measured in the pumping well and observation wells GA Fb 43 and GA Fb 44 using hand-held electric tapes and downhole pressure transducers. Stage and flow were monitored in Nydegger Run at 15-minute intervals by the U.S. Geological Survey. The stream gage is located approximately 200 ft northwest of the test wells; however, the stream itself is approximately 80 ft north of the test wells (fig. 2).

Transmissivity calculated from the Cooper-Jacob semi-logarithmic plot was 2 ft^2/d for both drawdown and recovery phases of the test (fig. 18). Both phases of the test show a decrease in slope in late time, indicating either an increase in transmissivity with distance (such as an increase in interconnected fractures with distance) or a recharge boundary at some distance from the well. The first alternative seems more likely as it is unlikely that there is a natural recharge boundary within the zone of influence of this well (open from 500 to 985 ft). However, flooded mine workings or an abandoned exploratory well could provide a recharge source that could produce this effect. For these reasons, the middle time (between 10 and 100 minutes) was chosen as representative of hydrogeologic conditions at the test-well site.

The hydraulic connection between the deep and shallow groundwater regimes and Nydegger Run is difficult to assess in this test because the pumping rate in GA Fb 42 (4 gpm) was not enough to adequately stress the groundwater system. Also, a torrential rainstorm about 6 ½ hours into the recovery test caused a quick increase in stream stage of about 0.2 ft, and probably an increase in water levels in the two observation wells. However, there was a decrease in water levels in the observation wells of about 0.2 ft during the pumping phase of the test (fig. 19), and an increase of less than 0.1 ft in the early part of the recovery phase before the rainstorm. The decrease during the pumping phase may be partially background trend (stream stage shows a gradual decrease before the rainstorm). The increase in water levels in the observation wells after the storm of about 0.4 ft appears to be caused primarily by recharge from the rainstorm, although recovery induced by the aquifer test probably also contributed to the increase.

An aquifer test was also run on the middle well at the Nydegger Run test site (GA Fb 43), which is open from 40 to 200 ft, on July 1-3, 2014 (fig. 20). The well was pumped at a discharge rate of 180 gpm for 24 hours, with a total drawdown of 15.99 ft, then allowed to recover for 24 hours. The specific capacity at the end of the test was 11.3 gpm/ft. Water levels were measured in the pumping well and observation wells GA Fb 42 and GA Fb 44 using hand-held electric tapes and downhole pressure transducers. Stage and flow also were monitored in Nydegger Run during the test.

Transmissivity calculated from the Cooper-Jacob semi-logarithmic plot was 2,000 ft^2/d for the drawdown phase and 2,700 ft^2/d for the recovery phase of the test (fig. 20). Both phases of the test show an increase in slope in late time, indicating a decrease in transmissivity with distance, probably caused by a decrease in interconnected fractures with distance. As with the test on well GA Fb 42, the middle time (between 10 and 100 minutes) was chosen as representative of hydrogeologic conditions at the test-well site. The high transmissivity (for fractured rock settings) calculated in this test is likely a result of secondary porosity caused by solution-enhanced fractures in the calcite-cemented sandstone at depths of 149 to 160 ft. Flowmeter testing suggested that 90 percent of the transmissivity for well GA Fb 43 is from fractured zones at 54 and 65 ft.

Both observation wells (GA Fb 42 and GA Fb 44) showed significant responses during the drawdown and recovery phases of this aquifer test (fig. 21). GA Fb 44 (the shallow water-table well) showed an immediate response, and had a drawdown of about 13 ft during the drawdown phase of the test, which was nearly as much drawdown as in the pumping well GA Fb 43. The water level in GA Fb 44 also recovered to about the same level as the pumping well. This indicates a strong hydraulic connection between the shallow and intermediate depth intervals. The deep observation well GA Fb 42 also showed a response to the pumping and recovery phases of the test, although not as pronounced as the shallow well. This response indicates a hydraulic connection between the deep and shallow groundwater regimes at this test site.

The stage in Nydegger Run shows a steady decrease throughout the aquifer test, with an upward spike that lasted a few hours during the early part of the recovery phase. No rainstorm was reported in the field notes of the test, but it is likely there was an isolated storm upstream of the test site that caused the spike. The steady decrease in stage and the upward spike seem to be unrelated to the aquifer test.

Water-level monitoring

The long-term hydrographs (fig. 22) for the period July 2014 through April 2015 show similar trends for the three test wells and the stream gage. The shallow wells GA Fb 43 and GA Fb 44 are nearly identical in both pattern and elevation, indicating a strong hydraulic connection between the water-table and shallow groundwater regimes. The hydrograph for GA Fb 42 is very similar to the shallower wells, although about a foot higher in elevation. Stage in Nydegger Run shows a similar pattern to the wells, but flashier, with steeper upward spikes caused by precipitation events, and occurs over a narrower range of about one foot. It is also substantially higher in elevation than water levels in the wells, which means the head gradient is from the stream toward the shallow groundwater regime. This indicates that this is a losing stream reach, a condition that is difficult to explain given there are no nearby groundwater withdrawals (the area is served by public water). It is possible that the shallow groundwater regime at this site is more strongly influenced by the Potomac River, which is about 1,500 ft to the south-southeast at its closest point and about 2,310 ft in elevation, than Nydegger Run.

Water quality

Water quality varies greatly between the three wells. GA Fb 42 (deep) is a sodium-bicarbonate water type, with low TDS (tab. 3). Wells GA Fb 43 (middle) and Fb 44 (shallow) are predominantly calcium-chloride and calcium-mixed anion water types, respectively (fig. 23). Both GA Fb 43 and 44 have above-background chloride (54 and 201 mg/L, respectively) and have elevated sulfate and iron relative to GA Fb 42. Cation percentages in the shallow and middle wells wells (GA Fb 43 and GA Fb 44) are similar to chemistry in Nydegger Run (fig. 23). The proportion of cations in GA Fb 43 (middle) and Fb 44 (shallow) is similar to those of Nydegger Run; however, stream water is predominantly sulfate and bicarbonate, with smaller proportion of chloride. The watershed is generally undeveloped, and the sampling site is upstream from Gorman Road and US Route 50, and thus unaffected by road salt runoff. The high proportion of sulfate is probably due to oxidation of sulfide minerals, such as pyrite, which is associated with coal beds. Chloride, sulfate, and iron are elevated in both shallow wells (tab. 3). Iron and sulfate levels are likely caused by oxidation of pyrite associated with coal beds, several of which were encountered, as shown in the lithologic log (app. D). The source of chloride is unclear; the site is close to Gorman Road, but on the opposite side of Nydegger Run, which does not appear to be affected by road salt runoff. The area is agricultural, but nitrogen concentrations are low, suggesting that fertilizer is not the source. Upwelling of deep brines is also unlikely because the chloride concentration in the deep well (GA Fb 42) is low.

Water chemistry in the deep well (GA Fb 42) is distinct both from wells GA Fb 43 and 44 and from Nydegger Run. It has a sodium-bicarbonate type, with low iron and manganese concentrations, indicating little influence of road-salt runoff and oxidation of sulfide minerals. Methane is notably higher in this well (6,080 ug/L) than in the two shallow wells (25.1 and 45.6 ug/L). Although the Pottsville Formation includes some coal beds, only minor amounts were noted in the lithologic log for the open interval of 500 to 985 ft (app. D).

DISCUSSION

A variety of hydrogeologic conditions were documented at the three sites evaluated in this study (tab. 4). Fractures and partings in the Buffalo Run and Nydeggar Run wells are subhorizontal or bedding-plane partings, whereas partings in the Savage River wells were bedding plane and higher-angle fractures. There was little evidence of hydraulic connection between the shallow and deep aquifers at either the Buffalo Run or the Savage River sites. At the Nydegger Run site, however, the response in observation wells during the drawdown and recovery phases of the aquifer tests indicates a strong hydraulic connection between the water table (very shallow) and shallow wells, and a lower but significant connection between the deep and shallow wells. Although this connection could be a result of nearby underground coal mining or other anthropogenic sources, it is more likely a natural connection caused by fractures in the intervening rock of the Allegheny and Pottsville Formations. The deeper Mauch Chunk Formation appears to be unfractured and fairly homogeneous, and unlikely to provide a hydraulic connection between the deeper rocks and the shallow water resources.

Relations between the wells and streams also varied. Water levels and stream-gage data at the Buffalo Run sites suggest a hydraulic connection between the shallow aquifer and Buffalo Run, whereas water levels at Nydegger Run wells are below the level of Nydegger Run, suggesting another control on groundwater levels. There was no consistent relation between the number of fractures and well depth, and only a small percentage (less than 2 percent) of fractures were water-bearing in any of the deep wells. The transmissive fractures were irregularly distributed with respect to depth, and the percentage of total flow contributed by each fracture varied greatly. The shallow and deep wells at Buffalo Run, while not hydraulically connected, nevertheless had very similar water-quality characteristics, while at Nydegger Run, water quality from the shallow, intermediate, and deep wells was quite distinct.

The varied and complex hydrogeologic conditions encountered at these sites (aquifer yields, groundwater levels, head gradients, and hydraulic connections) between the three areas tested in Garrett County underscore the difficulty in formulating predictive models of groundwater flow. Unlike conditions in the Maryland Coastal Plain, where hydrologic and geologic characteristics are sufficiently well understood to enable development of predictive flow models, data from this study illustrates the heterogeneity and anisotropy of the groundwater system in fractured-rock aquifers. Movement of groundwater is through discrete low-to high-angle fractures and bedding planes whose transmissive characteristics vary from site to site, and whose position and orientation cannot be determined prior to drilling wells. Although head distribution controls the overall direction of groundwater flow, the exact path of travel is difficult if not impossible to determine due to lack of information on orientation and size of secondary partings. This makes prediction of the fate and transport of contaminants in the subsurface very difficult, and also explains why well yields can vary so widely.

SUMMARY AND CONCLUSIONS

Seven test wells were drilled at three sites (Buffalo Run, Savage River, and Nydegger Run) in Garrett County, Maryland in the Appalachian Plateau physiographic province to (1) provide baseline data on hydrogeologic characteristics (hydraulic properties, water levels, and water quality) at depths typically utilized for water supply in Garrett County and western Allegany County at three different sites, and (2) provide a better understanding of the hydraulic connection between the deep (approximately 500 to 1,000 ft) and shallow (less than approximately 200 ft) groundwater regimes, and the relation between surface water and groundwater at the sites.

At the Buffalo Run test site, two wells were completed with open intervals of 40 to 120 ft (GA Aa 16, open to the Conemaugh Group and Allegheny Formations) and 125 to 230 ft (GA Aa 16, open to the Allegheny Formation), respectively. There was a significant upward head gradient between the wells. The deep well (GA Aa 15) was a flowing artesian well with a head of approximately 87 ft above land surface and a flow rate of about 110 gpm. The specific capacity of the deep well was 3.1 gpm/ft. The head in the shallow well (GA Aa 16) was approximately 5 ft above land surface with a flow rate of 0.8 gpm. Most fractures were subhorizontal and associated with bedding. Transmissive fractures in the deep borehole indicated by geophysical log analysis at 106-111, 216, 222, and 229 ft depth, which contributed almost all of the ambient flow. In the shallow borehole, a fracture at 114 ft contributed more than 40 percent of pumped flow, with fractures at 102, 110, 114 and 117 ft contributing the remainder. Transmissivities in GA Aa 15 were 710 ft^2 /d during the drawdown phase, and 945 ft^2/d during the recovery phase. No direct hydraulic connection likely exists between the deep and shallow aquifers and streamflow in Buffalo Run as a result of flow from the deep well. The shallow aquifer responds to rainfall events, therefore indicating a direct hydraulic connection with the surface. Water quality was similar between the two wells and Buffalo Run, although Buffalo Run had a higher percentage chloride and sulfate, which may reflect input of road salt and oxidation of sulfide minerals.

At the Savage River test site, two wells were completed in the Hampshire Formation, with open intervals in the shallow and deep wells ranging from 40 to 200 ft and 500 to 985 ft, respectively. The water level in the deep well (GA Bf 28) was approximately 854 ft below land surface, indicating a very low permeability; the water level is slowly increasing and projected to reach equilibrium at about 320 ft below land surface. Because of the deep water level in GA Bf 28, the well could not be pumped. The water level in the shallow well (GA Bf 29) was 75 ft below land surface. Transmissivity was calculated as 6 and 4 ft^2/d in the drawdown and recovery phases of the pump test, respectively. The specific capacity of the shallow well was 0.06 gpm/ft. Log analysis indicated that the borehole penetrated transmissive bedding and higher-angle fractures. Transmissive fractures indicated by geophysical-log analysis occur at 55, 72, 98, 139, 201, and 397 ft; there were virtually no transmissive fractures below 500 ft. Murky water and dry-hole conditions limited geophysical log collection in the deeper borehole. A lack of water-level response during aquifer testing indicated no direct hydraulic connection between the deep and shallow aquifers. The stage in the Savage River also showed no response to the aquifer test of GA Bf 29, which was not unexpected due to the intervening distance (nearly three miles) (fig. 2) and the relatively low discharge rate of the test (5 gpm). The shallow aquifer responded to rainfall events, indicating a direct hydraulic connection with the surface. GA Bf 29 and Savage River showed similar hydrograph patterns. GA Bf 29 had a mixed-cation water type, oxygenated, and low in dissolved solids; water samples from Buffalo Run had sodium and chloride as dominant ions and had higher overall dissolved solids.

At the Nydegger test site, one well was completed in the Pottsville and Mauch Chunk Formations, and two wells were completed in the Conemaugh Group. Open intervals in the shallow, middle, and deep wells ranged from 20 to 32 ft, 40 to 200 ft, and 500 to 985 ft, respectively. Water level in the deep well (GA Fb 42) was about 18 ft below land surface and about 19 ft below land surface in both the middle (GA Fb 43) and shallow (GA Fb 44) wells. Water levels in all three wells were below the level of Nydegger Run, indicating that it is a losing stream, and that there is some other control on groundwater flow in the area. The specific capacity in the deep and middle wells was 0.03 and 11.3 gpm/ft, respectively; transmissivity was 2 and 2,300 ft^2/d, respectively. (Static water level in the shallow well was too near the bottom of the well to facilitate a pump test.) Most fractures were subhorizontal and associated with bedding. In the deep borehole, transmissive fractures were indicated by geophysical-log analysis at 52, 66, 95, 101, 150, 407, 535, 627, 735,768, 792, and 841 ft. The 535-ft fracture zone accounted for more than 90 percent of the total transmissivity in the deep well (GA Fb 42). Water-level response during aquifer testing indicates hydraulic connection between the deep, middle, and shallow aquifers. The deep, middle, and shallow aquifers respond to rainfall events, indicating a direct hydraulic connection with the surface. Water quality in GA Fb 42 (deep well) was distinct from that of the middle and shallow wells. The deep well had a sodium-bicarbonate water type, was lower in dissolved solids, and had a higher methane concentration than the shallow and middle wells, which were calcium-chloride or calcium-mixed anion types. Both differed from the Savage River water samples which were predominantly calcium-sulfate water.

There are distinct differences between sites in fracture orientation (high-angle versus low-angle), fracture density (both transmissive and non-transmissive fractures), hydraulic head gradient, transmissivity and specific yield, response to pumping tests, water quality, and hydraulic relation to their respective streams. Between wells at each site, differences include hydraulic relation to the stream, head gradient, and water quality. The wide range of hydrogeologic conditions encountered at the three test sites indicates that it is difficult to generalize about the hydraulic connectivity of the shallow and deep groundwater regimes in the Appalachian Plateau region of Maryland.

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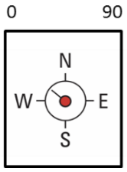
Appendix A. Geophysical and flow logs.

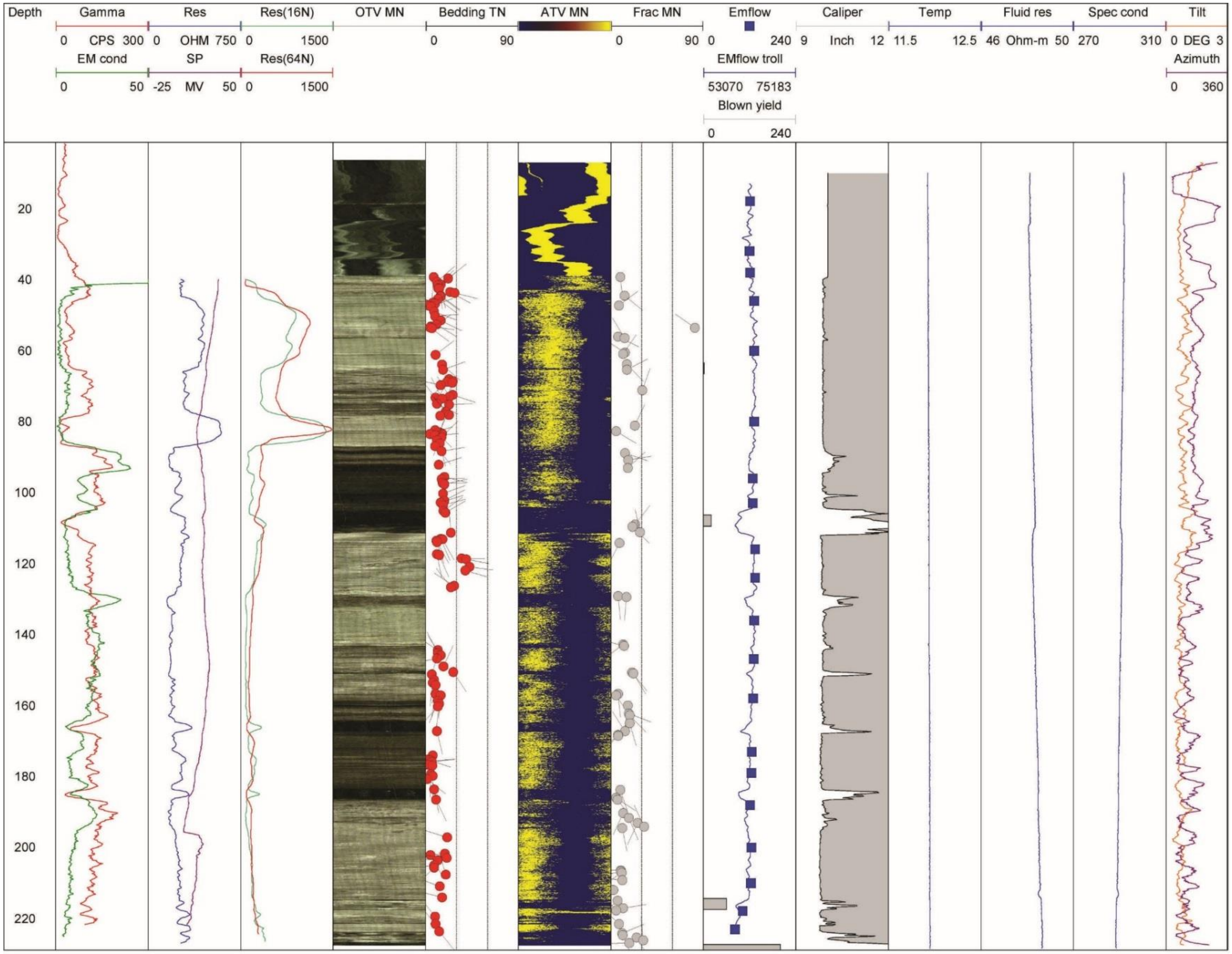
Explanation of Geophysical and flow logs

Depth	Depth, in feet below land surface (ft bls)
Gamma	Gamma radiation, in counts per second (CPS)
EM Cond	Electromagnetic conductivity, in millisiemens per meter (mS/m)
Res	Single-point resistance, in ohms (Ohms)
SP	Spontaneous potential, in millivolts (MV)
Res (16N)	Short-normal (16-inch) resistivity, in ohm meters (Ohm-m)
Res (64N)	Long-normal (64-inch) resistivity, in ohm meters (Ohm-m)
Caliper	Log of well diameter, in inches (In)
ATV MN	Acoustic-televiewer log, oriented to Magnetic North
OTV MN	Optical-televiewer log, oriented to Magnetic North
Bedding TN	Tadpole plot of planar bedding features, oriented to True Geographic North; body of tadpole indicates dip angle (0 to 90 degrees) along x-axis, and tail indicates the direction of dip (0 to 360 degree azimuth)
Fracture TN	Tadpole plot of planar fracture oriented to True Geographic North; body of tadpole indicates dip angle (0 to 90 degrees), and tail indicates the direction of dip (0 to 360 degree azimuth)

