Science-based decision-making on complex issues: Marcellus shale gas hydrofracking and New York City water supply

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Abstract

Complex scientific and non-scientific considerations are central to the pending decisions about "hydrofracking" or high volume hydraulic fracturing (HVHF) to exploit unconventional natural gas resources worldwide. While incipient plans are being made internationally for major shale reservoirs, production and technology are most advanced in the United States, particularly in Texas and Pennsylvania, with a pending decision in New York state whether to proceed. In contrast to the narrow scientific and technical debate to date, focused on either greenhouse gas emissions or water resources, toxicology and land use in the watersheds that supply drinking water to New York City (NYC), I review the scientific and technical aspects in combination with global climate change and other critical issues in energy tradeoffs, economics and political regulation to evaluate the major liabilities and benefits. Although potential benefits of Marcellus natural gas exploitation are large for transition to a clean energy economy, at present the regulatory framework in New York State is inadequate to prevent potentially irreversible threats to the local environment and New York City water supply. Major investments in state and federal regulatory enforcement will be required to avoid these environmental consequences, and a ban on drilling within the NYC water supply watersheds is appropriate, even if more highly regulated Marcellus gas production is eventually permitted elsewhere in New York state.

Keywords: hydrofracking, energy, fossil fuel; unconventional; natural gas; shale; water resources; environment; economics; regulation

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Key Points:

- Previous analyses have taken too narrow a perspective on the risks and benefits of hydrofracking or HVHF in New York state, with implications for unconventional natural gas production elsewhere around the world
- Benefits of HVHF natural gas production for reducing dependence on even more damaging coal-fired electrical power generation are great but so are environmental and public health liabilities
- Protecting watersheds for NYC and other major municipality water supply is paramount but strengthening of federal and state regulatory oversight is needed for reducing potential adverse impacts of HVHF elsewhere in NY state

1. Introduction

There is an urgent need to reduce the current global energy dependence on fossil fuels, because of the risks of rising greenhouse gas (GHG) emissions driving global climate change (IPCC, 2007), and because most conventional oil and gas reserves may no longer be reliably supplied due to political instability. New unconventional discoveries have dramatically expanded estimates of natural gas reserves (US DOE, 2009; IEA, 2011; US EIA, 2012) and natural gas is a preferred fuel for energy-efficient electricity production because it is cleaner-burning compared to coal (Hultman et al. 2011). Recent discovery of unconventional gas in the Marcellus shale in the northern Appalachian mountains of the US provides a potential new energy source close to major mid-Atlantic urban centers. Therefore, many have advocated a greater use of natural gas, as a “bridge” fuel towards a renewable energy future (e.g. IPCC, 2007; Moniz et al., 2010; Jenner and Lamadrid, 2012) despite controversy over the economics (Hughes, 2011; Brooks, 2012) and life-cycle GHG costs (Burnham et al., 2012; O'Sullivan and Paltsev, 2012) of unconventional gas compared to other energy options.

Unconventional gas production from shales like the Marcellus Formation in the eastern United States (Soeder and Kappel, 2009; Kerr, 2010; Kargbo et al., 2010; Lee et al., 2011) raises important questions about scientific decisionmaking, environmental protection, public health and water resources (US GAO, 2012). For this reason, in New York State , the governor has imposed a de-facto moratorium on the method for gas production: "hydrofracking" or high-volume hydraulic fracturing (HVHF), pending completion of further environmental and public health studies. An ongoing state regulatory process has resulted in a public document, the draft supplemental generic environmental impact study (dSGEIS available at http://www.dec.ny.gov/energy/58440.html), which is currently undergoing review by the New York State Departmental of Environmental Conservation (DEC). In contrast to a point-by-point evaluation of that lengthy draft dSGEIS, this paper focuses on the interaction among scientific and technical issues of local environmental protection and other relevant spheres of concern to humankind such as energy policy, land use, economics, regulation, politics and ultimately global climate change. These interactions really determine how to prioritize risks for health and wellbeing of affected populations. Formal risk assessment is premature without analysis of such interactions and initial screening of risk (AEA Technology 2012). This work therefore involves more the problem formulation of risk as opposed to formal risk assessment (US EPA, 2003; US NRC, 2008).

Public controversy over the hydraulic fracturing methods necessary for unconventional gas production has stimulated numerous highly focused and conflicting contributions in the literature on narrow technical issues (Schon 2011; Pyron 2011; Osborn et al. 2011; Howarth et al., 2011; Warner et al., 2012; O'Sullivan and Paltsev, 2012). While clarity on narrow issues is important, a sole focus on scientific and technical aspects is unlikely to have prevented such recent environmental catastrophes as the Fukushima Daiichi nuclear plant explosions/tsunami disaster in Japan or the Deep Horizon oil-well blowout in the Gulf of Mexico. A better analogy to potential unforeseen impacts of Marcellus natural gas production might be the slower-developing but even more disastrous epidemic of arsenic poisoning due to widespread consumption of contaminated groundwater in Bangladesh (Dhar et al., 1997). These unforeseen catastrophes result not just from scientific uncertainty but more importantly from an avoidable reactive cascade of events driven by economic and political choices.

While some have touched on broader considerations concerning Marcellus shale gas production (Howarth and Ingraffea, 2011; Engelder, 2011), scientifically-based decisionmaking needs to explicitly account for non-scientific issues related to human activities. Despite general studies of the intersection between energy use and water resources (Harte and El-Gasseir 1978; Harte 1983; Gleick 1994, Jenner and Lamadrid, 2012), there are few pertinent tradeoff analyses in specific situations (Rahm and Riha 2012; Stephenson et al., 2012). Scientists have particular responsibilities (Hansen 2007, Maxim and van der Sluijs, 2011) to help develop timely, systematic approaches that consider overlapping scientific, technical, environmental, sociological, economic and political considerations, evaluate their relative importance for the issue at hand, and thereby formulate recommendations for policy decisionmaking.

The novel aspect of this review is that it combines an analysis of the scientific and technical aspects of hydraulic fracturing to produce natural gas from the Marcellus formation in New York state compared to the risks of endangering the New York City (NYC) water supply (Figure 1), while also considering the broader impacts on global climate change and even more critical issues regarding energy tradeoffs, economics and political regulation. Because of its similarity to larger and equally time-sensitive natural resource issues that require policy responses, like global climate change, decisions about Marcellus shale gas drilling have much larger implications beyond the U.S. Mid-Atlantic region. Although the United States is currently the only country with widespread unconventional natural gas production using hydraulic fracturing, many countries are thought to have significant unconventional natural gas potential (Rogers 2011), and concerns have been expressed by the European Union about the potential environmental and human health risks of such production (AEA Technology 2012).

Starting with a narrow perspective on the scientific (hydrological and chemical) and technical aspects of water resources and natural gas drilling in the Marcellus shale, the underlying land-disturbance and geological factors are analyzed, then the broader energy and economic aspects, followed by the regulatory and ultimately political foundations of this issue. The intent is to develop a proactive framework for rational, timely decision-making by weighing relative merits in the face of incomplete information, and seek a broader perspective on common ground for consensus in the case of Marcellus shale drilling in and near the watersheds that provide New York City water supply.

