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Review

A review on risk assessment techniques for hydraulic fracturing water and produced water management implemented in onshore unconventional oil and gas production

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HIGHLIGHTS

- Unconventional oil and gas production poses risks to water quality and quantity.
- Risk levels vary with unconventional oil and gas production stages.
- Spill and leakage data limitations are obstacles for meaningful risk assessments.
- Social factors should be included in assessing water quality and quantity risks.

GRAPHICAL ABSTRACT

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ABSTRACT

The objective of this paper is to review different risk assessment techniques applicable to onshore unconventional oil and gas production to determine the risks to water quantity and quality associated with hydraulic fracturing and produced water management. Water resources could be at risk without proper management of water, chemicals, and produced water. Previous risk assessments in the oil and gas industry were performed from an engineering perspective leaving aside important social factors. Different risk assessment methods and techniques are reviewed and summarized to select the most appropriate one to perform a holistic and integrated analysis of risks at every stage of the water life cycle. Constraints to performing risk assessment are identified including gaps in databases, which require more advanced techniques such as modeling. Discussions on each risk associated with water and produced water management, mitigation strategies, and future research direction are presented. Further research on risks in onshore unconventional oil and gas will benefit not only the U.S. but also other countries with shale oil and gas resources.

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1. Introduction

Oil and gas (O&G) resources can be classified as conventional or unconventional depending on the geological formation. Conventional deposits, sand and carbonates such as limestone, have high porosity that allows the fluids (O&G) to flow into the wellbores (Freyman, 2014; Scanlon et al., 2014; USDOE, 2013a). Unconventional O&G deposits are trapped inside rocks such as shale and tight sands, which have high porosity and limited permeability (Freyman, 2014; Scanlon et al., 2014). These characteristics make production difficult, requiring stimulation to allow O&G to flow to the wellbore at an acceptable rate (Scanlon et al., 2014). The technologies of horizontal drilling and high-volume hydraulic fracturing (HF) have been combined to achieve the flow of hydrocarbons resulting in recent growth in onshore unconventional O&G development. In the U.S. from 2011 to 2013, 95% of oil production growth and 100% of natural gas production growth came from the Bakken, Niobrara, Marcellus, Utica, Permian, Haynesville and Eagle Ford (Fig. 1) (EIA, 2014).

This paper focuses on the following four shale formations due to their contribution to the total unconventional O&G produced in the U.S.: Bakken (North Dakota), Barnett (Texas), Eagle Ford (Texas), and Marcellus (Pennsylvania). The Eagle Ford ranked first in unconventional

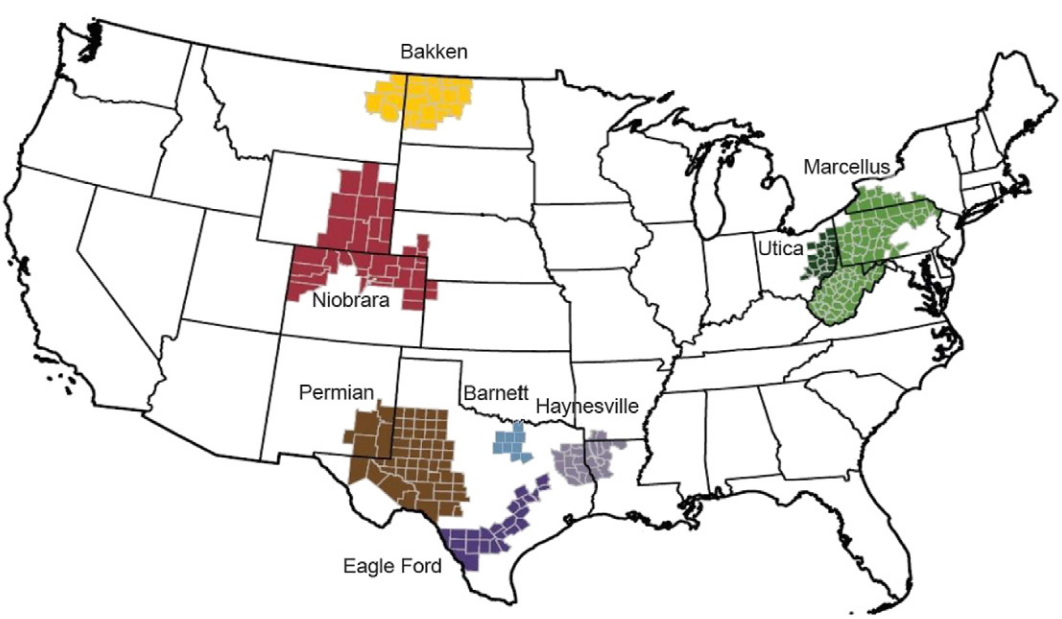

Fig. 1. Most important unconventional O&G regions (The blocks are counties.) in the United States.
Adapted from EIA (2014).

oil production in 2013 while the Bakken ranked second; together representing 67% of total unconventional oil production in the U.S. in 2013 (Scanlon et al., 2014). Shale gas development was first assessed in the Barnett, which was also the first shale in the world to be fully developed using hydraulic fracturing (Nicot et al., 2014; USDOE, 2014). In 2013, Pennsylvania produced more than 3 trillion cubic feet of natural gas, mostly from the Marcellus shale, making it the largest gas play in the U.S. (PADEP, 2013).

Onshore unconventional O&G development and production have boosted the U.S. economy, but along with this benefit environmental risks have emerged, similar to any other large volume extractions of underground resources. Some of the arguments by shale gas proponents are clean energy, future energy independence, economic benefits and jobs creation, reduction in greenhouse gases (GHG) emissions, and modest environmental risks (Stern et al., 2014). On the other hand, the opponents argue that safeguards and monitoring are not adequate; operations present significant risks; there are impacts to the environment, human health, and society; GHG emissions are high due to methane escape; and dependence on shale O&G is a step back from progress towards renewable energy (Stern et al., 2014). In addition, regulations in different states show inconsistencies and there are not enough staff and expertise to track, coordinate, and prevent risks (Stern et al., 2014; Wiseman, 2014).

Unconventional O&G development using hydraulic fracturing requires millions of cubic meters of water and chemicals, some of which are known to affect human health, and contaminate air and water (EPA, 2012). This could lead to impacts on water availability, human health, agriculture, livestock, and wildlife. This literature review focuses only on risks to water quantity and quality. Although more studies on this subject have become available, the information on risks related to the water and produced water management in unconventional O&G development and the impacts is still insufficient. Consequently, risk assessment in unconventional O&G merits further investigation.

The results from further research could contribute to practices in other countries that have unconventional O&G resources. The top 5 countries with technically recoverable shale oil resources are Russia, U.S., China, Argentina, and Libya while the top 5 countries with shale gas resources are China, Argentina, Algeria, U.S., and Canada (EIA, 2013). Some of these countries are still assessing the feasibility of unconventional O&G production but application of HF is likely to occur in the future.

The review begins with explaining the basics of unconventional O&G development process. The different stages in the water life cycle throughout the development process are described, including the possible risks to water quantity and quality. Risk assessment techniques applicable to unconventional oil and gas are discussed. Results from these assessments are reviewed to determine what is missing. Finally, the future research directions of risk assessment in unconventional O&G are considered.

2. Unconventional O&G development process

The unconventional O&G development process (Fig. 2) begins with planning for the water sources, the amount of water needed, and proper produced water management (API, 2010). Water is obtained from the source and transported to the well site, by pipeline or truck, where it is stored before chemical mixing. The next step is drilling which requires drilling mud; typically, a mixture of water, mud, and drilling additives (Lutz et al., 2013). During drilling, the well casing made of steel pipes is installed using cement to isolate all formations that contain water, oil, gas, coal or a combination (API, 2010; NDCC, 2012). Once the well is constructed, the HF process begins with mixing the water with additives. Using pumping trucks, the HF fluid is injected into the well at high enough pressure to fracture the formation rock to enable the release of O&G. Prior to production, the flowback process begins, which is designed to capture the initial production that contains a high percentage of produced water, a mixture of mainly injected (flowback) water and some formation water (stored in the shale) (EPA, 2012). After that, the transition to formation water and hydrocarbons occurs (WEF, 2013). During the production phase, which continues until the well is refractured or abandoned, oil, gas, and produced water (mostly or entirely formation water) enter the wellbore and are collected at the surface. (Nicot et al., 2014; WEF, 2013). Both the injected and formation water (produced water) are recovered and then subjected to one or more of the following four options: 1) storage, 2) disposal, 3) treatment and reuse; and 4) treatment and disposal. The HF process is then repeated if needed to continue stimulating the O&G production until the well is no longer productive (API, 2010). Once this happens, the well is plugged or isolated with cement barriers before abandonment (API, 2010). It should be noted that the diagram in Fig. 2 represents the general process and slight variations occur from location to location.

3. Water life cycle in unconventional O&G production

There are five major stages for the water life cycle associated with unconventional O&G development (EPA, 2012). These stages are 1) water acquisition, 2) chemical mixing, 3) well injection (HF), 4) flowback process and produced water generation, and 5) treatment and disposal (EPA, 2012). Possible risks in each stage of the water life cycle are shown in Table 1.

3.1. Water acquisition

The amount of water used per well varies from 7600 to 15,200 m^3 and up to 49,200 m^3, depending on the geological characteristics, well construction (depth and length) and fracturing operations (chemicals used and fracture stimulation design) (API, 2010; EPA, 2012; Freyman, 2014). Of the total water, 10% is used for drilling, 89% for HF, and the rest is consumed by infrastructure (USDOE, 2014). In the Bakken shale in North Dakota, it is estimated that each well requires around 8700 m^3 of water for drilling and HF (NDSWC, 2014). In Texas, for the Barnett shale the estimation is 18,900 m^3/well while it is 18,200 m^3/well for the Eagle Ford shale (Nicot et al., 2014; Scanlon et al., 2014). In Pennsylvania, the Marcellus shale requires 11,400 to 18,900 m^3/well (Lutz et al., 2013). From January 2011 to May 2013, there were a total of 39,294 shale oil and gas wells across the U.S. which equals to 5.95×10^8 m^3 of water (assuming 15,150 m^3/well) or the water consumed by 3 million Texans in a year (Environment Texas Research and Policy Center, 2013; Freyman, 2014).

Sources of water for onshore unconventional O&G production vary by region. The main source of water in the Bakken shale is the Missouri River although groundwater is sometimes used where access to the river is restricted (NDSWC, 2014). In 2012, from the 4.35×10^8 m^3 of water consumed in North Dakota, 1.74×10^7 m^3 (or 4%) were used for fracturing purposes (NDSWC, 2014). In the Barnett shale, operators depend on both groundwater and surface water, relying on different aquifers such as Ogallala and Carrizo–Wilcox and the Brazos River basin (Freyman, 2014; Nicot et al., 2014). In the Eagle Ford, 90% of the new oil wells use groundwater (RRCT, 2013). The amount of water used in the Barnett for HF purposes was 3.18×10^7 m^3 in 2011 while the Eagle Ford used 6.74×10^7 m^3 in 2013 (Nicot et al., 2014; Scanlon et al., 2014). In Pennsylvania, the Marcellus shale wells use surface water from the Susquehanna and Delaware River basins but in recent years the operators have switched to reusing and recycling, reaching almost 90% of the wastewater in 2012 (PADEP, 2014). Mining, where HF is included, accounts for 2% of the total water withdrawals in the state which withdraws 3.67×10^7 m^3 of water every day or 13.4×10^9 m^3 per year (PADEP, 2009).

