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Regional Variation in Water-Related Impacts of Shale Gas Development and Implications for Emerging International Plays

Meagan S. Mauter,*,[†] Pedro J. J. Alvarez,[‡] Allen Burton,[§] Diego C. Cafaro,[∥] Wei Chen,[⊥] Kelvin B. Gregory,[#] Guibin Jiang,[∇] Qilin Li,[‡] Jamie Pittock,[○] Danny Reible,[◆] and Jerald L. Schnoor[¶]

[†]Chemical Engineering and Engineering & Public Policy, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, Pennsylvania 15213, United States

[‡]Department of Civil and Environmental Engineering, Rice University, Houston, Texas 77005, United States

[§]School of Natural Resources and the Environment, University of Michigan, Ann Arbor, Michigan 48109, United States

[∥]School of Chemical Engineering, Universidad Nacional del Litoral, Santa Fe, Argentina

[⊥]College of Environmental Science and Engineering, Nankai University, Nanka, Tianjin, China

[#]Civil & Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

[∇]Chinese Academy of Sciences, China

[○]Fenner School of Environment and Society, Australian National University, Acton, Canberra 0200, Australia

[◆]Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, Texas 79409, United States

[¶]Civil & Environmental Engineering and Occupational & Environmental Health, University of Iowa, Iowa City, Iowa 52242, United States

The unconventional fossil fuel industry is expected to expand dramatically in coming decades as conventional reserves wane. Minimizing the environmental impacts of this energy transition requires a contextualized understanding of the unique regional issues that shale gas development poses. This manuscript highlights the variation in regional water issues associated with shale gas development in the U.S. and the approaches of various states in mitigating these impacts. The manuscript also explores opportunities for emerging international shale plays to leverage the diverse experiences of U.S. states in formulating development strategies that minimize water-related impacts within their environmental, cultural, and political ecosystem.

INTRODUCTION

Although the environmental impact of fossil fuel production has long been a topic of academic and public policy discussions, there are few historical precedents for the complete restructuring of the energy landscape caused by horizontal drilling and hydraulic fracturing. The celerity of technology diffusion, particularly in regions with little present-day conventional oil and gas activity, rekindles the discussion of environmental impacts of oil and gas extraction. It also raises questions about regionally specific impacts of unconventional extraction technologies and how these rapidly developing regions can most effectively respond to emerging risks and impacts.

From an environmental inventory perspective, a hydraulically fractured horizontal well in one location has similar characteristics to any other. The extraction process begets similar carbon emissions, land area demands, and water usage. The leap from environmental inventories to environmental impact analysis, however, requires that these impacts be contextualized within the region's existing human and environmental stressors. Detailing the specific environmental attributes of major shale plays is therefore essential to reducing the uncertainty associated with estimates of shale gas impacts and identifying regionally effective strategies for mitigation.

A critical attribute of U.S. unconventional resources is their widespread geographic distribution. The diversity of hydrospheres, land surfaces, and biospheres across the most developed U.S. shale plays leads to regionally specific stressors. For example, water resource stress in Texas' Barnett play is much more pronounced than it is for Pennsylvania's Marcellus play. The regional specificity of resources and stressors also muddles communication among researchers examining the impacts of development, and has generated significant tension between regional and federal agencies seeking to promote and regulate the safe and sustainable development of unconventional oil and gas resources.

There is growing recognition of the need for new impact assessment strategies that account for local and regional variability when estimating water-related impacts. While this article does not fully answer that call, it frames water-related risks and impacts of shale gas development in a regional context, emphasizing the underlying conditions that exacerbate

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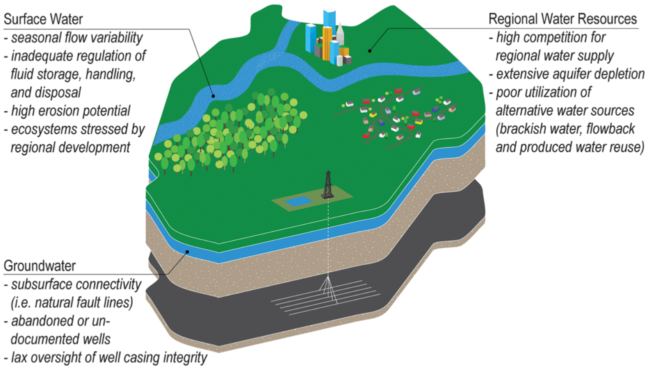