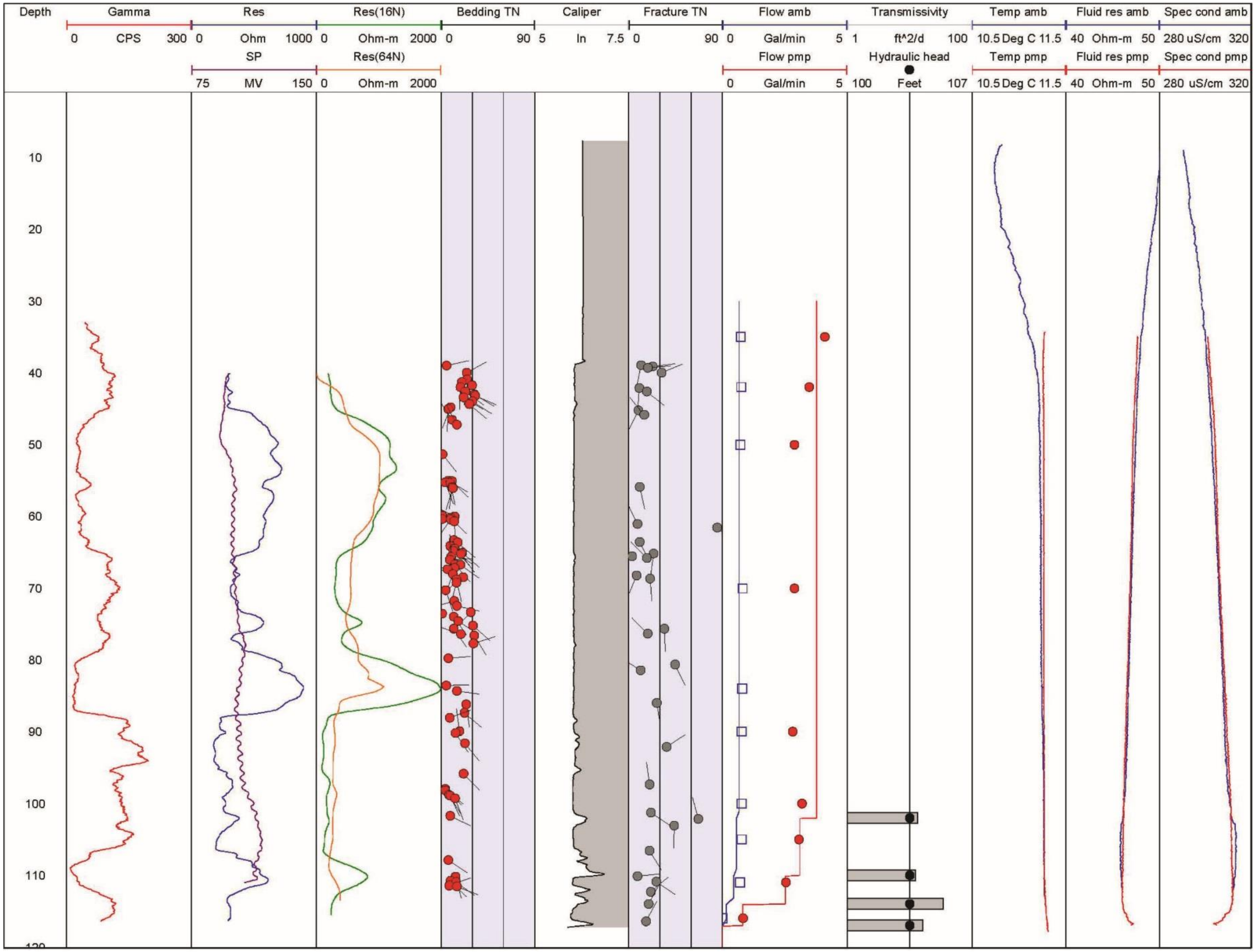


Fluid Res	Fluid resistivity collected under ambient (blue) and pumped (red) conditions, in ohm meters (Ohm-m)
Spec Cond	Specific conductance log collected under ambient (blue) and pumped (red) conditions, in microsiemens per centimeter at 25 degrees Celsius (μS/cm)
Temp	Temperature log collected on collected under ambient (blue) and pumped (red) conditions, in degrees Celsius (deg C)
Flow Amb	Vertical flow rate under ambient conditions; blue box indicates stationary measurement; blue line indicates calculated flow from flow-log analysis using Thiem analytical solution; in gallons per minute (Gal/min)
Flow Pmp	Vertical flow rate under pumped conditions; red box indicates stationary measurement; red line indicates calculated from flow-log analysis; using Thiem analytical solution; in gallons per minute (Gal/min)
Transmissivity	Transmissivity of flow zone estimated from Thiem analytical solution, in square feet per day (ft^2/d)
Hydraulic Head	Hydraulic head of flow zone estimated from Thiem analytical solution, in feet above sea level (ft asl)

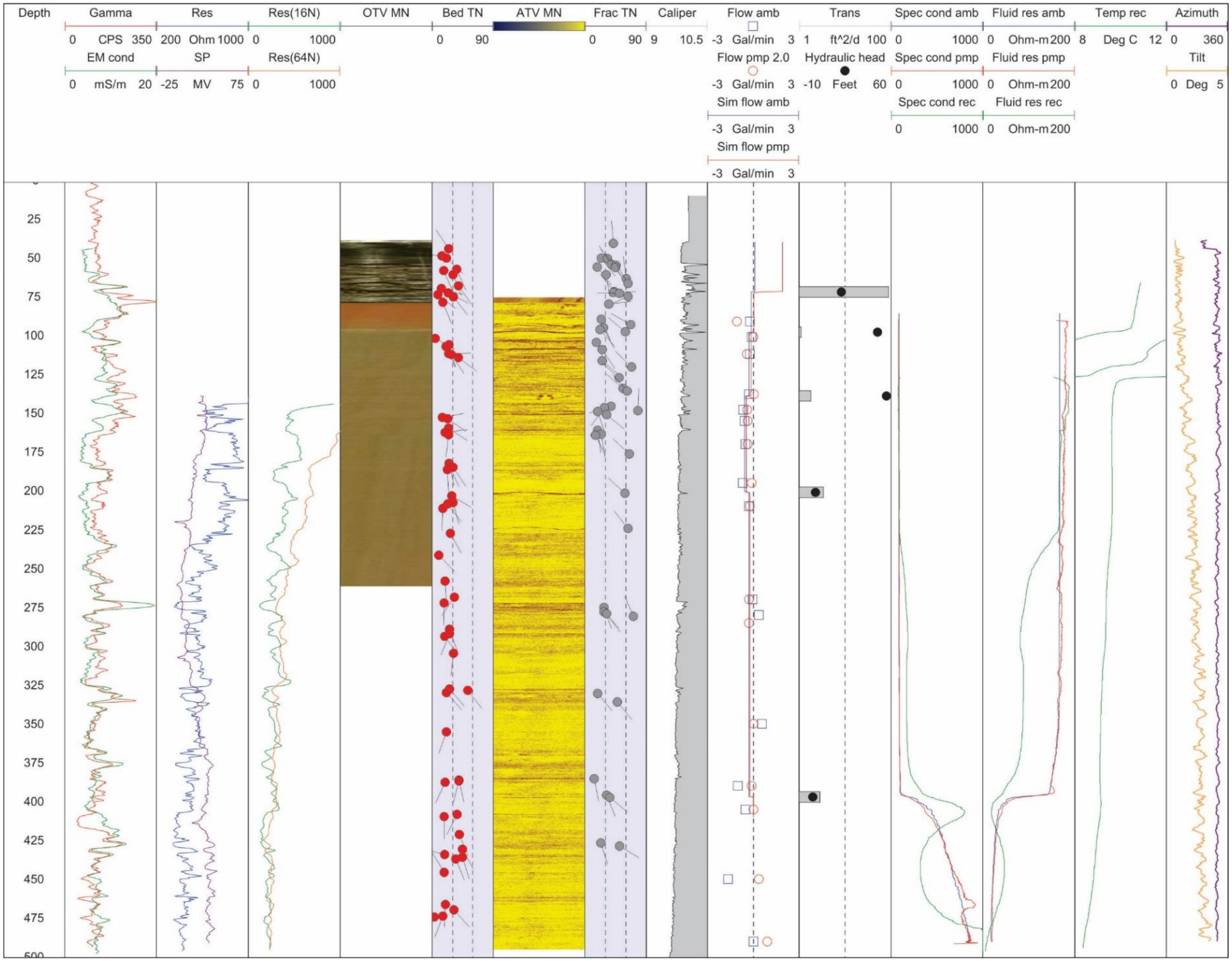
APPENDIX A1. Geophysical logs of well GA Aa 15.



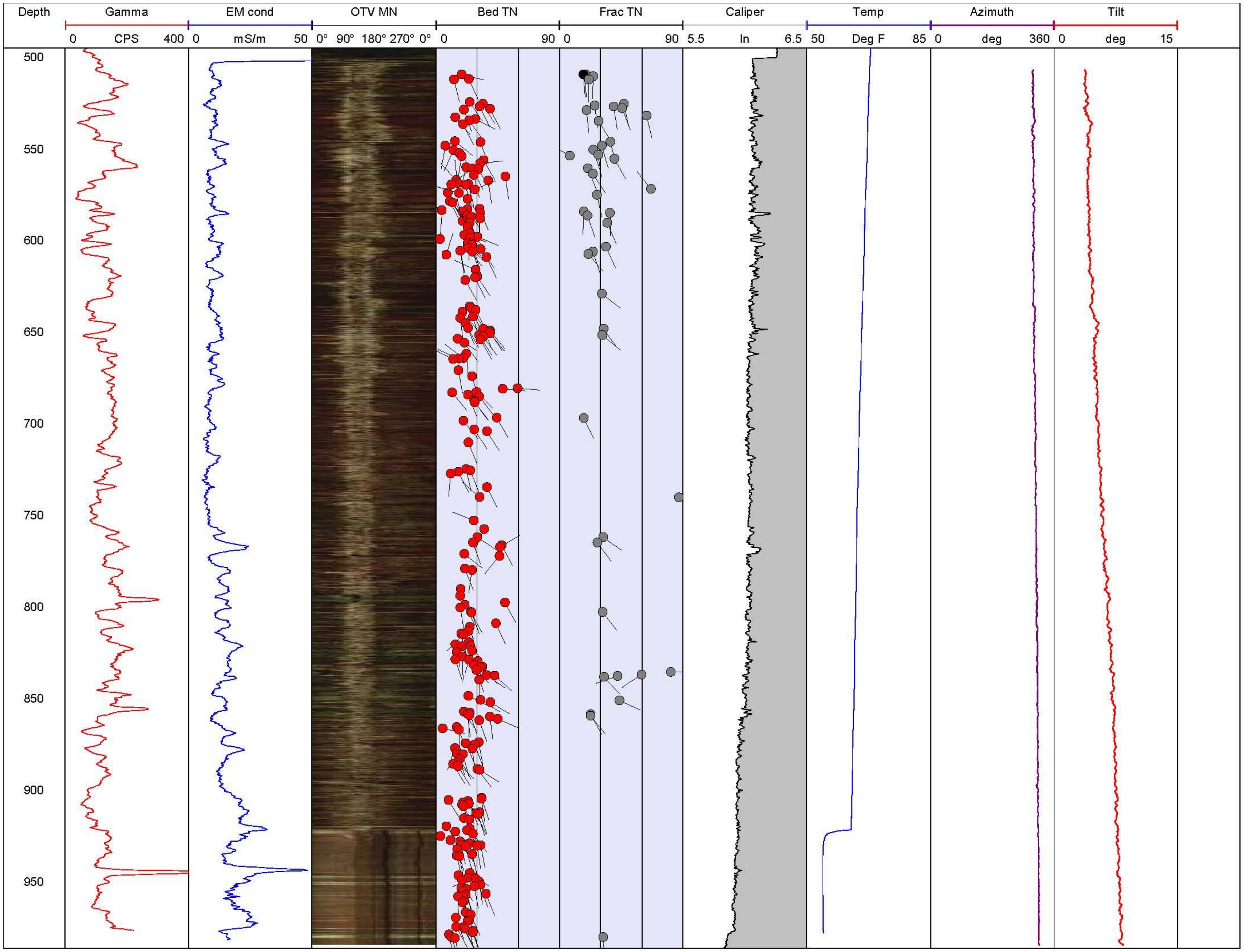
APPENDIX A2. Geophysical logs of well GA Aa 16.



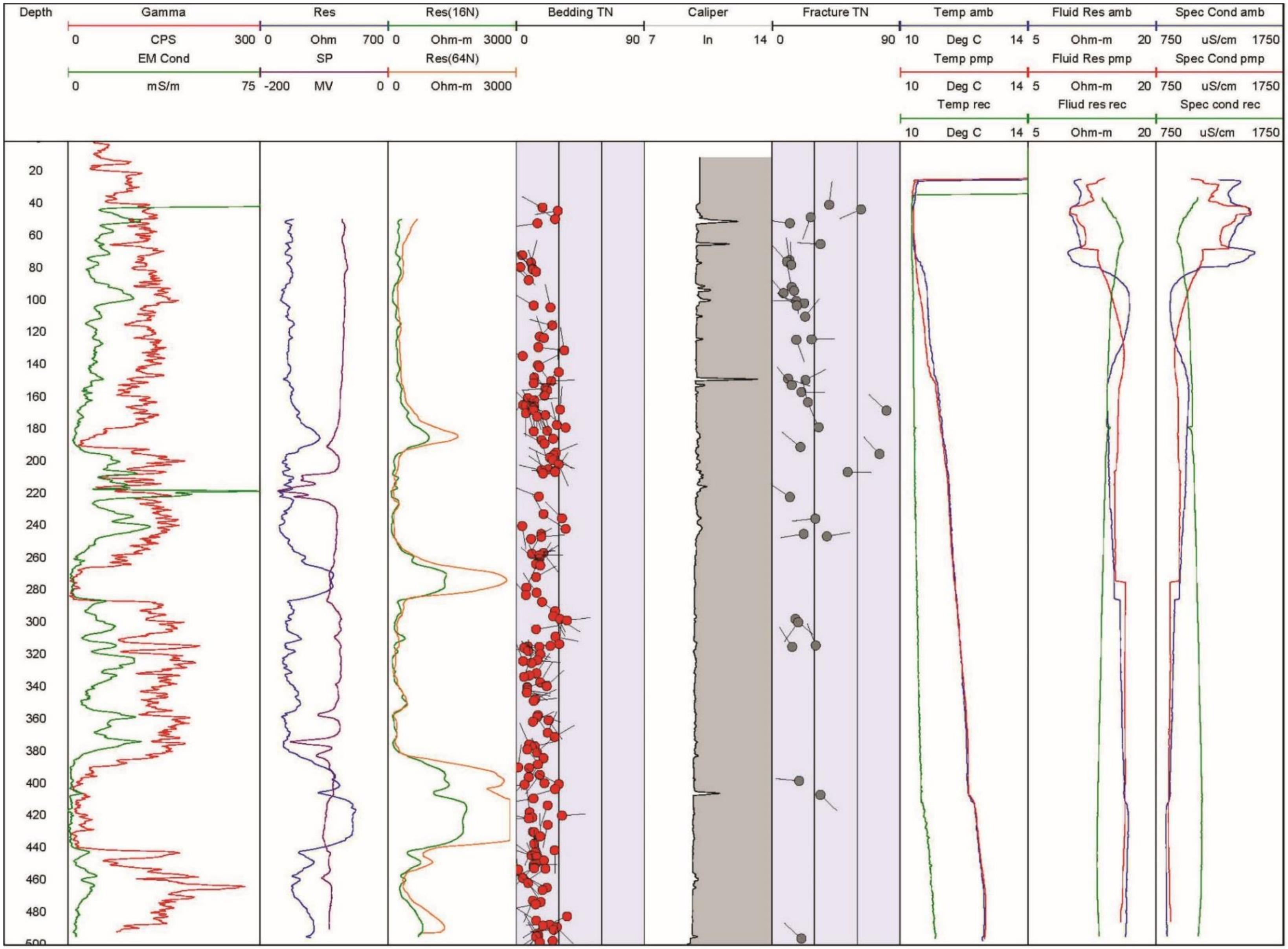
APPENDIX A3. Geophysical logs of well GA Bf 28.



