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Hydrologic Effects of Leakage from the Catskill Aqueduct on the Bedrock-Aquifer System near High Falls, New York, November 2019–January 2020

By Anthony Chu, Michael L. Noll, and William D. Capurso

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)

Datum

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

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

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

Abbreviations

NYCDEP	New York City Department of Environmental Protection
NYSDEC	New York State Department of Environmental Conservation
PVC	polyvinyl chloride
USGS	U.S. Geological Survey

Hydrologic Effects of Leakage from the Catskill Aqueduct on the Bedrock-Aquifer System near High Falls, New York, November 2019–January 2020

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Abstract

Historical observations by the New York City Department of Environmental Protection (NYCDEP) indicate that the Rondout pressure tunnel has been leaking in the vicinity of the hamlet of High Falls, New York. In the 74 days from November 11, 2019, to January 23, 2020, NYCDEP shut down and partially dewatered the pressure tunnel for inspection and repairs. On November 5–7, 2019 (during normal tunnel operations), and on January 21–22, 2020 (when the tunnel was shut down), the U.S. Geological Survey used a network of 31 groundwater wells to collect water-level elevations and determine the potentiometric surface of the bedrock aquifer adjacent to the Rondout pressure tunnel. When the tunnel was fully pressurized during normal operations, water levels indicated a two-mile-long groundwater mound which trended northeastward, approximately along the regional strike of the bedrock units. The mound ranged in elevation from 250 to 300 feet (ft) above the North American Vertical Datum of 1988 and extended from 1,500 ft southwest of a suspected leak at the Rondout pressure tunnel to about 8,500 ft northeast of the possible leak. During the 74-day shutdown, during which the aqueduct was nonoperational, this groundwater mound decreased in magnitude and extent as it reverted to equilibrium conditions. This resulted in a flattening of the potentiometric surface, represented by two remnant groundwater plateaus.

Water-level differences were calculated for wells that may be affected by potential tunnel leakage to determine the influence on the local bedrock aquifer. The five largest water-level differences (77, 61, 49, 42, and 41 ft) occurred in wells that were generally aligned with the northeastward trend of regional bedrock strike; these wells may penetrate the karstic Helderberg Group bedrock unit. Near the suspected tunnel leak, the Helderberg Group overlies the Binnewater Sandstone and the High Falls Shale, both of which produced substantial groundwater inflows during the construction of the Rondout pressure tunnel. Water levels in wells penetrating the Shawangunk Formation just east of Rondout Creek, where the unit is in contact with the High Falls Shale, and in wells penetrating the Esopus Shale, which is adjacent to the Helderberg Group and northwest of the tunnel leak, may be affected by tunnel leakage.

It is unclear if water levels in a well 9,000 ft northwest of the suspected tunnel leak are influenced by the tunnel leakage, by another source of artificial recharge, or by both. This well penetrates the Onondaga Limestone in the northwestern part of the study area. An unconsolidated aquifer composed of stratified gravel, sand, silt, and clay overlies the limestone bedrock in this part of study area—additional study is required to determine if this unconsolidated aquifer is affected by tunnel leakage.

Introduction

By the late 19th century, New York City's growing population had expanded to almost 3 million residents, who required a new and reliable source of potable water (NYCDEP, 2020). In 1905, the New York State legislature established the Board of Water Supply, which subsequently identified the Catskill region as a potential source of water supply for New York City. The Catskill watershed is within the Appalachian Basin, about 100 miles (mi) north of New York City and 35 mi west of the Hudson River, and is part of Greene, Ulster, and Schoharie Counties (sheets 1–3) (NYCDEP, 2019). Construction of the 92-mi-long Catskill Aqueduct, which begins at the Ashokan Reservoir in Ulster County and terminates at the Hillview Reservoir in southern Westchester County, was started in 1907 and was completed in 1915 (NYCDEP, 2020). About 60 percent (55 mi) of the aqueduct was built using a cut-and-cover method that required excavating a trench at the land surface before installing and burying the aqueduct. The remaining 40 percent of the tunnel is a combination of grade tunnels constructed through mountainous areas and pressure tunnels constructed under deep, glacially eroded valleys, including the Hudson and Rondout valleys. These parts of the aqueduct were built using a traditional drill-and-blast method. As of February 2020, the Catskill Aqueduct delivered about 400 million gallons of potable water (about 40 percent of total current demand) each day to more than 9 million people in New York State using a gravity-fed system (NYCDEP, 2019).

In 2013, NYCDEP and their consultants observed at least six areas of groundwater discharge (springs) along and adjacent to the pressure tunnel in the Rondout valley. On the basis of historical drilling documents, geologic records, and recent field observations, a hydraulic connection is suspected to exist between these springs and leakage from the Rondout pressure tunnel. As part of an effort to sustain a viable water-supply system for the approximately 8 million residents of New York City, along with the 1 million other residents in upstate New York who rely on water from the aqueduct, NYCDEP entered into a cooperative agreement with the U.S. Geological Survey (USGS) to study the source or sources of water to springs in areas along the Catskill Aqueduct near High Falls, NY.

Hydrogeologic Setting

The Port Jervis Trough (sheets 1–3) is a deep, northeast-trending valley that extends northeastward from the Delaware Water Gap to the Hudson River and is part of the Valley and Ridge Province in the Appalachian Highlands. The Rondout valley (see location map on sheets 1–3), which is part of the Port Jervis Trough near the hamlet of High Falls and the Towns of Marbletown and Rosendale, New York, is a geologic transition zone that has complex topographic and geologic features; primary source documents indicate construction of the Rondout pressure tunnel was one of the most difficult engineering problems of the entire Catskill Aqueduct project (Fluhr and Terenzio, 1984). Berkey (1911) described the complex topographic and geologic features in the Rondout valley as “irregularities” that are primarily structural rather than stratigraphic. Rondout Creek originates in the Catskill Mountains, flows northeast into the Rondout valley and over the High Falls waterfall (sheets 1–3), and ultimately joins the Hudson River as a tributary. The High Falls (the hamlet’s namesake) formed during the Pleistocene Epoch as northward-retreating glaciers created an ice dam that diverted flow in Rondout Creek to the east. Differential erosion along the new flow path of Rondout Creek exposed upper Silurian bedrock and structural features such as an asymmetric, anticlinal fault-propagation fold (related to the Acadian orogeny) in the Binnewater Sandstone and the High Falls Shale (Fluhr and Terenzio, 1984; Marshak and others, 2009). The asymmetric anticline is mesoscopic evidence of the fold-thrust belt near the Town of Rosendale to the east (Marshak and others, 2009) and indicates the potential presence of one or more local thrust faults at depth, which was verified by the drilling records of the pressure tunnel (Fluhr and Terenzio, 1984). The resistant Shawangunk Formation crops out on the east side of the valley and forms a smaller, northeast-trending anticlinal ridge (Berkey, 1911) that parallels the eastern ridge that bounds the Rondout valley, which is part of the Shawangunk Mountains. The Coxing Kill flows north through a synclinal valley (Berkey, 1911) formed by the two ridges and ultimately terminates at Rondout Creek. Groundwater levels within the ridges are generally higher than in the adjacent lower lying areas. Another unique topographic feature is found adjacent to Rondout Creek in the northeastern part of the study area (sheets 1–3), where a north-trending escarpment of what appears to be limestone of the Helderberg Group rises about 50–120 feet (ft) above the surrounding valley floor. Rondout Creek, which bounds the west and north sides of the escarpment, and Coxing Kill, which bounds the east side, merge at this location to flow northeastward through a valley in the Shawangunk Mountains near Rosendale and ultimately toward the Hudson River.

