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Evolving shale gas management: water resource risks, impacts, and lessons learned†

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Unconventional shale gas development promises to significantly alter energy portfolios and economies around the world. It also poses a variety of environmental risks, particularly with respect to the management of water resources. We review current scientific understanding of risks associated with the following: water withdrawals for hydraulic fracturing; wastewater treatment, discharge and disposal; methane and fluid migration in the subsurface; and spills and erosion at the surface. Some of these risks are relatively unique to shale gas development, while others are variations of risks that we already face from a variety of industries and activities. All of these risks depend largely on the pace and scale of development that occurs within a particular region. We focus on the United States, where the shale gas boom has been on-going for several years, paying particular attention to the Marcellus Shale, where a majority of peer-reviewed study has taken place. Governments, regulatory agencies, industry, and other stakeholders are challenged with responding to these risks, and we discuss policies and practices that have been adopted or considered by these various groups. Adaptive Management, a structured framework for addressing complex environmental issues, is discussed as a way to reduce polarization of important discussions on risk, and to more formally engage science in policy-making, along with other economic, social and value considerations. Data suggests that some risks can be substantially reduced through policy and best practice, but also that significant uncertainty persists regarding other risks. We suggest that monitoring and data collection related to water resource risks be established as part of planning for shale gas development before activity begins, and that resources are allocated to provide for appropriate oversight at various levels of governance.

Environmental impact

This critical review assesses our current scientific understanding of a variety of water resource risks associated with shale gas development, with a focus on the United States, and the Marcellus Shale, in particular. We also review and discuss how various stakeholders, including governments, regulatory agencies, industry, and others, have responded to these risks through practice and policy. Adaptive Management, a structured framework for addressing complex environmental issues, is discussed as a method for reducing polarization of important discussions on risk, and to more formally engage science in policy-making, along with other economic, social and value considerations.

Introduction

Unconventional natural gas extraction, particularly from shale, has captured the attention of global policy makers, energy and natural resource managers, and environmental advocates. There is good reason for this. Shale gas is expected to raise world technically recoverable gas reserves by 47%,[1] is thought to be plentiful on almost every continent, and has transformed the United States into the largest producer of natural gas in the world.[2] Some suggest this shale gas boom is a bridge to a more sustainable energy future that provides abundant and geologically distributed energy with environmental advantages relative to current alternatives such as coal.[3] Others view the environmental impacts from shale gas development, on water resources in particular, as being too uncertain and risky.

The modern shale gas "boom" originated and continues in the United States (US). The single largest gas producing play at present is the Marcellus Shale underlying portions of the states of Pennsylvania (PA), Ohio (OH), West Virginia (WV), and New York (NY). Other major gas plays in the US currently include the Haynesville, located in the states of Texas (TX) and Louisiana (LA), the Barnett in TX, and the Fayetteville in Arkansas (AR). Shale gas development in other parts of the world remains tentative. Development or exploration has begun in some countries such as Canada, Argentina, Poland, and China, while

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other countries have chosen to wait or ban development (*e.g.* France, Bulgaria). In the meantime, as more is learned about the environmental, social, and economic costs and benefits, various stakeholders from both within and outside the US are trying to understand the lessons learned.

Observed impacts and potential environmental risks associated with shale gas development have been delineated and described for some time.[4,5] A number of reports[6,7] and recent reviews[8,9] have documented and synthesized available information on various shale gas-associated risks, especially with respect to impacts on water resources, and with a general focus on the Marcellus Shale. Major environmental concerns in the subsurface receive intense media attention, and include risk of accidents or failures that result in fluid migration from well bores into surrounding shallow drinking water sources. Above the surface major concerns persist regarding accidents or failures associated with spills and leaks of waste fluids and chemicals, compounded by fears associated with insufficient chemical disclosure of hydraulic fracturing additives. Unintended impacts associated with stormwater runoff are also a concern. In terms of planned activities that are an integral part of shale development, concerns exist with respect to water withdrawals from ground and surface sources, and wastewater treatment, disposal and discharge.

To address environmental risks posed by shale gas development requires identification of the scope of potential risks; the data needed to assess those risks; policies and practices applicable to shale gas development activities; and mechanisms for adopting policy revisions that respond to new information in a timely and appropriate fashion. Such an exercise resembles Adaptive Management (AM). The AM process is a structured, iterative decision making process that can be well suited for environmental management challenges in which decisions are made in the context of significant uncertainty, limited scientific experience, and conflicting agendas of multiple stakeholders.[10,11] Such a formal decision making process does not exist at the federal level in the US, but similar frameworks have been explicitly applied to shale gas development at the state level[5] and abroad. In Canada, for example, the province of Quebec has utilized a Regional Strategic Environmental Assessment (RSEA) to "inform the preparation of a preferred development strategy and environmental management framework"[12] regarding shale gas.[13] In the European Union, Strategic Environmental Assessment (SEA) has been put forward as a means to address complex environmental activities and to formulate region-appropriate plans and policies.[14] Throughout this discussion, we will examine whether the *ad hoc* regulatory approach often taken in the US has been adequate to respond to risks associated with shale gas, or whether more formal decision making frameworks such as AM are necessary or beneficial.

Assessment and decision-making frameworks such as AM are difficult to execute in practice for a variety of reasons. In the case of shale gas development, cumulative and/or collective impacts may arise from the interaction of multiple activities taking place over time and space, thus complicating risk assessment even when individual activities are safe and relatively risk-free. Furthermore, risks and impacts associated with shale gas must be analyzed within the context of other activities that are or could be conducted. For example, road salt application, and industrial or extractive activities, including construction, agriculture, and coal mining, all have potential environment impacts similar in some ways to shale gas development. Regional and local factors are also important considerations for analysis of environmental risk. Water resource risks in the dry, warm landscape of north Texas may be qualitatively and quantitatively different than in the humid and seasonally variable US northeast. When environmental risks and impacts are regional, it follows that governance and regulatory approaches may also be regional. It is critical for decision-makers at all levels to understand what aspects of shale gas development may represent universal risks present anywhere drilling occurs, and what aspects may be caused or influenced by regional geology, hydrology, climate, infrastructure, and social and economic conditions. In short, management of shale gas development, like many complex activities, is a challenge. It is likely that any assessment of risk will be either incomplete or applicable to a limited set of contextual conditions. Still, many governments must make decisions about whether and how to proceed, and reviews such as this may help to populate difficult discussions with more accurate information regarding what we do and do not know.

