Appendix A: Geologic and Hydrogeologic Setting

The NYC West-of-Hudson (WOH) watershed region (Figure A-1) occupies the northeastern portion of the Catskill Delta in New York State. The topography of the region reflects the geologically driven dissection of the relatively flat-lying but uplifted sedimentary deposits of the Catskill Mountain plateau. The dissection of this plateau is manifested by dendritic, though locally linear, drainage patterns, which to a lesser extent, exhibits differential weathering effects corresponding to the resistive differences of the comprising bedrock units. The relatively more resistant bedrock units (i.e., coarser grained sandstones) typically form the upper elevations of ridges and upland areas, while less resistant units (e.g., siltstones) typically underlie the valley sides and floors. The interception of laterally extensive vertical and subvertical fractures by flowing water (and previously occurring glacial ice) generally exacerbate the effects of differential weathering, resulting in an extensive widening and lengthening of some valleys and tributaries. Several of the more extensive valleys within the WOH region formed the sites of NYC reservoirs. The same varied topography that afforded the establishment of reservoirs necessitated that some of the corresponding infrastructure components (e.g., tunnels) be locally routed at significant depths and through varying geologic and hydrogeologic conditions.

Geology

Geologically, the Catskill Delta refers to a geographically widespread sequence of sedimentary rocks deposited by moving water in terrestrial and shallow marine environments, primarily during the Devonian period (ca. 408 to 360 million years ago). The comprising sedimentary rocks are underlain by older (up to about 500 million years ago) sedimentary rocks that were deposited primarily in quiet marine environments. These sedimentary rock units are in turn underlain by older, non-sedimentary type rocks (i.e., Precambrian basement meta-igneous rocks). The deposition of these sedimentary rock units was followed by several different episodes of geologically-imparted stress related to regional uplift and folding, most recently followed by local loading and unloading associated with invasion of glacial ice through the region.

The bedrock units underlying the region[1,2,3,4,5] are primarily sedimentary with geologic features and topography reflective of their geologic ages (youngest to oldest are encountered shallowest to deepest, respectively), depositional origin, and subsequent topographic expression (e.g., plateau development). The shallowest sedimentary bedrock units that outcrop within and underlie the region are composed primarily of sandstone and shale units (cumulative thickness of less than 1,000 to over 2,000 feet) belonging to the Canadaway, West Falls, Sonyea, and Genesee Groups of the Late (Upper) Devonian. Anthracite coal and methane developed from fossilized plant debris has been encountered in the bedrock units of the West Falls Group in the region.

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[1] Isachsen, Y.W. and McKendree, W.G., 1977, *Preliminary Brittle Structures Map of New York, and Generalized Map of Recorded Joint Systems in New York*, New York State Museum, Map and Chart Series No. 31G.
[2] Hill, David G; Lombardi, Tracy E. and Martin, John P. 2008. *Fractured Shale Gas Potential in New York*. New York State Energy Research and Development Authority, Albany, New York.
[3] Griffing, D.H. and Ver Straeten, C.A. 1991. *Stratigraphy and Depositional Environments of the Lower Part of the Marcellus Formation (Middle Devonian) in Eastern New York State*. State University of New York.
[4] Rickard, Lawrence. 1975. *Correlation of the Silurian and Devonian Rocks in New York State*. State University of New York; New York State Museum Map and Chart Series Number 24.
[5] NYCDEP Record Drawings for WOH Infrastructure.