Figure 1. Regional characteristics and policies increasing the risk of water-related impacts associated with shale gas extraction.

or mitigate water-related risks (Figure 1). Next, this work describes impact avoidance and mitigation strategies appropriate at the local, regional, and national levels. Finally, we explore opportunities for emerging international shale plays in Argentina, Australia, and China to leverage the diverse experiences of U.S. states in formulating development strategies that minimize water-related impacts within their environmental, cultural, and political ecosystem.

■ THE REGIONAL CONTEXT FOR WATER IMPACTS

Increased Regional Competition for Water Supply. The specific water demand, or water usage per foot of a hydraulically fractured well is typically about 12,000 L/meter, or 10−20 million L of water per well.[1] In many regions, over most seasons, this demand for water will not account for a significant fraction of total local water consumption. Elsewhere, however, hydraulic fracturing operations introduce new water demands on top of historical water use patterns (Figure 2A), opening the possibility for water competition, price increases, aquatic biodiversity loss, and accelerated groundwater and surface water depletion.

In the arid Eagle Ford play of south Texas, for instance, extended droughts and continued population growth have strained water resources and raised the visibility of freshwater consumption for energy production. Although overall water use in the Eagle Ford play is a small fraction of the total annual water consumption of the region, it can account for of the majority of water consumption in some rural, low population counties.[2] In addition, hydraulic fracturing water needs, by themselves, are expected to exceed sustainable groundwater withdrawal rates in portions of the Eagle Ford play.[1] These conditions will likely be repeated in other areas such as the Golf San Jorge Basin of Argentina, the Cooper Basin of Australia, the Monterrey Basin in California, and the Denver-Julesburg Basin in CO where hydraulic fracturing activity may be constrained by water availability or accessibility.

Maximizing the use of low-quality or impaired waters in hydraulic fracturing fluids will alleviate some of the stress imposed on fresh water resources. Brackish groundwater is an underutilized resource throughout the world and, though poorly characterized for storativity and geochemical parameters, U.S. Geological Survey's 1965 survey suggests that U.S. brackish water resources are geospatially consistent with major U.S. shale basins (Figure 2B).[3] The total dissolved solids (TDS) of brackish groundwater resources are in the range of 1000−30 000 mg/L, concentrations that render water unsuitable for direct potable use and most agricultural uses. However, brackish groundwater is generally compatible with friction reducing agents and other frac water components that perform satisfactorily in the presence of high TDS (35 000−50 000 mg/L range), which allows this water to be used directly or blended with freshwater.[4,5]

An alternative to brackish water exploitation is to maximize the reuse of produced water.[6] Reuse of produced water refers to the practice of using treated or untreated produced water as the makeup water for subsequent hydraulic fracturing fluid. Significant differences in disposal options, as well as produced water quantity and quality parameters, have led to large differences in reuse rates among U.S. plays. High disposal costs in the Marcellus are a key driver for the attainment of nearly 90% reuse of Marcellus produced water,[5,7] while the vast majority of produced water in the Barnett is disposed of in deep injection wells.[2] Constraints to full reuse include water production volume that may exceed the injected volume, as is common in the Barnett, as well as potential issues with scale formation, biofouling, and limited performance of the frac fluid additives in high TDS makeup water. As mentioned above, a combination of blending with fresh water and the use of chemical additives designed for higher salinity have facilitated reuse of produced water. Research has now moved toward understanding the operational and logistical constraints to reuse, such as optimizing well placement and drilling schedule to maximize reuse potential.[5,8,9]

Together, the use of poor quality brackish waters and the growing practice of recovery and reuse of produced water will reduce the fresh water demands of hydraulic fracturing. Expansion of such best management practices are currently encouraged by both industry and independent groups supporting sustainable shale development,[10] and may lead to greater public acceptance of hydraulic fracturing[11] and more sustainable development of unconventional resources in water stressed regions.[12]

