In This Issue:

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Focus articles are part of a regular series intended to sharpen understanding of current and emerging topics of interest to the scientific community.

Hydraulic "Fracking": Are Surface Water Impacts An Ecological Concern?

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Abstract—*Use of high-volume hydraulic fracturing (HVHF) in unconventional reservoirs to recover previously inaccessible oil and natural gas is rapidly expanding in North America and elsewhere. Although hydraulic fracturing has been practiced for decades, the advent of more technologically advanced horizontal drilling coupled with improved slickwater chemical formulations has allowed extensive natural gas and oil deposits to be recovered from shale formations. Millions of liters of local groundwaters are utilized to generate extensive fracture networks within these low-permeability reservoirs, allowing extraction of the trapped hydrocarbons. Although the technology is relatively standardized, the geographies and related policies and regulations guiding these operations vary markedly. Some ecosystems are more at risk from these operations than others because of either their sensitivities or the manner in which the HVHF operations are conducted. Generally, the closer geographical proximity of the susceptible ecosystem to a drilling site or a location of related industrial processes, the higher the risk of that ecosystem being impacted by the operation. The associated construction of roads, power grids, pipelines, well pads, and water-extraction systems along with increased truck traffic are common to virtually all HVHF operations. These operations may result in increased erosion and sedimentation, increased risk to aquatic ecosystems from chemical spills or runoff, habitat fragmentation, loss of stream riparian zones, altered biogeochemical cycling, and reduction of available surface and hyporheic water volumes because of withdrawal-induced lowering of local groundwater levels. The potential risks to surface waters from HVHF operations are similar in many ways to those resulting from agriculture, silviculture, mining, and urban development. Indeed, groundwater extraction associated with agriculture is perhaps a larger concern in the long term in some regions. Understanding the ecological impacts of these anthropogenic activities provides useful information for evaluations of potential HVHF hazards. Geographic information system–based modeling combined with strategic site monitoring has provided insights into the relative importance of these and other ecoregion and land-use factors in discerning potential HVHF impacts. Recent findings suggest that proper siting and operational controls along with strategic monitoring can reduce the potential for risks to aquatic ecosystems. Nevertheless, inadequate data exist to predict ecological risk at this time. The authors suggest considering the plausibility of surface water hazards associated with the various HVHF operations in terms of the ecological context and in the context of relevant anthropogenic activities.* Environ Toxicol Chem 2014;33:1679–1689. © 2014 SETAC

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Introduction

The world's energy marketplace is shifting, and natural gas is becoming more prominent. This shift is driven by globally abundant natural gas reserves (Figure 1) and newfound extraction technologies such as high-volume hydraulic fracturing (HVHF) operations targeting shale gas (and oil) formations, coupled with mounting health, environmental, and geopolitical concerns over alternatives such as oil, coal, and nuclear energy sources. This shift includes, for example, new jobs, increased economic activity, and a more diverse and stable energy base. The shift may also reduce emissions of

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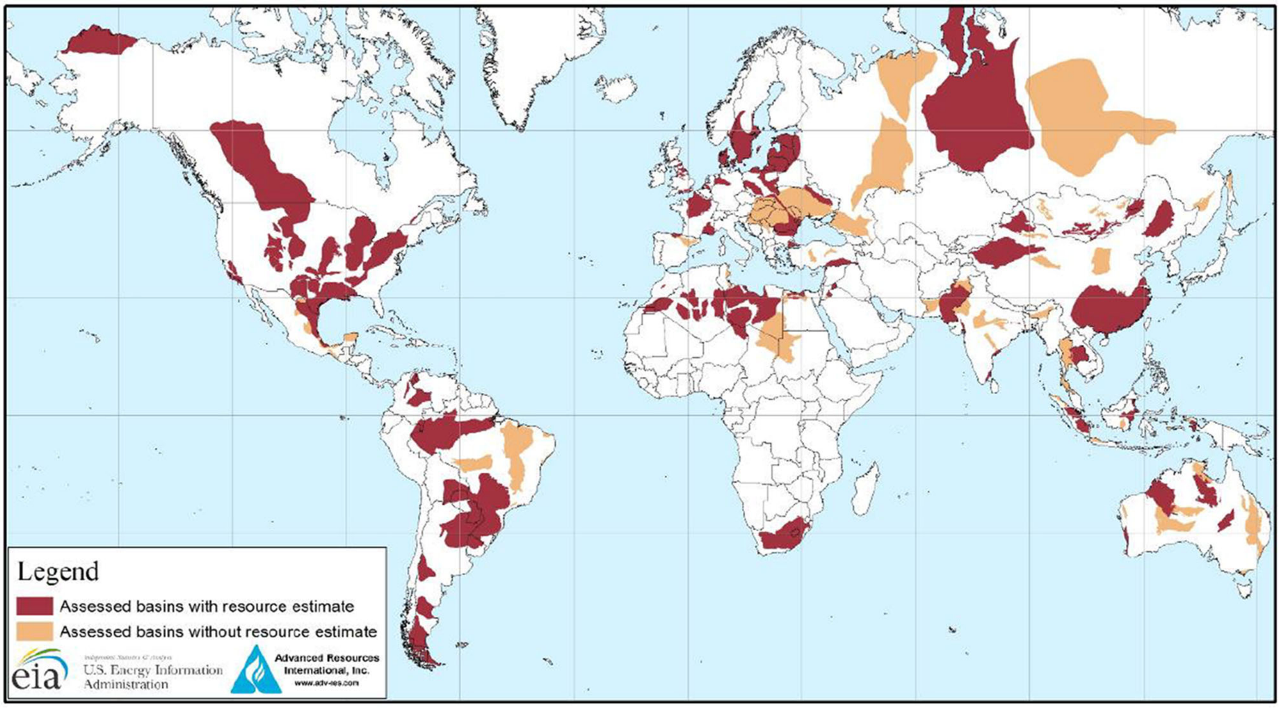


FIGURE 1: Areal extent as indicator of potential geographic footprint. Technically recoverable shale oil and shale gas resources from across 41 countries [22].