This review will focus on water resource related risks, particularly those relevant to the Marcellus Shale where a majority of peer-reviewed studies have been conducted, but with reference when appropriate to other shale plays in the US. We will build on previous reviews of risks associated with wastewater treatment, disposal and discharge, as well as fluid migration in the subsurface. We will also discuss risks associated with water withdrawal, stormwater runoff, and spills and leaks of waste fluids and chemicals at the surface. We will discuss why these risks may be important, whether they represent something new or an extension of an existing risk, and what recent scientific literature says about them. Lastly, we discuss the regulatory response to these risks, and the evolution of their management over time. Overall, we provide an updated picture of risks to water resources presented by shale gas development and, using an AM framework for comparison, discuss whether there is evidence that we have been managing these risks effectively.

Discussion

Water withdrawals

Hydraulic fracturing of shale gas wells requires large volumes of water, between approximately 10 000 and 30 000 m^3, depending on factors such as geology, depth to target formation, and length of laterals (the horizontal portion of the well bore) (Table 1). Water can be withdrawn from either surface or groundwater sources, and purchased from private and public suppliers. When many wells are being developed concurrently, multiple water withdrawals may be occurring simultaneously. Concerns related to water withdrawals generally include adequacy of water quantity for human and industrial uses, particularly in areas susceptible to drought or currently experiencing water stress.[25,26] The

Table 1 Select water management characteristics of prominent US shale gas plays

Shale play	Depth to shale (m)	Water needed[a] ('000 m^3)	Surface water (% of volume used)	Water produced (% of injected)[c]	Water recycled (% of produced)	Water disposed through re-injection (% of produced)	Produced water [chloride] (mg l^{-1})	Produced water [barium] (mg l^{-1})	References
Marcellus	1200–2600	17 (14 to 17)	90[d]	10 to 25	55 to 80	13 to 18	60 000	100–3000	7, 15–19
Barnett	2000–2600	11 (10 to 13)	80	35 to 70	5	"Most"	25 000–110 000	30–500	15, 16, 20–23
Haynesville	3200 –4100	22[b] (14 to 30)	30	<20	5	"Most"	20 000–105 000	100–2200	15, 16, 22 and 23
Fayetteville	300–2100	11					2000		15, 16 and 24

[a] An estimate of water needed for drilling plus fracturing. [b] Does not include water used for drilling, and is estimated from Texas portion of play only. [c] Water produced within approximately 1 year of well completion. [d] The remainder primarily consists of recycled water from previous fracturing operations.

impact on ecosystems due to disrupted water flows is also a major concern.[27] States, and in some cases regional authorities, have taken responsibility for regulating water withdrawals associated with shale gas development.

Some have suggested that water availability in arid regions may restrict shale gas development in part due to competing demands from other users, as well as declining water levels in aquifers stressed by urban and agricultural development.[22] In general, shale-related water withdrawals are small compared to total consumptive uses, especially with respect to irrigation and cooling associated with electricity production.[22,25] However, the timing and specific location of shale-associated withdrawals can create water quantity issues. An analysis of various withdrawal scenarios in the Marcellus, where surface water use predominates, found that small streams (<283 l s^{-1}) were particularly sensitive to withdrawals during seasonal low flow periods.[7] In the Barnett Shale, operators rely on groundwater for 45 to 100% of their supply, depending on the county and proximity to surface water alternatives.[22] This places additional stress on the underlying aquifer system, which already struggles to meet demand from rural and municipal pumping.[20]

Assessing the risks related to water withdrawals is a challenge in part because technology continues to evolve and alter industry fresh water needs. The ability to drill deeper wells, with longer laterals and a greater number of frac stages, has increased the volume of water required per well. At the same time, operators in many plays are decreasing fresh water need by moving toward increased reuse of waste flowback water, particularly in the Marcellus Shale where injection disposal is limited and/or expensive.[17,18,23] Increased recycling of flowback and produced fluids has been made possible by the development of fracturing formulations that can tolerate increased total dissolved solids (TDS) concentrations and other impurities.[9] In the Barnett, the ability to use brackish water rather than fresh water has led to the use of available but previously undesirable groundwater that has no potable uses.[22]

Monitoring and coordinating water withdrawals so that they occur in a sustainable manner is critical to the success and acceptance of shale gas development. Sustainable withdrawal practices include use of large rivers, continual but low rate pumping, and seasonal timing so as to acquire water when supplies are plentiful.[8] Some state and regional agencies have led the way in understanding and regulating water withdrawals and their impacts, most notably in states such as PA and TX with long histories of extractive industry. In PA, the Susquehanna River Basin Commission (SRBC) uses its interstate authority to permit and monitor all shale gas-related water withdrawals within the Susquehanna River watershed, and has prohibited withdrawals in the past during periods of drought.[28] Low flow guidelines have been established that account for seasonal flow variations and human uses, as well as ecological services.[29] In Texas, the Texas Commission on Environmental Quality responds to competing water demands and drought through a priority system that recognizes "senior" water rights of those who first establish a withdrawal for beneficial use, while "junior" water rights to acquisition may be suspended or curtailed.[30] What both of these systems share is the need to identify and define what drought is, both in terms of surface and ground water, as well as an effective course of action to prevent emergencies related to water quantity. Thus, careful monitoring of stream flows, groundwater, and water withdrawals is needed to supply the data to support water management decisions. Not all states have such robust systems. The authority, experience and resources of regulating agencies differs from state to state, depending largely on how each state's water rights are structured in general. Kulander[30] provides a deeper discussion of state water rights and their relationship to water acquisition for hydraulic fracturing and shale gas development. Overall, areas without previous oil and gas experience should revisit the nature of their authority over withdrawals and put in place monitoring systems that can establish what sustainable human and ecological flows should be.

