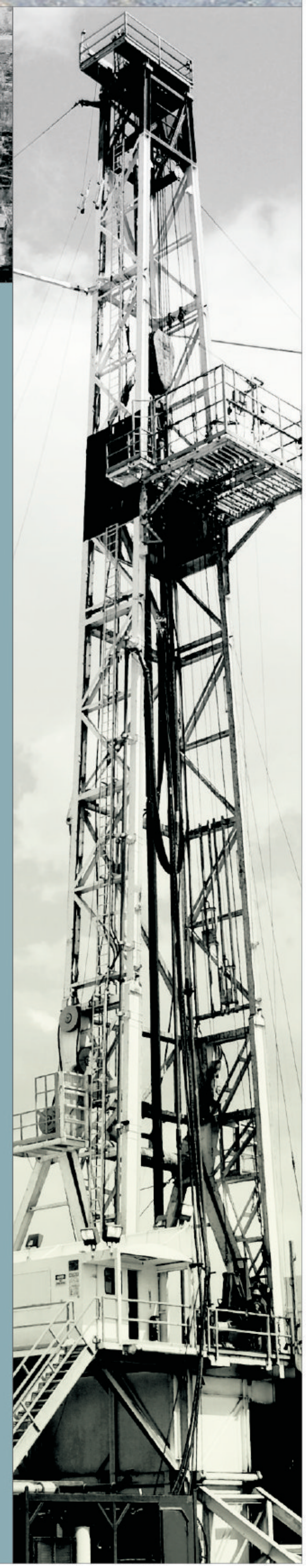
New York City Department of Environmental Protection



FINAL IMPACT ASSESSMENT REPORT

Impact Assessment of Natural Gas Production in the New York City Water Supply Watershed

December 2009

HAZEN AND SAWYER
Environmental Engineers & Scientists

LBG

a joint venture

New York City Department of
Environmental Protection

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Executive Summary

This report presents the results of an assessment performed by the New York City Department of Environmental Protection (NYCDEP) and its consultants, the Joint Venture of Hazen and Sawyer, P.C., and Leggette, Brashears and Graham, Inc., evaluating potential impacts to the NYC water supply resulting from development of natural gas resources in the Marcellus shale formation. The Marcellus[1] shale is one of the largest potential sources of developable energy in the U.S. and covers an area of 95,000 square miles; the New York State portion is approximately 18,700 square miles. The Catskill and Delaware watersheds that provide 90 percent of New York City's unfiltered drinking water supply are underlain by relatively thick sections of the Marcellus that are expected to have high gas production potential and be targeted for development. Within the watershed, there are approximately 1,076 square miles that are not currently protected and are potentially available for the placement of well pads, impoundments, chemical storage, and other elements of natural gas drilling.

Development Activities

Based on densities of development in other shale gas formations in the United States, the area of unprotected or nominally developable land in the watershed, and the number of wells needed to efficiently exploit the resource, it is estimated that between 3,000 and 6,000 gas wells could be constructed in the watershed in the next two to four decades. Initial rates of development would be relatively low (5 to 20 wells per year), but could escalate rapidly to 100 to 300 or more wells per year under favorable economic and regulatory conditions.

Extraction of natural gas from the Marcellus and other shale formations relies on horizontal drilling and high-volume hydraulic fracturing (fracking). A Marcellus well in the New York City (NYC) watershed region would likely be drilled vertically to a depth of 4,000 to 6,000 feet, and extend horizontally a comparable distance through the target shale formation. Natural gas extraction requires that the shale be hydraulically fractured along the lateral portion of the well to increase the permeability of the shale and allow gas to flow into the well at economically viable rates. The fracturing process involves pumping three to eight million gallons (MG) of water and 80 to 300 tons of chemicals into the well at high pressures over the course of several days. Roughly half the injected solution returns to the surface as "flowback" water containing fracturing chemicals plus naturally occurring and often very high levels of total dissolved solids, hydrocarbons, heavy metals, and radionuclides. Flowback water is not amenable to conventional wastewater treatment, and must be disposed of using underground injection wells or industrial treatment facilities. The region currently has insufficient treatment and disposal capacity to handle the expected wastewater volumes.

Water for the fracturing process is typically drawn from surface water bodies and trucked to the drill site; local groundwater supplies may also be used if available. Hauling of water, wastewater, and equipment to and from the drill site requires on the order of 1,000 or more truck trips per well. The entire process, from site development through completion, takes approximately four to ten months for one well. Multiple horizontal wells are typically drilled from a common well pad roughly five acres in size. One multi-well pad can accommodate six or more wells and can

[1] It should be noted that there are other gas-bearing formations such as the Utica Shale that may be targeted for development in the future.

recover the natural gas from a spacing unit covering a maximum of one square mile. New York requires that all wells from a pad must be drilled within three years of the first well, so sites will experience a relatively high and constant level of heavy industrial activity for at least one and up to three years. The fracturing process may be repeated multiple times over the life of a well to restore declining gas production rates. Wells will generally discharge poor quality brine water from the target formation over their useful life.

Table ES-1, described in more detail in Section 4.1, illustrates the magnitude of cumulative water, wastewater, and chemical volumes associated with large-scale hydraulic fracturing operations for a 6,000 well "full build-out" scenario, with and without refracturing.

Table ES-1: Cumulative Water, Wastewater, and Chemical Volumes Associated with Hydraulic Fracturing

Parameter (units) *Estimate (source)*	Without Refracturing	With Refracturing	
		10-Year Interval	5-Year Interval
Total Number of Wells	6,000	6,000	6,000
CUMULATIVE BASIS			
Total Number of Frack Jobs *Full build-out, high scenario*	6,000	24,000	48,000
Frack Chemicals Used (tons) *1.0% of fracture fluid*	1,000,000	4,000,000	8,000,000
Waste TDS (tons) *100,000 mg/l TDS (dSGEIS)*[2]	12,510,000	27,522,000	47,541,000
ANNUAL BASIS[1]			
Water Demand (mgd) *4 MG per frack job*	3.6 to 5.5	5.5 to 8.2	11.7 to 14.2
Wastewater Production (mgd) *50% Flowback + 0.075 MG/yr Produced Water*	2.6 to 3.5	3.9 to 5.3	6.7 to 8.4
Waste TDS for Disposal (tons/day) *100,000 mg/l TDS in waste (dSGEIS)*[2]	1,100 to 1,500	1,600 to 2,200	2,800 to 3,500
Water Req'd to Dilute TDS to 500 mg/l (mgd)	500 to 700	800 to 1,100	1,300 to 1,700
Frack Chemicals (tons/day) *1.0% of fracture fluid*	150 to 230	230 to 340	490 to 590

Notes:
1. Ranges describe the median and the maximum of the annual average values for each development year. Data for the no-refracturing scenario are drawn from the 20-year period of well development. Data for the refracturing scenarios are drawn from the full 60-year period of development and refracturing.
2. The dSGEIS reports median and maximum values of TDS as 93,200 mg/l and 337,000 mg/l, respectively. The concentration of TDS in flowback reportedly increases with time. The determination of median value may include relatively low concentration samples from initial flowback.

Potential Impacts

The West-of-Hudson watershed is a pristine, largely undisturbed landscape, with only minimal industrial activities. These natural and land use factors combine to yield water of very high quality with little or no chemical contamination. Natural gas well development in the West-of-Hudson watershed at the rates and densities observed in comparable formations will be accompanied by a level of industrial activity and heightened risk of water quality contamination that is inconsistent with the expectations for unfiltered water supply systems.

Intensive natural gas well development in the watershed brings an increased level of risk to the water supply: risk of degrading source water quality, risk to long-term watershed health and the City's ability to rely on natural processes for what is accomplished elsewhere by physical and chemical treatment processes, risk of damaging critical infrastructure, and the risk of exposing watershed residents and potentially NYC residents to chronic low levels of toxic chemicals. In addition to surface risks to the watershed, extensive hydraulic fracturing of horizontal wells will present subsurface contamination risks via naturally occurring faults and fractures, and potential alteration of deep groundwater flow regimes, as indicated by the geological cross-section presented as Figure ES-1.

Each of these risks is discussed in greater detail in this document. They have been identified based on review of the progression of natural gas development in other areas, documented incidents of surface water and shallow groundwater contamination associated with natural gas resource development, and review of regional geological features. NYC operates over 100 miles of water supply tunnels west of the Hudson River, the construction of which provided direct experience with respect to faults and deep fluid migration through bedrock. The assessment of risks to the City's water supply system takes into account seepages of methane and deep formation water, and faults and other natural geological features encountered during tunnel construction. As shown in Figure ES-2, water supply tunnel routes intersect numerous geological faults and fractures, many of which extend laterally for several miles, and vertically through several underlying geological strata. Each of these features represents an existing potential pathway for fluid migration.

The difficulty of remediating diffuse contamination and other risks once allowed into the environment, and the potentially catastrophic consequences of damage to critical water supply infrastructure, make clear that a conservative approach towards natural gas drilling in the NYC watershed and in the vicinity of infrastructure is warranted. In short, the rapid and widespread industrialization of the watershed resulting from natural gas drilling would upset the balance between watershed protection and economic vitality that the City, its State and federal regulators, and its upstate partners have established over the past 15 years.

Development of natural gas resources using current technologies thus presents potential risks to public health and would be expected to compromise the City's ability to protect the watershed and the continued, cost-effective provision of a high-purity water supply. A robust assessment of risks from drilling would consider site-specific factors assessed on a well-by-well basis and would consider detailed knowledge of local fracture, infrastructure, hydrologic, and other conditions at a finer scale than watershed-level analysis. In recognition of the possibility that horizontal drilling and hydraulic fracturing may one day be allowed to proceed, measures for reducing some, but not all, risks to water quality and water supply infrastructure are summarized in an appendix.

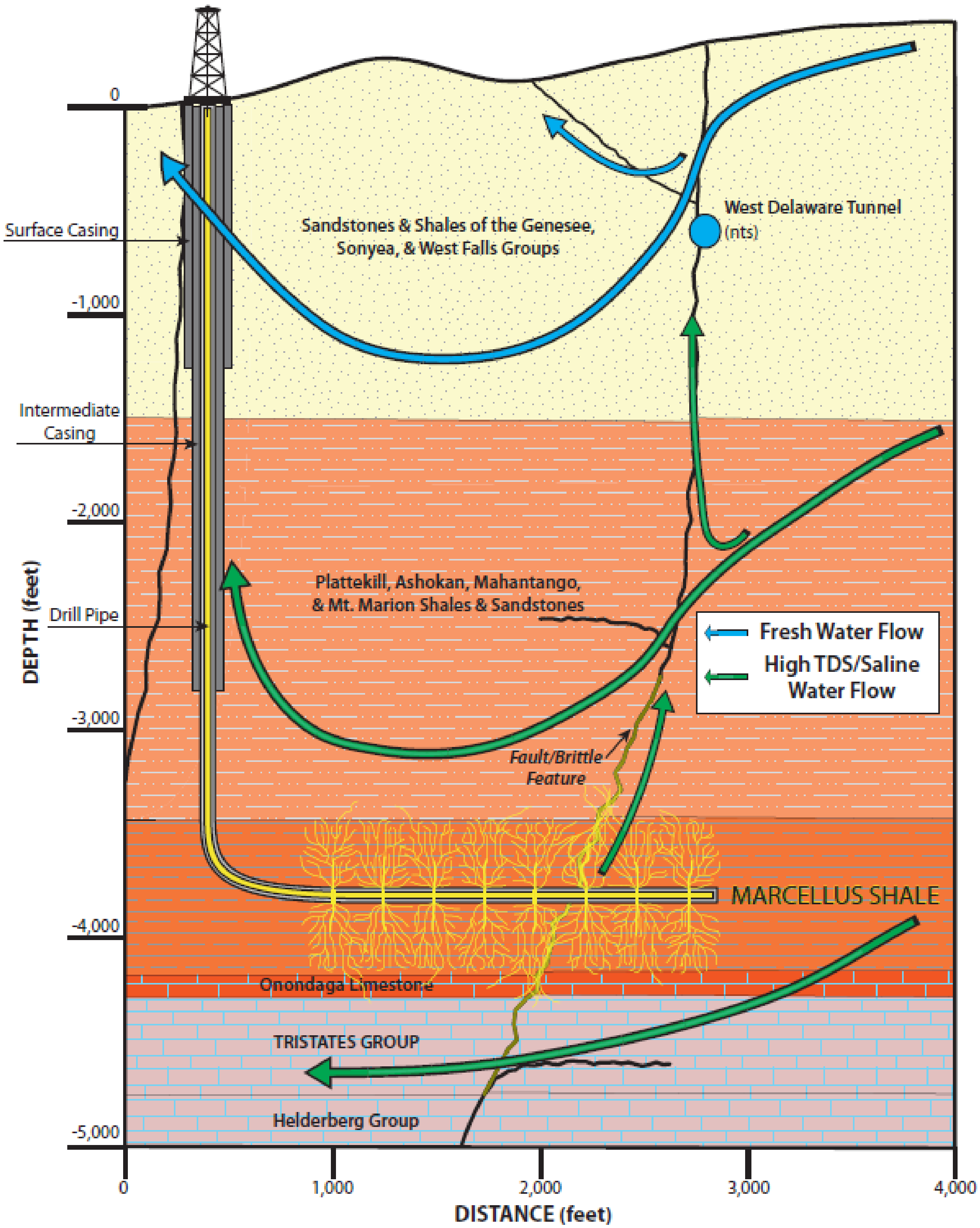

Figure ES-1: Potential Flow Disruption and Contamination Mechanisms

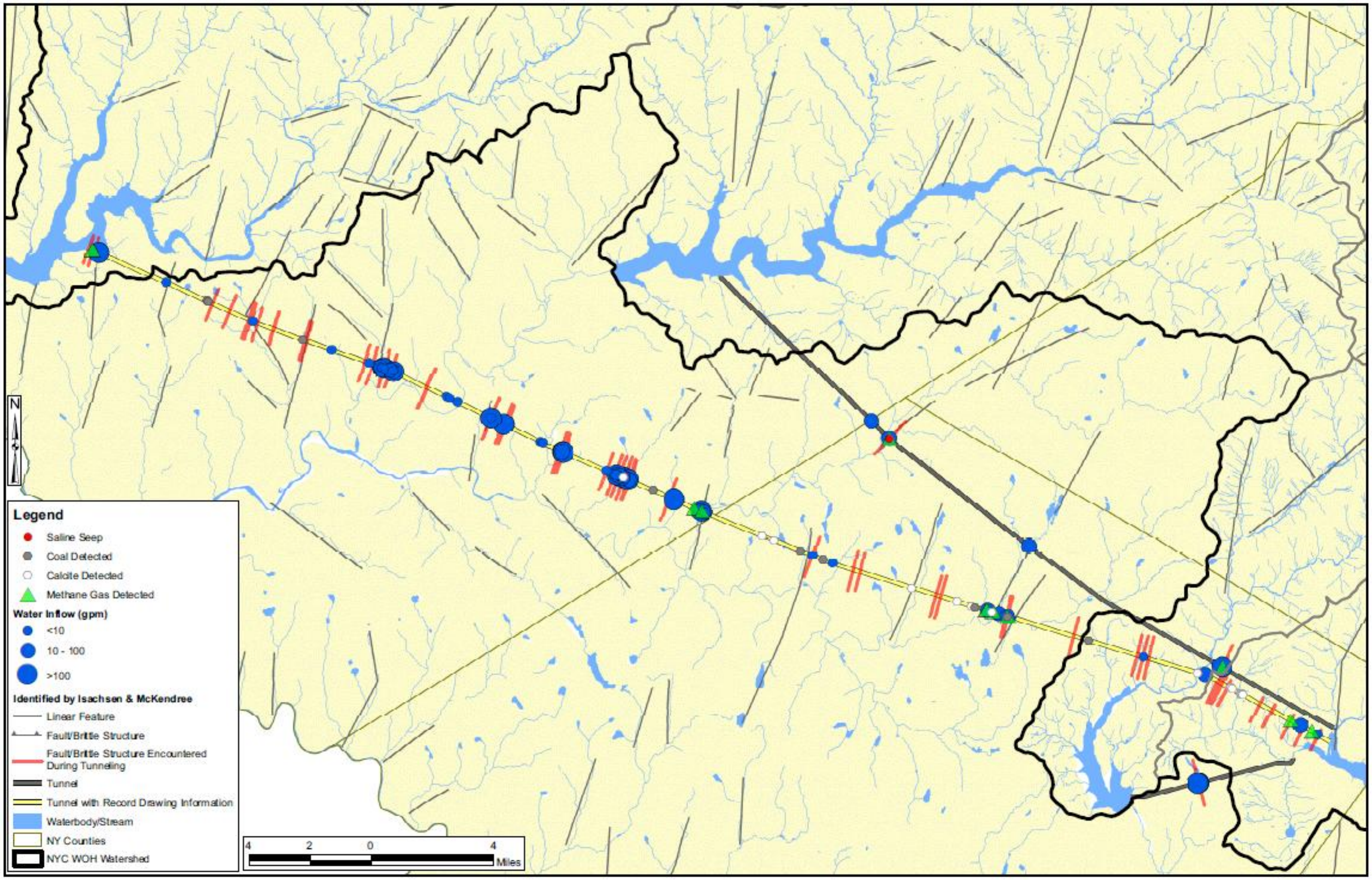

Figure ES-2: Map of the East and West Delaware Tunnels and Neversink Tunnel

Section 1: Introduction

1.1 Project Background

In recognition of increased natural gas development activity in New York State and its potential to impact New York City's water supply, the NYCDEP has undertaken the project, *Impact Assessment of Natural Gas Production in the NYC Water Supply Watershed*. Natural gas development activities have the potential to impact the quality and quantity of NYC's water supply through land disturbance, toxic chemical usage, disruption of groundwater flow pathways, water consumption, and waste generation. The overall goal of the project is to identify potential threats to the continued reliability and high quality of New York City's water supply by providing an assessment of the potential impacts of future natural gas development activities in or near the NYC watershed on water quality, water quantity, and water supply infrastructure.

NYCDEP retained the Joint Venture of Hazen and Sawyer, P.C., an environmental engineering firm, and Leggette, Brashears & Graham, Inc., a hydrogeologic and environmental consulting firm, to assist in performing this assessment. The first phase of the project included evaluation of regional hydrogeology and development of a conceptual hydrogeologic model of the region, characterization of activities and impacts associated with natural gas well development, review of a database of drilling and fracturing chemicals, examination of case studies from other formations, and preparation of a preliminary infrastructure assessment. Results from the first phase were summarized in a Rapid Impact Assessment Report issued in September 2009.

The current Final Impact Assessment Report incorporates the previous work into a cumulative watershed risk assessment and provides further evaluation of subsurface migration pathways and risks to NYC infrastructure.

1.2 New York City Water System and Source Protection Measures

The New York City water system is comprised of three separate supply systems – the Catskill, Delaware, and Croton systems. Approximately 90 percent of the City's water supply (more than one billion gallons per day) is drawn from the Catskill and Delaware systems located west of the Hudson River in upstate New York. As such, it is NYCDEP's mission and responsibility to protect both the NYC water supply system and public health and safety, ensuring continued reliability in serving nine million consumers within New York City and upstate communities (in Westchester, Putnam, Orange, and Ulster Counties) who depend on the New York City system as the primary source of their drinking water. The NYC watershed is a working watershed that supports multiple uses. The 1997 Watershed Memorandum of Agreement signed by New York State Department of Environmental Conservation (NYSDEC), NYCDEP, Environmental Protection Agency (EPA), environmental parties, and numerous local governments committed the parties to foster economic development within the watershed that is consistent with principles of watershed protection.

The City's decision to pursue source water protection was based in part on the existing quality of the water and in part on the belief that keeping pollutants out of the water was in the long term a more sustainable strategy than the more conventional approach used by most water suppliers – employing treatment technologies to remove pollutants after they get in the water.

The West-of-Hudson watershed is a pristine, largely undisturbed landscape, characterized by high rates of forest cover (78 percent) and predominantly rural land uses. Development has historically been confined to the river valleys and impervious surfaces cover a mere 1.2 percent of the land area. Dairy farms are a common part of the rural landscape, particularly in the far western reaches of the watershed, and there are minimal industrial activities. These natural and land use factors combine to produce a very high quality water from the Catskill/Delaware watershed.

Beginning in the early 1990s, NYCDEP initiated development and implementation of a suite of programs designed to preserve and enhance the existing quality of the Catskill/Delaware source waters. Prior to undertaking design of protection programs, NYCDEP initiated a comprehensive water quality monitoring program. Samples were taken at various locations and frequencies to accurately characterize water quality conditions throughout the watershed. Data acquired through this effort was used to identify existing and potential pollution sources and to identify pollution control strategies. Based on monitoring data, NYCDEP identified the primary threat to water quality as coliforms, pathogens, nutrients and turbidity. To this day, those pollutants – which largely derive from natural sources, limited residential development, and agriculture – remain the primary pollutants of concern for the New York City water supply.

DEP's watershed protection program is based on water quality science supported by extensive monitoring and water quality data. Various program elements seek to either remediate existing sources of pollution or to prevent future sources. The overall program has been tailored to be mindful of and support the economic vitality of the communities and the residents of the Catskills. The major elements of the watershed protection program include:

- Land Acquisition – increasing the amount of land to be preserved in its natural condition;
- Watershed Regulations – primarily targeting stormwater and wastewater pollution from development;
- The Watershed Agricultural Program – working with watershed farmers to implement pollution control practices on farms;
- The Stream Management Program – working with riparian landowners to restore degraded streams to more natural conditions;
- The Wastewater Treatment Upgrade Program – funding the upgrade of all pre-1997 WWTPs in the watershed to state-of-the-art tertiary treatment;
- The New Infrastructure and Community Wastewater Management Programs – designing and constructing new wastewater infrastructure for communities with concentrations of failing or likely-to-fail septic systems;
- The Septic Rehabilitation Program – funding the repair or replacement of failing septic systems for individual residences and small businesses;
- The Stormwater Retrofit and Future Stormwater Controls Control Programs – seeking to address pollution from stormwater runoff, either by retrofitting existing sites or funding compliance with the Watershed Regulations; and
- The Watershed Forestry Program – working with owners of forested land to promote a vigorous forest landscape and forestry practices that are protective of water quality.

Taken together, these programs effectively address the current range of human activity in the watershed that could threaten water quality. Instrumental to the success of the City's program has been the strong collaboration between a multitude of stakeholders – watershed representatives and residents, environmental groups, regulatory agencies and NYCDEP. These partnerships are key to the success of the programs because certain elements have the potential to modify individual property rights and community growth goals. The City has worked to develop programs that strike an appropriate balance between water quality preservation and community interests.

Due to the high quality of the West-of-Hudson water supplies and the extensive watershed protection efforts of NYCDEP and numerous stakeholders, EPA has determined in successive Filtration Avoidance Determinations that NYC's Catskill and Delaware supplies satisfy the requirements for unfiltered surface water systems established in the Surface Water Treatment Rule and the Interim Enhanced Surface Water Treatment Rule. The most recent Filtration Avoidance Determination was issued in 2007 and establishes requirements for continued watershed protection efforts through 2017. A core requirement for filtration avoidance is a watershed control program that can identify, monitor, and control activities in the watershed which may have an adverse effect on source water quality.

Proof of the effectiveness of the City's approach lies in the fact that water from the Catskill/Delaware system continues to be of exceptionally high quality and is virtually free of chemical contaminants. Water supply monitoring is extensive and far exceeds regulatory requirements, both in the watershed and in the distribution system. NYCDEP operates five modern water quality laboratories throughout the watershed and distribution system, and processes approximately 50,000 samples from 1,400 sample locations for up to 240 contaminants and 600,000 analyses per year. Analyses performed include those for basic physical parameters, nutrients and metals, and tests for disease-causing organisms such as bacteria, viruses and protozoans. Additionally, the water supply is routinely scanned for synthetic organic compounds at watershed locations and throughout the distribution system. Extensive monitoring is used to ensure that NYCDEP delivers the highest quality water to the consumer and helps to instill a high degree of public confidence in the water supply system.

1.3 Trends in Drinking Water Regulations

Currently, the federal Safe Drinking Water Act requires the monitoring of about 90 contaminants in water supply systems. Additionally, the Unregulated Contaminant Monitoring Rule and the Candidate Contaminant Listing process require EPA to establish criteria for expanding the number of contaminants subject to monitoring requirements, and require EPA to make determinations on regulating additional contaminants. As a result of these rules and listing processes, as public health concerns associated with chemical contaminants continue to increase, and as analytical techniques improve, the trend will be toward more stringent drinking water regulations in the future. The number of regulated contaminants will expand and the maximum contaminant levels (MCLs) of contaminants are likely to decrease. The recent heightened national concern over pharmaceuticals and emerging contaminants, and most recently the Environmental Working Group's report on chemical contamination in water supply utilities in the United States,[2] gives a clear indication that the public's expectation is for contaminant-free drinking water. This expectation is consistent with NYCDEP's mission to deliver the highest quality water possible to the consumer.

[2] Available at http://www.ewg.org/tap-water/home.

1.4 Overview of Natural Gas Well Development

Shale formations with gas producing potential are distributed throughout much of the United States (Figure 1-1). Recent technological advances such as hydraulic fracturing and horizontal drilling, in combination with market forces, have made the development of shale gas resources economically viable. The most heavily developed shale gas "play" is the Barnett in Texas and dates back only to the late-1990s. The Fayetteville in Arkansas and the Haynesville in Louisiana and Texas are other major plays that have been more recently developed. There is currently substantial interest in the Marcellus formation because of its size and gas-producing potential.

Source: Energy Information Administration based on data from various published studies
Updated: May 28, 2009

Figure 1-1: Gas-Producing Shale Formations in the US

Shales are generally considered geologically "tight" formations with limited permeability and primary porosity.[3] Hydraulic fracturing is employed to increase permeability and porosity of the rock mass and enhance the movement of gas to the well bore. Horizontal drilling is employed to increase the areal extent from which gas can be drawn to a single well location. The Marcellus and other potential gas-producing formations underlie most of New York, and the state is currently in the process of approving horizontal drilling and high-volume hydraulic fracturing for exploiting these resources.

The natural gas development process using horizontal drilling/high-volume hydraulic fracturing is initiated in a similar manner to traditional gas exploration and includes mapping and geologic

[3] Primary porosity is the void space that remains between grains of sediment deposits after initial deposition and rock formation. Sedimentary rocks, such as the Marcellus Formation, are formed from the compaction of sediments. Secondary porosity results from fractures or other post-depositional physical changes to the formation.

analysis, seismic testing, leasing of mineral rights from landowners, and submission of well permit applications. Each well is assigned to a spacing unit, which roughly corresponds to the area of land from which the well is assumed to be extracting natural gas. For multiple horizontal wells drilled from a common well pad, as is expected for most Marcellus wells, a spacing unit of up to 640 acres (one square mile) is allowed.[4] Spacing unit requirements do not limit the number of horizontal wells that may be drilled from a multi-well pad. Instead, the total number of wells per spacing unit is governed by the number of wells needed to efficiently and economically extract the natural gas resources within a given spacing unit. Industry reports cited in the draft Supplemental Generic Environmental Impact Statement[5] indicate that six to ten wells will be developed per well pad in the Marcellus.

Initial site activities include clearing, grading, and construction of site access road, well pad, and utilities. The size of the pad is expected to be on the order of five acres. Total area requirements including well pad and related features such as roads and pipelines are estimated at seven acres per well pad based on data from the Fayetteville shale.[6] Once the site is prepared and the drill rig and ancillary equipment are set up, operators begin drilling the well. In the New York area, wells will likely consist of a 3,000- to 7,000-foot deep vertical section that extends from the surface to the target formation, plus a horizontal section that extends laterally for an additional 2,000 to 6,000 feet. The lateral section is not allowed to extend beyond a specified setback distance from the spacing unit boundary.

Construction of gas wells in the Marcellus formation requires drilling through shallow freshwater aquifers and penetrating deeper geologic formations that contain naturally-occurring contaminants such as hydrocarbons, metals, radionuclides, and high salinity. The well borehole creates a conduit for fluid to flow between these previously isolated geologic formations. To prevent such flow, the annular space between the well casing and the formation is filled with grout.

After the well is drilled, cased, and grouted, the operator proceeds with hydraulic fracturing operations to stimulate gas production. The process entails injecting a mixture of water and chemicals into the well at high pressure to create fractures in the gas-bearing formation, thus increasing its permeability and enhancing the release of gas for collection. Sand or other inert materials (i.e., proppants) are injected with the fluid mixture to prop open the fractures. A typical fracturing operation may require on the order of three to eight million gallons of water, depending on formation characteristics, lateral length, and fracture design. Water may be obtained from surface or groundwater sources; to date most fracking operations have used fresh or low salinity water.

A variety of chemical additives are added to fracking fluid to control fluid properties. Chemicals are often cited as making up 0.5 to 2.0 percent of the fracking fluid. For a four million gallon fracture operation, this translates to 80 to 330 tons (160,000 to 660,000 lbs) of chemicals per

[4] Natural gas well spacing unit requirements are defined in ECL §23-0501.
[5] Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program – Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs.
[6] U.S. Department of the Interior. 2008. *Reasonably Foreseeable Development Scenario for Fluid Minerals: Arkansas*. Prepared for the Bureau of Land Management Eastern States Jackson Field Office. March 2008.

well. The exact chemical composition of many additives is not known. Of the known chemical components, many are toxic to the environment and human health.

The active drilling and fracturing process requires on the order of four to eight weeks per well. When support activities such as site clearing and grading, pad construction, mobilization and demobilization of drill rigs and other equipment, water delivery, and waste disposal are included, the time during which a drill site can be considered active is on the order of four to ten months for one well, depending on site-specific conditions. For a multiple well pad, site activities may be sequenced such that multiple wells are under various stages of concurrent development. All wells from a multi-well pad must be completed within the three year permit period. A high volume of heavy truck traffic (approximately 800 to 1,200 trips per well) is required during the development process to convey equipment, chemicals, water, and waste to and from the site.

Wastewater disposal is a critical feature of hydraulic fracturing operations. A sizeable fraction (approximately 10 to 50 percent or more) of the original fracturing fluid volume is returned to the surface as "flowback" over a period of several weeks. Flowback water contains chemical additives and naturally occurring formation materials, including high levels of total dissolved solids, metals and naturally occurring radioactive material (NORM). Flowback water is trucked off-site for disposal at underground injection wells, certain municipal wastewater treatment plants (WWTPs), or industrial WWTPs.

When drilling and stimulation operations are complete, the drill rig and equipment are removed and the site is partially restored. If the well produces gas, pumping and treatment equipment are installed at the site and pipelines are constructed to connect the well to the regional transmission network. Tanks are also constructed for temporary storage of the "produced" water that the gas well discharges during the course of normal operation.