2. Hydrological and chemical aspects

2.1 Protection of the New York City water supply

The almost nine million residents of New York City have been supplied since 1915 with drinking water from the Catskill-Delaware watersheds west of the Hudson River, which directly overlie the northeastern corner (about 4100 km^2 or 8.5%) of the Marcellus shale subcrop that extends from the Appalachians north across the southern tier of New York State. Land surface runoff from these watersheds drains into several reservoirs from which water is transported via aqueducts and tunnels to the city (Figure 1). New York City has the largest unfiltered water supply (NYC DEP, 2010) among United States large cities, most of which operate expensive water filtration and treatment facilities.

Over the last couple decades, New York City Department of Environmental Protection (NYC DEP) has demonstrated every five years that the system meets strict criteria according to the US Environmental Protection Agency (US EPA) Surface Water Treatment Rule, thereby enabling a federal Filtration Avoidance Determination (FAD) (NYC DEP, 2010). To accomplish this, the NYC DEP is pursuing an aggressive preventive campaign of subsidies for agricultural best management practices (BMPs), in collaboration with large and small landowners, to maintain contaminants such as excess coliforms, pathogens, turbidity and nutrients considerably below federally-mandated levels (NYC DEP, 2010). Water quality is carefully managed in all watersheds, and protection efforts in the largest and westernmost Cannonsville watershed have been topics of research and modeling (Bryant et al., 2008, Rao et al. 2009).

2.2 New water resources threats

In these watersheds supplying New York City potable water, drilling for Marcellus shale gas development presents additional threats to water resources, which the current BMPs cannot mitigate. Extracting natural gas from shale (Kerr, 2010; Lee et al., 2011) involves the latest drilling industry techniques of horizontal directional drilling and high-volume hydraulic fracturing (HVHF, hydrofracturing or "hydrofracking") (US GAO, 2012; Kargbo et al., 2010; Bybee, 2007). These techniques use 7500-38,000 m^3 of water per well (Kargbo et al. 2010; US DOE-NETL 2010) and various chemical additives (Waxman et al. 2011) injected at high pressures to open and force sand into fractures in the rock, enabling release of gas. Although the Marcellus shale lies hundreds to thousands of meters below land surface, these drilling activities present a threat to both groundwater and surface water resources.

2.3 Well drilling process

The well-drilling process itself, developed from oil and mineral exploration, uses a clay slurry as lubricant. The base fluid can be water, oil, or a synthetic such as vegetable esters or olefins (Sadiq et al., 2003). Although water-based fluids (WBF) are more environmentally benign, oil-based fluids (OBF) or synthetic-based fluids (SBF) are often preferable in shales because they are more stable, less reactive and support the borehole better. OBF-saturated rock fragments, or cuttings, removed from the borehole during drilling can be a significant source of contaminants to the environment because they do not degrade readily (Sadiq et al., 2003). Few studies have evaluated relative merits and risks of these various fluids and rock cuttings, however the high levels of natural radioactivity in cuttings from some Marcellus shale well borings have raised concern (Kargbo et al., 2010, Lee et al., 2011).

Clear evidence for past contamination by drilling fluids is slim (Kargbo et al., 2010; US EPA 2011), but natural gas that seeps into shallow groundwater presents an explosion risk if it degasses into confined areas such as basements. Although methane, the major component of natural gas, occurs naturally in shallow groundwater (Molofsky et al., 2011) in northern Pennsylvania and southern New York, controversy surrounds the role of gas drilling in shallow aquifer contamination. Careful geochemical analysis, and methane and strontium isotopic signatures (Osborn et al., 2011; Warner et al. 2012) have now shown that some methane and groundwater salinization in shallow drinking water wells is attributable to natural upward seepage of natural gas and brine, respectively, from reservoirs like the Marcellus formation. This has important implications for large-scale development of natural gas drilling using thousands of boreholes reaching depths of over a mile below land surface, as described later.

2.4 Surface water impacts

The greater threat appears to be to surface water because of local water demand and wastewater disposal, although groundwater concerns are revisited later in conjunction with bedrock integrity and well abandonment issues. There is also a need at land surface for effective management and safe disposal of the tens of thousands of cubic meters of water and additives (sand and chemicals) needed per well for hydrofracturing. The final environmental impact assessment commissioned by the New York City Department of Environmental Protection (Hazen and Sawyer, 2009) assumes a full build-out of up to 6000 hydrofractured Marcellus shale gas wells in the NYC water supply watersheds and presents a comprehensive evaluation of the environmental risks, the most important of which are addressed here.

Although few have examined water usage impacts of shale-gas drilling (O'Shea, 2011; Rahm and Riha 2012), natural gas production from shales elsewhere, using similar drilling methods, provides examples of likely impacts on surface water availability. Permitting requests of up to 2.5 x 10^5 m^3 of water per year over 10 years have been reported for the Barnett shale in Texas (Rahm, 2011). After initial hydrofracturing, wells decline rapidly in gas output after the first year or two, and repeated hydrofracturing and infill drilling is used to maximize ultimate recovery (as is now happening in Texas), which could increase water demand (US DOE-NETL 2010). More comprehensive analyses (Elcock, 2010) indicate that increased exploitation of unconventional energy resources like gas, and their use for electrical power generation will require significant growth in U.S. freshwater use.

For example, in the Susquehanna River basin, overlying the Marcellus in western NY state (Figure 1), a recent analysis (Rahm and Riha 2012) suggested that surface water availability in all but the largest rivers, and effective treatment capacity is inadequate to support the drilling of hundreds of gas production wells per year. In the NYC supply watersheds, projected diversions of water needed for hydrofracturing a maximum build-out of wells could range from 0.8 to up to 1.5 $x10^7$ m^3 per year of additional demand (Hazen and Sawyer, 2009). The higher level of diversion represents 1000x the amount anticipated to require significant expansion of NYC water supply storage for maintaining supply safety (Flexible Flow Management Program, 2008). Alternatively, groundwater withdrawals to supply such hydrofracturing would deplete shallow aquifers and baseflow that sustains current streamflow, also adversely affecting watershed storage.

Water quality impacts from natural gas exploitation depend on the constituents of produced wastewater from drilling operations (Fakhru'l-Razi et al., 2009), which include both additives (Waxman et al., 2011; Aminto and Olson 2012) and natural contaminants such as minerals and radionuclides in the Marcellus (Kargbo et al., 2010; Lee et al., 2011). As with coalbed methane (CBM) extraction (Clarke 1996; Healy et al., 2008), produced waste-water poses the most important environmental risks, often having total dissolved solids (TDS) concentrations in the tens to hundreds of thousands of mg/L (US GAO, 2012). Of the total volumes of water needed for hydrofracturing the Marcellus shale, gas production causes 10-40% return flow up the borehole (Gregory et al., 2011; Hazen and Sawyer, 2009) although an increasing proportion of this produced water is now recycled (US GAO, 2012). Recycling or disposal of the remaining waste brines will likely require dilution and treatment because deep reinjection, a common method in oilfields, is more expensive.

Industry accounts of hydrofracturing de-emphasize the amount of chemical additives, many of which are carcinogenic, as a proportion of hydrofracturing water (1-2% by volume). However, over the 20 year timeframe projected for the development of Marcellus shale gas drilling, the total mass of chemical additives (not including sand proppant) amounts to several hundred tons per day, and over 500 tons per day if repeated hydrofracturing is used to delay inevitable well production declines (Hazen and Sawyer, 2009). In addition to diesel fuel, until recently used in hydrofracturing (Kargbo et al., 2010), other less-well-known hydrocarbon additives are hazardous to human and environmental health (Waxman et al. 2011; Aminto and Olson 2012). These include biocides (Struchtemeyer et al. 2012), endocrine-disrupting compounds, mutagens, teratogens and other toxins that present human health risks at very low dosages with long-term exposure (Hazen and Sawyer, 2009). The mere introduction and usage of hundreds of tons per day, over decades, of such toxic chemical additives in watersheds that provide drinking water to millions of New York City residents, is a significant cause of concern.

