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Toward strategic management of shale gas development: Regional, collective impacts on water resources

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ABSTRACT

Shale gas resources are relatively plentiful in the United States and in many countries and regions around the world. Development of these resources is moving ahead amidst concerns regarding environmental risks, especially to water resources. The complex nature of this distributed extractive industry, combined with limited impact data, makes establishing possible effects and designing appropriate regulatory responses challenging. Here we move beyond the project level impact assessment approach to use regional collective impact analysis in order to assess a subset of potential water management policy options. Specifically, we examine hypothetical water withdrawals for hydraulic fracturing and the subsequent treatment of wastewater that could be returned or produced from future active shale gas wells in the currently undeveloped Susquehanna River Basin region of New York. Our results indicate that proposed water withdrawal management strategies may not provide greater environmental protection than simpler approaches. We suggest a strategy that maximizes protectiveness while reducing regulatory complexity. For wastewater treatment, we show that the Susquehanna River Basin region of New York State has limited capacity to treat wastewater using extant municipal infrastructure. We suggest that modest private investment in industrial treatment facilities can achieve treatment goals without putting public systems at risk. We conclude that regulation of deterministic water resource impacts of shale gas extraction should be approached on a regional, collective basis, and suggest that water resource management objectives can be met by balancing the need for development with environmental considerations and regulatory constraints.

1. Shale gas development: growing importance and concerns

Although there is significant uncertainty in assessing its recoverability, unconventional shale gas is expected to raise world technically recoverable gas resources by over 40% (USEIA, 2011). Shale gas resources are thought to be plentiful in the European Union (Poland and France), North America, China, Australia, Africa (South Africa, Libya, and Algeria), and South America (Argentina and Brazil) (USEIA, 2011). In the United States (US), natural gas production from shale resources has grown from 0.1 to 3 Tcf in the past decade and, as of 2009, accounts for nearly 14% of total gas production (MIT, 2011). By 2035, shale resources are projected to account for 46% of all US natural gas production (USEIA, 2010).

While shale gas resources appear to be relatively abundant and widespread throughout much of the world, the willingness to develop these resources varies. Heated debate continues as to whether the economic and energy benefits associated with shale gas extraction are worth the potential environmental impacts. Some countries such as the US,

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Canada, and more recently the United Kingdom have moved forward with development while France and some regional governments (Quebec, Canada) have placed temporary or permanent moratoria on the high-volume hydraulic fracturing process, citing concerns with respect to environmental safety, public health, and consistency with current policies.

Shale gas development entails a range of activities that have various environmental impacts. More comprehensive discussions of these activities and the risks associated with various impacts have been presented from various perspectives (e.g. Christopherson, 2011; Kargbo et al., 2010; NYSDEC, 2011; Zoback et al., 2010). Major environmental concerns generally revolve around several key activities associated with shale gas development. Water resources, their use, and their potential contamination as a result of a wide range of development activities figure prominently among those concerns. Other issues involve potential noise, visual and air quality impacts associated with vehicle traffic, well pad construction and land clearing activities, and use of diesel fuel for on-site compressors and equipment. Activities associated with establishment and construction of well pads and associated service roads and delivery pipeline networks have the potential to disrupt land use patterns, disturb sensitive habitat, and introduce invasive species. Trucking demands related to transportation of materials, water, and waste lead to concerns over road use, road safety, and road maintenance. Still other impacts are possible that are related to community character and the ‘‘boom and bust’’ cycle associated with extractive development. Our focus here, however, is on water resources.

Multiple activities associated with shale gas development have the potential to impact water resources and/or water-related infrastructure (e.g. Arthur et al., 2010; Soeder and Kappel, 2009; Veil, 2010). Developing shale gas requires a range of typical construction-associated activities. To establish well pads, soil is often removed and sometimes stored. Material and chemical storage areas are established. Roads, parking, and vehicle maintenance areas must be constructed. All of these activities lead to concerns over the risk of spills and leaks that could impact surface and groundwater quality, as well as erosion and water contamination resulting from storm events. Developing shale gas also involves more unique activities such as vertical drilling, often through potable groundwater supplies; and horizontal drilling through the shale formation itself. During these operations, millions of gallons of water need to be acquired and transported to the well pad, mixed with a number of chemical additives, and pumped under high pressure into the well in order to fracture the shale (high-volume hydraulic fracturing). This water then interacts with native constituents present at depth in the shale geology. When pressure is taken off the well, some of this water returns to the surface relatively quickly (flowback water), where it is sometimes treated and reused for hydraulic fracturing of other gas wells. Flowback water that is not reused, as well as water that is returned to the surface over the life of the gas well (produced water), must be stored and then treated and/or disposed of. Improper or poorly managed drilling, water withdrawal, or water treatment could potentially lead to water quantity and quality impacts.

Because of concerns for potential environmental impacts such as those discussed above, coupled with the broad occurrence of shale gas throughout the world, managing and regulating the development of shale gas resources is a growing global interest and challenge. In the United States, shale gas resources are currently being extracted in Pennsylvania, Texas, and several other states, despite concerns from some stakeholders that it carries understudied or unacceptable environmental risks (USEPA, 2011a). While rapid development has occurred, regulation of this growing industry has evolved more slowly, and has taken many forms. The federal government provides some oversight through the Clean Water Act, Safe Drinking Water Act, Clean Air Act, and National Environmental Policy Act. The implications of this legislation are discussed at length elsewhere (GWPC and AC, 2009; Tiemann and Vann, 2011). However, the role of the federal government in the US has so far been limited, although recent efforts by federal agencies such as the EPA could mean that this might change (USEPA, 2011a). For the most part states, and in some cases regional authorities, have taken the lead role in regulation of shale gas development in the US (GWPC, 2009).