Impairment of Surface Water Quality. Ecological risks to surface waters are present throughout the well life-cycle and may manifest themselves both locally and regionally. The risks also vary temporally, as development activity like surface water withdraw may only result in a single, brief impact, while the network of roads required for accessing the well pad could increase erosion and sediment runoff for years. Previous work has identified the primary risks to surface water quality as sediment runoff from devegetation, leakage and spillage of chemicals into surface waters, unsustainable water withdrawal, landscape fragmentation, and insufficient treatment of oil and gas wastewater prior to discharge.[13−16] Unfortunately, few sites exist where baseline environmental monitoring has occurred prior to hydraulic fracturing operations commencing.[17] This greatly complicates efforts to quantify impacts, particularly if these operations are occurring in watersheds with preexisting anthropogenic influence and a host of potential ecological stressors.

The surface water risks and impacts associated with unconventional resource development will vary significantly by region.[18] To date, those in the Marcellus region have been most extensively examined.[19−28] This scrutiny has been motivated by the nexus of regionally specific risk drivers such as high gradient terrains that could lead to increased erosion, an abundance of small streams, highly variable in-streamflow rates, and the high salinity of produced water in the Marcellus. Moreover, during the early development of the Marcellus in PA, the state permitted the disposal of hydraulic fracturing

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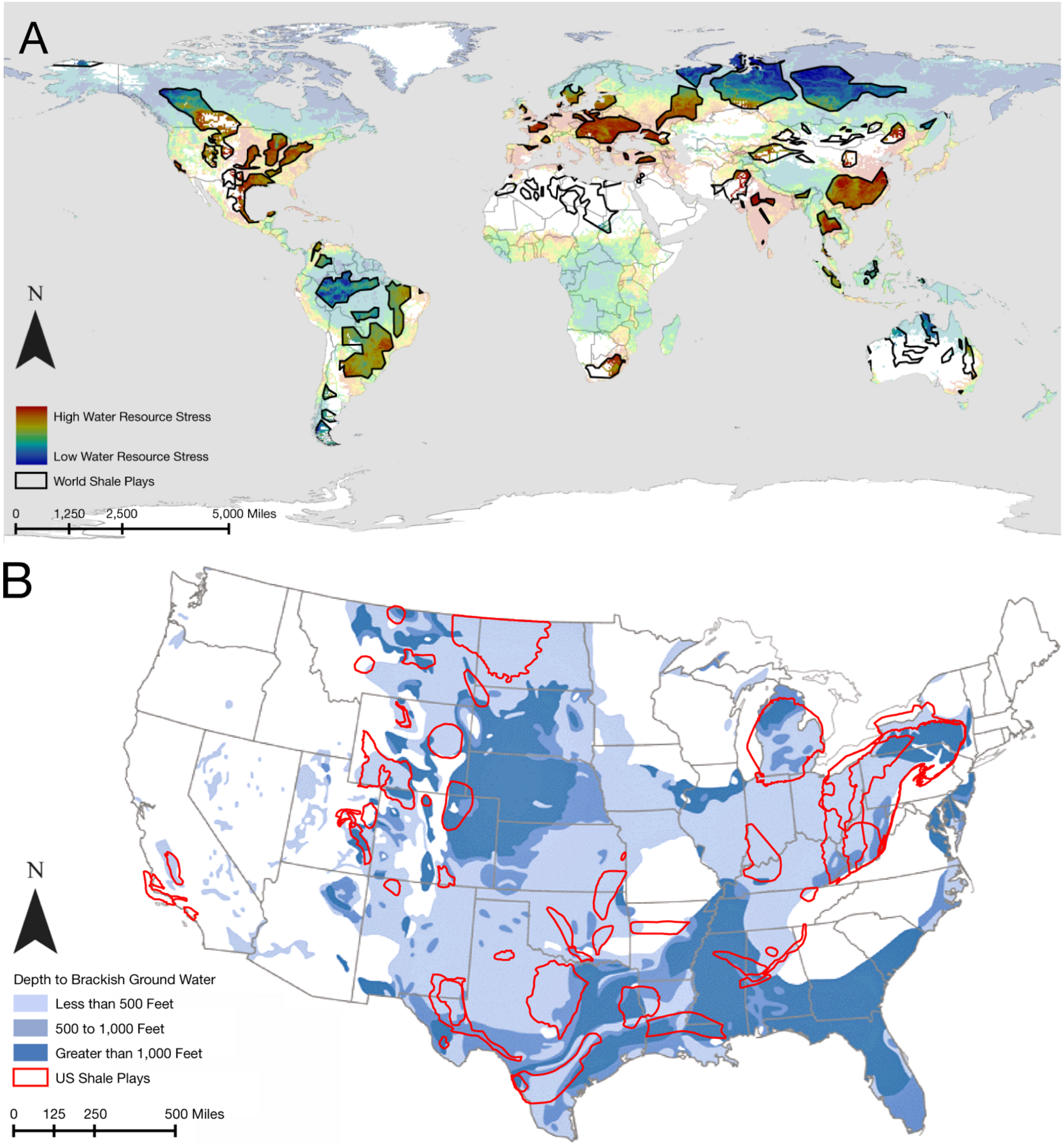