3.2. Chemical mixing

The fracturing fluid is composed of water (~94%), proppant (~5%) and other chemical additives (~1%) (API, 2010; EPA, 2012; Halliburton,

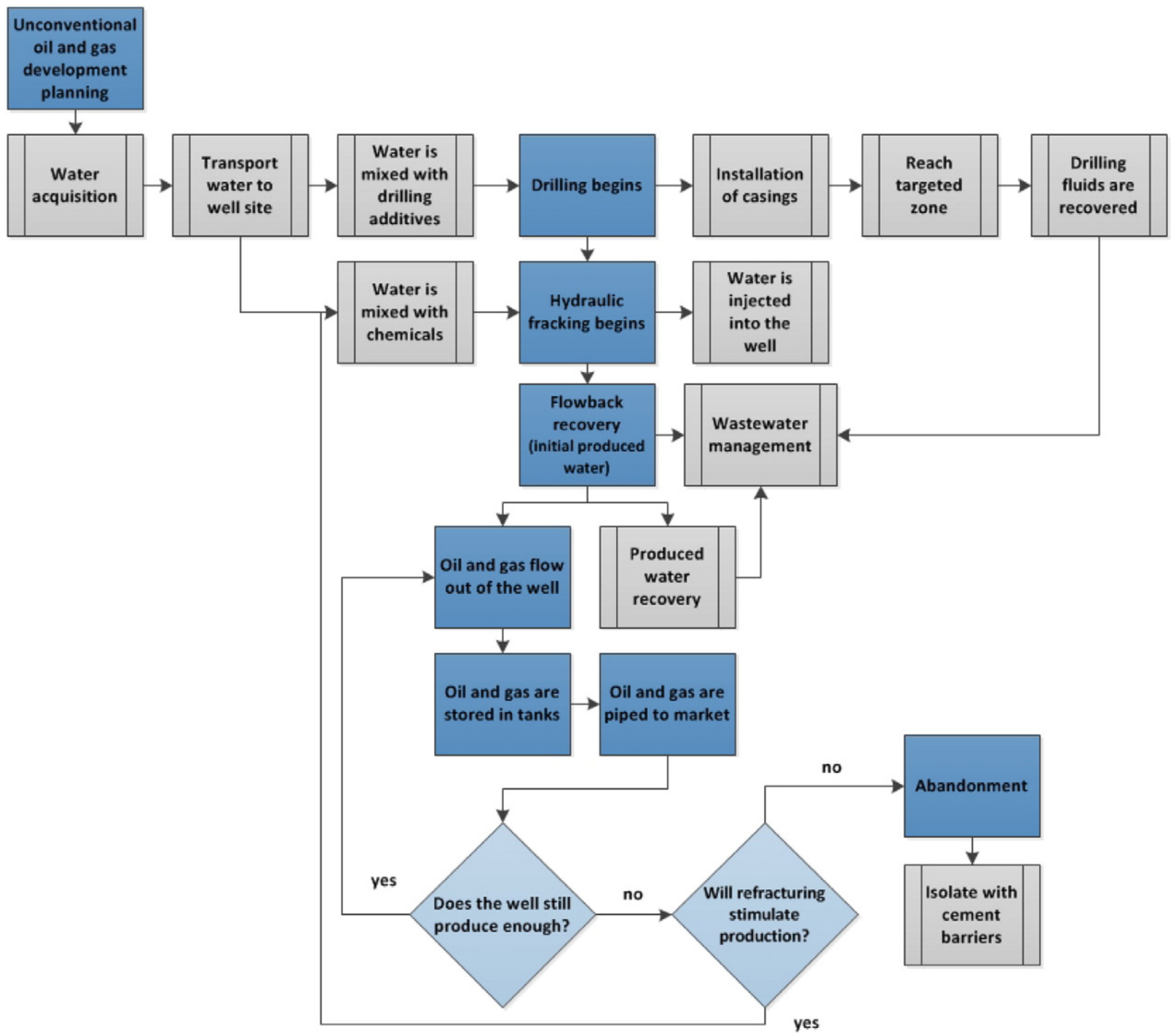

Fig. 2. General process of unconventional oil and gas production.

2015). The mixture varies according to the well location and operator but a typical combination requires 3 to 12 chemical additives (FracFocus, 2014a). Sand is commonly used as the proppant to help keep the fractures open to release the hydrocarbons (O&G). Other options for the proppant are resin coated sand, intermediate strength proppant ceramics, and high strength proppants such as sintered bauxite and zirconium oxide (Arthur et al., 2008). In addition, a generic formula for the additives is acid, acid/corrosion inhibitor, biocide, breaker, clay and shale stabilization/control, crosslinker, friction reducer, gel, iron control, non-emulsifier, pH adjusting agent, scale inhibitor, and surfactant (FracFocus, 2014b). The concentrations of some of these additives are detailed in Table 2 (Chesapeake Energy Corporation, 2011a). According to the Environmental Protection Agency (EPA) (2012), there are seven chemicals often used in the mixture appearing in over 2500 products reported by 14 operators between 2005 and 2009. These chemicals are methanol, isopropanol, crystalline silica, 2-butoxyethanol, ethylene glycol, hydrotreated light petroleum distillates, and sodium hydroxide (EPA, 2012). The concentrated additives are mixed with water and proppant using blender trucks (Fig. 3). Then, the fracturing fluid is transferred to pumping trucks, which inject the fluid into the well (API, 2010; EPA, 2012).

Table 1
Possible risks on the different water life cycle stages.

Stage	Possible risks
Water acquisition	Water shortage or limited access for other users' needs causing stress on water resources particularly during drought season.
Chemical mixing	Spills of chemicals could cause surface water and/or groundwater contamination. Health problems due to chemical exposure.
Well injection	Casing failure or induced fractures in the rocks could serve as pathway for HF fluid migration into water resources.
Flowback process and produced water	Surface spills, infiltration in the ground from the reserve pits or tanks, leaks from pipes, and effects on human health due to exposure to the chemicals, brine and other natural radioactive material.
Produced water treatment and waste disposal	Spills and leakage during on-site treatment, storage and transportation to off-site treatment facilities or disposal. Limitation of the treatment plants to completely eliminate contaminants which reach streams and impair drinking water sources. Deep-well injection could induce earthquakes and cause well casing failure.

3.3. Well injection (HF)

The fracturing fluid is injected inside the well using pumping trucks at high pressures to break the formation rock, allowing the release of O&G, which flow through the wellbore up to the surface where they are collected (EPA, 2012). Depending on the well depth, several

Table 2
Common groups of chemical additives in the HF fluid and associated chemical compounds and concentrations.

Additive	Chemical	Concentration
Friction reducer	Polyacrylamides	500–1000 ppm (0.05–0.1% of total fluid)
Biocide	Glutaraldehyde, glutaraldehyde/quaternary amine blends, tetrakis hydroxymethyl phosphonium sulfate, 2,2-dibromo, 3-nitriloproprionamide, and sodium hypochlorite	75–500 ppm (0.075–0.05% of total fluid)
Scale inhibitor	Polymers (carboxylic acid and acrylic acid)	75–120 ppm (0.075%–0.12% of total fluid)
Substitute	Potassium chloride	500–2000 ppm (0.05%–0.2% of total fluid)
Surfactant	Laurel sulfates, and fluoro and nano-surfactants	500–1000 ppm (0.05%–0.1% of total fluid)
Dissolvent	Hydrochloric acid	0.08%–2.1% of total (as acid volume). 0.012%–0.31% of total (as active acid)
Acid corrosion inhibitor	Formic acid, amines, amides, and amido-amines	2000–5000 ppm of acid volume 0.0004%–0.0043% of total (temperature and time dependent)
Iron control	Citric acid, acetic acid, thioglycolic acid, and ethylenediamine tetraacetic acid	5000 ppm of acid volume 0.0004%–0.011% of total fluid

injections or stages may be required (EPA, 2011). The depth where HF takes place depends on the geological formation usually being thousands of feet away from groundwater resources (AWWA, 2013). In North Dakota, potable water is located at 610 m deep while the oil-bearing formations are generally at 3050 m under the surface (NDSWC, 2014). In Texas, the Eagle Ford wells have an average depth of 3050 m while the Barnett shale is located at 2300 m from the surface and groundwater is found at 370 m (Chesapeake Energy Corporation, 2011a; Scanlon et al., 2014; USDOE, 2014). The well depth on the Marcellus shale ranges from 1520 to 2440 m while groundwater is found at 260 m from the surface (EPA, 2012; USDOE, 2014).

3.4. Flowback process and produced water

After the fracturing fluid is injected, the pressure is reduced allowing the fluid to come back to the surface. This fluid is called produced water and consists of the injected fluid and the formation water. Flowback process water is a subset of produced water and is defined by the time period in which it returns. The contents in produced water causing major concern are salt, oil and grease, natural organic and inorganic compounds, chemical additives, and natural radioactive materials from the shale formation (NPC, 2011). The EPA has identified over 1000 chemicals that are reported to be used in fracturing fluids or found in produced water (EPA, 2012). The content of produced water, as well as the amount, varies for every well depending on the formation that is being stimulated.

The fraction of the water volume injected that returns to the surface during the first 10 days is between 10% and 25% for the Barnett and Marcellus shale (Chesapeake Energy Corporation, 2011b; Wilson and VanBriesen, 2012). The Bakken shale returns 15 to 40% of the water volume injected during the initial flowback, which is considered relatively high (Boschee, 2014; EERC, 2010). On the other hand, in the Eagle Ford, less than 15% of the water volume injected returns immediately to the surface (Boschee, 2014; Maguire-Boyle and Barron, 2014). Some of the causes for which the remaining water, called residual treatment water, does not return to the surface include the fluid being trapped inside the shale matrix due to capillary and osmotic forces, formation pressure decrease, and fracturing fluid traveling beyond the capture zone (Engelder et al., 2014; EPA, 2004).

The content of produced water is relatively high in total dissolved solids (TDS), which are tied to salinity. The TDS ranges are up to 632,689 mg/L in the Bakken, up to 476,500 mg/L in the Marcellus, 21,581–300,155 mg/L in the Barnett, and 1033–317,876 mg/L in the Eagle Ford (USGS, 2014). Common elements in produced water are sodium, calcium, magnesium, chloride, potassium, iron, strontium, barium, lithium, and silicon (Maguire-Boyle and Barron, 2014; Wilson and VanBriesen, 2012). In addition, naturally occurring radioactive material (NORM), mostly radium isotopes, have been detected on soil near road spreading (Skalak et al., 2014), spill sites related to HF activities (Warner et al., 2013b), soil and sludge from reserve pits (Rich and Crosby, 2013), and soil and pipe-scale at oil production sites (Zielinski et al., 2001).