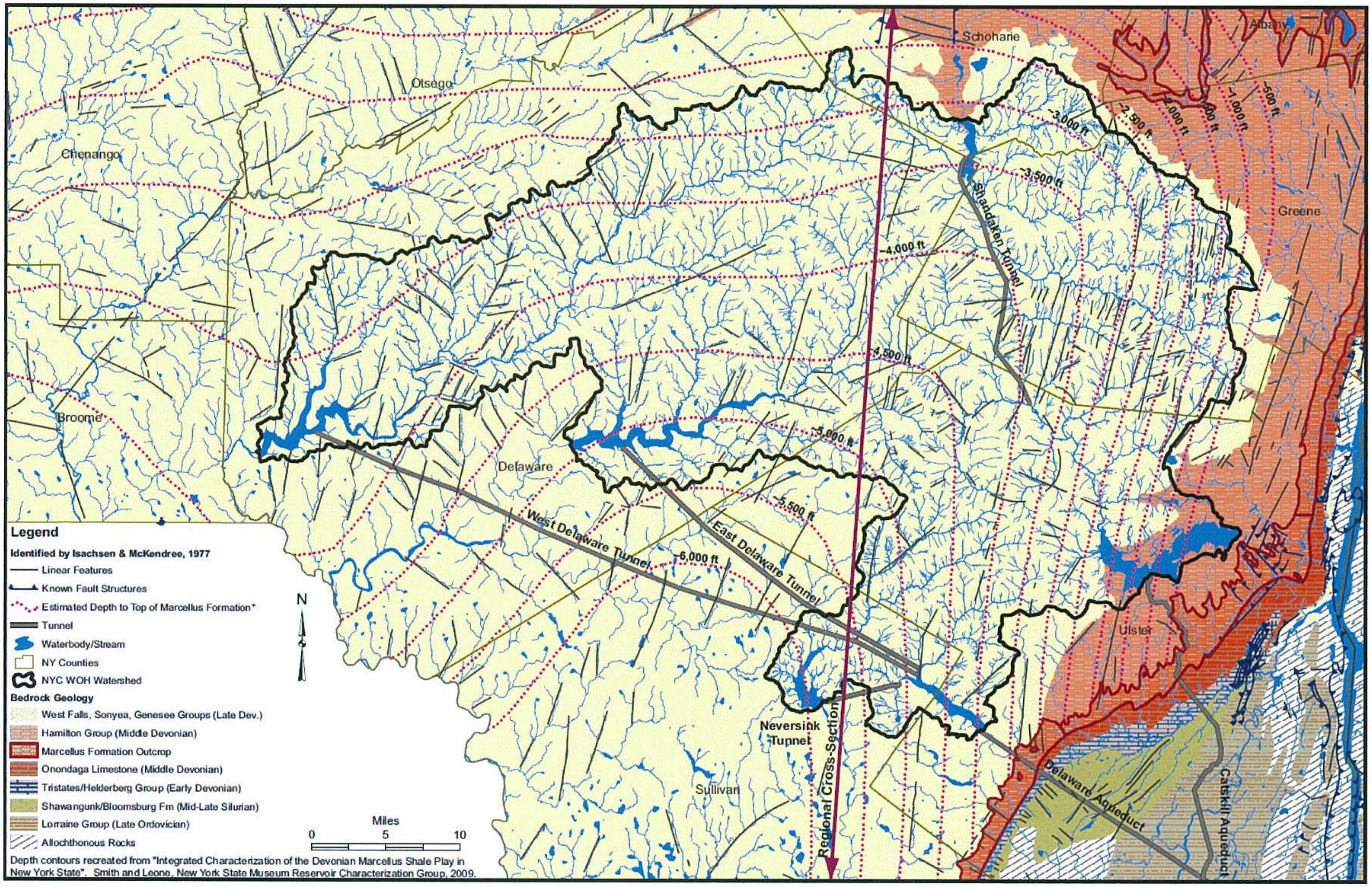

Figure A-1: Bedrock Geology of the Catskill Region

The Late Devonian strata in the region are underlain by the Middle Devonian aged rocks of the Hamilton Group (composed primarily of shale and sandstone units belonging to the Plattekill, Ashokan, Mahantango, Mt. Marion, and Marcellus Formations), and the Onondaga group (composed primarily of limestone units). The cumulative thicknesses of the rock units comprising these two groups are typically upwards of several thousand and several hundred feet, respectively. The Middle-Devonian Hamilton and Onondaga Groups are in turn underlain by Early Devonian, Silurian, Ordovician, and Cambrian Age sedimentary bedrock units that are described in detail in the RIA. The oldest of these sedimentary bedrock units consisting of Cambrian Age rocks, overlie Precambrian basement bedrock (meta-igneous rocks) occurring in the region at depths typically in excess of 9,000 feet.[6,7]

The rocks of the Genesee, Sonyea and West Falls Groups form the geologically youngest of the underlying formations, and as such are typically encountered at higher elevations and at shallower depths. Locally, these younger formations along with overlying unconsolidated deposits of glacial and alluvial formation are the most relevant as local sources of groundwater supply and are in closest communication, both hydrogeologically and hydrogeochemically, with the local surface water bodies. The underlying and older bedrock formations, typically starting with the Middle-Devonian aged bedrock and continuing through the Ordovician-Cambrian bedrock units crop out (i.e., are exposed at the surface) along the eastern and northern periphery of the Catskill Delta and WOH region. From their intersection with the surface, these units dip (slope) gently toward the west and south taking on a generally flat attitude (low slope angle) within the region.