CO_2 and other greenhouse gases, as well as criteria air pollutants such as mercury. Contentions and challenges do exist, however, and many of these require better understanding of the environmental risks that may occur throughout the life cycles of natural gas extraction or other energy technologies.

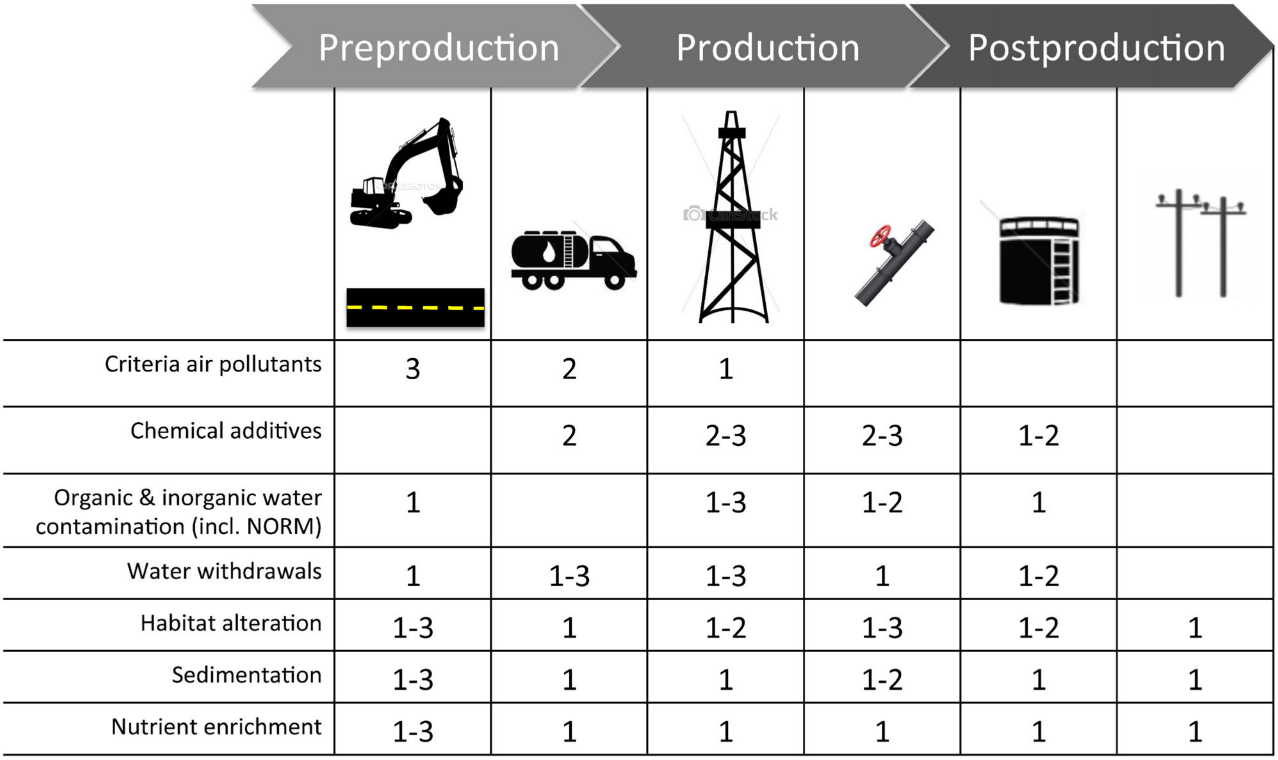
The present *ET&C* Focus article addresses the plausibility of primary environmental concerns (Figure 2) related to surface waters (and their groundwater interactions) that may occur if inadequate precautions are taken for HVHF operations and their siting. Many of these concerns are similar to those associated with other anthropogenic activities, such as silviculture, agriculture, mining, and urban development. In the United States, approximately 20% (442 million acres) of the land area is cropland, and 3% (69 million acres) is urban [1]. Environmental concerns associated with surface water and groundwater are driven largely by the sensitivity of the ecoregion to perturbations and the density of the HVHF operations.

Most of the attention on HVHF operations has related to the potential for groundwater contamination from the hydraulic fracturing fluid additives and the release of methane into groundwaters and, more recently, the atmosphere [2]. Activities associated with HVHF that potentially impact surface waters can be grouped into 3 areas: 1) spills and releases of produced water and chemicals from hydraulic fluids, 2) erosion from surface disturbances, and 3) altered surface water flows resulting from excessive surface water or groundwater withdrawals. Nevertheless, oil and gas development, whether from conventional or unconventional reservoirs, may also contribute to erosion, carrying loads of sediments and/or chemicals of concern into waters [3–8]. Onsite precautions during drilling operations are needed to lower the risk of chemical spills caused by tank ruptures, blowouts, equipment or impoundment failures, overfills, vandalism, accidents (including vehicle collisions), ground fires, or operational errors.

Hydraulic fracturing fluids contain a range of additives, including proppants, gelling agents, solvents, antiscalants, surfactants, corrosion inhibitors, and biocides (see Table 1). Some additives are known to be toxic; but toxicological data are limited regarding other additives, and not all degradation pathways and products of reactive additives are known. Furthermore, there is a potential for trace contaminants to be leached from the fractured shale and transported to the surface with the flowback and produced brine. Drill cuttings that are stored onsite and high-brine produced waters are 2 of the biggest threats to surface water quality.

Why the Concern?