The EPA requires the operators to apply reduced emissions completions, also known as reduced flaring completions or green completions, to separate gas from solids and liquids during the initial high-rate flowback process and production (EPA, 2011). This is done to reduce gas emissions to the atmosphere and the need for flaring (EPA, 2011). According to the EPA (2014), after HF, there are three stages of fluid handling namely initial flowback stage, separation flowback stage, and production stage. During the initial stage, the flowback is stored in vessels, any gas can be vented or flared, and the hydrocarbons present are filtered out and sold (EPA, 2011). The initial stage then shifts to separation stage when sufficient gas is present for a separator to operate. During the separation stage, the flowback is routed through the equipment

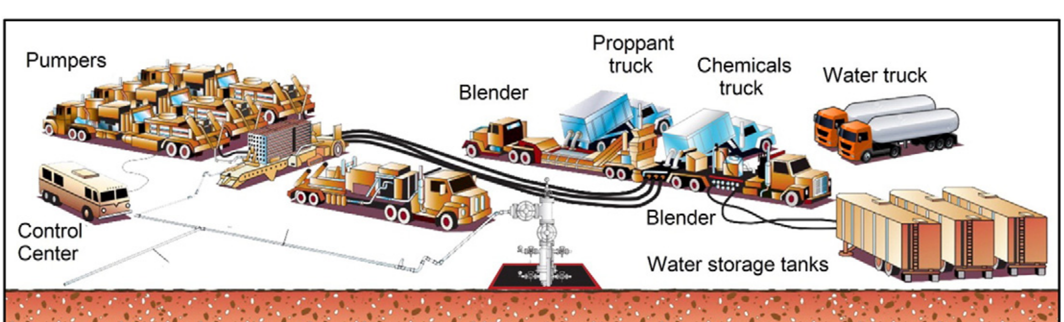

Fig. 3. Hydraulic fracturing units.
Adapted from API (2010).

that separates solids, gas, liquid hydrocarbons and water (EPA, 2014). These separations can be done using two, three or four phase separation hydrocyclones (Ditria and Hoyack, 1994; Manning and Thompson, 1995). Once the flowback process is completed, the production stage begins where phase separation is also applied and liquids, including produced water, are stored and the gas or oil recovered is routed to flow line or collection system (EPA, 2014).

3.5. Produced water treatment and waste disposal

The separated produced water is managed using one of the following techniques: evaporation ponds, deep-well injection, on-site treatment, off-site treatment, and centralized treatment plants. In North Dakota, evaporation ponds are not used for wastewater disposal; instead, the brine is stored in tanks before underground injection (NDCC, 2012). In 2012, the Industrial Commission of North Dakota modified the oil industry regulations with the purpose of reducing the use of evaporation ponds including the prohibition of open pits to store liquids left over from the drilling process for oil wells drilled below 1520 m and reclamation of the pit within one year after completing the well (ICND, 2012; NDDMR, 2011). In Texas, collecting pits for produced water storage are allowed before disposal and evaporation ponds; however, the practice of the latter varies throughout the state (RRCT, 2015a; TAC, 1977). In the west, evaporation before closing the reserve pit is allowed because the rates of evaporation are favorable compared to the east where pits are generally dewatered due to low evaporation rates (RRCT, 2015a). The on-site treatment, which occurs within the proximity of the wellhead, is applied in less frequency in the Barnett (Nicot et al., 2014).

In Pennsylvania, the use of impoundments has been banned (Easton, 2013). Another method is deep-well injection of wastewater in class II wells, which are exclusive for fluids associated with the O&G industry (EPA, 2012). This method is used the most in North Dakota and Texas while in Pennsylvania it is used in less frequency due to lack of sufficient class II wells (Nicot et al., 2014). Because of this, Pennsylvania has to send the wastewater to Ohio where more injection wells are available (Detrow, 2012). In 2009–2010, of the total produced water reported in the Marcellus shale, 77.5% was treated in industrial wastewater treatment plants, 16% was reused in other wells, 5% was treated in municipal wastewater facilities, 1% was classified as unknown disposal, 0.5% was disposed in deep wells, and 0.007% was spread on roads (Rozell and Reaven, 2012). In 2011, the Pennsylvania Department of Environmental Protection requested companies to reduce disposal through wastewater treatment plants as an effort to protect surface waters (Ferrar et al., 2013). As a result, between 2012 and 2014 the amount of the produced water disposed through municipal wastewater facilities was almost 0%, more than 69% was reused, and the rest was disposed mostly through industrial treatment facilities and deep-well injection (PADEP, 2014).

4. Risk assessment

4.1. Risk assessment methods used in industries

Risk analysis is used for characterizing, managing, and informing others about an identified risk. The risk, or potential loss, is related to the probability of exposure to a hazardous event and the consequences of it (Modarres, 2006). In addition, risk is the combination of possible consequences and associated uncertainties (Aven et al., 2007). According to the Food and Drug Administration, risk analysis has three elements: risk assessment, risk management and risk communication, which interact with each other (Fjeld et al., 2007). The process of characterizing the potential risks and its magnitude, through quantitative estimates and qualitative expressions, is called risk assessment (Fjeld et al., 2007; Modarres, 2006; NRC, 1983). Risk assessment uses deterministic or stochastic processes to characterize risks. Deterministic processes can be quantitative, qualitative or hybrid while stochastic processes are based on classic statistical approach and the accident or abnormal action forecasting methods (Marhavilas and Koulouriotis, 2012a,b). The classification of major risk assessment processes for both deterministic and stochastic approaches are shown in Table 3. Tables 4 and 5 summarize some of the most common deterministic and stochastic techniques, their type, advantages, and disadvantages.

4.2. Risk assessment in the O&G industry

Risk assessment in the O&G industry has evolved since the 1960s when risk was controlled only by applying proper safety management. In addition, risk estimates were very uncertain and data were very limited. It was until the 1970s to the 1990s when risk analysis was established as a technique to support regulatory decisions and safety management systems (Aven and Kristensen, 2005). Risk assessment in the O&G industry is widely used in offshore operations and in some countries, such as the U.K. and Norway, companies are required to perform risk analysis prior to operations (Cai et al., 2013; Skogdalen and Vinnem, 2012). Table 6, which is by no means exhaustive, shows some examples of the risk assessment methods and techniques that have been used in the O&G industry.

The environmental (ecological) risk assessment (ERA) was developed by the EPA to evaluate the likelihood of adverse ecological effects caused by exposure to physical, chemical or biological stressors (EPA, 1998a). The assessment is performed using data from field or laboratory studies with suitable models that produce two types of outputs: quantitative risk estimates and qualitative conclusions (EPA, 1998a). In addition, it intends to transform scientific data into information about the effects of human activities on the environment (EPA, 1998a). The EPA, U.S. National Imagery and Mapping, U.S. Department of Energy (USDOE), Russian Federal Center of Geological Systems, and the Ministry of Defense of the Russian Federation conducted an ERA of O&G activities in the Priobskoye oil field in western Siberia (EPA, 1998a). Different techniques were applied including geographical information system (GIS) database, National security systems-derived products, environmental impact assessment, and algorithms (EPA, 1998a).

The barrier and operational risk analysis (BORA) uses a detailed and quantitative model of barrier performance. The barriers are used to prevent occurrences of events from happening and reduce consequences. The BORA method includes development of the risk model, assignment of probabilities of events, identification and assessment of risk influencing factors, and calculation of specific probabilities (Aven et al., 2006). The hazard identification (HAZID) method is based on fault propagation and event tree analysis to evaluate failure sequence and consequences (McCoy et al., 1999). The basic process consists of decomposing the plant or system into equipment or units and then creates a model for each unit. The connection between the units is analyzed as well as a model of the fluids in the system.

The layers of protection analysis (LOPA) is a semi-quantitative method that estimates hazards based on the HAZOP output and the adequacy of protection layers used to mitigate risk (Habibi et al., 2013; Summers, 2003). The LOPA compares a scenario or impact event with a benchmark or the target factor to measure the gap between the existing situation and the tolerable level of risk (Habibi et al., 2013).

The quantitative risk assessment (QRA) was exclusively used in the offshore industry in Norway during the 1980s and also implemented in the U.K. afterwards (Skogdalen and Vinnem, 2012). This technique combines sub-models to analyze individual and societal risks and defines individual risk as the probability of an unprotected person to get hurt in a hazardous location (Marhavilas and Koulouriotis, 2012b). The disadvantage of QRA is that it does not include human and organizational factors (HOFs) such as working practice, communication, and procedures. Despite this, Norway and U.K. regulations require to include HOFs in offshore QRAs indicating that there have been efforts to develop methods to formally include these factors (Skogdalen and Vinnem, 2011). Cai et al. (2013) used Bayesian networks in QRA for assessing

Table 3
Risk assessment processes and techniques.

	Process	Technique	
Deterministic	Qualitative	• Check lists • What if analysis • Safety audits • Task analysis	• STEP technique • Hazard and operability studies (HAZOP)
	Quantitative	• Proportional risk assessment technique (PRAT) • Decision matrix risk assessment (DMRA) • Risk measures of societal risk • Quantitative risk assessment (QRA) • Quantitative assessment of domino scenarios (QADS) • Weighted risk analysis (WRA)	
	Hybrid	• Human error analysis techniques (HEAT) • Fault tree analysis (FTA) • Event tree analysis (ETA) • Risk-based maintenance (RBM) • Epistemic models (predictive epistemic approach — PEA)	
	Classic statistical approach	• Probability distributions (e.g. exponential and normal) • Event data-models (e.g. rate model, time and risk model, and Poisson model)	
Stochastic	Accident forecasting modeling	• Time-series • Markov chain analysis • Gray model • Scenario analysis	• Regression method • Neural networks • Bayesian networks

the risk of subsea blowout preventer operations. The approach in this study consists of five steps: 1) Translate the process flow chart into a Bayesian network, 2) classify the influencing factors of the nodes into human, hardware, software, mechanical, or hydraulic, 3) establish single Bayesian networks for each factor, 4) integrate the single networks into the main Bayesian network, and 5) analyze the Bayesian network model. The analysis shows that the factors that affect safety the most are mechanical and hydraulic, the least important are software and hardware, and human factors are in the middle (Cai et al., 2013). Although this study is about offshore O&G industry, it could be modified to apply on onshore operations.

4.3. Recent risk assessment in unconventional O&G development

4.3.1. Engineering approach

For many years, the engineering approach to assess risk has been preferred in many areas, including the O&G industry (Aven and Kristensen, 2005; Jacquet, 2014). This approach defines risks based on probabilities or expected values which are complemented with the estimation of uncertainties using different techniques such as Bayesian networks (Aven and Kristensen, 2005).