Unconsolidated material (i.e., overburden), largely of glacial and fluvial (i.e., recent stream deposits) origin, typically overlies the bedrock underlying the valley floors and sides throughout the region. In the upland areas and on valley sides, the bedrock is either exposed or typically overlain by till (directly deposited by glacial ice) ranging from several inches to several feet thick. The till generally consists of a poorly sorted mixture of clay through boulder size material. Along the bottoms of the valleys, stream-deposited sediments (i.e., alluvium) can form a shallow aquifer. In contrast to the till, these materials are generally comprised of well-sorted deposits of clay through gravel and cobble size materials, which can occur in layers. Thicknesses of the alluvium reportedly can exceed 30 feet in parts of the region, and extend laterally for tens of feet.

Bedrock Fractures

Many of the beds comprising the sedimentary geologic formations underlying the region are typically separated by planar discontinuities (i.e., bedding planes) formed during the deposition and compaction of the sediments comprising these bedrock units. These bedding planes generally tend to slope (dip) towards the southwest at angles ranging from 8° to 15° from the horizontal. In addition, the bedrock units are also broken by steeply inclined to near-vertical fractures (e.g., faults, joints, "brittle structures") formed in response to regional (i.e., tectonic) stresses. In many areas, the orientations of these steeply dipping fractures follow a regular pattern, which can be related to the intensity and direction of the formative stress field and

[6] Kreidler, Van Tyne, and Jorgansen. 1972 *Deep Wells in New York State*. New York State Museum and Science Service; Bulletin Number 418A.
[7] Bridge, J.S. and Willis, B.J., 1991. *Middle Devonian Near-shore Marine, Coastal, and Alluvial Deposits, Schoharie Valley, Central New York State*. State University of New York.

corresponding rock types. In particular, the Marcellus Formation and other Devonian Bedrock units tend to exhibit a dominant fracture (e.g., joint) orientation in the direction of 65° to 85° northeast (aka "J1" and "Set III").[8,9,10] Two secondary sets of fractures occurring in the bedrock units are reportedly oriented 0° to 20° north-northeast and 40° to 60° northwest. The distribution and frequency of over 300 readily recognizable "brittle structures" in the WOH region as identified by the NYSGS corroborate the reported dominant fracture orientations (Figure A-2).

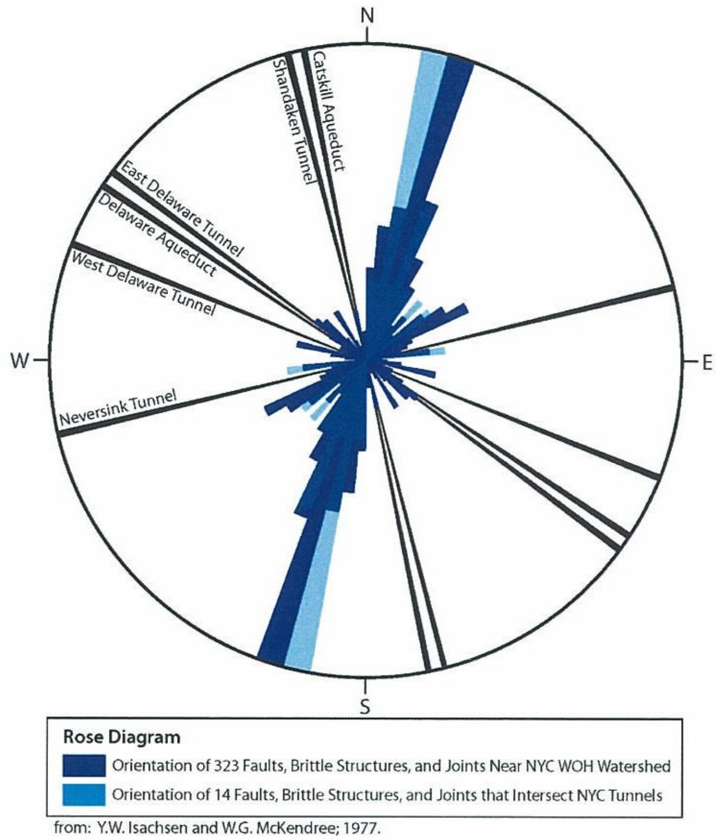

Figure A-2: Rose Diagram of Mapped Brittle Features for the WOH Watershed Area and Infrastructure