As the well ages and the gas production rate declines, the well may be re-fractured to boost productivity. Limited data from the Barnett shale indicates the interval between re-fracturing operations could range from one to more than ten years. The useful life of a well may be on the order of 20 to 40 years; at the end of this time the well is plugged and abandoned. For locations overlying "stacked" shale plays, which appears to be the case in the NYC West-of-Hudson watershed, it is unclear whether multiple gas-bearing formations in the "stack" would be developed simultaneously, or if development of other formations would ultimately require the service life of the site to be extended. Once there are no longer other wells or collection facilities operating on the same well pad, the site can be fully restored.

1.5 Regulatory Context for Gas Exploration and Development

Federal Regulations

Many of the activities associated with natural gas development have the potential to pollute air or water and therefore fall under the nominal jurisdiction of a number of federal environmental regulations, including the Clean Water Act, the Safe Drinking Water Act, the Clean Air Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act and the Toxic Release Inventory reporting requirements of the Emergency Planning and Community Right to Know Act. However, each of these regulations currently contain important exemptions regarding the definition, reporting, use, and disposal of the toxic chemicals required during hydraulic fracturing and other gas development activities. At this time there are few constraints on natural gas development at the federal level, and related activities are generally regulated at the state level.

State Regulations

Natural gas development in New York is regulated by the NYSDEC, which under the Environmental Conservation Law (ECL) is charged with conserving, improving and protecting natural resources and the environment, preventing water, land and air pollution, and authorizing the development of gas properties to increase the ultimate recovery of oil and gas resources.

In 1992, NYSDEC finalized a Generic Environmental Impact Statement (GEIS) on the Oil, Gas and Solution Mining Regulatory Program as part of the State Environmental Quality Review Act (SEQRA) process. At the time the GEIS was drafted, the use of horizontal drilling and high-volume hydraulic fracturing for oil and gas extraction in shale and tight sandstone reservoirs was not technologically feasible. Since that time extraction technologies have matured and led to commercially viable development of the Marcellus and other formations. In 2008, Governor Paterson directed NYSDEC to prepare a supplemental GEIS (SGEIS) to review potential additional impacts related to these technologies.

The draft SGEIS was released on September 30, 2009, and included analysis of potential impacts and established a number of permit conditions for drilling applications. Several salient conditions established in the dSGEIS include:

- A requirement for site-specific SEQRA reviews for wells within 1,000 feet of NYCDEP infrastructure, well pads within 300 feet of a reservoir, or well pads within 150 feet of other surface waters. Outside of these setbacks, no additional watershed-specific review is required (i.e., wells may be drilled anywhere else in the NYC watershed or adjacent to tunnels without additional review).
- Baseline and periodic ongoing groundwater water quality testing is required for private wells within 1,000 to 2,000 feet of a gas well.
- Operators are required to disclose to NYSDEC the fracturing products (i.e., additives) that will be used for a given well.
- Surface water withdrawals must allow a specified passby flow to maintain stream habitat.
- Various mitigation plans are required for visual impacts, noise impacts, invasive species, and greenhouse gases.

The dSGEIS is presently under review and is not anticipated to be finalized until 2010. Therefore the proposed permit conditions and mitigation requirements included in the final SGEIS may differ from those described herein.

NYC Watershed Regulations

With the exception of requiring NYCDEP approval of stormwater management plans for activities meeting certain impervious surface or disturbance thresholds, the NYC Watershed Rules and Regulations have little or no applicability to horizontal drilling and high-volume hydraulic fracturing activity in the watershed.

1.6 Report Organization

- Section 2 describes regional geology and hydrogeology and discusses pathways for subsurface migration of fracturing chemicals and formation water;
- Section 3 describes the rates and densities of natural gas well development in comparable formations, and estimates the number of wells that could be constructed in the NYC watershed on an annual basis and under a full build-out scenario;
- Section 4 presents an assessment of cumulative impacts of natural gas well development in the NYC watershed;
- Appendix A provides more detail on the geology and hydrogeology of the region;
- Appendix B provides more information on rates and densities of well development;
- Appendix C provides more detail on the analysis of surface spills; and
- Appendix D identifies potential mitigation measures for reducing the risk of impacts to the water supply.

Section 2: Area Geology

This section presents an overview of the subsurface conditions in the NYC watershed region, including evaluation of gas-producing potential, description of rock strata and geologic features, analysis of water resources, and a summary of data provided by tunnel construction records.

2.1 Shale Gas Potential and the NYC Watershed

The Marcellus formation is one of a series of "stacked" Appalachian plays that also include the Utica Shale. These formations underlie an area of approximately 95,000 square miles[7] that extends from eastern Kentucky, through West Virginia, Ohio and Pennsylvania and into southern/central New York. The Marcellus formation is estimated to contain 200 to 500 trillion cubic feet (tcf) of total natural gas reserves and is considered one of the largest potential sources of developable energy in the U.S.[8]

In New York, the Marcellus formation (Figure 2-1) lies beneath all or part of 29 counties and the entirety of the 1,585 square miles of NYC's West-of-Hudson watersheds. The maximum depth (ca. 6,500 feet) occurs along the Delaware River at the New York - Pennsylvania border, and the formation is shallowest to the east and north. The NYC watershed area is underlain by relatively thick areas of the Marcellus formation that are estimated to have relatively high gas production potential. Within the West-of-Hudson watersheds, 1,076 square miles are not protected and are subject to gas exploration and development activities. This area represents less than six percent of the approximately 18,700 square miles of the Marcellus formation that are in New York State.

Analysis of the depth, thickness, organic content, thermal maturity, and other characteristics of the Marcellus formation has been performed as part of an ongoing study by the New York State Museum.[9] Figure 2-1, which is drawn from the New York State Museum study, shows the approximate depth to the top of the Marcellus formation (top portion) and the approximate thickness of the formation (lower portion). The dotted contours also indicate the transformation ratio associated with the formation, which is an estimate of the thermal maturity of the organic material.[10] The higher the ratio, the more gas that is potentially available.

While acknowledging uncertainties that prevent precise delineation of areas with the highest gas production potential, the authors of the study suggest that drilling in New York is likely to start in the thickest and deepest areas of the formation, which includes southern Tioga, Broome, Delaware and Sullivan Counties, which border the northeast corner of Pennsylvania, before progressing north and west. These areas are also attractive for gas production because of their proximity to the Millennium pipeline and other regional natural gas transmission infrastructure.

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[7] ALL Consulting, Groundwater Protection Council. (2009). *Modern Shale Gas Development in the United States: A Primer.* Prepared for: U.S. Dep't of Energy Office of Fossil Energy and National Energy Technology Laboratory.
[8] Navigant Consulting, Inc. (2008). *North American Natural Gas Supply Assessment,* Prepared for: American Clean Skies Foundation.
[9] Smith, T. and J. Leone. New York State Museum. *Integrated Characterization of the Devonian Marcellus Shale Play in New York State*. Presented at the Marcellus Shale Gas Symposium of the Hudson-Mohawk Professional Geologists' Association, April 29, 2009. Accessed from www.hmpga.org/Marcellus_presentations.html.
[10] Transformation ratio refers to the percentage of Kerogen (an organic solid, bituminous mineraloid substance) occurring in the unit, that has been destructively converted to oil or gas by ambient geological forces (i.e., pressure, temperature) .

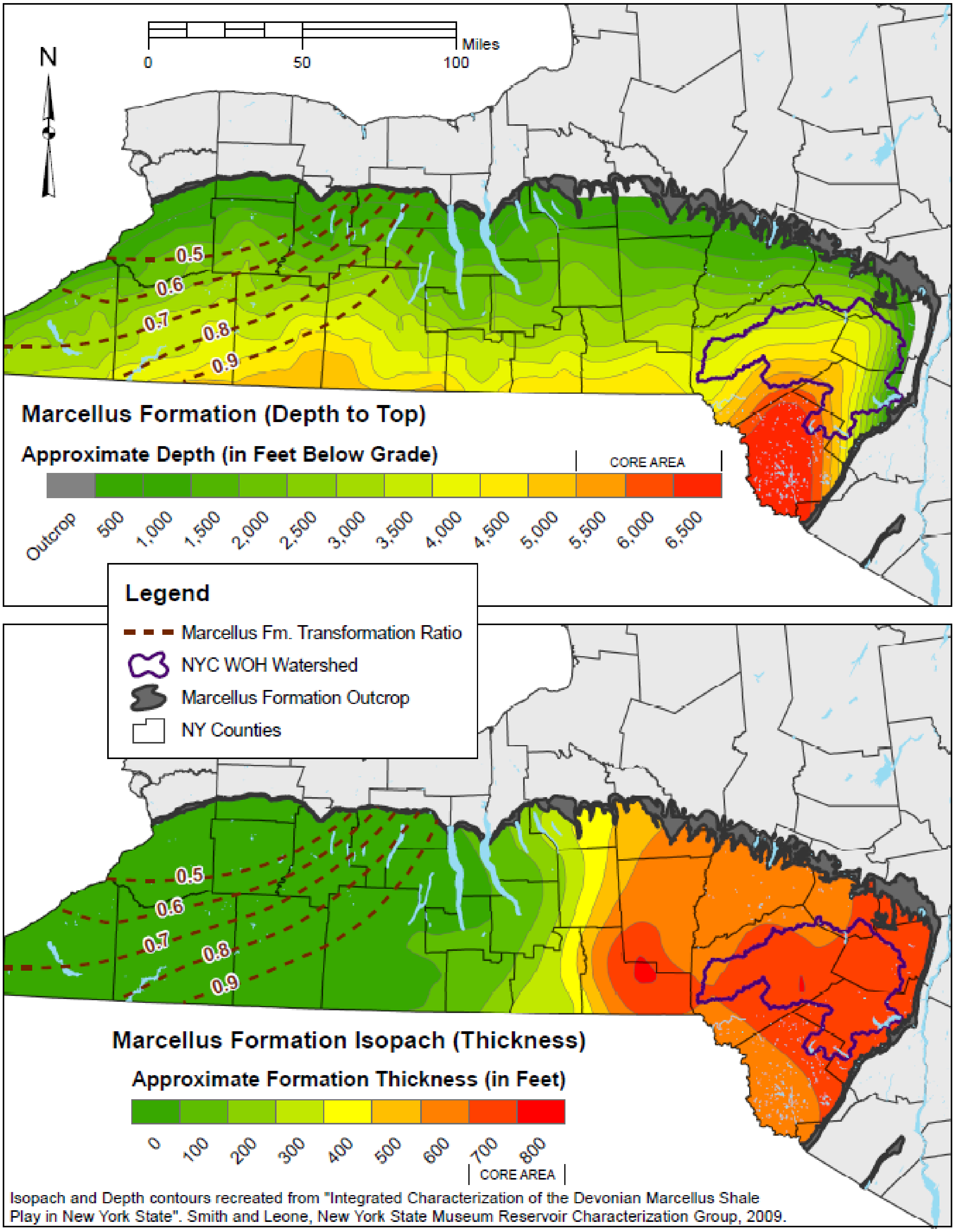

Figure 2-1: Extent and Characteristics of Marcellus Formation in New York

The supposition that the area identified in the New York State Museum study may be highly productive is supported by the intense leasing activity observed in this area and in neighboring counties in northeast Pennsylvania, as well as the ongoing development of a major regional drilling services facility in Horseheads (Chemung County), New York. County locations and additional detail on drilling activity in the region are presented subsequently in Figure 3-4.

2.2 Regional Geology

Figure 2-2 shows the bedrock geology underlying the West-of-Hudson components of NYC's water supply system (Appendix A). It identifies the uppermost layer of underlying bedrock, locations of mapped geologically brittle structures in relation to watershed boundaries, reservoirs, aqueducts, streams and rivers. The contours mapped in Figure 2-2 show the approximate depth to the top of the Marcellus formation. These contours indicate that the formation dips steeply westward in the eastern portion of the watershed, while the dip from north to south is less steep.

The uppermost layer of bedrock is identified in Figure 2-2 by color-coding keyed to the geologic cross-section of Figure 2-3. These figures indicate that virtually the entire watershed is underlain by rock of the West Falls, Sonyea and Genesee Groups, which are Upper (or Late) Devonian period in age (over 360 million years old). The Upper Devonian Groups are in turn underlain by Middle Devonian aged rocks of the Hamilton Group. The orange-shaded band framing the east boundary of the watershed corresponds to Middle Devonian formations and defines the extent of Upper Devonian rock.

The Marcellus formation occurs at the base of the Middle Devonian Hamilton Group and is primarily composed of organic-rich shale units. It is overlain and underlain by sedimentary rock units (e.g., sandstone, shale, siltstone and limestone) of varying natural gas and fossil fuel resource potential. As indicated by Figure 2-3, the Utica Shale, which is part of the Lorraine Group, underlies the Marcellus as well as the entirety of the West-of-Hudson watersheds.

2.3 Water Resources and Hydrogeologic Conditions

The topography of the region comprises six major drainage basins occupied by a NYC reservoir and its tributaries. The three western-most (Cannonsville, Pepacton, and Neversink) are sub-watersheds of the Delaware River Basin; the remaining three (Rondout, Schoharie, and Ashokan) are hydrologically within the Hudson River Basin.

Surface water in the region generally originates as precipitation, which is either captured directly within the waterbody itself, or indirectly, as runoff and groundwater discharge (known as "baseflow"). There is a hydraulically continuous relationship between groundwater and surface water in the region developed from a series of interdependent flow regimes. Under natural conditions, these flow regimes are in hydrogeologic equilibrium as evidenced by major ionic chemical signatures reflective of the comprising water types (i.e., shallow versus deep), indicating that groundwater in very deep geologic formations is typically older and chemically distinct from groundwater in overlying flow regimes.[11] Typically, groundwater from deep formations and flow regimes is not potable, due to high total dissolved solids, and does not mix directly with shallow, fresh groundwater and surface water.

[11] A Conceptual Hydrogeologic Model for the West-of-Hudson watershed region is developed and described in the September 2009 *Rapid Impact Assessment* report.

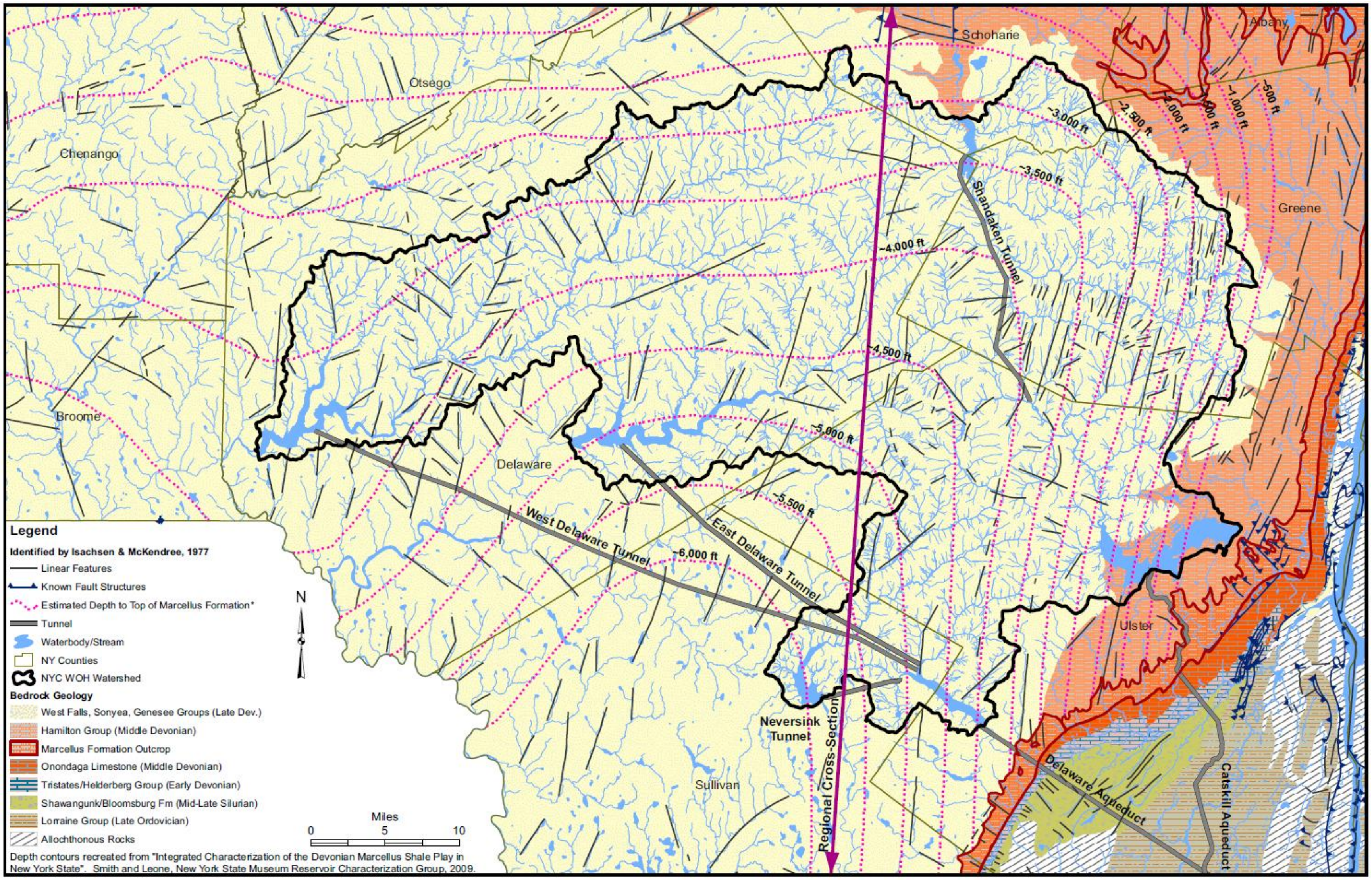

Figure 2-2: Bedrock Geology of the Catskill Region

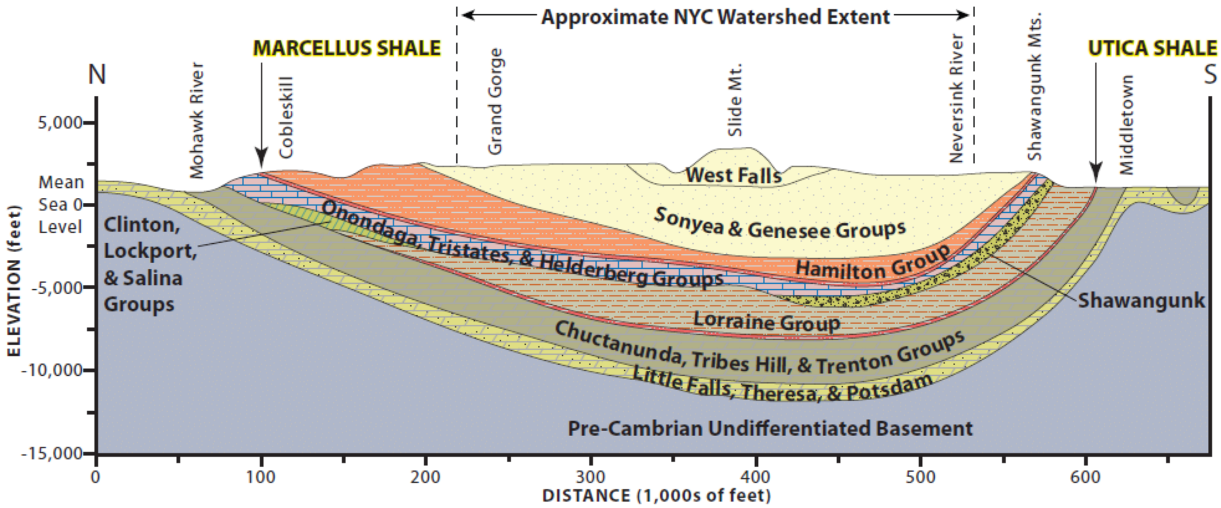

Figure 2-3: Cross-Section of Catskill Region Bedrock Geology

Limited inter-regime flow can be compromised by naturally-occurring, vertically extensive brittle structures as well as the interception of such structures during gas well drilling and stimulation. Abandoned or improperly sealed wells, casing or grouting failures, existing geologic fractures, and new fractures (generated during well development and stimulation) that propagate beyond the target formation can create or enhance hydraulic pathways between previously isolated formations. These hydraulic pathways can permit fluids within geologic formations (such as methane or brine water) to contaminate shallow groundwater, surface water, and subsurface infrastructure. In the case of the Marcellus formation, which is characterized as "overpressurized," fluids in the formation will follow the path of least resistance which, in addition to traveling toward the wellhead, will also follow any existing fractures and be forced upward toward the surface.[12]

2.4 Faults and Other Brittle Structures

The development of natural gas resources using hydraulic fracturing and horizontal well drilling technology relies upon vertical separation distance and low permeability of the intervening rock strata to prevent hydraulic communication between shallow aquifers and deeper gas bearing formations. Given the reliance on overlying rock to isolate hydraulically fractured strata from near-surface flow regimes, an evaluation of the presence and potential extent of geologically formed faults and fractures in the region has been performed. These geological features and other brittle structures can and do serve as conduits that facilitate migration of contaminants, methane, or pressurized fluids from deep formations towards the surface, potentially impacting aquifers and subsurface infrastructure.

Figure 2-4 presents faults, shear zones and other brittle structures as mapped by Isachsen and McKendree (1977) in New York State. The blue-colored features correspond to faults and shear

[12] The dSGEIS (pg. 5-131) reports a pressure gradient in the Marcellus formation of 0.55 to 0.60 psi per foot of depth (i.e., 1.27 to 1.39 feet of pressure per foot of depth). Gas reservoirs that exhibit greater than 0.4 to 0.5 psi per foot of depth (ranging up to 0.7 to 1.0 psi per foot) may be characterized as “overpressurized” (Craft, B.C. and Hawkins, M.F., 1991, *Applied Petroleum Reservoir Engineering*, Prentice Hall).

zones, and the gray features correspond to "Topographic and Tonal Linear Features." Many of these features represent breaks or fractures in the bedrock. The faults and shear zones identified in this study have been mapped on the basis of direct observation in outcrop or boreholes and are associated with movement of the comprising rock masses parallel to the feature. Such movement is commonly associated with "seismic events" such as earthquakes. The "linear features" are typically identified using aerial photographs, maps, and other related methods and may correspond to the suspected locations of faults (although not directly observed in outcrop). In some cases, these features are continuations of known, mapped faults and brittle structures. This data is not likely to present all faults and fractures that might exist at depth

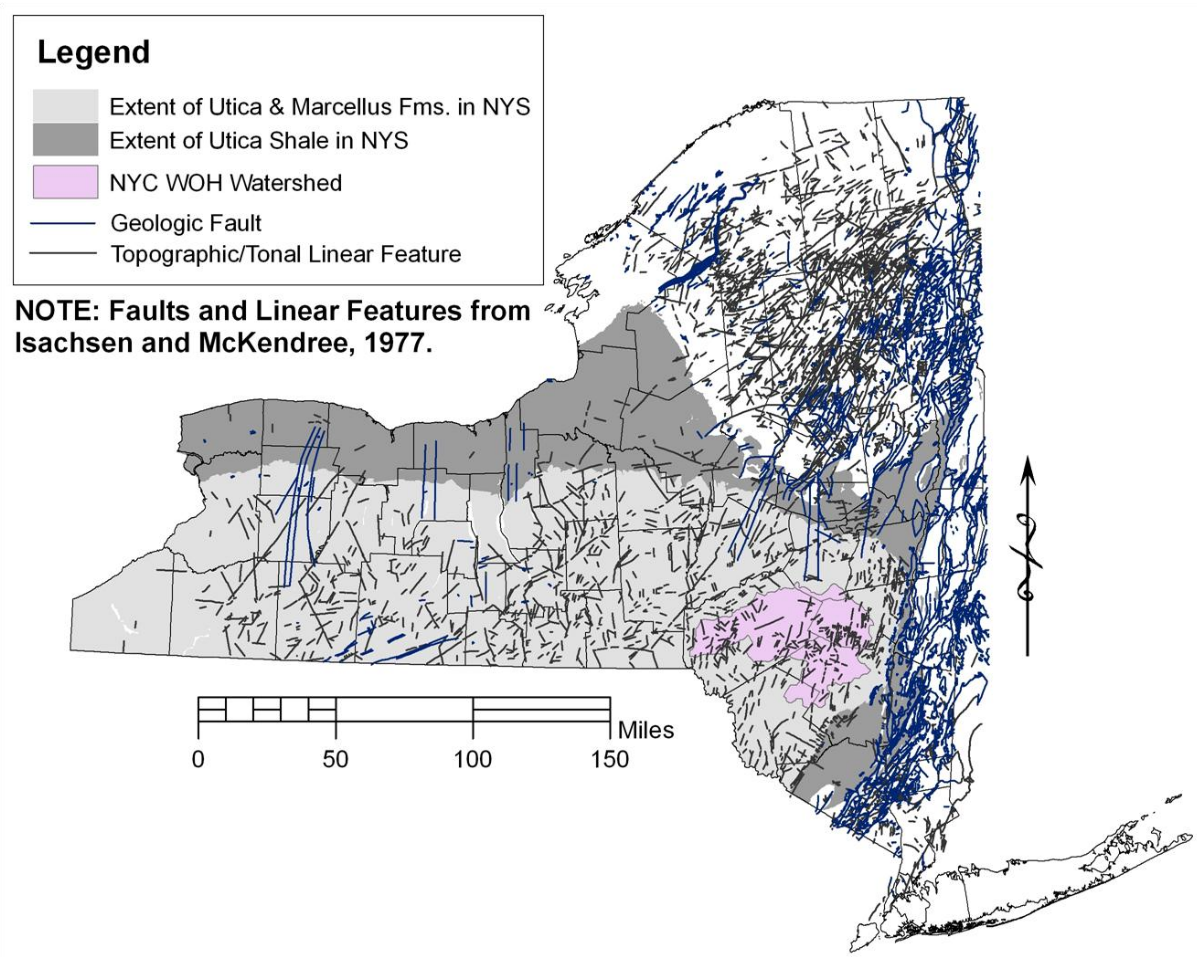

Figure 2-4: Map of Geologic Faults and Linear Features in New York State

Recognizing the significance of brittle structures (i.e., faults, shear zones, fractures and other linear features) to act as migration pathways for fluids from deeper formations, a statistical analysis of the lengths of these reported features in the vicinity of NYC's West-of-Hudson water system has been performed as part of this assessment. The 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. Some of these features intersect one another and some cross NYC infrastructure components. Given that the process relied upon by Isachsen and McKendree to identify the brittle structures concentrated on a large-scale area and recognized only those observable at the land surface, a reasonably conservative assumption is that even more such features and intersections with infrastructure are present. The lengths of identified fractures provide a guide for establishing buffer distances needed to ensure separation of water system components and natural gas drilling activities affecting deep formations.

Based on a statistical analysis of identified fractures and brittle structures in the region, 50 percent of the mapped features have lengths in excess of three miles, and more than 10 percent exceed seven miles in length (Appendix A).

Based on Isachsen and McKendree, the area within and around the NYC watershed is dominated by numerous “linear features” that typically correspond to fractures, both mapped and un-mapped. As such, the intervening rock masses (both horizontally and vertically) between the Marcellus formation and fresh water aquifers or subsurface infrastructure should not be considered as an impermeable barrier, since they are fragmented by a significant number of fractures. The existence of vertical fractures is evident in local rock outcroppings. A local example of such vertically persistent fractures that typify the bedrock character is presented in Figure 2-5, which shows two photos of Plattekill formation outcrops near Ashokan Reservoir. Evident in each photo are vertical fractures that extend across multiple layers of the formation. The Plattekill formation is part of the Hamilton Group of interbedded shales, siltstones and sandstones that overlie the Marcellus formation and underlie NYC tunnels and fresh groundwater and surface water sources.

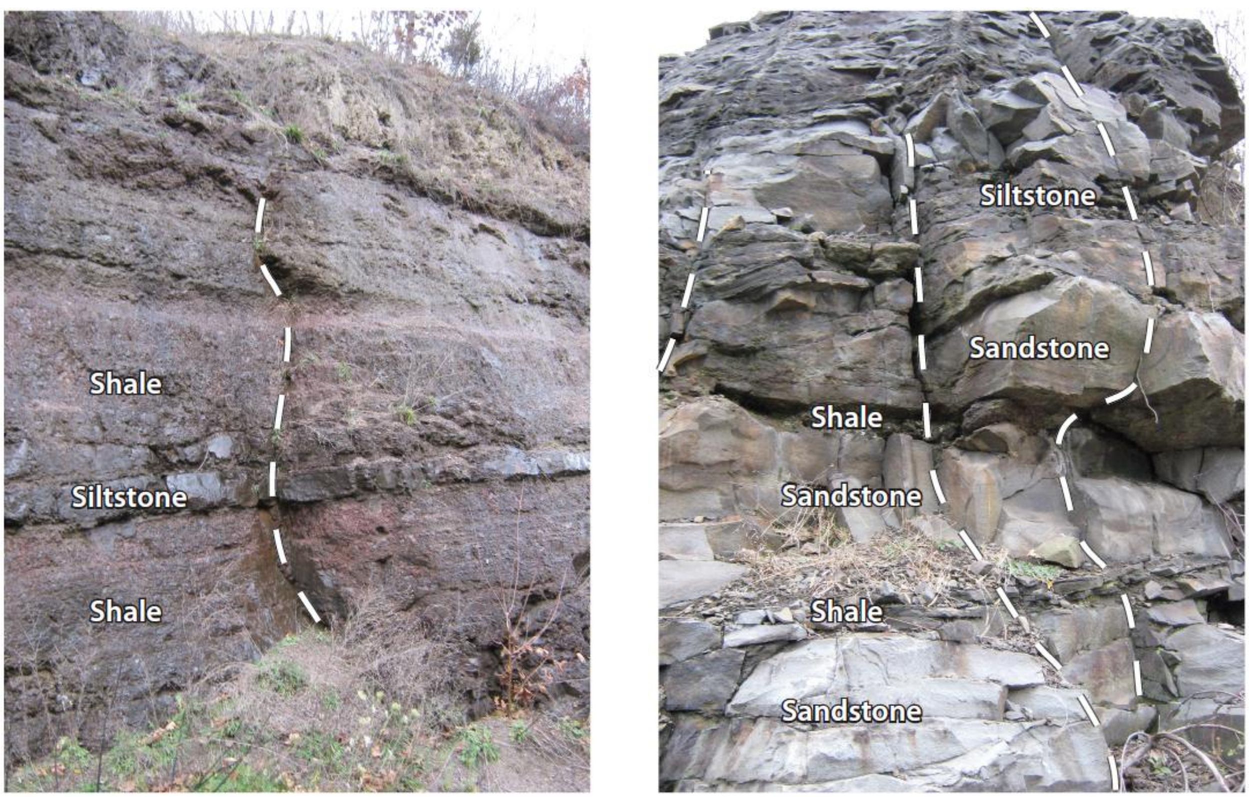

Figure 2-5: Outcrops of the Hamilton Group (Plattekill Formation) near Ashokan Reservoir Showing Persistence of Vertical Fractures across Lithologic Units

2.5 NYC Water Supply Infrastructure Relative to Geological Features

NYC's West-of-Hudson water supply infrastructure has been evaluated in relation to local and regional geologic features. This evaluation has included a review of record drawings and construction documentation, and focused on vertical separation from the Marcellus formation as well as geological features documented during tunnel construction.