Devonian sedimentary rocks, dipping to the northwest, define the southeasterly margin of the Catskill Mountains. In the area near High Falls, the rocks are truncated and form an escarpment that bounds the northwestern ridge of the Rondout valley. The southeastern ridge that bounds the Rondout valley is primarily conglomerate (a silica-cemented, milky-white quartz-pebble conglomerate) of the middle and upper Silurian Shawangunk Formation, which is part of the Shawangunk Mountains (Fluhr and Terenzio, 1984; Epstein, 1993; Marshak and others, 2009). In general, the course of the Catskill Aqueduct is orthogonal to the trend of the Rondout valley and to the regional northeast strike of the bedrock. A geologic cross section (fig. 1) shows the bedrock units that were penetrated during construction of the Rondout pressure tunnel, as well as the locations of eight vertical access shafts at varied intervals along the tunnel line (Fluhr and Terenzio, 1984). The approximately 4.5-mile-long Rondout pressure tunnel begins at the edge of the escarpment at downtake shaft 1, in sandstones and shales of the Hamilton Group. The tunnel proceeds southeastward beneath the Rondout valley and shafts 2–7 and ultimately reemerges at uptake shaft 8 near Bonticou Crag, a peak characterized by undifferentiated shale and sandstone of the Ordovician Martinsburg Formation (Berkey, 1911) overthrust onto the Shawangunk Formation as the footwall at the west slope of the Shawangunk Mountains (fig. 1). Listed in order from northwest (near shaft 1) to southeast (near shaft 8), the bedrock units penetrated by the tunnel as it crosses beneath the Rondout valley are the Marcellus Shale of the Hamilton Group, the Onondaga Limestone, the Esopus Shale, the Helderberg Group, the Binnewater Sandstone, the High Falls Shale, the Shawangunk Formation, and undifferentiated shale and sandstone of the Ordovician Martinsburg Formation (Berkey, 1911) (fig. 1). The elevation of the pressure tunnel between shafts 1 and 3 is generally 100 ft below the North American Vertical Datum of 1988 (NAVD 88) and about 600 ft below the hydraulic gradient line of the aqueduct. Between shafts 3 and 4, the tunnel elevation decreases to greater than 200 ft below NAVD 88 to avoid incompetent rock disturbed by a thrust fault. This structural contact between the High Falls Shale and the Shawangunk Formation is mostly impermeable, but the disturbed shale unit had water-bearing zones that produced 400–850 gallons per minute (gal/min) during tunnel construction (Berkey, 1911). The High Falls Shale produced between 1,000 gal/min (White, 1913) and 1,650 gal/min (New York City Department of Environmental Protection, written commun., 2018) where the porous and incompetent shale was in direct contact with an overlying thrust fault and with the karstic limestone of the Helderberg Group. A steel lining (interliner), which is used to provide additional structural support to the existing tunnel, was installed between shafts 3 and 4 after the newly installed concrete tunnel lining failed hydrostatic testing; during inspection, a 1/8-inch (in.)-wide crack observed in the concrete liner extended for several hundred feet into limestone of the Helderberg Group (Fluhr and Terenzio, 1984). In total, more than 700 ft of steel interliner was installed in three sections of the tunnel, and cracks in the rock (which may have been exacerbated by the pressure from hydrostatic testing) were grouted under high pressure—these repairs were reported to be successful. Drilling of the Rondout pressure tunnel also was hindered by hydrogen sulfide gas, water-bearing cavities, horizontal and vertical clay-filled joints and cavities, over-breakage, mud seams, fault and crush zones, additional water inflows, and the hardness of the grit in the Shawangunk Formation. After pumping out the tunnel, an inspection also indicated that a cave system with irregular and chainlike passages was formed by the dissolution of carbonate rock (Fluhr and Terenzio, 1984).

Observations in 2013 by NYCDEP and their consultants indicated the presence of new springs in at least five areas along an approximately 900-ft-long section of the pressure tunnel between shafts 3 and 4 in the Rondout valley. The elevations of these springs vary but are approximately 260 ft above NAVD 88. The rate of flow from the springs during March 2013 ranged from approximately 6 to greater than 70 gallons per minute. On the basis of historical drilling documents, geologic records, and recent field observations, a hydraulic connection is suspected to exist between these five areas of groundwater discharge and leakage from the Rondout pressure tunnel, located about 350–500 ft below land surface or 100–250 ft below NAVD 88. At maximum flow (591 million gallons per day), the hydraulic gradient line of the pressure tunnel across the Rondout valley section of the Catskill Aqueduct ranges from about 495 ft (near shaft 1) to 480 ft (near shaft 8) above NAVD 88. In general, the locations of springs in the Rondout valley correlate with locations along the pressure tunnel line where incompetent rock and groundwater inflows have been reported in the drilling records, and also where steel interliner was installed to reinforce the tunnel and suppress inflows during construction.

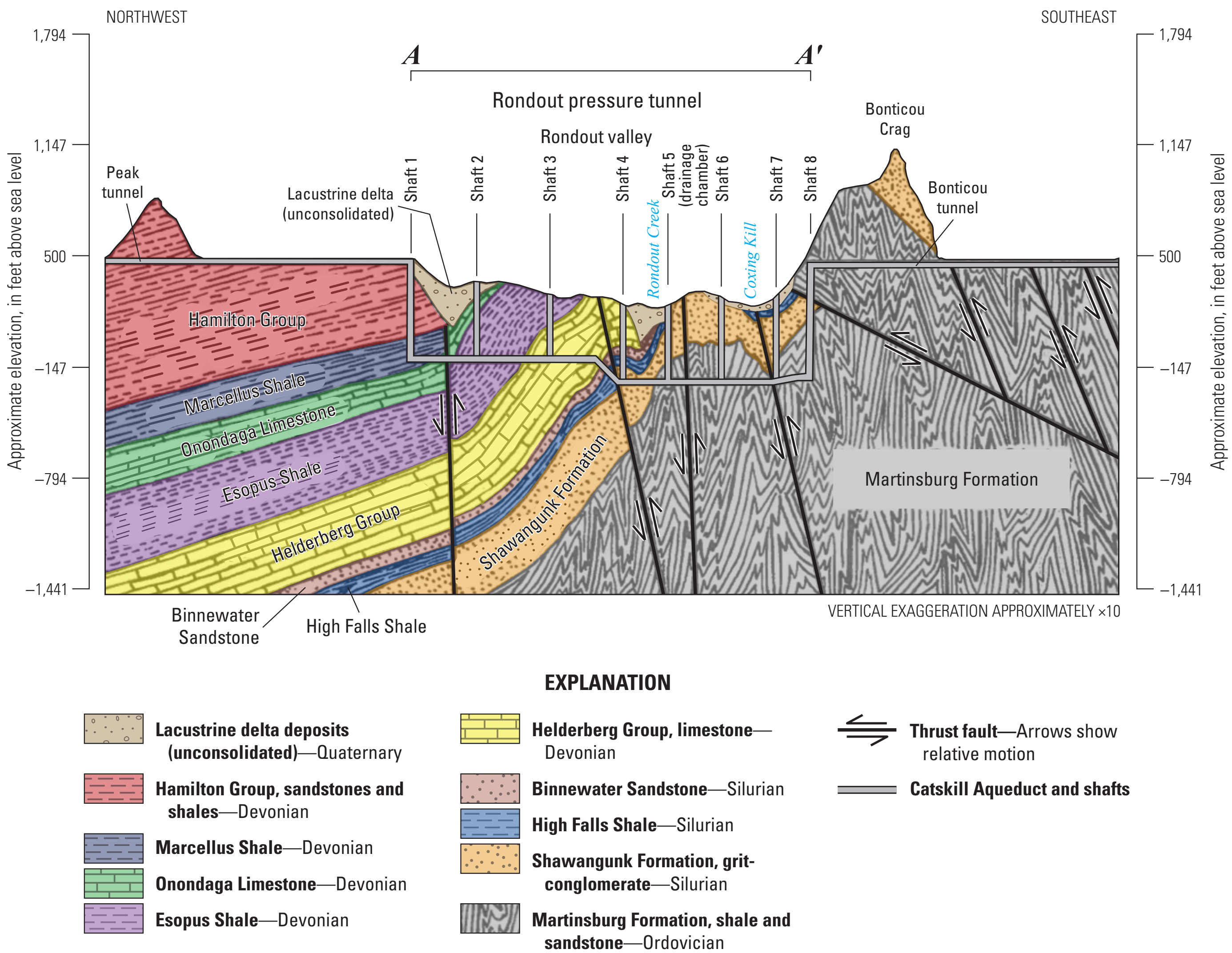

Figure 1. Cross section of the geology along the Rondout pressure tunnel line beneath the Rondout valley, Ulster County, New York (modified from Fluhr and Terenzio, 1984). The Rondout pressure tunnel, located between shafts 1 and 8, is shown on sheets 1–3. (The thin veneer of sediment in the Coxing Kill area is not shown on map sheets because it has no significance to water-bearing units.)