The fractures and brittle structures in the region commonly extend laterally for distances in excess of several miles and vertically to depths in excess of 6,000 feet (Figure A-3). In addition, the spacing between joints and fractures belonging to the dominant systems can be on the order of several feet to tens of feet. As such, some of these fractures and joints intersect one another and some cross WOH infrastructure components (Figure A-1). As indicated by the "rose diagram" presented as Figure A-2, of the approximately 323 brittle structures readily identified

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[8] Hill et al, 2008.

[9] Engelder, T., and Lash, G., 2008. *Systematic Joints in Devonian Black Shale: A Target for Horizontal Drilling in the Appalachian Basin*. Pittsburgh Association of Petroleum Geologists.

[10] Stankowski, R.J., Everett, J.R., and Jacobi, R.J., 2003. *Fracture Analysis for Petroleum Exploration of Ordovician to Devonian Fractured Reservoirs in New York State Using Satellite Imagery*. Presented at AAPG, Salt Lake City, Utah.

from surficial and topographic features in the region, at least 14 appear to intersect the NYCDEP infrastructure. Given that the process used to identify the brittle structures concentrated on a large-scale area and recognized only those observable at the land surface, it is safe to assume that even more such features occur in the region, a proportional number of which would intersect water supply infrastructure.

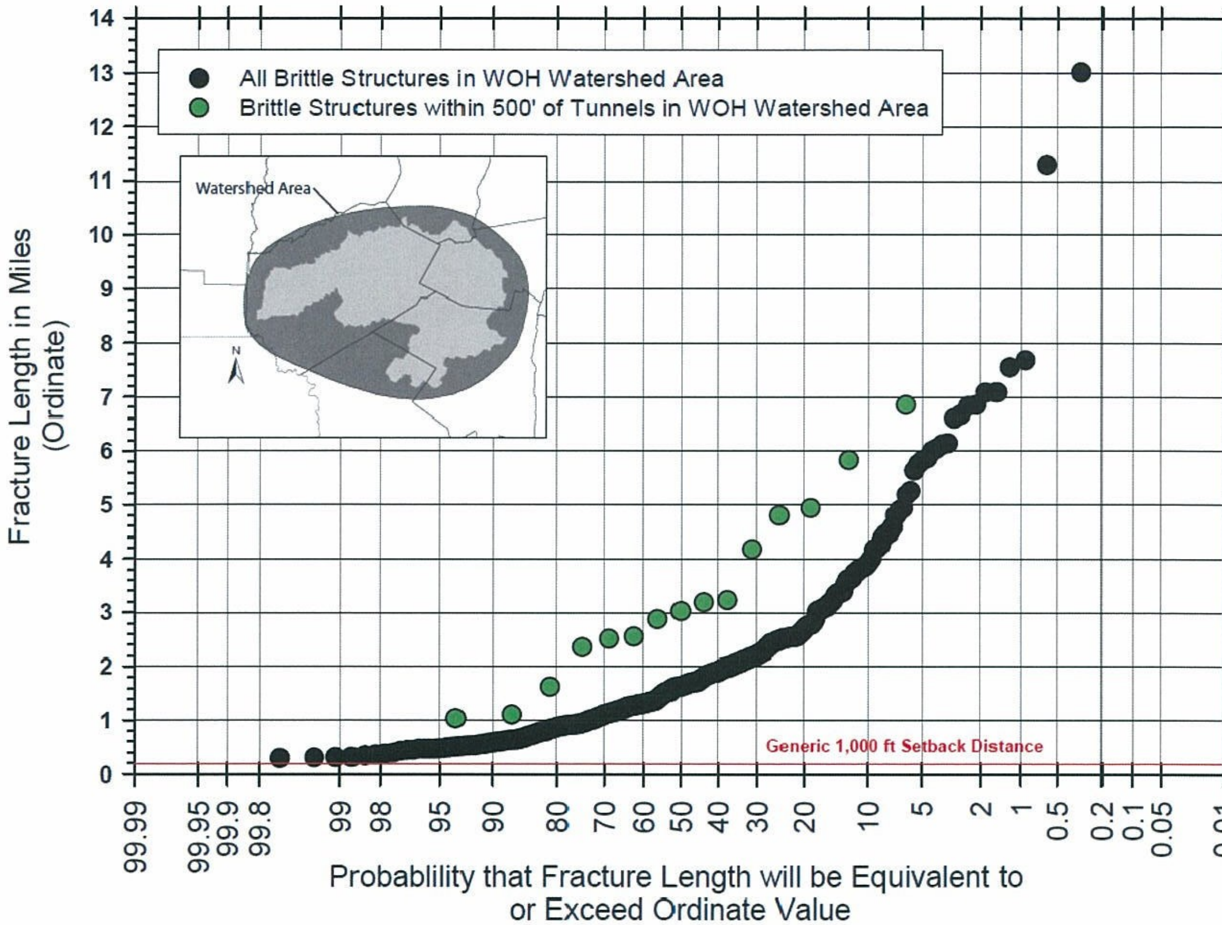

Figure A-3: Probability Plot of Mapped Brittle Feature Lengths for the WOH Watershed Area and Infrastructure

The occurrence and orientation of bedding planes and fractures are important controls on the hydraulic properties of the underlying bedrock units. The bedding planes are major discontinuities in the bedrock mass that can extend for significant distances, though their openings (aperture) can decrease with depth. The apertures of fractures in the Devonian bedrock units are typically on the order of tenths to hundredths of an inch. The relatively consistent orientation (average dip or slope of approximately 15^{o} towards the southwest) and irregularly spaced, though somewhat frequent, occurrence of the bedding planes imparts heterogeneous but relatively predictable hydrogeologic conditions in the comprising bedrock units.

As indicated by Figure A-3, the near-vertical and high-angle fractures have a greater than 80 percent probability of being over 1 mile in extent in the region. Several of the "identified" brittle structures, including some in contact with NYCDEP infrastructure, reportedly extend close to seven (7) miles in length. Hydraulic conditions favorable for the enhanced movement of groundwater and gas can be expected to occur where these fractures intersect one another and/or local bedding planes.

Natural Gas Potential