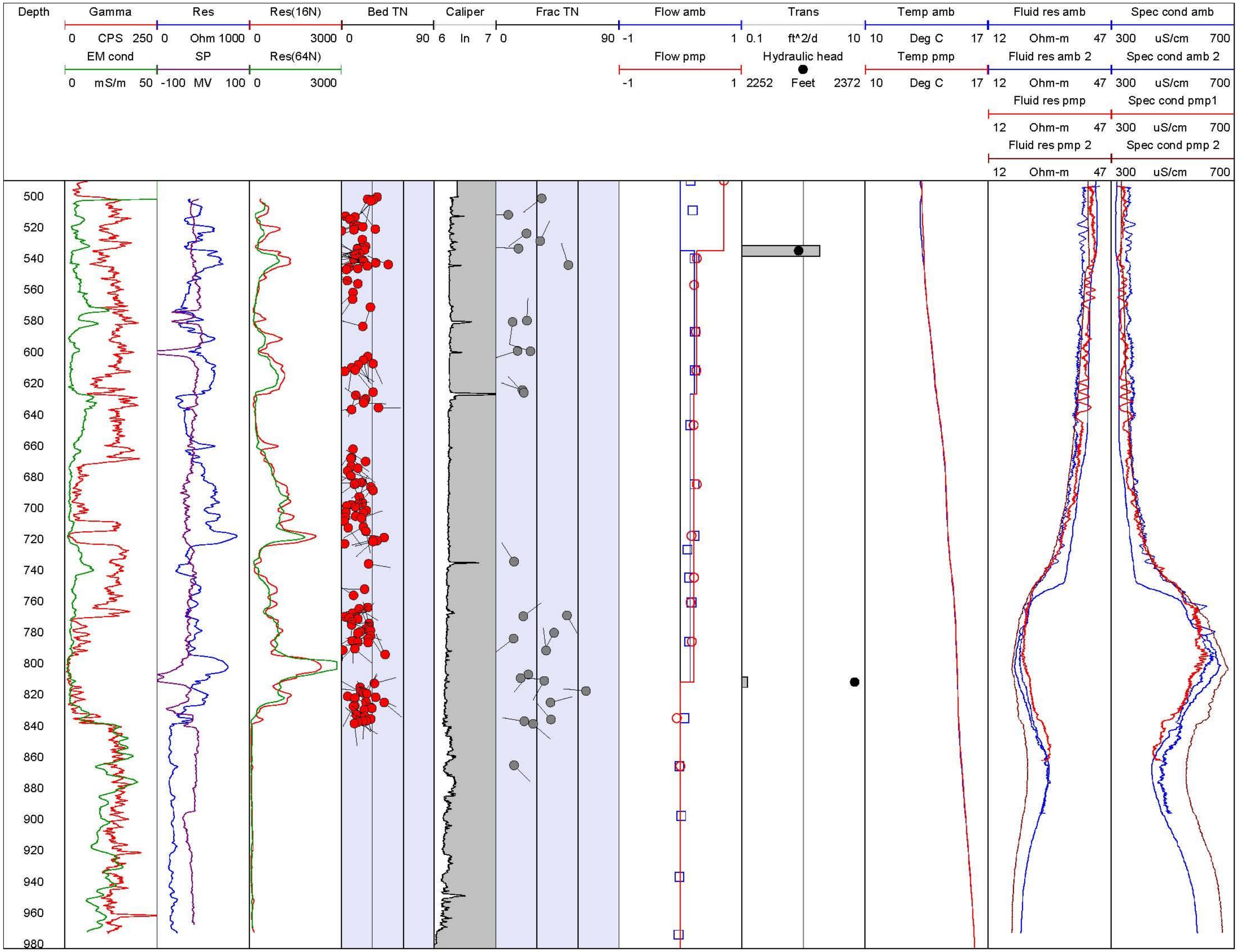
APPENDIX A3, continued



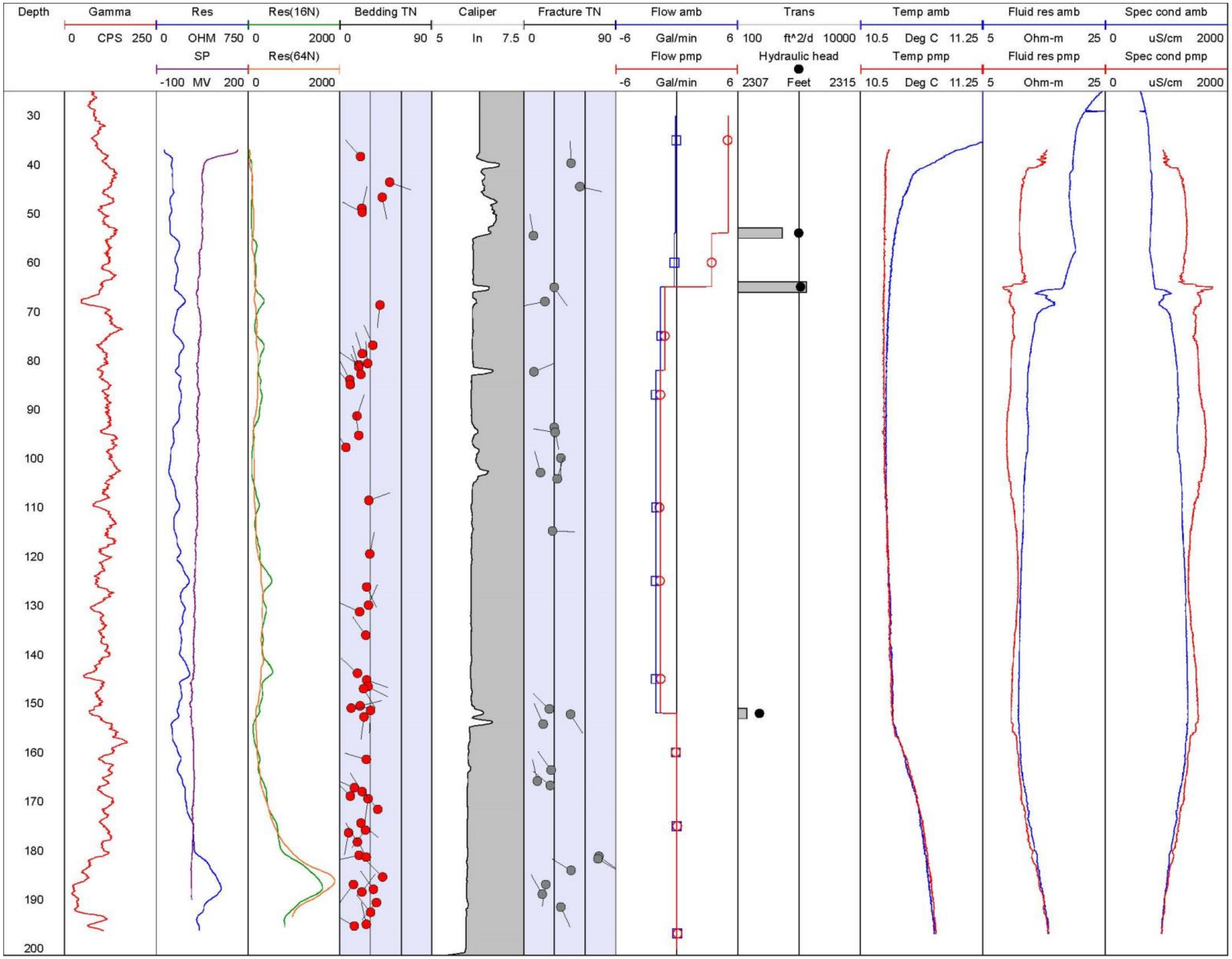
APPENDIX A4. Geophysical logs of well GA Fb 42.



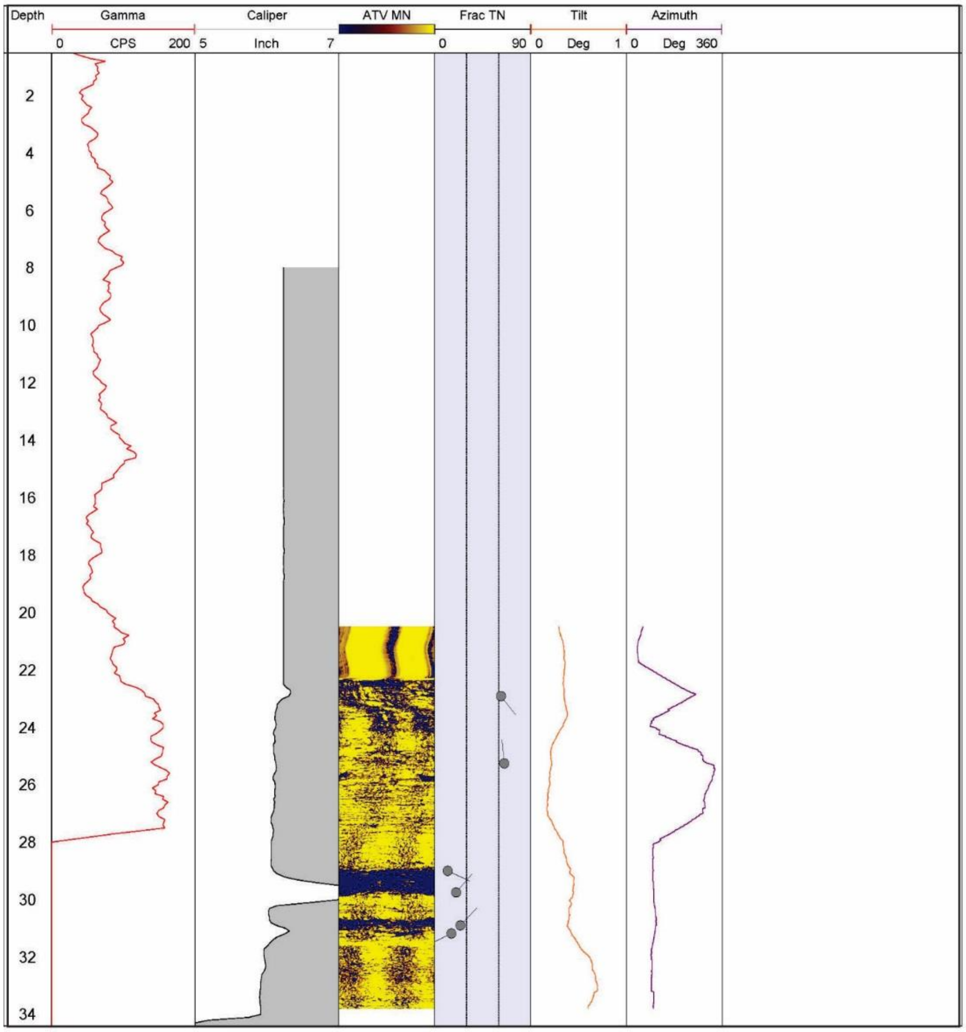
APPENDIX A4, continued



APPENDIX A5. Geophysical logs of well GA Fb 43.



APPENDIX A6. Geophysical logs of well GA Fb 44.



Appendix B. Lithologic description of drill cuttings for test well GA Aa 15, near Friendsville.

Buffalo Run test site
GA Aa 15
Altitude = 1,522 feet

Depth (feet)	Description
Alluvium	
0 – 20	Sand, fine to very fine, boulders, mixed brown (7.5YR 5/4), gray brown (10YR 6/3), and black (Gley 1 2.5/N).
Conemaugh Group (undivided)	
20 – 60	Sandstone, gray (Gley 1 7.5/10Y) and light brownish gray (2.5Y 6/3), with some dark reddish gray (5YR 4/2) from 40 to 50 ft.
60 – 88	Sandstone, dark greenish gray (Gley 1 4/10Y) to greenish black (Gley 1 2.5/10Y)
Allegheny Formation	
88 – 100	Coal, black (Gley 1 2.5/1), and shale, black (Gley 1 2.5/N) **(Upper Freeport Coal)**
100 – 160	Shale, greenish gray (Gley 1 4/10Y), to very dark greenish gray (Gley 1 3/10YN), with reddish-brown shale 129 to 130 ft, with some sandstone , olive gray (5Y 4/2) 108 to 110 ft and 130 to 140 ft; *water bearing zone 108 to 110 ft*.
160 – 180	Shale and siltstone, dark greenish gray (Gley 1 4/10Y) to black (Gley 1 2.5/1); some coal interbedded at 164 ft and 180 to 190 ft.
180 – 230	Sandstone and siltstone, greenish gray (Gley 1 5/5GY) to very dark gray (2.5Y 3/1) and black (Gley 1 2.5/1); interbedded coal layers 220 to 230 ft, with muscovite and pyrite; *water bearing zone 217 to 230 ft.*

Appendix C. Lithologic description of drill cuttings for test well GA Bf 28, near Avilton.

Savage River test site
GA Bf 28
Altitude = 2,588 feet

Depth (feet)	Description
Alluvium	
0 – 30	Sand, silt, pebbles, very pale brown (10YR 7/3) and dusky red (10R 3/2).
Hampshire Formation	
30 – 65	Shale, soft, dark reddish brown (5YR 3/2).
65 – 75	Sandstone, soft, dark grayish brown (2.5Y 3/2)
75 – 140	Shale, very dark reddish brown (2.5Y 3/2) to dark reddish gray (2.5YR 3/1).
140 – 208	Sandstone, mostly dark grayish brown (10YR 4/2) and reddish black (2.5YR 2.5/1) with some dark grayish green (G1 3/1).
208 – 225	Sandstone, dusky red (10YR 3/2), silty, poorly indurated.
225 – 285	Sandstone, dark reddish brown (5YR 3/2) with varying amounts of greenish gray (Gley 1 6/10 Y) and dark brown (7.5YR 3/2); well indurated.
285 – 370	Sandstone, some siltstone, dark reddish brown (5YR 3/2) and dark reddish gray (2.5YR 3/1).
370 – 410	Shale, some sandstone, dusky red (10 R 3/3) with minor greenish gray (Gley 1 5/1); micaceous.
410 – 418	Sandstone, gray (10YR 5/1).
418 – 465	Sandstone, siltstone, dusky red (10R 3/2), with varying amounts of greenish gray (Gley 1 5/5 GY).
465 – 525	Sandstone, siltstone, dusky red (10R 3/2), and dark reddish gray (2.5YR 3/1), and weak red (10R 4/3), micaceous.
525 – 795	Sandstone, dusky red (10R 3/3), and dark reddish gray (10R 3/1) and some dark greenish gray (Gley 1 4/10 GY); micaceous.

Appendix C (continued)

795 – 820	Sandstone, dark greenish gray (Gley 4/10 G/Y) and dark reddish gray (10R 3/1).
820 – 840	Shale, siltstone, dark greenish gray (Gley 1 4/10 GY) with some (30%) sandstone, as above.
840 – 905	Sandstone, dark greenish gray (Gley 1 4/10 GY) and dark reddish gray (Gley 1 4/10 GY)
905 – 985	Sandstone, dusky red (10R 3/2) and dark reddish gray (10R 3/1), and some dark greenish gray (Gley 1 4/10 GY); micaceous.

Appendix D. Lithologic description of drill cuttings for test well GA Fb 42, at Gorman.

Nydegger Run test site
GA Fb 42
Altitude = 2,330 feet

Depth (feet)	Description
Alluvium	
0 – 10	Clay, sand, rounded pebbles, olive brown (2.5Y 4/3).
Conemaugh Group (undivided)	
10 – 149	Siltstone, sandstone, and shale, greenish gray (Gley 1 6/10Y), dark greenish gray (Gley 1 4/5GY) to black (Gley 1 2.5/N), with faint bedding; micaceous; coal seams 17-20 ft, 90-92 ft, with sparse pyrite; thin (1-2 mm) beds of calcite-cemented sandstone 45-82 ft.
149 – 160	Sandstone, calcite-cemented, greenish-gray (Gley 1 5/10Y), with common blebs of pyrite and iron oxide; interbedded with sandstone (silica-cemented), dark greenish gray (Gley 1 4/5GY); large (up to 230 mm) fragments of calcite-cemented sandstone with solution edges.
160 – 180	Sandstone, greenish gray (Gley 1 5/10Y) to very dark greenish gray (Gley 1 3/10Y), with some siltstone, black (Gley 1 2.5/1)
180 – 198	Sandstone, dark gray (5Y 4/1), medium-grained
Allegheny Formation	
198 – 235	Coal, black (Gley 1 2.5/1), with common pyrite, and siltstone, shale, very dark greenish gray (Gley 1 3/10Y) with some black shale (Gley 1 2.5/N) **(Upper Freeport Coal)**
235 – 245	Shale, greenish gray (Gley 1 6/10Y), grayish brown (2.5Y 5/2), and greenish black (Gley 1 2.5/N).
245 – 320	Sandstone, greenish gray (Gley 1 5/10Y) to black (Gley 1 2.5N).
320 – 387	Siltstone, greenish black (Gley 1 2.5/10Y) to black (Gley 1 2.5N), micaceous.

Appendix D (continued)

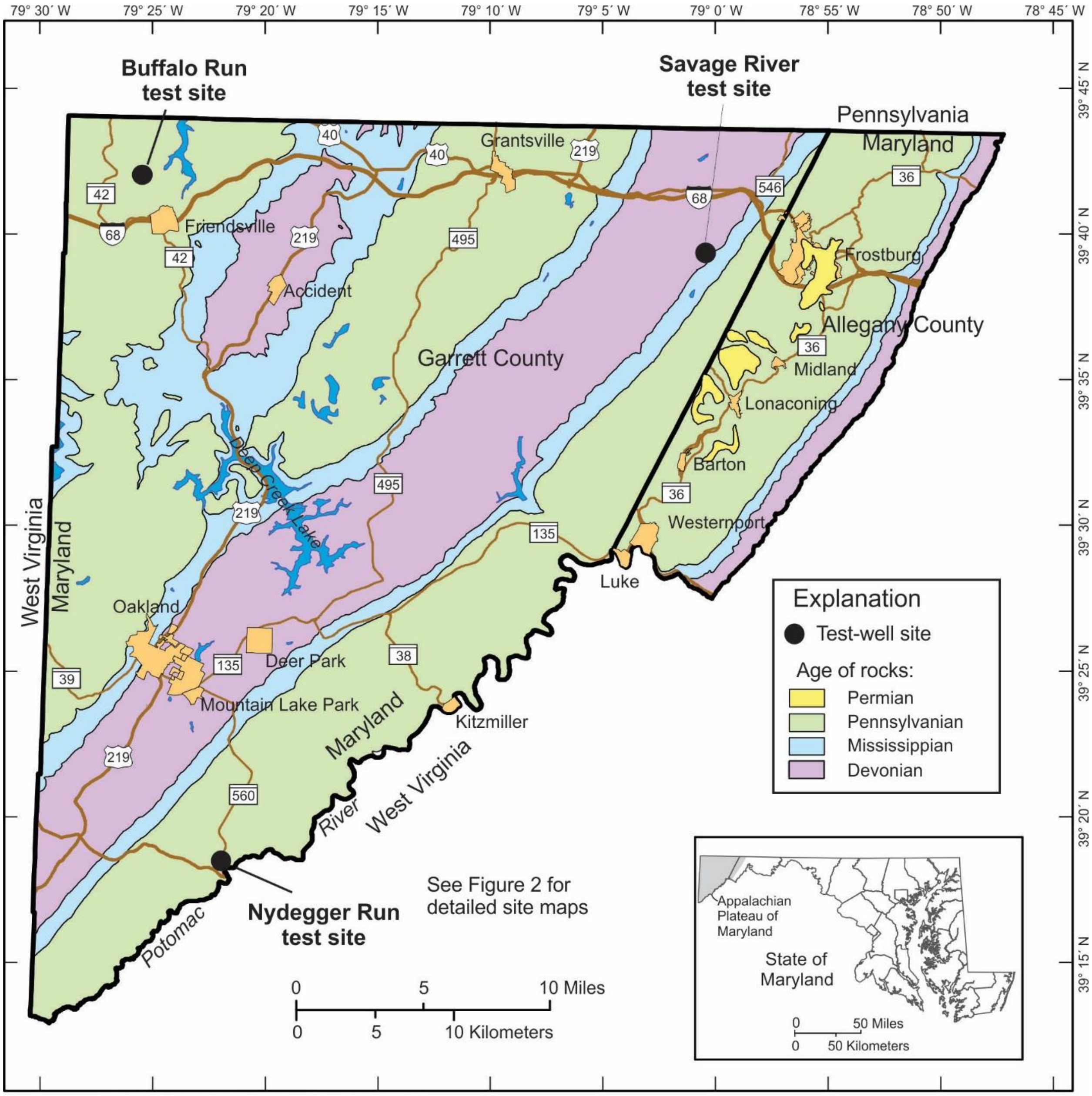
387 – 443	Sandstone, dark gray (Gley 1 4/N) to very dark greenish gray (Gley 1 3/10Y), well indurated, poorly sorted, with some coarse pebbles; black coal partings; a few fragments of calcite-cemented sandstone, olive gray (5Y 5/2).
443 – 468	Shale, black (Gley 1 2.5/N) interbedded with some (10-30%) sandstone, as above.

Pottsville Formation

468 – 490	Sandstone, siltstone, dark greenish gray (Gley 1 4/10Y) to black (Gley 1 2.5/N)
490 – 628	Sandstone, dark greenish gray (Gley 1 4/N) to black (Gley 1 2.5/N). fine to coarse-grained with siltstone and some shale; micaceous.
628 – 664	Shale, siltstone, black (Gley 2.5/N), some (2%) coal
664 – 837	Sandstone, light greenish gray (Gley 1 7/10Y), gray (2.5 Y 5/1) to black (Gley 1 2.5/N), medium to coarse-grained, with some siltstone, shale, very dark greenish gray (Gley 1 3/N), and coal

Mauch Chunk Formation

837 – 985	Shale, siltstone, mottled dusky red (2.5YR 3/2) and dark greenish gray (Gley 1 4/10Y); rare pyritized sandstone grains



Base map modified from USGS Digital Line Graph 1:250,000

Figure 1. Generalized geology of the Appalachian Plateau and locations of test-well sites.