Within the US, states regulate shale gas development and its impact on water resources in different ways (GWPC, 2009). In Pennsylvania (PA), for example, drilling for gas in the Marcellus Shale has increased dramatically in the last several years and regulatory approaches have been reactive in nature, administered to address and mitigate recognized environmental issues after they have occurred. Over time, regulations have become increasingly stringent, and regulatory agencies have moved toward establishment of publically accessible databases which track and compile water resource related information (PADEP, 2010). In New York (NY), parts of which are underlain by the Marcellus Shale, policy makers have chosen not to permit high-volume hydraulic fracturing activities needed to exploit this resource while the NY State Department of Conservation (NYSDEC) reviews possible environmental impacts and proposes regulations to mitigate those impacts (NYSDEC, 2011). While NY is the only state thus far to essentially prohibit shale gas development until an environmental assessment is completed, the focus of this assessment has been the subject of debate.

The preliminary environmental impact assessment (dSGEIS) developed by the NYSDEC was undertaken in response to a state law (State Environmental Quality Review Act) that directs the agency to conduct a comprehensive review of all the potential environmental impacts of new development activities. The dSGEIS contains a description of the activities associated with high-volume hydraulic fracturing and shale gas development in general, the potential environmental impacts associated with those activities, and proposed measures and regulations that have been identified to mitigate those impacts. It focuses largely on the project level and pays considerable attention to the potential impacts of an individual shale gas well on its immediate surroundings. This is valuable, especially to the state regulatory community who would be in charge of overseeing the day to day operations of developers. A major criticism of the dSGEIS, however, has been the lack of attention paid to cumulative impacts, which can be briefly defined as impacts resulting from interactions of multiple activities, and/or the collective impact of many similar activities over time and space. Although the dSGEIS acknowledges these impacts, it does not include a full analysis of cumulative environmental impacts at the regional scale, nor does it strategically assess policy alternatives and their potential effect on regional environmental impacts. For complex developments such as shale gas, environmental assessment approaches that explicitly analyze cumulative impacts from a state/regional perspective have been shown to be essential (e.g. CEQ, 1997; Kay et al., 2010; Zhao et al., 2009). Moreover, it is recognized that environmental assessments that combine the ''project-focused'' approach of the dSGEIS with more strategic ''planning-based'' approaches can be effective for minimizing negative cumulative environmental impacts (e.g. Cooper and Sheate, 2004; Spaling and Smit, 1993).

Here, we discuss the need to expand the scale of environmental impact analysis of shale gas development beyond the project level. We argue that the distributed nature of the shale gas resource, and the potential for rapid increase in well density within newly discovered plays, necessitate a need for strategic planning and management of development at the regional (state) scale, and that it is important to examine water resource consequences of shale gas development over time and space in addition to project-level impacts. We offer a shale gas development event framework that is useful for identifying activities that could potentially impact water resources, and for distinguishing between impacts that can be addressed through strategic planning and management, and impacts that are addressed through traditional regulations focused on prevention and mitigation. We then provide two simple scenario analyses that show how various policy options can affect a subset of collective water resource impacts in NY, and how the shape and effectiveness of policies can be influenced by regional characteristics. Although we recognize the desirability of full cumulative impact assessment, in which multiple activities are assessed together, we offer here a more simplified analysis of collective impacts that might result from repetition of similar development activities over time and space. We argue that strategic regional analysis of policy options allows regulating agencies to better understand and control development scale and collective environmental impacts. Although limited in scope, we hope that simple analyses such as these will help lead to the development of, and sit within, more comprehensive, strategic environmental assessments for shale gas development in the US and across the globe.

2. A framework for development events and water resource impacts: issues of certainty, scale and policy

As discussed above, shale gas extraction entails many activities that can and do affect water resources. Like many other industries, development of shale gas involves construction-like activity and transformation of the local landscape. In addition, however, development of shale gas occurs on a collective scale across the region and, once the resource has been extracted, attempts to return much of the landscape to its pre-construction state. Well pads and associated roads and pipelines must be built to accommodate the transportation and storage of large quantities of fresh water as well as wastewater. Materials and fluids from one site are often transported to other sites where they are treated in combination with fluids from other wells. Water withdrawals may take place in one location, while discharge of treated wastewater may take place in another. Besides these activities, all of which take place at the surface, well drilling and completion occur underground, cross property lines, and intersect public resources such as aquifers. This makes the task of environmental assessment and subsequent management of such development a complex one. We have proposed a conceptual framework for envisioning and organizing various shale gas development events and their subsequent, potential water resource impacts (Riha and Rahm, 2010).

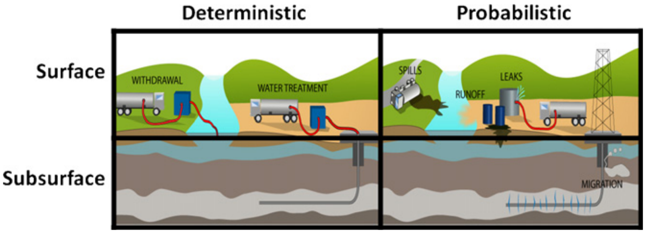

Fig. 1 – A simple framework for organizing and conceptualizing important distinctions between various shale gas development events with potential water resource impacts.

Briefly, this simple framework identifies events that might occur during shale gas development within a regional context (Fig. 1). Because of regional differences in geology, regulations, topography, biota, climate, and water use rights and laws, shale gas development in any particular region will involve a unique set of activities, will utilize specific technologies and best practices, and will occur within the context of region-specific environmental awareness and concerns. Since regional characteristics help to define the events taking place during shale gas development, it follows that environmental impacts are also regional in nature.