Infrastructure Depth and Vertical Separation from Marcellus Formation

The West-of-Hudson water supply tunnels are constructed from several hundred to about 1,000 feet below grade. Regional surface topography ranges from about elevation 1,000 to 2,500 feet. The tunnels upstream of the Rondout and Ashokan Reservoirs are located approximately 1,000 feet above sea level; the tunnels leading from these reservoirs are about 500 feet below sea level. The vertical distance between the Marcellus formation and NYC water supply infrastructure varies from direct contact at the eastern edge of the formation's occurrence, to about 4,500 feet in the western portion of the watershed. Portions of the Shandaken Tunnel, the Catskill Aqueduct, and the bottom of Ashokan Reservoir are separated by as little as 500 feet from the underlying Marcellus formation. Separation increases for infrastructure and reservoirs to the west and the south with increasing depth of the formation. To the west, vertical separation between Delaware system reservoirs and tunnels and the Marcellus ranges from about 2,000 to 4,500 feet.

Geological Features Documented During Construction

Evidence of naturally occurring fluid migration associated with brittle features is reported on record drawings that document the construction of NYC's infrastructure. NYCDEP records indicate that the East and West Delaware Tunnels and Neversink Tunnel construction encountered numerous groundwater seeps, saline water seeps, subsurface fractures, and methane inflows corresponding to the locations of mapped brittle structures. In 1957, methane that had seeped into the West Delaware Tunnel ignited, injuring three miners.[13] Construction of the Rondout-West Branch section of the Delaware Aqueduct also encountered numerous methane seeps. Frequent groundwater and saline water seeps were also encountered during construction of Shandaken Tunnel, sections of the Catskill Aqueduct, and the Rondout-West Branch tunnel.[14] These occurrences substantiate that fractures in the bedrock are naturally providing pathways for the movement of deep formation fluids.

Figure 2-6 highlights a section of the West Delaware Tunnel, where a linear feature identified from regional mapping was encountered as a fault at tunnel depth during construction, as documented in the accompanying excerpt from a tunnel geology drawing. Geological features encountered during construction, including faults and other geological brittle structures, and various seeps, are located on the geologic map of the Delaware system tunnels presented as Figure 2-7. Figure 2-8 shows the geologic features located along a profile of the West Delaware Tunnel, in relation to local surface topography and surficial features, and estimated depth of the Marcellus formation.

[13] The Delaware Water Supply News, April 1, 1964, 23:189, p. 1063.

[14] New York City geologic record drawings.

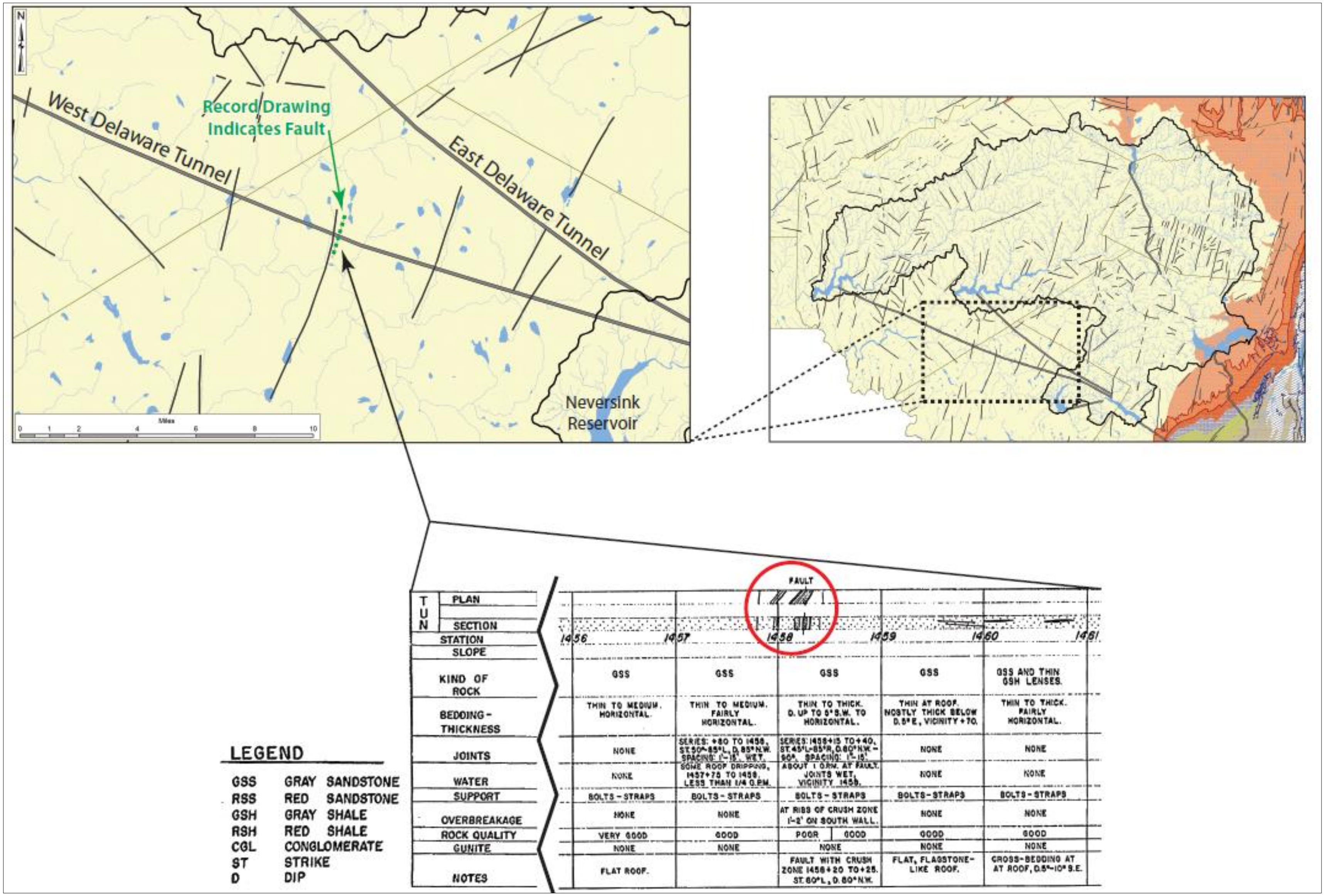

Figure 2-6: Example from West Delaware Tunnel Showing Correlation of Surface Linear Features with Faults Observed During Construction

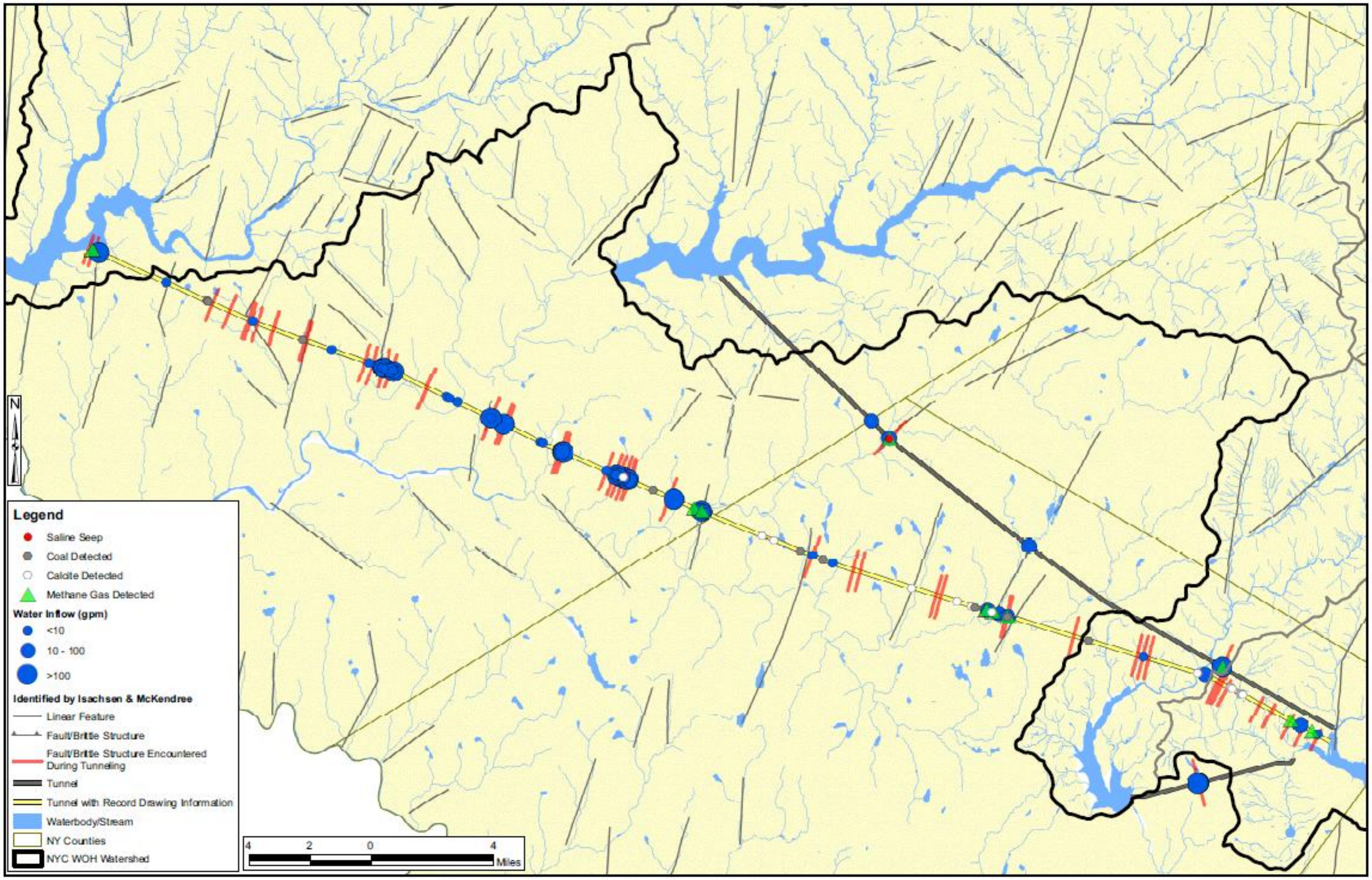

Figure 2-7: Map of the East and West Delaware Tunnels and Neversink Tunnel

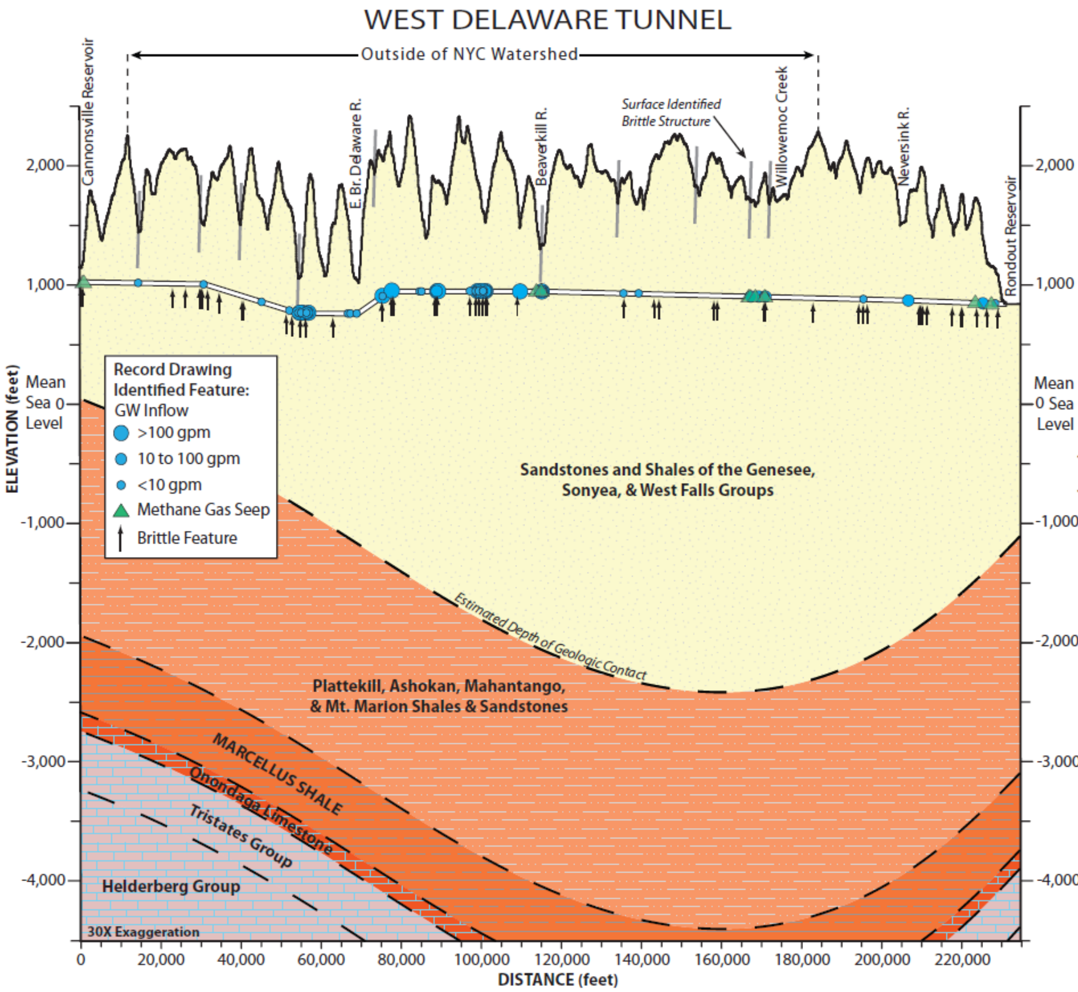

Figure 2-8: Geologic Cross Section of the West Delaware Tunnel

2.6 Summary

Available data, ongoing research performed by the New York State Museum, and comparison with natural gas development progress in northeast Pennsylvania suggests that the NYC watershed is underlain by relatively thick portions of the Marcellus formation with presumably high gas production potential. In addition to the Marcellus, other gas-bearing shale strata underlie the watershed and could be developed in the future. Overall, the NYC watershed area can be expected to be the focus of gas resource development activity comparable to or exceeding that of other contemporary shale gas plays, and this activity can be expected to last for decades.

Under natural conditions, upper geological strata are largely isolated from both methane and water in deep geological strata (formation water). Formation water is typically not potable, even before the addition of chemicals used in the hydrofracturing process. The saline water and methane seeps encountered at grade and in shallow formations near NYC infrastructure during the construction of water system tunnels provide the most reliable evidence that existing fracture systems and pressure gradients will transmit fluid from deeper formations. Taken together with the expected rate and development of gas drilling quantified in Section 3, this evidence of natural migration leads to the conclusion that there is a reasonably foreseeable risk to water supply operations from methane, fracking chemicals, and/or poor quality, saline formation water migrating into overlying groundwater, watershed streams, reservoirs, tunnels, and other infrastructure.

For these reasons, any evaluation of subsurface migration potential associated with future gas development must fully consider all known and foreseeable linear features and fractures. Extensive subsurface fracture systems and known "brittle" geological structures exist that commonly extend over several miles in length, and as far as seven miles in the vicinity of NYC infrastructure (Appendix A). In addition, the net hydraulic conductivity of a formation must be considered, including the influence of faults and fractures, not just the bulk properties of the rock matrix. Naturally occurring fractures in the rock can result in relatively high localized hydraulic conductivity values; these would be several orders of magnitude greater than those considered in analyses provided as technical support of the dSGEIS.

Section 3: Rates and Densities of Natural Gas Well Development

The Marcellus formation is an extensive resource that occurs beneath much of the State and will require tens of thousands of wells to fully exploit. The risks and impacts from any given individual well may be negligible and acceptable, but when evaluated in the context of hundreds or thousands of other wells, the risks and impacts may be significant and unacceptable. As such, cumulative impacts from many wells constructed throughout the watershed must be evaluated in order to fully characterize the potential risk from concurrent activities at multiple locations. Consistent with this understanding, the dSGEIS establishes the *aggregate* and not the *individual* as the appropriate basis for analysis of regional impacts: "*The level of impact on a regional basis will be determined by the amount of development and the rate at which it occurs.*"[15]

This section provides estimates for the annual rate and ultimate density of natural gas wells that could be developed in the NYC watershed under proposed regulations. These rates and densities are then combined with quantity estimates for various activities associated with one individual well to develop cumulative values (Section 4).

Sufficient data is available from shale gas plays that have been under development in other areas over the last two to ten years to develop reasonable ranges of annual rates of well construction (Appendix B). Since these other plays are still under development, the data from these plays underestimates the expected full build-out density. Therefore, estimates for the total number of wells to be constructed in the watershed are derived from estimates of developable area within the NYC West-of-Hudson watershed combined with average expected well densities per square mile.

3.1 Rates and Densities of Well Development in other Formations

Four major shale gas plays were identified for comparison purposes: Barnett (Texas), Fayetteville (Arkansas), Haynesville (Louisiana), and Marcellus (Pennsylvania) (Figure 1-1). These formations are all gas-bearing shales that require hydraulic fracturing for economic production and have been developed using a combination of horizontal and vertical wells.

Data on New York's Marcellus formation depth, thickness, organic content, thermal maturity, and other factors that have been analyzed by the New York State Museum's Reservoir Characterization Group indicate that the NYC watershed is underlain by portions of the Marcellus with high gas production potential. As such this assessment focuses on counties in other formations that have similarly high potential for gas production. Salient features of these formations and the counties selected for comparison are summarized in Table 3-1.

Well development rates and density for the four shale gas formations and their selected counties are summarized in Figure 3-1, Figure 3-2, and Figure 3-3. Figure 3-1 shows the annual rate of development in the other shale gas plays. Figure 3-2 depicts the density trends noted in the four comparable shale gas plays over the past decade, and Figure 3-3 presents current densities (2009).

15 dSGEIS Chapter 6.13.2.

Table 3-1: Areas of Major Shale Gas Plays Comparable to Marcellus formation in NYS

Formation (State)	Approximate # Years under Development	Total Formation Area (mi2)	Selected Counties	Area (mi2)	% of Formation Area in Selected Counties
Barnett (TX) (Newark East field)	13	5,000	Denton, Johnson, Tarrant, Wise	3,512	70%
Fayetteville (AR) (B-43 field)	6	9,000	Cleburne, Conway, Faulkner, Van Buren, White	3,589	40%
Haynesville (LA)	3	9,000	Bossier, Caddo, De Soto, Red River	3,100	34%
Marcellus (PA)	2	95,000	Bradford, Lycoming, Susquehanna, Tioga	4,374	5%

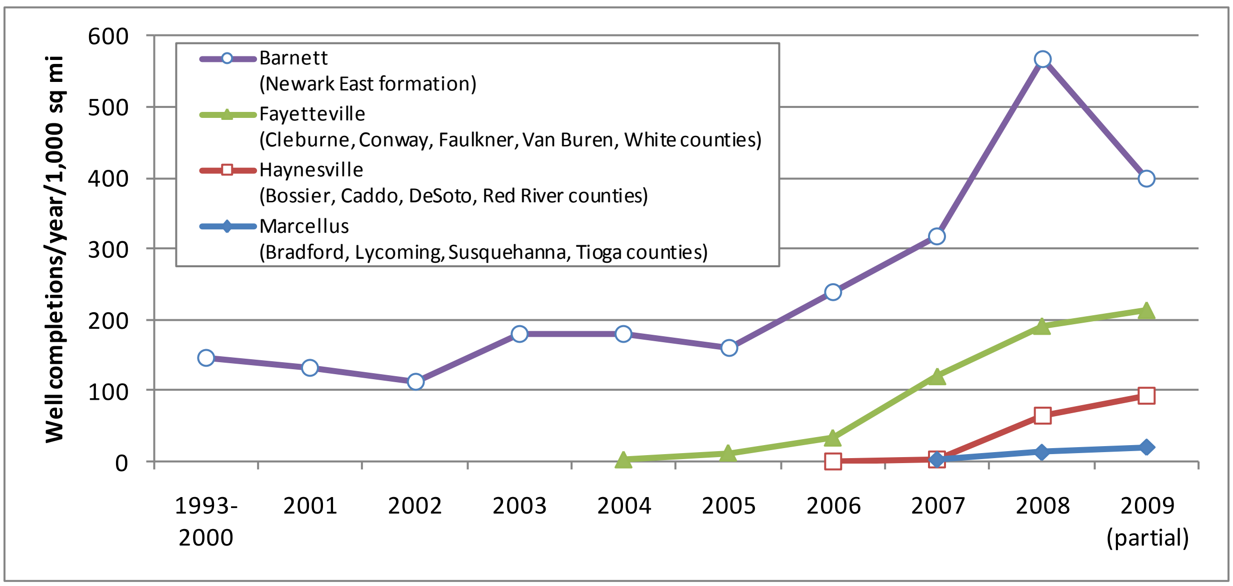

Figure 3-1: Annual Well Completion Rates in Core Counties of Comparable Shale Gas Plays (2001-2009)

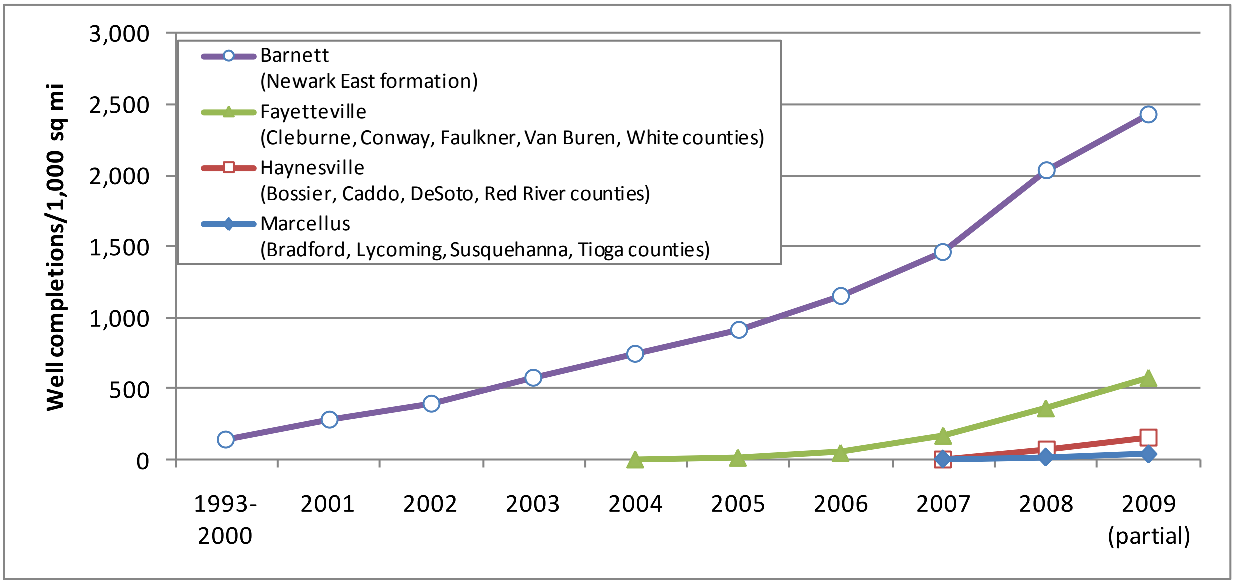

Figure 3-2: Well Density in Comparable Shale Gas Plays (2001-2009)

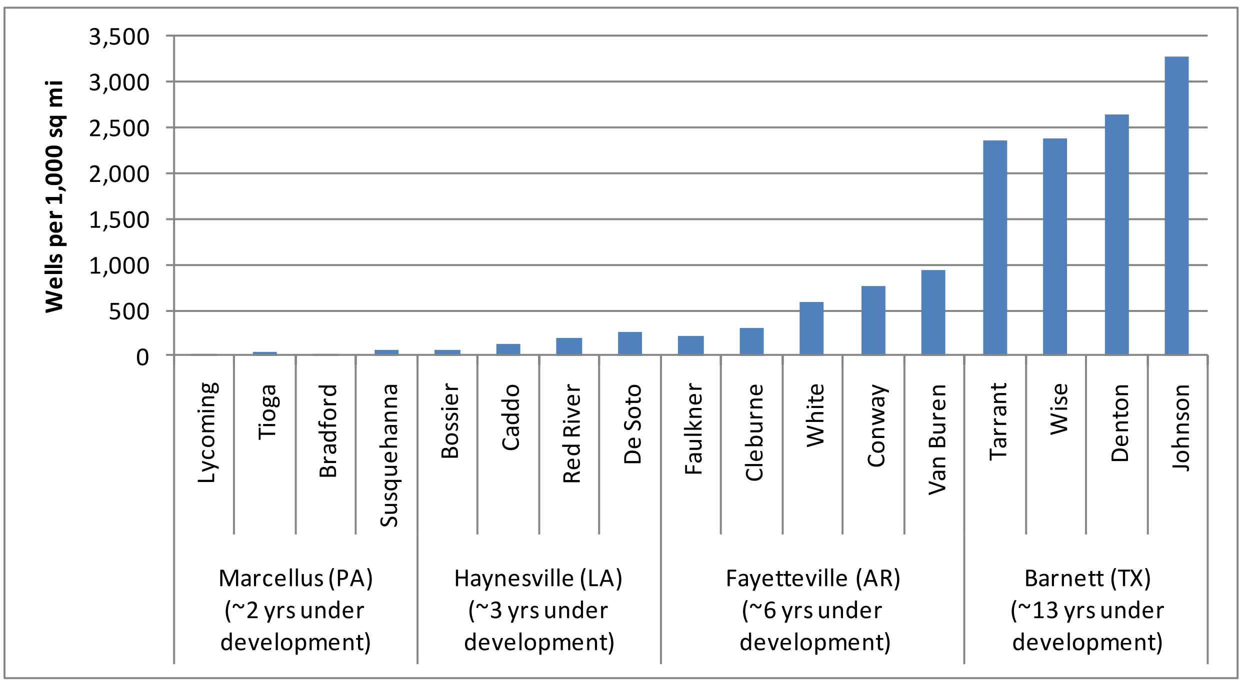

Figure 3-3: Current Well Density in Core Counties of Comparable Shale Gas Plays (2009)

Mapping of natural gas exploration activities in the Marcellus formation in eastern Pennsylvania reveal an accelerating rate of well construction over the two-year period from 2007 to 2009, as shown in Figure 3-4. NYSDEC Notices of Intent to issue well permits in neighboring portions of New York State are also shown. It is reasonable to expect that the pattern and pace of development that could occur in New York State would be similar to that experienced in eastern Pennsylvania. It is important to note that the level of well development shown in the bottom figure reflects the very early stages of development of the formation, and that a roughly one order of magnitude increase in well density should be anticipated.

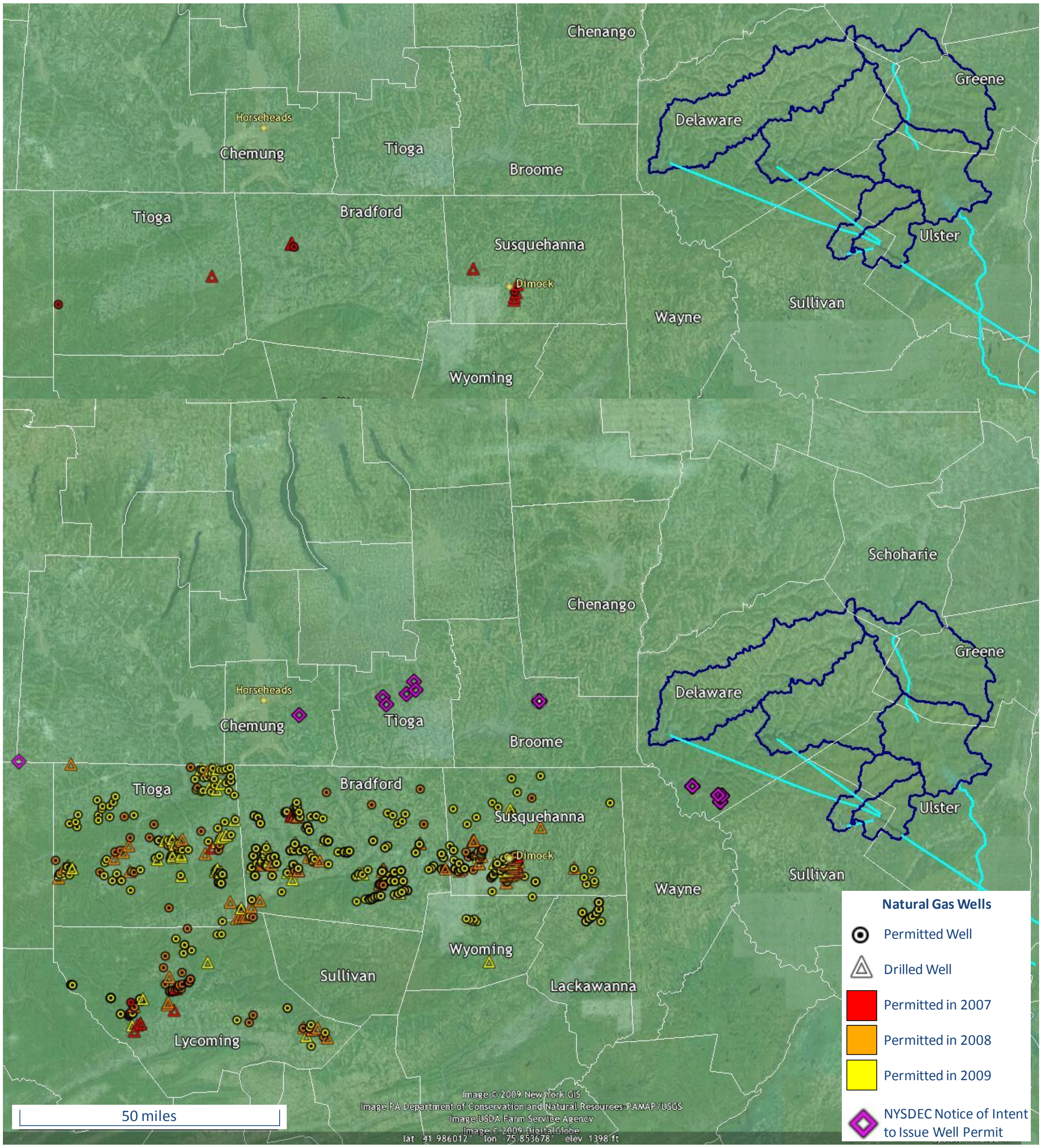

Figure 3-4: Marcellus Formation Gas Well Permitting and Completion in New York and Pennsylvania Core Counties in 2007 (Top) and 2009 (Bottom)[16]

[16] Pennsylvania Department of Environmental Protection Well Data as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09). NYSDEC data on Notices

Rates of natural gas well development in the comparable major shale gas formations provides the basis for the scenarios presented in Table 3-2 and are consistent with well development patterns observed to date. Therefore, the scenarios provided are reasonable for estimating potential impacts within the NYC watershed even though the actual rate of development is uncertain due to numerous factors, including natural gas prices, regional economic conditions, State regulations, and formation productivity.