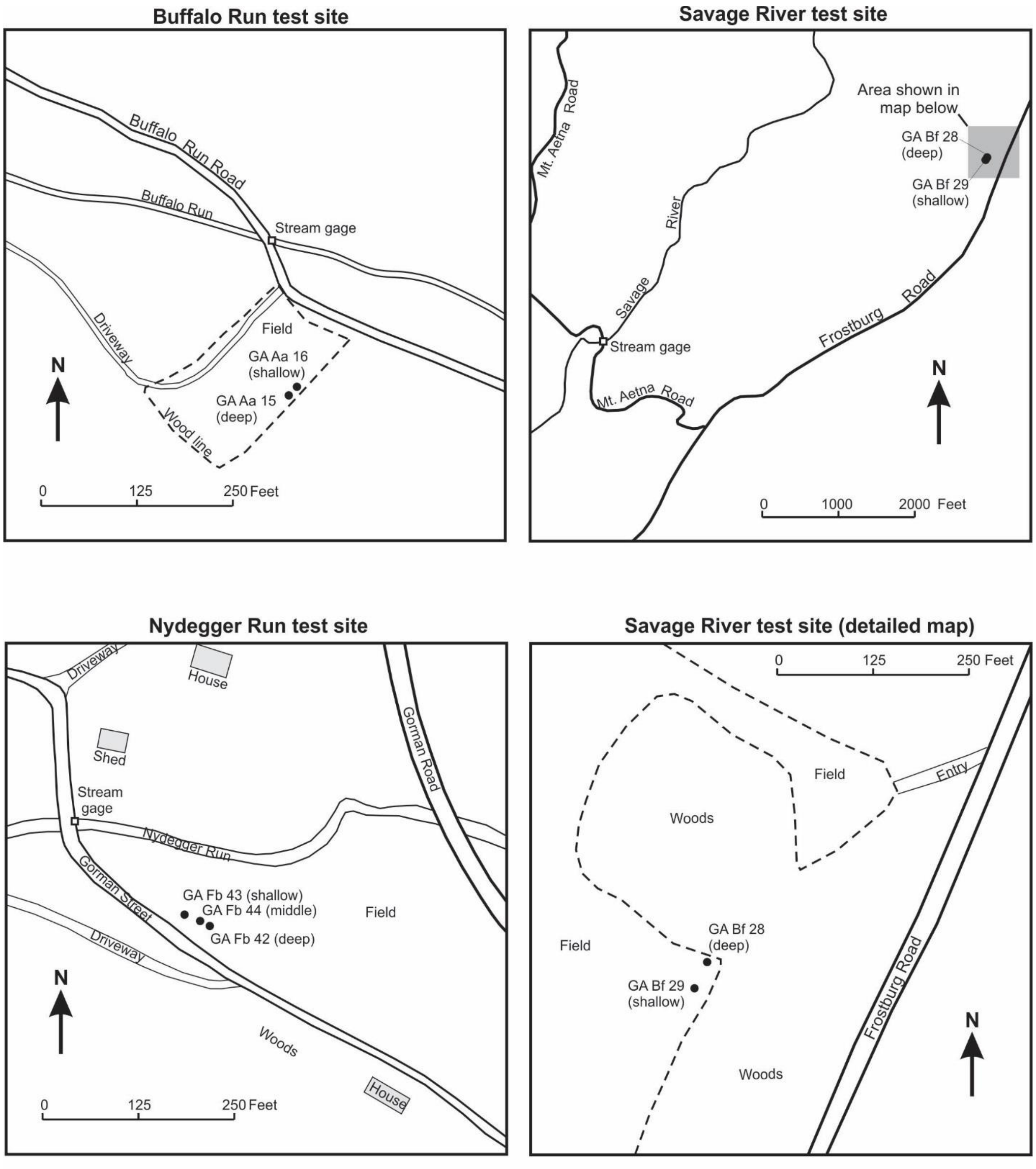
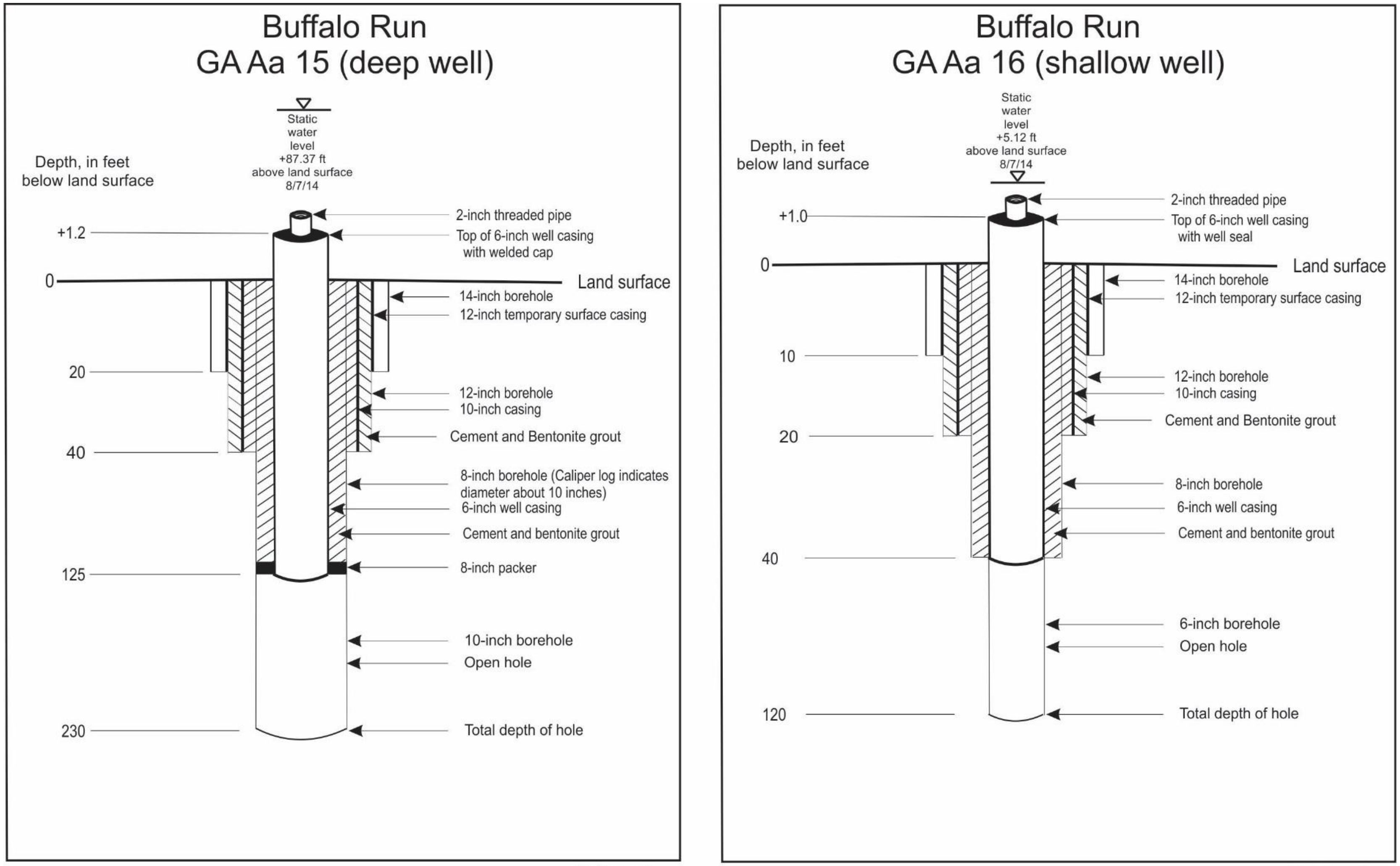


Figure 2. Details of the test-well sites.



Not to scale

Not to scale

Figure 3. Construction schematic diagrams for test wells GA Aa 15 (deep) and GA Aa 16 (shallow) at the Buffalo Run test site.

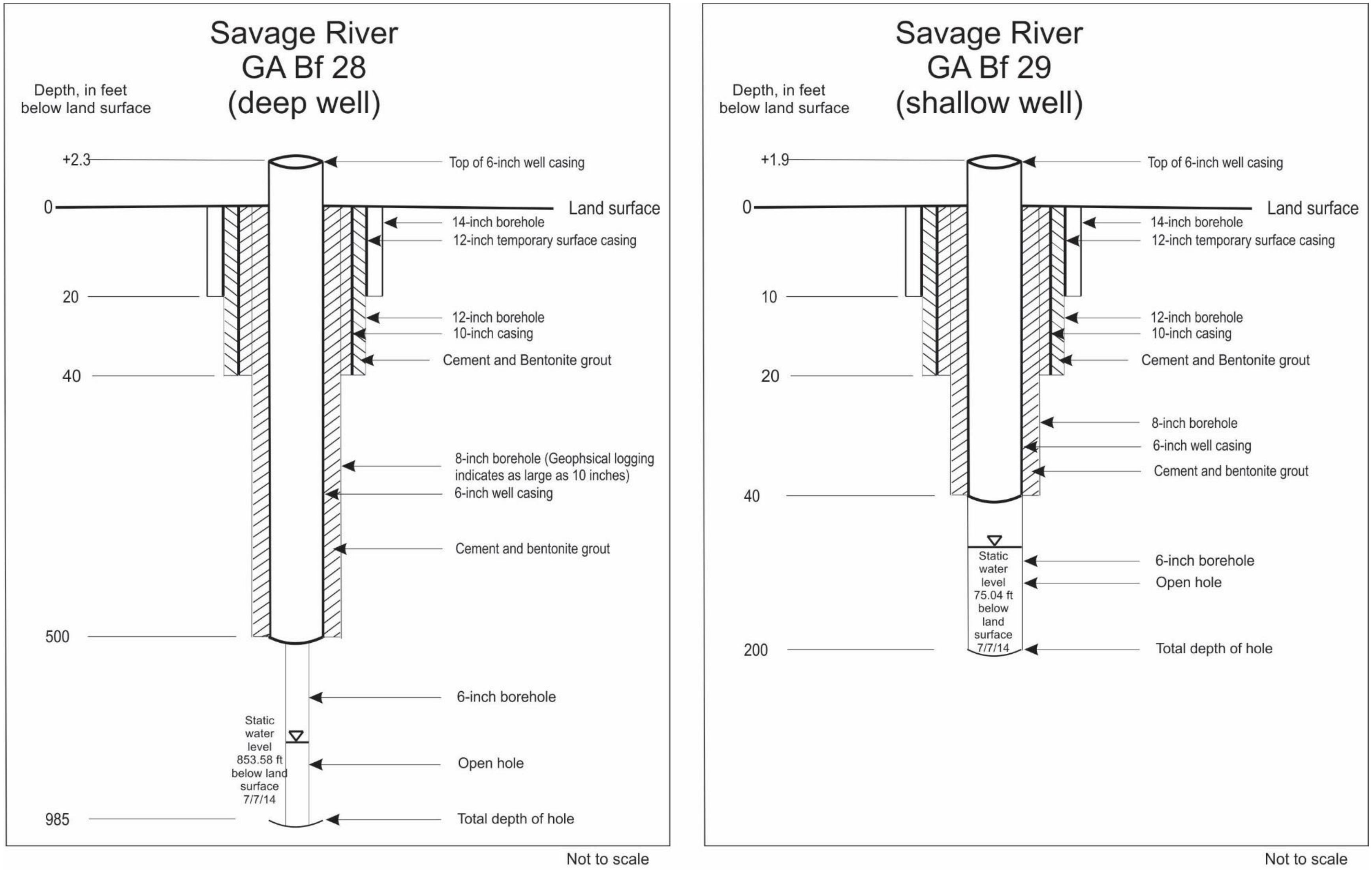


Figure 4. Construction schematic diagrams for test wells GA Bf 28 (deep) and GA Bf 29 (shallow) at the Savage River test site.

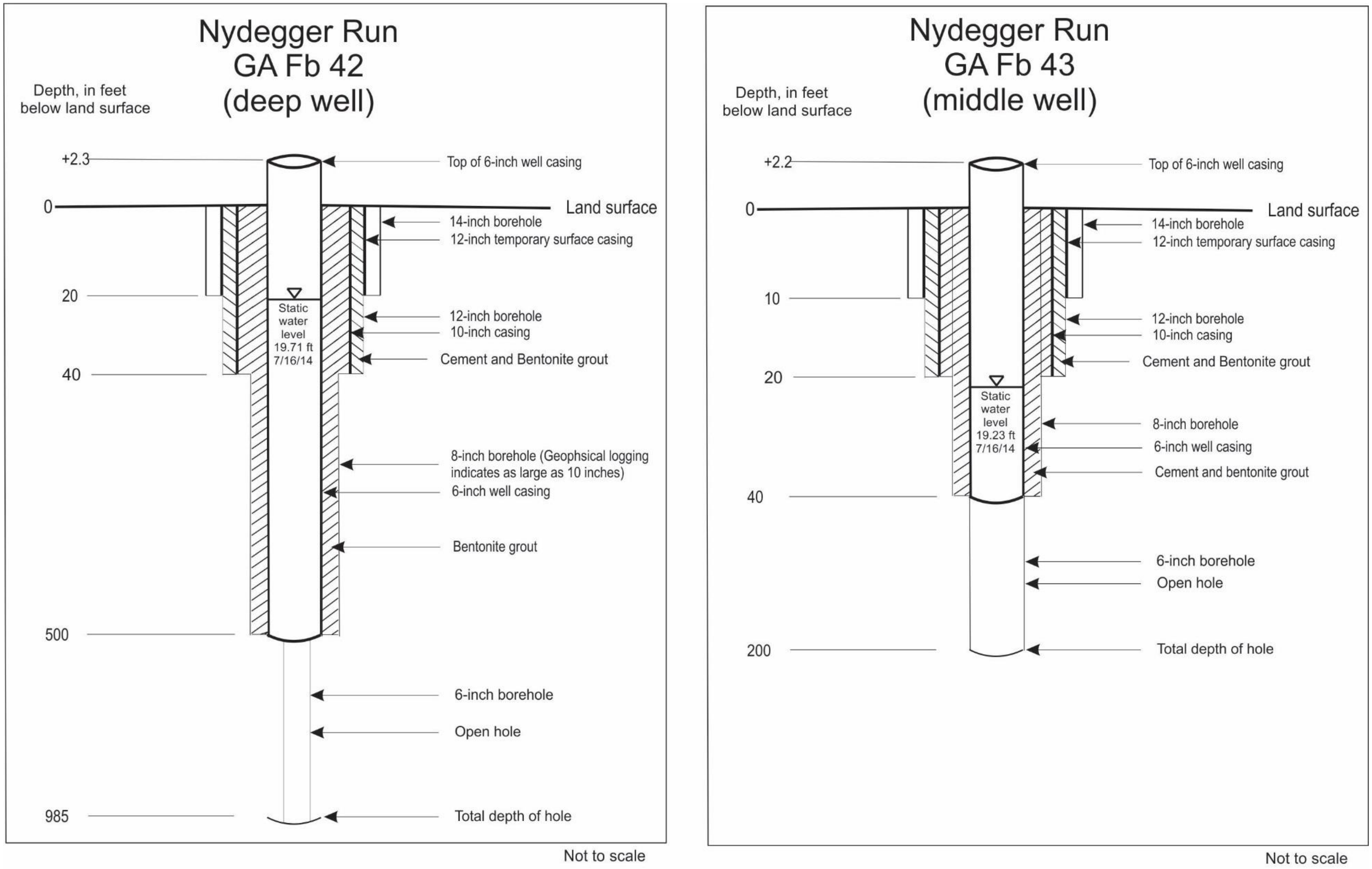


Figure 5. Construction schematic diagrams for test wells GA Fb 42 (deep), GA Fb 43 (middle), and GA Fb 44 (shallow) at the Nydegger Run test site.

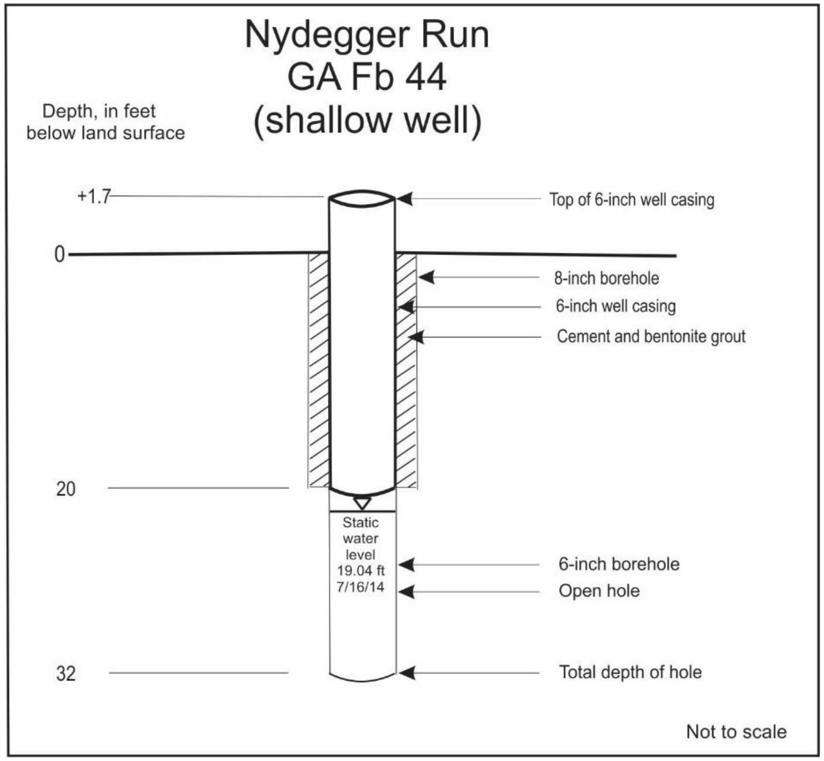


Figure 5, continued.

Figure 6. Flowing-well conditions for well GA Aa 15 (Deep well) at the Buffalo Run test site (May 19, 2014).

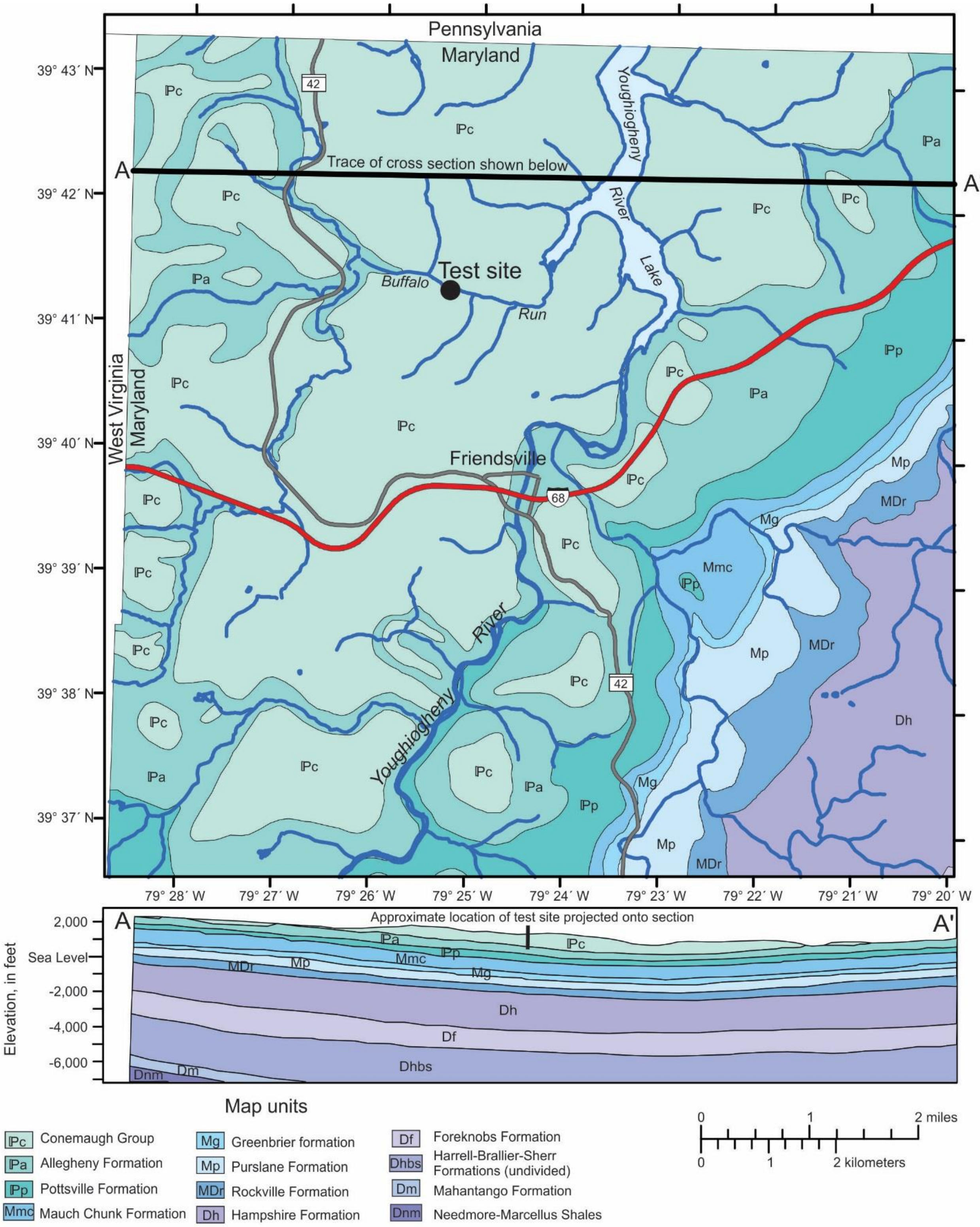
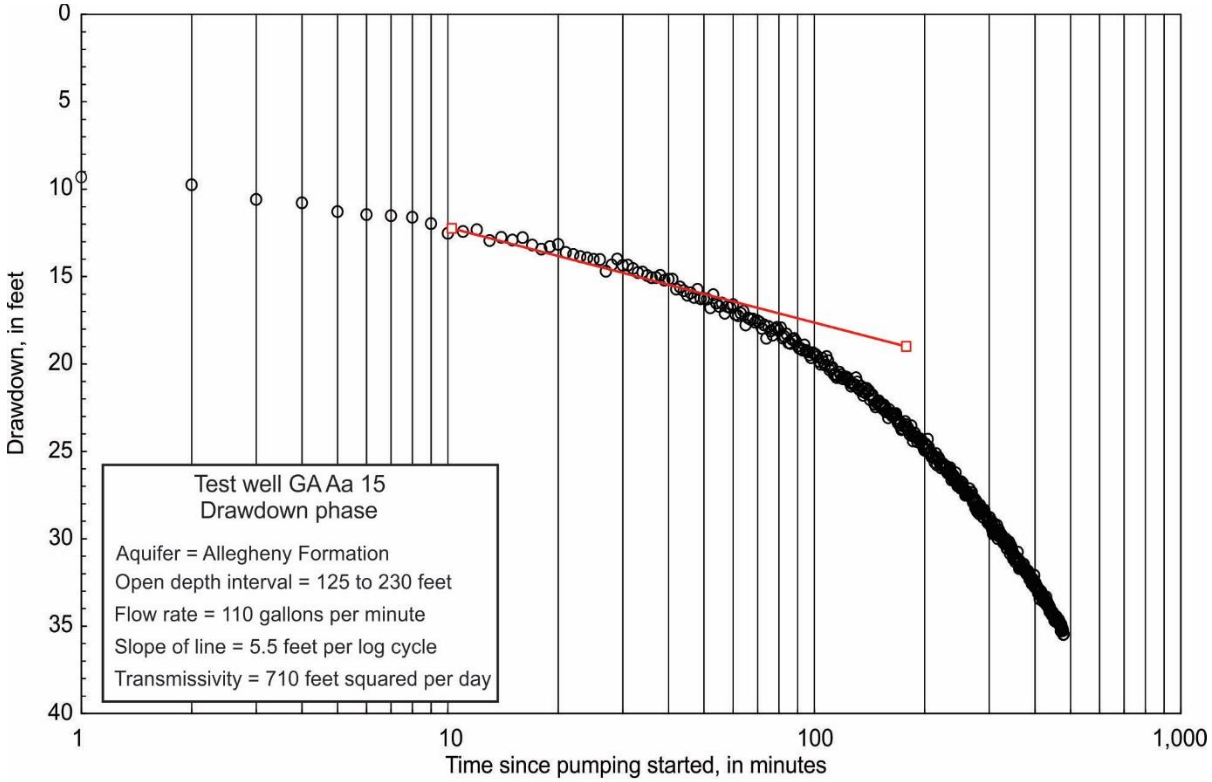


Figure 7. Geologic map and cross section of the Buffalo Run test site. Modified from Brezinski and Conkwright (2013).