Wastewater treatment, discharge, and disposal

As soon as drilling commences, and especially after hydraulic fracturing, the wastewater challenge begins. Waste fluids from shale gas development activities include drilling muds, flowback, and produced water or brine. The volume of waste fluid requiring management per well depends on physical properties of the geological formation, and can vary by almost an order of magnitude depending on shale play (Table 1). Between 2010 and 2011, approximately 5 000 000 m^3 of Marcellus Shale-associated wastewater was generated in PA alone.[17,18] Evaluation of wastewater chemistry in the Marcellus[5,31–34] has revealed the presence of constituents such as chloride, bromide, calcium, barium, strontium, radium, and iron, many of which tend to increase in concentration over time after initial hydraulic fracturing. These fluids often require treatment for subsequent reuse, disposal, or discharge to the environment. The large volume of wastewater being produced in the Marcellus and in other plays,[21,35] and the level of sophistication needed to adequately treat this wastewater, has stakeholders concerned about risks associated with human and environmental health wherever it is handled and managed.

Options for managing wastewater are varied and are influenced by existing infrastructure, shale properties, economics of gas production, and the political and social climate of a given play.[17,18,36] Wastewaters may be treated on-site or at public or private facilities for discharge or reuse, or may be sent for disposal *via* injection, often with pretreatment of some kind. Nationwide, it has been reported that 90% of produced brine (from oil and gas) is injected.[21] However, this estimate obscures regional variability (Table 1). Reports have indicated that current wastewater injection rates in the Marcellus range from only 13 to 18% of wastewater produced,[17,18,21] and that this depended largely on where the activity was in relation to Ohio-based injection disposal wells. In contrast, operators in the Barnett Shale in Texas use injection far more, as the state has over 50 000 such disposal sites.[9,21] Discharge of waste fluids without treatment has been shown to have detrimental effects on nearby surface and groundwater in Texas,[37] and to negatively impact vegetation.[38] This is not surprising. TDS concentrations alone are often high enough to warrant careful management of gas wastewaters (Table 1).

Treatment of wastewater for reuse or discharge is the most common management strategy in the Marcellus, and occurs *via* one or more of three general management pathways: publically owned sewage treatment works (POTWs); private, centralized wastewater treatment facilities (CWTs); and on-site treatment approaches. More complete descriptions of the options available for wastewater treatment are provided elsewhere.[36,39] Wastewater that is treated and then discharged to surface waters is of concern because of the region's dependence on surface sources for public water supplies, industrial cooling water, and because of the prevalence of high quality, high value fisheries. While such discharges are subject to regulation under the federal National Pollutant Discharge Elimination System,[40] the location and water quality of such discharges remain as important environmental concerns. Even when wastewater is treated, there is evidence that discharges can negatively impact downstream water quality.[41,42] This is because some facilities, particularly POTWs, are not designed to treat constituents such as chloride that can be found in wastewater at high concentrations. Important statistical evidence for regional impacts related to treated discharge was provided by Olmstead *et al.*[6] who determined that, in the Marcellus, discharge from POTWs accepting gas field wastewater led to downstream increases in chloride concentrations in 2011, at least on a seasonal basis. Since then, PA has enacted regulatory changes, such as rules requiring TDS discharge strategies from operators, increased reporting requirements, and establishment of a statewide database for wastewater management information.[43,44] In 2011 the Pennsylvania Department of Environmental Protection (PADEP) asked operators to stop using POTWs as a management option altogether,[45] leading to decreased volumes of wastewater being sent to these facilities. While POTWs are unlikely to be utilized by shale gas operators in the future, research efforts such as those by the Shale Network, US Geological Survey (USGS), US Environmental Protection Agency (USEPA), and others, continue to monitor potential surface water quality impacts, both good and bad.[9]

Wastewater management also entails other risks. For example, researchers recently observed radium accumulating in sediments downstream of one CWT facility in PA, even though effluent dissolved radium was within the established limits.[46] Elsewhere, halides in produced brines have been hypothesized to react with disinfection chemicals during treatment to form disinfection byproducts (DBPs). DBPs can form during normal sewage treatment, but research has shown that CWTs and POTWs accepting shale gas wastewater may generate DBPs at greater concentrations.[47] High wastewater bromide concentrations, in particular, have been linked to DBPs such as brominated tri-halomethanes (THMs) that tend to be more toxic relative to chlorine-based DBPs common in typical POTW effluents.[48] Increasing trends toward reuse in the Marcellus, along with the cessation of POTWs as viable treatment options, help to minimize the risk of DBP formation in CWT and POTW facilities. However, as plays mature, and fewer wells are drilled, the demand for reused fluid may go down, and discharge *via* treatment may become a prominent issue. More work is needed to understand DBP formation and impacts on environmental and human health, and to identify disinfection processes that are appropriate for bromide-containing water and waste streams. Likewise, the fate and transport of radionuclides associated with shale gas waste streams deserves additional research.