In 2010, the EPA started working on a study titled “Potential Impacts of Hydraulic Fracturing on Drinking Water Resources” at the request of the U.S. Congress. This study intends to assess and determine the risks HF has on drinking water by “identifying the driving factors that may affect the severity and frequency of such impacts” (EPA, 2012). The progress report published in 2012 collects information about existing data, scenario evaluations, laboratory studies, toxicity assessment and case studies. In June 2015, the EPA released a second draft for review titled “Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water”, which will be used to develop the final report.

The USDOE published a report “Environmental Impacts of Unconventional Natural Gas Development and Production” in May 2014, which summarizes, from different publications, the potential environmental impacts of operations within the lower 48 states shale plays (USDOE, 2014). The type of environmental impacts documented are greenhouse emissions and climate change, air quality, water use and quality, induced seismicity, and land use and habitat fragmentation.

Intensive water usage during unconventional O&G production could decrease water availability, especially in arid regions or during drought season (USDOE, 2013b). Drought risk assessment is necessary to enhance energy security by forecasting and quantifying risk. Different methods, such as the Standardized Precipitation Indices and the Palmer Drought Severity Index, have been used (Strzepek et al., 2010). Markovian models have been applied for hydrological processes but they are not adequate to describe drought events due to longer time dependence (Chung and Salas, 2000). Chung and Salas (2000) proposed the use of low-order discrete autoregressive moving average models combined with probability distribution of drought events, expected values, variances, and Monte Carlo simulation to describe the associated risks. Another widely used method is remote sensing and GIS, which uses satellite derived indices and exact spatial information to analyze drought-risk sensitive areas and quantify the risk (Lin and Chen, 2011; Vicente-Serrano, 2007; Wu and Wilhite, 2004).

Rozell and Reaven (2012) studied the likelihood of water contamination during the production of natural gas from the Marcellus shale. The risks were calculated using probability bounds analysis based on

Table 4
Deterministic risk assessment techniques used in different industries.

Technique	Application	Advantages	Disadvantages
Safety audits Cacciabue (2004), Marhavilas and Koulouriotis (2012b)	Operational procedures are inspected according to safety programs (norms and standards). It is used to study human factors.	The evaluations are recurrent which could ensure safety levels and detect risk early.	Limited to the identification of safety critical factors.
Fault trees and event trees Aven and Kristensen (2005), Iannacchione et al. (2008), NASA (2011)	Fault trees: Failure relationship of more complex events with more basic events. Event trees: Practical quantification of accident scenarios. Probabilities and expected values from hard data and expert opinions. The uncertainty can be expressed by confidence intervals.	Well-suited to quantitative analysis when probabilities can be assigned.	High level of details needed for each event. Mostly used for timed events.
Risk matrix Iannacchione et al. (2008)	Qualitative categories are defined (low-to-high or unlikely-to-likely).	Used in many qualitative risk analysis techniques.	Ranking of risk is subjective.

Table 5
Stochastic risk assessment techniques used in different industries.

Technique	Application	Advantages	Disadvantages
Monte Carlo simulation SARS (2011)	The probability of a variable is determined by random numbers. By repeating this process the distribution of the output random variable may be built up, from which estimates of the parameters of interest may be calculated.	Good for complex systems that may be subject to change later. Very flexible.	Large calculations. Solutions are not exact and depend on the number of runs.
Bayesian analysis Aven and Kristensen (2005)	Probability is a measure of uncertainty which is divided in two parts: variation in the population and uncertainty about what value is the true value of this chance.	Can be used with fault trees and event trees.	Uses subjective probability distribution.
Probabilistic distributions Aven and Kristensen (2005), Pidgeon (1998), SARS (2011)	Quantifications of risk are based on statistics using historical data resulting in numbers that are not facts. Assumptions are necessary to obtain sufficient volume of data.	Understanding the distribution of random events allows users to apply practical solutions to operational problems.	Risk expressed by probabilities is subjective. This narrow view of risk alone cannot establish safety levels. Statistics may result in low risk numbers.
Numerical models (Aven and Kristensen (2005)	Theories and laws used to simplify representations of the world. Needs a balance between simplicity and accuracy.	Different choices depending on the context. Uncertainties are assessed. Not limited to the engineering community.	Not useful if not considered sufficient accurate.

different sources including databases from state environmental agencies. The study presents the best and worst case scenarios with the aim of providing a technique for decision-making instead of exact results. In addition, the study only focuses on the Marcellus shale and makes several assumptions due to the lack of information.

The environmental and public risk of different pathways of contamination focusing on fluid containment and transport systems associated with the Marcellus shale was analyzed by Ziemkiewicz et al. (2014). The pathways analyzed are integrity of the lining in pits and impoundments and pipelines used to transport fluids to and from the sites studied. Data were collected in the field, including water samples, and with it a probabilistic analysis was performed using event trees and categorization by severity ranking. Likelihood was calculated by taking the ratio of the number of times the problem was observed to the total number of sites evaluated. A binomial distribution was developed based on a population of 70 pits and impoundments with a sample size of 14 sites.

Soeder et al. (2014) performed an engineering risk assessment using an integrated assessment model (IAM), which has been used to assess carbon dioxide storage in geologic systems. The approach to evaluate environmental risk elements is similar for shale formations. Hence, the IAM can be modified for HF by including risk elements that are different from carbon dioxide storage sites. The process intends to identify short and long term risks known as features, events, or processes (FEP). The FEP analysis uses high-fidelity models to evaluate the risks. The output from these numerical models is simplified to reduced-order models which are then used for the IAM (Soeder et al., 2014). The IAM uses laboratory analysis (e.g. microbiological analysis and cement/wellbore analysis), data collected in the field, and numerical modeling (e.g. Monte Carlo simulations of field-scale performance). The disadvantage of the IAM process is that health and ecosystem impacts are beyond its scope.

Casing and cement impairment in conventional and unconventional O&G wells in Pennsylvania was studied by Ingraffea et al. (2014a) using statewide data and the Cox proportional hazards model. The Cox regression, or proportional hazards regression, is a semi-parametric and multivariate analysis that uses the hazard function to study the survival of an individual or object based on a rate instead of a proportion (Ingraffea et al., 2014b). With this model, it was possible to capture temporal and geographic dimensions and hazards ratios of the count of impairment events that were inspected (Ingraffea et al., 2014a). Siegel et al. (2015) collected samples from water wells that were located near 661 O&G wells to study the relationship of methane migration and proximity to existing O&G wells. To evaluate this hypothesis, four statistical tests were used which are: 1) test of proportions to compare samples with a threshold concentration, 2) logistic regression to find a trend, 3) survival analysis to compare statistical distributions between two groups, and 4) correlation analysis between methane concentration and distance (Siegel et al., 2015).

Risk assessment from an engineering perspective has its challenges including the difficulty of assessing uncertainties and assigning probabilities and appropriate values for estimations, ability to distinguish between objective knowledge and subjective judgments, difficulty of working with intangibles and uncertainties, and failure to include temporal data (Aven et al., 2007; Ingraffea et al., 2014a). Some risks are easier to manage than others and the manageability and uncertainties depend on the stage of development of the system (Aven et al., 2007).

Table 6
Risk assessment methods and techniques used in the O&G industry.

Method	Technique	
Environmental risk assessment EPA (1998a)	• Geographic information system (GIS) • Historical imagery data • National security systems (NSS) imagery data	• Boolean logic • Environmental impact assessment • Hazard assessment
Barrier and operational risk analysis (BORA) Aven et al. (2006)	• Risk influencing factors (RIFs) • Barrier block diagrams and influence diagrams	• Frequencies/probabilities • Event trees and fault trees • Checklists and manual inspection
Hazard identification (HAZID) McCoy et al. (1999), Silvianita et al. (2011)	• Failure modes, effects and analysis (FMEA) • Fault/logic tree analysis (FTA)	• Event tree analysis (ETA) • HAZOP
Layers of protection analysis (LOPA) Habibi et al. (2013), Summers (2003)	• Process flow diagrams (PFDs) • Piping and instrumentation diagrams (P&IDs)	• Hazard scenarios • Risk tolerance criteria • HAZOP
Quantitative risk assessment (QRA) Standards Norway (2010)	• RIFs • Frequencies/probabilities • Sub-models • FTA and ETA	• PFDs and P&IDs • FMEA • Task analysis

In the early stages of the system development, the uncertainties and manageability are larger. In addition, non-disclosure agreements that allow companies to hold back contamination reports limit the data availability for risk assessments. Some results from risk assessments regarding contamination cannot always be attributed to HF due to insufficient relevant databases, and lack of pre- and post-information on the presence of methane and petroleum byproducts in the basins (Adgate et al., 2014).

4.3.2. Holistic approach

It is common to include a cost/benefit or cost/effectiveness analysis to the risk assessment but this is not the most adequate approach for unconventional O&G because there will always be an economic justification (Aven et al., 2007). Similarly, using the engineering approach solely will result in an incomplete analysis or even bias because there have been cases of overconfidence in judgments by experts (Aven and Kristensen, 2005; Pidgeon, 1998). A better approach would be a balance between scientific judgments and social beliefs (Pidgeon, 1998; Renn et al., 1992). This unification is based on the idea that hazards are related to psychological, social, institutional and cultural processes in ways that can affect perceptions of risks and dictate risk behaviors (Renn et al., 1992).

Recent expansion of O&G activities has caught the attention of different stakeholders including the general public. This has resulted in sociological studies that consider the public engagement in risk characterization and decision making (North et al., 2014). A review of the different parameters affecting how people perceive risk revealed that the two most important factors are familiarity with the process and trust (Wachinger et al., 2013). Theodori et al. (2014) conducted a survey in the Marcellus shale to study social perception of HF. They found that almost half of the respondents are unfamiliar with the practice and the natural gas industry is considered the least trustworthy source of information. The public mistrust and perception of lack of transparency produces higher levels of stress and with it other health problems (Adgate et al., 2014).

Natural resources dependent communities are often benefited with employment opportunities and business; however, these benefits are short-term (Jacquet, 2014). Previous studies show that massive industrialization and worker immigration in a short period of time result in overwhelmed housing supplies, stressed municipal services (e.g. potable water) and government programs, and disruption in social and economic patterns (Jacquet, 2014). Also, national and regional surveys indicate that perceptions of the impacts are polarized, for example, between financial gain and environmental impacts (Jacquet, 2014). Negative public perceptions of unconventional O&G production can be improved by developing non-toxic fracturing chemicals, community adaptation, use of alternative water sources, full communication between and among the stakeholders, and sharing more information and educating the public about wastewater treatment technologies (Theodori et al., 2014).