Objective

As part of an effort to sustain a viable water-supply system for more than 8 million residents in New York City and the 1 million residents in upstate New York who rely on water from the aqueduct, the NYCDEP and the USGS initiated a collaborative multidisciplinary study to determine the source or sources of water to springs in areas adjacent to the Catskill Aqueduct. This map is the first step to better understanding (1) the local bedrock groundwater-flow system in the Rondout valley adjacent to the Catskill Aqueduct and (2) the spatial distribution and magnitude of the potential influence of tunnel-water leakage into the bedrock aquifer. The latter involved assessing water-level differences in the monitoring-well network (described in the “Well Network” section below) during normal operations (pressurized conditions) of the Catskill Aqueduct compared to when the aqueduct was shut down and partially dewatered.

Well Network

From October 2018 to November 2019, the USGS established a groundwater-monitoring network of 31 sites in preparation for a 74-day shutdown of the Catskill Aqueduct, which would take place from November 11, 2019, to January 23, 2020. The 31-well monitoring network, intended to assess groundwater levels in the bedrock aquifer adjacent to the Rondout pressure tunnel, consisted of 24 domestic-supply wells and 7 observation wells that were completed in the bedrock aquifer. Drilling records and well-construction information is sparse or missing for many domestic-supply wells, so historical drillers’ logs and (or) anecdotal information from the well owners were the primary sources of information for these wells. In contrast, most observation wells in the network had more detailed information available. For example, in the hamlet of High Falls, geologists’ logs were available for a few extant monitoring wells that were drilled to characterize local hydrogeology and sample water-quality conditions as part of an effort to remediate a plume of contaminated groundwater (EPA, 2019). Wells used in this study were constructed with steel or polyvinyl chloride (PVC) surface casings that extend from each wellhead at the land surface through unconsolidated sediments (overburden) and into the top of competent bedrock. The wells were completed as open holes that typically intersect one or more water-bearing structures, including fractures, joints, faults, and bedding separations, that convey water to the well. The permeability of some fractures in carbonate and calcareous shale bedrock has been enhanced by secondary dissolution. Pump test records were not available, but domestic-supply wells are typically considered ready for use when they can produce enough water to sustain daily household usage, which is approximately 2–5 gallons per minute (NYSDEC, 2021).

Multiple groundwater-level measurement synoptics were performed across the network by the USGS during the shutdown period. The synoptics of November 5–7, 2019, and January 21–22, 2020, best illustrate the effect of the tunnel leakage and are discussed below. These periods did not follow precipitation recharge events, were prior to the tunnel shut down and just before repressurization to determine the maximum water-level difference, and were during times when static water level conditions in domestic wells could be measured. All water level data are available through the USGS National Water Information System (USGS, 2021; appendix 1).

Water-level data were produced in the following two ways: (1) by manual measurement using a chalked, graduated steel tape or a calibrated electric tape from a surveyed wellhead (measuring point), or (2) by calculation from pressure-transducer outputs recorded automatically by data loggers installed in select wells. Manual depth-to-water measurements were made in accordance with standard USGS procedures and were converted to groundwater-level elevation values (Cunningham and Schalk, 2011). Depth-to-water measurements using the steel-tape or calibrated-electric-tape methods are considered accurate to about 0.01 ft (Cunningham and Schalk, 2011). Vented submersible pressure transducers were installed at select wells and programmed to measure groundwater levels every 60 minutes. The accuracy of a pressure transducer rated to 30 pounds per square inch (lb/in^2) is less than ±0.05 ft (In-Situ Inc., 2022). Data recorded on these instruments were corrected for instrument drift using discrete measurements of groundwater-level elevations that were made from wellhead measuring points during periodic field inspections from November 2019 through January 2020. Hydrographs were created for five wells from these continuous-record data (figs. 2–6). Discrete field measurements shown on the hydrographs verify the continuous-record measurements, and they provide data where continuous-record measurements are missing.

Four wells (U-135, U-244, U-245, and U-259) were flowing above the land surface during the groundwater synoptic of November 5–7, 2019. Two of the flowing wells (U-135 and U-259) were not measured during this synoptic because a representative water level could not be obtained; however, a reliable water-level measurement (212.86 ft above NAVD 88) made at well U-259 on October 29, 2019, is considered representative of synoptic conditions and is shown, rounded to the nearest foot, on sheet 1. Domestic-supply wells U-265 and U-2992 could not be accessed during the January 21–22, 2020, synoptic, so a representative static water level was determined from the continuous-record hydrograph record from this period and is shown in sheet 2. All synoptic water-level measurements (rounded to the nearest whole number) were used to develop contours of the potentiometric surface at a 20-ft interval on sheets 1 and 2. Potentiometric surfaces were created from measured water levels using Natural Neighbor interpolation (Sibson, 1981) which was applied in a GIS. Contours were created from the surfaces at fixed (20 ft) intervals using the contouring tool. Experienced analysts then reviewed and modified the contours if, for example, an anomaly or erroneous contour line was detected. In some cases, jagged contours were smoothed using GIS contouring tools. The modified contours, along with the original measured water levels, were then loaded back into the natural neighbor interpolator and reprocessed to eliminate any artificial interpolation results. This iterative process was continued until experienced analysts were satisfied with the results and no rules of hydrologic contouring were violated. Digital shapefiles of the potentiometric surfaces and well locations are available in Capurso and others (2022).

Vented submersible pressure transducers could not be installed in the four flowing wells; thus, only discrete measurements from synoptics are available for those wells. A hydrograph of discrete measurements for well U-244, including measurements during flowing conditions, is shown on figure 6. The water levels in each well are the sum of the hydraulic heads from contributing transmissive zone(s) intersected by those wells.

Bedrock Aquifer

Groundwater generally flows from upland recharge zones along the ridges of the Rondout valley, where harder, more resistive, and more competent rock forms the aquifer, downgradient towards the eroded, weathered, and less competent units in the valley, and ultimately northeastward along the regional strike of the bedrock units. In general, bedrock aquifers in Ulster County have virtually no primary or intergranular porosity and have low transmissivity and storage capacity. Frimpter (1972) estimated the yields of domestic wells completed