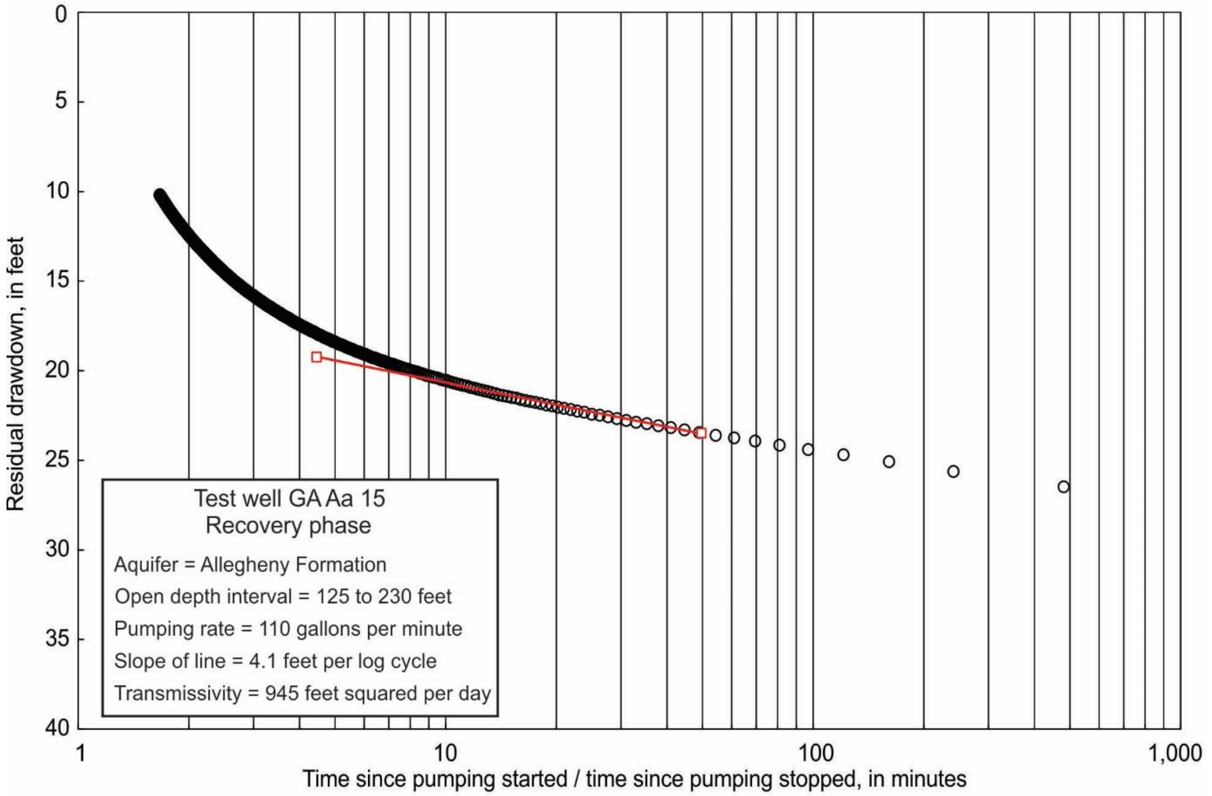


Figure 8. Drawdown data, recovery data, and transmissivity values from aquifer test of well GA Aa 15 (deep) at the Buffalo Run test site.

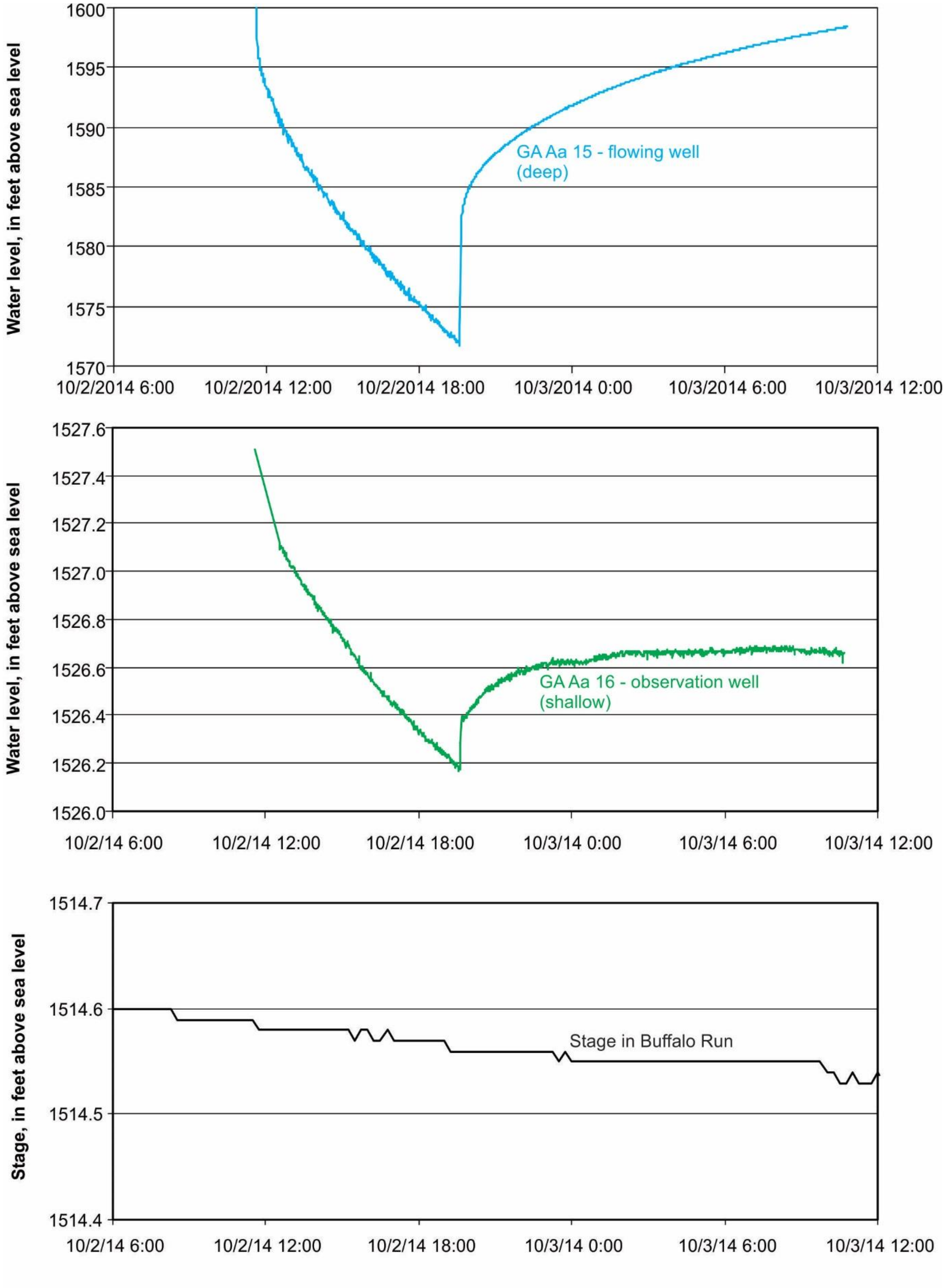


Figure 9. Hydrographs showing water levels in the flowing and observation wells and stage in Buffalo Run during the aquifer test of well GA Aa 15 (deep).

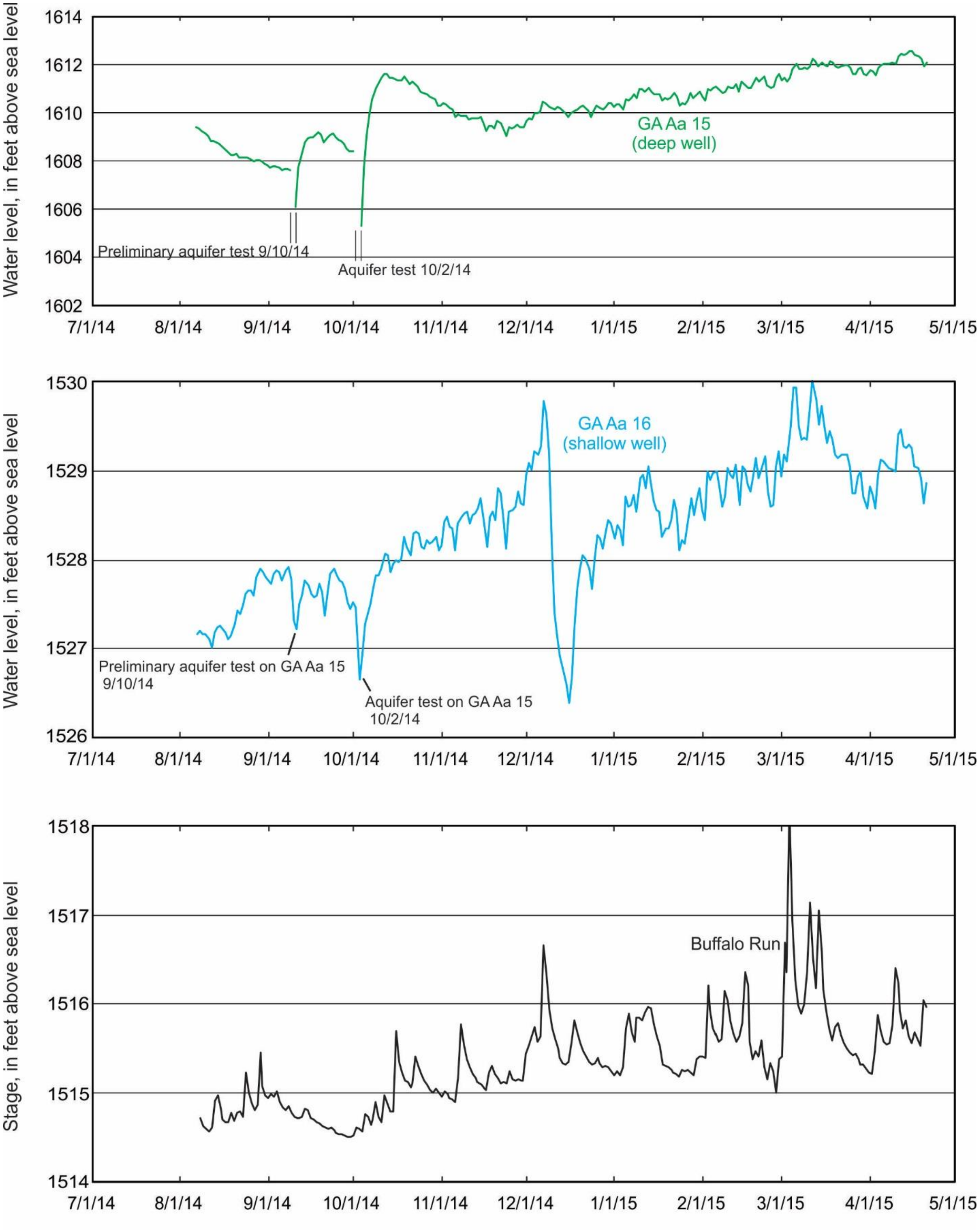


Figure 10. Hydrographs showing daily mean water levels in test wells and the stream gage at the Buffalo Run test site, from July 2014 to April 2015.

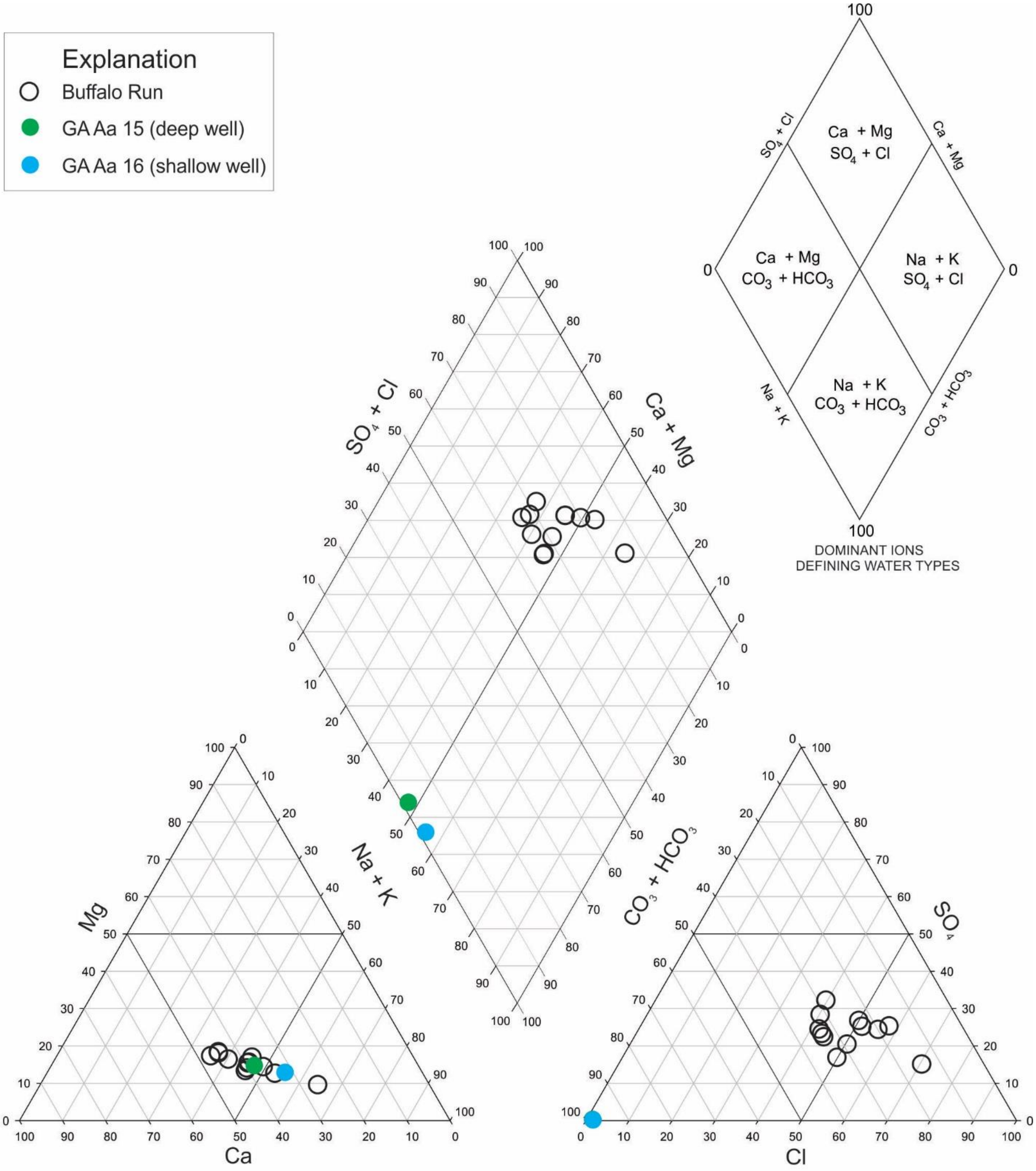


Figure 11. Piper diagram showing hydrochemical facies in groundwater and stream water at the Buffalo Run test site.

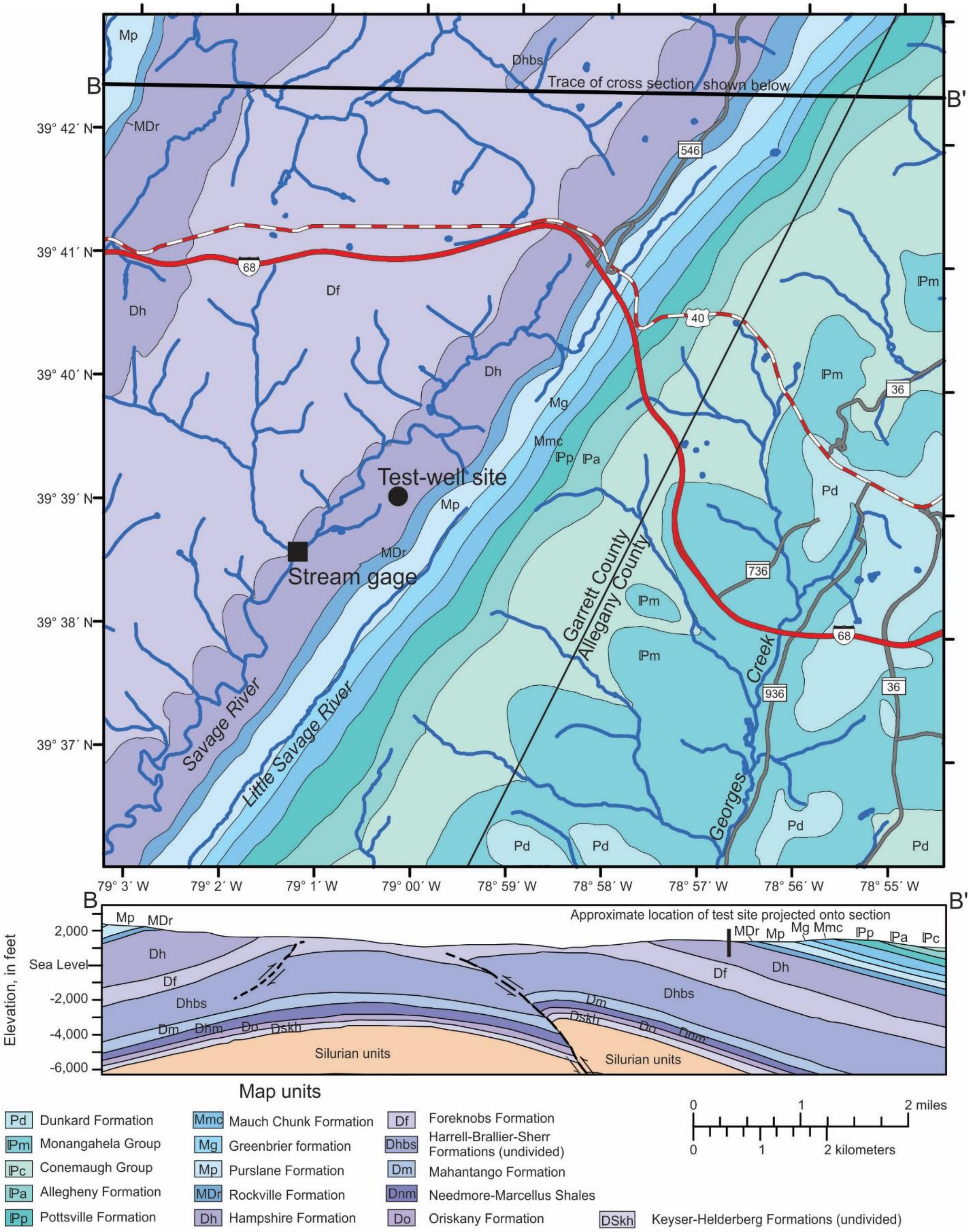


Figure 12. Geologic map and cross section of the Savage River test site. Modified from Brezinski and Conkwright (2013).