Perry (2012) discussed the first draft report by the EPA, Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, and pointed out the flaws it may have regarding the lack of social factors. Thus, the author proposes the use of an iterative analytic-deliberative process, where deliberations are carried out by all the parties involved resulting in better long-term decision making. The uncertainties and risks regarding social, community, and human health factors (societal cost) are evaluated not only by quantitative measurements but also by using local, community and temporal scale and other qualitative criteria (Perry, 2012). The analytic-deliberative process is a promising alternative for a holistic approach to risk governance; however, it has not yet been completely adopted in shale risk assessment (North et al., 2014). Likewise, Aven (2012), Aven and Kristensen (2005), and Pidgeon (1998) proposed a combination of engineering and social science research to open up for new ways of measuring risk and its uncertainties.

Just like risk assessment from an engineering approach, social science research also faces limitations. Some of these constraints are self-selected populations, small sample sizes, short follow-up times and unclear loss to follow-up rates, limited exposure measurements, unavailable exposure data, and if available it is inconsistent, particularly for non-cancer health effects (Adgate et al., 2014). One way to perform risk assessment effectively in the O&G industry would be combining the available information, both engineering and social sciences databases, and use the different techniques mentioned in the previous section to estimate the gaps. This holistic approach would be able to move narrow risk concept based on probabilities to a broader view (Aven and Kristensen, 2005; Pidgeon, 1998). Furthermore, this broader view can help make decisions based on both scientific judgment and public perception (Pidgeon 1998). An idea or suggestion to perform holistic risk assessment in unconventional O&G is proposed by Aven and Kristensen (2005) as shown in Fig. 4.

5. Results from previous risk assessments related to unconventional O&G

Data have shown that most environmental or safety incidents related to shale gas wells result from operations not being performed according to the recommended engineering practices or procedures (Soeder et al., 2014). The potential risks in every stage of the water life cycle that could result from improper procedures and management are discussed in details below.

5.1. Water acquisition

North Dakota is less susceptible to water stress compared to Texas but is still prone to droughts and floods. The North Dakota State Water Commission issues groundwater and surface water withdrawal permits and requires annual reports from users. Furthermore, water from the Missouri River is readily available but only ten miles of it are accessible to O&G operators due to a restriction imposed by the U.S. Army Corps of Engineers (NDSWC, 2014). Despite this, in 2012, HF used 2.08×10^7 m^3 of water, more than the amount used by Fargo, the largest city in the state with a population of 110,000 people (Freyman, 2014).

Hydraulic fracturing is intensively used in Texas where more than half of the wells are located in regions that have medium to extreme high water stress (Freyman, 2014). This means that water is limited since it is already used for other purposes. The climate in Texas ranges from semiarid west to sub-humid east, and in the past years drought has been exceptional or extreme. In 2011, 88% of the state faced maximum drought, with record temperatures above 100 °F (Scanlon et al., 2013). Although water used per well has increased in recent years in the Barnett shale, so has the length of the lateral or horizontal portion of the well, indicating that the water used per length has remained constant (Nicot et al., 2014; Scanlon et al., 2014). Despite this, it is expected that by 2020 the water used for HF in Texas will reach 1.51×10^8 m^3 per year, equivalent to 19,700 Olympic-sized swimming pools (Freyman, 2014).

Pennsylvania is considered to be at low risk of droughts and groundwater challenges (Freyman, 2014). Despite this, the majority of wells (62%) in the Marcellus shale are located in regions considered to have medium water stress, particularly during summer months. This makes the risk of water shortage to be associated mostly with the time of withdrawal rather than the quantity of water available (Freyman, 2014). From 2005 to mid-2013, Pennsylvania used 1.14×10^8 m^3 of water for HF, which is the amount of water consumed by 156,000 people in the same time period (Environment America, 2013; PAPUC, 2014).

The impacts of drought can be environmental or socioeconomic including land degradation, desertification, water scarcity, agriculture and food security, services (e.g. water and energy supply), and conflict over resources (Yan, 2010). A study, where the Standardized Precipitation Indices and the Palmer Drought Severity Index were combined,

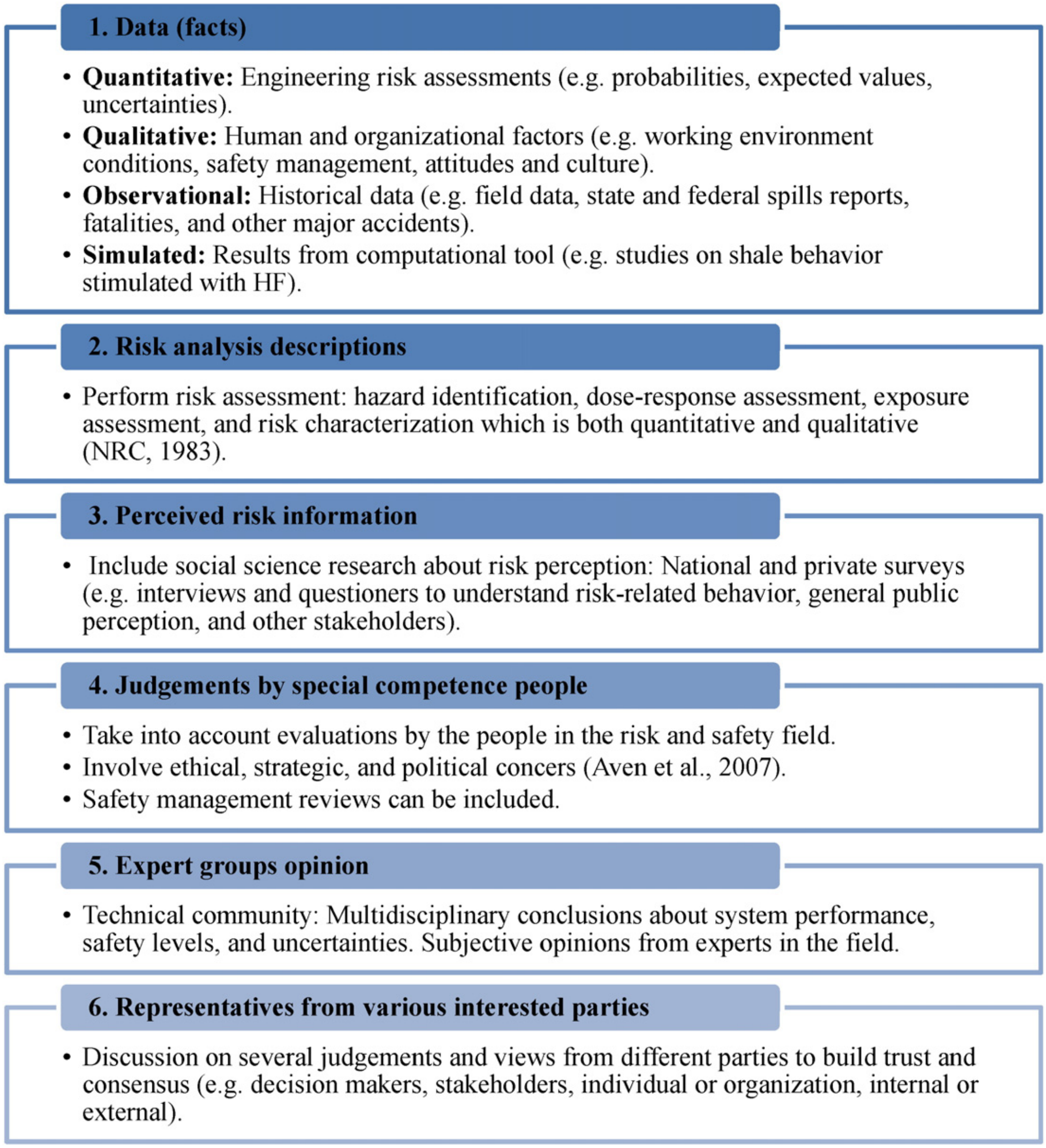

Fig. 4. Holistic approach components to perform risk assessment.

showed that meteorological drought (based on precipitation alone) is expected to increase in some regions of the U.S. while the hydrological drought (based on precipitation and temperature) will affect most of the country by 2050 (Strzepek et al., 2010). Since the beginning of the 20th century, temperature across the U.S. has been increasing to the point that 60% of the country experienced some level of drought during summer of 2012 (USDOE, 2013b). In the last decade, there have been several events that reflect the vulnerability of the energy sector due to decreased water availability including the prohibition by the city of Grand Prairie (Texas) to use city water for HF because of extreme drought in the Fall of 2011 and high prices for water or water access denied to operators for several weeks in Kansas, Texas, Pennsylvania, and North Dakota in 2012 (USDOE, 2013b).

Mitigation of water scarcity can be achieved by prioritizing the application of integrated, cross-enterprise water management, which includes best practices, investment in new technology and application of strategies designed locally because of regional regulations and specific environmental attributes of the shale play (Gay and Slaughter, 2014; Mauter et al., 2014). Environmental stressors associated with shale plays are region specific because of the diversity of hydrospheres, land surfaces, and biospheres (Mauter et al., 2014).

5.2. Chemical mixing

In 2012, the EPA identified more than 1000 chemicals used in HF from which 27 chemicals (Table 7) are known or suspected carcinogens, or listed as hazardous air pollutants that may impact drinking water. In addition, 82 chemicals are considered confidential business information and therefore undisclosed to the public (EPA, 2012). A major concern at this stage is the possible risk of fracturing fluid spills and contamination of drinking water sources but data to quantify the risk are not available. Several databases were analyzed by the EPA (2012) and the information regarding incidents is unclear. It is difficult to quantify the risk of contamination directly related to chemicals and produced water when the reports do not specify the content of the fluids spilled. In addition, most of these spills are reported only by the media (EPA, 2012).

The North Dakota Department of Health (NDDOH) database shows almost 8000 spills of oil, brine, and other chemicals between 2000 and 2013 (Cwiak et al., 2015). Fig. 5 shows the location of the spills reported by the NDDOH. The entities in charge of keeping track of O&G spills in Texas are the Railroad Commission (RRC) and the Commission on Environmental Quality. The Texas RRC keeps reports of spills, which are

Table 7
Chemicals suspected to be carcinogens, hazardous air pollutants (HAP) or regulated under the Safe Drinking Water Act (SDWA) and number of products used in HF that contain these chemicals (EPA, 2012).

Chemicals	Category	No. of products	Chemicals	Category	No. of products
Methanol	HAP	342	Phenol	HAP	5
Ethylene glycol	HAP	119	Benzene	Carcinogen, SDWA, HAP	3
Naphthalene	Carcinogen, HAP	44	Di (2-ethylhexyl) phthalate	Carcinogen, SDWA, HAP	3
Xylene	SDWA, HAP	44	Acrylamide	Carcinogen, SDWA, HAP	2
Hydrochloric acid	HAP	42	Hydrofluoric acid	HAP	2
Toluene	SDWA, HAP	29	Phthalic anhydride	HAP	2
Ethylbenzene	SDWA, HAP	28	Acetaldehyde	Carcinogen, HAP	1
Diethanolamine	HAP	14	Acetophenone	HAP	1
Formaldehyde	Carcinogen, HAP	12	Copper	SDWA	1
Thiourea	Carcinogen	9	Ethylene oxide	Carcinogen, HAP	1
Benzyl chloride	Carcinogen, HAP	8	Lead	Carcinogen, SDWA, HAP	1
Cumene	HAP	6	Propylene oxide	Carcinogen, HAP	1
Nitrilotriacetic acid	Carcinogen	6	p-Xylene	HAP	1
Dimethyl formamide	HAP	5			

categorized as crude, combined liquids, gas well liquid, or products. In 2013–2014, there were 2316 reported spills from which 312 are classified as gas well liquid or products (RRCT, 2015b). In Pennsylvania, according to the EPA, in the period of 2006 to 2012, there were 4319 inspections with violations in the Marcellus shale region. Once again, the nature of the incidents is not clear.