When are these potential problems a significant ecological concern for surface waters? The nature of hydraulic fracturing means that ecological impacts will manifest in a variety of manners (Figure 2). From the construction of new roads and infrastructure to the use and release of harmful pollutants, the resulting activities may have profound effects on a region's ecosystems and organisms; and these effects may change from the near term to the longer term. The assessment and management of such surface water impacts will undoubtedly benefit from a better understanding of their plausibility for



	Preproduction		Production		Postproduction	
Criteria air pollutants	3	2	1			
Chemical additives		2	2-3	2-3	1-2	
Organic & inorganic water contamination (incl. NORM)	1		1-3	1-2	1	
Water withdrawals	1	1-3	1-3	1	1-2	
Habitat alteration	1-3	1	1-2	1-3	1-2	1
Sedimentation	1-3	1	1	1-2	1	1
Nutrient enrichment	1-3	1	1	1	1	1

FIGURE 2: Ranges indicate a dependence on the ecological context and/or operational controls. Potential for ecological hazards (1 = low potential, 3 = high potential). NORM = naturally occurring radioactive material.

potential adverse effects in the context of ecosystem sensitivities and impacts of other anthropogenic activities. In this section, we briefly outline the most pertinent ecological impacts.

Rapid and concentrated HVHF development near small streams has the potential to degrade surface water quality, just as many anthropogenic activities do. The US Environmental Protection Agency's (USEPA's) evaluations of State 305b reports suggests that the majority of aquatic life impairments are the result of nonpoint-source runoff in human-dominated watersheds [9]. A ranking of the top causes of stream impairment (from greatest to least) is as follows: pathogens, sediment, nutrients, and organic enrichment/oxygen depletion. The USEPA lists the national probable sources of impaired streams as (from greatest to least) agriculture, unknown sources, atmospheric deposition, hydromodification, urban area–related runoff, municipal discharges, natural/wildlife, other habitat alterations, resource extractions, and silviculture. Evaluations of fracturing operations in central Arkansas found that surface water–quality violations at site operations were caused by erosion (22%), illegal discharges (10%), and spills (10%). Impacts to receiving water streams and their biota were significantly linked to well and pad densities, rates of installation, distance from well pads to stream channels, pipeline density, and a combination of roads/pasture and well density proximity. One critical factor is that gas wells are often located adjacent to small streams. In shale basins with a high density of HVHF operations, numerous well pads may be located within the same watershed, thus compounding the cumulative impacts of industrial activity within that particular watershed. To date, most federally funded research on environmental impacts of hydraulic fracturing has focused on contamination of groundwater and drinking water sources. However, fewer data are available to address concerns associated with surface water and terrestrial ecosystems. The ongoing studies of Entrekin (S. Entrekin, unpublished data) (see sidebar *Assessment of High-Volume Hydraulic Fracturing Impacts on Streams: A Case Study Example*) highlight the need for comprehensive scientific evaluations of the cumulative impacts of fracturing operations on receiving waters. That study can be considered as applicable for other basins with similar topographic relief and climate conditions (e.g., Michigan basin, USA) in regard to runoff issues associated with site development. Comparisons can be made in the broad similarities of vegetation percentage, surface cover type, moisture availability, and amount of runoff to guide future studies in shale plays with ongoing or impending HVHF development.

Water withdrawals

It is important to consider the connection between water quantity and quality. Taking water from a small stream concentrates contaminants in the stream water. If stream flow is reduced by groundwater withdrawals, the lower dilution rate of solid loadings or other contaminants from the watershed can

Table 1. Categories of chemicals used in hydraulic fracturing, their purposes, and example(s) of a commonly used chemical[a]

Functional category	Purpose	Example(s) of chemical
Diluted acids	Improve injection and penetration; dissolve minerals and clays to minimize clogging, open pores, and aid gas flow	Hydrochloric acid
Biocide	Minimizes bacterial contamination of hydrocarbons, reduces bacterial production of corrosive by-products to maintain wellbore integrity and prevent breakdown of gellants	Glutaraldehyde
Breaker	Added near end of sequence to assist flowback from wellbore, breaks down gel polymers	Ammonium persulfate
Clay stabilizer	Establishes fluid barrier to prevent clays in formation from swelling, keeps pores open, creates a brine carrier fluid	Potassium chloride
Corrosion inhibitor	Maintains integrity of steel casing of wellbore by preventing corrosion of pipes and casings	*N,N*-Dimethylformamide
Crosslinker	Thickens fluid to hold proppant	Borate salts
Defoamer	Lowers surface tension and allows gas escape	Polyglycol
Foamer	Reduces fluid volume and improves proppant carrying capacity	Acetic acid (with NH_4 and $NaNO_2$)
Friction reducer	Improves fluid flow efficiency through wellbore by reducing friction between fluid and pipe, alleviates friction caused by high-pressure conditions	Polyacrylamide
Gel/gellant	Thickens fluid (water) to suspend proppant	Guar gum
Iron control	Prevents materials from hardening and clogging wellbore, prevents metal oxide precipitation	Citric acid
Oxygen scavenger	Maintains integrity of steel casing of wellbore, protects pipes from corrosion by removing oxygen from fluid	Ammonium bisulfate
pH adjusting agent/buffer	Controls pH of solution, protects pH-dependent effectiveness of other chemicals (e.g., crosslinkers)	Sodium carbonate, potassium carbonate
Proppant	Holds open (props) fractures to allow gas to escape from shale	Silica, sometimes glass beads
Scale control	Prevents mineral scale formation which can clog wellbore and block fluid or gas flow	Ethylene glycol
Solvents	Improve fluid wettability or ability to maintain contact between the fluid and the pipes	Stoddard solvent
Surfactant	Improves fluid flow through wellbore by reducing surface tension	Isopropanol

[a] Information from references [23–26].