This framework allows for the outline of water resource impacts associated with shale gas extraction by differentiating between surface and below-surface events, and also by recognizing the difference between deterministic events (activities that are planned and certain to occur), and probabilistic events (accidents that are unplanned and uncertain at any single project site) (Table 1). Probabilistic events, by their very nature as accidents, cannot be eliminated altogether. They inevitably lead to negative environmental impacts even when plans, practices, and regulations are crafted perfectly. Probabilistic events can be addressed in at least two different ways. Environmental impact assessments, such as the dSGEIS, generally address these issues through project-focused minimization and mitigation measures. These measures can include best practice requirements, site monitoring, as well as inspection by regulatory personnel. A second approach to minimizing probabilistic events is to limit the pace and magnitude (scale) of development in general. Since these events occur in some proportion to the collective magnitude of overall development, planning mechanisms that modulate the pace and scale of development can influence the rate at which probabilistic events and their negative impacts occur. Planning mechanisms can include limiting or controlling

Table 1 – Events associated with Marcellus Shale gas development and their potential water resource impacts (not exhaustive).

Events	Potential impacts
Surface	
Withdrawal (surface or groundwater)	Decreased water quantity in streams, lakes or aquifers, leading to degradation of wildlife habitat, alteration of natural hydrology, and/or inadequate downstream water availability for human uses
Water treatment (flowback and produced waters)	Inadequate treatment of wastewaters and subsequent discharge into surface or groundwater leading to receiving water impairment
Spills/leaks (during transport, storage and handling of chemicals and waste)	Spills and leaks occur at well pads or result from accidents during transport of chemicals and wastes leading to surface water and groundwater impairment
Runoff	Stormwater interaction with sediment and chemicals on well pads and service roads, leading to erosion and impairment of local surface and groundwater quality
Subsurface	
Migration (drilling and well casing, cementing, hydraulic fracturing)	Alteration of local hydrology and groundwater chemistry leading to water quantity and quality impairment. Migration of fluids from within or nearby the wellbore leading to impairment of adjacent groundwater. Improper management of well pressures leading to blowouts and the uncontrolled release of fluids into local water resources.

deterministic events such as the withdrawal of water for the hydraulic fracturing process and the treatment and/or disposal of wastewater (flowback and produced fluids). It is this potential to control deterministic events that we focus on in this paper.

At the project level, managers of shale gas development will be concerned with ensuring that each water withdrawal and wastewater treatment *event* occurs within acceptable environmental and regulatory limits. At a more strategic level, however, it is important to consider how many such events will be happening over the regional landscape in time and space, and what *collective* impacts may arise. Since these activities (water withdrawal and wastewater treatment) are central components of the development of every well, the size of the collective water resource impact associated with each on a regional level reflects to some degree the pace and scale of shale gas development within the region. Regulation or restriction of these activities – for example, allowing only a limited amount of water to be withdrawn within the region during a given time period – could have a direct effect on potential environmental impacts. This presents an opportunity for policy makers and regulators to monitor and control regional development, as they potentially have the authority to implement permitting, reporting and compliance systems. This also provides decision makers with information that may allow them to determine how or whether shale gas development fits within the context of regional plans and policies. In the following section we use two simple scenario analyses to illustrate the possible effects of various policies on regional environmental impacts resulting from collective deterministic events. We focus specifically on the Susquehanna River Basin in New York State (SRB-NY) (Fig. 2) because it contains much of the land area in NY thought to comprise the Marcellus Shale "fairway," or area in which shale gas extraction is expected to deliver the highest yield. This region was also chosen because of its similarities with Northeastern PA (in terms of geology, topography, population, and economy), a region in which shale gas development has proceeded rapidly within the context of quickly evolving state policy. As NY has yet to finalize its environmental assessment of shale gas development and is in the process of formulating draft policy, PA acts as a case study and provides data on the potential effect of management options on industrial activity and environmental protection.

3. Strategic policy analysis of collective impacts resulting from deterministic events: water withdrawal

3.1. *Water withdrawal for Marcellus Shale development*

Hydraulic fracturing of shale gas wells requires large volumes of water. The distributed nature of development (i.e. across a

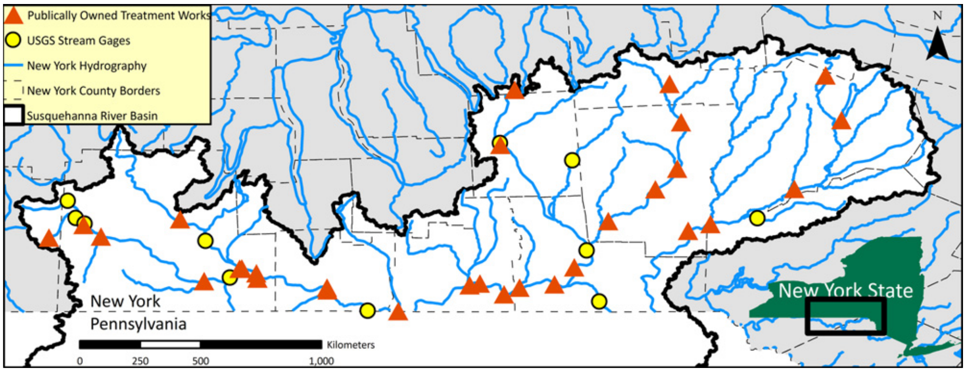

Fig. 2 – The Susquehanna River Basin of New York State (SRB-NY) with selected stream gages and wastewater infrastructure.

region) means that multiple locations for water withdrawals need to be identified. Two major concerns with these withdrawals include ensuring adequate downstream water availability for human uses and adequate water availability for ecological maintenance (habitat for fish, insects, wildlife, etc.). These concerns hold true not just for individual withdrawals occurring at the project level, but also for the collective withdrawals that could occur throughout a watershed and their effect on downstream flows. States, and in some cases interstate watershed basin commissions, have an interest in regulating water withdrawals in a manner that addresses these concerns. Existing regional differences between and within states in hydrologic systems, water demands, water quality, water treatment infrastructure, and water resource governance mean that regions will adopt various policies for regulating water withdrawals. To date, in the Susquehanna River Basin region of PA, surface water is the primary source for water withdrawals related to hydraulic fracturing (SRBC, 2010). In other shale gas regions however, such as the Barnett Shale in Texas, ground water is the major source of water for hydraulic fracturing (Bené et al., 2007; Soeder and Kappel, 2009). In its preliminary environmental impact assessment, the NYSDEC proposed a specific surface water withdrawal management policy (NYSDEC, 2011). The Susquehanna River Basin Commission (SRBC), an interstate regional authority, also has policy regarding water withdrawals for shale gas drilling, which are in effect in the PA portion of the basin (SRBC, 2002).