Table 3-2: Annual Natural Gas Development Scenarios

Rate Scenario	Average Annual Well Completions per 1,000 Square Miles	Description
Low	5 to 20	Drilling rate during the early years of the play as operators refine their understanding of the resource and continue to lease land and apply for permits.
Moderate	100 to 300	Rate of well completion that has been sustained for a number of years in other shale gas plays
High	500, based on well completions (potentially as high as 800, based on permit applications)	Rate of development that could potentially occur in the most profitable areas under favorable conditions (e.g., gas prices are very high).

3.2 Rate and Density of Well Development in the NYC Watershed

To calculate the total number of wells that could be developed in the NYC watershed, an average well density was estimated and then applied across the total developable area within the watershed.

In estimating the developable area within the watershed, state forest preserve area[17] and lands controlled by NYC through ownership and conservation easements (shown in Figure 3-5 and Figure 3-6) were excluded.[18] The remaining "uncontrolled" area (1,076 square miles, or 68 percent of the watershed) was then assumed to be between 50 and 100 percent developable. This range of development is consistent with other nearby areas of the Marcellus formation region, such as Bradford County, which has experienced mineral leasing of nearly 85 percent of the total county land area. The resulting estimate of the land area in the NYC watershed available for natural gas development is thus on the order of 500 to 1,000 square miles.

Although New York regulations allow up to 16 wells per square mile, the dSGEIS indicates a lower density, approximately six to nine wells per square mile, is more likely. This estimate is corroborated by recent permit applications in Sullivan County, which are based on five to six wells per square mile.[19] Well densities to date in excess of three wells per square mile over areas comparable in size to the NYC watershed have been documented in other shale gas plays with significantly higher localized densities (e.g., Denton County, TX has a well density of 5.5 wells

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of Intent to Issue Well Permits in Spacing Units Which Conform to Statewide Spacing in New York State as of 10/26/2009 (http://www.dec.ny.gov/dmndata/Well_Reports/Unit_Spacing_SW_Rpt.html, accessed 10/27/2009)

[17] The estimates of State forest preserve land in Figure 3-6 only include land in the Catskill State Forest Preserve, which cannot be leased or sold without a constitutional amendment. The estimates do not include other state land in the NYC watershed which is not afforded a similar level of protection.

[18] Compulsory integration may bring peripheral areas of NYC-controlled or state lands under development.

[19] NYSDEC. 2009. *Notices of intent to issue well permits in spacing units which conform to statewide spacing in New York state*. (http://www.dec.ny.gov/dmndata/Well_Reports/Unit_Spacing_SW_Rpt.html, accessed 9/2/09).

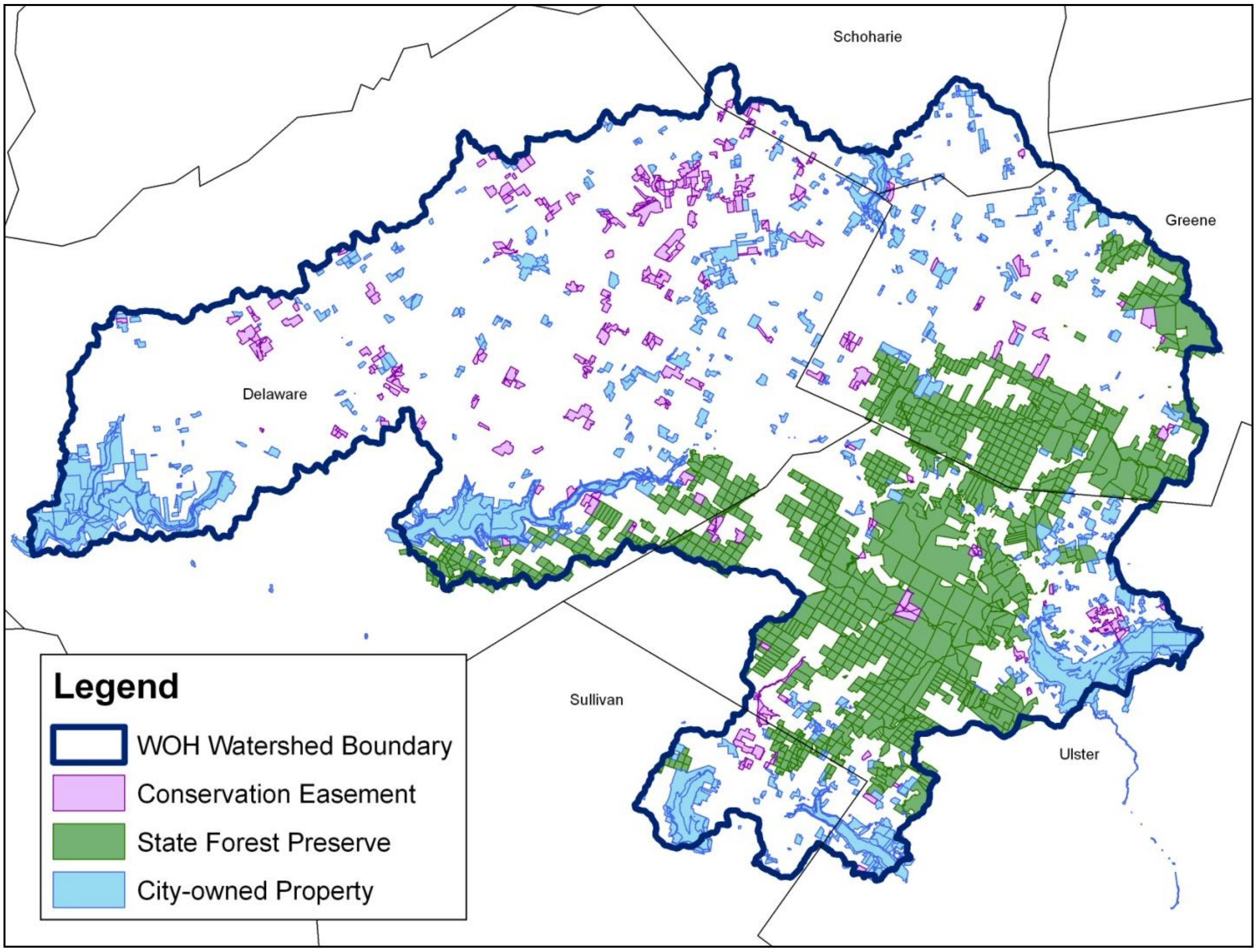

Figure 3-5: NYC West-of-Hudson Watershed Land Ownership (April 2009)

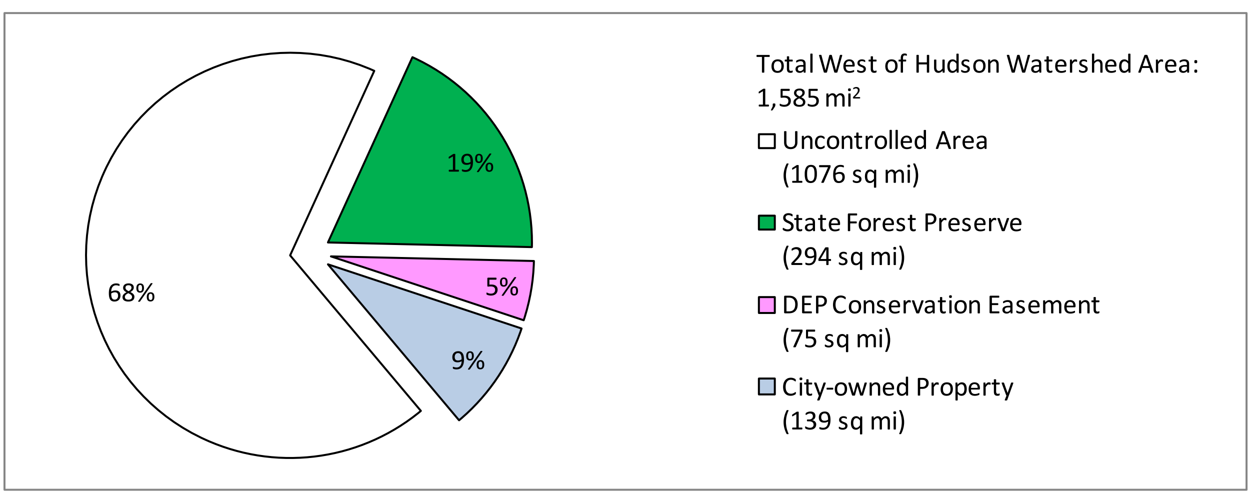

Figure 3-6: Ownership Status of West-of-Hudson Watershed Land (April 2009)

per square mile over approximately 400 square miles [40 percent] of the county area). It has not been established that these areas have been completely developed so still higher densities are possible. Similarly, annual well completion rates in excess of five wells per square mile have been documented, and permit applications suggest that these rates could be higher also. Given the available data, a working estimate of six wells per square mile over the developable area within the watershed is reasonable.

At six wells per square mile, and assuming that 50 to 100 percent of the currently uncontrolled land is ultimately developed, it is estimated that on the order of 3,000 to 6,000 wells could potentially be drilled in the watershed. This estimate is based on the best available data on industry intent for developing the resource in conformance with New York state regulations at this time, and presents a range of development within the watershed that is consistent with that observed in comparable plays.

3.3 Summary

Reasonably foreseeable natural gas well development scenarios for the NYC watershed can be calculated based on experience in comparable formations. Annual well completion rates would likely be 5 to 20 wells per year initially, but could accelerate rapidly under favorable economic and regulatory conditions, averaging 100 to 300 wells per year, and potentially peaking at 500 wells per year. Consistent with NYSDEC spacing unit requirements and development in other formations, it is estimated that between 3,000 and 6,000 wells could ultimately be drilled and fractured in the NYC watershed. This does not include re-fracturing of the same wells, nor does it include drilling and fracturing of wells to tap natural gas in the Utica, Oriskany, or Trenton/Black River formations underlying the NYC watershed.

Section 4: Cumulative Impacts

This section presents an assessment of cumulative impacts associated with natural gas well development in the NYC watershed. The primary focus of the analysis is on drinking water quality, water supply reliability, and infrastructure integrity. This section does not address other potential impacts (e.g., noise, air pollution, habitat disruption, induced growth), though such impacts may occur and deserve full consideration. A summary of estimates of quantifiable gas well development activities is presented for an individual well, for well development on an annual basis, and for a "full build-out" scenario. Subsequent subsections review cumulative impacts in greater detail.

4.1 Quantification of Gas Well Development Activities

Table 4-1 quantifies several critical activities that occur during well drilling and fracturing operations, including site disturbance, water usage, chemical usage, flowback and produced water generation, and truck trips. Estimates for each of these activities are presented for one individual well, based on data presented in the Rapid Impact Assessment Report and the dSGEIS and supporting technical reports. These individual well estimates are then applied to multiple wells to develop order of magnitude estimates of cumulative quantities on an annual basis and a full build-out basis. Assumptions for the annual and total number of well completions under low and high development scenarios are based on estimates presented in Section 3.

Table 4-1 does not account for impacts associated with refracturing that may be conducted to restore declining gas well production rates. Experience in the Barnett shale provides some guidance with respect to the frequency of re-fracturing that may occur in the Marcellus. Based on data in the dSGEIS,[20] two re-fracturing intervals, five and ten years, were examined for the purpose of developing a screening-level assessment of impacts associated with refracturing (Table 4-2).

To develop these estimates, it was assumed that the natural gas wells are constructed over the course of a 20-year development period, and that each individual well has a service life of 40 years.[21] As such, natural gas development and production activities occur over the course of 60 years. Alternative scenarios describing the rate of well completion during the 20-year development period were developed; in all cases the peak annual rate of well completion was limited to 500 wells per year. For the high (6,000 well) build-out scenario and a five year refracturing interval, an additional 42,000 hydrofracturing operations would occur in the watershed over the life of the gas play. For a ten-year interval, an additional 18,000 hydrofracturing operations would occur.

[20] The dSGEIS states that "*Hydraulically fractured wells in tight gas shale often experience production rate declines of over 50% in the first year. Fractured Barnett shale wells generally would benefit from refracturing within 5 years of completion, but the time between fracture stimulations can be less than 1 year or greater than 10 years*." (dSGEIS, ICF Task 1 Report - Technical Analysis of Hydraulic Fracturing).

[21] The typical well-life expected for horizontally drilled wells in the Marcellus Shale has not yet been established or identified in the dSGEIS. The 40-year service life assumption is made in light of reported estimates for Barnett Shale wells. As an example, a recent article concerning potential royalty estimates assumed a 30-year well life without re-fracturing, but also indicated that it was expected that most Barnett wells would be re-fractured within 7 years, and that continuous re-fracturing could double or even triple the life of the wells. Other sources also estimate Barnett well-life in excess of 30 years. Source: *2008 Tarrant County Barnett Shale Well Revenue Estimate for Neighborhoods* by Gene Powell. Excerpt from May 5, 2008 *Powell Barnett Shale Newsletter.*

Table 4-1: Summary of Individual and Cumulative Impact Estimates

Parameter (units) *Estimate (source)*	Quantity for One Well (range)	Annual Well Development (Quantity/year)		Full Build-out (Total Quantity)	
		Low	High	Low	High
Developable Area (sq mi)	--	--	--	500	1,000
Percent of Total Watershed Area *Total Watershed area is 1585 sq. miles*	--	--	--	32%	63%
Number of Wells *Assume 6 wells/square mile*	1	20	500	3,000	6,000
Site Disturbance (acres) *4 – 6 wells/pad (dSGEIS)*	7	28	700	4,200	8,400
Water Consumption (MG) *Industry and dSGEIS*	4 (3 to 8)	80	2,000	12,000*	24,000*
Chemical Usage (tons) *0.5 to 2% of fracture fluid; assume 1% (dSGEIS)*	167 (83 to 334)	3340	83,500	500,000*	1,000,000*
Flowback (MG) *10 to ~70% of fracture fluid; assume 50%* [1]	2 (0.4 to 2.8)	40	1,000	6,000*	12,000*
Produced Water (MG /yr) *Industry and dSGEIS*	0.075 (0.015 to 0.15)	1.5	37.5	225	450
Truck trips *800 – 2000 per well (RIA)* *890 – 1340 per well (dSGEIS)*	1,200 (800 to 2000)	24,000	600,000	3,600,000*	7,200,000*

Notes:
1. Flowback volume estimates vary widely. The dSGEIS cites flowback as 9% to 35% of fracture fluids for horizontal Marcellus wells in Pennsylvania, but also assumes flowback as 50% of fracture fluid in its estimates of truck trips. NETL cites 25% to 100%.[22] Annual well development calculations use 0.4 MG and 2.8 MG for the low and high estimates, respectively.
* These totals do not include allowance for re-fracturing operations.

Related quantities of water, wastewater and chemicals are summarized in Table 4-2 for the high (6,000 well) development scenario with and without refracturing. Estimates for wastewater quantities assume the same values for fracturing fluid volume, fracture fluid flowback and produced water as for the initial fracturing job, as indicated in Table 4-1. Flowback and produced water estimates are combined to estimate total wastewater production. Waste disposal requirements are represented by calculation of the total dissolved solids (TDS) load assuming a TDS concentration of 100,000 mg/l for both flowback and produced water, which is based on the median reported in the dSGEIS. In order to provide an initial assessment of the feasibility of disposal through dilution with other waste streams, dilution calculations have also been performed that assume that the maximum permissible effluent concentration would be limited to 500 mg/l. Lastly, the total mass of fracturing chemicals is totaled, assuming that these constitute one percent by weight of hydro-fracturing fluid. The resulting estimates are summarized in Table 4-2.

[22] National Energy Technology Laboratory (NETL). 2009. Project description for *Sustainable Management of Flowback Water during Hydraulic Fracturing of Marcellus Shale for Natural Gas Production*.

Table 4-2: Impact of Refracturing on Cumulative Water, Wastewater, and Chemical Volumes

Parameter (units) *Estimate (source)*	Without Refracturing	With Refracturing	
		10-Year Interval	5-Year Interval
Total Number of Wells	6,000	6,000	6,000
CUMULATIVE BASIS			
Total Number of Frack Jobs *Full build-out, high scenario*	6,000	24,000	48,000
Frack Chemicals Used (tons) *1.0% of fracture fluid*	1,000,000	4,000,000	8,000,000
Waste TDS (tons) *100,000 mg/l TDS (dSGEIS)*[2]	12,510,000	27,522,000	47,541,000
ANNUAL BASIS[1]			
Water Demand (mgd) *4 MG per frack job*	3.6 to 5.5	5.5 to 8.2	11.7 to 14.2
Wastewater Production (mgd) *50% Flowback + 0.075 MG/yr Produced Water*	2.6 to 3.5	3.9 to 5.3	6.7 to 8.4
Waste TDS for Disposal (tons/day) 100,000 mg/l TDS in waste (dSGEIS)2	1,100 to 1,500	1,600 to 2,200	2,800 to 3,500
Water Req'd to Dilute TDS to 500 mg/l (mgd)	500 to 700	800 to 1,100	1,300 to 1,700
Frack Chemicals (tons/day) *1.0% of fracture fluid*	150 to 230	230 to 340	490 to 590

Notes:
1. Ranges describe the median and the maximum of the annual average values for each development year. Data for the no-refracturing scenario are drawn from the 20-year period of well development. Data for the refracturing scenarios are drawn from the full 60-year period of development and refracturing.
2. The dSGEIS reports median and maximum values of TDS as 93,200 mg/l and 337,000 mg/l, respectively. The concentration of TDS in flowback reportedly increases with time. The determination of median value may include relatively low concentration samples from initial flowback.

The calculations summarized in Table 4-2 indicate that a 5-year refracturing interval would require sustained water diversion needs on the order of 12 to 14 mgd and approximately 10 mgd of wastewater disposal capacity on an annual average basis. Even without including re-fracturing quantities, sustained water demands of 5.5 mgd and wastewater generation of 3.5 mgd can be anticipated within the watershed. Given the expected development of gas drilling and therefore wastewater services across the entire region, it is reasonable to assume that wastewater generated locally may be disposed of locally. Fracturing chemical usage is estimated to range from 150 tons per day without refracturing to nearly 600 tons per day for refracturing at a 5-year interval.

Note that the analysis summarized in Table 4-2 presents annual average rates; shorter-term variations can be expected to exceed these estimates. The analysis includes well drilling activities for Marcellus spacing units only; additional drilling to develop other formations, if these prove feasible, would be in addition to these estimates. Finally, these estimates are only for wells which are assumed to be located within roughly two-thirds of the NYC West-of-Hudson watershed. Water, wastewater and disposal requirements for wells elsewhere in NYS would be in addition to the quantities summarized above.

Impacts of the estimates presented in Table 4-1 and Table 4-2 are discussed further in the following sections.

4.2 Land Disturbance, Site Activity, and Truck Traffic

Land Disturbance

Site development for a natural gas well begins with clearing and grading land for the well pad, water and wastewater storage area, access road, and utility corridor. Most Marcellus wells are expected to be drilled on multi-well pads; industry estimates cited in the dSGEIS suggest these pads will be on the order of five acres in size. These estimates do not include the area required for access roads, gas transmission lines, or centralized impoundments. The total site disturbance including pad and related features such as road and pipelines is estimated at seven acres per well pad based on data from the Fayetteville Shale.[23]

Once all wells are drilled and completed on a pad, the site is partially restored, leaving an area of roughly one to three acres for maintenance access, produced water storage, and gas production equipment. The site will remain in a partially restored state for the duration of the well's productive life (~20 to 40 years). Full surface restoration of the site occurs after the well is plugged and abandoned.

Assuming a pad size of seven acres and four to six wells per pad, the total land disturbance associated with 3,000 to 6,000 wells in the watershed is on the order of 4,200 to 8,400 acres (6.5 to 13.1 square miles). The total amount of land disturbance on an annual basis will depend on the number of active drill pads in a given year. This is expected to range from less than five active pads per year (fewer than 35 acres per year) in the early years of development to 100 or more (700+ acres per year) during peak years.

Impacts associated with site development activities include habitat loss and fragmentation, conversion of forest or pasture land to gravel or other low permeability compacted material, and increases in stormwater runoff and erosion potential due to reduced infiltration rates, increased flow velocities, and lack of vegetative protection. Drilling sites will likely require a NYCDEP-approved stormwater pollution prevention plan that can be expected to help reduce some of the impacts associated with site disturbance. Review and inspection of stormwater plans/facilities will increase the workload of NYCDEP personnel compared to current levels.

Site Activity

Though well sites and associated disturbance are generally described as temporary impacts, it is important to note that sites will remain active for much longer than the nominal four to eight weeks required to drill and fracture one well. When the time required for initial pad construction, mobilization and demobilization of drill rigs and other equipment, water delivery, flowback time, and waste disposal is considered, the total duration of pre-production activities during which a drill site can be considered active is on the order of four to ten months for one well, depending on site-specific circumstances.[24] During this time, activities may be staged so that multiple wells are under various stages of concurrent development at any given time.

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[23] U.S. Department of the Interior. 2008. *Reasonably Foreseeable Development Scenario for Fluid Minerals: Arkansas*. Prepared for the Bureau of Land Management Eastern States Jackson Field Office. March 2008.
[24] See dSGEIS Table 5-15.

Given that six to ten wells are expected to be required to fully exploit the natural gas resources in a 640-acre spacing unit, and given that ECL §23-0501 requires all horizontal wells in a multi-well shale unit to be drilled within three years, it is reasonable to expect that a given well site will be undergoing a relatively high and constant level of industrial activity for at least one and up to three years. This same level of activity can be expected to recur periodically over the life of the well, depending on the frequency of subsequent re-fracturing operations.

Truck Traffic

Development of natural gas resources in the watershed will be accompanied by a significant increase in the level of heavy truck traffic compared to current conditions. The dSGEIS estimates the number of truck trips per well at roughly 900 to 1,300, approximately two-thirds of which are for water and wastewater hauling. On an annual basis, the number of additional truck trips per year could range from 24,000 to 600,000, depending on the number of wells drilled in a given year (Table 4-1). The increased number of travel cycles in the area will increase the risk of accidents.

NYCDEP owns and maintains 94 miles of secondary two-lane highways and 32 bridges in the West-of-Hudson watershed. Large volumes of truck traffic will stress these and other local roads and bridges, thus increasing maintenance and capital costs but also increasing the risk of accidents that result in leakage or spillage of hazardous materials. The risks associated with such spills are quantified in Section 4.5.

Other Drilling Infrastructure

In addition to trucking activity, gas well development in the watershed will be accompanied by provision of equipment and material supply systems (warehouses, garages, support services), gas gathering and pipeline systems, compressor stations, and waste disposal systems.

4.3 Water Withdrawals

The volume of water required to fracture a horizontal well depends on a variety of factors, including characteristics of the target formation, the length of the lateral, and fracture goal. Industry data cited in the dSGEIS indicates that on the order of three to eight million gallons of water may be required to fracture a horizontal well in the Marcellus formation. Assuming an average of four million gallons per well, the estimates presented in Table 4-2 indicate that on the order of one to two billion gallons per year of additional demand could be placed on the watershed’s resources. Note that these estimates do not include possible diversions of water from the NYC watershed for fracturing of wells outside the watershed. Withdrawals of this magnitude may appear insignificant; however, given current and future demands for water from the NYC system any reduction in system yield is of concern. Extrapolating from OASIS modeling done to support the development of the current Delaware Reservoirs Flexible Flow Management Program (FFMP), a reduction of system inflows on the order of four million gallons per day would require the expansion of system storage by approximately 1 billion gallons to maintain safe yield.[25]

[25] Flexible Flow Management Program, Agreement of the Parties to the 1954 U.S. Supreme Court Decree, Effective December 10, 2008 (http://water.usgs.gov/osw/odrm/documents/FFMP_FINAL.pdf).

Excessive surface water withdrawals could reduce inflow to NYC reservoirs, reduce available supplies, and decrease the probability of refilling reservoirs prior to drawdown. Excessive groundwater withdrawals could deplete aquifers, resulting in reduced baseflow in watershed streams or wetlands. The severity of such impacts will depend heavily on the total amount of withdrawals from the West-of-Hudson watersheds, as well as the timing of such withdrawals. Withdrawals during periods when reservoirs are full and spilling would likely have little or no impact on supply reliability. In contrast, withdrawals during dry periods could increase the length of time spent under drought watch, warning, or emergency conditions.

Excessive withdrawals could also impact water system operations by requiring increased reservoir releases to meet in-stream flow requirements. For example, large volume water withdrawals downstream of Pepacton, Cannonsville, or Neversink Reservoirs could necessitate additional releases from those reservoirs to satisfy Delaware Basin release requirements. Similarly, withdrawals from the Upper Esopus Creek could require increased releases from Schoharie Reservoir to meet Esopus Creek minimum flow requirements. Excessive water withdrawals may also impact aquatic habitat and biota.

It has been reported that in the absence of control mechanisms, a number of streams in Washington County in southwestern Pennsylvania (outside the jurisdiction of the Delaware and Susquehanna River Basin Commissions) have been nearly drained or pumped dry from excessive withdrawals for Marcellus wells.[26] Such a scenario in the NYC watershed could result in adverse impacts to water supply reliability.

4.4 Chemical Usage

Water and sand have been reported to comprise 98 to 99.5 percent of the fracturing fluid mixture, with the remaining 0.5 to 2.0 percent consisting of an array of chemical additives used to control fluid properties during the various stages of the fracking process.[27,28,29] Though the *proportion* of chemicals in fracturing fluid is indeed low relative to the large amounts of water required by the fracturing process, meaningful assessment of potential water quality impacts requires that chemicals additives be expressed on a mass basis.

Table 4-3 summarizes the proportion and the mass of water, proppant (sand), and each of 12 major classes of chemical additives required for a single four million gallon fracture operation. The proportions in this mixture are based on data from the Fayetteville Shale, as presented in the dSGEIS.[30] Chemical additives make up 0.446 percent of this mixture, or roughly 82 tons. For a frack mix with one to two percent chemicals, the mass of chemical additives would be approximately 167 tons and 324 tons, respectively. Chemical usage estimates presented in Section 4.1 assume that chemical additives make up one percent of the fracturing fluid mixture. Under this assumption, development of 6,000 wells over a 20 year period would entail fracturing

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[26] Parsons, J. (2008). *Pa. Streams Drained Dry By Drillers*. WTAE, Pittsburgh, November 13, 2008.
[27] Arthur, J.D., B. Bohm, B.J. Coughlin, and M. Layne. (2008). *Evaluating the Environmental Implications of Hydraulic Fracturing in Shale Gas Reservoirs*. ALL Consulting, Tulsa OK.
[28] Fortuna Energy (2009). *Marcellus Natural Gas Development*. Presented at NYWEA 2009 Spring Technical Conference, West Point, NY, June 2, 2009.
[29] U.S. Department of Energy, Office of Fossil Energy. (2009). *Modern Shale Gas Development in the United States: A Primer*, prepared by the Ground Water Protection Council and ALL Consulting, Washington, DC.
[30] dSGEIS, URS Technical Report *Water-Related Issues Associated With Gas Production in the Marcellus Shale*, Figure 2-1.

chemical usage at a rate of 150 to 230 tons per day, or up to 590 tons per day with refracturing at 5-year intervals.

Table 4-3: Mass of Water, Sand and Major Classes of Fracturing Fluid Chemical Additives Required for one 4 MG Fracture Operation

	Percent by mass[1]	Mass required for one 4 MG fracturing operation (tons)
Water	90.6%	16,690
Proppant	8.96%	1,651
Acid	0.11%	20.3
Surfactant	0.08%	14.7
Friction Reducer	0.08%	14.7
Gelling Agent	0.05%	9.2
Clay Stabilizer/Controller	0.05%	9.2
Scale Inhibitor	0.04%	7.4
pH Adjusting Agent	0.01%	1.8
Breaker	0.01%	1.8
Crosslinker	0.01%	1.8
Iron Control	0.004%	0.7
Bactericide/Biocide	0.001%	0.2
Corrosion Inhibitor	0.001%	0.2
Total (all constituents)	100.0%	18,423 tons
Total (chemicals only)	**0.446%**	**82.2 tons**

Notes:
1. dSGEIS, URS Technical Report *Water-Related Issues Associated With Gas Production in the Marcellus Shale*, Figure 2-1.

Chemicals in drilling and fracturing fluid may be introduced into surface waters and ultimately into the water supply as a result of vehicle accidents during transport of raw chemicals to a drill site or removal of wastes from the site, via spills resulting from improper chemical storage and handling at drill sites, and via airborne and subsurface pathways. Chemicals introduced into the ground during the hydraulic fracturing process are not fully recovered. Based on data from horizontal Marcellus wells in northern Pennsylvania reported in the dSGEIS, on the order of 65 to 90 percent of the fracturing fluid may remain in the subsurface. As described in Section 2 and subsequently in Section 4.6, these chemicals can migrate beyond the fracture zone into overlying groundwater, watershed streams, reservoirs, and directly into tunnels and ultimately enter the water supply.

Chemical usage is a significant concern for watershed water quality because many drilling and fracturing fluid additives contain chemicals that are known to be toxic to the environment and hazardous to human health. This concern is heightened by the fact that the exact chemical composition of many additives is not disclosed. Well drilling and fracking products are proprietary and typically protected by trade secret laws, thereby limiting disclosure requirements. Consequently data is limited on the identity and amounts of specific chemicals that could be used during drilling and fracturing operations in or near the NYC watershed.

The fracturing chemical data obtained by NYSDEC from service companies and chemical suppliers during the dSGEIS preparation process highlights the difficulty in obtaining full chemical composition data. Data was received for 197 products, 23 percent of which were not characterized by full chemical composition data. The 197 products were composed of 260 unique chemical components and another 40 components which are mixtures or otherwise not fully characterized. This challenge is also evidenced in a database of fracturing products and chemicals developed by The Endocrine Disruption Exchange (TEDX, Paonia, CO) and reviewed in connection with this project. The database identifies 435 products composed of over 340 individual chemical constituents. The exact chemical composition of over 90 percent of the products in the database is unknown.