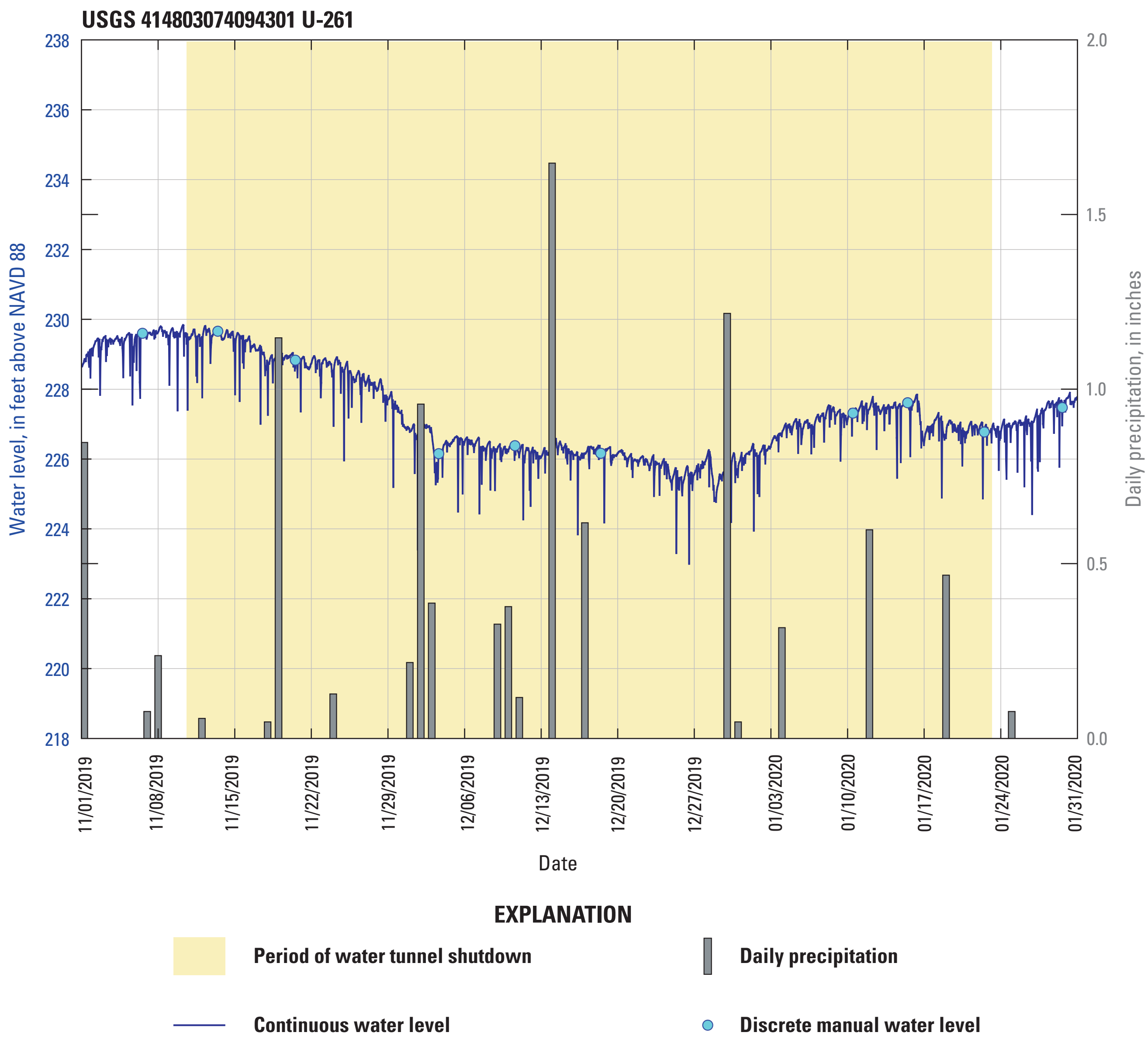

Figure 2. Plot of discrete and continuous-record water levels for domestic-supply well U-261 compared to daily precipitation at the Mohonk Lake Cooperative Weather Station, Ulster County, New York, from November 1, 2019, to January 31, 2020. The locations of the well and weather station are shown on sheets 1–3. Dates shown as month/day/year. NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey.

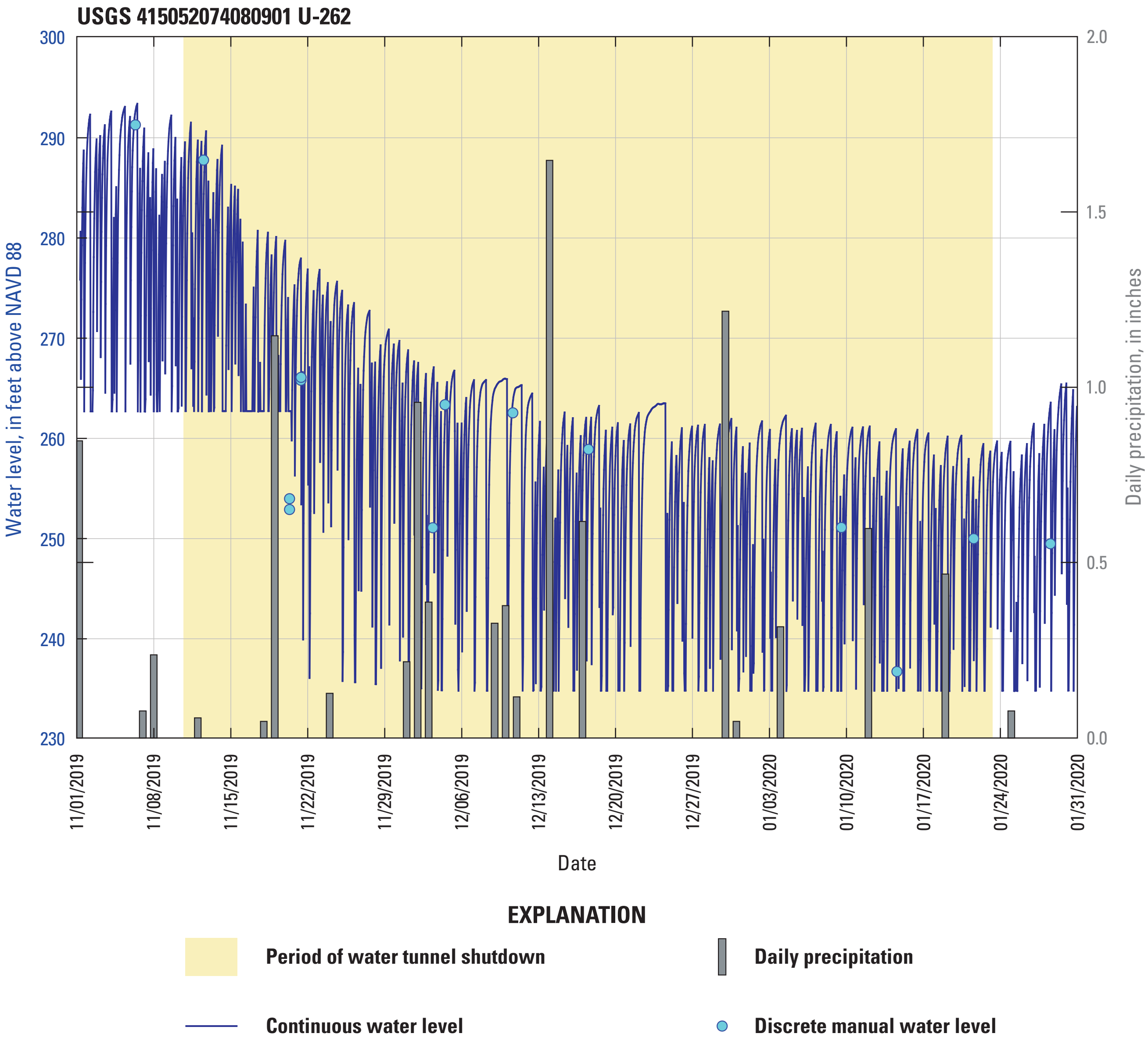

Figure 3. Plot of discrete and continuous-record water levels for domestic-supply well U-262 compared to daily precipitation at the Mohonk Lake Cooperative Weather Station, Ulster County, New York, from November 1, 2019, to January 31, 2020. The locations of the well and weather station are shown on sheets 1–3. Dates shown as month/day/year. NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey.

in sandstone, carbonate, shale, and crystalline-rock aquifers to be 0.18, 0.17, 0.15, and 0.12 gal/min, respectively, per foot of well open in the aquifer. Data from exploratory test borings along the proposed tunnel line in the Rondout valley indicate that the bedrock units are nearly impermeable along bedding planes, except for in the High Falls Shale and the Binnewater Sandstone (Berkey, 1911). High transmissivity zones are derived from secondary porosity features, such as faults and fractures in sandstones and shales, and from dissolution features in carbonate rock where solution openings are created by the circulation of groundwater through preexisting fractures and crush zones. A north-northeast-striking fault zone, which likely formed from orogenic processes, created secondary porosity (fractures) in the carbonate rock and in adjacent bedrock units within the Port Jervis Trough near the hamlet of High Falls (Frimpter, 1972; Fluhr and Terenzio, 1984). This fracturing increased the transmissivity and storage of the local bedrock units, subsequently increasing groundwater yield to wells completed in the bedrock aquifer. One well drilled into a faulted carbonate (calcareous) rock unit near High Falls produced 50 gal/min (Frimpter, 1972).