Although hydrofracturing fluids can be highly variable in their composition depending on the geology and fracturing outcome desired, most of these additives are unregulated with regard to drinking water standards and do not have maximum contaminant levels (MCLs) established by federal (US EPA) or state (NYS Dept of Health) authorities. A recent modeling study (Aminto and Olson 2012) of a hypothetical spill into air, water and soil of additives used in Pennsylvania Marcellus hydrofracturing has shown that resulting concentrations in a receiving surface water body exceed the 5 μg/L MCL standard for many organic compounds in New York state. Furthermore, the environmental impact study commissioned by the NYC Dept of Environmental Protection (Hazen and Sawyer, 2009) presents two dilution scenarios in which acute spills of hydrofracturing chemicals from a dozen wells or less could threaten the volumes of water contained in several major reservoirs (assumed partial mixing, reservoirs at low levels). Resulting exceedances of the US EPA MCL in those reservoirs highlights the severe risk posed by large-scale Marcellus shale gas exploitation. The risk is likely even greater, and more insidious, of numerous small site spills which go undetected and eventually enter drinking water reservoirs, with irreversible consequences. Aggressive enforcement of BMPs for pollution prevention, stormwater control, waste minimization and handling could reduce, but never eliminate such risk.

3. Land-disturbance, and geologic factors

The expansion of similar unconventional natural gas drilling in other areas of the United States has been dramatic (Figure 2) in the last decade. While future growth is difficult to predict (recent production drilling in the Barnett shale has since lagged due to declines in natural gas prices (Rogers, 2011)), projected expansion of the Marcellus shale drilling from neighboring Pennsylvania into New York is likely to follow similar trends, starting from the date that HVHF permits are issued. To compensate for the different regional extents of the shales in the locations illustrated, the data (adapted from Hazen and Sawyer 2009) have been normalized for well density per 2600 km^2 (1000 mi^2). However, even this data reduction cannot fully account for evolution in well densities as natural gas fields are developed, because future well siting and infill development depends on production records of existing wells. Nevertheless, since exponential trends cannot be sustained, applying a logistic function fitted to existing data for the much smaller Barnett Formation in Texas, but offset in time, suggests that extremely rapid development can be expected in the Marcellus in New York State for at least 6-8 years from initiation.

3.1 Land use changes

Such large-scale exploitation of natural gas resources from the underlying Marcellus shale would necessarily fragment the largely rural, forested and agricultural landscape near the NYC water supply watersheds. Of immediate concern are land use changes such as the construction of roads, well-pads and pipelines that accompany intensive natural gas drilling. While the impact of each individual well drilling operation is relatively minor, the cumulative impact of thousands of wells scattered across the watershed threatens the quality of runoff to streams and water supply reservoirs over time (Mitchell and Casman, 2011). Experience in other shale-gas-producing areas shows that a density of 3.5 or more wells per km^2 can be anticipated in highly productive areas for fully developed gas fields (Hazen and Sawyer, 2009; US DOE NETL 2010), although these densities have not been reached to date in most unconventional fields (Figure 2). Multiple directional wells are expected to be drilled from each wellpad for natural gas production in the Marcellus shale. Each wellpad is likely to have a footprint of about 2.8 ha., part of which will remain in operation for the well’s productive life of up to 20 years.

Industrial operation involving heavy truck traffic requires a compacted gravel substrate, leading to increased stormwater runoff and erosion potential (Hazen and Sawyer, 2009). Each well is estimated to require 900 to 1300 truck access trips, up to 6600 for multiple horizontal well pads (NTC, 2009), resulting in tens to hundreds of thousands of additional truck trips for many wells over a large area. In Wyoming, Huntington and Ksaibati (2009) showed that county roads suffered severe damage from heavy truck traffic associated with well drilling, with one half of road repairs concentrated on only 15% of the roads. These impacts in a semiarid environment likely underestimate the damage and repair costs necessary for a more humid climate like New York.

3.2 Aquifer, well and bedrock integrity

Contamination of shallow aquifers, used for individual home water supply in rural areas, could result from either infiltration of wastewater (Healy et al., 2008) or subsurface leakage of drilling fluids or natural gas through or along drill casings (ODNR, 2008; US EPA 2011). Standard techniques in well drilling, such as cementing casing pipe, are increasingly scrutinized (Ladva et al., 2005) since effective seals may not be achieved in many cases (Harrison, 1985; US EPA, 2011). Although casing defects and the subsurface migration of natural gas through fractures are rare, the consequences can be catastrophic, resulting in surface explosions over 11 km away from a leaking deep gas storage well in Kansas in 2001 (Nissen et al. 2004a, 2004b; Watney et al. 2003). Regulatory oversight of natural gas and oil-well seals has lagged the proliferation of well borings in the 20th century, such that even in a highly regulated operation in Alberta, Canada, up to 10% of existing wells have been found to have inadequate seals, though more recent failure rates are down to 2% (Watson and Bachu, 2009).

The geology underlying the NYC water supply watersheds (Hazen and Sawyer, 2009; US DOE NETL 2010), consists of thin surficial deposits and Devonian-age sedimentary rocks (sandstone, shale, siltstone and limestone) that include the Marcellus shale. Although conventional hydrogeologic analyses assume extremely slow flow rates through these rocks based on equivalent porous medium assumptions (ICF International, 2009), more sophisticated detailed studies (e.g., Runkel et al., 2006) show that even non-karstic sedimentary rocks (sandstone and shale) contain significant brittle fractures, which allow faster preferential flowpaths along bedding-planes over distances of kilometers. While solute transport is typically slower than pressurized gas flow in such fractures, both are highly unpredictable and essentially undetectable, barring major events. The limited flow between deep and shallow formations that has already been shown using isotope tracers (Warner at al., 2012) can be locally enhanced by interconnection of existing preferential flowpaths by well drilling and hydrofracturing, which destabilize existing hydraulic gradients by changing pressure regimes.

Understanding of flow and leakage through such heterogeneous connected fracture networks even in sedimentary rock requires new paradigms (Eaton, 2006, and references therein), and is at the forefront of hydrogeologic research especially for purposes of geological carbon sequestration (DOE NETL, 2010). Considerable information on brittle fault structures and linear features extending laterally for kilometers and vertically for thousands of meters has been documented by engineering studies for the emplacement of the current water supply tunnels (Figure 1) that transport water outside the watersheds to New York City (Hazen and Sawyer, 2009).   The NYS DEC dSGEIS study anticipates buffer zones between sensitive resources or infrastructure and permitted natural gas drilling locations, but the widths of those buffer zones (100s of m) are well short of the known lengths of many mapped linear fault features.

The New York City DEP has expressed concern about possible impacts on this tunnel infrastructure from extensive hydrofracturing in close proximity (Hazen and Sawyer, 2009). A major issue is that the tunnels extend up to 8 km outside the hydrographic boundaries of the watersheds (Figure 1) and therefore are not entirely included in the currently proposed protected area described in the NYS DEC dSGEIS. These bedrock water tunnels lie 100-300 m below grade (well below the water table), are concrete-lined, and have served well for decades, but are designed to retain transported potable water, not resist external overpressures. In fact, existing chronic leakage through tunnel liner cracks indicates they would be vulnerable to additional damage from changing external stresses, accumulation of explosive natural gas in access and maintenance infrastructure and even fracture-flow contamination at occasional low operating pressures (atmospheric) due to groundwater inflow (Hazen and Sawyer 2009).