damage ecosystems and harm aquatic life. In some regions of the country where HVHF is occurring, there are concerns that excessive extraction of surface water and groundwater will result in periods of water shortage that impact agricultural irrigation, drinking water wells, or surface water levels. Of perhaps equal concern are increasing groundwater withdrawals by agriculture resulting in the depletion of aquifer reservoirs. Some of these agricultural water demands are co-occurring in areas where HVHF operations are increasing, presenting cumulative demands on water resources that may impact surface water flows. In Michigan (USA), large-scale commercial agricultural water withdrawals are increasing as climate change leads to longer seasons and the ability to migrate north. Water withdrawals for irrigation purposes increased between 2010 and 2012 from 85 541 million gallons to 159 552 million gallons (Figure 3). During that same period, HVHF water withdrawals increased from 10 million to 55 million gallons (35 million in 2013; Michigan Department of Environmental Quality, public data). Although groundwater reservoirs in Michigan are considered abundant, there are sensitive fisheries, designated as "cold transitional" and "cold water" streams whose headwaters are shallow. These streams are particularly at risk from neighboring HVHF operations during drought and low-flow periods. Careful water-level monitoring and assessment are critical to protect streams with sensitive biota, but this is very context-dependent (geographically and ecologically). The following research questions need to be addressed: Will local hydrologic cycles be altered? How long before cycles recover? How do water withdrawals impact fish during this sensitive time for their survival? Are stream base flow estimates accurate? What are critical base flows for headwater streams?

Construction and transportation

Any disturbance of land, such as the planting of crops and the construction of buildings, increases the likelihood of soil erosion and subsequent loadings to receiving waters of solids and associated chemicals. Such is the case with HVHF operations, which lead to a number of earth-disturbing activities, such as clearing, grading, and excavating land to create a pad to support the drilling equipment or other necessary industrial process materials. In general, well pads increase the potential for sediment erosion on and off location [5,6,10]. These newly constructed well pads also often require construction of access roads to transport

Assessment of High-Volume Hydraulic Fracturing Impacts on Streams: A Case Study Example

A geographic information system–based case study characterizing relative ecological risk based on various land-use factors, including variables related to gas activity, was conducted for the Fayetteville Shale Play in Arkansas (Figure 4) for 16 watersheds in 2011. Although this exercise is simplistic and limited by data availability, it provides an example of how associations between land use and potential biological impact may be delineated and integrated to communicate relative risk.

Components of geographic information system case study for high-volume hydraulic fracturing watershed assessment

Study area	16 watersheds in the Fayetteville Shale (mean drainage area 29 km^2; minimum = 2.5, maximum = 84).
Field sampling data	Replicate benthic macroinvertebrate samples (analyzed as community metrics) and various associated water chemistry parameters (per watershed).
Land-use characteristics	General land-use variables (percentages of pasture, urban, forest), geology (rock type), soil erodability, road density (paved and unpaved), mean inverse flowpath length from roads to streams, gas activity including well density and mean inverse flowpath length from well pads to streams, and pipeline density (per watershed).
Variable importance ranking	Random forest analysis used to evaluate the relationship (relative variable importance values) between land-use variables (after removing highly correlated variables) and associated water chemistry and community metrics.
Watershed ranking (cumulative risk)	Geographic information system spatial overlay conducted to rank watersheds for potential cumulative ecological impact (e.g., decreased Plecoptera percentage). Watersheds were represented as rasters for each land-use variable having high relative variable importance for Plecoptera percentage and simplified to binary rasters based on the value thresholds for each variable roughly corresponding to the spatial pattern of decreased Plecoptera percentage (observations below the 75th centile). Each binary watershed raster was then weighted by its mean variable importance value, and the rasters were aggregated as an overlay map representing relative rank of potential cumulative ecological impact.

Case study outcomes:

- Watershed well density and pipeline density were highly positively correlated (Spearman rho $>$ 0.7) and had a significant positive correlation to mean inverse flowpath length to unpaved roads.
- Based on this exploratory analysis, land-use variables related to gas well development and activity (well density, mean inverse flowpath length to well pads, and unpaved roads) had relatively high variable importance for the prediction of conductivity (positive association), which was also highly positively correlated with metals, chloride, and total suspended solids.
- Among the benthic community metrics, Plecoptera percentage (stoneflies, key indicators of water quality) had a negative relationship with land-use variables related to gas well development and activity compared with other community metrics, as well as a negative relationship with conductivity.
- Watersheds having multiple land-use conditions predictive of decreased Plecoptera percentage (e.g., high mean inverse flowpath length to unpaved roads, high well density) were ranked with a higher relative impact potential compared with other watersheds.

equipment and other materials to the site. If sufficient erosion controls to contain or divert sediment away from surface water are not established, then surfaces exposed to precipitation and runoff could carry sediment and other harmful pollutants into nearby rivers, lakes, and streams. Sediment clouds water, decreases photosynthetic activity, and scours organisms and their habitat. In addition, nutrients and other chemicals tend to sorb to sediments, where they accumulate and can contaminate overlying waters and biota [11].

Industrial chemicals

Hydraulic fracturing chemicals are transported to drilling sites in tank trucks and are stored and mixed onsite. The USEPA has identified more than 1000 possible chemicals that may be used in hydraulic fracturing fluids within the United States [12]. However, most well completions use about 10 different chemical additives in their particular slickwater formulations [13]. Although these chemical additives generally comprise less than 1% by volume of the total fracturing fluid, a typical high-volume hydraulic fracturing completion uses several million gallons of fluid, meaning that many thousands of liters of chemicals will need to be transported and secured onsite prior to injection. Chemical and wastewater transport vehicles can potentially be involved in traffic accidents, and it is estimated that a 30-ton tank truck will have an accident every 333 000 kilometers [10]. Although this does not necessarily mean that chemical emissions will occur at every site, the potential for release into the environment remains. Moreover, truck accidents that