Of the known constituents identified in the dSGEIS and by TEDX, many are recognized as hazardous to water quality and human health. The dSGEIS identified chronic or acute health effects such as cancer or impacts to the reproductive, respiratory, gastrointestinal, liver, kidney, or nervous systems for one or more chemicals in nine of eleven chemical structural categories. The analysis did not characterize health effects for each individual chemical, citing “very limited” compound-specific toxicity data for many fracturing chemicals. Of the products identified in the TEDX database, significant percentages contain one or more chemicals that are associated with negative health effects: cancer (33% of products contain one or more chemicals associated with cancer), endocrine disruption (41%), reproductive problems (34%), immune suppression (58%), genetic mutation (43%), and other adverse health impacts.

The use of fracturing fluid additives containing known or suspected carcinogens, endocrine disrupting compounds (EDCs), or other contaminants that may cause human health impacts from long-term or chronic exposure at very low doses is of particular concern to the water supply. As mentioned above in Section 1.3, the regulations concerning drinking water quality are continually evolving. It is reasonably foreseeable that future regulations will include lower thresholds and encompass emerging contaminants of concern, including EDCs. Accordingly, the introduction of hundreds of tons per day of fracturing chemicals into the watershed over a period of several decades, the possibility of subsequent gradual penetration of low levels of contaminants into the environment and the water supply via multiple transport pathways, and the difficulty of removing many of these contaminants from groundwater and surface supplies, pose public health risks that should be carefully considered and avoided.

4.5 Surface Spills

Accidental spills, leaks, and releases associated with natural gas well drilling and fracturing activities have resulted in hundreds of documented groundwater and surface water contamination incidents across the country. Surface spills can be a relatively common occurrence at well sites because the drilling and fracturing process involves transfer of large volumes of fluids between trucks, tanks, wells, pits, etc., often at high flow rates and pressures, substantially increasing the likelihood of a spill due to human error, equipment failure, or accident.

Surface spills in the NYC watershed may be categorized as resulting in either acute or chronic impacts based on proximity to streams and reservoirs. Acute spills are considered here to include accidental or intentional chemical releases that occur adjacent to or in a stream or reservoir. Chronic spills are considered to occur at the well site or beyond the immediate vicinity of a stream or reservoir.

Acute Spills

There are a number of acute surface spill scenarios of concern in the NYC watershed, such as a truckload of raw fracking chemicals or a tanker of flowback/produced water releasing its contents into a NYC reservoir or tributary stream. In addition to substantially compromising operations and public confidence in the water supply, acute spills could also result in MCL violations. Given the enormous volume of chemicals and wastewater that could be transported into and generated within the NYC watershed over a multi-decade development period, acute spill scenarios are realistic and should be expected. This is particularly true in light of the proximity of roads adjacent to NYC reservoirs and the heavy volume of truck traffic required to haul wastewater and chemicals.

To examine the sensitivity of the NYC water supply to acute spills of fracturing chemicals, an analysis of the mass of fracturing chemicals required to violate an MCL at Kensico Reservoir was conducted (Appendix C). The analysis is based on fracturing chemical data and assumptions presented in dSGEIS supporting documents.[31] Both the dSGEIS analysis and the following analysis are structured as simple dilution calculations that assume the chemical mass enters a reservoir directly and is completely and instantaneously mixed with its contents.

Consistent with dSGEIS assumptions, reservoirs were assumed to be one-third full. Such low storage levels would only be expected to occur under severe drought conditions. However, the one-third full assumption is equivalent to the more realistic situation in which the reservoirs are relatively full and the contaminant mass mixes with only one-third of the reservoir's volume as a result of short-circuiting. Complete mixing in reservoirs with volumes as large as NYC's is not a reasonable assumption under most circumstances. Short-circuiting due to stratification, density currents, and prevailing flow patterns is considered more typical.

Two spill scenarios were considered, the key difference between them being the volume into which the chemical mass is diluted:

- Scenario 1 dilutes the contaminant mass with the contents of Kensico Reservoir. This represents a situation in which a load of fracturing chemicals spills into Rondout and the chemicals short-circuit into the intake chamber and are conveyed downstream to Kensico Reservoir.
- Scenario 2 dilutes the contaminant mass with the contents of Kensico and Rondout Reservoirs. This represents a situation in which a load of fracturing chemicals spills into Rondout or near its mouth and mixes completely with the contents of Rondout and Kensico. This is also representative of the impact of spill into Cannonsville, Pepacton, or Neversink Reservoirs that occurs near their respective intake structures.

Under these simple dilution assumptions, the mass of chemical required to violate an MCL is simply the product of the reservoir volume and the MCL, which is 0.05 mg/l for all chemicals considered here. To gauge the number of wells or hydrofracturing operations associated with the mass of chemical required to violate an MCL, data from the dSGEIS analysis was used to

[31] dSGEIS, Alpha Technical Report, *Survey of Regulations in Gas-Producing States, NYS Water Resources, Geology, New York City Watershed, Multi-Well Operations, and Seismicity*, Section 4.8 and Tables 4.3 – 4.5.

develop an estimate of the mass of each chemical required to fracture one well.[32] This data is presented in Table 4-4, along with an estimate of the mass of chemicals required to violate an MCL in Kensico, expressed in terms of fracture job equivalents, for both Scenarios 1 and 2.

Table 4-4: Fracturing Chemical Spill Scenarios for Kensico Reservoir

Chemical *0.05 mg/l MCL for all chemicals*	Estimated mass required to fracture one well (kg)	Fracture job equivalents required to exceed MCL	
		Scenario 1 (dilution with volume of Kensico)	Scenario 2 (dilution with volume of Kensico + Rondout)
2,2,-Dibromo-3-Nitrilopropionamide (1)	3019	0.6	1.7
Methanol (1)	1565	1.2	3.2
Ethylene Glycol (1)	1110	1.7	4.6
C12-15 Alcohol, Ethoxylated (2)	1110	1.7	4.6
Ethoxylated Castor Oil (2)	555	3.5	9.1
Isopropanol (Isopropyl Alcohol) (2)	555	3.5	9.1
Ethoxylated C11 Alcohol (1)	555	3.5	9.1
Alcohols C9-11, Ethoxylated (1)	391	4.9	12.9
(1) dSGEIS Frack Mix 1 (2) dSGEIS Frack Mix 2			

For Scenario 1, the mass of chemicals associated with just one to five hydraulic fracturing operations could be sufficient to violate an MCL at Kensico Reservoir. For Scenario 2, the mass of chemicals associated with two to thirteen hydraulic fracturing operations could be sufficient to violate an MCL at Kensico Reservoir.[33]

This analysis should not be taken to indicate that these or comparable spill scenarios would constitute an imminent threat to public health. In the event of a major spill operators would respond immediately upon learning of the event and take appropriate operational measures to protect the water supply, including water quality sampling, adjusting intake levels, reducing flow rates or taking reservoirs off-line, etc.

This analysis does suggest that large scale development of natural gas wells in the watershed, and associated substantial increases in chemical and waste hauling, can be fairly characterized as increasing the risk of water quality impairment relative to current conditions. It also highlights the importance of stream and reservoir buffers in mitigating such risks.

Though this analysis has focused on MCLs, it is important to note that water quality contamination is important in and of itself, even if it does not trigger an MCL violation. NYCDEP's mission is not to supply water that merely meets regulatory limits but "to reliably

[32] Due to confidentiality requirements the dSGEIS analysis does not present data on the mass composition of additives or the mass of additives or constituent chemicals required to fracture a well. The scenarios presented in the dSGEIS analysis do provide sufficient information to back-calculate the mass of chemicals required to fracture a well.

[33] Undiluted hydrofracking chemicals are trucked to well sites and then mixed with large volumes of water. Multiple wells may be fractured on a well pad sequentially or at nearby wellpads and therefore significant quantities of undiluted chemicals could be involved in a surface spill.

deliver a sufficient quantity of *high quality drinking water* and to ensure the *long term sustainability* of the delivery of this most valuable resource."[34]

Chronic Spills

In addition to acute spills, it is reasonable to expect that development of natural gas resources in the watershed will be accompanied by an increased frequency of chemical, wastewater and fuel spills at or near well pads. This is a natural outcome of a complex and intensive industrial activity occurring dozens or hundreds of times per year across the watershed. Site spills can be reduced through implementation of best management practices (BMPs) for pollution prevention, waste minimization, chemical handling and storage, etc. Even with appropriate BMPs and regulations, however, mechanical failures, human errors, and accidents are inevitable. Impacts will be minor when on-site personnel respond quickly and limit the impacts of the incident. But significant contamination can occur when spills go undetected, plans are not followed, equipment is not maintained, and/or BMPs are not implemented.[35]

Even if most site spills are mitigated with minimal impact, the chronic occurrence of multiple spills per year over a period of several decades can be expected to compromise public confidence in the quality of NYC's unfiltered water supply.

4.6 Subsurface Migration

Subsurface migration of fracturing fluids or formation water and pressures could present risks to potable water supplies if such fluids were to intercept a shallow fresh water aquifer or NYC infrastructure. Potential migration pathways include migration of fracturing and formation fluids along the well bore as well as migration across and out of the penetrated and hydraulically fractured strata. This section identifies risks associated with these migration pathways. Containment of fluids within the well-bore is provided for by well construction techniques that include multiple casings and cemented annular spaces extending below fresh water aquifers. The competency of the overlying strata and control of the fracturing process to limit induced fractures to the target formation are relied upon to provide a hydraulic barrier for containment of fracturing and formation fluids within the gas-bearing formation.

The review of regional geology and tunnel construction data presented in Section 2 indicates that vertical migration of deep groundwater, methane and/or fracking chemicals is a foreseeable occurrence, given the existence of naturally occurring and laterally extensive vertical brittle geological structures, and the documentation of faults and seeps during tunnel construction. This section also considers whether activities and subsurface alterations that can be anticipated to accompany natural gas exploration and development would present a risk to subsurface water supply infrastructure or operation.

The presence of numerous brittle structures in the regional bedrock is well documented. Presently identified brittle structures that have been mapped in the Catskill/Delaware watershed can extend up to seven miles laterally and up to 6,000 feet in depth.[36,37] The vertical and lateral persistence of these features in conjunction with the potential for failed casings or other

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34 NYCDEP-BWS Mission Statement.
35 Case studies are provided in the Rapid Impact Assessment, NYCDEP, 2009.
36 Hill et al, 2008.
37 Engelder and Lash, 2008.

unforeseen occurrences could result in significant surface and subsurface contamination of fresh water aquifers, as illustrated by incidents in other well fields, most notably documented in Garfield County, Colorado (migration of toxic formation material through subsurface fractures) and Dimock, Pennsylvania (migration of natural gas to the surface via improperly cased wells). Similar mechanisms could permit migration of material into the fresh water aquifers that comprise the NYC West-of-Hudson watersheds and present potential risks to water quality and tunnel lining integrity.

Existing Migration Pathways

Brittle geological features such as faults, fractures and crushed zones were encountered during water supply tunnel construction. Groundwater inflows were also encountered at numerous locations during tunnel construction, and in several cases, these align with mapped faults, fractures or linear features. More importantly saline, methane, and hydrogen sulfide seeps were encountered as well. These seeps are considered to be indicative of a hydraulic connection to naturally-occurring pressurized groundwater/fluids from much deeper strata. Existing connections to deeper strata can transmit pressurized fluids (e.g., saline and/or radioactive formation water and residual hydrofracturing chemicals) upward to the vicinity of the fresh water aquifer and tunnels (and to the surface).

Casing and/or grouting problems, improper plugging or abandonment of wells, extensive subsurface fractures and the region-wide development requiring the operation of thousands of wells may enhance existing hydraulic connections and/or create new connections. Wells that are not properly plugged and abandoned could become a conduit for the introduction of contaminated fluids into the fresh water aquifer. It is estimated that location and condition records are lacking for over 50 percent of the previously constructed oil and gas wells in New York State. State-wide this amounts to approximately 40,000 existing wells that could serve as migration pathways for injected fluids but for which regulators do not have sufficient information to take protective actions. Given the prior history of oil and gas development, most of these are presumably in the western part of the state. However, some gas wells were drilled in the watershed region, indicating prior interest in developing the resource and the possibility of undocumented or improperly abandoned wells.

Effects on Underlying Strata and Migration Pathways

The force of thousands of feet of overlying rock produce high lithostatic pressures in deep low permeability gas reservoir rock units such as the Marcellus formation. Given the low primary porosity of these units they are often considered to act as a hydraulic barrier that can prevent the migration of fluids from lower formations to overlying strata. Hydrofracturing for natural gas development diminishes the isolating properties of the targeted shale, compromising the integrity of this subsurface barrier between surface aquifers and naturally occurring, low quality formation water, as well as other fluids introduced into the shale.

New fractures generated during well development and stimulation that propagate vertically beyond the target formation can create or enhance hydraulic pathways between previously isolated formations. Technical supporting documents provided with the dSGEIS indicate that:

> *"Hydraulically induced fractures often grow asymmetrically and change directions due to variations in material properties. In formations with existing natural fractures, such as*

> *the Barnett and Marcellus shales, hydraulic fracturing can create complex fracture zones as fracturing pressure reopens existing fractures and as induced fractures and existing fractures intersect. Actual fracture patterns are generally more complex than the current conceptual models predict." (dSGEIS ICF Task 1 Report, p5)*

This, and several other similar statements in technical documentation provided in support of the dSGEIS, suggest that extension of induced hydraulic fractures above the target formation, although not an intended result, can be anticipated to occur in some cases when hydrofracturing a large number of wells. Furthermore, subsurface features are expected to be stressed or altered in the future as a result of naturally occurring geologic changes and/or disturbances associated with widespread hydraulic fracturing. The dSGEIS indicates that fracturing may be accompanied by "as much as" a one percent increase in volume of the hydrofractured rock. It is reasonable to anticipate that this would alter rock stresses over an indeterminate distance which could facilitate fluid migration along existing brittle geological structures. The long-term impacts from thoroughly and extensively fracturing and expanding a rock unit that underlies a widespread area to the greatest extent that is economically feasible and then depressurizing the formation through the removal of compressed gas is difficult to quantify; especially in terms of how the overall activity will impact brittle structures in the overlying strata. Potential impacts that can be anticipated include movement of fluids at faults and fractures, alteration of subsurface flow pathways, vertical migration of fluid and depressurization of confined material as illustrated in Figure 4-1.

Injection Well Operations

Underground injection is an alternative sometimes used for disposal of waste water produced by natural gas production. Class II underground injection wells are employed in other gas plays, and as of November 2008, there were reportedly over 60 permits for Class II UIC wells for flowback water disposal in New York.[38] While there is uncertainty as to the geological feasibility of underground injection in the watershed region, the potential operation of injection wells could create additional risk to the NYC West-of-Hudson watershed and related water supply infrastructure, as injection well operation presents many of the same risks for subsurface migration of fluids and has been associated with seismic events elsewhere.

Pressure Gradients

Lithostatic pressures acting on the Marcellus formation and its limited transmissivity account for the observed high confining pressures of the fluids occurring within the formation.[39] These confining pressures can result in hydraulic grades well above the elevation of any of NYC's reservoirs, or the pressure in water supply tunnels, even without considering the pressure increases imposed during hydrofracturing. Vertical migration of fluids (e.g., brine, methane, hydrogen sulfide) from deeper strata and infiltration into water supply tunnels is hydraulically possible, even with tunnels in operation.

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[38] ALL Consulting, LLC (Arthur, J.D, Bohm, B., Coughlin, B.J., Layne, M.). *Evaluating the Environmental Implications of Hydraulic Fracturing in Shale Gas Reservoirs.* Presented at the International Petroleum & Biofuels Environmental Conference, Albuquerque, NM, November 11-13, 2008.

[39] 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.

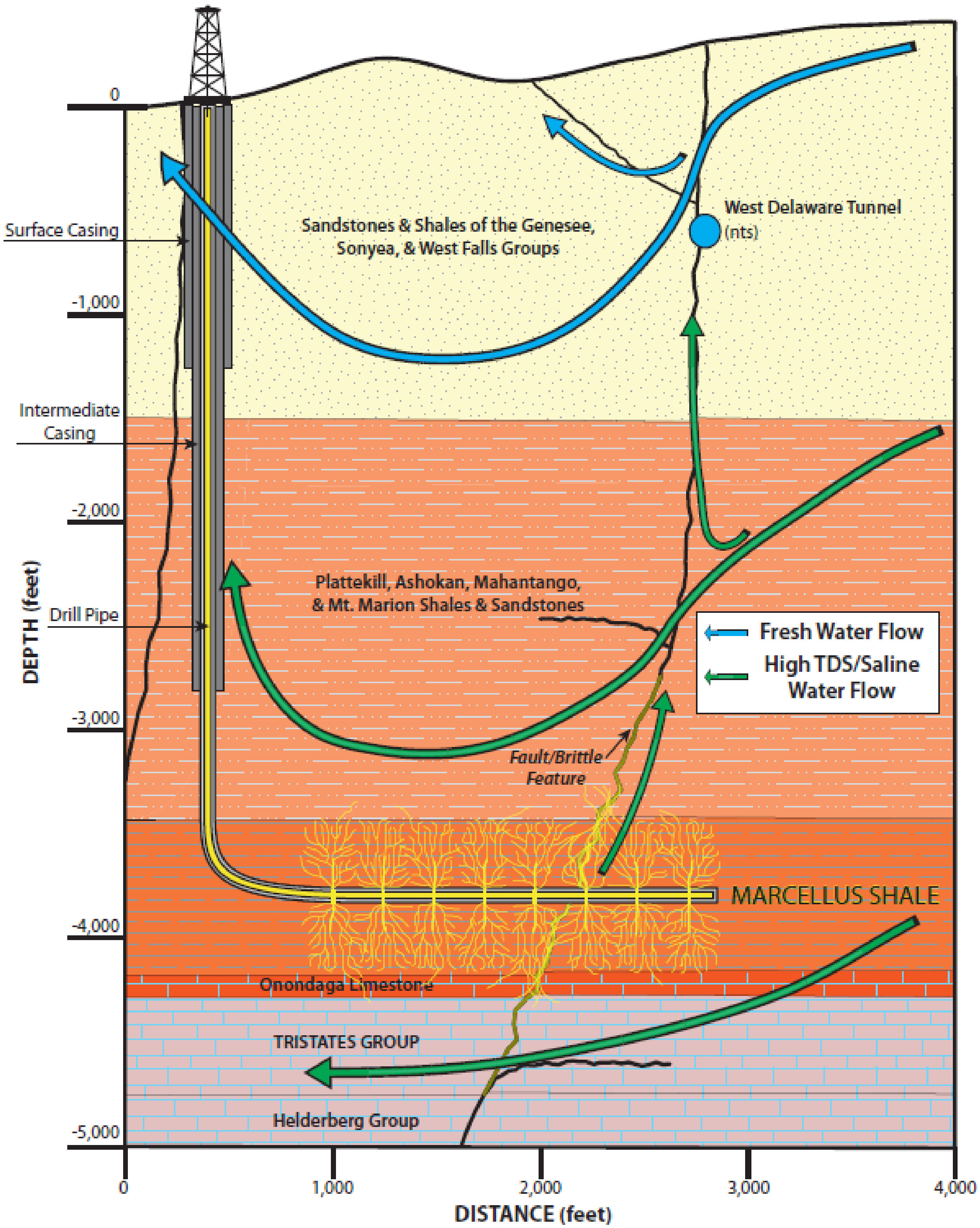

Figure 4-1: Examples of potential flow regime disruption mechanisms

NYC Tunnel and Aqueduct Impacts

NYC operates over 100 miles of deep-rock water supply tunnels in the West-of-Hudson region. Although these tunnels are generally located in overlying strata, in some locations they are in direct contact with the Marcellus formation. Primary impact considerations for this infrastructure are described below.

Tunnel Lining Structural Considerations

The unreinforced linings of NYC tunnels were designed to keep water in, not to withstand external pressures beyond those anticipated in their design. The incremental increase in fluid pressure that could theoretically be transmitted from the Marcellus could exceed the compressive strength of tunnel liners. Structural analysis of concrete tunnel liners exposed to asymmetric external pressure loads indicates that there is potential for detrimental effects on the liners upon the imposition of uneven external pressures as low as 25 psi. These detrimental effects could include liner cracks, which would facilitate infiltration of pressurized fluids. Pressure transmission to the vicinity of tunnels could occur during fracturing, or it could occur after fracturing, when newly expanded fractures expose tunnel linings to naturally occurring formation pressures. During hydrofracturing operations, tunnel liners could be exposed to still higher pressures.

Infiltration to Water Supply Tunnels

Sections of deep-rock tunnels could be subject to inflow of fluids from deeper strata through cracks in tunnel lining. This could occur most readily during the rare occasions when a tunnel is out of service, dewatered, and internal pressures are reduced, or in a tunnel which operates at atmospheric pressure, as does much of the Shandaken Tunnel that leads from Schoharie Reservoir to Esopus Creek. As indicated by the consideration of the degree of confining pressures occurring in the Marcellus, it is also hydraulically possible for pressurized fluids from deeper formations to infiltrate an operating tunnel. Additional liner cracks can be anticipated to develop as the tunnels age, due to normal geologic activity (e.g., seismic activity), and to changes in subsurface conditions associated with widespread hydrofracturing, gas reservoir depletion/withdrawal and injection well operation.

An analysis of the chemical concentrations in flowback water documented in the dSGEIS and their potential influence on water quality in flow conveyed by NYC's water supply tunnels is summarized in Table 4-5. The analysis has been performed for tunnels operating at 500 mgd, using both the maximum and median concentrations reported in the dSGEIS for flowback water.[40] It shows that there are several constituents of flowback water which could cause tunnel discharges to exceed prevailing water quality limits upon infiltration into water supply tunnels at relatively modest rates. Most of these exceedances are associated with infiltration rates of several hundred gallons per minute, rates which were documented during tunnel construction. However, documented concentrations of barium, a toxic heavy metal, would cause water quality exceedances upon infiltration to tunnels at rates as low as 10 to 20 gallons per minute. Also of note are the analyses for elevated concentrations of chlorides and total dissolved solids (TDS). These constituents are associated with the target formation and are most characteristic of

[40] With the exception of the Rondout-West Branch section of the Delaware Aqueduct, which has a hydraulic capacity of 890 mgd, the capacities of the remaining West-of-Hudson tunnels range from 500 to 700 mgd, although they are typically operated at flow rates several hundred mgd below capacity.

produced water rather than flowback. As such, the available mass of these constituents would not be limited to that introduced directly by hydrofracturing.

Table 4-5: Infiltration Rate to Tunnels that Would Cause Tunnel Discharge to Exceed NYSDEC Part 703 Water Quality Limit

Parameter	NYSDEC Part 703 Water Quality Limit (mg/l)	Flowback Concentration Estimates[1] (mg/l)		Infiltration Rate that Would Cause Tunnel Discharge to Exceed Part 703 Limits[2] (gpm)	
		Median	Maximum	At Median Flowback Concentration	At Maximum Flowback Concentration
Chlorides	250	56,900	228,000	1,520 gpm	380 gpm
TDS	500	93,200	337,000	1,860 gpm	510 gpm
Barium[3]	1	662	15,700	520 gpm	20 gpm
Benzene	0.001	0.48	1.95	720 gpm	180 gpm

Notes:
1. Flowback concentrations per dSGEIS Table 5-9.
2. Assumes aqueduct flow of 500 mgd. Infiltration rates calculated for water quality standard violations would be proportionately lower at lower aqueduct flows.
3. Supporting documents included with the dSGEIS list barium concentrations as high as 19,200 mg/l.

Given that the lengths of the West-of-Hudson tunnels range from 5 to 45 miles, and groundwater infiltration was encountered at rates of 100 gpm or more at some locations during construction, the calculated infiltration rates are not implausible especially if existing fractures are widened or additional fractures are created. Allowing for the long-term influence of extensive hydrofracturing and possible injection well operation, the possibility of infiltration from an overpressurized source at rates calculated above is a realistic risk to water quality conveyed by NYC's water supply tunnels. If maximum contaminant levels become more stringent, as is likely, then even lower infiltration rates could violate regulatory limits.

In summary, there is sufficient pressure under natural and gas-well enhanced conditions to drive fluids or gas upward from deep formations into tunnels or above grade, via geological faults or fractures, and there is potential for both structural damage to tunnel liners and violations of regulatory limits.

Water Supply Operations

The enhanced migration of fluids from deep formations could also include the migration of gases such as methane and hydrogen sulfide. Migration could occur through pre-existing brittle structures and may be further influenced by laterally extensive zones of elevated hydraulic conductivity associated with tunnel routes and vertically drilled shafts. Tunnel and shaft routing configurations may also permit the accumulation of methane and/or hydrogen sulfide in pockets of the infrastructure that require access from time to time for inspection and/or maintenance purposes. In such instances, the accumulation of either of these gases could represent an increased health and safety risk. The most serious potential consequence would be a methane gas explosion, which could threaten personnel and seriously damage critical infrastructure.

Related Precedent

The migration of fracking chemicals and/or poor quality formation water into overlying groundwater, watershed streams, reservoirs, and directly into tunnels is a reasonably foreseeable risk. The failures postulated above are not theoretical: they have occurred, at least with respect to impacts on streams and groundwater. A well-documented case occurred in Garfield County, Colorado in 2004 where natural gas was observed bubbling into the stream bed of West Divide Creek.[41] In addition to natural gas, water sample analyses indicated ground water concentrations of benzene exceeded 200 micrograms per liter and surface water concentrations of benzene exceeded 90 micrograms per liter – 90 times the NYSDEC Part 703 water quality limit for discharge of benzene to surface waters. Operator errors, in conjunction with the existence of a network of faults and fractures, led to significant quantities of formation fluids migrating vertically nearly 4,000 feet and horizontally over 2,000 feet, surfacing as a seep in West Divide Creek. It should be noted that the vertical separation between the Marcellus Shale and the West Delaware Tunnel ranges between 3000 and 5500 feet, well within the vertical distance seen in this incident in Garfield County, Colorado. Clearly there is a very real potential for methane migration from the Marcellus shale to the City water supply tunnels.

Although remedial casings installed in the well reportedly reduced seepage, the resulting benzene plume has required remediation since 2004. Subsequent hydrogeologic studies have found that ambient groundwater concentrations of methane and other contaminants increased regionally as gas drilling activity progressed, and attributed the increase to inadequate casing or grouting in gas wells and naturally occurring fractures.[42]

Groundwater contamination from drilling in the Marcellus shale formation was reported in early 2009 in Dimock, PA, where methane migrated thousands of feet from the production formation, contaminating the fresh-water aquifer and resulting in at least one explosion at the surface.[43,44] Migrating methane gas has reportedly affected over a dozen water supply wells within a nine square mile area. The explosion was due to methane collecting in a water well vault. Pennsylvania Department of Environmental Protection has since required additional ventilation, installed gas detectors and taken water wells with high methane levels offline at impacted homes to reduce explosion hazards. At this time the root cause remains under investigation and a definitive subsurface pathway is not known. This case is of particular concern since the terrain and geology in Pennsylvania is very similar to that of the NYC watershed: Dimock is only 35 miles from Deposit, NY and the Cannonsville Reservoir Dam.

In addition to these cases, there have been numerous reports of smaller, localized contamination incidents that have resulted in well water being contaminated with brine, unidentified chemicals, toluene, sulfates, and hydrocarbons.[45] In most cases the exact cause or pathway of the contamination has not been pinpointed due to the difficulty in mapping complex subsurface features. The accumulating record of contamination events that are reportedly associated with, or

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[41] Colorado Oil and Gas Conservation Commission (COGCC). 2004. *Order no. 1V-276.* (http://cogcc.state.co.us/orders/orders/1v/276.html accessed 3/13/09).

[42] G. Thyne. *Review of Phase II Hydrogeologic Study.* Prepared for Garfield County. (CO) December 12, 2008.

[43] Wilber, T., *DEP zeros in on gas tainting water.* Binghamton Press and Sun Bulletin. January 30, 2009.

[44] Wilber, T., *PA officials reviewing Cabot drilling plan.* Binghamton Press and Sun Bulletin. October 13, 2009.

[45] See Rapid Impact Assessment Report for a discussion of various case studies of contamination.

in close proximity to hydrofracturing and natural gas well operations, suggests water quality impairments and impacts can be reasonably anticipated.

4.7 Wastewater Treatment and Disposal

Fracturing fluids that are returned to the surface as flowback and produced water from the formation tend to have very high TDS and chlorides, and may be contaminated with hydrocarbons, radionuclides, heavy metals, and fracturing chemicals, thus requiring specialized treatment and disposal. Approaches to treatment and disposal of drilling wastewater that have been employed elsewhere include:

- Underground injection wells;
- Industrial wastewater treatment followed by reuse or surface disposal; and
- Industrial pretreatment, followed by conventional treatment and surface disposal.

Underground injection is a common and frequently preferred method for disposal of drilling and fracturing waste. The feasibility of underground injection at the capacity that will be needed to accommodate waste from extensive development of the Marcellus formation as a natural gas resource has not been established. If underground injection proves feasible, the number of injection wells in New York could increase substantially. Injection well failures resulting in surface and groundwater contamination have been reported elsewhere.[46] Injection well operation has also been associated with induced seismicity which could increase subsurface migration of fluids from hydrofractured strata and other deep formations.

Treatment and disposal of wastewater is complicated by the high concentrations of numerous constituents of the waste stream and the presence of constituents that are not amenable to conventional treatment, such as naturally-occurring radionuclides and high concentrations of heavy metals. Experience in Pennsylvania to date is relevant to the issues that will face New York, and a concise summary of the waste disposal situation in Pennsylvania is provided in the abstract for a paper presented at the September 2009 Eastern Regional Meeting of the Society of Petroleum Engineers:

> *"In the Commonwealth of Pennsylvania, new regulatory limits have been proposed further limiting discharges. The Pennsylvania Department of Environmental Protection announced on April 15, 2009 that all industrial discharges will be limited to 500 mg/l TDS on January 1, 2011. There are currently no facilities in the state that can treat flowback fluids to this level. The options for an economic solution are few for operators in dealing with these saline flowback fluids. Evaporation/crystallization (EC), the only established technology for treatment of the produced waters that can achieve the newly proposed TDS limit, produces a very highly concentrated brine solution or large volumes of crystalline salt cake that still must be disposed. A 1 million gal/day crystallization plant will generate approximately 400 tons/day of salt waste. Unless some beneficial use for these residues can be found, they will require disposal in a secure solid waste facility. A typical municipal landfill cannot accept large volumes of crystalline salts and suitable facilities can do so only at a premium. Further, an EC plant is very energy intensive and*

[46] Hudak, P.F., Wachal, D.J. *Effects of Brine Injection Wells, Dry Holes and Plugged Oil/Gas Wells on Chloride, Bromide, and Barium Concentrations in the Gulf Coast Aquifer, Southeast Texas, USA.* Environment International. Vol. 26. Issues 7-8. June 2001. Pages 497-503. Copyright 2001. Elsevier Science, Ltd.

thus has the potential for increased air quality impact and greenhouse gas emissions in addition to its cost of operation. The Marcellus shale gas industry may be left with no economically viable disposal options."[47]

The 400 ton per day figure cited above corresponds to a solids concentration of approximately 100,000 mg/l, which is comparable to the median value reported for flowback samples in the dSGEIS (93,200 mg/l), and well below the maximum reported value of 337,000 mg/l.[48] As such, the solids load generation rate of 400 tons per million gallons could be higher.