During chemical mixing, there is also a concern of exposure to some of the additives in the fracturing fluid that are known to be toxic; however, the maximum exposure levels without any adverse effects are not clear. Table 8 lists seven chemicals most commonly used in the fracturing fluid, mentioned in Section 3, and their health effects. Due to lack of data about pre- and post-drilling activities, extensive and long-term studies on chemicals exposures and health effects are not available (Adgate et al., 2014). Also, the data required for this type of studies is usually extensive and difficult to collect (Shonkoff et al., 2014; Stern et al., 2014). To date, there are no population-based studies that explain the health impacts of unconventional gas production related to water contamination (Adgate et al., 2014).

Colborn et al. (2011) found that from the total chemicals reported to be used in HF to extract natural gas, more than 75% could affect the skin, eyes, and other sensory organs, and the respiratory and gastrointestinal systems. Also, around 40–50% could affect the nervous system, immune

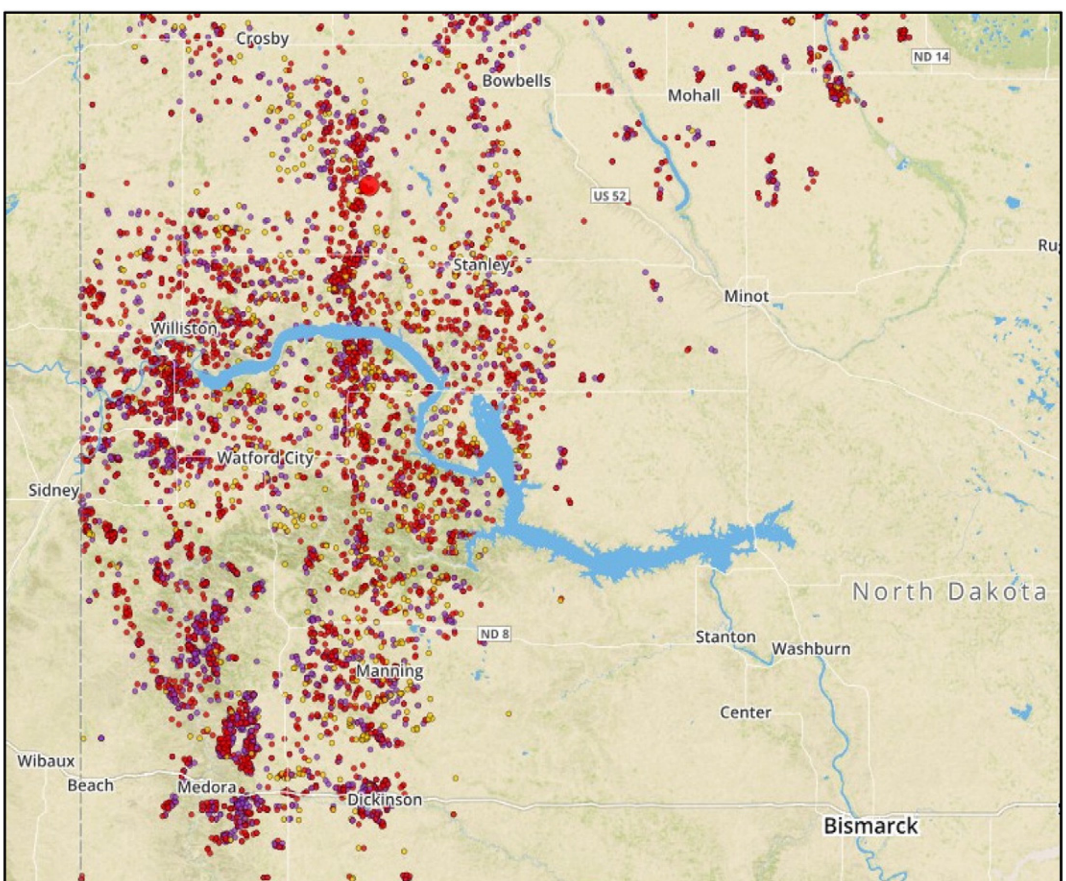

Fig. 5. Spills in North Dakota from 2000 to 2013. Red: oil, purple: brine, and yellow: other.
Adapted from Gage Cartographics (2014).

Table 8
Most common chemicals used in HF fluid, and their limits and health effects.

Chemical	Level	Health effects
Methanol	0.5 mg/kg-day reference dose (RfD), intake level at or below which no health effects are likely to occur even with long-term daily exposures (Saba et al., 2012).	Narcosis, metabolic acidosis. Severe abdominal, leg, and back pain occur and visual degeneration can lead to blindness. High doses of methanol (80–150 mL) are usually fatal to humans.
Isopropanol	400 ppm (980 mg/m^3) total weight average (TWA) — OSHA* permissible exposure limit (PEL)**	Narcosis, mild eye, nose, and throat irritation.
Crystalline silica	50 $\mu g/m^3$ proposed PEL by OSHA.	Silicosis, lung cancer, chronic obstructive pulmonary disease, and kidney disease.
2-Butoxyethanol	240 mg/m^3 OSHA PEL, 1.6 mg/m^3 EPA inhalation reference concentration (RfC).	Mild irritation. Not likely to be carcinogenic to humans at or below the RfC.
Ethylene glycol	100 mg/m^3 threshold limit value (TLV). NIOSH*** recommended exposure limit (REL) has not been established.	Irritation—eye, nose, throat, skin.
Hydrotreated light petroleum distillates	100 mg/m^3 NIOSH recommended TWA 10 h.	Irritation, nausea, headache, drowsiness, symptoms of drunkenness, lung congestion, convulsions, coma.
Sodium hydroxide	2 mg/m^3 TWA OSHA PEL.	Ulceration of nasal passages. Eye, skin, and respiratory irritation.

* OSHA: Occupational Safety and Health Administration.
** PELs are based on 8-h time weight average exposure limit.
*** NIOSH: National Institute for Occupational Safety and Health.

and cardiovascular system and kidneys. In addition, of the total chemicals used, 37% affect the endocrine system and 25% could cause cancer.

5.3. Well injection (HF)

Groundwater contamination could be caused by fluid migration through natural or induced fractures. Previous studies suggest that pathways for gas can also serve as pathways for HF fluid migration (Osborn et al., 2011; Warner et al., 2012). Osborn et al. (2011) analyzed 68 private groundwater wells to determine the concentrations of dissolved salts, water isotopes, and isotopes of dissolved carbon, boron, and radium. From these wells, 60 were also analyzed for methane and higher-chain hydrocarbons content. The study found that 85% of the wells contained methane concentrations within the defined action level for hazard migration. The source of methane in shallow groundwater for active extraction sites was thermogenic (shale) while a more biogenic or mixed biogenic/thermogenic methane source was the case for non-active sites.

Results from Engelder et al. (2014) indicate that the flowback and produced water that remain inside the well do not pose a threat to shallow aquifers by migrating upward along natural pathways because the capillary and osmotic forces keep the fluids permanently inside the shale matrix. Flewelling et al. (2013) reported that fractures after the hydraulic stimulation are less than 600 m above well perforation which is insufficient to reach groundwater resources. In addition, Reilly et al. (2015) found through chemical analysis that the most common source of groundwater contamination is septic effluent. Similar to the observations made by Osborn et al. (2011), Jackson et al. (2013) found that 82% of the drinking well water samples contained methane and from the different factors analyzed, distance to gas wells was the dominant one. Their results show that the methane found is of thermogenic origin, which suggests that it reaches shallow well water through casing failures or imperfections in cement annulus of the gas wells. A more recent study has found no relationship between dissolved methane concentrations and proximity to existing O&G wells (Siegel et al., 2015). Siegel et al. (2015) analyzed groundwater samples from locations near gas wells and found no evidence of systematic increased methane concentration closer to these wells.

Groundwater contamination could be also caused by HF fluid migration due to casing failure. According to the study conducted by Rozell and Reaven (2012), the probability of a well failing ranges from 2.0×10^{-8} to 2.0×10^{-2} and the chance of a well leaking per year is from 1×10^{-6} to 0.1. Pennsylvania records show that between 0.7% and 9.1% of the O&G wells developed since 2000 show a loss of well integrity and the higher risks are observed in unconventional wells (Ingraffea et al., 2014a). However, the hazard modeling conducted in the same study indicates that the loss of structural integrity is actually 12% for unconventional wells drilled since 2009. Furthermore, this and other studies indicate that the most common methane migration mechanism, if not coming from a natural source, is this loss of integrity of the cement and casing of the wells (Ingraffea et al., 2014a; Vengosh et al., 2014).

5.4. Flowback and produced water production

The risk of spills and/or leaks could result in surface and groundwater contamination similar to the stages of chemical mixing and well injection (EPA, 2012). A constraint to assessing risks associated with this stage is that specific spill data related to produced water is not completely available to the public. During 2012, in North Dakota, 25.5 million barrels of brine were generated and there were 141 reports of pipeline leaks from which approximately 8000 barrels of brine were spilled (Al Jazeera America, 2014). The Texas RRC and the Commission on Environmental Quality track spills mostly from oil, gas and liquid condensate but there are no reports related to HF fluids (EPA, 2012).

Flowback and produced water contain high concentrations of different contaminants which complicate the treatment to reach acceptable levels for discharge and reuse. Some of the organic and inorganic contaminants found in produced water are listed in Tables 9 and 10, respectively (ATSDR, 1999; EPA, 2004; Maguire-Boyle and Barron, 2014; Orem et al., 2014; Wilson and VanBriesen, 2012). Organics constituents can be originated in the produced water, the shale itself, the oil in the shale, or the fracturing fluid (added chemicals) (Orem et al., 2014). One additive used intensively in the fracturing fluid is gel, generally guar gum and its derivatives, to increase the viscosity of water and improve the transport of sand into the fractures (Lester et al., 2014). The gel does not pose a threat to health but it may have effects on membrane separation treatment processes affecting the efficiency of contaminant removal (Lester et al., 2014).

Studies indicate that the radioactivity in most produced waters is directly proportional to the content of salts (Brown, 2014; Fisher, 1998). The content of radium-226 in the Marcellus shale produced water can be higher than 10,000 pCi/L while the standard for drinking water (Ra-226 and Ra-228) is just 5 pCi/L (Brown, 2014; Osborn et al., 2011). In North Dakota, radioactive material has been found in different waste streams from O&G activities, mostly scale in equipment, in concentrations above natural backgrounds (Argonne National Laboratory, 2014). Also, a study conducted in the Barnett shale found that the

Table 9
Organic contents of produced water from typical shale gas wells and their health effects.