Here we assess two policy options for managing shale gas water withdrawals at a number of locations within the SRB-NY region. Policies are assessed based on their ability to protect surface waters of various sizes from impacts related to single and collective withdrawal events. Additionally, policies are compared on their appropriateness to the region in which these events will occur, and the governance structure in place to manage these activities and execute policy.

3.2. *Water withdrawal analysis methodology*

Hypothetical water withdrawal locations were chosen at sites of US Geological Survey (USGS) stream gages that met the following conditions:

1. They were within the geographical boundaries of the Susquehanna River Basin of New York State.
2. They had at least 50 years of approved historical discharge data.
3. They had complete records of approved discharge data from the years 2000 through 2009 (with the exception of the Otselic River at Cincinnatus, for which the years 1999 through 2008 were used).

Hypothetical withdrawal locations represent a wide range of stream sizes. Specific information related to locations chosen for analysis is provided in Supplementary Material (Table S1).

Water withdrawal ''Policy 1'' is similar to that proposed by the NYSDEC and utilizes the Natural Flow Regime Method (Poff et al., 1997) to determine a minimum passby flow that must be maintained at any given water withdrawal location (NYSDEC, 2011). For Policy 1 average daily flow (ADF) and average monthly flow (AMF) statistics were collected from the USGS WaterWatch New York website (USGS, 2011). As prescribed in the dSGEIS, a passby flow was then calculated for each month at each location using either 30% of the ADF, or 30% of the AMF, whichever was greater.

''Policy 2'' is a simplified version of the policy currently utilized by the SRBC in PA (SRBC, 2002). For Policy 2, ADF statistics were collected as described above. As prescribed by the SRBC, it was then necessary to determine whether a passby flow would be required. Passby flows are required for all locations at which a proposed water withdrawal is likely to be ≥10% of the Q7-10, where the Q7-10 is defined as the lowest average, consecutive 7-day flow that would occur with a frequency or recurrence interval of one in ten years. The SRBC has determined that water withdrawals of volumes <10% of the Q7-10 are small relative to the flow of the stream, and therefore do not require as stringent regulation as larger withdrawals. Volumes of proposed water withdrawals were estimated as described below. If a passby flow was found to be necessary, it was calculated for each day as 20% of the ADF.

Once passby flows were calculated for each policy at each location, they were used to determine the number of ''natural low flow'' days that had occurred at a given gage station during the period from 2000 to 2009. We define ''natural low flow'' days as days during a typical year on which the flow drops below the prescribed passby flow for a given policy. This was accomplished by comparing daily flows from that ten year period to passby flows calculated above. For Policy 2, if a passby flow was not found necessary, it was assumed that no natural low flow days would exist at that location. We acknowledge that, in actuality, the SRBC uses a more complex set of criteria for classifying streams and determining acceptable withdrawal rates. Without more detailed knowledge of each potential withdrawal location, however, we have chosen to use the method outlined here as a rough approximation suitable to our purposes.

We also introduce a second form of low flow that we call ''induced low flow.'' Here, the natural flow is adequate to satisfy the passby flow requirement. However, additional water withdrawal events, such as two withdrawals happening on the same day on the same stream, cause the flow to drop below the passby threshold. In other words, induced low flow occurs when a steam has some withdrawal capacity, but not enough for large or multiple withdrawals. Induced low flows were calculated in a similar fashion as natural low flows, except that an additional passby flow was required in order to account for multiple withdrawals on a given stream. Withdrawal rates were initially set at 198 l/s (7 ft^3/s), which was calculated based on the assumption that all the water needed to hydraulically fracture a single well (approximately 17,000 m^3 [4,500,000 gallons] based on a variety of sources [e.g. GWPC and AC, 2009; Kargbo et al., 2010; NYSDEC, 2011; SRBC, 2010]) would be withdrawn within a single 24-h time period. In reality, this is likely a conservative estimate. The SRBC, for example, does not usually allow withdrawal rates this high, and withdrawals may occur over time periods longer than 24 h. On the other hand, several withdrawal locations may be sited on the same stream. To show the effects of a range of multiple withdrawal scenarios, withdrawal rates of

28.3 through 283 l/s (1 through 10 ft^3/s) were also analyzed. This analysis is meant to illustrate how significant collective withdrawal activity could affect passby flow exceedances, and should not be taken as predictive.

For GIS analyses, maps were created using data obtained from the Cornell University Geospatial Information Repository (CUGIR, 2011) and the New York State Geographic Information System Clearinghouse (NYSOCS, 2011). ''Large'' rivers are defined here as having a median flow >2830 l/s (1000 ft^3/s). Once large river stretches were approximately identified using USGS stream gage data, a 16 km (10 mi) and 32 km (20 mi) buffer was created around them. The area within this buffered region was then compared to the total SRB-NY regional area. The Marcellus Shale fairway boundaries were approximated using information available in NYSDEC (2011).