Recycling of flowback can help to reduce the volume of wastewater generated, but the high concentration of scale-forming constituents limits the amount that can be recycled. Treatment and further dilution with fresh water is typically needed for re-use of flowback water, and significant quantities of residuals remain to be disposed. As noted above, currently available industrial treatment options are very limited. Treatment of Marcellus gas well wastes is the subject of several current research initiatives, but these are at very early stages. In general the availability of adequate treatment and disposal facilities for natural gas wastewater is severely limited.

Table 4-2 estimates the annual average wastewater generation rate for the full build-out scenario of 6000 wells in the watershed at 2.6 to 3.5 mgd, without allowance for additional load that could be generated by refracturing operations. To meet a 500 mg/l effluent limit for a 3.5 mgd, 100,000 mg/l TDS waste stream by dilution only would require 700 mgd of fresh water. The solids load associated with this waste stream would be *1,100 to 1,500 dry tons per day*. For comparison, the NYCDEP wastewater treatment plants serving NYC treat approximately 1.2 billion gallons of sewage per day and produce about 400 tons per day of dry sludge solids.

Judging by the flow rates calculated to dilute this waste stream, it is evident that dilution is unlikely to provide a feasible solution, once the gas resource is developed to a significant degree. The viability of injection wells in this region for waste disposal is unproven. Lastly, the only established technology for treatment would produce large volumes of solids which will need to be transported and disposed of, and which will likely include elevated levels of radioactivity which would further limit solids disposal options.

The quantities cited above are for an assumed 6,000 well full build-out scenario, and necessarily rely on a number of estimates with respect to flowback and produced water rates. However, these estimates are for potential gas well development within the NYC West-of-Hudson watershed alone, and do not take into account gas industry waste streams that would be generated in any other areas in New York State or Pennsylvania. If allowance is made for refracturing, these waste estimates could be about 2.5 times higher.

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[47] Blauch, M.E. (Superior Well Services, Inc.); Myers, R.R., Moore, T. R.; Lipinski, B.A. Exco - North Coast Energy, Inc.; Houston, N.A. (Superior Well Services, Inc.). *Marcellus Shale Post-Frac Flowback Waters - Where is All the Salt Coming from and What are the Implications?* SPE Eastern Regional Meeting, 23-25 September 2009, Charleston, West Virginia, USA. Copyright 2009. Society of Petroleum Engineers Paper Number 125740-MS. Abstract referenced at http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-125740-MS&soc=SPE December 2009.

[48] NYSDEC. 2009. *Draft supplemental generic environmental impact statement on the oil, gas and solution mining regulatory program (SGEIS)*. New York State Department of Environmental Conservation Division of Mineral Resources, Albany, NY.

Clearly, the development of natural gas resources will present a significant waste disposal challenge for which there is no clear or viable solution evident at this date. Failure to adequately account for regional wastewater disposal needs has resulted in at least one recent incident of surface water quality violations. In October 2008 excessive gas well brine disposal at publicly-owned treatment works (POTWs) in the Monongahela Basin contributed to high TDS in the river and its tributaries.[49] The elevated TDS concentrations caused taste and odor problems in drinking water, high levels of brominated disinfection by-product precursors at water treatment plants, and violations of particulate limits in power plant emissions. Waste disposal is a direct concern for NYCDEP, as the absence of economically viable disposal options will incentivize irresponsible and illegal waste handling and disposal practices.

[49] *Pennsylvania DEP Investigates Elevated TDS in Monongahela River*. Water and Wastes Digest. October 27, 2008

Section 5: Summary

This section summarizes the impacts of natural gas development using horizontal drilling/high-volume hydraulic fracturing on the NYC water supply watershed and infrastructure.

Rate and Density of Well Development in the NYC Watershed

Reasonably foreseeable natural gas well development scenarios for the NYC watershed based on experience in comparable formations suggest that under favorable economic and regulatory conditions annual well completion rates would increase from initial rates as low as 5 to 20 wells per year to an average of 100 to 300 wells per year, potentially peaking at 500 wells per year. Consistent with NYSDEC spacing unit requirements and development in other formations, it is estimated that on the order of 3,000 to 6,000 wells could ultimately be drilled and fractured in the NYC watershed. This does not include re-fracturing of the same wells, nor does it include drilling and fracturing of wells to tap natural gas in the Utica, Oriskany, or Trenton/Black River formations underlying the NYC watershed. Development of these formations would require additional well construction but not necessarily new ancillary infrastructure.

Meaningful assessment of risks and impacts must be guided by the scale of natural gas development. Any individual hydraulic fracturing operation poses a relatively small risk to the water supply. But at the rates and densities of development as currently practiced elsewhere in the Marcellus and comparable formations, the likelihood of negative impacts and the subsequent risk to the water supply is substantially higher. When the issue is considered from the standpoint of not one well but of hundreds or thousands of wells, the cumulative risks become significant. Prevention of polluting activities is certain to protect water quality and infrastructure from these cumulative risks. To illustrate minimum mitigation measures that would be required to reduce risks for any one individual impact, Appendix D sets forth certain mitigation strategies.

The following are considered foreseeable risks, and merit detailed consideration:

Land Disturbance, Site Activity, and Truck Traffic (Industrialization)

- High levels of site disturbance, truck traffic and intensive industrial activity, on a relatively constant basis, over a period of decades, and attendant impacts on overall watershed health.
- Trucking activity will be accompanied by provision of equipment and material supply systems (warehouses, garages, support services), gas gathering and pipeline systems, compressor stations, and waste disposal systems.
- Without some limits on the rate or density of development in the watershed, it is reasonable to expect that a significant and relatively rapid industrialization of the NYC watershed could occur.

Tunnel Integrity and Subsurface Migration

- Widespread hydraulic fracking will permanently and irreversibly compromise a significant geological formation that presently constitutes part of the subsurface system that isolates near-surface, fresh water flow regimes from non-potable, highly saline waters of deeper formations.
- The subsurface impact of repeated and extensive fracturing on intervening strata will increase the likelihood of the migration of hazardous chemicals and/or poor quality formation water and infiltration into overlying groundwater, watershed streams, reservoirs, and tunnels.

- The inadvertent extension of fractures beyond the target strata, and long-term changes in subsurface stresses will likely increase the number and capacity of migration pathways through the geologic strata underlying the watershed, and increase the likelihood of subsurface contamination of the water supply system.
- Infiltration of formation or fracking fluids could cause tunnel discharges to exceed NYSDEC discharge standards even at low infiltration rates.
- Transmittal of pressurized fluids from presently isolated deep formations could expose the external surfaces of the unreinforced concrete tunnel liners to excessive pressures and compromise liner integrity.

Water Withdrawals

- Despite representing a small portion of overall watershed yield, withdrawals for hydrofracturing could significantly impact commitments for water supply and habitat protection, particularly during periods of drought. The severity of impacts will depend on the amount and timing of withdrawals. Withdrawals while reservoirs are spilling would have little impact. Withdrawals during dry periods could increase the duration of drought watch, warning, or emergency conditions.
- Delaware Basin withdrawals downstream of the NYC West-of-Hudson reservoirs could impact system operations by requiring increased releases to meet in-stream flow requirements. Similarly, withdrawals from the Upper Esopus Creek could require increased releases from Schoharie Reservoir to meet minimum downstream flow requirements.
- Excessive water withdrawals may also impact aquatic habitat and biota.

Chemical Usage

- Introduction of hundreds of tons per day of fracturing chemicals into the watershed over a period of several decades will likely be accompanied by the gradual dispersion of low levels of toxic chemicals into the environment and potentially the water supply via multiple transport pathways.

Surface Spills

- A chronic and persistent occurrence of small scale surface spills and contamination incidents will inevitably accompany the thousands upon thousands of fluid transfer activities necessary for widespread hydrofracturing and gas well operation, and can be expected to reduce public and regulatory agency confidence in the quality and safety of the water supply.
- Occasional acute spills that could cause operational impacts, potential MCL violations and further undermine confidence in the ability to maintain current high water quality standards.

Wastewater Treatment and Disposal

- The flowback and produced waters resulting from hydrofracturing and gas well operations will produce an industrial-strength waste stream characterized by exceptionally high concentrations of a wide range of substances with the potential for adverse health and water quality effects which can be expected to exceed existing treatment and assimilative capacities within a few years.
- There is high level of uncertainty as to whether effective waste treatment processes and sufficient capacity will be available in the future. Sufficient dilution capacity is unlikely to be available. Residuals productions associated with the only presently available treatment

technology could produce a waste stream that amounts to three to four times the dry sludge total disposed of by NYC's fourteen wastewater treatment plants.

- Solids disposal options will be further limited by elevated levels of radioactivity.
- Waste management and transport will likely contribute to a long-term, low level increase in truck traffic and transport of hazardous chemicals.
- Siting of injection wells and or treatment facilities will add an additional category of industrial activity to the region.
- Widespread use of injection wells, if geologically feasible, would provide additional contaminant transport pathways and could possibly increase low-level seismic activity, increasing opportunity for subsurface contaminant transport.

Filtration Avoidance Determination

- Given the importance of watershed protection for unfiltered water supply systems, major changes in land use and/or increased levels of industrial activity in the watershed could jeopardize the Filtration Avoidance Determination granted to the Catskill and Delaware water systems and decrease public confidence in the high quality of the NYC water supply.
- In the event that filtration is ultimately required, NYC expects that the current $10 billion filtration plant design would not be adequate to remove the chemicals that could be introduced into the watershed. Advanced oxidation, granular activated carbon adsorption, and/or membrane filtration processes could be required. All of these advanced processes are significantly more expensive than the current design, and it is quite possible that the available treatment site would not even accommodate the additional treatment technology. Net impacts on overall treatment facility requirements processes would be expected to increase costs by at least 50 percent and possibly more than 100 percent relative to the current design.

Taken together, these potential impacts - some very likely, some less so, many simply unknown –suggest that large-scale horizontal drilling/high-volume hydraulic fracturing in the NYC watershed will substantially increase the overall risk to the NYC water supply compared to current conditions.

This assessment has focused on activities and impacts that would most directly affect NYC's water supply system. Other effects, which for the purposes of this effort have been considered to be secondary, would not necessarily be minor or insignificant. Induced growth, and the economic changes that it would bring, can adversely impact water quality. It often results in additional demand on roads and other local infrastructure, including schools, local water supply and municipal wastewater treatment systems, hospitals and emergency services. Adverse air quality impacts and impacts on flora, wildlife and soil chemistry can also be expected given the level of industrial activity that would accompany hydraulic fracturing and horizontal drilling operations, particularly if implemented at rates and densities employed elsewhere.

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.

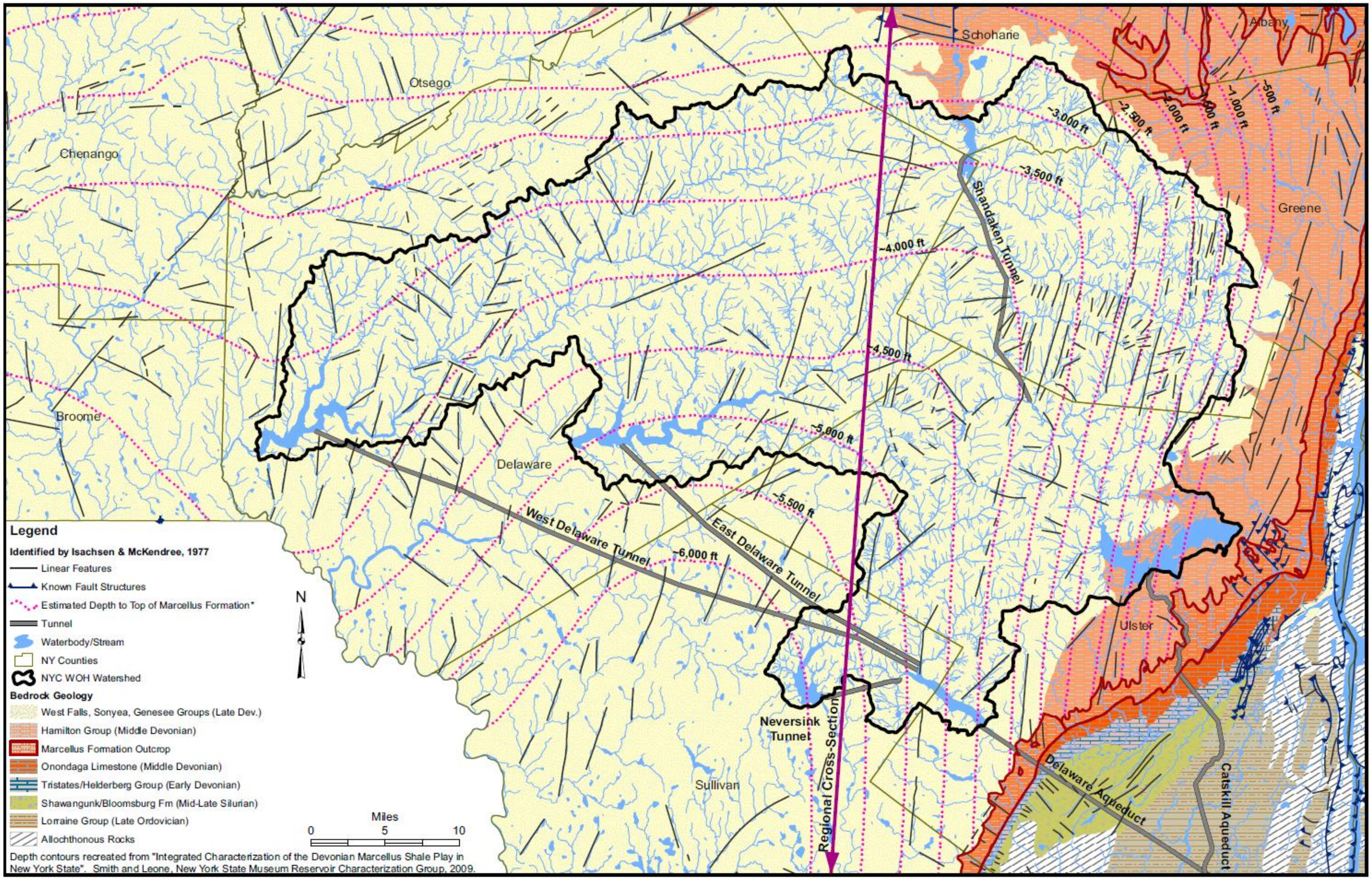

Figure A-1: Bedrock Geology of the Catskill Region

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^o to 15^o 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).

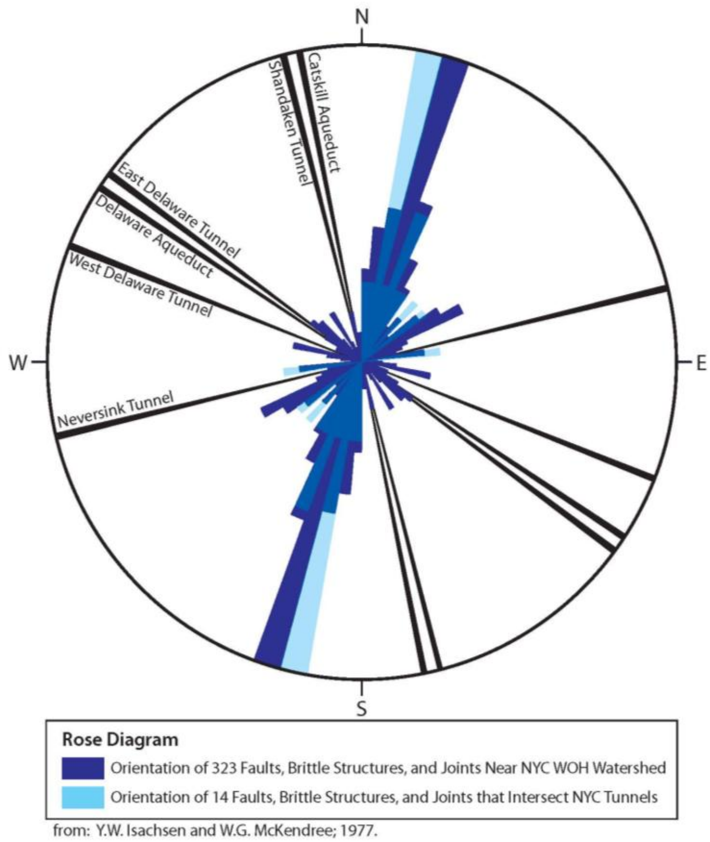

Figure A-2: Rose Diagram of Mapped Brittle Features for the WOH Watershed Area and Infrastructure

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.

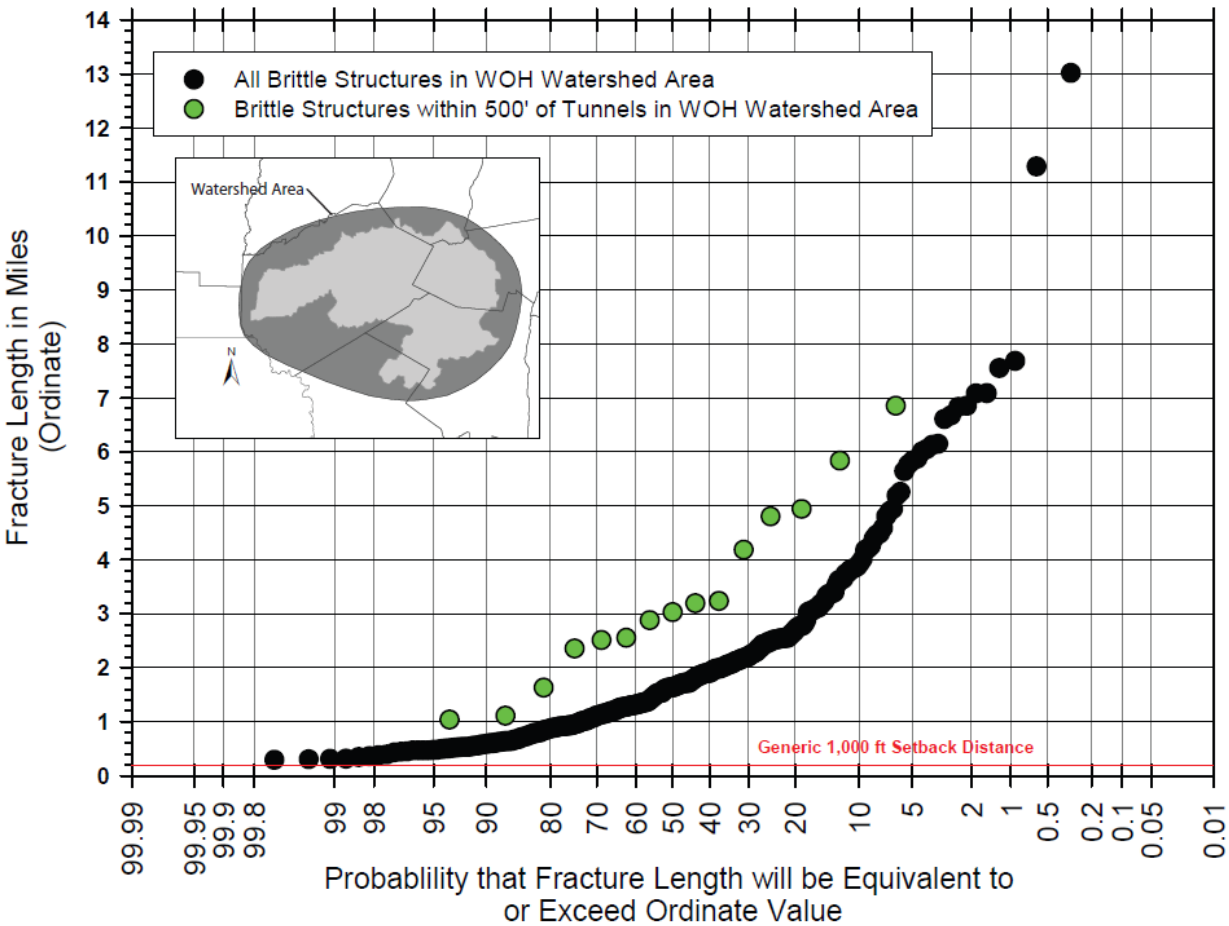

Figure A-3: Probability Plot of Mapped Brittle Feature Lengths for the WOH Watershed Area and Infrastructure

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

Appendix B: Rates and Densities of Natural Gas Well Development

The rate and ultimate density of natural gas well development in the NYC watershed will depend on a variety of economic, technical and regulatory factors. In order to characterize potential development scenarios in the watershed and the resulting cumulative impacts, historical rates and densities of drilling in other formations were evaluated. Sufficient data exists from other shale gas plays that have been under development for the last two to ten years to estimate reasonable ranges for rates and densities of well construction.

The rates and densities of natural gas well development in other major shale gas formations were characterized based on well completion and permitting data from state regulatory agencies and drill rig activity data from industry sources. Four major shale gas plays were identified for comparison purposes: Barnett (Texas), Fayetteville (Arkansas), Haynesville (Louisiana), and Marcellus (Pennsylvania). These formations are all gas-bearing tight shales that require hydraulic fracturing for economic production and have been developed using a combination of horizontal and vertical wells. This assessment focuses on the "Core" and "Tier I" areas within these formations, which are loosely defined in the natural gas industry as the areas that have the highest potential for gas production. Salient features of these formations and the Core/Tier I counties selected for comparison are summarized in Table B-1.

Table B-1: Representative Core/Tier I Counties of Major Shale Gas Plays

Formation (State)	Approximate # Years under Development	Total Formation Area (mi^2)	Selected Counties	Area (mi2)	% of Formation Area in Selected Counties
Barnett (TX) (Newark East field)	13 [(28)]	5,000	Denton, Johnson, Tarrant, Wise	3,512	70%
Fayetteville (AR) (B-43 field)	6	9,000	Cleburne, Conway, Faulkner, Van Buren, White	3,589	40%
Haynesville (LA)	3	9,000	Bossier, Caddo, De Soto, Red River	3,100	34%
Marcellus (PA)	2	95,000	Bradford, Lycoming, Susquehanna, Tioga	4,374	5%

Core and Tier I areas were selected as the basis of comparison because available data suggests that the NYC watershed is underlain by portions of the Marcellus with high gas production potential. Analysis of the depth, thickness, organic content, thermal maturity, and other characteristics of the Marcellus formation has been performed as part of an ongoing study by the New York State Museum.[29] Figure B-1, which is drawn from the NYS Museum study, shows the approximate depth to the top of the Marcellus formation (top portion) and the approximate

[28] The Newark East Barnett Shale field was discovered in 1981 but exploitation was low for nearly two decades due to technology limitations. The pace of well development accelerated dramatically in the late 1990s and early 2000s with the advent of water-based fracturing (1997).

[29] Smith, T. and J. Leone. New York State Museum. *Integrated Characterization of the Devonian Marcellus Shale Play in New York State*. Presented at the Marcellus Shale Gas Symposium of the Hudson-Mohawk Professional Geologists' Association, April 29, 2009. Accessed from www.hmpga.org/Marcellus_presentations.html.

thickness of the formation (lower portion). The dotted contours also indicate the transformation ratio associated with the formation, which is an estimate of the thermal maturity of the organic material.[30] The higher the ratio, the more gas that is potentially available.

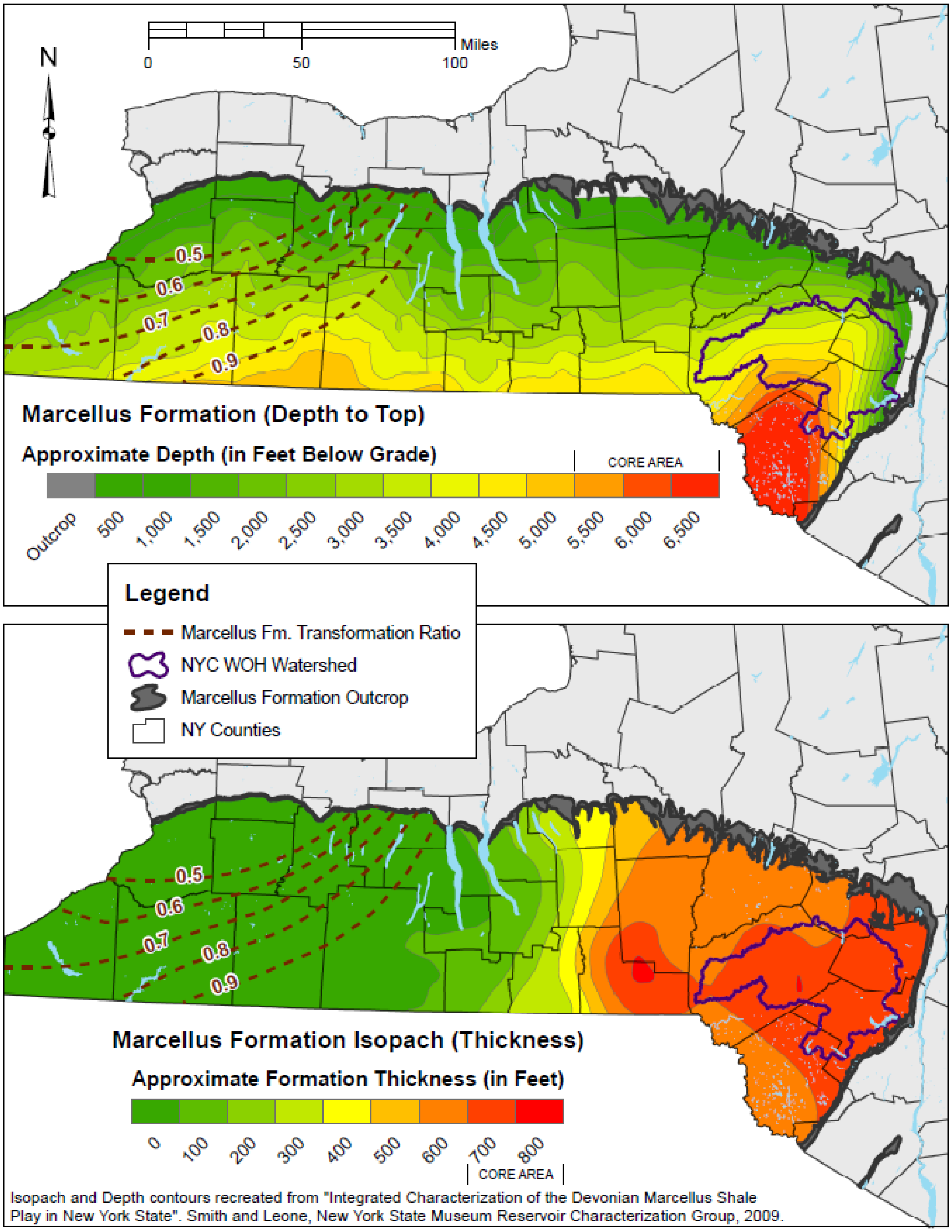

Figure B-1: Extent and characteristics of Marcellus formation in New York

[30] Transformation ratio refers to the percentage of Kerogen (an organic solid, bituminous mineraloid substance) occurring in the unit, that has been destructively converted to oil or gas by ambient geological forces (i.e., pressure, temperature).

While acknowledging uncertainties that prevent precise delineation of areas with the highest gas production potential, the authors of the study suggest that drilling in New York is likely to start in the thickest and deepest areas of the formation, which includes southern Tioga, Broome, Delaware and Sullivan Counties, which border the northeast corner of Pennsylvania, before progressing north and west. These areas are also attractive for gas production because of their proximity to the Millennium pipeline and other regional natural gas transmission infrastructure.

The supposition that the area identified in the New York State Museum study may be highly productive is supported by the intense leasing activity observed in this area and in neighboring counties in northeast Pennsylvania, as well as the ongoing development of a major regional drilling services facility in Horseheads (Chemung County), New York.

Well Completions

Well completion data provides a guide to the historical progression of the development of other shale gas plays and is useful in characterizing potential development scenarios in the NYC watershed area. Annual well completion rates in the selected Core/Tier I counties of the four major shale gas plays are presented in Figure B-2. Natural gas well completion data was derived from state regulatory agency databases and reports.[31] Well completion data was normalized to the area of the selected counties[32] to facilitate comparison among formations, and is expressed as number of wells per 1,000 square miles. The data does not include wells that have been permitted but not drilled.

Development of each of the plays has been characterized by an initial low rate of well completions as drilling and stimulation techniques are adapted to the formation. In the case of the Newark East Barnett Shale field, this period lasted nearly two decades after discovery of the field in 1981. The pace of Barnett well completion accelerated dramatically in the late 1990s and early 2000s with the advent of water-based fracturing (~1997) and horizontal drilling (~2003), and has continued to increase with successive improvements in extraction technology (e.g. improvements in chemical treatments, re-fracturing of existing wells, simultaneous fracturing of two or more adjacent wells).[33] Since 2002, well completion rates in the Barnett Newark East formation have grown from roughly 500 to 2,800 wells per year. On a unit area basis, these rates correspond to *annual* rates of 100 to 560 wells per 1,000 square miles.[34]

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[31] Marcellus data from Pennsylvania Department of Environmental Protection as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09). Haynesville data from Louisiana Department of Natural Resources SONRIS Well Data as of 10/23/09 (http://dnr.louisiana.gov/haynesvilleshale/haynesville.xls, accessed 11/1/09). Fayetteville data from Arkansas Oil and Gas Commission B-43 Field Well Completions as of 10/30/09 (http://www.aogc.state.ar.us/Fayprodinfo.htm, accessed 11/1/09). Barnett data from Texas Railroad Commission as of 9/8/09 (http://www.rrc.state.tx.us/barnettshale/barnettshalewellcount1993-2008.pdf, and http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf, accessed 11/1/09).

[32] County-level annual data is not readily available for the Barnett shale; data in Figure B-2, Figure B-3, and Figure B-5 is based on the entire Newark East formation and is normalized to a nominal formation area of 5000 mi^2. Actual well density in core counties is higher (see e.g. Figure B-4).

[33] Powell, M.E. (2009). *Recent Developments in the Barnett Shale*, presented at Texas Alliance of Energy Producers 2009 Alliance Expo & Annual Meeting, 4/22/09.

[34] Low Barnett completion rates in 2009 reflect in part a substantial drop in natural gas wellhead prices since their peak in mid-2008.