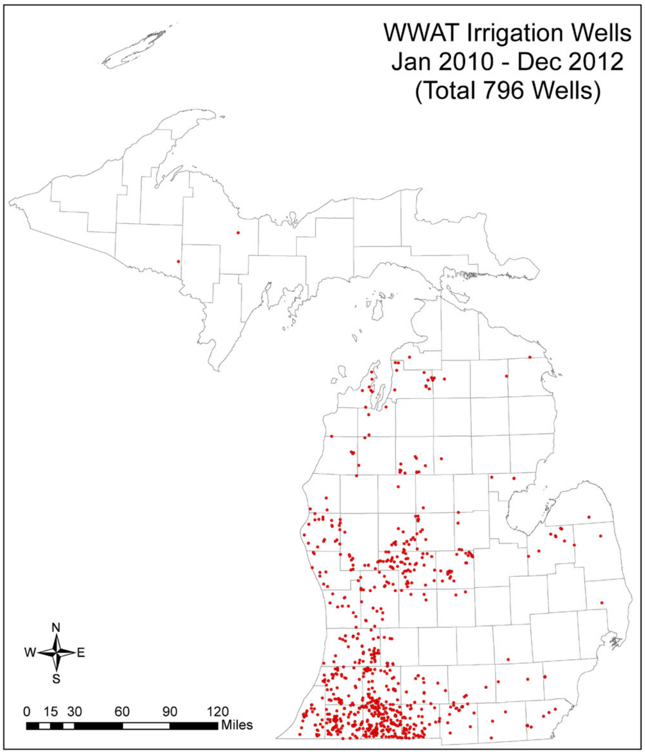


FIGURE 3: Irrigation wells in Michigan drilled from January 2010 to December 2012. WWAT = water withdrawal assessment tool.

occur on roads could result in chemicals being spilled on unpaved areas and draining into surface water and groundwater [10].

Chemicals are integral to the hydraulic fracturing process and perform a number of functions, yet they have intrinsic toxic properties that raise concerns. In the absence of empirical evidence from toxicity studies, researchers have inferred the potential for harm by studies that have identified constituent chemicals and cross-referenced them with known or suspected health effects. Although performed for human health, the outcomes of such studies have applicability to ecotoxicology. The Endocrine Disruption Exchange identified and classified chemicals using Chemical Abstracts Service numbers and comparing them against databases (e.g., MSDS sheets, TOXNET) to increase understanding of plausible health effects. More than 75% of the chemicals were shown to possibly affect the respiratory and gastrointestinal systems as well as eyes, skin, and other sensory organs. Nearly half (40–50%) of the chemicals could affect the neurological, immune, cardiovascular, and renal systems. One-fourth of the chemicals were known, probable, or possible carcinogens. Finally, 37% of the identified chemicals could have effects on the endocrine system. The researchers also noted that 44% of the chemicals were not evaluated because they were not disclosed or they did not have adequate toxicological data. However, the importance of these knowledge gaps must be considered in terms of their ecological and geographic context as well as state regulatory controls.

Flowback and produced water

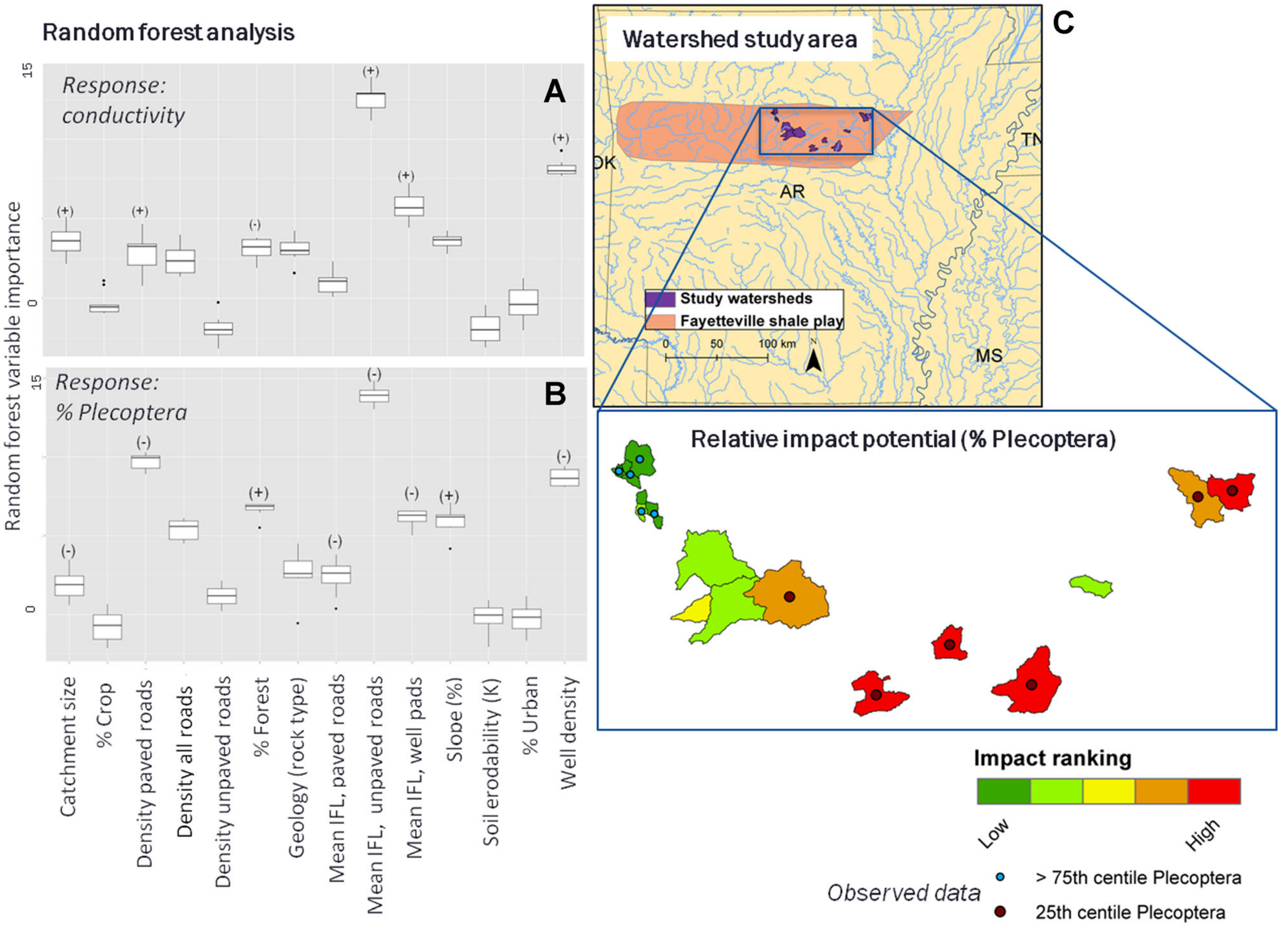
Water that is produced from hydraulic fracturing activities will form a significant waste stream. Management of this waste often requires extensive trucking to offsite injection wells. Regulations govern the proper handling of this waste stream, with the most common method of disposal being deep well injection via brine disposal wells. Alternatives to deep well injection of flowback and produced water include reuse for additional hydraulic fracturing completions or treatment at industrial wastewater treatment facilities. In areas such as Pennsylvania (USA), where only a few brine injection wells are available to accept wastewaters, reuse of flowback water is becoming the dominant management strategy [14]. Prior to mid-2010 some publically owned treatment works in the Marcellus region were accepting flowback waters and were unable to remove the high concentrations of dissolved salts. This practice led to discharge of high-salinity treated effluent to receiving waterways. Specific problems associated with this practice include elevated bromide in drinking water intake streams, which can lead to the formation of brominated disinfection byproducts in treated drinking water [15] and concentration of radium in river sediments near wastewater treatment outflows [16]. The use of publically owned treatment works in Pennsylvania to treat flowback waters has since been all but discontinued because of these environmental concerns and treatment challenges [14]; in Arkansas (USA), however, surface discharge is permitted following onsite treatment.