Shaft excavation records indicate the maximum pump rates that were required to remove groundwater from the bottom of each shaft, the presence of which was due to inflows along the vertical profile (Berkey, 1911). These values are not representative of the aggregated inflow along the entire shaft,

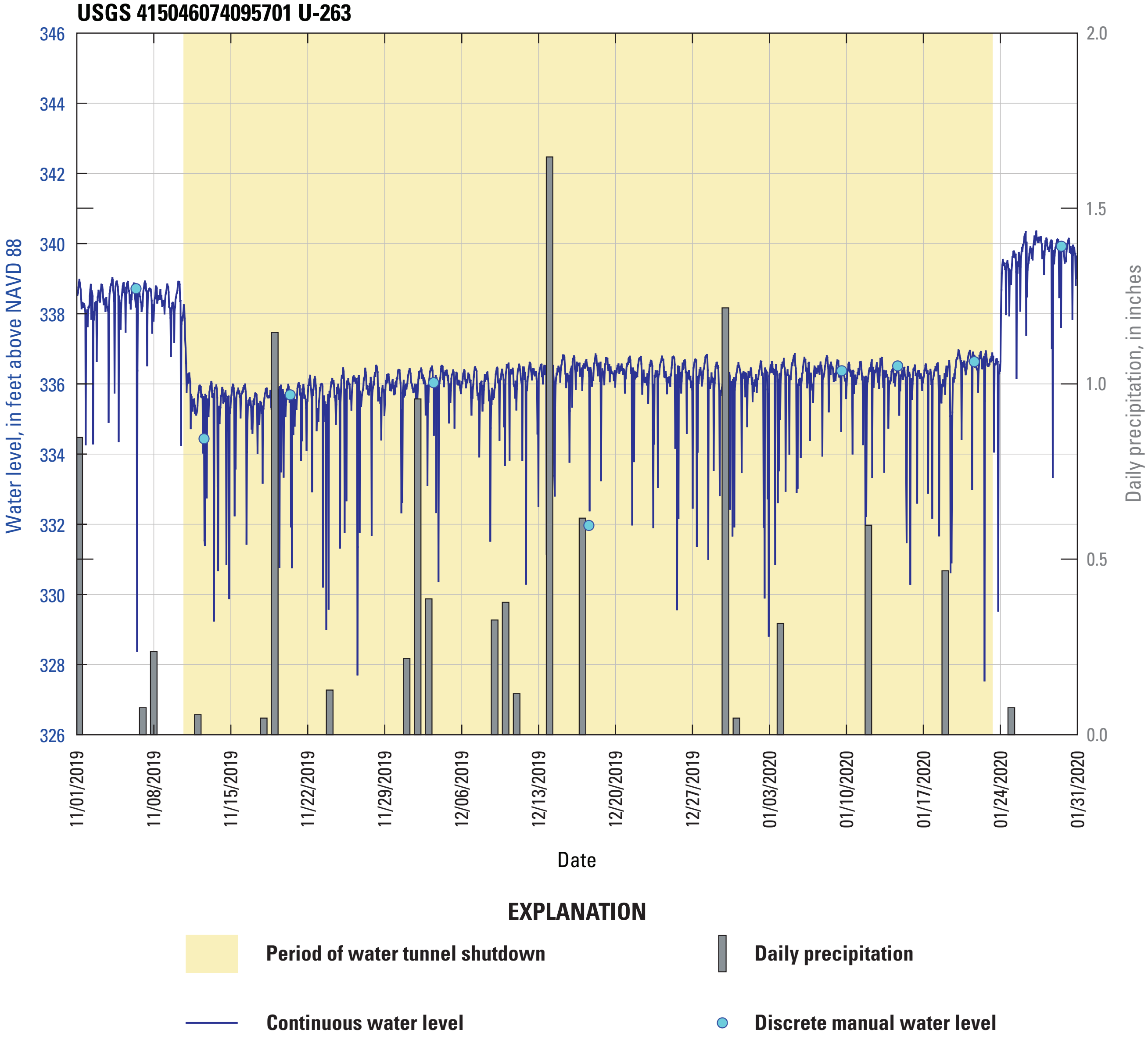

Figure 4. Plot of discrete and continuous-record water levels for domestic-supply well U-263 compared to daily precipitation at the Mohonk Lake Cooperative Weather Station, Ulster County, New York, from November 1, 2019, to January 31, 2020. The locations of the well and weather station are shown on sheets 1–3. Dates shown as month/day/year. NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey.

just of the part of inflow that could not be removed by grouting, pumping, or other water-suppression methods at intermediate and higher elevations within the shaft; however, the values do provide some insight regarding the water-bearing properties of the rock units that were penetrated during the excavation of each shaft. The maximum pump rates from the bottom of shafts 1–8 were 0.5, 4, 25, 745, >80, 35, 115, and 18 gal/min, respectively. Shaft 4 produced the greatest inflows of the eight shaft sites and its excavation involved substantial engineering problems. It penetrated 6 ft of overburden, 200 ft of the Helderberg Group, 40 ft of the Binnewater Sandstone, 90 ft of the High Falls Shale, and 159 feet of the Shawangunk Formation, and it was finished at a depth of about 495 ft (Fluhr and Terenzio, 1984). During the excavation of shaft 4, an inflow of 600–800 gal/min was documented in the limestone of the Helderberg Group at a depth of about 80 ft, flooding the shaft to a groundwater level of about 40 ft below the land surface (Berkey, 1911). Aggregated inflows of 225 gal/min were documented between 230 and 260 ft below the land surface in the Binnewater Sandstone. An inflow of about 600 gal/min was also documented just below 260 ft, flooding the shaft again to a groundwater level of about 70 ft below the land surface (Berkey 1911; Fluhr and Terenzio, 1984). Additional inflows of 125 and 150 gal/min were documented below 315 ft (Fluhr and Terenzio, 1984). Even after four months of grouting to reduce leakage into shaft 4, aggregated inflows were greater than 725 gal/min at the bottom of the shaft.