3.3. *Water withdrawal analysis results and discussion*

On days of low flow, regardless of whether it was natural or induced, water withdrawals would be prohibited. A summary of the number of days per year each policy results in water withdrawal prohibitions at studied locations is illustrated in Fig. 3. Two features are readily apparent. First, Policy 1 results in withdrawal prohibitions even on large rivers, whereas Policy 2 does not. This is because Policy 2 does not assign passby flow requirements in these instances, as it is assumed that withdrawals at these locations of the size examined here are small compared with stream flow (<10% of the Q7-10). Second, both policies result in increasingly frequent withdrawal prohibitions as stream size decreases. This is especially true for induced low flow, where days on which withdrawals would be prohibited increase substantially on smaller streams. Interestingly, induced low flow does not occur for the largest rivers using either policy, implying that collective impacts of multiple withdrawals are primarily a concern on smaller streams. Overall, Policy 1 results in greater withdrawal prohibition. This is potentially more environmentally protective, but also leads to more days that the industry cannot withdraw water, thus requiring considerable regulatory oversight. Policy 2 provides similar protection for small streams, but results in an overall need for less regulatory oversight, particularly on large rivers. Given the potentially limited capacity for state and regional authorities to oversee this activity, these results suggest that a hybrid policy may combine the desirable aspects of each individual approach. What might such a policy look like?

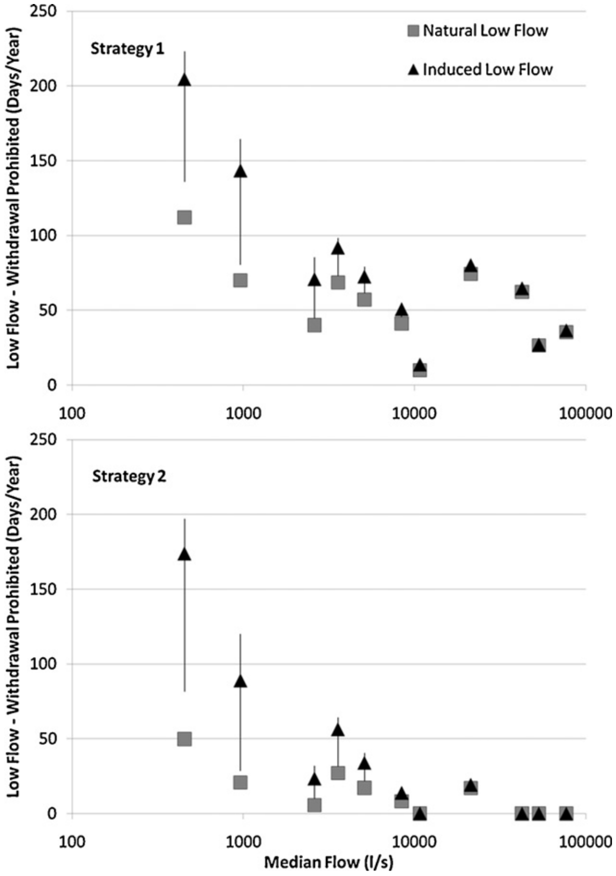

Fig. 3 – Comparison of water withdrawal regulation policies. Data points represent the number of days in an average year that withdrawals would be prohibited given the chosen policy. For induced low flow, a range of scenarios are depicted: the solid triangle represents a withdrawal rate of 198 l/s (7 ft^3/s), the approximate rate at which water for hydraulic fracturing of a single gas well would need to be withdrawn over 24 h. Solid lines show the effect of a range of withdrawal rates (28.3–283 l/s [1 to 10 ft^3/s]). In Policy 2, rivers with high median flows are not assigned passby flows, and so are not regulated (i.e. there are no low flow days).

First, it is worth considering Policy 2 for use on large rivers (median flows approximately >2830 l/s [1000 ft^3/s]). While large rivers experience fluctuations in flow just as small streams do, it is evident from the analysis here that relatively small water withdrawals (less than 2% of AMF for any month) do not significantly affect the flows of such rivers. Therefore, careful monitoring of individual water withdrawal events at the project level would not necessarily lead to significantly greater environmental protection for large rivers. Instead of tracking and assigning passby flows to multiple, individual withdrawal locations, regulatory agencies might choose to monitor the river on a collective basis only in a few locations (e.g. wherever significant drinking water withdrawals occur, or in locations that are currently gaged). Water withdrawals related to shale gas extraction might be prohibited only during notable drought conditions, as signaled by some minimum flow (e.g. the Q7-10). This monitoring approach could be combined with a withdrawal permitting structure that ensures that shale gas water withdrawals occur at reasonable rates, and are timed to occur during periods of relative water abundance. In the SRB-NY region, it is still unclear what a permitting structure might look like. However, it is worth exploring policies that potentially provide equivalent environmental protection while requiring less regulatory oversight.

Second, the use of smaller streams for water withdrawals should be critically questioned. Neither policy explicitly excludes small streams from use. It is clear from Fig. 3 that there are at least dozens of days annually when withdrawals from small streams (<283 l/s [100 ft^3/s]) will not be permitted, especially when considering withdrawal induced low flows. This suggests that, regardless of management approach,

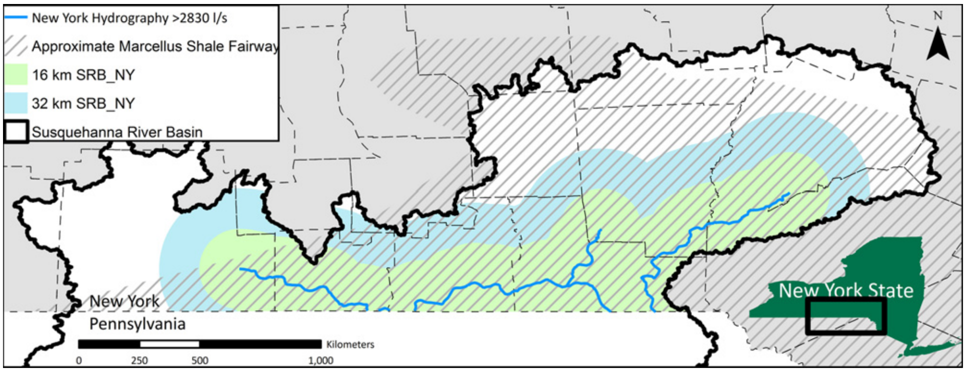

Fig. 4 – The Susquehanna River Basin of New York State (SRB-NY) showing hydrography features with median daily flow larger than approximately 2830 l/s (1000 ft^3/s). Area shaded in light green indicates the portion of the SRB-NY located within 16 km (10 mi) of these large rivers. Area shaded in light blue indicates the portion within 32 km (20 mi). This provides a rough illustration of access to major water sources for potential withdrawal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