Figure 2. Water Resources and Shale Gas Development. (A) Global threats to human water security[69] and their spatial relationship to major shale plays.[70] White indicates regions with no appreciable river flow, incomplete groundwater assessment, or high data uncertainty. White is not an indicator of low stress. (B) U.S. brackish groundwater (>1000 TDS) resource availability[3] underlying U.S. shale plays.[70] White indicates incomplete assessment of depth to saline water.

brines in municipal wastewater treatment plants. To reduce the human and environmental impacts associated with this practice, energy and production companies have adopted a moratorium on the disposal of produced water in wastewater treatment plants in PA.[22,26,27,29,30]

In the Marcellus and Fayetteville plays, more than 80% of the active gas wells are located within 300 m of drainage areas[17,19] and recent studies have reported a positive correlation between total suspended solids (TSS) and the density of upstream gas wells in both the Marcellus and Fayettville.[19,23] One study of Denton County, TX estimated the annual sediment loss from a natural gas well pad to be 54 t/ha.[31] Though this value is typical of construction sites, a high regional density of shale gas pads has the potential to result in significant cumulative impact to surface waters.[23] Best management practices, including drilling multiple wells per pad, establishing setbacks, practicing "double-ditching" in gas infrastructure development, laying impermeable mats, and designing tailored revegetation schemes are critical to mitigating some of the effects of sediment erosion.[32]

Successful mitigation practices and policies will need to address both local impacts as well as the cumulative regional impacts of development. Michigan, for example, has a Wetland Protection Program and a Water Withdrawal Assessment Tool (WWAT) that, combined with a comprehensive permitting program by its Department of Natural Resources and the Department of Environmental Quality, aids in the consideration of local environmental impacts and source controls. Such programs allow for effective evaluations of potential ecological impacts from fracturing operations by considering

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their proximity and density in relation to sensitive and vulnerable wetlands and fisheries.

Risk of Groundwater Contamination. Risks of groundwater impairment are associated with accidental release or mishandling of chemicals or wastewater at the surface, as well as the potential for hydraulic fracturing fluid, formation brine, or natural gas to migrate into shallow freshwater resources. Although great effort is put toward isolating the well-bore from surrounding formations, it has been suggested that accidental migration might occur through faulty well casing or cementing of the well, through natural or induced fractures intersecting abandoned wells, or through natural or induced connectivity between subsurface layers, especially in regions with vertical fault lines.

The regional differences in subsurface geology create variable risk profiles between U.S. shale plays. Transport of fluids from the formation to a shallow aquifer is typically mitigated by low hydraulic conductivity in the underlying formations and large vertical distances between the source and potential recipient formation. However, research suggests that connectivity between formations varies within and between plays. One study demonstrated that elevated concentrations of thermogenic methane in shallow groundwater was inversely correlated to distance from hydraulically fractured gas wells[33,34] while another suggests that it was correlated with topography.[35] Conversely, no thermogenic methane was found in groundwater in the vicinity of gas extraction wells in the Fayetteville shale.[36] Although methane is not regulated as a toxin, it poses fire hazards through vapor intrusion, and is a more potent greenhouse gas than carbon dioxide.