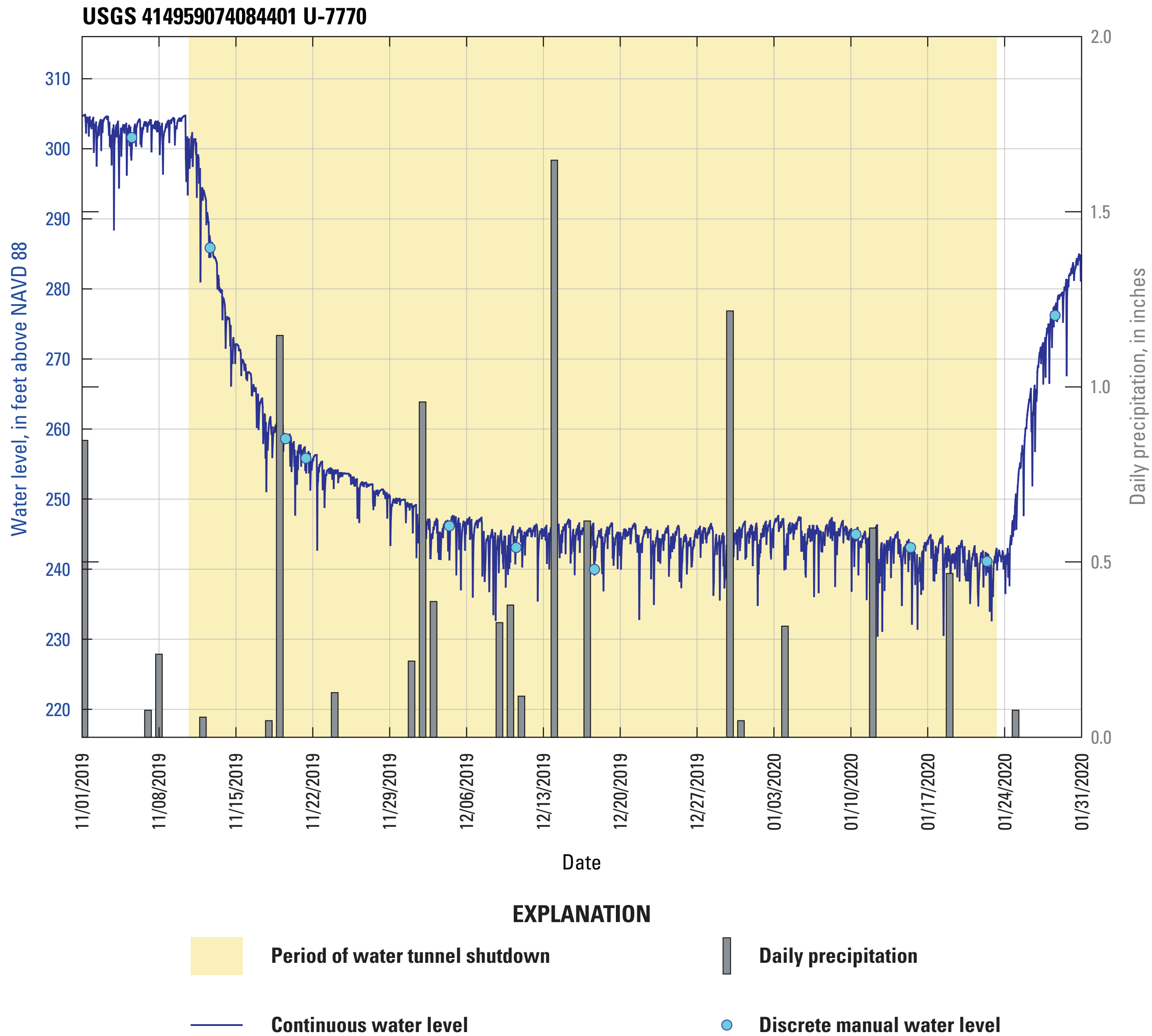

Figure 5. Plot of discrete and continuous-record water levels for domestic-supply well U-7770 compared to daily precipitation at the Mohonk Lake Cooperative Weather Station, Ulster County, New York, from November 1, 2019, to January 31, 2020. The locations of the well and weather station are shown on sheets 1–3. Dates shown as month/day/year. NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey.

Unconsolidated Aquifers

A lacustrine delta composed of stratified gravel, sand, silt, and clay (Cadwell, 1989; Connally, 2011) forms an unconsolidated aquifer in the northern and northwestern parts of the study area (sheets 2, 3). This delta was deposited during the Pleistocene Epoch into a pro-glacial lake and is locally known as the "School" aquifer because of its proximity to the Marbletown Elementary School. Some residential wells tap the School aquifer as a primary source of domestic-water supply. The School aquifer may overlay the Hamilton Group and the Onondaga Limestone in the northwestern part of the study area. Recent alluvium, kame deposits, and lacustrine-delta deposits adjacent to Rondout Creek (fig. 1, sheets 1–3) (Cadwell, 1989) form another unconsolidated aquifer. Drillers' logs of bedrock wells that penetrated these unconsolidated deposits indicate that their thicknesses range from 7 to 211 ft, but average 83 ft (NYSDEC, 2021). The unconsolidated aquifer overlies the Helderberg Group and the Shawangunk Formation near the Rondout pressure tunnel between shafts 4 and 6 (fig. 1, sheets 1–3). Based on their proximity to the tunnel, both the School aquifer and the aquifer adjacent to Rondout Creek may be affected by potential leakage from the Rondout pressure tunnel or from another source of artificial recharge; however, additional study is required to verify this hypothesis.

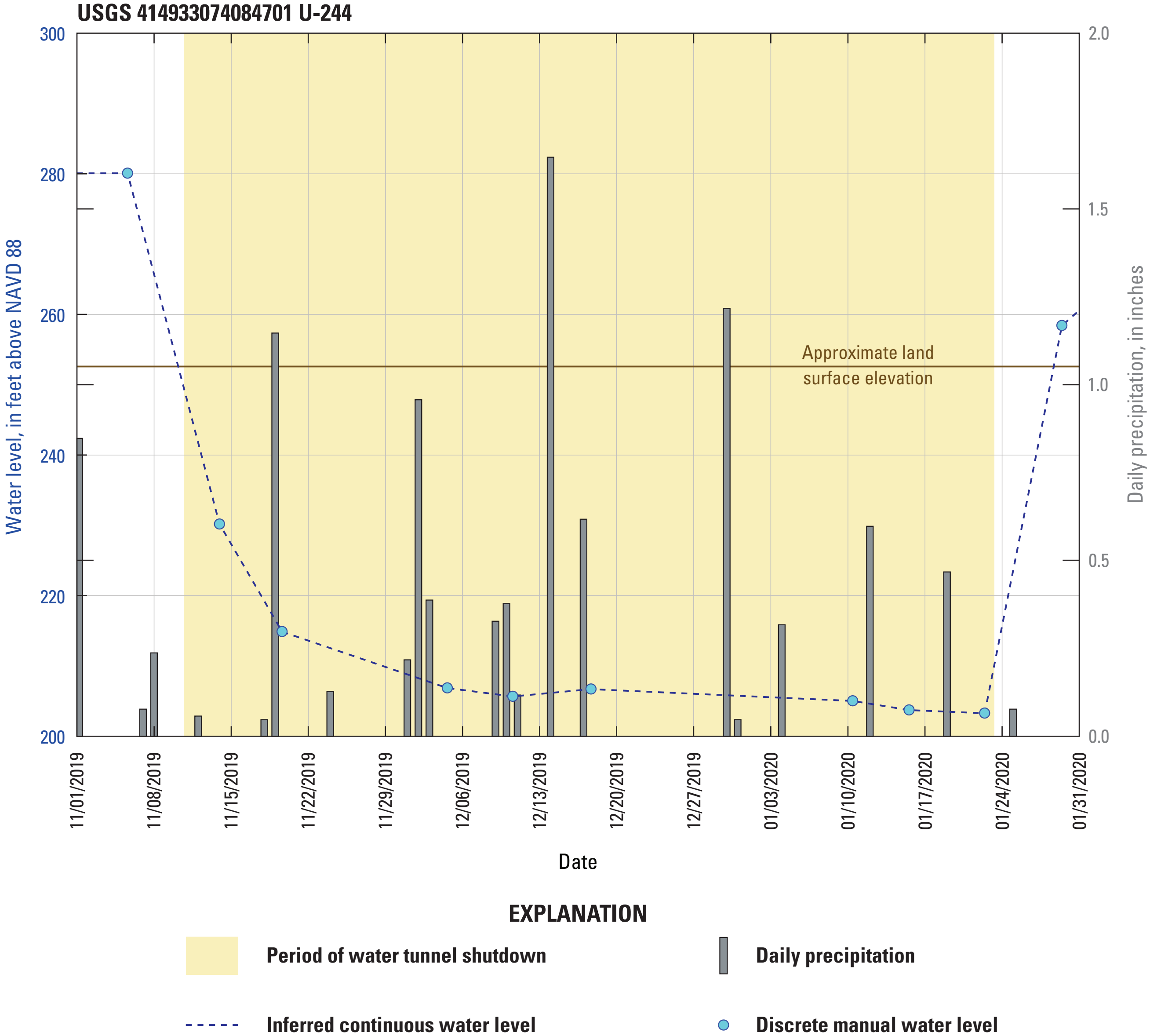

Figure 6. Plot of discrete water levels for domestic-supply well U-244 compared to daily precipitation at the Mohonk Lake Cooperative Weather Station, Ulster County, New York, from November 1, 2019, to January 31, 2020. The locations of the well and weather station are shown on sheets 1–3. Dates shown as month/day/year. NAVD 88, North American Vertical Datum of 1988; USGS, U.S. Geological Survey.

Shutdown of the Rondout Pressure Tunnel

The Rondout pressure tunnel was shut down and partially dewatered for maintenance by NYCDEP beginning on November 11, 2019, and it was put back into service (repressurized) on January 23, 2020. This 74-day shutdown was the second of at least four shutdowns planned for the Catskill Aqueduct during the study period. During this shutdown period, the USGS measured water levels from a 31-well bedrock-aquifer-monitoring network.