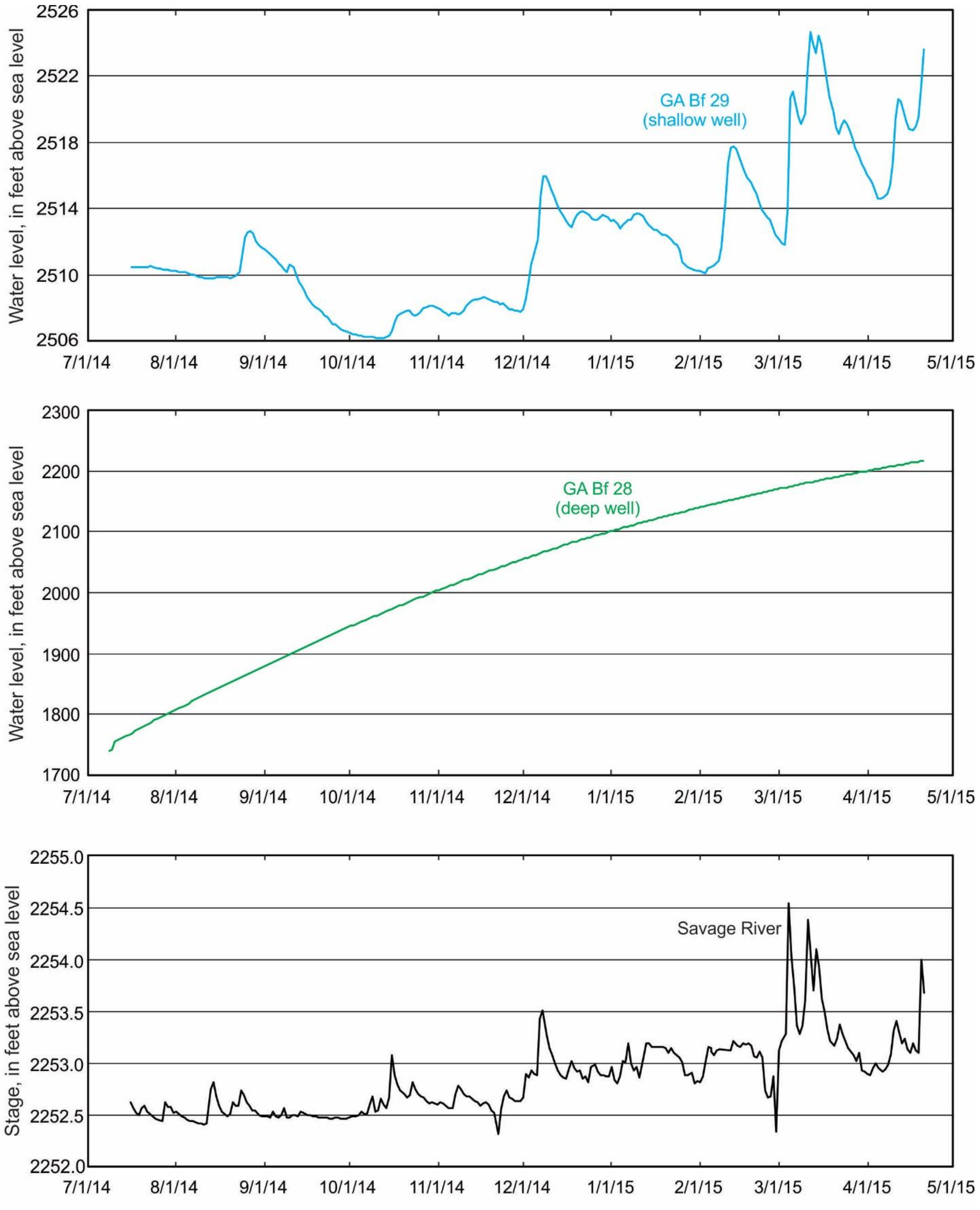


Figure 13. Hydrographs showing daily mean water levels in test wells and the stream gage at the Savage River test site, from July 2014 to April, 2015.

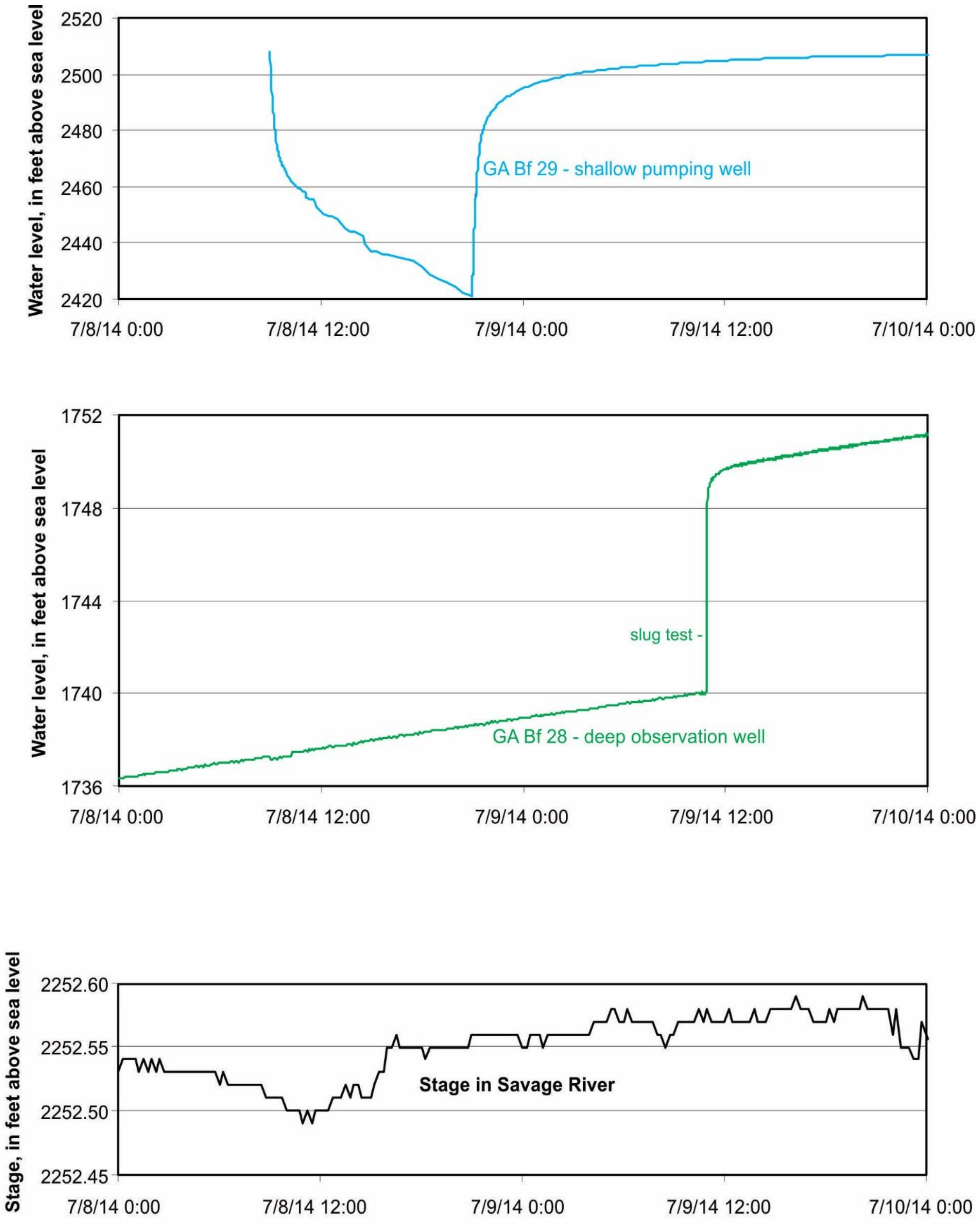


Figure 14. Hydrographs showing water levels in the pumping and observation wells and stage in Savage River during the aquifer test of well GA Bf 29 (shallow).

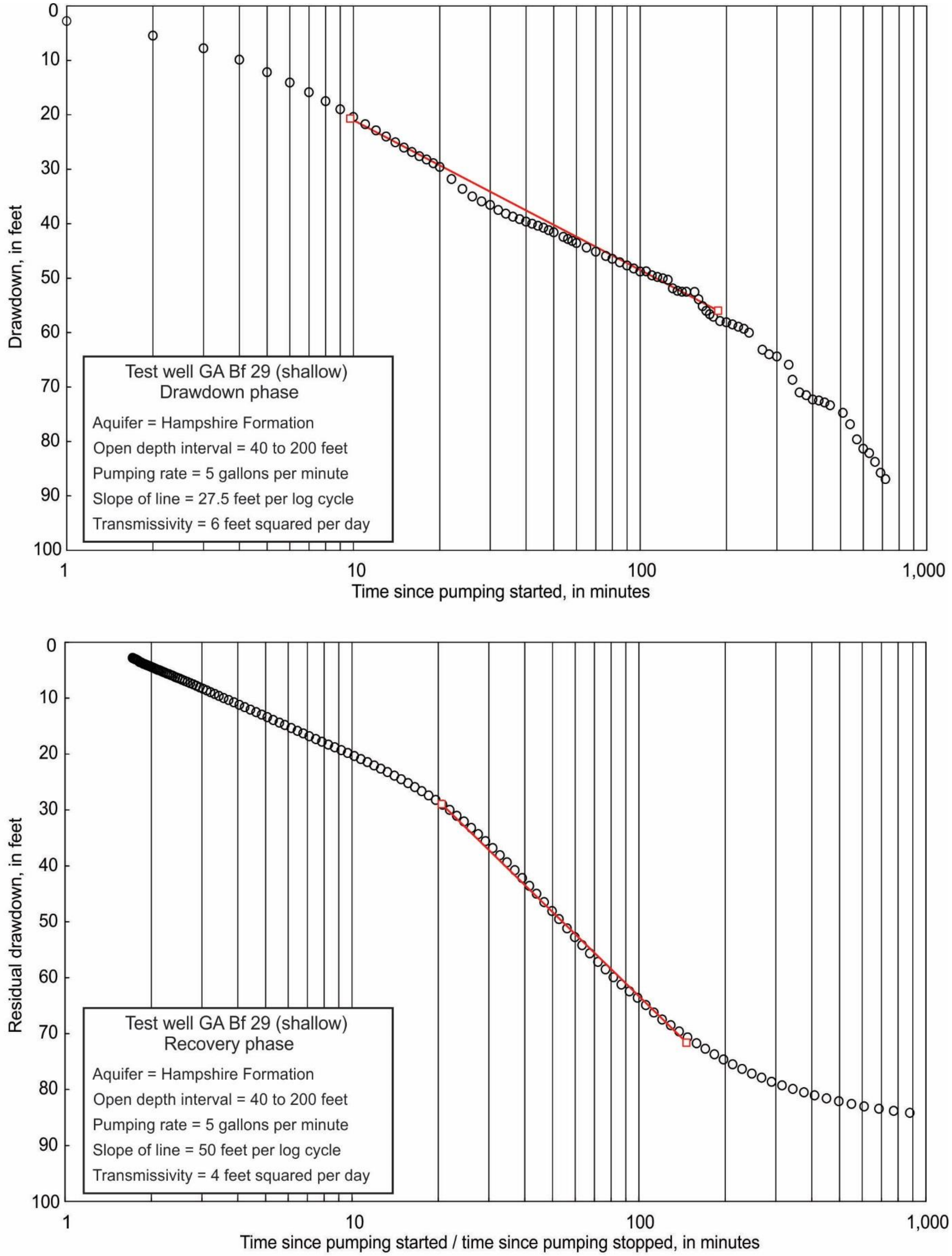


Figure 15. Drawdown data, recovery data, and transmissivity values from aquifer test of well GA Bf 29 (shallow) at the Savage River test site.

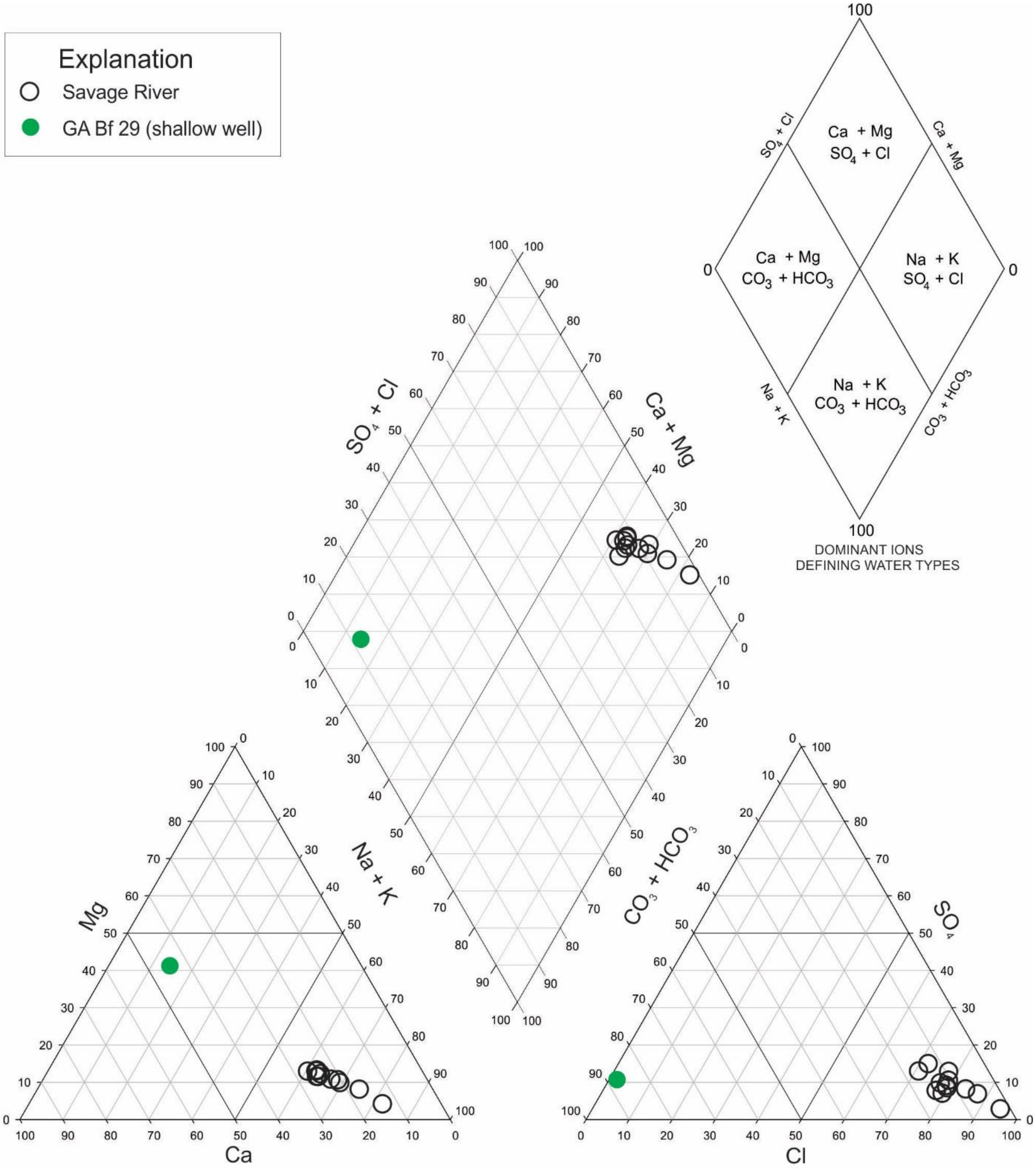


Figure 16. Piper diagram showing hydrochemical facies in groundwater and stream water at the Savage River test site.

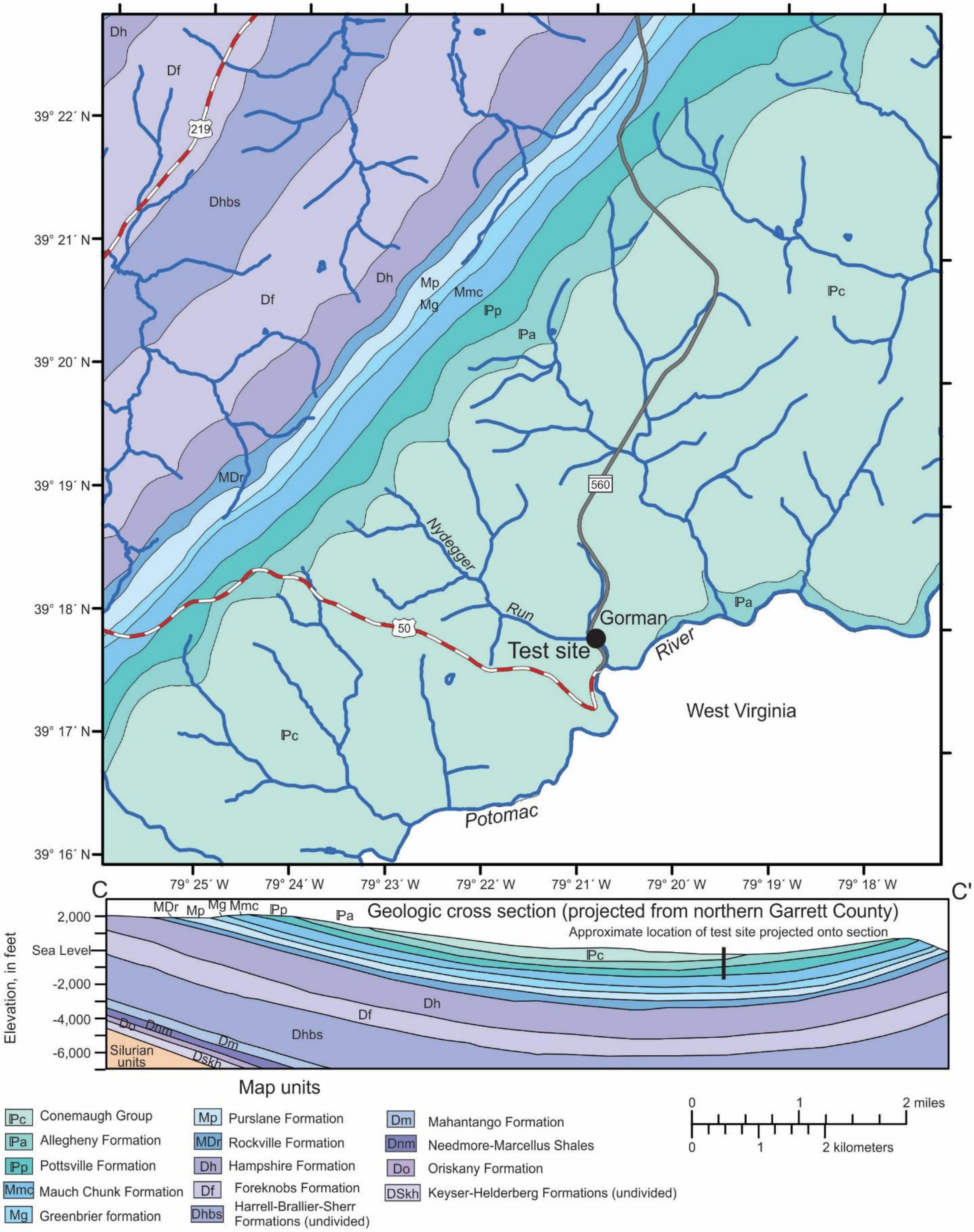


Figure 17. Geologic map and cross section of the Nydegger Run test site. Modified from Brezinski and Conkwright (2013).