The potential contamination of shallow groundwater with formation brines or fracturing fluids has been investigated through both modeling[20,37] and direct observation,[36,38] but remains a contested subject of ongoing research.[39] Considering the high number of hydraulically fractured wells in the U.S., there is relatively little direct evidence for groundwater contamination by formation brines or fracturing fluids.[38,40] Unfortunately, study of those sites where contamination may have occurred has often been restricted by the terms of legal settlements. In Pennsylvania, for instance, several shale gas drilling operations were halted in 2009 due to concerns regarding groundwater contamination, but comprehensive investigation providing explanations of the events leading to reports of contamination have not been published in the peer-reviewed literature.[41,42] Perhaps the strongest conclusion to be made at this point in time is that the impact of hydraulic fracturing on groundwater is heavily debated and the outcome appears to depend on local geological characteristics.[43]

Despite little evidence for short-term fluid migration to shallow formations, the presence of natural migration pathways and the potential for increased connectivity through abandoned wells presents an unknown and long-term risk of groundwater contamination by formation brines, natural gas, or fracturing fluid.[37] Compromised well casing, cement, and abandoned wells that were inadequately plugged are purported to be the primary cause of methane contamination of groundwater.[33,38,43] In regions where both conventional and unconventional oil and gas are produced, the proximity of shale gas wells to historical and poorly sealed producing or abandoned wells may lead to unforeseen connectivity and risk of groundwater contamination. Such connectivity among oil and gas wells has been reported up to 1.2 km surface distance in Texas[44] and Alberta, Canada.[45]

Water quality monitoring before, during, and after hydraulic fracturing will help to assess the risk to groundwater, characterize potential contamination pathways, and provide reliable exposure data to inform epidemiological studies that protect both land-owners and energy companies.[41,46] Additionally, a minimum distance between hydraulically fractured wells and those utilized for drinking water, as well as other producing or nonproducing wells, should be considered to minimize the potential for human exposure and environmental release. Minimization of this risk will benefit from the development of robust methods for monitoring the integrity of the well casing and detection of hydraulic communication between wells.[32]

■ LEVERAGING U.S. EXPERIENCE TO MINIMIZE WATER RISKS IN EMERGING INTERNATIONAL SHALE PLAYS

The regional stressors that determine water management strategies and the potential for deleterious water-related impacts from hydraulic fracturing in the U.S. are likely to have analogues in other emerging shale plays around the world. As these plays are developed, there is opportunity for both operators and policy makers to learn from and improve upon the U.S.'s past experience in managing water-related risks to the environment.

Argentina. Conventional natural gas reserves in Argentina have decreased by 50% over the past decade due to reduced exploration activity and increased demand for natural gas. As a result, the country has become dependent on natural gas imports, the cost of which threatens continued economic development. In this context, there is current pressure to develop Argentina's estimated 802 trillion cubic feet (tcf) of recoverable resources, the second largest unconventional shale gas reserves in the world.[47] The Argentinian national energy company, Yacimientos Petrolíferos Fiscales (YPF), adopted the perspective that the most expedient route for development is via contractual agreements with multinational companies experienced in unconventional resource extraction.

Approximately one-half of Argentina's reserves are in the Vaca Muerta Shale formation around the Neuquén Basin. This geological formation covers four different provinces and has an estimated surface of 30 000 km^2 and an average depth greater than 2400 m.[48,49] Promising geological features, including high total organic carbon, high pressure, and thick shale layers (100−400 m), are coupled with attractive regional features including low population density and extensive existing natural gas infrastructure originally constructed to collect conventional oil and gas resources. Together these attributes make future development in the Neuquén Basin promising, but minimizing impacts associated with rapid development will require regionally conscious implementation of best management practices and the enforcement of Argentina's recently developed regulations governing shale gas extraction.