Precipitation

The Mohonk Lake Cooperative Weather Station, located about 5 mi south of the hamlet of High Falls (see location map of sheets 1–3), has collected precipitation data since it was established in 1896 by the U.S. Weather Bureau (Mohonk Preserve, 2021). The total precipitation recorded at the station from November 1, 2019, to January 31, 2020, a timespan that includes the 74-day tunnel shutdown, was 9.97 in. (Feldsine, 2021; Feldsine and Long, 2021). The station recorded more than 1 in. of precipitation on three separate days, all in 2019 (figs. 2–6); the maximum precipitation value of 1.65 in. was measured on December 14, whereas 1.22 and 1.15 in. were measured on December 30 and November 19, respectively. Four of the 21 days that had precipitation were measured at between 0.5 and 1.0 in.; these events, which occurred on December 2, November 1, and December 17, 2019, and on January 12, 2020, were measured at 0.96, 0.85, 0.62, and 0.60 in., respectively. The remaining 14 days of precipitation were measured at less than 0.5 in. each.

Precipitation events produced no definable response at wells U-7770 (fig. 5), U-244 (fig. 6), U-262 (fig. 3), or U-263 (fig. 4); however, the hydrographs for these wells showed some of the greatest responses to the tunnel shutdown. Additionally, the hydrograph for U-261 (fig. 2) may have showed a muted response to the tunnel shutdown but showed no definable response to precipitation.

Sheet 1—Elevation of the Potentiometric Surface in the Bedrock Aquifer near High Falls, New York, November 2019

Water-level measurements were made at 30 of the 31 wells in the bedrock-aquifer-monitoring network during November 5–7, 2019. Four wells in the network (U-135, U-244, U-245, and U-259) were flowing, but a representative water level could not be obtained at well U-135 because a substantial amount of hydraulic pressure was lost to leakage in the annular space of the well. Water levels in the network ranged from 78 to 346 ft above NAVD 88, with the lowest and highest values measured at wells U-2992 and U-266, respectively. Water levels at the three measurable flowing wells in the network ranged from 13 to 25 ft above the measuring point, with the lowest and highest values measured at wells U-245 and U-244, respectively. Three of the four flowing wells (U-135, U-244, and U-245) are within 1,500 ft of the suspected tunnel leak near shaft 4 and potentially penetrate limestone of the Helderberg Group. In addition to being proximal to shaft 4, wells U-135 and U-244 are also along the line of the Rondout pressure tunnel. Well U-259, which is about 4,000 ft southwest of shaft 4 and the Rondout pressure tunnel, may also penetrate the Helderberg Group.

A northeast-trending mound of groundwater extends from well U-245, about 1,500 ft southwest of shaft 4, to wells U-262 and U-274, approximately 8,500 ft and 7,900 ft northeast of shaft 4, respectively. Both wells are about 7,000 ft from the Rondout pressure tunnel and shaft 3. This approximately 2-mi-long, 0.7-mi-wide groundwater mound trends northeastward along the regional strike of the bedrock units and ranges in elevation from about 250 ft near well U-245 to a maximum elevation of 302 ft above NAVD 88 near well U-7770, about 2,700 ft north of shaft 4. Drilling records and the cross section of the tunnel-line geology (Fluhr and Terenzio, 1984) indicate that well U-7770 may partially penetrate the Helderberg Group.

A groundwater mound may exist in the vicinity of shaft 2, as indicated by the hydrograph of well U-263. Well U-263 is about 500 ft from the tunnel orthogonally and about 700 ft due north of shaft 2. An unconsolidated aquifer (a lacustrine delta composed of stratified gravel, sand, silt, and clay) overlies the Onondaga Limestone in this part the study area (Cadwell, 1989; Connally, 2011). Although no driller’s log was available for well U-263, records were analyzed for domestic-supply wells U-2117 and U-1760 (neither shown on the map sheets) (NYSDEC, 2021), located within 400 ft of well U-263 to the north and northwest, respectively. The drilling records for both sites indicate the domestic-supply wells were completed in a limestone bedrock aquifer after penetrating about 80–150 ft of unconsolidated deposits.

It is unclear whether this groundwater mound is related to the suspected tunnel leak near shaft 4, located about 9,000 ft southeast of well U-263, or if the mound was caused by another source of artificial recharge to the bedrock aquifer. It is suspected that the groundwater mound is distributed along regional bedrock strike northeast and southwest of well U-263. To better understand the magnitude and extent of this mound, the bedrock-aquifer-monitoring network could be extended along regional strike in the vicinity of well U-263 and shaft 2.

Sheet 2—Elevation of the Potentiometric Surface in the Bedrock Aquifer near High Falls, New York, January 2020

Water-level measurements were made at each site in the 31-well bedrock-aquifer-monitoring network on January 21–22, 2020. Water levels in the network ranged from 79 to 349 ft above NAVD 88, with the lowest and highest values measured at wells U-2992 and U-266, respectively. Of the four wells flowing on November 5–7, 2019, only well U-259 was still flowing on January 21–22, 2020. The water level in well U-259 was about 4 ft above the measuring point. Water levels in the other three wells (U-135, U-244, and U-245) had declined and leveled off at about 200 ft above NAVD 88 by January 21–22, 2020, indicating quasi-equilibrium conditions. None of the flowing wells have continuous water-elevation records. These wells potentially penetrate the Helderberg Group and are near the high-angle thrust fault and incompetent bedrock adjacent to the aqueduct between shafts 3 and 4. During construction, a steel interliner was installed in this section of the aqueduct to help suppress inflows of 1,650 gal/min (Fluhr and Terenzio, 1984).

The approximately 2-mi-long and 0.7-mi-wide, northeast-trending groundwater mound near shaft 4, identified when the Catskill Aqueduct was operating on November 5–7, 2019 (sheet 1), had decreased in magnitude and extent by January 21–22, 2020 (sheet 2). This resulted in a flattening of the potentiometric surface, represented by two remnant plateaus that are northeast-trending and partially overlie the aqueduct near shafts 3 and 4. The first plateau is represented by a partly inferred, closed contour at 240 ft above NAVD 88 that encircles well U-7770 and is constrained to the west by the water level in well U-8877 (sheet 2). This 240-ft plateau extends from the aqueduct (between shafts 3 and 4 near well U-8877) northeastward towards wells U-262 and U-274, which previously defined the north slope of the groundwater mound (sheet 1). The extent of the inferred closed contour between wells U-7770, U-262, and U-274 is unknown because groundwater-level measurements were not collected in this part of the study area. The second plateau, represented by another closed contour at 200 ft above NAVD 88, partly overlies the tunnel near shaft 4 and is defined by wells U-135 and U-244 (sheet 2); the southwestern extent of the plateau is defined by well U-245, which previously defined the southwestern extent of the groundwater mound when the aqueduct was operational. On January 22, 2020, the water level in well U-245 was in flux owing to recent pumping for domestic supply; however, it was conservatively estimated to be at about 200 ft above NAVD 88 on the basis of the rate of recovery in previous pumping cycles and previous measurements during ambient conditions. Both plateaus are interpreted as remnants of the groundwater mound determined from the November 2019 hydrologic conditions (sheet 1) as it returned to near-equilibrium conditions when the tunnel was not operational during January 2020 (sheet 2).

Sheet 3—Water-Level Change in Wells Potentially Influenced by Tunnel Leakage in the Bedrock Aquifer near High Falls, New York, November 2019–January 2020

Water-level measurements collected during January 2020 (sheet 2) were subtracted from the measurements made in November 2019 (sheet 1) to determine the potential effect of tunnel leakage on the bedrock aquifer adjacent to the Rondout pressure tunnel. The differences are plotted on sheet 3 as graduated symbols whose sizes are proportional to the magnitude of the water-level change. Hydrographs of the wells shown on sheet 3 were also analyzed to help determine if each well is potentially affected by tunnel leakage. For clarity, only the wells potentially affected by tunnel leakage are plotted on the map. Well U-135 is potentially affected by tunnel leakage, but a representative water level could not be obtained for it during November 5–7, 2019, so a water-level difference could not be calculated for this well. Qualitative observations of the well indicated that it was flowing on November 5–7, 2019, and not flowing on January 21–22, 2020. The depth-to-water at well U-135 was about 50 ft (or about 201 ft above NAVD 88) on January 21–22, 2020.