4. Energy and economic aspects

Analysis of possible impacts of Marcellus shale gas drilling must consider the resulting tradeoffs in the larger context of global climate change driven by fossil fuel GHG emissions. Specifically, compared to current domination of coal-fired electrical generation in the United States, what are the environmental consequences that may be avoided by a potential substitution with natural gas? In fact, a recent study (Lu et al. 2012) has shown that such substitution has already contributed to a reduction in CO_2 emissions from US electrical generation from 2008 to 2009. Potential economic and environmental benefits of natural gas drilling, representing a desirable transition to a cleaner energy economy, need to be weighed against the economic and environmental costs, that are not necessarily limited to New York state.

4.1 Global greenhouse gas (GHG) emissions

Closure of coal-fired power plants and their substitution by higher efficiency, lower-emission electrical generation, like using natural gas, has been identified as one of the principal options to reduce greenhouse gas (GHG) emissions (Pacala and Socolow, 2004). Other than natural gas, there is no other readily deployable energy generation technology that provides the necessary replacement base load to balance the intermittency of renewable energy generation like wind. Therefore, increased natural gas production from the Marcellus would be beneficial in this regard. But economic and cleaner energy benefits of natural gas may be illusory if only GHG emissions at the point of combustion are considered (Hughes 2011). Furthermore, natural gas consists of mostly methane, a more powerful driver of global climate change than carbon dioxide (Howarth et al., 2011, Shindell et al. 2009).

Due to poor regulation, production and pipeline transportation of natural gas causes numerous unaccounted-for sources of GHG emissions to the atmosphere, the magnitude of which is under debate (Howarth et al. 2011; O'Sullivan and Paltsev 2012). Unconventional gas exploitation causes methane emissions from the wellhead during and after the drilling is completed, and while the gas is processed and transported. These fugitive methane emissions are poorly constrained (US EPA, 2010), but could conservatively amount to up to 7.9% of lifecycle well production (Howarth et al., 2011). While modeling studies of GHG emissions from shale gas production with differing assumptions are proliferating (e.g. Jiang et al. 2011; Weber and Clavin 2012), there is a shortage of actual field studies. However, recent work (Petron et al., 2012), focusing on VOCs and methane from a natural gas field in Colorado, showed that the uncertainty of and actual GHG emissions percentages are higher than many assumed values in the models, and closer to those of Howarth et al. (2011).

4.2 Substitution for coal, and public health impacts

Many existing "lifecycle" analyses in the debate over the environmental impact of natural gas do not take into account the default (current) GHG emissions of coal-fired generation (Weber and Clavin, 2012), and others do not evaluate environmental impact other than GHG emissions (Howarth et al., 2011; Hultman et al. 2011; Burnham et al., 2012) in their assessment of different fuels for electrical generation. However, non-GHG impacts dominate current U.S. electricity production, almost half of which is generated using coal, and 34% of that capacity is from plants more than 40 years old, with little to no modern pollution controls, such as scrubbers or other technology (Hughes, 2011). Many existing "lifecycle" analyses focusing on GHG impacts are therefore too narrow for comparison of tradeoffs related to increased Marcellus shale gas production.

In fact, in contrast to natural gas production, most "externalities" or environmental damages from coal-fired electricity are not related to climate change (Levy et al., 2009; US NRC, 2009; Epstein et al., 2011). These impacts are largely due to air pollution from sulfates and other particulates and related cumulative public health consequences. Others are related to water contamination due to coal sludge storage accidents, and ecological and economic costs (including opportunity costs) of land transformation due to mountain-top removal (MTR) in Appalachia (Epstein et al., 2011). Estimates of non-climate-related total hidden annual costs of coal for electrical generation range from $62 billion (US NRC, 2009) to $281 billion (Epstein et al., 2009). The total hidden cost (environmental and health) damage from the most polluting coal-fired electrical generation plants is estimated to be seven times as much as the damage from the most polluting natural gas-fired electrical generation plants (US NRC, 2009). US national net impacts from substitution of natural gas for coal in electrical production are likely to be positive due to reduction of coal-related externalities along with GHG emissions, however the full economics of the global climate change problem (Goodstein, 2011) are beyond the scope of this work.

Nevertheless, a more-straightforward assessment of economic costs of shale gas exploitation is possible based simply on potential health impacts, and effects on local populations in New York. Air quality has deteriorated in the United States where natural gas resources are currently being exploited (Kargbo et al., 2010, Petron et al. 2012). Public health impacts in Colorado and Pennsylvania have been estimated (Colorado School of Public Health, 2011; Lauver, 2011; McKenzie et al. 2012). The leading air-quality risk to public health in Colorado is increased subchronic exposures to airborne hydrocarbon carcinogens and increased cumulative cancer risks for those residing within 0.8 km (0.5 mile) of gas-producing wells compared to those living farther away (McKenzie et al., 2012). Other impacts considered in the Colorado public health study (Colorado School of Public Health, 2011) and elsewhere (Lauver, 2012) involve particulates, degradation of water quality, light pollution, and industrial noise from drilling and compressor stations. These health impacts are clearly potentially severe for residents of New York state where Marcellus drilling may be permitted, and would need to be substantially mitigated.

4.3. Economic impacts and tradeoffs in New York State

The tradeoffs between who benefits and who is adversely affected by natural gas drilling, what size these populations are and where they are located, are relevant here. Conventional environmental economics methods (willingness to pay, choice experiments, contingent valuation or analytical hierarchy processes) for assessing risks and costs of natural resources degradation (Martin-Ortega and Berbel, 2010) suffer from incomplete information (Konishi and Coggins, 2008) and depend on polling the inhabitants of the landscape affected. Further issues for such local market-based, cost-benefit analysis are that widely accepted watershed protection methods such as the US EPA total maximum daily load (TMDL) approach simply do not produce positive benefit-cost ratios (e.g. Borisova et al., 2008), and most studies do not consider spatial heterogeneity (populations not inhabiting the areas in question) (Brouwer et al., 2010). Such environmental economics methods are impractical in the case of Marcellus shale drilling and the New York City water supply because the benefits and costs accrue at least in part to different populations.

Even so, natural gas drilling has been promoted, in industry-sponsored economic impact reports, as either an economic boon to the state and struggling communities in rural areas (see Kinnaman, 2012 and references therein), or alternatively a threat to the current tourism-based economy in rural counties (Rumbach, 2011). Detailed analysis of these dueling economic impact perspectives is beyond the scope of this work, but many of their assumptions and economic modeling procedures have been questioned (Kinnaman, 2012). What is clear is that lower natural gas prices due to increased production from the Marcellus will benefit electricity consumers and many others by reducing the percentage of power produced from coal-fired plants and associated externalities. The difference between the shorter term (10-20 years) of the "boom" type economic development benefits associated with natural gas production and the eventual long-term costs of the permanent transformation of the landscape would depend on the economic discount rate used (Goodstein 2011).