The governance structure for oil and gas resources in Argentina is concentrated at the provincial level, with provinces granting exploration permits and overseeing operations. Provinces also have the authority to increase the stringency of environmental regulations beyond those issued by the Federal Secretary of Energy. Neuquén Province, for instance, recently augmented its oil and gas legislation with a provincial decree regulating water acquisition and management associated with hydraulic fracturing.[50] Specifications include the prohibition of groundwater use as a hydraulic fracturing fluid, full disclosure of chemicals contained in the fracturing fluid, requirements for water storage, and directives surrounding the treatment and disposal of oil and gas wastewaters. No limits were established for surface water withdrawal rates, but companies will need to report the volumetric water use on a per well basis. Despite this enhanced regulatory framework, there is public concern over lackluster enforcement in a country that is in need of new investment and energy resource development.

Though the U.S. adopted a similar state-led approach to regulation of the unconventional extraction industry, this approach imposes higher regulatory burdens on operators in basins like the Neuquén where four provinces have jurisdiction. Public concerns have increased pressure to craft comprehensive national regulation addressing the specific surface water and air pollution impacts associated with unconventional natural gas development, but short of this step, intrabasin coordination is imperative.

Increased regional competition for water resources is another likely impact of shale gas development in the semiarid Neuquén Basin, where annual rainfall averages around 7 in. Although the average water availability per person is adequate within the basin, regional water stress is frequently observed.[51,52] Water consumption by local agriculture irrigation is particularly high, with a total of 150 000 ha of pome fruit production. Large-scale development of shale gas may give rise to conflicts between the agricultural and extraction industries.[53] In this region, maximizing produced water reuse and enabling the use of impaired waters such as brackish groundwater or other wastewaters may help mitigate these conflicts.[54]

Although the extent of the Neuquén Basin's resources are still being assessed, Argentina hopes that shale gas development will help to meet its growing energy demands and reduce the costs associated with natural gas imports. As development of Argentina's unconventional natural gas resources progresses, policy interventions will be critical to minimizing conflicts over water demand and ensuring the implementation of regionally applicable best management practices within the water management life cycle.

Australia. As many as 396 tcf of technically recoverable shale gas resources underlie nearly one-quarter of Australia's land area.[55] The first well was drilled in the Cooper Basin in South Australia in 2011, and interest in developing unconventional gas is likely to accelerate to meet increasing national energy demands, as well as those in the Asia-Pacific region. Efforts to reduce the environmental and social impacts of shale gas exploitation will benefit from recently developed regulatory guidelines for coal seam methane as well as lessons learned from the U.S. experience.[56,57]

Land and water use are key concerns in Australian shale gas development. In terms of land use there is apprehension over the potential impacts on Australia's unique biodiversity in light of of road, pipeline, and port development. Except for Indigenous people in the Northern Territory, Australians landholders gain no royalties from mineral exploitation and have little incentive to support resource production. Land use conflict is likely since most of the land overlying shale gas deposits are owned by either Indigenous communities or by state governments, as conservation reserves or leased for livestock production.

Water is also publicly owned in Australia and is governed under the 2004 National Water Initiative policy.[58] Under this policy all major water use from surface or groundwater is capped within sustainability limits and formalized in tradable access shares. However, implementation of this policy by state governments is lagging, especially in economic sectors associated with mineral production and energy generation.[59] For example, while coal seam gas producers in New South Wales are required to purchase groundwater access licenses within local caps, this is not required in Queensland. Exploitation of shale gas in arid Australia is likely to rely on groundwater access and will be constrained by water scarcity and competition with other water users.

Although Australia lacks specific shale gas legislation at this time, much of Australia's national policy on shale gas development is likely to be shaped by recent policy addressing another unconventional resource, coal seam gas. Exploitation of coal seam gas has sparked intense community and political conflict, with similar concerns around land access and impacts on water quality and availability. Under pressure to upgrade regulatory institutions managing coal seam gas, state governments consulted U.S. academic, environmental, and industry experts in the design of a policy framework.[56] The resulting policy statements, though specific to coal seam gas, may place Australia in a stronger position to regulate incipient shale and tight gas industries.