In locations where naturally occurring radioactive material–bearing produced water and solid wastes are generated, mismanagement of these wastes can result in radiological contamination of soils or surface water bodies [12,16–18]. Elevated concentrations of naturally occurring radioactive materials, most commonly ^{226}Ra and ^{228}Ra, have been observed in flowback waters [19]. Naturally occurring radioactive material waste problems are generally associated with long-term operations of oil and gas fields because of buildup of mineral scaling, such as $BaSO_4$ in which Ra is coprecipitated, in production equipment. Proper management of naturally occurring radioactive material–bearing produced water and solid wastes is critical to prevent both occupational and public human health risks as well as environmental contamination.

Wildlife impacts

There are a number of stressors from hydraulic fracturing operations that may affect wildlife health. For example, a US Government Accountability Office study found that of the 575 National Wildlife Refuges in the United States 105 contain a total of 4406 oil and gas wells. Though rigorous scientific studies are lacking, the information available reveals that construction-related activities that result in habitat fragmentation, as well as spills, have had detrimental effects on wildlife and habitats.

Besides the aforementioned stressors, exposure of wildlife to light and noise is an additional concern; and impacts on wildlife will likely vary among types of wildlife and species



(+) Significant positive Spearman correlation with response
(-) Significant negative Spearman correlation with response

FIGURE 4: Results of exploratory analysis of a 16-watershed case study in the Fayetteville Shale relating field data to an array of land-use variables. Land-use variables highly correlated with one another (Spearman rho ≥ 0.7) were limited to 1 representative variable to enhance interpretation of results. Panels (**A**) and (**B**) are random forest analysis results (10 runs with different starting seeds) showing relative variable importance of land-use variables in the prediction of (**A**) conductivity (positively correlated with metals, total suspended solids, and chloride concentrations) and (**B**) % Plecoptera. the (+) and (–) signs indicate the direction of Spearman's correlation ($p < 0.05$). The map (**C**) shows results of an overlay analysis using the land-use variables of highest importance in the random forest analysis to predict potential "impact" to % Plecoptera (decrease below 75th centile), with field observation values plotted on the map (points). IFL = inverse flowpath length.

(e.g., game species, migratory birds, amphibians). The main sources of noise during the production phase would include compressor and pumping stations, producing wells (including occasional flaring), and vehicle traffic. Compressor stations produce high noise levels. The primary impacts from noise would be localized disturbance to wildlife, livestock, recreationists, and residents. Flooding an ecosystem with excessive light can disrupt feeding, breeding, and rest patterns in micro- and mega-flora and -fauna, providing a potential for ecosystem degradation. Unfortunately, quantifying these effects and their causality linkages is difficult.

What Can Be Done to Mitigate and Monitor Environmental Impacts?

Given the potential for ecological impacts from the stressors mentioned in the *Why the Concern?* section, it is imperative that proactive assessment methods be incorporated into the regulatory process. Examples are given below of proven methods.

Geographic information systems

A useful way to assess the potential impacts of hydraulic fracturing operations is through geographic information system–based models that incorporate ecological, political, and fracturing features [4]. In the Marcellus Shale region, the USEPA undertook a biological assessment of the Allegheny and Monongahela Rivers. To design the study, the USEPA evaluated conditions via probabilistic survey for fish, fish habitat, macroinvertebrates (such as mussels), water chemistry, plankton, and sediment. The resultant data assisted in risk assessment from potential stressors and aided in analyzing the potential seasonal and yearly variability (see sidebar *Assessment of High-Volume Hydraulic Fracturing Impacts on Streams: A Case Study Example*).