The extent of the tunnel-leakage influence on the bedrock aquifer appears to roughly trace the extent of the northeast-trending groundwater mound depicted on sheet 1 that extends from near well U-245 to wells U-262 and U-274. However, the tunnel-leakage influence may extend (1) across Rondout Creek, about 10,000 ft southwest of shaft 4, to well U-261 (fig. 2); (2) about 3,300 ft southeast of shaft 4 and 800 ft northeast of the tunnel line to well U-257, which penetrates the Shawangunk Formation (grit); and (3) about 4,800 ft northeast of shaft 4 and 4,700 ft northeast of the Rondout pressure tunnel to well U-246 (sheet 3). The distribution of tunnel-leakage influence appears to be along the regional bedrock strike (to the northeast), primarily in the Helderberg Group and potentially in the Esopus Shale and Shawangunk Formation for wells near the tunnel line and shaft 4 (Fluhr and Terenzio, 1984). However, the lack of geologic and (or) drilling records for many of the domestic-supply wells shown on this map makes the distribution difficult to interpret, especially at a distance from the tunnel line.

Water-level differences for the wells that were potentially affected by tunnel leakage ranged from 77 ft in well U-244 (fig. 6) to 2 ft in wells U-246 and U-263 (fig. 4). Similar to the extent of the tunnel-leakage influence, the largest differences also appear to be distributed along regional bedrock strike (to the northeast). The five largest differences of 77, 61, 49, 42, and 41 ft in wells U-244 (fig. 6), U-7770 (fig. 5), U-245 (from estimated data; hydrograph not shown), U-274 (hydrograph not shown), and U-262 (fig. 3), respectively, all occurred along regional bedrock strike. The three wells that have the largest differences are also near shaft 4, at distances of 10, 2,700, and 1,400 ft (wells U-244, U-7770, and U-245, respectively). On the basis of the cross section of the tunnel-line geology (Fluhr and Terenzio, 1984), all three wells may penetrate the karstic Helderberg Group, which is characterized by secondary porosity features such as solution openings created by the circulation of groundwater through preexisting fractures and crush zones. Near shaft 4, the Helderberg Group overlays the Binnewater Sandstone and the High Falls Shale, both of which produced substantial groundwater inflows during the construction of the Rondout pressure tunnel (Fluhr and Terenzio, 1984).

Wells U-261 and U-257, located 10,000 ft southwest and 3,300 ft southeast of shaft 4, respectively, may penetrate the Shawangunk Formation. Both wells potentially penetrate the formation just east of Rondout Creek, where the grit of the Shawangunk Formation is in contact with the High Falls Shale along the tunnel line (fig. 1). The fracture network in the Shawangunk Formation may be interconnected and extensive, both laterally and with respect to depth, because of multiple high-angle thrust faults that may have disturbed the grit of the Shawangunk Formation and of adjacent bedrock units. Along the northeast-trending anticlinal ridge of the Shawangunk Formation, east of the lithologic contact between the grit and the Helderberg Group (Fluhr and Terenzio, 1984), water levels in wells U-271, U-265, U-253, and U-255 did not indicate an influence from potential tunnel leakage. In fact, in wells U-271 and U-265, water levels were 22 and 14 ft higher, respectively, in January 2020 than in November 2019.

Wells U-8877, U-251, and U-252 had water level differences of 30, 15, and 7 ft, respectively. All three wells potentially penetrate the Esopus Shale adjacent to the Helderberg Group between shafts 3 and 4, where a steel interliner was installed in the Rondout pressure tunnel during construction to help suppress inflows of 1,650 gallons per minute (Fluhr and Terenzio, 1984). These wells are within 700 ft of the tunnel line and within 3,700 ft of shaft 4.

Wells U-262 and U-274 are located within 8,500 ft and 7,900 ft of shaft 4, respectively, and both are within 7,000 ft of the tunnel line. Water levels in wells U-262 and U-274 decreased by 41 and 42 ft, respectively, between November 2019 and January 2020, ranking these as the 4th and 5th largest differences of all wells potentially affected by tunnel leakage in the study. Water levels in these wells defined the north slope of the groundwater mound that was present when the tunnel was operational during November 2019 (sheet 1). The maximum water level of the groundwater mound was 302 ft above NAVD 88, measured in well U-7770 on November 5–7, 2019, when the tunnel was operational. By January 21–22, 2020, the water level in this well dropped to 241 ft above NAVD 88 (sheet 2), indicating a potential influence from tunnel leakage of about 61 ft (sheet 3).

Well U-263 is about 700 ft north of shaft 2 and potentially penetrates the Onondaga Limestone (NYSDEC, 2021). The School aquifer overlies the bedrock aquifer in this part of the study area. Water levels in this well indicated a potential influence from tunnel leakage of about 2 ft. It is unclear if this potential influence is from the suspected leak near shaft 4, from another local source of tunnel-related recharge, or from both. Additional study is required to better understand the hydraulic connection between the bedrock and School aquifer, and whether either aquifer is affected by leakage from the Rondout pressure tunnel.

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Appendix 1. List of monitoring stations used in study

Table 1. Station names, 15-digit U.S. Geological Survey (USGS) station identifier (ID) numbers, and links to station data in the National Water Information System (NWIS).

Station name	USGS station ID	Link to station data in NWIS
U-135	414938074085301	https://waterdata.usgs.gov/monitoring-location/414938074085301
U-244	414933074084701	https://waterdata.usgs.gov/monitoring-location/414933074084701
U-245	414926074090301	https://waterdata.usgs.gov/monitoring-location/414926074090301
U-246	414953074075001	https://waterdata.usgs.gov/monitoring-location/414953074075001
U-247	414827074074001	https://waterdata.usgs.gov/monitoring-location/414827074074001
U-249	415036074085501	https://waterdata.usgs.gov/monitoring-location/415036074085501
U-250	415020074112001	https://waterdata.usgs.gov/monitoring-location/415020074112001
U-251	414958074091501	https://waterdata.usgs.gov/monitoring-location/414958074091501
U-252	414957074092401	https://waterdata.usgs.gov/monitoring-location/414957074092401
U-253	414857074080201	https://waterdata.usgs.gov/monitoring-location/414857074080201
U-254	414939074074601	https://waterdata.usgs.gov/monitoring-location/414939074074601
U-255	414926074072701	https://waterdata.usgs.gov/monitoring-location/414926074072701
U-256	414937074073301	https://waterdata.usgs.gov/monitoring-location/414937074073301
U-257	414912074081101	https://waterdata.usgs.gov/monitoring-location/414912074081101
U-258	414747074104301	https://waterdata.usgs.gov/monitoring-location/414747074104301
U-259	414857074091401	https://waterdata.usgs.gov/monitoring-location/414857074091401
U-260	415108074082401	https://waterdata.usgs.gov/monitoring-location/415108074082401
U-261	414803074094301	https://waterdata.usgs.gov/monitoring-location/414803074094301
U-262	415052074080901	https://waterdata.usgs.gov/monitoring-location/415052074080901
U-263	415046074095701	https://waterdata.usgs.gov/monitoring-location/415046074095701
U-265	414837074081801	https://waterdata.usgs.gov/monitoring-location/414837074081801
U-266	414952074095701	https://waterdata.usgs.gov/monitoring-location/414952074095701
U-269	415032074070801	https://waterdata.usgs.gov/monitoring-location/415032074070801
U-270	414940074100001	https://waterdata.usgs.gov/monitoring-location/414940074100001
U-271	414810074084401	https://waterdata.usgs.gov/monitoring-location/414810074084401
U-274	415042074080001	https://waterdata.usgs.gov/monitoring-location/415042074080001
U-1708	414749074081301	https://waterdata.usgs.gov/monitoring-location/414749074081301
U-2992	415018074063101	https://waterdata.usgs.gov/monitoring-location/415018074063101
U-7770	414959074084401	https://waterdata.usgs.gov/monitoring-location/414959074084401
U-8877	415002074090601	https://waterdata.usgs.gov/monitoring-location/415002074090601
U-9428	414906074104401	https://waterdata.usgs.gov/monitoring-location/414906074104401