An emerging field of research is the identification of tracers and indicators that can be used to track shale gas-derived wastewater and differentiate it from other sources of contamination in both surface and ground waters (Table 2). In the Marcellus Shale region, existing water quality issues such as chronically high TDS concentrations and acidity persist because of historic coal mining and conventional gas extraction. Forensic techniques that can distinguish between various sources of contaminants are desirable in order to better plan for treatment challenges, and to generate effective strategies for reducing environmental impact. In some cases researchers have worked out relationships between shale geology and brine water chemistry.[31,49,50] For example, Barbot *et al.*[31] found that, in the Marcellus, cations tend to correlate with chloride concentration, while barium correlates with geographic location; divalent cations also suggested a Marcellus-specific signature that differed from other brines commonly experienced in PA, although other researchers did not find such a divergent signature.[32] Other monitoring efforts have presented findings on possible surface water quality indicators, including barium, bromide, and strontium.[9] Barium could be an important indicator for the Marcellus, as it is present in shale gas wastes, but not waste associated with coal. Tracers and indicators effective for the Marcellus may not be applicable elsewhere, as they are linked to regional geology and water quality. More work is needed to identify water quality indicators in other plays.

Some researchers have suggested that the risk for potential water resource contamination from, and uncertainty associated with, shale gas wastewater disposal is greater than risks from other pathways.[55] Issues in the Marcellus related to increased chloride, and detection of DBPs in surface waters provide examples of why it is important to continue to assess and study these risks in order to reduce uncertainty and develop continually improving management strategies. As PA data shows, practices that have been used extensively in the past, such as POTW use for treatment of conventional brine, may not be appropriate for unconventional waste. While treatment technologies exist for unconventional waste streams, there is a general challenge associated with the rapid pace and scale of development that can occur. What risks a region is likely to face depends on a mix of factors, including existing infrastructure and its location in relation to development, as well as evolving policies at the state and federal level. Overall, however, further research is needed on the link between geology and wastewater chemistry, and the treatment challenges that might arise in a particular region. This will require more monitoring, the sharing of data over space and time, and a willingness to adapt

Table 2 Examples of tracers or indicators in fluids associated with shale gas development in the Marcellus Shale; not necessarily applicable to other plays, but illustrative of possible geochemical tools

Indicator	Application	Rationale	Reference
Barium (Ba)	Differentiate between Marcellus and coal source	$[Ba^{2+}]$ high in Marcellus brine, low in coal mine drainage due to high $[SO_4{}^{2-}]$	9
	Differentiate between Marcellus and conventional brines	$[Ba^{2+}]$ high in Marcellus relative to conventional brine	31
Bromide (Br)	Differentiate between Marcellus and coal source	$[Br^-]/[Cl^-]$ ratio high in Marcellus relative to conventional brine	9
Strontium (Sr)	Differentiate between Marcellus and conventional brines	$[Sr^{2+}]/[Cl^-]$ ratio high in Marcellus relative to conventional brine	9 and 31
Chloride (Cl)	Unconventional wastewater discharge (even treated) into surface water	$[Cl^-]$ high in Marcellus wastewater relative to surface water, and is not treated at some facilities	6
$^{228}Ra/^{226}Ra$	Differentiate between Marcellus and conventional brines	$^{228}Ra/^{226}Ra$ ratio low in Marcellus relative to conventional brine	34
$^{87}Sr/^{86}Sr$	Differentiate between Marcellus and other sources such as coal drainage or conventional brines	$^{87}Sr/^{86}Sr$ ratio of Marcellus has unique range	49
$\delta^2H/\delta^{18}O$	Unconventional wastewater discharge (even treated) into surface water	δ^2H and $\delta^{18}O$ values higher in unconventional-derived waters relative to natural surface waters	46
δ^2H–CH_4/$\delta^{13}C$–CH_4	With additional data on parameters such as δ^2H and $\delta^{18}O$ of formation water, as well as concentration and fractionation values for higher-chain hydrocarbons; differentiate between Marcellus-derived methane and other thermogenic and biogenic sources	Marcellus-derived methane has unique geochemical "fingerprint" relative to other methane sources	51–54

policy and best practice to region-specific issues. Establishment of databases, such as the PADEP database on wastewater information, and the Shale Network database,[56] will be crucial for spotting cumulative, regional impacts that may occur slowly over large areas, even when operators are complying with existing laws. Where possible, monitoring efforts should focus on water quality indicators and tracers that can differentiate between possible contaminant sources.

Methane and fluid migration in the subsurface

Much of the public debate on shale gas development has focused on risks to groundwater. The possibility of groundwater contamination evokes fear, in large part because it is a process that is poorly understood and outside the control of the average citizen, and because it is perceived to be potentially catastrophic.[57] Vertical drilling through aquifers and gas bearing strata, particularly without proper casing and cementing controls, can lead to fluid migration and contamination of nearby water wells. Debate continues as to the role of hydraulic fracturing itself in the occurrence and severity of such accidents, particularly when geologic formations overlying target geologies are not well characterized. The risk of fluid contamination due to gas well drilling, and methane contamination more specifically, is not new.[58] Industry, engineers, and scientists have been discussing the role of proper cementing and pressure control in the well annulus for decades.[59] That being said, it remains important to understand under what conditions fluid migration might occur, so that private and public groundwater supplies can be protected. Risks associated with fluid migration during modern shale gas development are reviewed elsewhere.[9] Here, we will summarize some of the key points of this review, as well as highlight the most recent literature on methane migration in the Marcellus, and policy updates across the country.

The presence and/or migration of methane into potable groundwater is not a health hazard *per se*, but methane can be explosive if allowed to vent into and accumulate in confined spaces. When evaluating the risk of methane migration as a result of shale gas development, high quality baseline information is critical. Sampling and research throughout the Marcellus region has shown that methane can be naturally present, sometimes at high concentrations (*e.g.* in West Virginia,[60] New York,[61] and in National Park units[62]). In some areas methane migration may be complicated by a variety of natural and man-made circumstances. For example, a 2007 investigation into possible migration of methane from an underground gas storage field in PA could not identify a specific contamination source despite using a variety of tools, including stable isotope ratios.[54] The authors acknowledged a variety of challenges, including natural microbial methane inputs, mixing of different types of gases within the subsurface, and inadequate geochemical characterization of the study area.