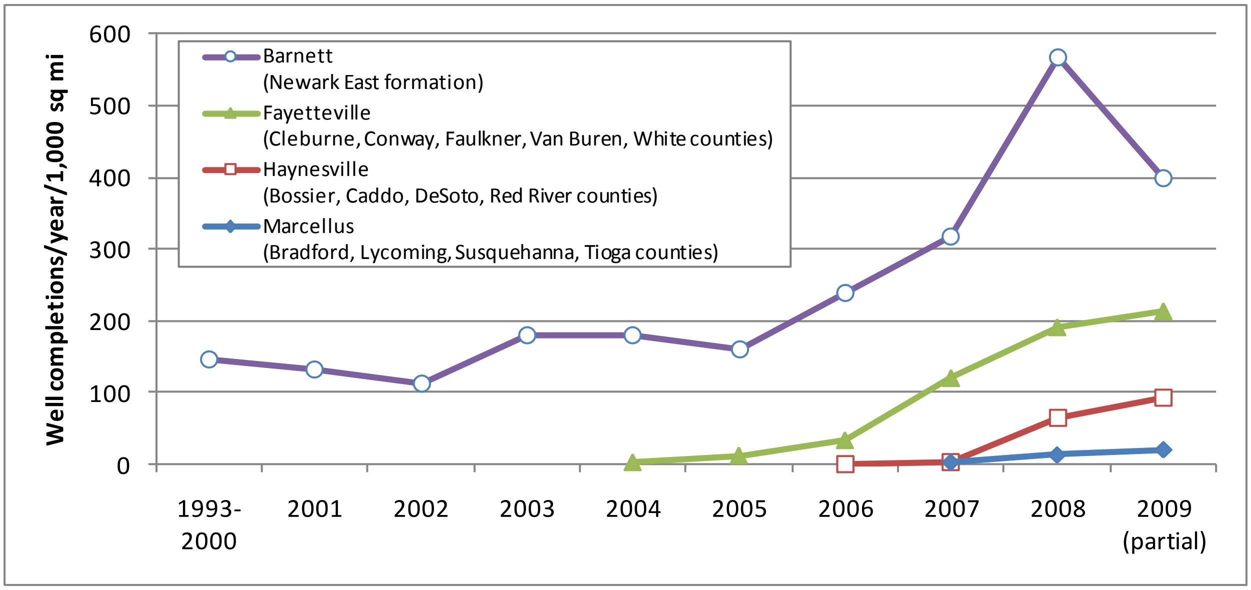

Figure B-2: Annual Well Completion Rates in Core/Tier I Counties of Major Shale Gas Plays

Based in large part on adoption of mature horizontal drilling and hydraulic fracturing techniques from the nearby Barnett formation, the rate of well completion in the Fayetteville formation B-43 Field increased rapidly, from 10 wells in 2004 to 430 wells in 2007 (3 – 120 wells/yr/1,000 mi^2). From January 2009 to October 2009, over 760 wells were completed in the Fayetteville B-43 core counties. A similar rapid increase in development rates is observed in the Haynesville formation, where roughly 200 wells were completed in 2008, compared to nine wells in 2007 and one well in 2006. In the Marcellus formation in northeastern Pennsylvania, nine completions were recorded in 2007, 55 in 2008, and 88 through September 2009.

Evaluation of well completion data on a cumulative basis (Figure B-3) tracks the increase in well density that occurs as a formation is developed. The current density in the Marcellus northeastern Pennsylvania core counties is on the order of 35 wells per 1,000 square miles, as this play is at an early, exploratory phase of development in the selected counties.

The current density of the Fayetteville core counties after approximately six years of activity is about 570 wells per 1,000 square miles. Well density in the Barnett Newark East formation after 13 years of development has reached 2,400 wells per 1,000 square miles across four core counties, and has exceeded 3,000 wells per square mile in one county. Well development rates in the Barnett were increasing through 2008, suggesting that the play is still not fully developed.

These rates and densities are considered indicative of the overall spatial well density that could be expected in the NYC watershed area as development in the play progresses.[35] Current county-level density for the selected formations and core counties is summarized in Figure B-4.

[35] The NYC West of Hudson watershed has an area of 1585 mi^2, roughly two-thirds of which (~1000 mi^2) is not subject to constraints on natural gas well development (Section 3.2).

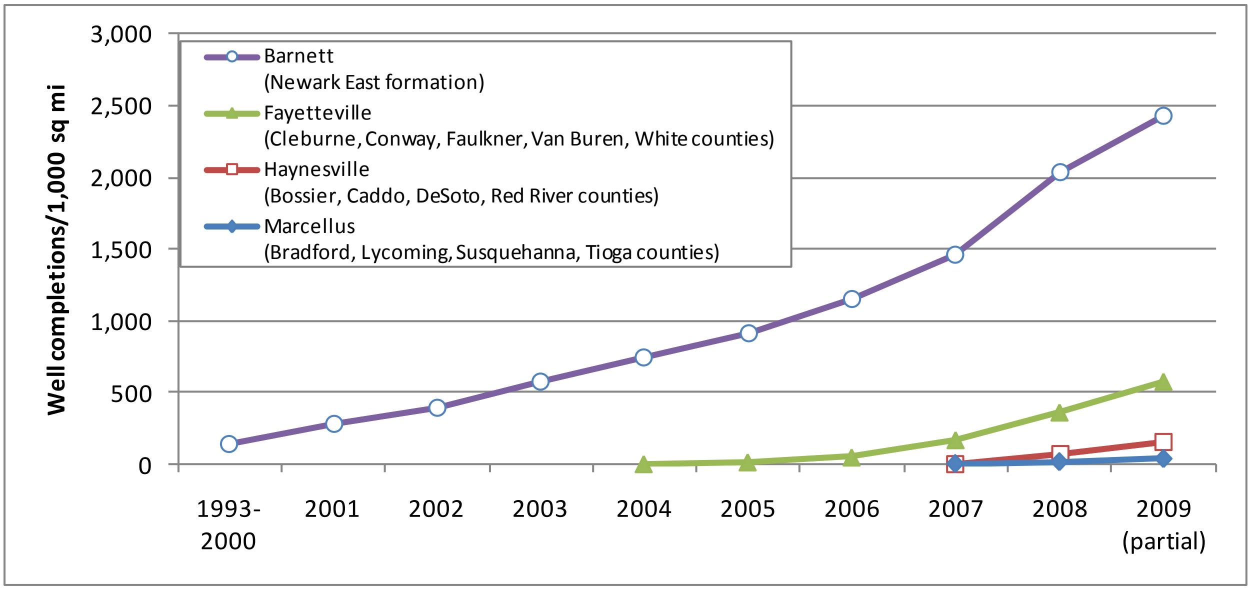

Figure B-3: Well Density in Core/Tier I Counties of Major Shale Gas Plays (2001-2009)

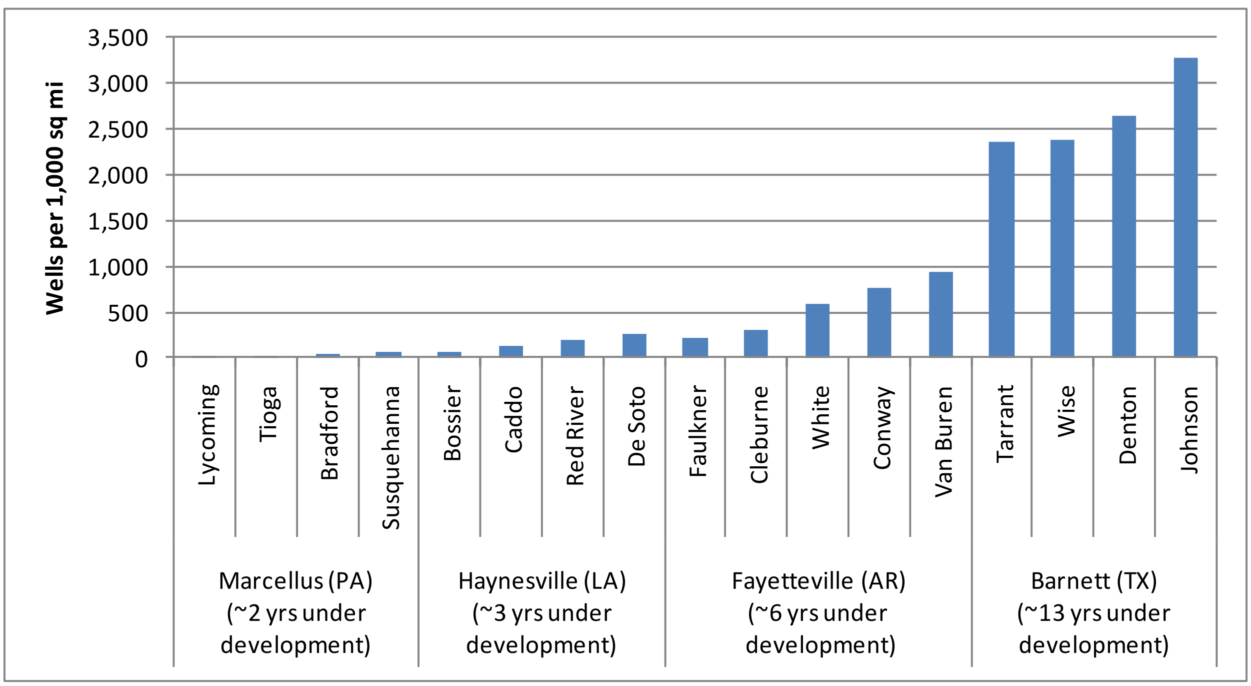

Figure B-4: Well Density in Core/Tier I Counties of Major Shale Gas Plays (2009)[36]

Well Permit Approvals

Wells must be permitted before they can be developed; a backlog of approved permits reflects the industry's understanding of future development potential in a given region and indicates

[36] All data sources identical to Figure B-2 except for the Barnett. County-level Barnett well information is based on data through 2008 presented in Powell, M.E. (2009). *Recent Developments in the Barnett Shale*, presented at Texas Alliance of Energy Producers 2009 Alliance Expo & Annual Meeting, 4/22/09.

likely near-term development. Annual well permitting rates for Core/Tier I counties of major shale gas plays are presented in Figure B-5. In some cases the backlog of permits can indicate substantial amounts of planned well development: in the Barnett, roughly three-quarters of the permits issued in the Barnett formation had been drilled as of August 2009, leaving over 3,500 approved permits awaiting development.[37]

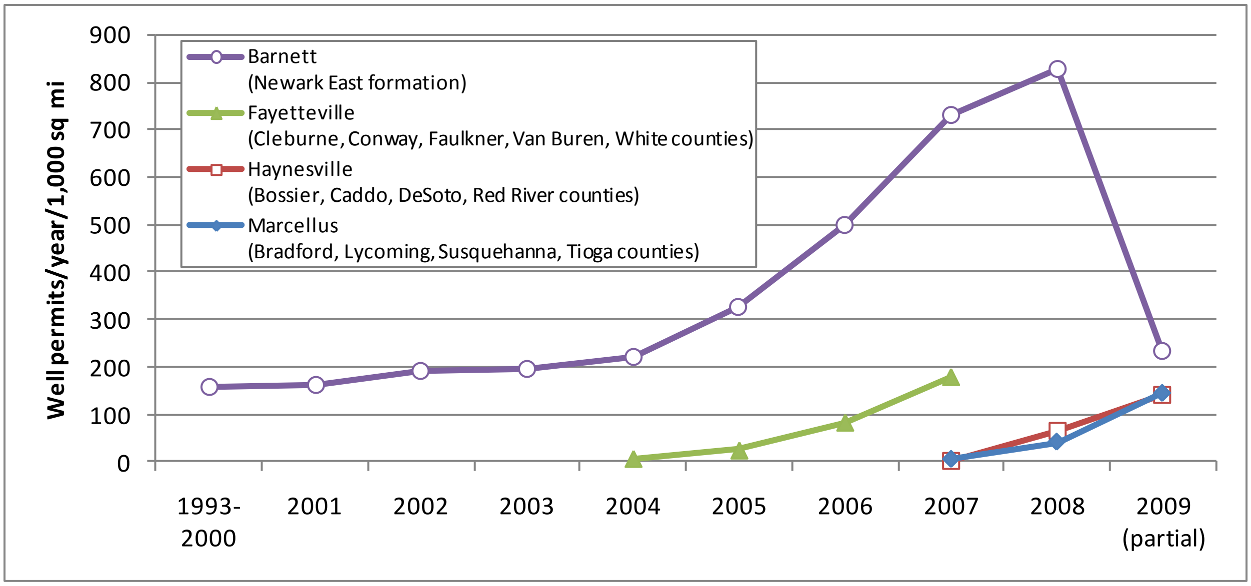

Figure B-5: Annual Well Permitting Rates in Core/Tier I Counties of Major Shale Gas Plays[38]

Data from northeastern Pennsylvania Marcellus counties (Figure B-6) also indicate the likelihood of sustained development in the region: of the roughly 800 permits approved since 2007, approximately 650 (~80 percent) await development. The greatest number of permits (approximately 340 through September 2009) have been filed in Bradford County, which at 1,151 square miles, covers an area equivalent to 73 percent of the entire area of NYC's West-of-Hudson watersheds.

As economic conditions improve and extraction techniques continue to be adapted to the regional geology, the rate of well development in the region can be expected to increase. Rotary drill rig[39] activity reveals the number of wells under development at any given time and is indicative of the natural gas industry's current and potential future level of activity in an area. Rotary drill rig activity over the past two years (Figure B-7) indicates that the pace of development in the Marcellus core counties is increasing, despite the economic downturn and low gas prices. Currently there are 30 to 35 rigs operating in the Marcellus core counties,

[37] Texas Railroad Commission (http://www.rrc.state.tx.us/data/fielddata/barnettshale.pdf, accessed 11/1/09).

[38] Data sources as described in Figure B-2, with the exception of the Fayetteville shale. Permitting dates are not readily available from the Arkansas Oil and Gas Commission; data presented in Figure B-5 is based on *Projecting the Economic Impact of the Fayetteville Shale Play for 2008-2012* (University of Arkansas, Center for Business and Economic Research, March 2008).

[39] Rotary drill rigs are the only types of rigs capable of horizontal drilling and are the most common type of rig used for oil and gas development.

compared with one rig at this time last year. The high levels of rig activity in the Barnett core in 2007-2008 (i.e. 120 rigs active at a given time) also indicate that the rate of development in the Marcellus is unlikely to be limited by industry drilling capacity.

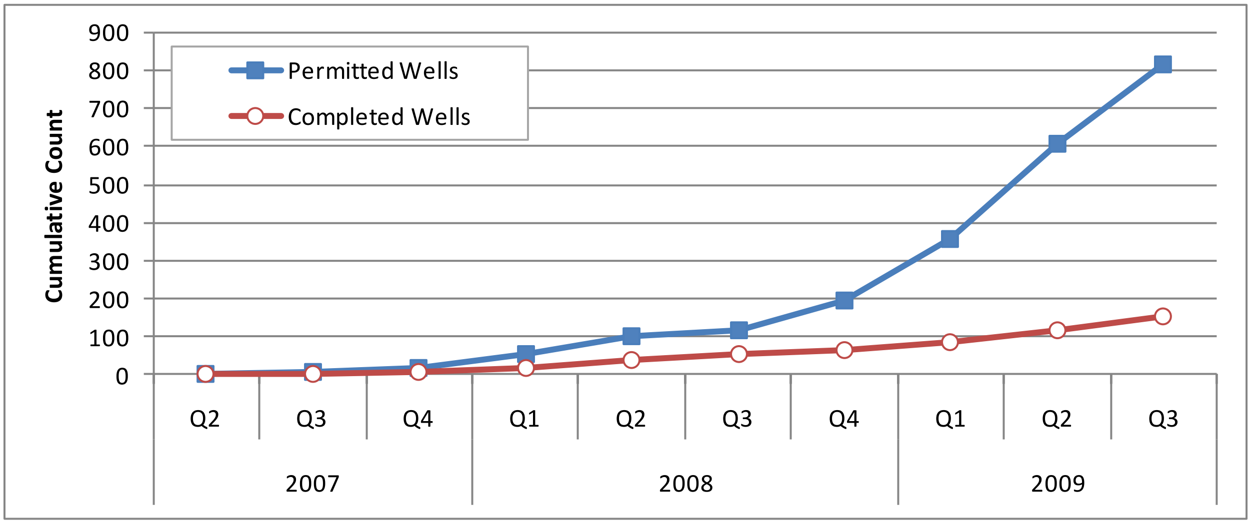

Figure B-6: Comparison of Marcellus formation well completion and permitting data (Bradford, Lycoming, Susquehanna and Tioga counties, Penna.)

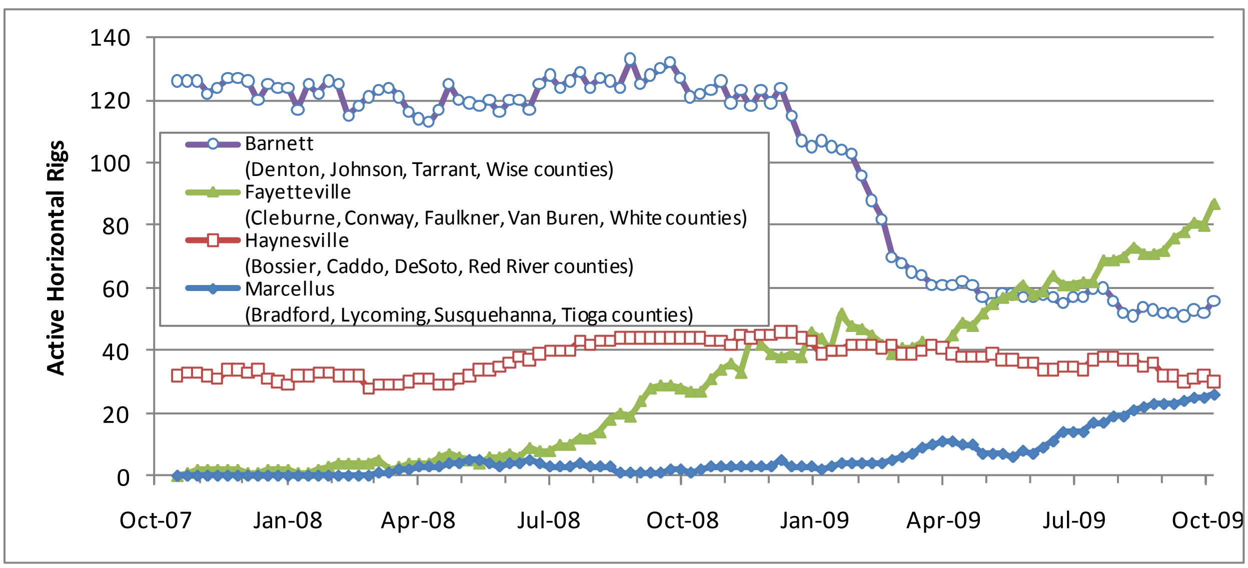

Figure B-7: Horizontal Drill Rig Activity in Core/Tier I Counties of Major Shale Gas Plays[40]

Distribution of Permitted and Completed Wells in other Formations

The geospatial distribution of wells is presented below for core areas of the Marcellus (Figure B-8), Haynesville (Figure B-9), Fayetteville (Figure B-10), and Barnett (Figure B-11). Marcellus

[40] Weekly county-level horizontal drill rig data from Baker Hughes U.S. Rig Count Reports (http://gis.bakerhughesdirect.com/Reports/RigCountsReport.aspx)

and Haynesville data is color-coded to reflect progression in the rate of development from 2007 through 2009. Permitting data is also presented where available.

In reviewing the spatial distribution of wells, it is clear that formations do not conform to political boundaries and wells are typically clustered in areas of high productivity; therefore, actual densities in some areas are much higher than the county average values presented above. Denton County in Texas, for example, has approximately 2,200 completed wells over a 400 square mile area, resulting in a localized density of twice the average for the county. It is important to note that given the scale of these figures, many of the plotted permit and gas well locations are obscured by neighboring symbols, thus a count of the visible symbols would yield a low estimate of actual activity.

Mapping of natural gas exploration activities in the Marcellus formation in eastern Pennsylvania reveal an accelerating rate of well construction over the two-year period from 2007 to 2009, as shown in Figure B-12. NYSDEC Notice of Intent to issue well permits in neighboring portions of New York State are also shown. It is reasonable to expect that the pattern and pace of development that could occur in New York State would be similar to that experienced in eastern Pennsylvania. It is important to note that the level of well development shown in Figure B-12 reflects the very early stages of development of the formation, and that a roughly one order of magnitude increase in well density should be anticipated.

Summary

Rates of natural gas well development in the comparable major shale gas formations provide the basis for the scenarios presented in Table B-2 and are consistent with well development patterns observed to date. Therefore, the scenarios provided are reasonable for estimating potential impacts within the NYC watershed even though the actual rate of development is uncertain due to numerous factors, including natural gas prices, regional economic conditions, state regulations, and formation productivity.

Table B-2: Annual Natural Gas Development Scenarios

Rate Scenario	Average Annual Well Completions per 1,000 Square Miles	Description
Low	20	Drilling rate during the early years of the play as operators refine their understanding of the resource and continue to lease land and apply for permits.
Moderate	100 to 300	Rate of well completion that has been sustained for a number of years in other shale gas plays
High	500, based on well completions (potentially as high as 800, based on permit applications)	Rate of development that could potentially occur in the most profitable areas under favorable conditions (e.g., gas prices are very high).

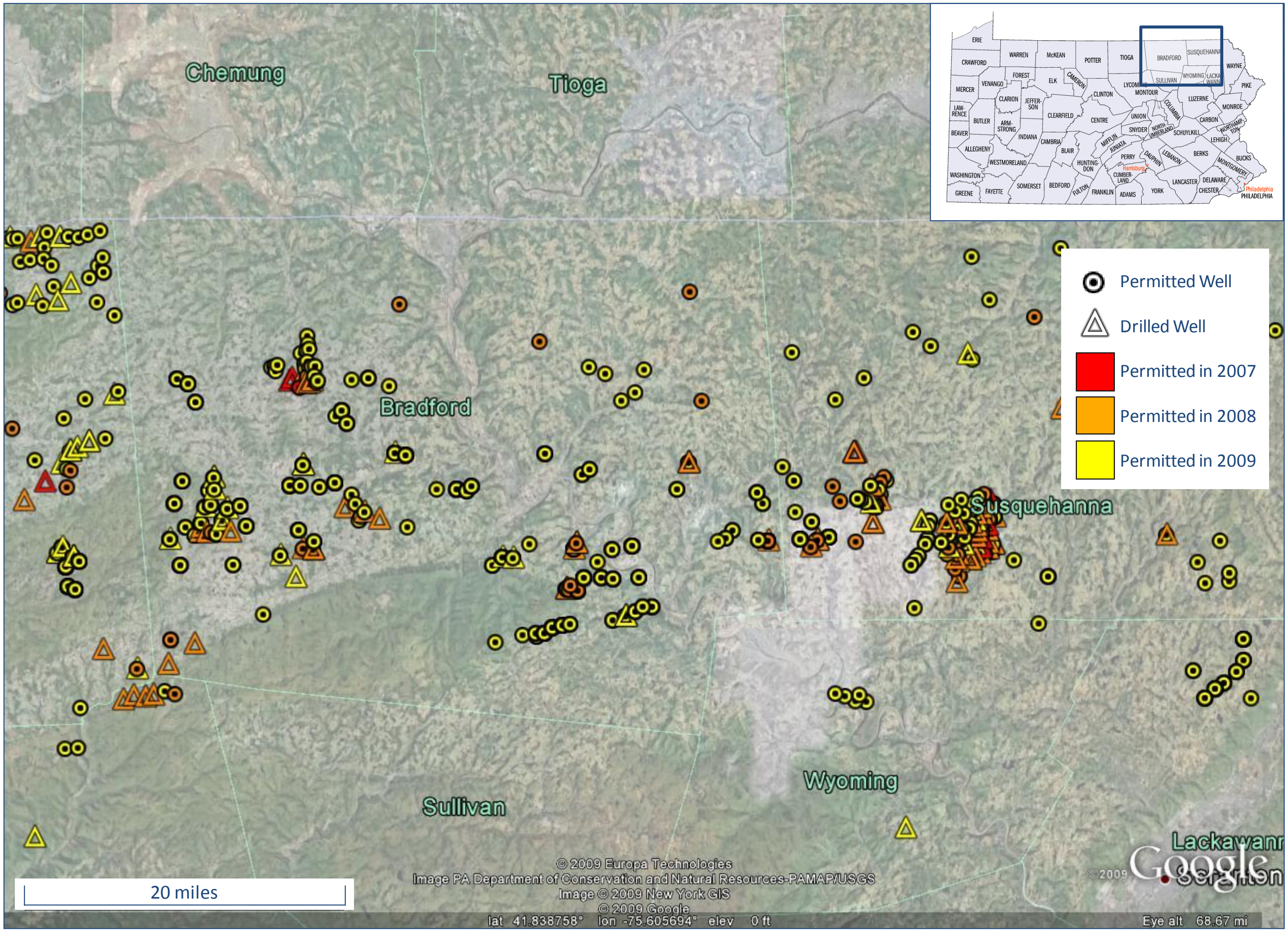

Figure B-8: Well density in the Marcellus formation (Bradford and Susquehanna counties, Penna.), development since 2007[41]

[41] Pennsylvania Department of Environmental Protection Well Data as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09).

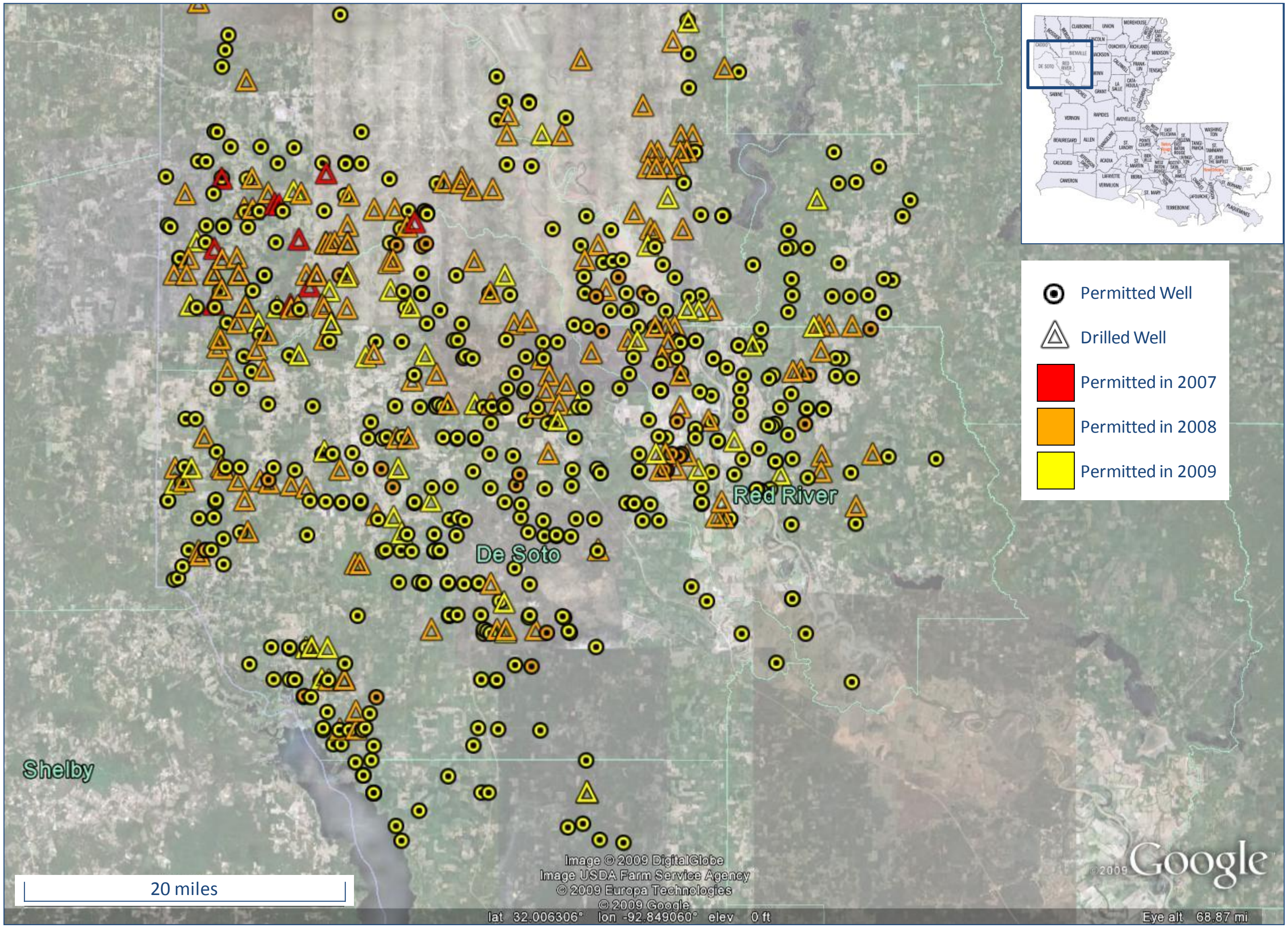

Figure B-9: Well density in the Haynesville formation showing development since 2007[42]

[42] Louisiana Department of Natural Resources SONRIS Well Data as of 10/23/09 (http://dnr.louisiana.gov/haynesvilleshale/haynesville.xls, accessed 11/1/09).