preventing withdrawals on streams with flow $<$283 l/s (100 ft^3/s) could result in decreased need for state regulatory oversight. Streams with flow $<$566 l/s (200 ft^3/s) also would require significant oversight, and permitting withdrawal from these small to medium size surface waters should be evaluated critically as well. An environmentally protective policy, with least regulatory cost, could be to prohibit all withdrawals on small to medium size streams (e.g. $<$2830 l/s [1000 ft^3/s]). While environmentally protective, this policy is more restrictive of shale gas development. This places a potentially increased burden on the shale gas industry, as increased distance between water withdrawal locations and well pad sites results in larger costs associated with water transportation.

To explore the extent to which this might restrict shale gas development, we performed a GIS analysis of the area of the SRB-NY region and its proximity to ''large'' rivers. Results show that 34% of the SRB-NY region is located within 16 km (10 mi) of large water sources, while 57% is located within 32 km (20 mi) (Fig. 4). From the perspective of shale gas development, most of the Marcellus Shale fairway within the SRB-NY region is within the 32 km buffer area. This suggests that water resources would still be accessible for Marcellus Shale gas development in much of the region and that a strategy that balances ready accessibility and the need for effective regulation may be possible. Overall, therefore, preventing withdrawals on small to medium size streams in the SRB-NY region could be a prudent way to protect sensitive surface waters from collective withdrawal-related impacts while simultaneously enabling the more efficient use of limited state regulatory resources.

4. Strategic policy analysis of collective impacts resulting from deterministic events: wastewater treatment

4.1. *Wastewater treatment for Marcellus Shale development*

A portion of the water used for high-volume hydraulic fracturing is returned to the surface after fracturing procedures and contains not only the chemicals that were added as part of the fracturing mix, but also any constituents that may have dissolved into the fluid from the geologic formation. Once at the surface, this water must be treated and/or disposed of. In some shale regions, such as the Barnett Shale in Texas, this wastewater is often re-injected underground (GWPC and AC, 2009; Soeder and Kappel, 2009). In the Marcellus Shale, however, geologic constraints prevent the establishment of large numbers of nearby injection well facilities. Thus, wastewater re-injection is not generally an attractive option, as injection well facilities are usually located long distances from well pads, requiring significant transportation and incurring high costs (PADEP, 2010; Veil, 2010). Instead, wastewater is often treated and then reused or discharged to surface waters (PADEP, 2010; Veil, 2010). Three main concerns related to wastewater treatment include: capacity to treat required volumes given available infrastructure within the region of development; treatment quality for downstream use (drinking water; industrial water uses); and treatment quality for ecological purposes (toxicity in fish and other freshwater species). Proposed policy in NY with respect to wastewater treatment is discussed in the NYSDEC preliminary environmental impact assessment (NYSDEC, 2011). However, to our knowledge, the capacity to treat these wastes under various policy regimes, and using existing infrastructure in the SRB-NY region has not yet been systematically evaluated. As with the water withdrawal scenario analysis above, various wastewater treatment policy alternatives are evaluated here for their ability to provide protection from environmental impacts, as well as for their appropriateness within the SRB-NY region.

4.2. *Wastewater treatment analysis methodology*

For this analysis, we make the initial assumption that all wastewater generated within the region must also be treated within the region. This is not entirely realistic, as there are no existing legal limitations to the transportation of wastewater outside the region. However, this approach has merit for at least two reasons. First, due to the economic costs of transportation, industry looks to treat its wastewater as close to its point of generation as possible. Second, due to the controversial nature of the shale gas industry and strong social and political opposition in some areas, many communities outside as well as in the SRB-NY have resisted the acceptance of this waste at public facilities.

Shale gas wastewater, due to its high total dissolved solids (TDS) concentration and its chemical complexity and variability, can present treatment challenges for many typical publically owned treatment works (POTWs) (Keister, 2010; NYWEA, 2011). Allowing POTWs to accept these waste streams might require considerable and new regulatory guidance. We therefore structure the following analysis around a simple set of policy scenarios that might be applied to the acceptance of wastewater by POTWs in the SRB-NY region. The policy scenarios we have chosen roughly reflect actual policy enacted in PA as regulations evolved to match growing shale gas development. In policy scenario A, all POTWs are allowed to treat shale gas wastewater; however, such wastewater may only comprise a maximum of 1% total daily flow through the plant (Veil, 2010). In policy scenario B, all POTWs are again included, but now must meet effluent discharge limits of 500 mg/l TDS (PAEQB, 2010). Policy C requires that POTWs accepting shale gas wastewater must have NYSDEC certified pre or mini-pre treatment capability (NYSDEC, 2011). It is not our goal to predict what actual policy will look like in NY, but rather to show how the region's capacity to support shale gas development might change given potential policy choices.

For wastewater treatment analyses, a list of current POTWs was first generated using information on State Pollutant Discharge Elimination System (SPDES) permits found at the NYSGIS Clearinghouse (NYSOCS, 2011). Facilities were included in the analysis if they were within the geographical boundaries of the Susquehanna River Basin of New York State and had an average flow rate of >0.25 m^3/min (0.1 MGD) (Table S2). Average wastewater flow rates were computed from monthly averages recorded between January 2008 and December 2010, as given by the Enforcement and Compliance History Online database managed by the US Environmental Protection Agency (USEPA, 2011b).