Compound type	Level/source	Health effect of different compounds
Dissolved organic carbon	Hydrocarbons found in the produced water at levels as high as 5500 mg/L	• Cyclic octaatomic sulfur: microbiological activity indicator • Straight chain alkanes/alkenes: mucosal irritation in nasal turbinates and larynx in rat, cystic uterine endometrial hyperplasia in mice, and carcinogenic potential • Aromatics and aliphatics: hepatic and renal effects, hemolytic anemia, and respiratory irritant effects in animals • Carboxylic acids: low genotoxic potential
Added organic chemicals	Found in the flowback water at levels >1000 μg/L per individual compound	• Aliphatic hydrocarbons (solvents): respiratory irritant effects in animals, asphyxia and chemical pneumonitis • Brominated nitrilopropionamides and hexahydro-1,3,5-trimethyl-1,3,5-triazine-2-thione (biocide): developmental, reproductive, mutagenic, carcinogenic, or neurological effects • Ethylene glycol and derivatives (cross linker and scale inhibitors): central nervous system depression, cardiopulmonary effects, and renal damage • Guar gum and diesel fuel (gelling agent): guar gum does not pose a threat but diesel fuel contains known carcinogens • Ethanol (foaming agent): malnutrition, effects on hepatic metabolism and immunological functions • Methanol (corrosion inhibitor): visual disturbances, neurological damage, dermatitis • Fatty acid phthalate esters (breaker): liver effects
Benzene, toluene, ethylbenzene, and xylene (BTEX)	Contained in diesel used as a gelling agent	• Cancer risk, neurological effects, primarily central nervous system depression, ototoxicity, hemato-logical, immunological, and lymphoreticular effects.
Polycyclic aromatic hydrocarbons (PAHs)	Lower than off-shore produced waters	• Carcinogenic, reproductive problems in mice, and respiratory effects
Volatile fatty acids (VFAs)	Produced by bacteria. Maximum level of 53.7 mg/L.	• Aliphatic acid anion (primarily acetate): induces headache in sensitized rats, corrosive for the skin, eye damage, and mucous membranes irritation. VFAs are responsible for unpleasant odor in wastewater

total beta radiation in a reserve pit was eight times higher than the regulated limit (Brown, 2014).

5.5. Wastewater treatment and waste disposal

Surface spills can be caused by leaking reserve pits and pipes, transportation accidents, and improper treatment followed by stream discharge. All of these scenarios present a threat of drinking water contamination (EPA, 2012). The purpose of wastewater treatment is to eliminate the TDS, which are mostly derived from the subsurface or lower the concentration to acceptable level before discharge (Lutz et al., 2013). However, not all treatment plants have the capacity or the technology to successfully remove naturally occurring salts (Wilson and VanBriesen, 2012). Another limitation of wastewater treatment plants is that the content of the produced water is difficult to predict because it varies with time, location, and composition of the fracturing fluid (Barbot et al., 2013).

Ferrar et al. (2013) found that in Pennsylvania prior to a voluntary cessation of off-site treatment (requested by the Pennsylvania Department of Environmental Protection) in 2011, the concentrations of contaminants in the wastewater treatment plants effluents were above quality criteria. After the cessation, the contaminant concentrations in the receiving waters decreased suggesting that on-site treatment is more effective than off-site plants (Ferrar et al., 2013). Brine treatment can reduce concentrations of NORM by more than 90% (Warner et al., 2013a). However, there are still high levels of NORM in receiving stream sediments, which pose the risk of bioaccumulation in the food chain (Brown, 2014; Warner et al., 2013a). Health effects of radium consumption in drinking water include tooth fracture, anemia, cataracts, and cancer if the exposure is chronic (Rich and Crosby, 2013). In addition, trihalomethanes and other disinfection by-products are produced during the water treatment process due to the elevated bromide and chloride concentration and their reaction with organic compounds which present health risks (Brown, 2014; EPA 2012; Vengosh et al., 2014; Warner et al., 2013a).

Wilson and VanBriesen (2012) found that operators in Pennsylvania have been shifting to recycling and reusing methods and have reduced discharges to surface water bodies. The study shows an increasing rate of water reuse within operations and treatment at publicly owned treatment works and centralized waste treatment plants with effluent limitations established by the EPA (EPA, 2003). These non-discharging methods have reduced the levels of bromide that were being released to the environment, but acceptable levels for water treatment plants have not been determined (Wilson and VanBriesen, 2012).

Table 10
Inorganic contents of produced water from typical shale gas wells, and their health effects and regulatory levels.

Contents	Health effects	Regulatory levels
Sodium	Unlikely to have adverse health effects	20–60 mg/L for esthetic effects (recommended)
Calcium and magnesium	Causes hardness in water but don not represent a threat to health	500 mg/L (total dissolved solids)
Potassium	High doses can affect health in people with kidney disease, heart disease, coronary artery disease, hypertension, diabetes, adrenal insufficiency, and people with limited renal reserve are more vulnerable.	4.7 g/day adequate intake for adults
Iron	Not a threat to health	0.3 mg/L recommended
Strontium	Strontium accumulates in bones. Children are more vulnerable to excess strontium.	4.0 mg/L lifetime health advisory level
Barium	Causes increase in blood pressure	2 mg/L
Chloride	Unlikely to have adverse health effects	250 mg/L
Bromide	In high and chronic doses, vomiting or stupor, depression, loss of muscle coordination and psychoses. Increases formation of disinfection by-products that are carcinogenic and potentially teratogenic	1.0 ppm

Transportation of wastewater for treatment or disposal requires a considerable number of trucks, which increases the probability of traffic accidents that could result in spills. In the Bakken shale region, there was an increase of 68% of crashes involving trucks from 2006 to 2010 (Environment America, 2013). In the Eagle Ford region, the Texas Department of Transportation reported a 40% increase in fatal motor vehicle accidents from 2008 to 2011 (Adgate et al., 2014). Likewise, the Crash Reporting System from the Pennsylvania Department of Transportation reported an increase in accidents involving heavy trucks between 1997 and 2011 (Adgate et al., 2014).

According to the EPA, 7.6×10^6 m^3 of brine is disposed per day in the 144,000 class II injection wells all over the country. Deep-well injection is one of the most common methods used but additional research is required to determine the long term impacts, especially on groundwater and seismic activity, and to accommodate the demand of produced water volumes (Arthur et al., 2008). There is one study by the EPA (1998b) that determined that the probability of wastewater migration to groundwater resources is very unlikely and depends on the thickness of the low permeability strata overlying the receiving formation.

6. Future research directions

Earlier risk assessment techniques focused mostly on providing numerical results giving a narrow view of the issue. The best way to assess risks to water quantity and quality due to unconventional O&G production is through a comprehensive approach that includes an analysis of every stage of the water life cycle where social factors are considered as well. This holistic risk assessment approach should include results from previous risk assessments, social perception studies, and opinions of different parties involved. With this, a comprehensive model for risk characterization could be developed. Different sources of information can be used to perform the holistic risk assessment including the EPA study, which is in the final peer-review stage. The comprehensive model should take into account different factors, both quantitative and qualitative, such as mechanical, human and organizational aspects and public perception. The model could evaluate the risks in every stage of the water life cycle and determine the level of impact (low, medium or high). By doing this, the risks can be prioritized based on every factor involved, which is lacking in previous risk assessments, and the best mitigation plans to control them can be developed.

7. Conclusions

Unconventional O&G production is a water-intensive process that requires great collection of data to perform risk assessment and reduce uncertainties. To date, there are very few risk assessments on onshore unconventional O&G that include social factors. The public information about the chemicals and effects on health is incomplete because some of them are considered confidential, which has created mistrust towards the industry. A holistic risk assessment should be performed to completely understand the impacts involved in the process. In addition to this analysis, risk mitigation strategies can improve safety and reduce negative perceptions from different stakeholders.

The risk of spills that is present in several stages of the process can be avoided with proper handling and management techniques. During well injection, the chances of well failure and leakage are very low but proper well integrity tests are always required. Produced water management can be improved by applying proper handling techniques, reducing transportation, and increasing inspection of storage tanks, pits/impoundments, and pipes. Finally, zero discharge wastewater techniques minimize the risk associated with improper treatment followed by stream discharge.

Understanding the water issues present in the U.S. due to unconventional O&G production is necessary for the development of strategies to minimize water shortage and contamination. These strategies have to consider environmental, cultural, and political systems to offer integrated solutions. Emerging international shale plays have the opportunity to learn from the U.S. experience to develop their own strategies for water and wastewater management.

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References

Adgate, J.L., Goldstein, B.D., McKenzie, L.M., 2014. Potential public health hazards, exposures and health effects from unconventional natural gas development. Environ. Sci. Technol. 48, 8307–8320.

Al Jazeera America, 2014. Cleanup of North Dakota pipeline spill may take weeks. http://america.aljazeera.com/articles/2014/7/10/north-dakota-saltwater.html (accessed 12.12.15).

API, 2010. Water management associated with hydraulic fracturing. http://www.api.org/~/media/files/policy/exploration/hf2_e1.pdf (accessed 9.15.14).

Argonne National Laboratory, 2014. Radiological dose and risk assessment of landfill disposal of technologically enhanced naturally occurring radioactive materials (TENORM) in North Dakota. TENORM Landfill Study (ANL EVS-14_13) Final Report.pdf (https://www.ndhealth.gov/EHS/Tenorm/ArgonneStudy/ANL-NDDH, accessed 5.25.15).

Arthur, D., Bohm, B., Coughlin, B., Layne, M., 2008. Evaluating the environmental implications of hydraulic fracturing in shale gas reservoirs. http://www.all-llc.com/publicdownloads/ArthurHydrFracPaperFINAL.pdf (accessed 10.14.14).

ATSDR, 1999. Toxicological profile for total petroleum hydrocarbons (TPH). http://www.atsdr.cdc.gov/toxprofiles/tp123-c6.pdf (accessed 3.20.15).

Aven, T., 2012. The risk concept—historical and recent development trends. Reliab. Eng. Syst. Saf. 99, 33–44.

Aven, T., Kristensen, V., 2005. Perspectives on risk: review and discussion of the basis for establishing a unified and holistic approach. Reliab. Eng. Syst. Saf. 90, 1–14.

Aven, T., Hauge, S., Sklet, S., Vinnem, J.E., 2006. Methodology for incorporating human and organizational factors in risk analysis for offshore installations. Int. J. Mater. Struct. Reliab. 4, 1–14.

Aven, T., Vinnem, J.E., Wiencke, H.S., 2007. A decision framework for risk management, with application to the offshore oil and gas industry. Reliab. Eng. Syst. Saf. 92, 433–448.

AWWA, 2013. Water and hydraulic fracturing. http://www.awwa.org/Portals/0/files/legreg/documents/AWWAFrackingReport.pdf (accessed 9.15.14).