Work underway in the Marcellus is aiming to improve understanding of groundwater geochemistry, specifically how physical factors may correlate with increased natural methane, and why. McPhillips *et al.*[63] look at baseline methane and well-water quality information in a county in the Marcellus region of NY and find that methane concentrations do not significantly correlate to topographic features or conventional gas wells in the area. They do find, however, that methane concentrations were significantly higher in groundwater dominated by dissolved sodium compounds, indicating long residence times during groundwater–bedrock interactions as possible controls. An on-going effort by the USGS[64] should provide additional baseline methane data in southern NY. Other studies conducted by the USGS include a description and evaluation of water and gas well logs, with an attempt to identify gas shows in various geological groups that might overlay target formations, and their impact on geochemistry in associated water wells.[65] They note that both gas and water wells hit gas pockets, and that greater knowledge of geology overlying target formations may provide insight in how best to cement and control for gas shows.

Recent studies have come to various conclusions regarding the likelihood and impact of methane migration as a result of shale gas drilling and hydraulic fracturing. As Vidic *et al.*[9] describes, one set of studies came to the conclusion that the average and maximum methane concentrations in water wells increased within 1 km of active shale gas wells compared to wells farther away, although such studies were conducted without baseline data and in an area with a known and highly publicized case of leaking well casings.[53,66] Other studies have argued against both the interpretation and methods of these studies,[67,68] while some have conducted water quality surveys of their own, without finding a significant relationship between methane concentration and distance to active wells.[51,69] Boyer *et al.*[70] combined baseline and post-drilling data for private water wells, and also found no statistical evidence for contamination *via* methane or other constituents. Given the sum of evidence available so far, it seems most likely that active gas drilling does not in itself lead to systemically higher methane concentrations in nearby water wells. That being said, accidents do occur that can significantly impact local groundwater environments, with some researchers suggesting cementing and/or casing problems at 1 to 3% of wells drilled.[9,71]

In other shale plays such as the Fayetteville in Arkansas[72] and the Barnett,[73] researchers found no evidence to suggest that distance to shale gas wells alone is an explanatory factor for poor groundwater quality. Authors do suggest, however, that urban development in the Barnett, combined with shale-related water withdrawals, may together be placing stress on the aquifer and leading to increased concentrations of arsenic and barium. Based on such studies, it seems that different factors drive methane concentrations in different places, and that increases in groundwater constituents are possible when accidents occur, and when aquifers are subject to the cumulative stresses of urban and shale gas development in the absence of proper planning and regulation. What underlies variations in the relationship between shale gas development and groundwater quality is a major question that needs to be addressed on a local and regional basis, and highlights the need for more geological data to complement hydrology and water quality studies.

To prevent fluid migration as a result of shale gas development, policy makers at various levels and in different plays have been revising and strengthening oversight of cementing and casing. At the federal level, the Bureau of Land Management (USBLM) has recently proposed new rules for federal lands that increase well construction oversight, although it is unclear what the final rules will be.[74] At the state level, researchers point out that casing and cementing are "heavily regulated by almost all states with shale gas development," but also note a large degree of heterogeneity in the manner in which such regulations are applied.[75] Requirements for, and regulation of, intermediate casing (a third casing string between production and surface casing) is becoming more common. Recent trends in construction rules stipulate some form of pressure testing for casing, as well as proof that cementing has cured properly, prior to hydraulic fracturing (see Richardson *et al.*[75] for examples of specific references to Arkansas, Texas, and West Virginia policies). Other protective measures, such as setbacks from private water wells, and prohibition of drilling within certain aquifers that serve as major municipal water supplies, have been established or proposed in some states.[5] Indeed, the American Petroleum Institute, an industry group, has promulgated best practice guidance that includes many of these protective measures,[76] but such guidance is not law. More research, dialogue, and policy-making is needed to ensure that best practices become the norm so that accidents, however rare, become even more so.

Spills and erosion at the surface

Shale gas development is an industrial activity that entails risks shared by other industrial activities, construction, and agricultural development. For example, spills at the surface during shale gas development might result from transportation of chemicals and waste fluids to and from the well pad, and from storage, mixing, injection, and recovery of fluids during drilling, hydraulic fracturing and production. Spills are unintended releases of chemicals, wastewater, or other hazardous materials, and can result from accidents, poor management and planning, and illicit dumping. They may be small – a few liters – and relatively harmless, or they may be major events that threaten or pollute nearby wetlands or streams. Likewise, risks associated with erosion may threaten nearby surface waters with increased suspended sediment loads, and may damage wetlands, issues that have been associated with conventional gas drilling in the past.[37,77] Erosion is a risk because construction of well pads, access roads, and pipeline infrastructure involve the clearing and grading of land that is then exposed to stormwater and altered hydrological patterns. These risks from spills and erosion are not unique to shale gas development; however, the pace and scale of shale gas activity can cause them to become significant.

Tracking spills through a system of self-reporting is one way to try to understand the risk these events pose. Some states, such as NY[78] and Utah,[79] have systems in place for tracking spills from a variety of industries and activities. For spills associated with shale gas development, a similar tracking system is available in PA, where the PADEP maintains a public database of violations issued to operators in the Marcellus.[80] While not a direct measure of environmental impact, violations help to provide important components of risk analysis by contributing data on how frequently spills occur and, in some cases, the conditions that might have led to spills. A study of PA's violation database conducted in 2012 found that spills on land plus those that impacted surface water in some way together made up the largest number of environmentally concerning incidents recorded.[81] While many spills appeared to be small and contained, posing no or minimal environmental risk, some were large, with demonstrable negative impact on nearby water resources. The authors noted that preparation and training of inspectors is key to proper oversight. A more recent analysis[71] again found spills, defined as any unintended release of fluids or waste at the surface, the most common violation type issued, with 5 to 20 violations issued for every 100 wells drilled between 2008 and 2013 (Fig. 1). Unfortunately, a vast majority of violation entries had insufficient data to determine spill size, location, cause, or environmental impact. What was clear was that some operators had better violation records than others, and that adherence to best management practices occurred at some times, and not others. It may be possible to understand the risk presented by spills better in the future if more descriptive information were to accompany violation entries. For example, it may be good to know how often inspectors believe particular Best Management Practices (BMPs) should have been used, or how prevalent a particularly bad practice is, so that this data can be turned into meaningful regulatory action.