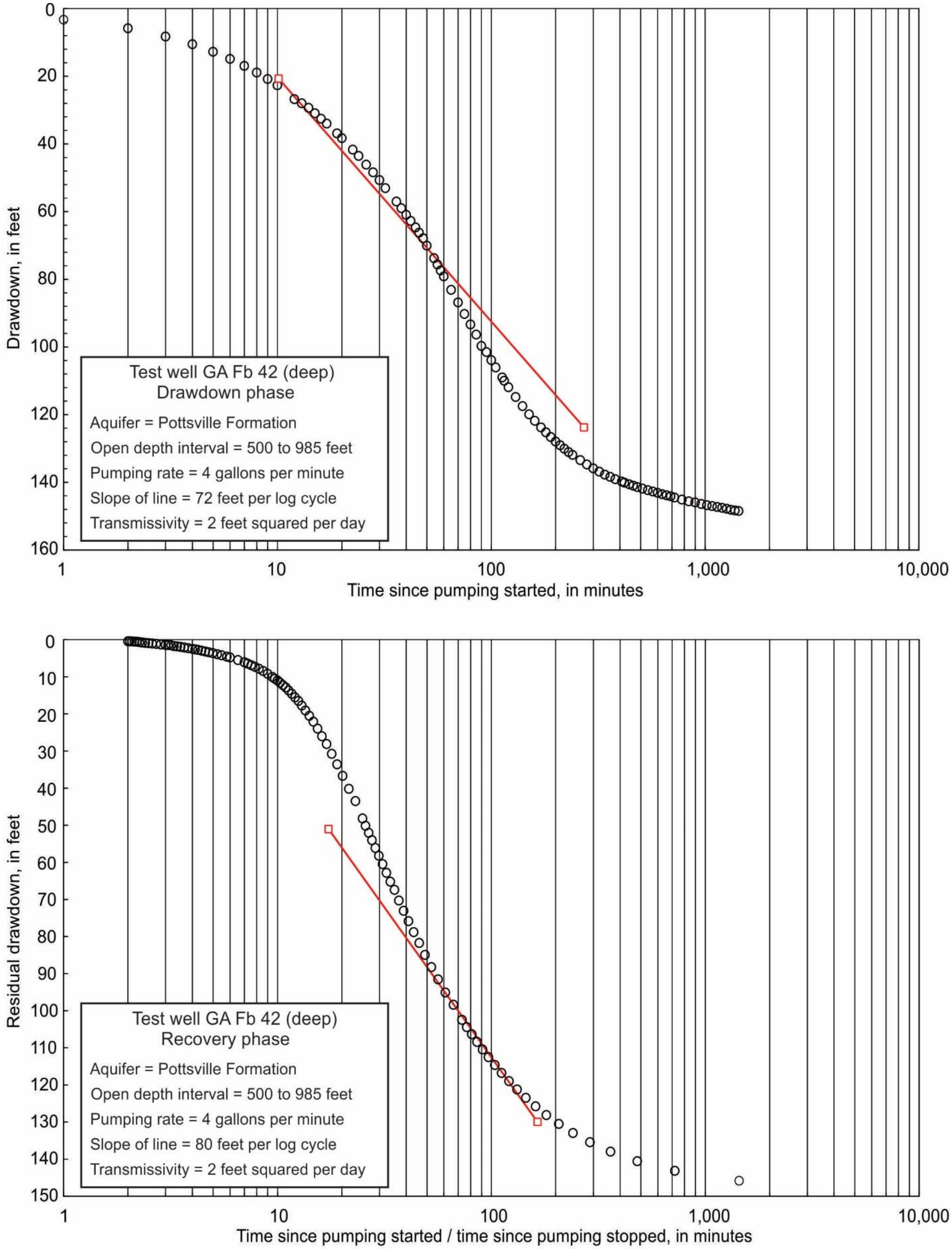


Figure 18. Drawdown data, recovery data, and transmissivity values from aquifer test of well GA Fb 42 (deep) at the Nydegger Run test site.

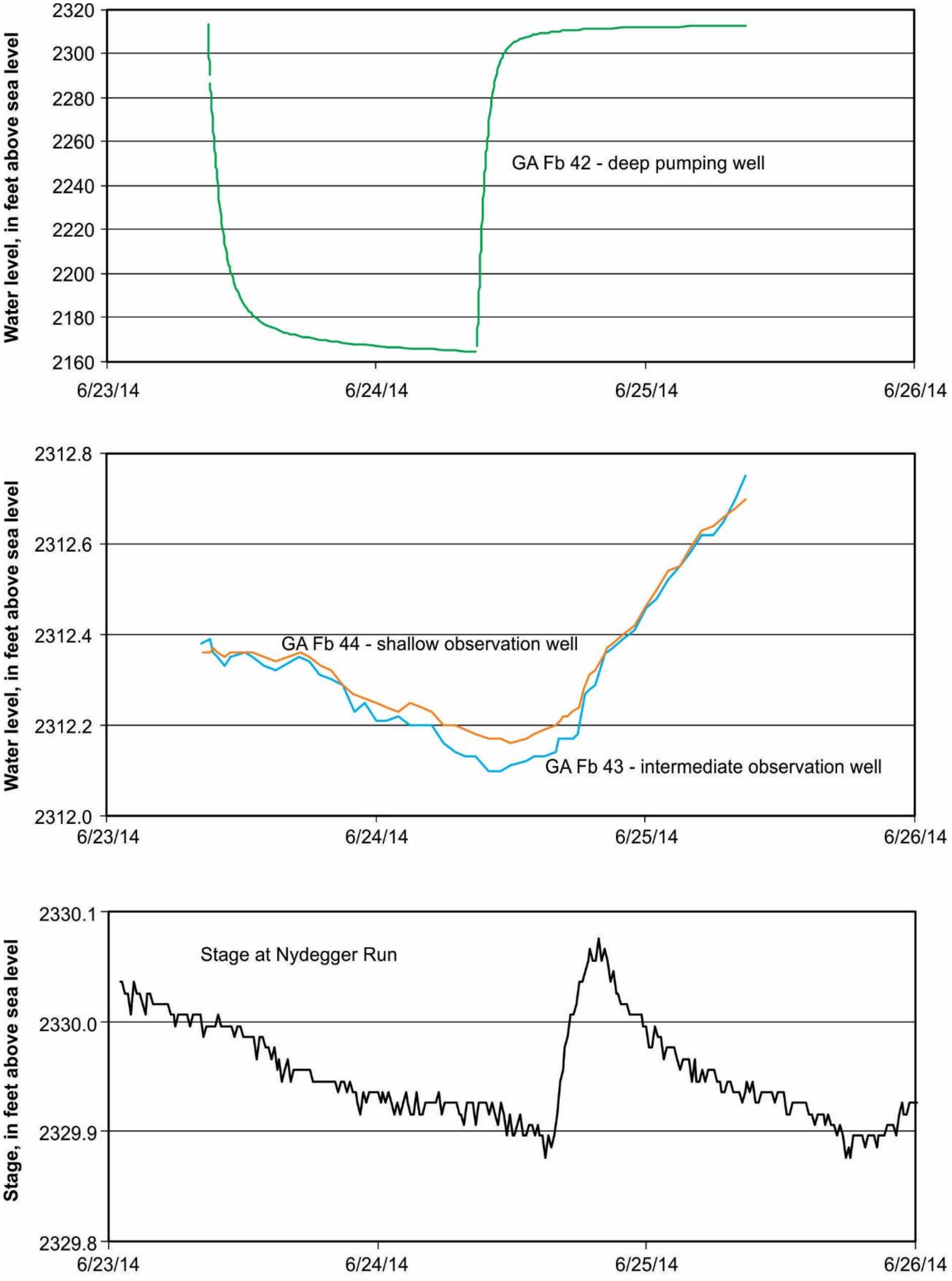


Figure 19. Hydrographs showing water levels in the pumping and observation wells and stage in Nydegger Run during the aquifer test of well GA Fb 42 (deep).

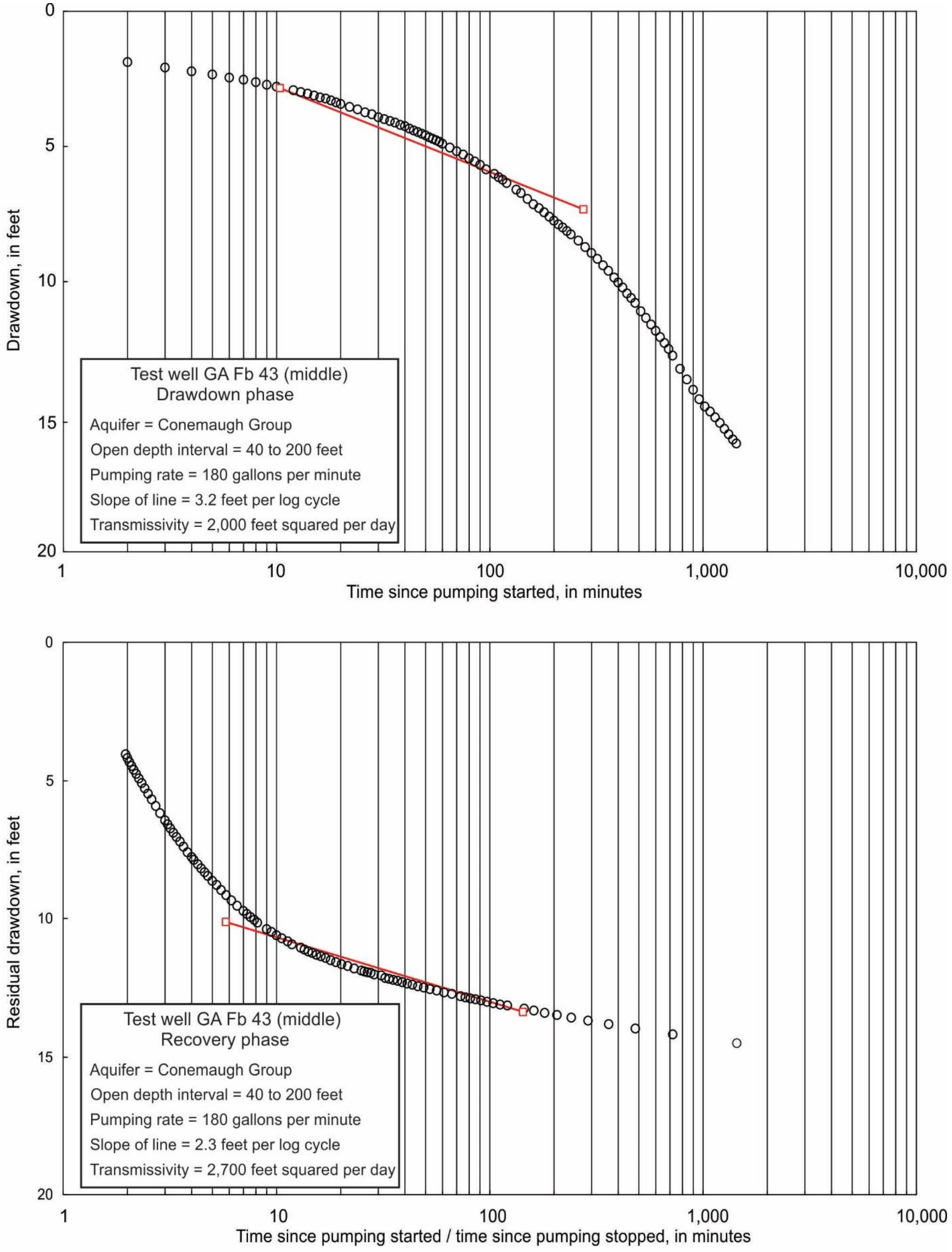


Figure 20. Drawdown data, recovery data, and transmissivity calculations for aquifer test of well GA Fb 43 (middle) at the Nydegger Run test site.

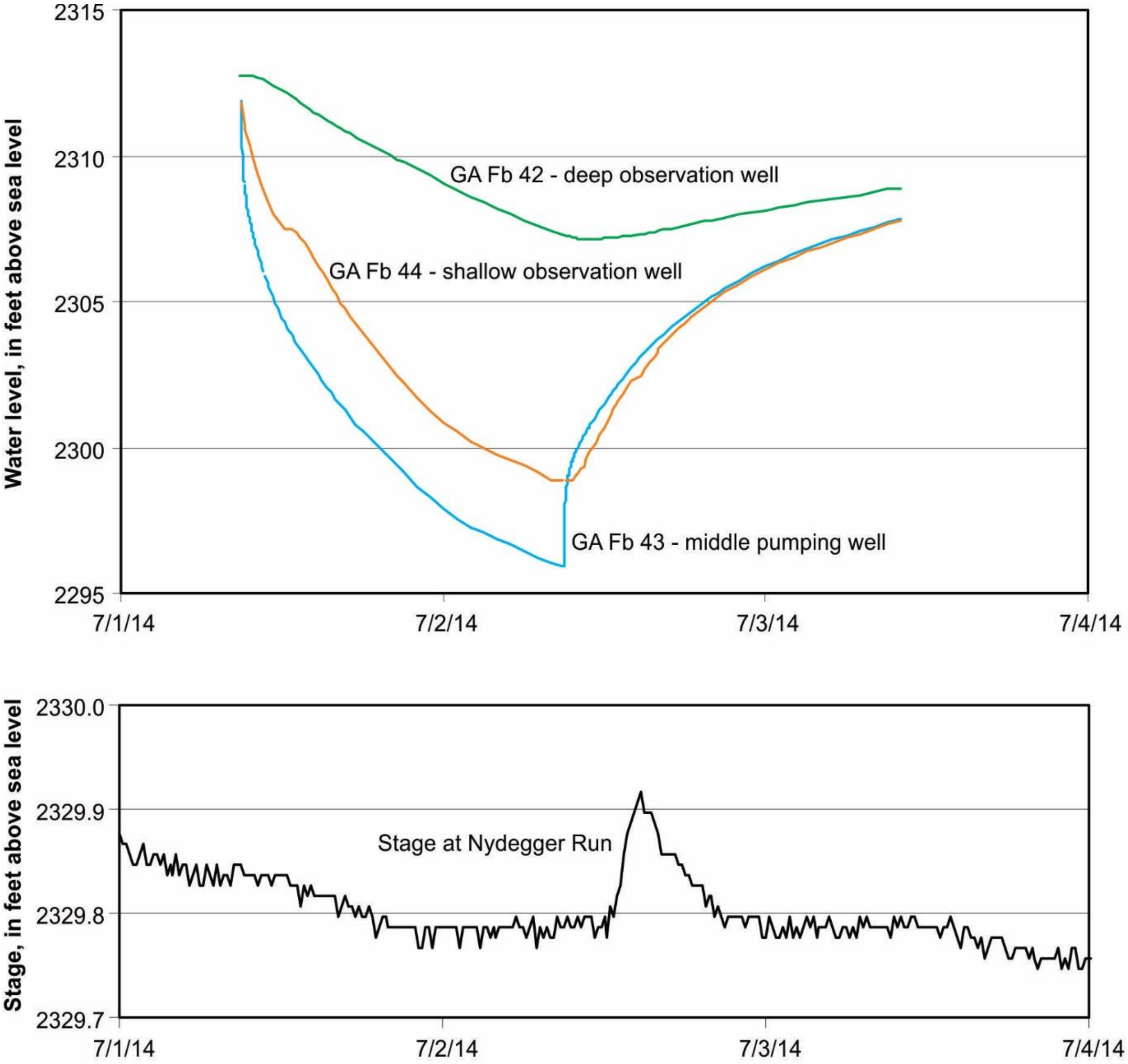


Figure 21. Hydrographs showing water levels in the pumping and observation wells and stage in Nydegger Run during the aquifer test of well GA Fb 43 (middle).

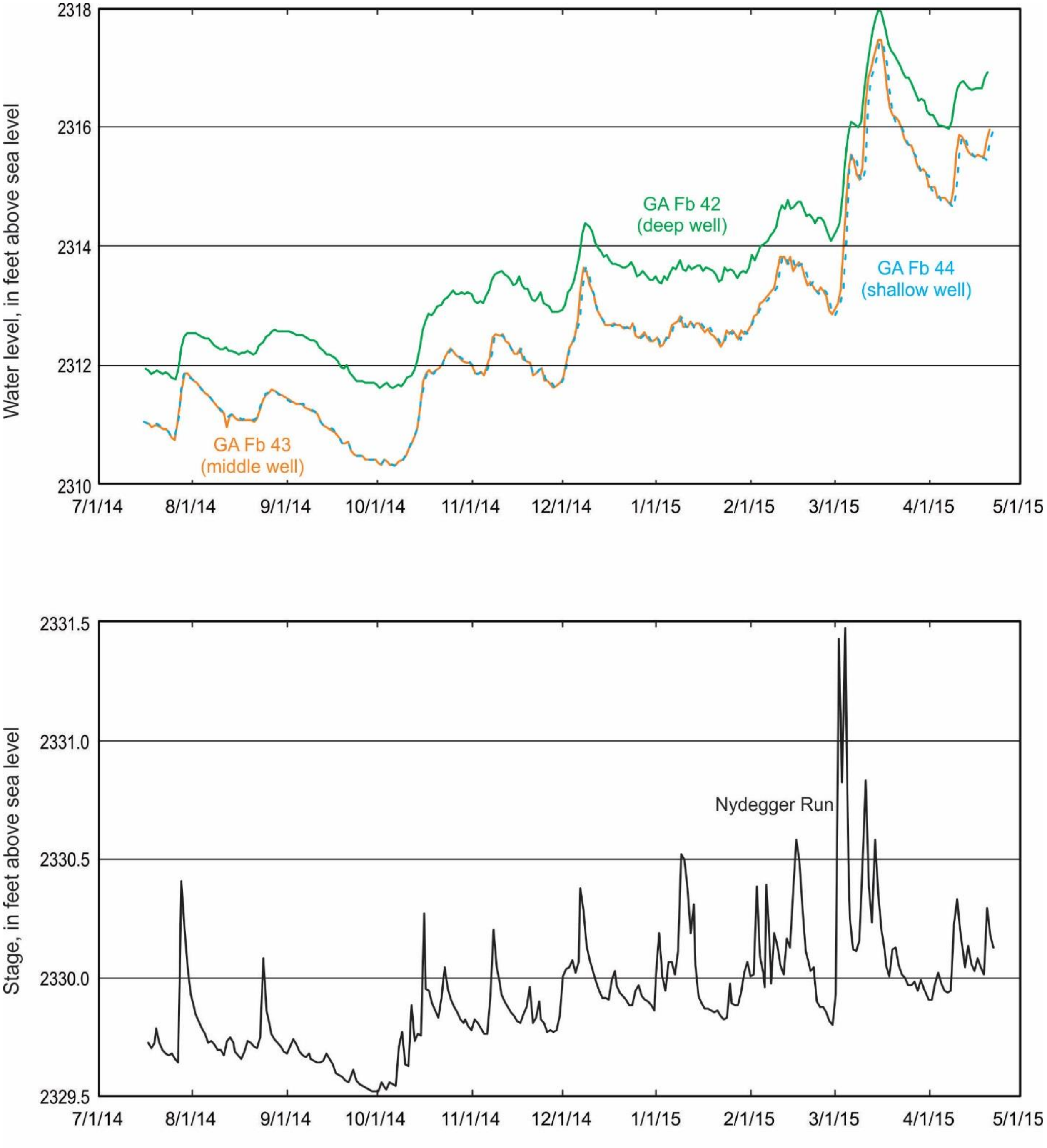


Figure 22. Hydrographs showing daily mean water levels in test wells and the stream gage at the Nydegger Run test site, from July 2014 to April, 2015.