However, considering the relative populations concerned who stand to benefit or suffer adverse consequences provides a baseline for comparison. The southern tier New York state counties along the Pennsylvania border (Figure 1) have a population of less than 700,000, many of whom would benefit from royalties due to leasing of mineral rights to natural gas producers (Kargbo et al., 2010). This population could suffer health-related impacts from proximity to the gas-producing wells and economic impacts from landscape transformation. Compared to this are the costs and public health consequences of potential degradation of a public water supply for a much larger population (almost 9 million) in New York City. Currently, New York City taxpayers invest a modest US$3 million/yr to support conservation practices in the Cannonsville watershed (Bryant et al., 2008), and about US$50 million/yr for the combined watershed protection program. However, if the US EPA rescinds its filtration avoidance determination (FAD), the alternative costs of water filtration and treatment for New York City have been estimated in the billions of US$ (Bryant et al., 2008), largely for the construction and operation of the facilities needed.

5. Regulatory and political aspects

Finally, the ultimate consideration when assessing a scientific and technical issue with major public policy implications is the political and regulatory landscape. Experts tend to view the scientific and technical aspects in isolation, whereas the success of public policy decisions about these issues can depend more on politics. Despite solidifying scientific consensus (IPCC, 2007) on the need for GHG emissions reduction, and widespread international ratification of the 1997 Kyoto Protocol, the unwillingness of the United States to ratify and the collapse of the former Soviet Union and Eastern European industrial production have probably had more impact on GHG emission trends over the last 20 years. Recent attempts in the field of uncertainty analysis to address this dilemma have called for scientific knowledge that is used in political decisionmaking to be placed in the proper socio-political context to be relevant (Maxim and van der Sluijs, 2011), and such is the intent of this work.

5.1 Federal regulatory gaps

There are numerous exemptions and limitations in federal environmental legislation and US EPA authority to regulate unconventional natural gas drilling (Wiseman, 2012; US GAO, 2012). Of the eight major pieces of legislation (Safe Drinking Water Act - SDWA; Clean Water Act - CWA; Clean Air Act - CAA; Resource Conservation and Recovery Act - RCRA; Comprehensive Environmental Response, Compensation and Liability Act - CERCLA; Emergency Planning and Community Right-to-Know Act - EPCRA; Toxic Substances Control Act - TSCA; and Federal Insecticide, Fungicide and

Rodenticide Act - FIFRA), the first six have important exemptions related to oil and natural gas development.

The most important exemptions to these laws were created by the 2005 Energy Policy Act, by which hydraulic fracturing is specifically exempted from regulation under the SDWA Underground Injection Control program, except if diesel fuel is injected (US GAO, 2012; Wiseman, 2012). Under the CWA, pollutant discharges from industrial sites and wastewater treatment facilities are regulated, however oil and gas production well sites are exempted from National Pollutant Discharge Elimination System (NPDES) permitting. The CAA exempts certain naturally-occurring hydrocarbon mixtures from air quality regulation and prohibits aggregating emissions from multiple well sites, pipelines or pumping stations, hence no oil and gas wells have been regulated as air pollutant sources to date (US GAO, 2012).

The US EPA issued a controversial determination in 1988 that oil and gas development waste are not covered under RCRA, governing hazardous solid waste, but the agency retains "imminent and substantial endangerment" authorization to intervene. It is clear that these major gaps and exemptions hinder federal oversight of environmental protection in the case of hydraulic fracturing, and legislation (the FRAC Act) to close the CWA exemptions has been introduced in Congress (Rahm, 2011), but not yet passed. Due to the limitations in federal legislation, the primary responsibility for enforcement of environmental regulation of oil and gas production has rested at the state level, in particular where states have been delegated responsibility ("primacy") to enforce federal law.

5.2 State regulatory authority and experience

The considerable differences in state authority, regulatory structure and history of oil and gas exploration make comparisons among states' levels of regulatory effectiveness very difficult. Several recent studies have analyzed various aspects of regulatory experience, focusing on Pennsylvania (Mitchell and Casman, 2011), Texas (Rahm, 2011) and a comparison of these and several other states (Wiseman, 2012). Over the period 2008-2011, Pennsylvania and Texas, both with long histories of oil and gas exploration, provide a comparison between a state with fairly aggressive enforcement (PA) leading to the largest number of violations of state environmental or oil and gas laws (Wiseman, 2012); and a state (TX) with a very "oil and gas-friendly" regulatory environment and looser enforcement (Rahm, 2011).

One concern that emerges is that oil and gas production operational methods developed under less restrictive state regulatory structures (Texas) are inconsistent with prevailing regulation (Pennsylvania) that is being established by states with higher environmental protection standards. Another is that technological innovations and economic incentives that do not currently include the costs of environmental protection are now driving the boom in unconventional natural gas production. Gas well productivity is declining, and unconventional natural gas is now being produced at a loss, given that the marginal cost of production is much higher than world gas prices (Rogers, 2011; Hughes, 2011). Current regulatory authority and environmental protection have not been able to keep up with the economic drivers of unconventional gas production where it is now occurring in the United States. These regulatory shortfalls are manifest especially in the areas of well plugging or sealing and in the ability of states to field sufficent inspectors for oversight.

5.3 State regulatory shortfalls

At the end of their economically useful life, wells in oil and natural gas fields must be properly sealed with cement to close direct pathways between the reservoir and the surface, or even shallow groundwater, to avoid environmental damage as detailed previously. Many of the hundreds of thousands of wells estimated to have been drilled over the last century in Pennsylvania and New York have not been adequately plugged (Crain 1969), in part because modern record-keeping and verification of well sealing only began in the 1980s. While more modern oil and gas fields in Alberta (Watson and Bachu 2009) have such records numbering in the hundreds of thousands, older oil and gas provinces in Pennsylvania and New York where wells were drilled to 2000 ft depth or more (Hartnagel and Russell 1925; Van Tyne 1998) only have records of tens of thousands of wells (NYSDEC regulates approximately 40,000 known wells, most of which are not sealed, but operational or on "inactive status"). The mismatch in numbers corresponds to numerous leaking "legacy wells" whose location is often unknown (Watson and Bachu, 2009; Mitchell and Casman, 2011).

While enforcement has undoubtedly improved, the economic incentives that led to this poor regulatory compliance still exist. As natural gas wells decline in production after the first couple years, they are generally transferred from the original gas producers to smaller entities, either other gas producers or even landowners. Furthermore, many wells are put on "inactive status" or otherwise escape regulatory oversight when operators default. Costs of proper well sealing, which ranges from $100,000 to $700,000 per well, are thereby avoided because minimum federal and state bonding levels are generally inadequate and reclamation costs are often deferred for decades (Mitchell and Casman, 2011).

The other major concern is the need for adequate field-based monitoring and inspections by regulatory personnel to ensure compliance with environmental standards. Beyond the gaps in federal legislation and the historical development of the oil and gas industry, the states' regulatory framework has often been reactive and inadequate to prevent violations, notably in Pennsylvania (Rahm, 2011). Some of the reasons for this ineffectiveness include lack of state funding (Mitchell and Casman, 2012), inefficient organization or incompleteness of records (Wiseman, 2012), fragmentation of environmental regulation authority and an anti-regulatory political climate (Rahm, 2011). For example, prior to the growth in unconventional gas drilling in Pennsylvania, it was estimated that due to inadequate funding rates, it would require 160 years to plug known existing "orphan" wells (Mitchell and Casman, 2012). Furthermore, in Texas, for natural gas extraction from the Barnett shale, violations recorded declined in 2009-2011 from the rates in 2008, apparently because the Texas Railroad Commission regulator suffered personnel losses due to a hiring freeze (Wiseman, 2012).