Risks associated with erosion can also be tracked using violation databases, as well as broader sampling and modeling approaches. As Fig. 1 shows, infractions in the PA Marcellus related to erosion were found at up to 26 out of every 100 wells drilled during the first six months of 2008, and on average at 8 out of every 100 wells drilled across all years studied. As with spills, data needed to assess the exact causes and impacts of these events is lacking in most cases. To address these unknowns, some researchers have tried to monitor surface water quality in regions where shale gas development has expanded rapidly. Water quality parameters such as total suspended solids (TSS) and total dissolved solids (TDS) can act as indicators of cumulative impact provided adequate baseline data are available to account for natural and existing man-made variability. In the Marcellus, increased well pad density was found to correlate to increased regional TSS, although a statistically significant link to precipitation and stormwater could not be made.[6] Well pad placement in the landscape, particularly distance from surface waters and runoff flow paths, has also been raised as an important consideration to mitigate erosion-related water impacts, both in the Marcellus[82] and the Barnett.[83] For instance, McBroom *et al.*[83] reported that erosion rates from poorly sited well pads could be orders of magnitude greater than those from nearby land uses such as forestry. Researchers stressed that land use changes and their impacts on surface waters were an understudied issue, with inadequate regulation and enforcement, and that BMPs needed to be targeted to the specific hydrology of each location.

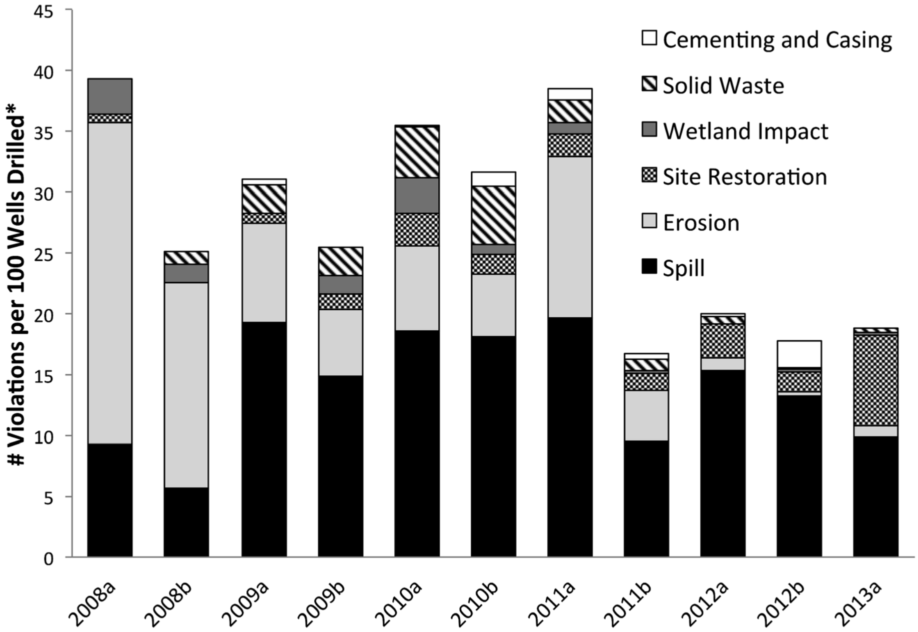

Fig. 1 Number of violations issued by PADEP that represent individual events of concern with respect to risks to water resources, by six month time increments (* violations normalized to number of wells drilled within the same 6-month period) (figure derived from B. G. Rahm, L. R. Bertoia, V. S. Vanka and S. J. Riha, unpublished work).

Baseline water quality monitoring is one way that a region can prepare for assessing surface water impacts related to spills and erosion. The Susquehanna River Basin Commission, an interstate agency with regulatory authority, has established more than 50 water quality stations, collecting real-time information on basic parameters such as conductivity, as well as periodic data on a broader suite of parameters.[84] While such water quality information is valuable, both for monitoring shale gas development and for other scientific purposes, it will likely take years of data collection to make conclusions about any alteration of water quality. In NY, the USGS has compiled regional surface water quality data and has noted past monitoring efforts in which active oil and gas development, as well as road salt and urban sewage effluents have been shown to increase specific conductance.[42] For now, monitoring efforts remain a challenge because of the dispersed nature of shale gas drilling, and because of technical limitations in collecting real-time information on anything other than basic water quality parameters. Still, rigorous monitoring is capable of providing insight on regional water quality trends over time, and may help to indicate when more detailed water quality sampling and investigation is warranted.

Regulations with the aim of preventing risks associated with spills and erosion at the surface of well pads exist in some states where conventional drilling has occurred in the past. Still, evidence that rapid shale gas development has the potential to impact regional surface water quality suggests that policy makers should revisit these risks and acknowledge their importance in protecting water resources. One possibility is to treat shale gas sites more like construction sites, where stormwater management and chemical handling is often more strictly controlled.[83] NY, for example, has proposed a specific permit for stormwater discharges that addresses some of the unique challenges associated with modern shale gas sites.[85] In general, best management practices should focus on prevention and containment of spills and sediments, and should be tailored to the phase of development (construction, hydraulic fracturing, production) that a particular well pad is in.[86] Monitoring and reporting are also important for addressing spill and erosion risks. As with BMP's, rules pertaining to monitoring should account for the development phase a well is in, and might also stipulate what needs monitoring and where.[87]

Policy and adaptive management

Policy and regulation are important aspects of managing risks associated with water resources and shale gas development. Policy is important for ensuring that water withdrawals are conducted safely, that waste fluids, stormwater, and hazardous materials are managed effectively, and that well pads and well bores are constructed properly. Still, policy making in the US occurs at various levels of government, is conducted from different political perspectives, and must work within regions with different physical, social, and economic characteristics. What are the trends in policy making related to shale gas in the US, and what lessons might be learned for regions facing development in the future?