The first is a 2013 endorsement of a "National harmonized regulatory framework for natural gas from coal seams".[60] This framework is intended to enable Australian governments to develop well integrity, water management and monitoring, hydraulic fracturing and chemical use "regulatory regimes [that] are robust, consistent and transparent across all Australian jurisdictions".[61] In parallel, a 2013 amendment extends the Environment Protection and Biodiversity Conservation Act to enable the Federal Government to directly regulate for the "protection of water resources from coal seam gas development and large coal mining development".[62] Finally, an expert scientific committee was appointed to undertake regional strategic environmental assessments to inform the federal Minister for the Environment on regulation of proposed developments.[63,64] Continued revision of regulation to reflect emerging science on the water-related risks of unconventional resource development in the U.S. will be critical to ensuring sustainable development of these resources in Australia.

China. China holds the world's largest shale gas reserves, with estimates of technically recoverable shale gas at 1115 tcf.[65] Geological complexity and limited pipeline infrastructure, however, make shale gas an uncertain near-term solution for China's fast rising energy demand. In the mid- to long-term, China would benefit from leveraging international experience in shale gas development and implementing best-management practices to minimize water-related risks.

Technical challenges to shale resource exploitation are imposed by formation depth and complex subsurface geology. The shallowest shale oil and gas formations in China are typically deeper than those in the U.S. For example, Sichuan Basin shale gas formations are typically 2000 to 3500 m below the surface, whereas the typical depth of shale gas formations in U.S. are normally from 800 to 2600 m.[66] Deeper formations present greater technical challenges and higher drilling, fracturing, and production costs for the operators. In addition to depth, major reserves in the mountainous terrain of southwestern area of China (Sichuan, Yunnan, and Guizhou Provinces) are crosscut by faults that lead to complex subsurface geology and seismic hazards.[67,68] These technical conditions are likely to elevate the cost and environmental risks

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associated with of unconventional well development. The use of predrilling seismic characterization and real-time monitoring of the fracturing process may help to mitigate some of these risks.

Water resource constraints may also limit the pace of unconventional extraction in China. China is highly resource limited in terms of available fresh water on a per capita basis. The Tarim Basin, covering nearly a million square kilometers holds a major fraction of the natural gas resources in China and is collocated with well documented and severe water stress.[69] Should development in the Tarim Basin proceed, Chinese legislators will need to balance the water demands of hydraulic fracturing and the already pressing concerns associated with existing water stress.

Development of China's unconventional oil and gas resources will need to advance with a regulatory framework that enables economic exploitation of the resource while minimizing the potential for adverse environmental impacts. This calls for a national plan for exploration, vigorously enforced rules and regulations, and effective mechanisms for collaboration between government agencies such as the Ministry of Land Resources, the Ministry of Water Resources, the Ministry of Environmental Protection, and the many levels of local government. In certain areas, enforcing rigorous protective measures for the environment during the exploitation of natural resources is nontrivial. Development of shale gas in China also faces other barriers, such as high population density (and thus limited land accessibility), less developed technology and infrastructure, a lack of experience among operators and associated service companies, and even the relatively low-level of education level in rural areas. All these factors combine to create a challenging venue for economical and environmentally sustainable shale gas market in China. Nonetheless, these unique challenges provide the opportunity for technical collaboration between China and the U.S. as both countries seek to reduce local air pollution and global greenhouse gas emission burdens.

■ IMPLICATIONS

U.S. shale plays have been developed under vastly different geological, hydrological, environmental, regulatory, and infrastructure resources. These different plays provide a useful reference for framing the variance expected between international shale plays and identifying the major categories of water-related risks. The U.S. experience also suggests that minimizing water-associated impacts of shale gas development will require a contextualized understanding of the unique regional water stressors that unconventional fossil fuel development poses. Developing and communicating regionally appropriate solutions will be imperative to maximizing the human, environmental, and economic benefits of resource extraction internationally.