6. Discussion

To evaluate these major scientific and technical issues, the related geological, land use, economic and energy aspects, as well as the regulatory and political context of the Marcellus shale gas exploitation and the New York City water supply, a framework for decisionmaking is needed. Consider the semiquantitative interplay of three general domains originally identified by Rogers (2011): geology; technology; and regulatory and public acceptance. A

Venn-type graphical approach used in pharmacology and bioinformatics (Ruskey et al., 2006; Chen and Boutros, 2011) allows plotting the overlap of these three areas to analyze common ground for decisionmaking. It is useful to consider Venn diagram circles overlaid on a triaxial plot (Figure 3) to constrain relative size, corresponding to domain possibility, and proximity to origin, corresponding to how well the possibility is put into practice for that domain. An arbitrary scale on the axes represents increasing implementation toward the origin in an abstract "decision-space". Since perfect implementation (concentric circles at origin) is unattainable, the centers of the circles, for which the relative size needs to be determined, plot at different locations on the three axes.

6.1 Triaxial Venn diagram logic and analysis

A convenient starting point is the known geographical setting of the Marcellus shale, the northeastern end of which underlies the southern tier of New York state (Figure 1). From a geological perspective, all of the Marcellus shale is potentially a source of natural gas, but only a subset (unknown until sufficient wells have been drilled) of that area will be the most highly productive. Extraction of natural gas from such shales was not even technologically viable until recent decades with the advent of hydraulic fracturing, and depth, thickness and organic content are still limiting factors. Therefore, the size of the circle representing technology is necessarily smaller than the circle representing geology, analogous to the difference between reserve and resource of any fossil fuel.

The development of hydraulic fracturing has enlarged the circle of technological viability and moved it closer to the center, enabling considerable overlap with the area of geological resource. Similarly, United States' energy needs and growth of natural gas production have enlarged the circle of regulatory and public acceptance and moved it closer to the center, enabling overlap with the other two circles. It is clear, however, that the circle of regulatory and public acceptance is the smallest of the three, and the challenge is to identify what is the overlap of the three circles, what lies inside and outside, and what might be necessary to maximize the size of the intersecting common ground for publicly acceptable Marcellus shale gas drilling.

6.2 Application to decisionmaking about hydraulic fracturing in New York state

The dramatic expansion of drilling for natural gas in the Marcellus shale indicates that there is considerable growing overlap of technology and geology due to rapidly advancing technological innovation in the drilling industry, however this may be counterbalanced by economic considerations such as low natural gas prices. The trend of the much smaller overlap for regulatory and public acceptance in New York state is not as evident due to the continuing controversy in the scientific literature and public media over the environmental impact. In any event, a careful weighing of the different merits and liabilities described earlier is necessary for expansion of the area of regulatory and public acceptance. The major pros and cons are summarized in Table 1, taking into account a broader range of issues than are commonly discussed.

A key consideration must be that the geographical area occupied by the watersheds supplying municipal water to New York City is less than 10% of the area of the Marcellus underlying New York state. A reasonable first step in decisionmaking would therefore be to recognize that for the NYC watersheds overlying the Marcellus, the risks clearly outweigh any merits, and that the de-facto moratorium on drilling within a generous buffer setback of those watersheds and associated infrastructure (water supply tunnels), be formalized into a ban. This would include directional drilling from areas outside those buffer zones, and accept that the NYC watersheds lie permanently outside the circle of regulatory and public acceptance for Marcellus drilling (Figure 3).

Beyond the boundaries of the buffer setbacks around the NYC water supply watersheds and infrastructure, the situation is less clear-cut. The benefits of increased natural gas use from the Marcellus shale (Table 1) are potentially great for transition to cleaner energy if the liabilities could be substantially reduced. Much of the environmental impact from Marcellus shale drilling is due to regulatory lapses, either at the federal or state level. This suggests that considerable strengthening of state and federal regulatory oversight is a possible avenue for reducing the environmental liability. In other words, enhancing oversight could enlarge the circle of regulatory and public acceptance (Figure 3) in New York state and move it down the axis of increasing implementation to expand the area of overlap or common ground for publicly acceptable HVHF.

6.3 Regulatory enhancement recommendations

Federal oversight is increasing with the US EPA promulgation in 2012 of the final rules on GHG reporting by operators of petroleum and natural gas systems, with a minimum facility threshold of 25,000 metric tons carbon dioxide equivalent (CO_2e) per year (http://www.epa.gov/ghgreporting/reporters/subpart/w.html). Furthermore, the US EPA is tightening New Source Review (Bushnell and Wolfram 2012) requirements for airborne emission standards for the oil and gas sector (http://www.epa.gov/airquality/oilandgas/pdfs/20120418rtc.pdf), regulations due to be in place by 2015, barring potential litigation. An obvious next step would be for the U.S. Congress to close the gaps in federal law (CWA, SDWA, CAA, RCRA, CERCLA, EPCRA) that have long exempted the oil and gas industry from national environmental protection legislation (US GAO, 2012; Wiseman, 2012). However, such an outcome is uncertain due to the current ideological deadlock in the U.S. Congress.

State regulatory oversight in New York, as proposed in the draft supplemental generic environmental impact study (dSGEIS) currently undergoing review by the NYS Dept of Environmental Conservation, is more rigorous than in many other states, particularly with respect to mandated buffer zones for natural gas infrastructure from natural resources (Wiseman, 2012) and requirements for closed-tank systems for wastewater capture in most cases. However, budget reductions at both the U.S. state and federal levels have thinned out regulatory personnel ranks below the minimum needed for current enforcement responsibilities. In 2010, the head of New York State DEC was dismissed following the release of an internal memo that documented a 21% reduction in workforce since 2008, and warned that fewer staff will be available for oversight of Marcellus natural gas drilling. Over the last 3 years, Pennsylvania, with several hundred inspectors, has been unable to effectively prevent serious violations (Wiseman, 2011; Rahm, 2011), so it is unlikely that New York, with a widely reported number of inspectors less than 20 in 2012, will be able to enforce effective regulations, no matter how rigorous they are. The major step to build public confidence that regulation will be able to reduce the environmental liabilities (Table 1) is to hire and train skilled regulatory inspection staff in the thousands, as is currently the case in major gas-producing states like Michigan and Texas (Wiseman, 2011).

While it is technically feasible to mitigate much of this environmental impact of expanded Marcellus gas drilling in New York State, market forces will cause natural gas companies to avoid the responsibility and costs of such mitigation (Mitchell and Casman, 2011). Many technologies exist for treatment of produced water (Fakhru'l-Razi et al., 2009; Gregory et al. 2011), and New York state regulations should mandate such treatment and a 90% minimum for recycling instead of simply encouraging such practices. Recently reported alternatives to massive water usage and wastewater generation include hydrofracturing using liquid petroleum gas and liquid CO_2 (Kargbo et al., 2010), which could be strongly encouraged. While limits on gas venting and flaring, reduced emissions completions (REC) to minimize gas well GHG emissions, and restrictions on diesel engines are proposed as part of the revised NY state dSGEIS, more is needed to ensure necessary environmental protection. For example, requiring gas distribution lines to be in place upon well completion would allow a ban on all venting and flaring except in case of emergency, and onsite engines could be required to operate with a 20% minimum percentage of biodiesel or compressed natural gas (CNG), limits that would increase in 5 year increments.