To determine POTW treatment capacity for shale gas wastewaters, it was first necessary to approximate the wastewater generated from an average Marcellus Shale gas well, along with its average TDS load. In these calculations we assumed the following:

1. Average water use per well ranged from 12,500 to 16,100 m^3 (3,300,000–4,260,000 gallons based on SRBC information from 220 wells reported between June 2008 and May 2010 [SRBC, 2010], and 36 well completion reports of Range Resources & EQT during 2010 [RR and EQT, 2011], respectively).
2. Average fraction recovered as either flowback or produced wastewater within one year ranged from 0.1 to 0.2 (an approximation based on information from the SRBC [SRBC, 2010]).
3. Average shale gas wastewater TDS concentration ranged from 100,000 to 200,000 mg/l (an approximation based on various sources [e.g. Keister, 2010; NETL, 2010; NYSDEC, 2011; Tamblin, 2010).

It was also assumed that typical POTW influent (non-shale gas related) could be roughly characterized as "low strength wastewater," and therefore would have had a pre-existing TDS concentration of 270 mg/l (Tchobanoglous et al., 2003). Again, we recognize that actual values for these parameters will change by location and over time. Parameter values are also subject to change as more is learned from water managers in Marcellus Shale gas development states.

In order to compare POTW capacity in the SRB-NY with industrial treatment capacity in PA, data on shale gas wastewater handling in PA was collected from the PADEP Oil & Gas Reporting Website (PADEP, 2010). We used a data set that compiled information on wastewater volumes sent to industrial treatment facilities from July 2010 through December 2010. We multiplied these volumes by two to approximate the volumes treated by these facilities in a year. Facilities were included in the analysis if they were found to treat wastewater volumes that corresponded to ≥10 wells per year (Table S3).

4.3. *Wastewater treatment analysis results and discussion*

Results of wastewater treatment scenario analyses are summarized in Table 2. POTW treatment capacity is defined in units of wells/year, roughly showing the level of regional shale gas development that can be supported given the various policy scenarios summarized above. Based on current POTW capacity within the SRB-NY region, policy scenario A would allow development of between approximately 270 and 690 wells/year. This range in values reflects uncertainty in the amount of water used to hydraulically fracture each well, and also in the volume of wastewater recovered from each well. Under scenarios B and B + C, however, treatment capacity decreases to between approximately 30 and 160 wells/year, and between 30 and 140 wells/year, respectively. This range of values accounts for the uncertainties listed above related to

Table 2 – Wastewater treatment capacity in the SRB-NY region under various policy scenarios.

Regulatory scenario	POTW treatment capacity within SRB-NY (wells/year)	# of POTWs utilized (*n*)	# of industrial treatment facilities needed to replace POTW capacity (*n*)
A	270–690	30	6–7
B	30–160	30	1–2
B + C	30–140	14	1–2

Scenario descriptions: (A) wastewater allowed at all POTWs; maximum volume set at 1% daily flow; (B) wastewater allowed at all POTWs; effluent [TDS] set at 500 mg/L; (C) wastewater allowed only at POTWs with NYSDEC certified pre-treatment capabilities.

water and wastewater volumes, and also reflects a range of potential shale gas wastewater TDS concentrations. It is interesting to note that application of scenario C roughly cuts the number of facilities available for use in half. Despite this, the regional treatment capacity does not differ much from scenario B alone. This can be explained by noting that regional treatment capacity is dominated by a small number of relatively large facilities, all of which have NYSDEC certified pre-treatment programs (Table S2).

The prospect of treating shale gas wastewater at POTWs has produced considerable opposition from environmental advocacy groups and citizens. In PA, the PA Department of Environmental Protection has discouraged the direct treatment of shale gas wastewater at POTWs, leaving industry to find alternatives such as industrial treatment facilities (PADEP, 2011). In recognition of this movement toward the use of industrial treatment facilities, we asked the question: how many industrial treatment facilities would need to be established in the SRB-NY region in order to replace current POTW treatment capacity? To answer this question, we examined industrial facilities currently operating in PA in order to roughly determine the amount of development an average facility can support (Table S3). As shown in Table 2, POTW treatment capacity in the SRB-NY region can be replaced using a relatively small number of industrial treatment facilities. Under policy scenarios B and B + C, investment and construction of only 1–2 industrial plants could provide treatment capacity equivalent to that of the region's POTWs.

Encouraging establishment of purpose-built industrial treatment facilities has several technical and regulatory advantages over using POTWs. Compared with POTWs, far fewer industrial facilities provide equivalent treatment capacity, an important consideration in the face of collective wastewater treatment needs that could quickly outpace regional infrastructure. In addition, assuring the compliance of a small number of industrial facilities is likely to present a significantly smaller regulatory burden than assuring compliance of 14 to 30 POTWs. Furthermore, purpose-built industrial facilities are better suited to treating these complex wastewaters, and thus less likely to encounter problems meeting effluent water quality standards. Lastly, this approach would allow for more rigorous monitoring of surface waters receiving treated discharges, as fewer locations would need to be targeted. In any case, based on the POTW analysis above it is unlikely that regional POTW treatment would offer an acceptable solution for industry within the regulations NY is likely to adopt. From an economic planning perspective, private facilities may be built at a pace and scale concurrent with industry needs, and may have more flexibility than public entities in choosing business models that accommodate the volatile nature of this extractive development.

5. Toward strategic regional management

Assessment approaches that are capable of evaluating environmental impacts of shale gas development are needed not just at the project level, but also on a regional scale where there will be collective impacts from multiple projects. Shale gas development occurs in a distributed manner across regional landscapes. In PA over the last five years, the number of Marcellus Shale gas wells has grown from a handful to around 4000, spread over about 30 counties (roughly 50,000 km^2). While individual well pads may have limited or sporadic impact on water resources, the collective impact of such rapid and dense industrial activity is likely to lead to further negative environmental consequences if not managed properly. Collective impacts, and more broadly cumulative impacts, can be significant challenges that accompany unmanaged shale gas development (Handke, 2009; HS, 2009).