Aside from groundwater, natural gas is the most abundant resource occurring within the bedrock formations underlying the region. Locally, other fossil fuels (coal and petroleum) also occur in these same formations. Additionally, saline groundwater ("brine") characterized by high total dissolved solids, chloride and sulfate concentrations, is quite prevalent in these units, especially at depths greater than approximately 1,500 feet below grade. All of the aforementioned fluids exist in some degree of equilibrium with one another, as well as with the prevailing hydrostatic and lithospheric forces. Of the bedrock formations underlying the region, several have been identified as being consistent sources of gas and other fossil fuels. The most recently notable of these formations is the Marcellus shale (a member of the Hamilton Group).

Tight or "unconventional" shale "plays" like the Marcellus Formation generally exhibit a low permeability, which is reflective of the primary (inherent in the comprising granular makeup) and secondary (fracture controlled) porosities of the comprising rock. Such shale plays typically require well-yield stimulation (e.g., hydraulic fracturing, etc) to be commercially viable for development. In recent years, the use of horizontal drilling techniques has also been found to economically enhance product yield. Both techniques are intended to take advantage of the secondary porosity control on permeability by reopening and extending those fractures considered providing the best control of gas migration to the well.

The Marcellus Shale occurs at depths of about 500 to over 6,000 feet within the WOH region (Figure A-1). Local gas well logs indicate that the Marcellus in the region can be up to 1,000 feet thick. Another well-known gas-bearing shale play occurring within the region is the Utica shale of the Ordovician Lorraine Group, which occurs stratigraphically below the Marcellus shale. Given its generally low permeability, but naturally occurring extensive fracturing, the use of horizontal wells (to take advantage of the relatively limited thickness) and hydrofracturing have been pursued as the current methods of choice for developing the Marcellus Formation. Specifically, the preferred orientation of horizontal well tapping the Marcellus is from northwest to southeast in order to optimize penetration of the dominant northeast oriented vertical fractures (J-1). As such, hydraulic fracturing would be anticipated to direct most of its energy along these fractures, as well as the numerous bedding planes, resulting in significant increases in permeability along the respective orientations.[11]

Groundwater

Groundwater occurs within both the overburden and bedrock units underlying the region.[12,13,14,15,16] The groundwater in the underlying geologic formation is primarily recharged

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[11] Engelder and Lash, 2008.