A serious concern remains about proper well construction and sealing or plugging. Outside the NYC watersheds to the west (Figure 1), the counties along the Pennsylvania state line (the "Southern Tier") account for over 77% of oil and natural gas wells registered in New York State, and are likely to be centers of Marcellus shale gas production. According to a recent survey of public records, most (89%) depleted oil and gas wells in New York state have not been adequately plugged or sealed over the last 25 years, leaving tens of thousands as potential conduits for contamination, most of which have unknown locations.

Current proposed regulations (revised dSGEIS) require Marcellus well drilling permit applicants to identify non-producing or abandoned (sealed) wells within one mile of the proposed drilling location for HVHF, however it is not clear if this entails locating all previously unknown or improperly sealed wells that may pose a catastrophic environmental protection risk during new well drilling. Mitigating the rare but very real hazards posed by such historical wells would require substantially strengthened regulatory oversight.

Fortunately, New York State has a strong tradition of environmental protection of part of the NYC watersheds in question, which is off-limits to development in perpetuity in the Catskill State Forest Preserve (Figure 1). The Catskill State Forest includes private land within a boundary known as the “blue line”, which encompasses an area occupying effectively the southeastern half of the New York City water supply watersheds. Current regulatory proposals anticipate including all watersheds or major aquifer areas that supply major municipalities like NYC, which are already partially protected by other City-owned property or conservation easements, in the area prohibited to HVHF drilling (Figure 1). It would also be important to prohibit deep directional drilling underneath those areas (from surface locations outside) and to increase necessary setbacks to that protected area and associated water supply infrastructure (currently proposed to be only ~1200 m).

7. Conclusions

Even if consensus can be achieved on the scientific and technical issues outlined earlier, gas production from the Marcellus shale is so economically important that the New York State governor and legislature will ultimately decide whether and how to allow such natural resource development to proceed. The nature of political decision-making is primarily non-scientific, and as in recent integrated water management (Kragt et al., 2009), other interdisciplinary factors enter into consideration and may even trump science-based analysis. Avoiding this outcome can be accomplished by maintaining the present moratorium while addressing the broader issues described in this work.

It may never be possible to quantify all of the costs and benefits associated with the prospect of natural gas drilling in and near the watersheds that supply New York City with drinking water. However, while potential benefits may be great in the context of future energy policy towards a low-carbon economy, liabilities are also very significant and could outweigh benefits (Table 1). Whether benefits of Marcellus shale gas drilling exceed liabilities thus depends on enforcement of strong environmental regulations to minimize liabilities and achieve greater public acceptance of HVHF in New York State (Figure 3). In the current political and regulatory climate, it remains unclear whether this can be accomplished. Specific recommendations from this analysis for New York State to obtain greater public acceptance and environmental protection include:

- Immediate hiring and training of sufficient NYS DEC inspectors (1000+) and increasing agency funding for monitoring eventual HVHF and gas pipeline operations in NY state
- Permanent banning of HVHF within NYC and other major municipal water supply watersheds, including a 5000 m buffer zone from associated infrastructure (water supply tunnels) and watershed perimeter, and prohibiting deep directional drilling underneath such watersheds or major aquifers.
- Mandating a minimum of 90% produced water recycling, minimum 20% biodiesel or CNG for all drilling site and truck operations, banning gas venting or flaring except in case of emergency, mandating immediate connection to gas distribution lines.

Without significant investment in state and federal regulatory enforcement, the intense scrutiny of thousands of gas wells necessary to avoid incremental degradation of watershed protection or shallow groundwater will not be possible. However, recent developments provide grounds for guarded optimism. The history of mineral exploitation in the United States is one of dramatic reduction of adverse environmental consequences of mining operations. 19th century practices resulted in acid mine drainage and numerous Superfund site designations in Colorado and other western states, but 21st century mine reclamation with sufficient regulatory oversight has avoided environmental degradation in several U.S. states and Canada.

In this situation involving politics, economics, geology, hydrology and water quality, the usual methods of risk assessment may not provide useful answers (Hattis and Goble, 2003) and the "precautionary principle" may be the best benchmark for decision-making (Stayner et al., 2002). Maintaining the current New York State moratorium on hydrofracturing of horizontal wells seems a prudent step in light of the legislative uncertainty. It is likely that HVHF will be highly regulated and eventually permitted in the remaining 90%+ of the Marcellus shale subcrop across the southern tier of New York. Time will tell whether the potential liabilities or benefits (Table 1) of natural gas exploitation from the Marcellus shale will be realized.

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Table 1. Considerations for assessing environmental impact of Marcellus shale gas drilling in New York State

Major Liabilities	Major Benefits
1. Degradation of watershed and groundwater protection • US EPA FAD may not be renewed, requiring NYC water supply filtration • Long-term increase in chronic contamination of NYC and other water supply, requiring increased storage, health degradation of NY residents	**1.** Substitution for coal in electricity generation • Less particulate air emissions, lower health impacts • Enables phase-out of coal to combat climate change • Reduction of mountaintop removal for coal mining
2. Industrial infrastructure degradation of rural landscape • Loss of recreational tourism and resulting local and state revenue • Fragmentation of wildlife habitat by roads and pipelines	**2.** Transition fuel to carbon-constrained economy • Lower natural gas prices speed rather than slow closing obsolete coal power plants • Enhance baseload electrical generation capability substituting for intermittent sources (e.g. wind, solar)
3. Uncertainty of effect on global GHG emissions reduction efforts • Fugitive emissions may result in increased global warming potential	**3.** Proximity of energy source for electrical generation to the urban centers of the NE United States • Avoids natural gas supply bottleneck due to imports and long-distance transportation costs • Lower costs for locally-produced gas, electricity
4. Local pollution of air by VOCs/ozone precursors • Long-term health effects on local populations • Reduction of regional air quality	**4.** Local economic investment in upstate NY • Employment year-round in contrast to current seasonal tourism • Per-capita revenue for local landowners from mineral leasing
5. Local pollution and depletion of streams • Long-term health effects on local populations • Ecological impact of increased pollution on local wildlife	

Figure Captions

Figure 1. Location of the watersheds (inset) that supply drinking water to New York City (adapted from NYC DEP) in relation to the subcrop of the Marcellus Formation (USGS); heavy line indicates eastern boundary of Marcellus shale subcrop (Milici and Swezey, 2006). Contours in regional map indicate shale thickness; dashed lighter line on inset indicates boundary of Catskill Forest Reserve (NYS DEC).

Figure 2. History and projected growth of U.S. unconventional natural gas development in different shale formations. Curves are a logistic function fitted to data from the Barnett Formation in Texas, showing expected trends for other production areas, including the Marcellus shale in New York State (data from Hazen and Sawyer (2009))

Figure 3. Conceptual triaxial Venn diagram showing common ground among domains of geology, technology, and public and regulatory acceptance for HVHF in New York State. Axes show increased implementation towards origin. Vertical hachures show present limited acceptance of Marcellus HVHF, angled hachures show possible future consensus if regulatory and public acceptance domain can be expanded and moved inward along implementation axis.