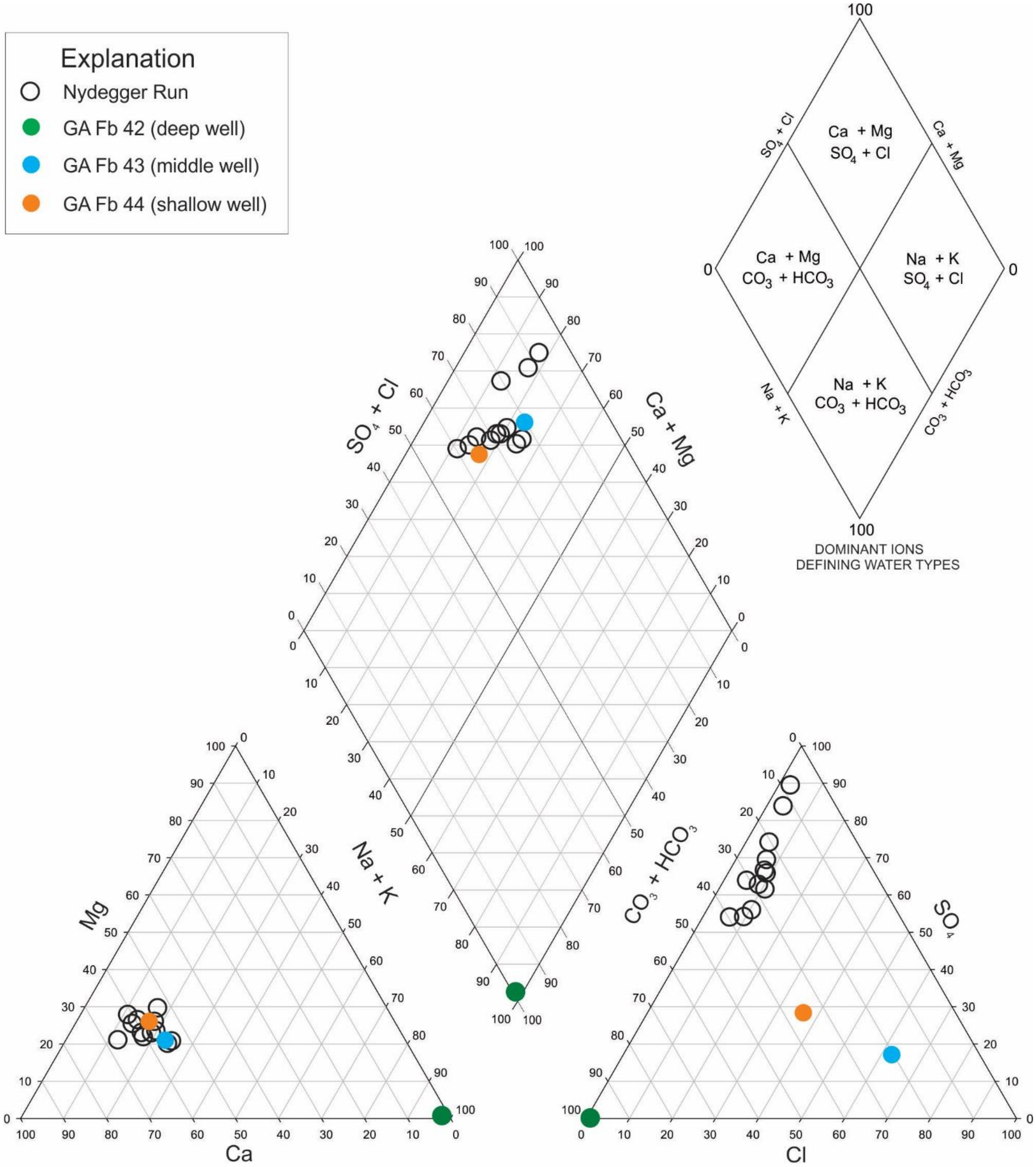


Figure 23. Piper diagram showing hydrochemical facies in groundwater and stream water at the Nydegger Run test site.

Table 1. Description of geologic formations in the study area. Adapted from Brezinski and Conkwright (2013).

Quaternary	**Alluvium** Unconsolidated reddish brown to tan, sand, silt, pebbles and cobbles that weathers yellow, orange, and orange-brown. Mapped alluvium deposits include those formed along modern and ancient streams, and marsh deposits formed over older bog deposits.
Permian?	**Dunkard Formation** Interbedded, medium gray to dark gray, carbonaceous, silty shale and siltstone; light to medium gray, micaceous, medium- to coarse-grained sandstone; and thin, discontinuous nodular limestone, and thin coal beds. The Dunkard Formation caps several hills in the Georges Creek Syncline, and may be as much as 250 feet (76 m) thick.
Pennsylvanian	**Monongahela Group** Interbedded, medium gray to dark gray, carbonaceous, silty shale and siltstone; light to medium gray, micaceous, medium- to coarse-grained sandstone, and thin, discontinuous, nodular limestone, and coal beds. The thickness of the Monongahela Group is 225 to 250 feet (68 to 76 m).
	Conemaugh Group (Undivided) Interbedded, light gray, micaceous sandstone and gray silty shale and thin, dark gray, marine shales in the lower half of the group, and greenish-gray and reddish brown to variegated mudstone, shale, claystone, and nodular nonmarine limestone in its upper part. The Conemaugh Group is 800 to 900 feet thick (245 to 275 m).
	Allegheny Formation Interbedded, medium to dark gray shale and siltstone, tan to light gray sandstone, claystone, and mineable coal beds. The Allegheny Formation is between 200 to 250 feet thick (61 to 76 m).
	Pottsville Formation Dominantly light gray to tan, medium- to coarse-grained sandstone and conglomerate with subordinate amounts of dark gray shale, siltstone, and coal. Total thickness for the unit is 180 to 200 feet (55 to 61 m).
Mississippian	**Mauch Chunk Formation** Interbedded, reddish brown shale; variegated, root-mottled mudstone and siltstone, and reddish brown to greenish gray lenticular sandstone. The Mauch Chunk Formation is approximately 600 feet thick in Allegany County and thins westward to 300 feet in thickness in western Garrett County (90 -180 m).
	Greenbrier Formation Light gray, cross-bedded, sandy limestone to calcareous sandstone at the base (Loyalhanna Member); overlain by interbedded, reddish, fossiliferous mudstone, and tan to reddish brown, fine-grained sandstone, and reddish brown siltstone and variegated shale (Savage Dam Member); succeeded by thin- to medium-bedded, light to medium gray, argillaceous, fossiliferous limestone at the top (Wymps Gap Member). The Greenbrier Formation is 150 to 200 feet thick (45-60 m).
	Purslane Formation Light gray, tan, and reddish brown, coarse-grained to conglomeratic, thick-bedded to cross-bedded sandstone and thin beds of gray shale, and coaly shale. The Purslane is more than 300 feet thick in western Washington County and thins westward to approximately 150 feet thick in western Garrett County (45-90 m).
Devonian	**Rockwell Formation** Interbedded, gray, silty shale, light gray to tan sandstone, and coaly and reddish shale. In Allegany and Washington counties a reddish brown to gray, polymictic diamictite marks the base of the formation. The Rockwell Formation is less than 100 feet in southern Garrett County (30-120 m).
	Hampshire Formation Interbedded, reddish brown to brownish red, locally greenish gray sandstone, reddish brown siltstone, shale, and rooted claystone. The thickness of the Hampshire is approximately 2,000 feet in Garrett County.
	Foreknobs Formation Interbedded, olive-gray medium- to coarse-grained, cross-bedded sandstone; greenish gray to dusky red, fossiliferous shale and siltstone. Thick (>30 feet, 10m) sandstone intervals occur both near the base and near the top of the formation. The Foreknobs is about 1,200 feet thick in Garrett County.
	Harrell-Brallier-Sherr Formations (undivided) The Harrell Shale is a dark gray, fissile, calcareous, thinly laminated, shale that weathers to thin yellowish gray shale chips. The base of the Harrell is marked by the black, very fissile **Burket Shale Member**. The Harrell grades eastward into the Brallier Formation. The Harrell Shale is up to 150 feet thick (45m). The Brallier Formation is a succession of thinly interbedded, gray to olive-gray shale and siltstone and thin, fine-grained sandstone. The Brallier is 2,000 to 2,500 feet thick (600-760 m). The Sherr Formation is interbedded, reddish- -brown to grayish brown shale; thin, gray siltstone; and fine-grained, bioturbated and fossiliferous sandstone. The thickness of the Sherr is approximately 1,000 feet in Garrett County.
	Mahantango Formation Medium gray to olive-gray, massive siltstone to fine-grained sandstone near the base and top of the formation; interbedded with these siltstone intervals are thinly interbedded siltstone, sandstone, and silty, hackly shale. Weathers brownish gray to grayish brown. The Mahantango Formation is approximately 1,400 feet thick in Allegany County and thins westward to less than 1,000 feet in thickness in the subsurface of Garrett County (300-425 m).
	Needmore-Marcellus Shales The Needmore Shale is a dark-brownish-gray to medium-dark gray, calcareous, fossiliferous shale, with thin (1 foot, 30 cm) beds of dark gray, argillaceous limestone. The upper Needmore Shale consists of approximately 35 feet (10 m) of interbedded, dark gray, argillaceous limestone and black shale. This interval is correlative with the Onondaga Limestone of New York. The top of the Needmore Shale is marked by the Tioga Bentonite, a brown, tuffaceous claystone. The Needmore Shale is 150 feet thick in Allegany County (45 m). The Marcellus Shale consists of black, brittle, fissile shale in the lower 100 feet (30 m); interbedded, thinly bedded, black limestone and shale in the middle; and very dark gray, fissile shale containing thin (0.5-1 inch, 1-2 cm) siltstone beds at the top. The Marcellus Shale is approximately 150 feet in the subsurface at Keysers Ridge (45-105 m).
	Oriskany Formation Interbedded, medium to dark gray, siliceous shale and sandy and cherty limestone near the base (Shriver Shale Member); overlain by tan fine-grained, calcareous sandstone; and then by light gray, medium- to coarse-grained, thin- to thick-bedded, calcareous sandstone at the top (Ridgely Member). The Oriskany Formation is approximately 50 feet thick in western Washington County and thickens westward into Allegany County where it is up to 300 feet thick (15-90 m).
	Keyser-Helderberg Formations (undivided) Light to medium gray, fossiliferous limestone.

Table 2. Construction and yield characteristics of test wells.

[d-m-s, degree-minute-second; ft, feet; in, inches; asl, above sea level; gpm, gallons per minute; ft2/day, feet squared per day; Gp, Group; Fm, Formation]

		Buffalo Run site		Savage River site		Nydegger Run site		
		GA Aa 15	**GA Aa 16**	**GA Bf 28**	**GA Bf 29**	**GA Fb 42**	**GA Fb 43**	**GA Fb 44**
Well-permit number		GA-13-0004	GA-13-0005	GA-13-0010	GA-13-0009	GA-13-0014	GA-13-0015	GA-13-0019
Latitude (d-m-s)		39-41-17.74	39-41-17.85	39-39-00.27	39-38-59.93	39-17-49.49	39-17-49.63	39-17-49.55
Longitude (d-m-s)		79-25-16.70	79-25-16.57	79-00-08.75	79-00-08.95	79-20-57.88	79-20-58.30	79-20-58.05
Elevation of land surface (ft)		1,522.0	1,522.1	2,587.8	2,587.6	2,329.8	2,330.3	2,330.1
Elevation of measuring point (ft)		1,523.2	1,523.1	2,590.1	2,589.5	2,332.1	2,332.5	2,331.8
Height of measuring point (ft asl)		1.2	1.0	2.3	1.9	2.3	2.2	1.7
Geologic unit of open hole		Allegheny Fm.	Conemaugh Gp. Allegheny Fm.	Hampshire Fm.	Hampshire Fm.	Pottsville Fm. Mauch Chunk Fm.	Conemaugh Gp.	Conemaugh Gp.
Depth to bottom (ft)	12-in casing	20	10	20	10	20	10	--
	10-in casing	40	20	40	20	40	20	--
	6-in casing	125	40	500	40	500	40	22
	Open hole	230	120	986	200	985	200	32
Water level	Date	8/7/2014	8/7/2014	7/7/2014	7/7/2014	7/16/2014	7/16/2014	7/16/2014
	Below measuring point (ft)*	-86.17	-4.12	855.88	76.94	20.21	21.43	20.74
	Below land surface datum (ft)*	-87.37	-5.12	853.58	75.04	17.91	19.23	19.04
	Above mean sea level (ft)	1,609.38	1,527.19	1,734.23	2,512.55	2,311.90	2,311.05	2,311.03

* Negative numbers indicate water levels are above land surface

Table 2 (continued)

Aquifer test							
	Buffalo Run site		**Savage River site**		**Nydegger Run site**		
	GA Aa 15	**GA Aa 16**	**GA Bf 28**	**GA Bf 29**	**GA Fb 42**	**GA Fb 43**	**GA Fb 44**
Date of test	10/2— 10/3/14	--	--	7/8 — 7/9/14	6/23 — 6/25/14	7/1— 7/3/14	--
Length of discharge test (hours)	8	--	--	12	24	24	--
Discharge (gpm)	110	--	--	5	4	180	--
Drawdown (ft)	35.49	--	--	86.91	148.47	15.99	--
Specific Capacity (gpm/ft)	3.1	--	--	0.06	0.03	11.3	--
Transmissivity, drawdown phase (ft^2/day)	710	--	--	6	2	2,000	--
Transmissivity, recovery phase (ft^2/day)	945	--	--	4	2	2,700	--

Table 3. Water-quality data from wells drilled during this project.

[C., Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius;
<, less than; >, greater than; µg/L, micrograms per liter; pCi/L, picocuries per liter]

	Buffalo Run site		Savage River site	Nydeggar Run site		
Well	**GA Aa 15**	**GA Aa 16**	**GA Bf 29**	**GA Fb 42**	**GA Fb 43**	**GA Fb 44**
Sample date	7/28/2014	7/28/2014	7/8/2014	6/23/2014	7/1/2014	8/12/2014
Color (platinum-cobalt units)	8	5	5	12	2	18
Dissolved oxygen (mg/L)	<1	<1	5.4	na	<1	<1
pH	8.0	8.1	7.2	8.9	7.0	6.7
Specific conductance (µS/cm)	293	294	142	307	988	458
Temperature (degrees C.)	11.9	12.0	11.7	14.1	12.9	10.5
Dissolved solids (residue on evaporation at 180°C.)	147	167	86	178	726	240
Calcium (mg/L)	24	20.2	13	1.12	100	47.9
Magnesium (mg/L)	5.58	4.91	7.26	0.256	22.7	13.2
Potassium (mg/L)	1.54	2.04	1.13	0.53	4.62	2.42
Sodium (mg/L)	33.2	38.9	4.15	68.5	45.1	15
Alkalinity (mg/L as $CaC0_3$)	147	146	61	147	93	74
Bicarbonate (mg/L)	179	178	74	179	113	90
Bromide (mg/L)	<0.03	<0.03	<0.03	<0.03	0.066	0.043
Chloride (mg/L)	1.78	1.95	1.04	1.17	201	54
Fluoride (mg/L)	0.32	0.35	0.06	0.73	0.11	0.09
Silica (mg/L)	7.45	7.64	15	8.43	6.57	6.59
Sulfate (mg/L)	0.32	0.16	7.08	0.08	74.1	56.7
Ammonia (mg/L as N)	0.74	0.99	<0.01	0.37	1.68	0.4
Nitrate + nitrite (mg/L as N)	<0.04	<0.04	0.201	<0.04	<0.04	<0.04
Nitrite (mg/L as N)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Orthophosphate (mg/L as P)	0.015	0.015	0.071	0.077	<0.004	<0.004
Phosphorous (mg/L as P)	<0.02	<0.02	0.07	0.07	<0.02	<0.02
Aluminum (µg/L)	<2.2		10.4	5.2	<2.2	<2.2
Barium (µg/L)	501	586	116	21.4	151	70.6
Beryllium (µg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cadmium (µg/L)	<0.03	<0.03	<0.03	<0.03	<0.03	0.031
Chromium (µg/L)	<0.3	<0.03	1.6	<0.03	<0.03	0.31
Cobalt (µg/L)	<0.05	<0.05	0.083	<0.05	2.48	6.51
Copper (µg/L)	<0.8	<0.8	1.4	1.2	<0.8	<0.8
Iron, dissolved, (µg/L)	170	180	8.9	10.6	1790	1520
Iron total (µg/L)	245	216	133	964	2000	1600
Lead (µg/L)	<0.04	<0.04	0.135	0.084	<0.04	<0.04
Lithium (µg/L)	2.97	2.95	6.9	2.42	9.64	6.09
Manganese dissolved (µg/L)	23.6	9.5	4	5.68	303	198
Manganese total (µg/L)	20.6	8.18	5.47	14.4	257	179
Molybdenum (µg/L)	0.302	0.21	0.548	0.467	0.498	0.419
Nickel (µg/L)	0.33	0.48	0.5	<0.2	4	7.6
Silver (µg/L)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Strontium (µg/L)	245	263	31.6	22.8	762	220

Table 3 (continued)

	Buffalo Run site		Savage River site	Nydeggar Run site		
Well	**GA Aa 15**	**GA Aa 16**	**GA Bf 29**	**GA Fb 42**	**GA Fb 43**	**GA Fb 44**
Sample date	7/28/2014	7/28/2014	7/8/2014	6/23/2014	7/1/2014	8/12/2014
Thallium (µg/L)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Vanadium (µg/L)	0.09	<0.08	0.37	<0.08	0.3	0.1
Zinc (µg/L)	7	2.8	15.5	111	34.8	8.6
Antimony (µg/L)	<0.027	<0.027	0.071	0.126	0.465	0.092
Arsenic (µg/L)	<0.1	<0.1	1.7	0.17	1	12.4
Boron (µg/L)	61	71	<5	64	24	12
Selenium (µg/L)	<0.05	<0.05	0.39	<0.05	0.2	<0.05
Total organic carbon (mg/L)	<0.7	<0.7	<0.7	<0.7	<0.7	1
Gross alpha-particle activity, 30-day (pCi/L)	<0.6	<1.4	<0.2	<0.5	2.3	<0.2
Gross alpha-particle activity, 72-hour (pCi/L)	2.4	2.2	<0.5	1.3	1.9	2.5
Gross beta-particle activity, 30-day (pCi/L)	1.3	2	2	<0.3	6.4	3.4
Gross beta-particle activity, 72-hour (pCi/L)	5.6	4	2	1.1	4.7	4
Radon (pCi/L)	126	169	2,360	25	150	18
Uranium (µg/L)	<0.014	<0.014	0.468	<0.014	0.711	0.176
Methane (µg/L)	1,720	2,200	<1.5	6,080	45.6	25.1
Ethane (µg/L)	10.2	13.3	<3.3	23.9	<3.3	<3.3
Ethene (µg/L)	<2.4	<2.4	<2.4	<2.4	<2.4	<2.4
n-Butane (µg/L)	<4.3	<4.3	<4.3	<4.3	<4.3	<4.3
Isobutane (µg/L)	<4.6	<4.6	<4.6	<4.6	<4.6	<4.6
Propane (µg/L)	<3.2	<3.2	<3.2	<3.2	<3.2	<3.2

Table 4. Summary of hydrogeologic characteristics at the three test-well sites in Garrett County.

[ft, feet]

	Buffalo Run site		**Savage River site**		**Nydeggar Run site**		
	GA Aa 15	**GA Aa 16**	**GA Bf 28**	**GA Bf 29**	**GA Fb 42**	**GA Fb 43**	**GA Fb 44**
Open interval (ft below land surface)	125-230	40-120	500-986	40-200	500-985	40-200	22-32
Partings characterization	Subhorizontal, bedding planes		Bedding planes, high-angle fractures		Subhorizontal, bedding planes		
Response of wells to pumping tests in adjacent wells	Response seen but not likely a hydraulic connection		No		Response seen between all wells		
Hydraulic relation to stream	No	Likely	--[1]		Losing stream		
Head gradient	Upward	Upward	Downward		From shallow and deep zones to intermediate zone		
Density of fractures (fractures per 100 ft)[2]	24.8	--	9.3	--	6.6	--	--
Density of transmissive fractures (fractures per 100 ft)[2]	1.7	--	0.51	--	1.1	--	--
Percent of transmissive fractures	7.0	--	5.4	--	16.9	--	--
Transmissivity (ft^2/day) [3]	828	--	--	5	2	2,350	--
Water quality	Sodium-calcium bicarbonate	Sodium-calcium bicarbonate	--	Calcium-magnesium bicarbonate	Sodium bicarbonate	Calcium chloride	Calcium chloride-bicarbonate-sulfate
Comments	Flowing artesian wells		Virtually no water produced below 500 ft depth		Complex head distribution within wells		

[1] Gage located too far from well to evaluate
[2] Calculated from deep well
[3] Average of drawdown and recovery transmissivity