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.

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[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

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[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.

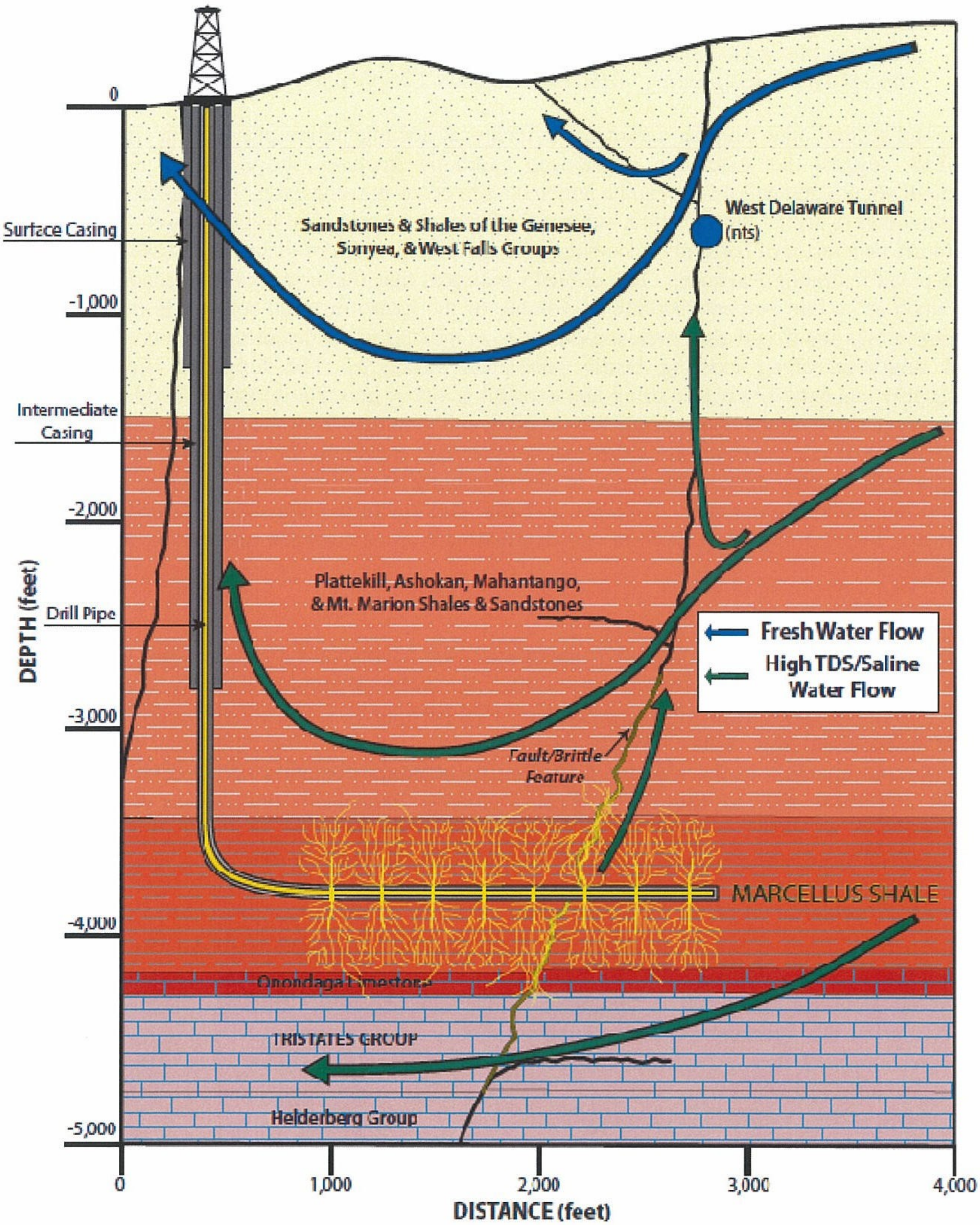

Figure 4-1: Examples of potential flow regime disruption mechanisms

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*

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[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