[12] Berdan, Jean, US Geological Survey, 1961. *Ground Water Resources of Greene County, NY.* State of New York Department of Conservation Water Resources Commission Bulletin GW-34.

[13] Frimpter, M.H., 1972. *Ground-Water Resources of Orange and Ulster Counties, New York.* USGS Water-Supply Paper 1985.

by infiltrating precipitation in outcrop areas and by groundwater flow from hydraulically connected geologic formations. Depending on the location within the region, the timing of recharge influence under natural conditions can range from several days to months and years for shallow formations (overburden and Late Devonian bedrock), and upwards of tens to hundreds to thousands of years for deeper formations (Cambrian through Middle Devonian bedrock).

Overburden in the region is typically characterized by primary porosity, with permeability being directly related to dominant grain size (i.e., gravel is more permeable than clay). In contrast, the hydrogeologic characteristics and groundwater yield potential of the Upper (Late) Devonian bedrock formations in the region are primarily controlled by the combination of their relatively shallow occurrence (limited stress from overlying formations) and the dominant granular (sandstone), fractured nature of the rock units. As such, these rock units exhibit both primary and secondary porosity[17], resulting in moderate to high permeability values and recharge capacities. The Middle Devonian bedrock units, including the Marcellus Formation and deeper sedimentary bedrock formations underlying the region also exhibit primary and secondary porosity. However, because of the dominance of finer grain-size rock matrix (shale), the hydraulic characteristics of these formations are dominated by secondary porosity (fractures) associated primarily with vertical fractures and joints.

Where the influence of primary porosity prevails in the bedrock units of the region (e.g., massive sandstone, siltstone, shale), low permeability values can be expected while moderate permeability values can be expected where secondary porosity (e.g., intensely fractured and bedded rock units) prevails. The overall permeability and porosity of the deeper bedrock formations in the region can be expected to be less due to increased lithostatic pressure from overlying rock units, though vertical fractures under such conditions may increase in significance with respect to the permeability of these rocks. Illustrative of this point on the respective variability of the rock formations of the Late Devonian in the region (e.g., West Falls Group) which reportedly exhibit permeability values on the order of 10^{-3} to 10^{0} feet per day (ft/d), while the rocks of the Marcellus Formation exhibit permeability values ranging on the order of about 10^{-8} to 10^{0} ft/d.[18,19,20,21,22,23,24] The larger range in values for the Marcellus Shale is reflective of

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[14] Heisig, Paul; U.S. Geological Survey. 1999. *Water Resources of the Batavia Kill Basin at Windham, Greene County, New York*. Water Resources Investigation Report 98-4036.

[15] Soren, Julian. U.S. Geological Survey. 1961. *The Ground-Water Resources of Sullivan County, New York*. State of New York Department of Conservation Water Resources Commission Bulletin GW-46.

[16] Soren, Julian. U.S. Geological Survey. 1963. *The Ground-Water Resources of Delaware County, New York*. State of New York Department of Conservation Water Resources Commission Bulletin GW-50.

[17] Primary porosity is porosity that remains after initial deposition and rock formation and is generally attributable to the granular permeability of the rock. Secondary porosity results from fractures or other post-depositional changes to the formation.

[18] Fluer, T. and Terenzio, G., 1984. *Engineering Geology of the New York City Water Supply System*. New York State Geological Survey Open File Report 05.08.001.

[19] Gould, G. and Siegel, D.I., 1988. *Simulation of Regional Ground Water Flow in Bedrock, Southern New York - Northwestern Pennsylvania*. AWRA, Water Resources Bulletin V. 24, No. 3.

[20] Isachsen and McKendree, 1977.

[21] Heisig, 1999.

[22] Driscoll, F.G., 1995. *Groundwater and Wells*. Johnson Screens.

[23] US Dept. of the Interior, Bureau of Reclamation, 1985. *Ground Water Manual*.

the difference between permeability dominated by primary porosity versus secondary porosity, respectively. The corresponding porosity for the bedrock formations in the region reportedly ranges from 10% to less than 1%, although locally higher porosity values upwards of 20% may occur.