Emerging shale gas regions will benefit from improving on the U.S. experience to reduce the water-related risks and unintended impacts. Dissemination of experience is likely to occur via two pathways, though both come with potential pitfalls. The first is active knowledge transfer by the companies managing drilling operations. For instance, the nationalized Argentinian energy company YPF has contracted with a U.S. company to develop wells in the Neuquén Basin. Experience managing the complex logistics and breadth of water-related risk associated with unconventional natural gas extraction has the potential to speed development and minimize impacts. While experience may translate fluidly across plays with similar water-related stressors, well-established companies in the shale development space may also be less adaptive to emerging risks unique to the newly developing region. This phenomenon was observed when operators with experience in the Barnett began shale gas development in the Marcellus, but were under-prepared to manage oil and gas wastewater given the paucity of injection wells in the region.

Another method for disseminating experience is to adapt aspects of regulatory structure from developed shale gas regions. Within the U.S., this process has been aided by a nonprofit, multistakeholder venture known as the State Review of Oil and Natural Gas Environmental Regulations, or STRONGER. A cooperative venture between the U.S. Environmental Protection Agency and the Interstate Oil and Gas Compact Commission, STRONGER has assisted states in reviewing oil and gas regulations and recommending programmatic improvements. The drawbacks of this approach are that legislative recommendations are voluntary and regulatory enforcement, which is often dependent on the expertise of the inspectors monitoring the drilling process, can vary considerably. In the U.S., implementation of voluntary STRONGER recommendations has been incomplete, and without federal regulation under mandatory statues like the Clean Water Act, water-related risks persist. A second organization, the Center for Sustainable Shale Development, offers an independent, third-party evaluation process to certify companies that achieve and maintain rigorous performance standards.

In addition to using the U.S. experience as a reference point, there are a number of opportunities for international plays to surpass the U.S. in protecting water resources during unconventional natural gas extraction. For instance, in countries where mineral rights are held by the state, regulators can work with drilling companies to select drilling locations that maximize resource return while minimizing water-related risk. Large leases may also provide companies greater opportunities for unitization of drilling processes and of more efficient infrastructure use, water recycling, and risk management. Stronger regulatory oversight, such as full disclosure of fracturing chemicals, is another important opportunity.

As the international community evaluates objectives for extraction of shale gas resources, they will face a major challenge in creating viable regulatory, legal, and technical frameworks that support best practices for operational implementation of shale gas extraction. Leadership from both industry and the U.S. government may be needed to ensure that economic benefits of shale gas development are realized without significant regional impairment of water resource quantity and quality.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mauter@cmu.edu.

Notes

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Biographies

Meagan S. Mauter is an Assistant Professor in the departments of Chemical Engineering and Engineering & Public Policy at Carnegie Mellon University.

Pedro J. J. Alvarez is the George R. Brown Professor and Chair of the Department of Civil and Environmental Engineering.

Allen Burton is Professor of the School of Natural Resources & Environment and Director University of Michigan Water Center.

Diego C. Cafaro is an Associate Professor of Chemical and Industrial Engineering at the School of Chemical Engineering in the Universidad Nacional del Litoral, and Assistant Researcher at the Argentine National Scientific and Technical Research Council.

Wei Chen is a professor in the College of Environmental Science and Engineering at Nankai University.

Kelvin B. Gregory is an Associate Professor of Civil & Environmental Engineering at Carnegie Mellon University with research interests in environmental microbiology and biotechnology.

Guibin Jiang is a professor at Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences.

Qilin Li is an Associate Professor in the Department of Civil and Environmental Engineering and the director of the Water and Energy Research Center at Rice University.

Jamie Pittock is Senior Lecturer at the Fenner School of Environment and Society at the Australian National University, Director of International Programs for the UNESCO Chair in Water Economics and Transboundary Water Governance, and Program Leader for the Australia and United States—Climate, Energy and Water nexus project of the U.S. Studies Centre and Australian National University Water Initiative.

Danny Reible is the Donovan Maddox Distinguished Engineering Chair at Texas Tech University and Director of the Unconventional Production Technology and Environmental Consortium (UpTec).

Jerald L. Schnoor is the Allen S. Henry Chair in Engineering at the University of Iowa where he holds appointments in Civil & Environmental Engineering and Occupational & Environmental Health. Prof. Schnoor is also the co-director of the Center for Global & Regional Environmental Research and the Editor in Chief of Environmental Science & Technology.

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