At the federal level, various agencies are involved in regulating shale gas development and, along with elected officials, have been tracking evolving technologies, practices, and water resource issues.[88–91] The USEPA is currently conducting a Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, and has released a Progress Report,[92] while the USBLM has proposed new rules for unconventional gas development on federal lands.[74] It is unclear what the final results of these studies and rule-making processes will be. State-level policies and regulations with respect to shale gas are also evolving. A recent review conducted by Resources for the Future, a non-profit organization, provides the best available summary of what and how states regulate shale gas development, as well as how stringent these regulations are.[75] They illustrate that each state regulates certain aspects of development in its own way, and point out that this can make it difficult to understand which approaches work and why. Interestingly, underlying drivers to heterogeneity in gas regulations across states could generally not be identified, suggesting that policies might have arisen somewhat arbitrarily over time. In response to the shale gas boom some states (Colorado, Ohio, Pennsylvania, West Virginia) have made broad revisions of their oil and gas codes while others (Arkansas, Montana, Texas) have made modest, targeted changes. At a local level, particularly in states traditionally associated with strong local controls, there is on-going debate about local government's authority to regulate and restrict shale gas activities happening within its jurisdiction. These contentious debates are playing out in NY[93] and PA.[94] This likely reflects the fact that extractive industries often have economic benefits that are regional or national in nature, with some locally negative environmental and social impacts.[95]

Indeed, it seems that the important debate is not whether there are water resource risks that should be regulated, but rather at what governmental level regulation should occur.[96] Federal agencies such as the EPA are best equipped to provide guidance and regulation on universal risks that concern stakeholders everywhere, regardless of the state they live in or the nature of the geology under their feet. Well construction standards, chemical disclosure requirements, and wastewater treatment guidelines are examples of areas where federal rule-making could be helpful in setting a regulatory "floor" – the guaranteed minimum level of protection. For risks more regional in nature, such as withdrawals of surface or ground water, or specific BMPs for spill and erosion prevention, a one-size-fits-all federal approach might be cumbersome and inefficient. State policy, on the other hand, could be used to address play-specific or regional risks, and to go beyond the federal regulatory floor where stakeholders and/or science deem it appropriate. The question of where regulation is most effective is and ought to be an openly contested question, both in the US and elsewhere.

Governments in the US at all levels have responded to shale gas development. Some have created rules where before there were none, and some have revised rules to better suit current conditions. This response shows *de facto* policy evolution. However, the response to shale gas in the US has generally fallen short of the careful, structured dialogue and "process of continuous improvement" that some suggest is needed,[7,97,98] and which is the hallmark of decision making frameworks such as Adaptive Management. In order for AM-type strategies to successfully inform complex environmental policy and decision-making, they must generally involve certain steps, and conform to certain conditions: stakeholders and policy makers must be able to discuss and roughly agree on the risks or issues they are going to address; they must acknowledge the importance of governance; they must have or be willing to explore multiple management and regulatory options; they must have the authority, means, and capacity to monitor and evaluate the effectiveness of management and regulatory options once they are chosen; and they must have a willingness and mechanism for adapting and revising options in the face of new information.[99–102] How do we move closer to AM, and what are the potential benefits?

In the context of water resource risks related to shale gas development, Fig. 2 illustrates a simplified AM-inspired flow chart for how stakeholders might ideally approach management and policy creation. Step 1 involves acknowledgment that risks exist and that they are worth additional consideration, and it is here that polarized discussions of shale gas too often stall. Some feel that water resource risks are managed well, and that government oversight is not warranted, while others feel that risks are unacceptable and that the occurrence of negative impacts justifies government-imposed bans on development altogether. In truth, there are varying levels of uncertainty surrounding many important risks to water resources, but scant evidence at the moment to suggest that water contamination is catastrophic and/or unmanageable, at least in the Marcellus. Unfortunately, the polarized debate between "good" and "bad" obscures the complexities of the many trade-offs inherent in energy choices, and prevents the dialogue from progressing toward subsequent steps. By the time stakeholders move to step 2, development has often begun, and the ability to plan for and mitigate impacts is supplanted with reactionary policy making without adequate data, a regional strategy, or assessment and adaptation mechanisms. If stakeholders cannot agree on a set of risks of concern, they are unlikely to be willing to invest resources in studying them. Refusal to study risk may seem justified for those who feel that greater regulation should be avoided, particularly at the federal level. However, this is a narrow way to address such an important and complex policy challenge. Shale gas development is a relatively new activity, and so it is understandable that our knowledge of risks is incomplete. Stakeholders have the responsibility to better understand these risks over time, and making commitments to study them is a necessary part of that process.

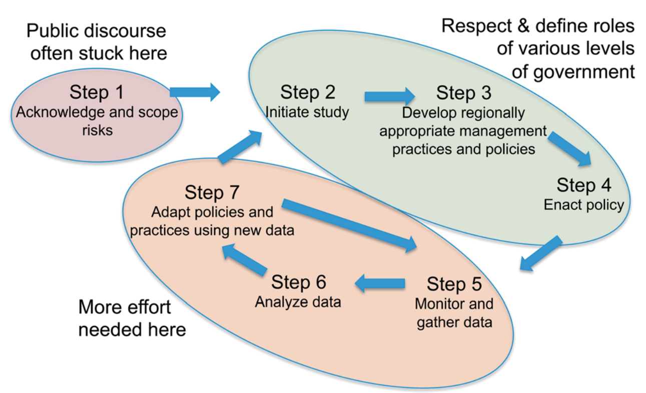

Fig. 2 Example of an AM-type flow chart that might be used for decision making with respect to shale gas development policy.