Variations in permeability and porosity account for the reported range in groundwater yield from the respective formations. Typically the more extensive a water-bearing fracture, the greater the groundwater yield potential. As an illustration of the role of fractures relative to groundwater yield, a fault penetrated in the Late Devonian bedrock units near the Neversink River reportedly yielded groundwater in excess of 600 gpm.

The groundwater in the bedrock units underlying the region can be expected to range from unconfined (i.e., water table) conditions to confined (i.e., artesian) conditions. Groundwater in the bedrock units underlying the region generally moves from areas of high elevation (e.g., recharge zones) to areas of low elevation (e.g., discharge zones), moving primarily through and locally in the direction of the network of lateral and vertical fractures that permeate the comprising rock formations. Water-table conditions generally prevail in the shallow groundwater bearing formations and recharge areas of the WOH watershed, while artesian conditions are generally associated with deeper formations and discharge areas. While moving through the bedrock units in recharge areas, some of the groundwater may continue vertically downward into deeper bedrock units (e.g., Middle Devonian formations), or mix with groundwater being discharged upward (artesian flow) from deeper bedrock units. Groundwater was frequently encountered during construction of the WOH tunnels. Given the depths at which these tunnels were constructed, much of the groundwater encountered most likely occurred under artesian conditions associated with fractures in the respective geologic formations.

Groundwater quality in the region is consistent with the conditions elsewhere in the Catskill Delta formation.[25] These conditions include the natural occurrence of saline groundwater [typically exhibited by TDS concentrations greater than 1,000 milligrams per liter (mg/l)] usually at depths in excess of 1,000 feet below grade, and hydrogeochemically developed gases such as methane and hydrogen sulfide. Typically, the concentrations of these substances increase directly with the depth of the geologic formations that produce and/or serve as their reservoir. Additionally, they generally occur at depths of more than several hundred feet below grade for much of the region, with the exception being areas where deeper groundwater is rising toward the surface.

Under naturally occurring conditions, the groundwater quality in the geologic formations underlying the region can vary naturally based on location, rock type, depth, and hydrologic conditions (e.g., precipitation patterns). Local variations can result in a range of concentrations of various constituents (e.g., iron, salinity, hydrogen sulfide, radon, etc.) resulting in reduced suitability for potable use. Many of these quality issues are generally related to the deeper bedrock formations (Middle and Early Devonian, Salina Group) in the region, which are typically not targeted for water supply development. However, it is not uncommon for the deeper

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[24] Michalski, A. and Britton, R., 1997. *The Role of Bedding Plane Fractures in the Hydrogeology of Sedimentary Bedrock - Evidence from the Newark Basin, New Jersey*. Ground Water, V. 35, No. 2.
[25] Rapid Impact Assessment Report.

bedrock formations to influence the water quality in the shallower bedrock formations where existing transmissive brittle structures exist.[26] Several such occurrences are documented[27] as having been encountered during construction of NYCDEP WOH infrastructure.

Hydrogeologic Flow Regimes

Local, intermediate, and regional flow regimes are all present within the NYCDEP WOH watershed. Most of the water supply infrastructure occurring at depth is likely within the intermediate or regional flow regimes. In the intermediate and regional flow regimes, flow through interconnected fractures penetrating the Late Devonian formations extends downward into the shale and sandstone units of the Middle Devonian Formations that comprise the Hamilton Group. As per the Conceptual Hydrogeologic Model described in the *Rapid Impact Assessment Report*, lateral groundwater flow in these Middle Devonian units will discharge into the larger order stream valleys, such as Schoharie Creek, whereas vertical groundwater flow in these Middle Devonian units will move downward into the underlying Marcellus Shale. The potential for groundwater flow occurring within the Marcellus Shale to discharge naturally to the surface within the region is anticipated to occur locally and be dependent on the occurrence of significant fractures and other brittle structures. Evidence of such naturally-occurring discharge is repeatedly found in the record drawings for the NYCDEP infrastructure where reports of saline groundwater and methane gas are documented.

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[26] Kantrowitz, I.H. 1970. *Ground-Water Resources in the Eastern Oswego River Basin, New York*, prepared for the Eastern Oswego Regional Water Resources Planning Board.
[27] Fluer and Terenzio, 1984