Databases

Another tool used by the USEPA in its 2008 Marcellus study was the River Alert Information Network (RAIN). This network integrates information from water treatment, source water protection, and distribution system maintenance into a multiple barrier approach. The goal of RAIN is to employ protection measures to form a first barrier to a multiple-barrier approach to drinking water protection. This includes providing information and tools to aid water suppliers in making decisions and improving communication between water suppliers about water-quality events. The network implements these goals by installing monitoring equipment at appropriate locations and providing operational training. The USEPA RAIN administrators will develop a secure website to share information about water quality and to improve communication between water suppliers, the US Army Corps of Engineers, and emergency responders.

As a tandem effort to RAIN, the USEPA initiated a waste characterization study to measure total dissolved solids, metals, organics, and naturally occurring radioactive materials. The study is dual-phased, with phase 1 focusing on site-specific characteristics across the region. In Pennsylvania, the rapid pace of Marcellus Shale drilling has outstripped Pennsylvania's ability to document predrilling water quality, even with some 580 organizations focused on monitoring the state's watersheds. More than 300 organizations are community-based groups that take part in volunteer stream monitoring. Water quality–monitoring efforts, such as that of the Shale Network (www.shalenetwork.org), are working to overcome this monitoring challenge by leveraging the activity of citizen scientists and providing a public database for collection and dissemination of water-quality data across the Appalachian basin.

State-level activities

As an example, in Michigan, the state permitting process dictates that all hydraulic fracturing operations reduce their potential impact onsite through a variety of measures. These include construction of the well pad at least 1320 feet from the nearest stream for state leases. For private properties, the Department of Environmental Quality requires optimal location that protects surface water while considering a host of other property and environmental issues. The state's considerations also include land elevations, avoiding hillsides, and always using silt curtains. All pervious site grounds are covered in plastic to capture any potential spillage. Permitted sites are for a drilling unit (a tract which the Department of Environmental Quality has determined can be efficiently drained by 1 well) and typically a minimum of 80 acres in size but often much larger, whereas the working pad area is usually less than 5 acres. Lined berms are put in place to contain tank or pipe spills. The Department of Environmental Quality (and the Department of Natural Resources when state acreage is involved) also evaluates where roads may be constructed. The service companies are required to have spill pollution prevention plans, but these may not be available to the actual rig operators. Rig operators must have a spill pollution prevention plan. After site operations cease, the owners are required to reclaim the site using native species of vegetation.

The state of Michigan utilizes the novel and useful Water Withdrawal Assessment Tool (http://www.miwwat.org/) to estimate the likely adverse resource impact of a water withdrawal on nearby streams and rivers [20]. Use of the Water Withdrawal Assessment Tool is required of anyone proposing to make a new or increased large-quantity withdrawal (more than 280 L/min) from the waters of the state, including all groundwater and surface water sources, prior to beginning the withdrawal. This system allows for an evaluation of potential impacts to many sensitive ecosystems. It has several limitations, however, including that it does not currently account for shallow stream morphology and that water withdrawal impacts to wetlands and lakes are based on fewer than 150 US Geological Survey stream gauges, which tend to be located on medium-sized and large-sized streams [20]. It is also a concern that the massive quantities being removed from the aquifer are not being replaced but rather deep-well–injected. Given that fracturing operations can be dense and adjacent to one another, this creates the possibility for negative cumulative impacts from high-volume water withdrawals. Indeed, recent operations will be in the tens of millions of liters extracted for each operation. The Water Withdrawal Assessment Tool should be updated to address concerns of cumulative withdrawals from sensitive shallow headwater streams and could serve as a useful model for other regions to adopt.

Challenges and Opportunities

Of all the scientific disciplines within the hydraulic fracturing arena, ecotoxicology will feature prominently for 2 main reasons, one philosophical and the other practical. Philosophically, ecotoxicologists are trained to think across scales of time, space, and disciplines. They are trained to coalesce diverse concepts and perspectives into a coherent consonant. Such thinking is highly pertinent to the hydraulic fracturing debate that is greatly polarized and often driven by incomplete information, miscommunication, or misunderstandings on various sides of the issue. Practically, the nature of the hydraulic fracturing industry means that ecotoxicological impacts will manifest in a variety of manners. From the injection of chemicals into subsurface environments to the development of new roads and infrastructure, the resulting activities may have profound effects, from the cellular level all the way to the level of landscapes and ecosystems, in current and future time. Below, we outline some of the challenges associated with understanding plausible hazards or risks associated with HVFV on streams and opportunities for improving the process (see sidebar *Moving Forward: Options for Improving the Assessment of Hydraulic Fracturing on Surface Waters*).

One of the greatest challenges in quantifying the ecological effects of hydraulic fracturing is the enormous potential for variation within and among different ecosystems and the

Moving Forward: Options for Improving the Assessment of Hydraulic Fracturing on Surface Waters

- Develop a decision matrix that guides decision making on establishing hydraulic fracturing operations in sensitive or susceptible ecosystems.
- Establish baseline (reference condition) ecosystem monitoring in susceptible areas that continues through postoperation periods to determine whether detrimental impacts occur in an ecological context–based approach.
- Assess the cumulative impacts of multiple hydraulic fracturing operations within a watershed for downstream surface waters and groundwater. Establish to what degree other likely stressors in watershed, unrelated to fracturing operations, impact aquatic communities.
- Identify areas for improved quality control and best practices in fracturing operations, especially near riparian zones, surface waters, and shallow aquifers.
- Establish a publically available database for high-volume hydraulic fracturing studies and data.
- It is important that close attention be paid to the findings published in the peer-reviewed scientific literature in the coming months to years to improve decision making.
- Any assessment of ecological impact from high volume hydraulic fracturing should in turn evaluate how potential impacts compare to the environmental impacts of other anthropogenic activities in the relevant watershed(s).