In the US, all levels of government have important roles to play at steps 3 and 4 (Fig. 2), and it is critical that stakeholders communicate with each other about the definition of those roles. The large size and broad authority of the federal government gives it the ability to address general concerns of water resource risks raised by communities, particularly those involving cumulative impacts that go beyond state boundaries and jurisdictions. This may be necessary even when individual activities are conducted safely and in accordance with rules and regulations. Institutions or agencies with broad interstate, regional, or federal missions are also needed so that transparent analyses can be conducted with the input of all involved stakeholders, especially when stakeholders may not otherwise have any responsibility to engage each other. State agencies are often intimately familiar with local conditions, and are best placed to respond to regional challenges with the kinds of appropriate strategies needed for step 3.

Unfortunately, too little attention is paid to steps 5 through 7, which are critical for AM strategies to be effective. In some cases, such as the PA database on violations, data is being collected. But to do this takes political will, time to establish reporting systems that operators can become familiar with, and money to hire staff to build and maintain database architecture. Political will might be conflicted or lacking because of fear of public reproach should information on government performance and environmental risk be made publically available. There is also the worry that moves toward greater transparency and more stringent oversight and compliance might drive industry away, along with its potential economic benefits. It is unclear if this has happened in the US. As our discussion of risks related to ground and surface water quality shows, baseline information – before shale gas development begins – is generally needed to assess subsequent impacts. Planning, therefore, is critical. However, revenues that might support such planning efforts are often derived from shale gas activity itself, meaning that money to hire adequate planners, inspectors, and scientists only comes after the activity they are meant to plan for begins. Thus, many agencies put the cart before the horse by design. More broadly, funding cuts exacerbate the fact that state agencies often do not have staff, time, or mandate to engage in organized data collection efforts, or to analyze such data in a way that might inform adaptive policy. Indeed, some have argued that the provision for adequate staff and compliance penalties remains among the largest challenges of minimizing environmental impact due to shale gas development, particularly in states where such activity is new.[7,97,103,104] An ideal approach would be to have a clearly articulated plan for what data to collect, how that data will help evaluate risk, and a policy mechanism by which such data can inform future regulatory revisions. Most importantly, funding needs to be made available for appropriate levels of staff, which must have enforcement and compliance tools that can bring about desired best practices and management.

The final step in this simplified AM decision-making process is to adapt policies according to new information. There is a tendency for all stakeholders to assume that old oil and gas regulations are good enough, because they have worked in the past. But, as we have seen, shale gas development, particularly its rapid pace and large scale, brings with it new risks, and new variations of old risks. These new and different risks do not necessarily mean that development should stop. But, it is critical that all stakeholders commit to continued discussion of risks, and policies that might address them. Adaptive policies should use recent science and stakeholder experience to build a more realistic picture of risk, and should balance this with other stakeholder considerations and values. Ultimately, the AM process forms a circle, and the collaborative definition of important issues begins again.

The lessons to be learned from shale gas development in the US are complicated, as is the potential role and advantage of using frameworks such as AM. While many states appear to manage water resource risks associated with shale gas well, some are still catching up, even while development is occurring. Although it makes sense that regional characteristics should drive better-adapted rules, there is insufficient evidence to conclude that this is what actually happens in practice. Polarized, politicized debates prevent the kind of rule-making and pragmatic discussions that we ought to be having about such complex issues. The result is that rules rarely get articulated until they are absolutely necessary, are highly reactive in nature, and reflect the risks that are of popular concern rather than those that may actually exist. AM approaches could solidify support for research, assessment, and planning, could serve to normalize the need to set aside funding for staff before development begins, and could ease some of the conflict that accompanies discussions around the necessity to revisit and revise old policies and management paradigms.

Conclusion

Data from a variety of studies across various shale plays indicates that negative impacts and risks do exist with respect to shale gas development and water resources. Impacts depend on management choices, incentives to engage in best practices, regulations, and oversight, and can be both exacerbated or substantially reduced by these same factors. Risks to water resources are also a function of the context in which unconventional activities take place. Other forms of development, as well as extant infrastructure, also stress ground and surface waters, and influence development and management choices faced by unconventional gas operators. Cumulative impacts, resulting from a set of activities over time and space, may occur even when individual activities are conducted safely. Baseline data and monitoring is essential for understanding when impacts occur, and what they may be caused by. From evidence available on the Marcellus Shale and other plays, water resource risks evolve and change over time as stakeholders adapt and respond to economic, technological, social, and political pressures. Therefore, it is difficult to say to what extent risks and impacts experienced in the past will continue in the future. Additionally, our current understanding of risks and impacts is biased towards the Marcellus Shale, where a majority of peer-reviewed studies have been focused. Thus, our ability to extrapolate to other plays, regions, and countries is limited.

Research conducted on other plays, within varying contexts and within different regulatory regimes, should help create a clearer picture of national trends.

Management of water resource risks by government agencies at all levels has evolved *de facto* over time. However, it is difficult to say whether this evolution has been "adequate." The recalcitrant polarization of the subject suggests that we could collectively meet this challenge in a more effective way. Adaptive Management or similar strategies could help to lessen polarization and deadlock in public discourse on policy responses to shale gas development by: helping to establish consensus risks; solidifying support for research, assessment and planning; providing a rationale for funding important aspects of governance before activity begins; and decreasing resistance to adaptive policy-making that seeks to combine state-of-the-art science with regional economic, social, and value considerations.

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