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Figure 1

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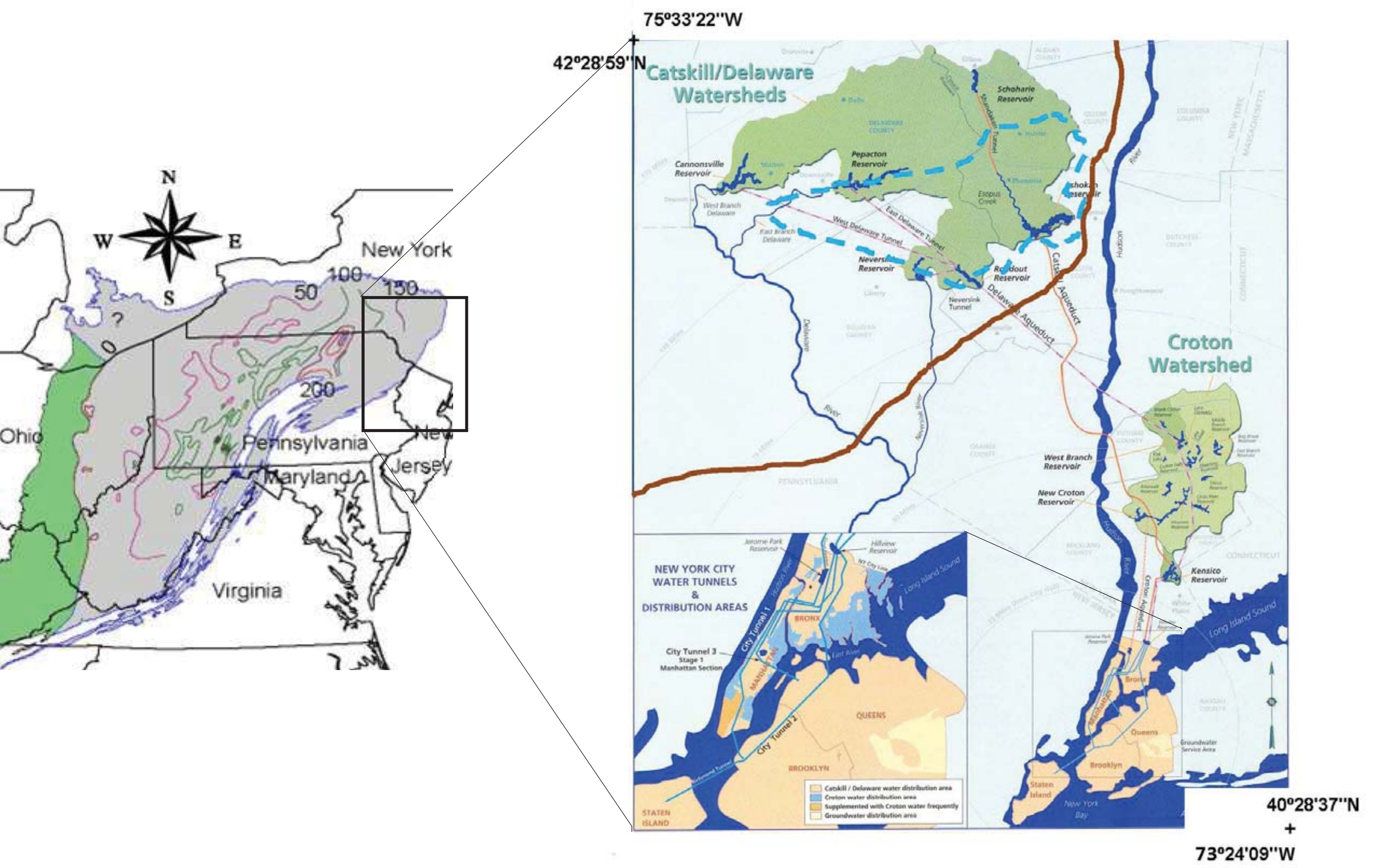

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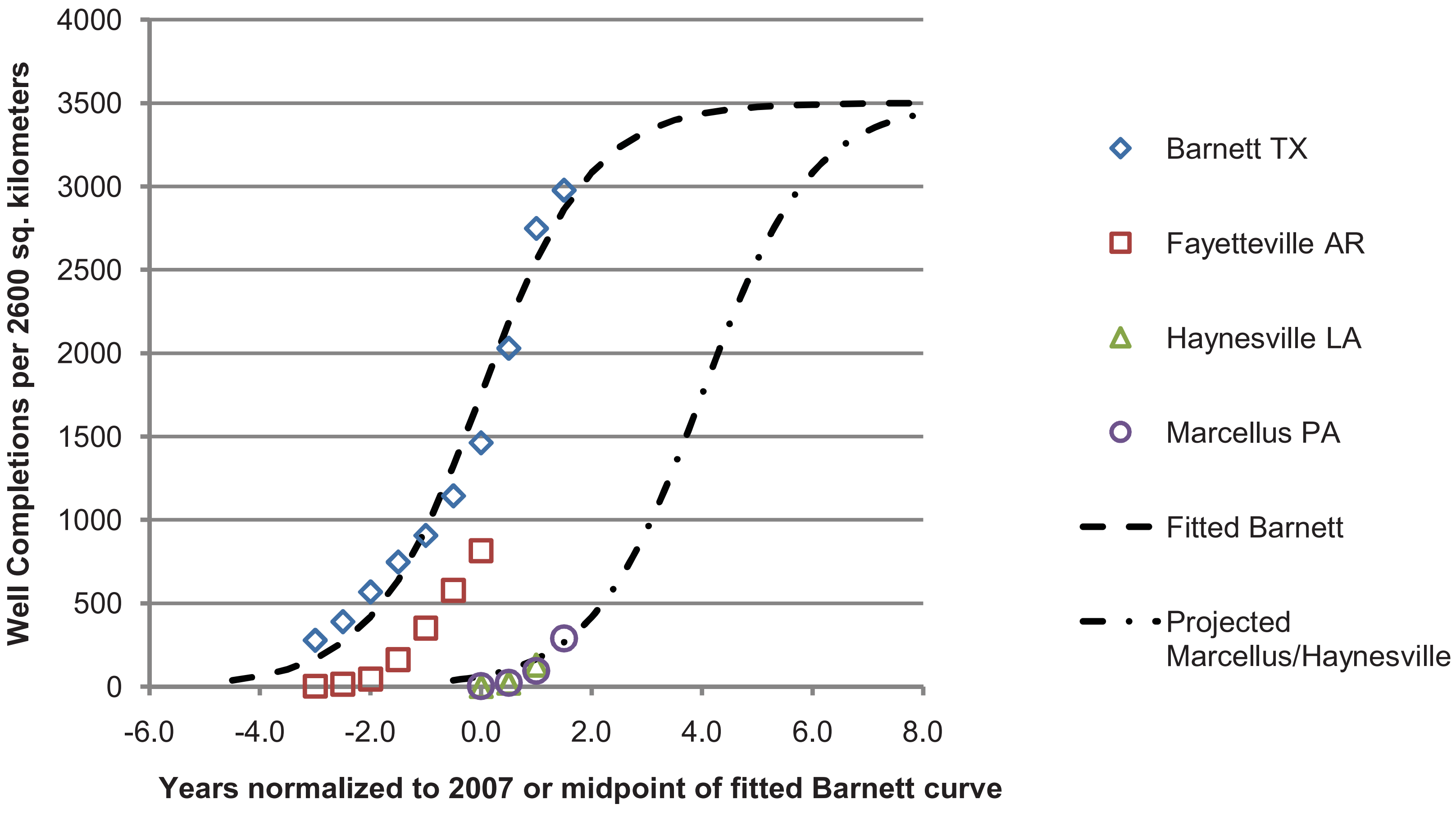

Figure 3

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