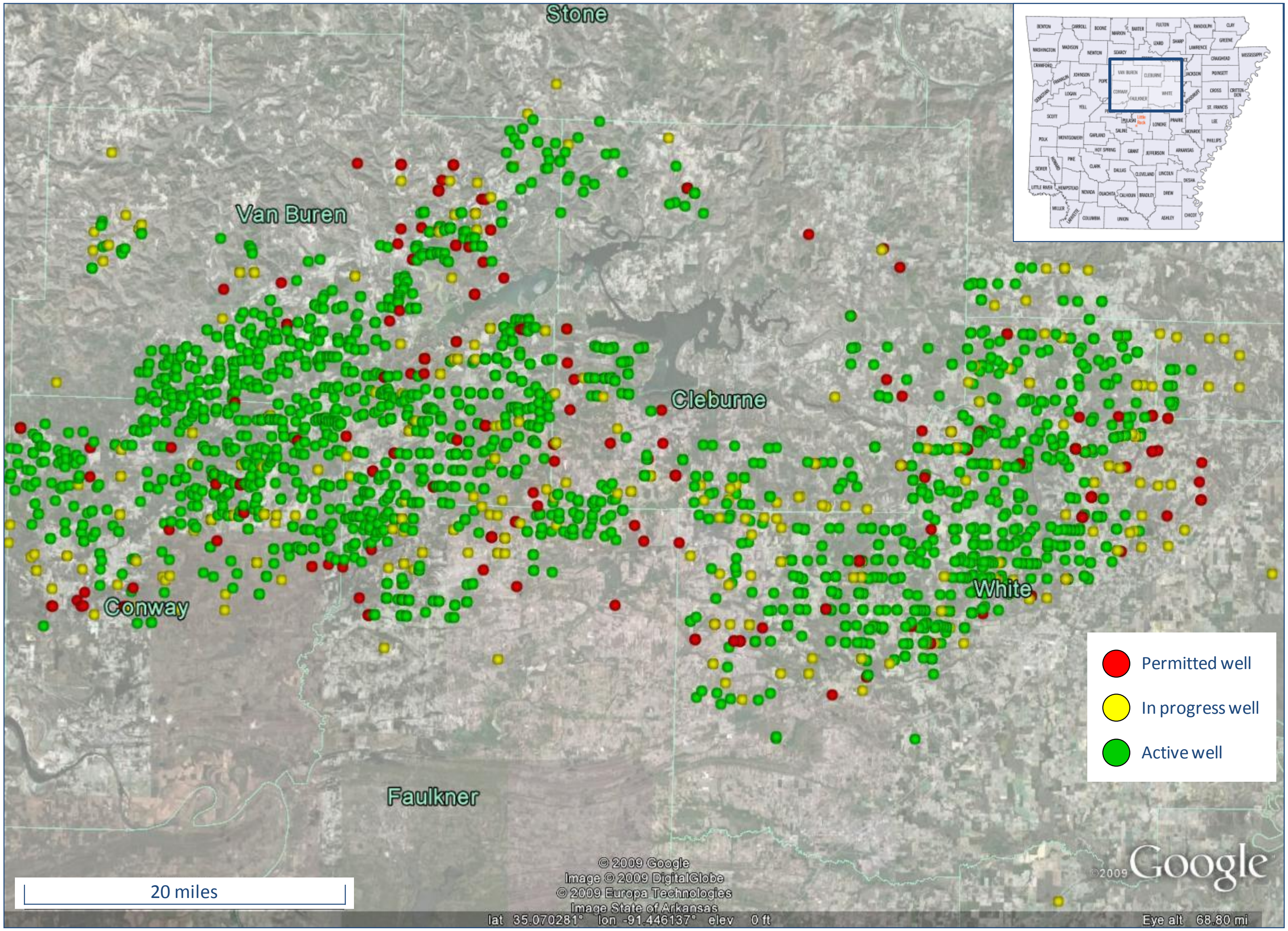

Figure B-10: Well density in the Fayetteville formation showing development since 2004[43]

[43] Arkansas Oil and Gas Commission well data as of 10/22/09 (http://www.aogc.state.ar.us/GIS_GOOGLE/Natural_Gas_and_Oil_Wells.kmz, accessed 11/1/09).

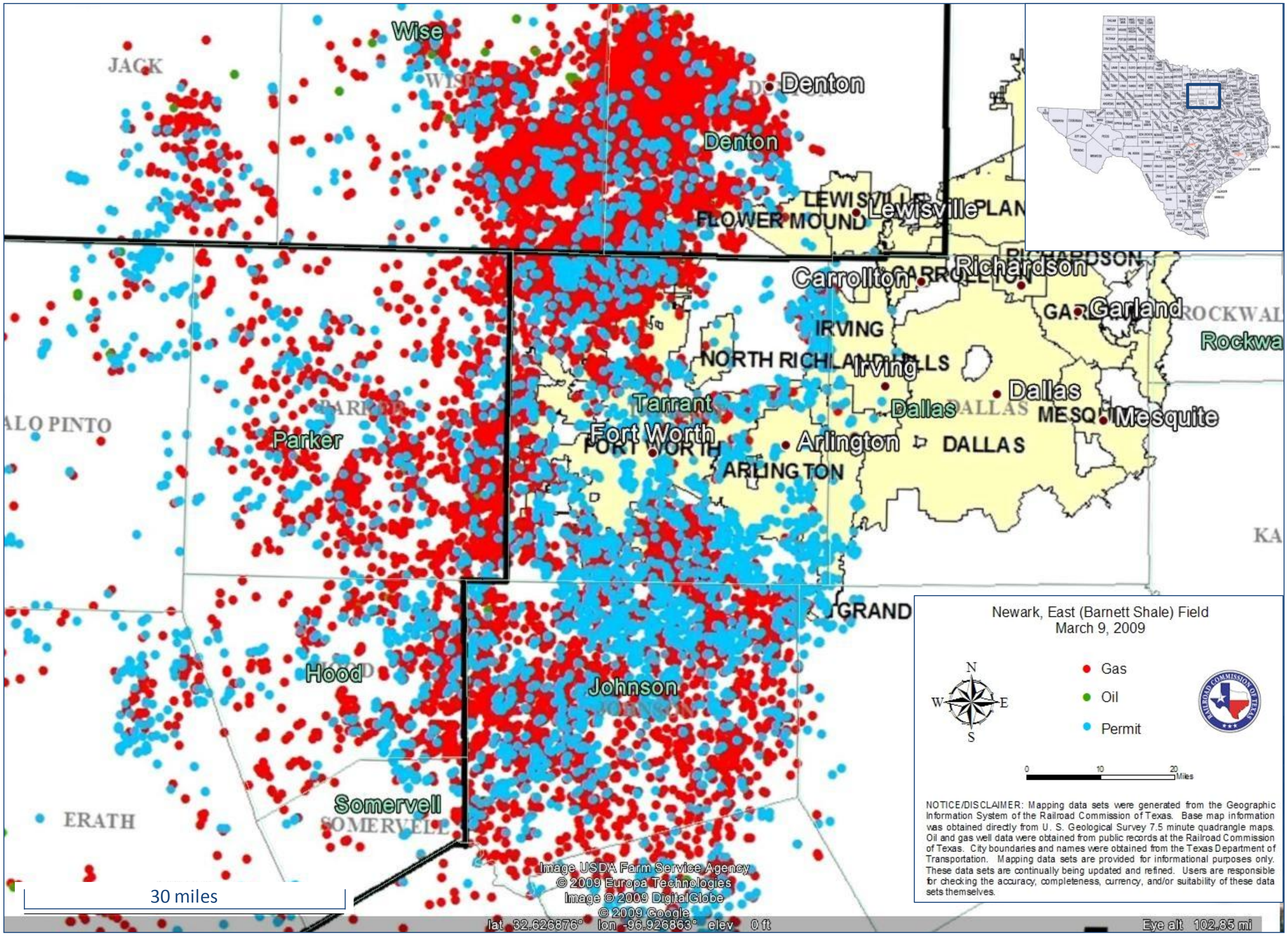

Figure B-11: Well density in the Barnett formation showing development since ~2000[44]

[44] Based on Railroad Commission of Texas image showing density as of 3/9/09 (http://www.rrc.state.tx.us/forms/maps/specialmaps/images/OGM0023.jpg, accessed 11/2/09).

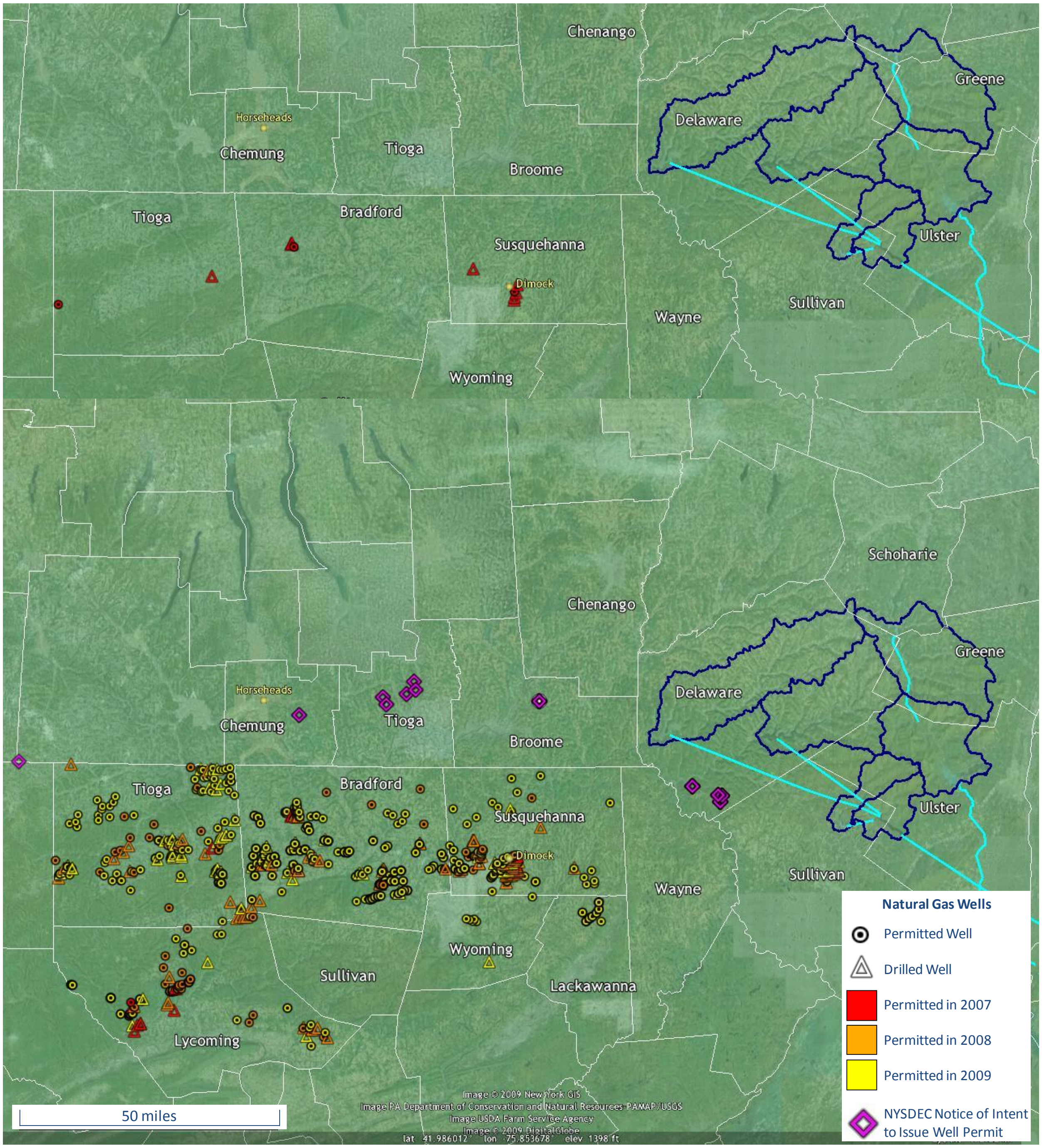

Figure B-12: Marcellus Formation Gas Well Permitting and Completion in New York and Pennsylvania Core Counties in 2007 (Top) and 2009 (Bottom)[45]

[45] Pennsylvania Department of Environmental Protection Well Data as of 9/30/09 (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/RIG09.htm, accessed 10/21/09). NYSDEC data on Notices of Intent to Issue Well Permits in Spacing Units Which Conform to Statewide Spacing in New York State as of 10/26/2009 (http://www.dec.ny.gov/dmndata/Well_Reports/Unit_Spacing_SW_Rpt.html, accessed 10/27/2009)

Appendix C: Draft SGEIS Surface Spill Contamination Analysis

The draft SGEIS released by NYSDEC on September 30, 2009 was supported by several consultant reports prepared for New York State Energy Research and Development Authority (NYSERDA). Chapter 1 of the report prepared by Alpha Environmental Consultants provided analyses of surface contamination scenarios within the watershed that could occur during natural gas development.[46] The evaluation estimated the potential for exceeding maximum contaminant levels (MCL) in individual West-of-Hudson reservoirs, at the Catskill and Delaware Aqueduct outlets, and within the NYC distribution system (Hillview Reservoir). The analysis considered contamination due to an acid spill, a non-acid chemical spill, or a spill of flowback water. All analyses assumed that the mass of contaminant was introduced directly into a reservoir, with no spill detection or mitigation, no soil adsorption, and no evaporation. The analyses were structured as simple dilution calculations in which the contaminant mass was completely and instantaneously mixed with the volume of one or more reservoirs.

Undiluted Non-Acid Chemical Spill

Undiluted fracture fluid chemicals, volumes, and concentrations used for the analysis were based on confidential data submitted by natural gas operators to NYSDEC. The analysis considered two fracture fluid mixtures provided by industry sources and focused on chemicals in those mixtures with MCLs. These chemicals are identified in Table C-1. Concentrations and volumes were not revealed in the report. It was assumed that the total amount of chemicals needed to fracture a well was released directly into an individual reservoir (at 1/3 storage level) and mixed instantaneously. The analysis was structured as a simple dilution, and was repeated for the mass of chemicals associated with one, two, and eight wells.

Table C-1: Representative Fracture Fluid Mixes and MCLs from Alpha Report

Mix 1	NYSDOH Part 5 MCL (mg/L)	Mix 2	NYSDOH Part 5 MCL (mg/L)
2,2,-Dibromo-3-Nitrilopropionamide	0.05	2,2,-Dibromo-3-Nitrilopropionamide	0.05
Alcohols C9-11, ethoxylated	0.05	C12-15 Alcohol, Ethoxylated	0.05
Ethoxylated C11 Alcohol	0.05	Ethoxylated Castor Oil	0.05
Methanol	0.05	Isopropanol	0.05
Ethylene Glycol	0.05	Propylene Glycol	1

The analysis was conducted for individual West-of-Hudson reservoirs, for the Catskill outlet into Kensico, the Delaware outlet into West Branch, and for water entering Hillview. Individual reservoir analyses indicated that MCLs could be exceeded in all of the West-of-Hudson reservoirs for most of the contaminants (except propylene glycol). The number of wells required to result in MCL violations ranged from one to eight, with smaller reservoirs being more susceptible. A spill equivalent for a single well resulted in an MCL being exceeded at Schoharie and Neversink Reservoirs. A spill equivalent for two wells resulted in one or more MCLs being

[46] dSGEIS, Alpha Technical Report, *Survey of Regulations in Gas-Producing States, NYS Water Resources, Geology, New York City Watershed, Multi-Well Operations, and Seismicity*.

exceeded at Schoharie, Neversink, Rondout, and Cannonsville Reservoirs. A spill equivalent for eight wells resulted in all reservoirs exceeding one or more MCLs.

The analysis for the Catskill outlet into Kensico, the Delaware outlet into West Branch, and for water entering Hillview was conducted in a similar fashion, except that for these three scenarios, the mass of contaminant was mixed with the entire contents of upstream system components. Thus the results for the "Kensico" scenario are based on the contaminant mass divided by the combined storage in Ashokan and Schoharie. Similarly, "West Branch" results are based on dilution with the volume of the four Delaware reservoirs, and "Hillview" results are based on dilution with the total volume of the Catskill and Delaware reservoirs, West Branch, and Kensico.

These latter scenarios have very limited utility, since conceptually they could only apply when the contaminant mass is introduced at the uppermost reservoir in a system of reservoirs in series (e.g. the "Kensico" scenario is conceptually valid for Schoharie). All other scenarios are conceptually flawed and do not pertain to a physically possible scenario (e.g. under the "West Branch" scenario, a spill into Rondout would be instantaneously mixed with the volume of Cannonsville, Pepacton, and Neversink, all of which are located upstream of Rondout).

Given the errors inherent in the analysis provided as support for the dSGEIS conclusions, an alternate analysis was performed using fracturing chemical data and assumptions presented in the Alpha Report.[47] The sensitivity of the NYC water supply to acute spills of fracturing chemicals was examined by calculating the mass of fracturing chemicals required to violate an MCL at Kensico Reservoir. Both the dSGEIS analysis and the following analysis are structured as simple dilution calculations that assume the chemical mass enters a reservoir directly and is completely and instantaneously mixed with its contents.

Consistent with dSGEIS assumptions, reservoirs were assumed to be one-third full. Such low storage levels would only be expected to occur under severe drought conditions. However, the one-third full assumption is equivalent to the more realistic situation in which the reservoirs are relatively full and the contaminant mass mixes with only one-third of the reservoir's volume as a result of short-circuiting. Complete mixing in reservoirs with volumes as large as NYC's is not a reasonable assumption under most circumstances. Short-circuiting due to stratification, density currents, and prevailing flow patterns is considered more typical.

Two spill scenarios were considered, the key difference between them being the volume into which the chemical mass is diluted:

- Scenario 1 dilutes the contaminant mass with the contents of Kensico Reservoir. This represents a situation in which a load of fracturing chemicals spills into Rondout and the chemicals short-circuit into the intake chamber and are conveyed downstream to Kensico Reservoir.
- Scenario 2 dilutes the contaminant mass with the contents of Kensico and Rondout Reservoirs. This represents a situation in which a load of fracturing chemicals spills into Rondout or a proximate tributary and mixes completely with the contents of Rondout and

[47] dSGEIS, Alpha Technical Report, *Survey of Regulations in Gas-Producing States, NYS Water Resources, Geology, New York City Watershed, Multi-Well Operations, and Seismicity*, Section 4.8 and Tables 4.3 – 4.5.

Kensico. This is also representative of the impact of spill into Cannonsville, Pepacton, or Neversink Reservoirs that occurs near their respective intake structures.

Under these simple dilution assumptions, the mass of chemical required to violate an MCL is simply the product of the reservoir volume and the MCL, which is 0.05 mg/l for all chemicals considered here. To gauge the number of wells or hydraulic fracturing operations associated with the mass of chemical required to violate an MCL, data from the dSGEIS analysis was used to develop an estimate of the mass of each chemical required to fracture one well.[48] This data is presented in Table C-2, along with an estimate of the mass of chemicals required to violate an MCL in Kensico, expressed in terms of fracture job equivalents, for both Scenarios 1 and 2.

Table C-2: Fracturing Chemical Spill Scenarios for Kensico Reservoir

Chemical *0.05 mg/l MCL for all chemicals*	Estimated mass required to fracture one well (kg)	Fracture job equivalents required to exceed MCL	
		Scenario 1 (dilution with volume of Kensico)	Scenario 2 (dilution with volume of Kensico + Rondout)
2,2,-Dibromo-3-Nitrilopropionamide (1)	3019	0.6	1.7
Methanol (1)	1565	1.2	3.2
Ethylene Glycol (1)	1110	1.7	4.6
C12-15 Alcohol, Ethoxylated (2)	1110	1.7	4.6
Ethoxylated Castor Oil (2)	555	3.5	9.1
Isopropanol (Isopropyl Alcohol) (2)	555	3.5	9.1
Ethoxylated C11 Alcohol (1)	555	3.5	9.1
Alcohols C9-11, Ethoxylated (1)	391	4.9	12.9
(1) dSGEIS Frack Mix 1 (2) dSGEIS Frack Mix 2			

For Scenario 1, the mass of chemicals associated with just one to five hydraulic fracturing operations could be sufficient to violate an MCL at Kensico Reservoir. For Scenario 2, the mass of chemicals associated with two to thirteen hydraulic fracturing operations could be sufficient to violate an MCL at Kensico Reservoir. These findings indicate that the sensitivity of Kensico Reservoir to spills of fracturing chemicals is substantially higher than presented in the dSGEIS.

This analysis should not be taken to indicate that these or comparable spill scenarios would constitute an imminent threat to public health. In the event of a major spill, operators would respond immediately upon learning of the event and take appropriate operational measures to protect the water supply, including water quality sampling, adjusting intake levels, reducing flow rates or taking reservoirs off-line, etc.

Though this analysis has focused on MCLs, it is important to note that water quality contamination is important in and of itself, even if it does not trigger an MCL violation.

[48] Due to confidentiality requirements the dSGEIS analysis does not present data on the mass composition of additives or the mass of additives or constituent chemicals required to fracture a well. The scenarios presented in the dSGEIS analysis do provide sufficient information to back-calculate the mass of chemicals required to fracture a well.

NYCDEP's mission is not to supply water that merely meets regulatory limits but "to reliably deliver a sufficient quantity of *high quality drinking water* and to ensure the *long term sustainability* of the delivery of this most valuable resource."[49]

Discussion of Assumptions

The Alpha report indicates that an actual MCL violation for any of the modeled scenarios is highly unlikely due to the conservative assumptions used in the analysis. Whereas some of the assumptions (e.g., drought conditions, no spill detection) are conservative, others (e.g., complete mixing) are not. The plausibility of assumptions used in the Alpha analysis is discussed below.

Complete/instantaneous mixing in reservoirs – Complete mixing in reservoirs with volumes as large as those in the NYC system may be a reasonable assumption under limited circumstances, but short-circuiting, stratification, or spills in proximity to inlet structures must be taken into consideration. Even within the confines of simple dilution analysis, the methods used to evaluate the possibility of MCL violations at downstream system components (e.g. West Branch, Kensico, Hillview) is conceptually flawed.

Spill directly to a reservoir – Given the large volume of heavy truck traffic required to develop the Marcellus formation and the proximity of state highways to all West-of-Hudson reservoirs, it is not unreasonable to assume that at some point a chemical spill results in direct contamination of a reservoir.

Drought conditions (reservoirs at 1/3 of full capacity) – The Barnett shale has been under development for 15 years and may continue to be developed for many more. It is not necessarily "conservative" to anticipate a spill occurring during a drought during the multi-decade timeframe anticipated for development of the Marcellus formation. Further, it does not require a declared drought for one or more reservoirs to be drawn down.

No spill detection or attempt at mitigation – This assumption is not necessarily "conservative" with respect to identifying impacts associated with spills. As it is reasonable to assume that hundreds or thousands of wells may be drilled in the watershed, and billions of gallons of wastewater generated and trucked to disposal sites, it is also reasonable to expect that some spills will go undetected due to negligence, human error, or intentional misconduct (see e.g. Dimock, PA incident).

Evaluation of individual chemicals with MCLs – Operators submitted to NYSDEC chemical compositions of nearly 200 products containing almost 300 chemical constituents. The TEDX database tabulated data on 450 products containing over 300 constituents. The industry is continuing to develop new products at a much faster rate than can be incorporated into water quality regulations. The absence of an MCL for a particular chemical does not guarantee it cannot degrade the water supply and result in adverse health impacts to consumers.[50]

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[49] NYCDEP-BWS Mission Statement.

[50] NYSDOH attempts to address this issue through the 0.05 mg/L MCL for Unspecified Organic Contaminant (UOC), which are any organic chemical compound not otherwise specified in Subpart 5-1. The dSGEIS analysis did not evaluate the risk of exceeding the UOC MCL from the sum of organic contaminants found in fracture fluid mixtures.

Chemical quantity present on-site is sufficient for up to eight wells – Given the large volumes of chemicals needed to fracture hundreds or thousands of wells in the region, well pads or other sites may be used to store large volumes of material for efficient distribution to other sites. Therefore it is reasonable to assume that sites in the watershed may store volumes of chemicals larger than that needed for a single well on a single pad. Further, this “conservative” assumption fails to consider the need to transport fracturing additives from central storage or supply facilities to individual well pads, and the associated risk of introducing concentrated chemicals directly into watershed streams or reservoirs as a result of vehicle accidents. The results presented in Table C-2 indicate that the chemicals needed for one or two fracturing operations could be sufficient to exceed MCLs for some chemicals.

No soil adsorption and no evaporation – Hydraulic fracturing requires specialized chemicals to manipulate the physical properties of fracture fluid. Therefore, of the hundreds of potential chemicals available for fracture operations, many of the chemicals will be unaffected by evaporation or soil adsorption. One example, 2,2,-Dibromo-3-Nitrilopropionamide, which was evaluated as part of both fracture fluid mixes, is toxic and does not readily evaporate, volatilize, or adsorb to soil particles.[51]

Summary

It is acknowledged that the chances of every assumption provided in the NYSERDA analysis occurring simultaneously are low. However, every assumption does not need to hold true for a spill to result in significant adverse impacts to source water quality.

NYCDEP seeks to operate its water supply system to provide water of the highest quality possible. All spills will require NYCDEP operations staff to take remedial action, potentially including taking contaminated reservoirs offline, regardless of the potential for an MCL violation. This may result in significant impacts to the reliability of the system, depending on the frequency, timing, and location of the incident(s), and can be expected to affect public confidence in the ability of watershed protection efforts to ensure the purity of the water supply. Additionally, accidents and spills in the watershed have the potential to negatively impact NYCDEP’s Filtration Avoidance Determination. This is true for both large acute spills and for a chronic level of smaller effectively mitigated spills.

[51] Material Safety Data Sheet, Dow Chemical.

Appendix D: Potential Mitigation Measures

If natural gas development utilizing high-volume hydraulic fracturing were to proceed in the NYC watershed, mitigation measures would be necessary to reduce the risks to the water supply. Potential mitigation measures are described below. It should be noted that the risks associated with natural gas well development cannot be eliminated, and to be effective, all mitigation measures would require provision of sufficient regulatory and inspection staffing, increased coordination, and communication and information sharing with respect to natural gas, injection well and waste disposal permits and applications among NYSDEC, USEPA, NYSDOH and NYCDEP.

Water Withdrawals

Effective mitigation of cumulative water withdrawal impacts on system operations, supply reliability and in-stream habitat would entail development of appropriate monitoring, enforcement, and diversion permitting or other control mechanisms to curtail withdrawals during low flow conditions or when such withdrawals adversely impact existing uses. In principle, diversion permits should be based on an analysis of long-term stream flow data, in-stream habitat requirements, existing SPDES discharges, pre-existing consumptive withdrawals, and other pertinent parameters, on a stream-by-stream basis, to determine the allowable level of additional consumptive withdrawals while avoiding adverse impacts.

In the Delaware River Basin, the Delaware River Basin Commission has established an interim withdrawal permitting and approval process that addresses many of the concerns associated with cumulative water withdrawal impacts. This process provides some protection against excessive diversions in the Cannonsville, Pepacton and Neversink watersheds. It does not apply to Schoharie, Ashokan and Rondout Reservoirs, though it could potentially help inform the development of comparable protections in these basins. Furthermore, regulatory and administrative accommodations to natural gas industry priorities have been made to the Susquehanna River Basin Commission's water diversion permit approval process over the past year. To the extent that activities in Pennsylvania provide a guide to natural gas development in New York, it is possible that established Delaware River Basin Commission procedures may also be subject to change.

The City will require the following limitations be included in any water taking permit:

- The withdrawal of surface water for the exploration, development or operation of natural gas wells from the Delaware River, or any of its tributaries, affecting the flow at the USGS gage at Montague New Jersey shall be prohibited when the Delaware River Master, as required by his/her obligations under the 1954 U. S. Supreme Court Decree, is directing releases from New York City reservoirs to support the Montague flow objective.
- The withdrawal of surface water for the exploration, development or operation of natural gas wells from the Esopus Creek, or any tributaries, affecting the flow at the USGS gage at Allaben New York shall be prohibited when New York City is making required releases from the Schoharie Reservoir to meet a minimum combined flow of 160 mgd in the Esopus Creek in compliance with NYSDEC regulations, 6NYCRR, Chapter X, Part 670.3 and NYSDEC SPDES Permit # NY0268151.

Chemical Usage

Watershed pollution prevention is one of the most fundamental components of the multiple-barrier approach to protecting drinking water quality and human health. In light of the known pathways for chemical contamination of the water supply, as well as the public health community's limited understanding of the human health risks of chronic exposure to low doses of various contaminants, provisions that eliminate or limit the introduction of large volumes of hazardous and potentially hazardous chemicals into the watershed would represent a prudent mitigation measure.

The known and unknown environmental, water quality, and human health risks associated with introducing large volumes of hazardous chemicals into the watershed could be further reduced by provisions for sharing of complete chemical composition and usage data (by mass) for all drilling and fracturing additives used in the watershed, and provisions for use of drilling and fracturing additives that are non-toxic, or whose toxicity is at least well understood.

Surface Spills

The risk of water quality and operational impacts associated with acute and chronic spills in the watershed could be mitigated by the following measures:

- Provisions for establishing buffers around streams and reservoirs within which drilling and fracturing operations could not occur. Exclusion of spacing units within a 1,000 foot buffer of streams and a 2,000 foot buffer around reservoirs would substantially reduce the risk of adverse surface water quality impacts compared with dSGEIS setbacks, which would allow wellpads to be located 150 feet from streams and 300 feet from reservoirs (and could allow fracturing to occur directly underneath watershed streams and DEP reservoirs); and
- Provisions that would prohibit the transport of fracturing chemicals and waste products on roads adjacent to public water supply reservoirs or major inflow streams. This would reduce the risk of acute spills directly into reservoirs from vehicle accidents.

Subsurface Risks

Site-specific SEQRA reviews are required for issuance of a permit to drill any well subject to Article 23 of the Environmental Conservation Law, whose location is determined by NYCDEP to be within 1,000 feet of subsurface water supply infrastructure. The 1,000 foot infrastructure setback was developed in connection with vertical geothermal wells and was based on concerns associated with drilling through a NYC tunnel. While a similar precaution is appropriate for the vertical section of natural gas wells, there are overriding concerns associated with horizontal drilling and hydraulic fracturing that are entirely different:

- Horizontal well laterals can extend for over a mile from the actual well pad. The dSGEIS would allow hydraulic fracturing to occur underneath a DEP tunnel or reservoir. Isolation of water supply infrastructure from the hydraulically fractured strata depends entirely on the characteristics of the intervening rock.
- The hydraulic fracturing process is specifically designed to fracture rocks and intercept and enhance existing hydraulic pathways, and this process is difficult to predict accurately.
- Hydraulic fracturing operations in proximity to the naturally occurring fracture systems that intersect DEP tunnels will increase the risk of (a) contaminating drinking water with drilling

and fracturing chemicals and poor quality formation water; (b) methane accumulation around and within DEP subsurface infrastructure; and (c) tunnel liner structural failure.

Mitigation of risks to drinking water quality and infrastructure integrity will require revision of current setback provisions to reflect the occurrence of laterally extensive subsurface faults, fractures, and brittle structures. Based on the preceding analyses, it is recommended that natural gas well construction be precluded within a buffer zone of seven miles from NYCDEP subsurface infrastructure. Further, since the primary area of concern is not the vertical borehole but instead the well lateral and the hydraulic fracturing induced along its length, the buffer zone should be measured from the furthest extent of the lateral (or spacing unit boundary) and not the well pad or wellhead.

Waste Stream Risks

Mitigation of risks associated with the production of large volumes of high-strength wastes requires that the effectiveness of feasible waste treatment and management provisions be established before approval of initial well development or refracturing, and that gas well permit approvals be limited to the treatment/disposal capacity in place at the time of well permit approval. This will require a comprehensive assessment of regional waste production and disposal needs and capacities, and will mitigate impacts by assuring that the rate of gas well construction is limited to a rate that is matched by treatment/disposal capacity. It is noted that the provision of adequate treatment capacity and transport to such facilities will further industrialize the watershed, and that it will be necessary that the impacts associated with provision of waste management systems also be identified and mitigated.s

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