Approaches that attempt to incorporate analyses of collective and cumulative impacts, as well as planning-based approaches that consider regional policy and region-appropriate development have been proposed under the rubric of Strategic Environmental Assessment (SEA) (e.g., Partidário, 2000). In the European Union, SEA is increasingly being viewed as a systematic way to synthesize various elements of environmental assessment and policy making, as well as additional components of regional development such as public participation and communication (e.g., Partidário, 2007; Sheate et al., 2003). Similarly, the Canadian government has been developing Regional Strategic Environmental Assessment (RSEA) (Noble and Harriman, 2008), the overall objective of which is to ''inform the preparation of a preferred development strategy and environmental management framework for a region'' (CCME, 2009). The RSEA approach is focused on strategies for regional development that outline and then actively move toward desirable development futures.

Adaptive Management (AM) has also been developed as an approach for addressing complex environmental issues where decisions must be made despite uncertainty, limited scientific experience, and conflicting agendas of multiple stakeholders (Holling, 1978; Walters, 1986). Like SEA, AM too requires a regional perspective for appropriately framing environmental issues. Environmental assessment is ideally conducted within the context of the institutions, governing agencies, and stakeholder communities that both shape, and are affected by, development and policy (e.g. Larsen and Gujer, 1997). It is widely recognized that AM strategies must have certain characteristics in order to be effective. Among those characteristics are a conceptual framework (model) that attempts to describe the system in a way that is agreeable to all stakeholders and which acknowledges the critical role and challenge of governance; a survey of possible or existing management strategies; means to monitor and evaluate the effectiveness of these strategies; and a willingness to learn and adapt over time (e.g. Gunderson, 1999; Lee, 1999; NRC, 2004; Pahl-Wostl et al., 2010). These are not easily accomplished. In fact, the task of properly coordinating approaches such as SEA or AM has been recognized as a significant challenge (e.g., Bina, 2007; McLain and Lee, 1996).

Despite the practical difficulties in executing SEA or AM approaches, moving toward strategic environmental assessment can yield distinct benefits. In particular, a mixture of project-focused environmental impact assessment and more strategic planning-based regional assessments has been discussed as a way to begin to address collective and cumulative impacts (Cooper and Sheate, 2004). Project-focused assessment provides detailed information on individual impacts while planning-based assessment helps to put those impacts into a regional context. Simple regional analyses that account for the extant natural and built landscape and that use readily available, pertinent data could be used for making relatively rapid assessments of alternative policies and their environmental effects. At the very least they may indicate areas that warrant further study and eliminate certain options that are clearly inconsistent with regional concepts of environmental protection and development. They may also increase decision-maker awareness with respect to how development and policy interact on a larger scale. Lastly, they may help to identify policies that are infeasible given current regulatory resources.

The environmental impact assessment approach taken by NY with respect to shale gas development is a good start, but could be improved upon. For example, the shale gas development event framework outlined here can be used to identify deterministic events that may lead to collective, regional impacts on water resources. With these events in mind, "planning-based" regional assessments can be used to evaluate policies that may affect or address these impacts. The simple analyses offered in this study illustrate just this. Within the SRB-NY region, there are a range of potential options for managing water withdrawals and wastewater treatment. The options explored here have been proposed, or are/were in use in other states (PA) where development of Marcellus Shale is underway. Some of these options may be perfectly appropriate for addressing impacts resulting from individual development events, but unsuitable for addressing collective impacts that occur at the regional scale. Policy approaches to water withdrawals provide a case in point. We suggest that it could make sense to adopt a hybrid of currently proposed or used policies that regulate withdrawals differently based on stream size. Compared to other policies, this approach could provide similar levels of environmental protection using fewer government and regulatory resources. For wastewater treatment, results imply that the SRB-NY region has limited infrastructure capacity to adequately handle shale gas development. Promoting the establishment and use of industrial treatment facilities in the region appears to be a reasonable alternative to utilization of POTWs.

While we believe these analyses are valuable for generating insight and discussion with respect to broad policy alternatives, we also acknowledge that several factors have the potential to alter these results. Water withdrawal and wastewater treatment activities would not likely be confined to the region we have analyzed. We used a fixed geographic boundary when, in fact, boundaries will be defined by benefit/cost analyses associated with factors such as transportation, facility rates, and regulatory requirements. We also made assumptions related to water use and wastewater recovery per well, water withdrawal rates, and water quality associated with wastewater. All of these parameters are subject to change over time and with geographic location. Nevertheless, it is clear that each option has advantages and disadvantages under various conditions. As these conditions change, or as more information is known about the ranges that can be expected of these parameters, simple analyses like these can be repeated and revised. To be clear, it is not our intent to suggest specific optimal policies or to predict future development, but rather to illustrate the potential of strategic regional assessment approaches for identifying alternative policies that are appropriate for collective impacts related to complex, distributed development associated with shale gas.

As shale gas development increases, regions without previous history of extractive industry will have to assess and develop new management approaches. At the same time, policies in place in regions where development already exists will have to be re-assessed and revised as more is learned about collective and cumulative impacts of shale gas extraction on water resources. Effective management will likely come down to an ability to recognize key characteristics of a region, and to learn and adapt over time. We argue here that planning-based assessments of policy alongside and in coordination with project-focused environmental assessments are needed to identify region-appropriate strategies for managing shale gas development. We provide examples of relatively simple, regional scenario analyses to assess potential water withdrawal and wastewater treatment policy in the face of collective environmental impacts in NY. Such exercises can help to generate discussion about important tradeoffs between development, environmental protection, and governance, and help to guide and bound decision-making processes. An emphasis on deterministic impacts, combined with a semi-quantitative approach to assessing governance and the capacity of a region to support various levels of shale gas development, may help move managers and policy makers toward strategic environmental assessments that go beyond the project level and provide insight into preferred strategies for managing complex, distributed development so as to provide desired economic benefits while minimizing environmental consequences. More broadly, this approach illustrates the importance of regional characteristics of water resources in defining effective management strategies for shale gas development across the globe.

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Appendix A. Supplementary data

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