differing hydraulic fracturing operation sizes, pad densities, and quality-control measures. Additionally, as multiple well sites are established within watersheds, there is potential for the ecological effects of these fracturing operations to interact. Upstream wells, for example, could impact water flows, turbidity, or nutrient and total dissolved solid loadings of aquatic communities far downstream, particularly if impacts of downstream wells are additive or synergistic. In addition, other potential stream stressors and their sources present in the watershed must be considered, such as from agricultural and urban land uses, or simply additional HVFV operations. As discussed above, many of the potential stressors resulting from HVHF operations are the same as those associated with other anthropogenic activities, which may also be occurring within the same watershed. In addition, these considerations must be evaluated within the proper ecological context [21]. Impacts to surface water in a pristine watershed will be assessed very differently from those in an arid area with ephemeral streams or in large riverine systems dominated by human disturbances. This suggests that a strategic "anthropogenic and ecological context–based" approach should be used to determine the likelihood for adverse ecological effects to occur [21].

Another challenge lies in the examination of the effects of fracturing operations before, during, and after the actual hydraulic fracturing occurs. Typically, wells will be actively fractured during a period of only 1 wk to 2 wk. However, the ecological effects associated with the hydraulic fracturing activity begin as soon as infrastructure construction is initiated and last for an unestablished period of time after fracturing is completed. Related to this is the inability to assess whether an actual ecological impact has occurred. This is a particular challenge because of a lack of baseline data and continued monitoring efforts. Very few sites exist in the United States for which baseline (reference condition) environmental monitoring has occurred prior to hydraulic fracturing operations commencing. From both scientific and practical perspectives, it is difficult to establish "impacts" if the baseline is unknown, particularly if these operations are occurring in human-dominated watersheds. It is essential that at least a subset of hydraulic fracturing operations have pre- and postmonitoring of environmental conditions to establish whether detrimental impacts are occurring.

A number of potential hazards clearly exist in hydraulic fracturing operations, but the presence of a hazard does not necessarily indicate a high level of risk. As such, it next needs to be determined whether organisms and ecosystems are exposed and affected. Although hazards have been identified, few exposure assessments have been conducted in hydraulic fracturing sites, and even fewer have tried to account for their possible cumulative health impacts. Nevertheless, a wealth of relevant ecotoxicological studies exist in relation to predicting and understanding the impacts of land development and resource extraction, which directly relate to HVHF potential impacts. Chemicals intentionally used in hydraulic fracturing serve a number of functions, but few of them have undergone rigorous toxicological or ecotoxicological testing. Although chemical spills are less frequent than chronic habitat disturbance and erosion, it is important to begin to understand the toxicity of the wide range of hydraulic fracturing chemicals and combinations of these chemicals that may be released in produced waters, in addition to any pure chemical products stored onsite. The most prominent chemicals are proven human health hazards and, thus, are likely to be of concern to ecological health as well. In addition, an outstanding feature in the toxicological sciences, which is of clear relevance to hydraulic fracturing, is the lack of understanding concerning toxicant–toxicant interactions (mixture effects), how these toxicants may change with varying temperatures and other conditions, and how toxicants may interact with nonchemical stressors (e.g., habitat loss, food availability) to influence health. Many of these challenges will require toxicological evidence that spans multiple organisms and ecosystems.

Full assessment of the complex task of determining whether ecological systems are at risk from hydraulic fracturing operations requires a comprehensive, watershed-based research and management approach. To date, inadequate information exists to determine ecological risk to surface waters, but we can determine the plausibility that hazards may occur. An appropriate analogy, and future model, that may be useful is the Total Maximum Daily Loading (TMDL) program, used widely by the USEPA and states, the TMDL offers a watershed-based framework for this task and accounts for the cumulative contributions of multiple sources to receiving waters. Although oil and gas operations are not granted surface water discharges, the idea of considering environmental and groundwater "loadings or use" on a watershed-by-watershed basis is appropriate. The TMDL is a useful tool in establishing particular watersheds, water bodies, or water basins that may be impaired. The TMDL was developed under section 303(d) of the Clean Water Act that requires states or territories to develop lists of waters that are "impaired" or otherwise too degraded to meet water-quality standards. The TMDL actually calculates a maximum amount of pollutant that a body of water can maintain, while still adhering to the approved water-quality standards. The TMDL tool provides curves that aid in calculation of the duration that a particular pollutant or chemical of concern can last in a certain water body. Thus, an industrial operator or monitoring agency could use this approach to evaluate how to assess the potential terrestrial and surface water impacts of multiple HVHF operations within a watershed. Water withdrawal modeling tools, such as Michigan's Water Withdrawal Assessment Tool, must consider cumulative withdrawal impacts from operations drawing on the same aquifer, at extremely high volumes, during biologically sensitive seasonal periods.

Given that this tool will not assess the potential impacts of HVHF operations on habitat, wildlife, and nearby waters receiving site runoff, routine site inspections will be required to ensure that site erosion is minimal and spill prevention plans are being followed. Geographic information system–based modeling and site monitoring will allow for these potential impacts to be evaluated, thereby ensuring that proper siting and operational controls are established and followed.

There is no completely risk-free energy development scheme, and all activities (renewable and nonrenewable) pose some degree of risk to the environment. Therefore, any assessment of hydraulic fracturing needs to be conducted with careful consideration of other anthropogenic activities, including energy sources, relative trade-offs, and associated risks and benefits to environmental health. It must also be realized that risks and benefits can vary from the local to regional/state, national, and international levels. Any assessment of ecological health impacts from this energy-driven activity should in turn evaluate how these potential impacts compare to the environmental impacts of other energy-related activities, as well as in the context of other non–energy-related stressors. This comparison must consider both regional and international impacts resulting from energy markets and cross-boundary pollutant transport.

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