Barbot, E., Vidic, N.S., Gregory, K.B., Vidic, R.D., 2013. Spatial and temporal correlation of water quality parameters of produced waters from Devonian-age shale following hydraulic fracturing. Environ. Sci. Technol. 47, 2562–2569.

Boschee, P., 2014. Produced and flowback water recycling and reuse: economics, limitations, and technology. Oil Gas Facil. 3, 16–21.

Brown, V.J., 2014. Radionuclides in fracking wastewater: managing a toxic blend. Environ. Health Perspect. 122, A50–A55.

Cacciabue, P., 2004. Human error risk management for engineering systems: a methodology for design, safety assessment, accident investigation and training. Reliab. Eng. Syst. Saf. 83, 229–240.

Cai, B., Liu, Y., Liu, Z., Tian, X., Zhang, Y., Ji, R., 2013. Application of bayesian networks in quantitative risk assessment of subsea blowout preventer operations. Risk Anal. 33, 1293–1311.

Chesapeake Energy Corporation, 2011a. High rate HF in non-Marcellus unconventional shale. http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/highratehfinnon-marcellusunconventionalshale.pdf (accessed 10.12.14).

Chesapeake Energy Corporation, 2011b. Produced water reuse and recycling challenges and opportunities across major shale plays. http://www2.epa.gov/sites/production/files/documents/09_Mantell_-_Reuse_508.pdf (accessed 08.17.15).

Chung, C., Salas, J.D., 2000. Drought occurrence probabilities and risks of dependent hydrologic processes. J. Hydrol. Eng. 5, 259–268.

Colborn, T., Kwiatkowski, C., Schultz, K., Bachran, M., 2011. Natural gas operations from a public health perspective. Hum. Ecol. Risk. Assess. 17, 1039–1056.

Cwiak, C., Avon, N., Kellen, C., Mott, P., Niday, O., Schulz, K., Sink, J., Webb Jr., T., 2015. The new normal: the direct and indirect impacts of oil drilling and production on the emergency management function in North Dakota. https://www.ndsu.edu/fileadmin/emgt/FINALThe_New_Normal_January_2015_a.pdf (accessed 2.10.15).

Detrow, S., 2012. Deep injection well: how waste water gets disposed underground. http://stateimpact.npr.org/pennsylvania/tag/deep-injection-well/ (accessed 10.6.14).

Ditria, J.C., Hoyack, M.E., 1994. The separation of solids and liquids with hydrocyclone-based technology for water treatment and crude processing. SPE Asia Pacific Oil and Gas Conference. Society of Petroleum Engineers, Melbourne, Australia.

Easton, J., 2013. Centered on wastewater treatment. Ind. Water Waste Dig. 10–13.

EERC, 2010. Bakken water opportunities assessment – phase 1. http://www.nd.gov/ndic/ogrp/info/g-018-036-fi.pdf (accessed 08.17.15).

EIA, 2013. Technically recoverable shale oil and shale gas resources: an assessment of 137 shale formations in 41 countries outside the United States. http://www.eia.gov/analysis/studies/worldshalegas/ (accessed 1.20.15).

EIA, 2014. Drilling productivity report for key tight oil and shale gas regions. http://www.eia.gov/petroleum/drilling/archive/dpr_oct14.pdf (accessed 11.15.14).

Engelder, T., Cathles, L.M., Bryndzia, L.T., 2014. The fate of residual treatment water in gas shale. J. Unconv. Oil Gas Resour. 7, 33–48.
Environment America, 2013. Fracking by the numbers key impacts of dirty drilling at the state and national level. http://www.environmentamerica.org/reports/ame/fracking-numbers (accessed 11.18.14).
Environment Texas Research and Policy Center, 2013. Keeping water in our rivers strategies for conserving limited water supplies. http://environmenttexas.org/reports/txe/keeping-water-our-rivers (accessed 8.13.15).
EPA, 1998a. Guidelines for ecological risk assessment. http://www2.epa.gov/sites/production/files/2014-11/documents/eco_risk_assessment1998.pdf (accessed 9.8.14).
EPA, 1998b. Technical support document for section 194.32: fluid injection analysis. Docket A-93–02, V-B-22. Washington, DC.
EPA, 2003. Effluent limitations guidelines, pretreatment standards, and new source performance standards for the centralized waste treatment point source category final rule. https://www.federalregister.gov/articles/2003/12/22/03-31346/effluent-limitations-guidelines-pretreatment-standards-and-new-source-performance-standards-for-the (accessed 11.26.14).
EPA, 2004. Chapter 4 hydraulic fracturing fluids. http://www.epa.gov/ogwdw/uic/pdfs/cbmstudy_attach_uic_ch04_hyd_frac_fluids.pdf (accessed 1.4.15).
EPA, 2011. Reduced emissions completions for hydraulically fractured natural gas wells. http://www.epa.gov/gasstar/documents/reduced_emissions_completions.pdf (accessed 1.14.15).
EPA, 2012. Study of the potential impacts of hydraulic fracturing on drinking water resources progress report. http://www2.epa.gov/sites/production/files/documents/hf-report20121214.pdf (accessed 10.1.14).
EPA, 2014. Final updates and clarifications for requirements for well completions, storage tanks and natural gas processing plants. http://www.epa.gov/airquality/oilandgas/pdfs/20141219fs.pdf (accessed 1.14.15).
Ferrar, K.J., Michanowicz, D.R., Christen, C.L., Mulcahy, N., Malone, S.L., Sharma, R.K., 2013. Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania. Environ. Sci. Technol. 47, 3472–3481.
Fisher, R.S., 1998. Geologic and geochemical controls on naturally occurring radioactive materials (NORM) in produced water from oil, gas, and geothermal operations. Environ. Geosci. 5, 139–150.
Fjeld, R.A., Eisenberg, N.A., Compton, K.L., 2007. Quantitative Environmental Risk Analysis for Human Health. John Wiley & Sons, Hoboken, New Jersey.
Flewelling, S.A., Tymchak, M.P., Warpinski, N., 2013. Hydraulic fracture height limits and fault interactions in tight oil and gas formations. Geophys. Res. Lett. 40, 3602–3606.
FracFocus, 2014a. Introduction to chemical use. http://www.fracfocus.org/water-protection/drilling-usage (accessed 10.6.14).
FracFocus, 2014b. Why chemicals are used. http://www.fracfocus.org/chemical-use/why-chemicals-are-used (accessed 10.6.14).
Freyman, M., 2014. Hydraulic fracturing & water stress: water demand by the numbers. http://www.ceres.org/issues/water/shale-energy/shale-and-water-maps/hydraulic-fracturing-water-stress-water-demand-by-the-numbers (accessed 10.20.14).
Gage Cartographics, 2014. North Dakota oilfield spills. http://gagecartographics.com/portfolio/north-dakota-oilfield-spills/ (accessed 3.20.15).
Gay, M., Slaughter, A., 2014. Water management, a new paradigm for the oil and gas sector. http://blog.ihs.com/q11-water-management-a-new-paradigm-for-the-oil-and-gas-sector (accessed 1.14.15).
Habibi, E., Zare, S., Keshavarzi, M., Mousavi, M., Yousefi, H., 2013. The application of the Layer of Protection Analysis (LOPA) in sour water refinery process. Int. J. Environ. Health Eng. 2, 48.
Halliburton, 2015. Fluids disclosure. http://www.halliburton.com/public/projects/pubsdata/Hydraulic_Fracturing/fluids_disclosure.html (accessed 8.11.15).
Iannacchione, A., Brady, T., Varley, F., 2008. The application of Major Hazard Risk Assessment (MHRA) to eliminate multiple fatality occurrences in the US minerals industry. http://stacks.cdc.gov/view/cdc/9742 (accessed 9.10.14).
ICND, 2012. Industrial commission OKs rule changes governing oil industry. http://www.nd.gov/ndic/ic-press/dmr-oilrules.pdf (accessed 3.3.15).
Ingraffea, A.R., Wells, M.T., Santoro, R.L., Shonkoff, S.B.C., 2014a. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. Proc. Natl. Acad. Sci. U. S. A. 111, 10955–10960.
Ingraffea, A.R., Wells, M.T., Santoro, R.L., Shonkoff, S.B.C., 2014b. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania: 2000–2012. Supplemental information. http://www.pnas.org/content/suppl/2014/06/26/1323422111.DCSupplemental/pnas.1323422111.sapp.pdf (accessed 3.20.15).
Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., Osborn, S.G., Zhao, K., Karr, J.D., 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proc. Natl. Acad. Sci. U. S. A. 110, 11250–11255.
Jacquet, J.B., 2014. Review of risks to communities from shale energy development. Environ. Sci. Technol. 48, 8321–8333.
Lester, Y., Yacob, T., Morrissey, I., Linden, K.G., 2014. Can we treat hydraulic fracturing flowback with a conventional biological process? The case of guar gum. Environ. Sci. Technol. Lett. 1, 133–136.
Lin, M., Chen, C., 2011. Using GIS-based spatial geocomputation from remotely sensed data for drought risk-sensitive assessment. Int. J. Innov. Comput. Inf. Control 7, 657–668.
Lutz, B.D., Lewis, A.N., Doyle, M.W., 2013. Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development. Water Resour. Res. 49, 647–656.
Maguire-Boyle, S.J., Barron, A.R., 2014. Organic compounds in produced waters from shale gas wells. Environ. Sci. Process. Impacts 16, 2237–2248.
Manning, F.S., Thompson, R.E., 1995. Oilfield Processing of Petroleum: Crude Oil. PennWell Books, Tulsa, Oklahoma.
Marhavilas, P., Koulouriotis, D., 2012a. The deterministic and stochastic risk assessment techniques in the work sites: a FTA-TRF case study. http://cdn.intechopen.com/pdfs/36098.pdf (accessed 11.5.14).
Marhavilas, P., Koulouriotis, D., 2012b. Developing a new alternative risk assessment framework in the work sites by including a stochastic and a deterministic process: a case study for the Greek Public Electric Power Provider. Saf. Sci. 50, 448–462.
Mauter, M.S., Alvarez, P.J.J., Burton, A., Cafaro, D.C., Chen, W., Gregory, K.B., Jiang, G., Li, Q., Pittock, J., Reible, D., Schnoor, J.L., 2014. Regional variation in water-related impacts of shale gas development and implications for emerging international plays. Environ. Sci. Technol. 48, 8298–8306.
McCoy, S.A., Wakeman, S.J., Larkin, F.D., Jefferson, M.L., Chung, P.W.H., Rushton, A.G., Lees, F.P., Heino, P.M., 1999. HAZID, a computer aid for hazard identification. Process. Saf. Environ. Prot. 77, 317–327.
Modarres, M., 2006. Risk Analysis in Engineering: Techniques, Tools, and Trends. CRC Press, Boca Raton, Florida.
NASA, 2011. Probabilistic risk assessment procedures guide for NASA managers and practitioners. http://www.hq.nasa.gov/office/codeq/doctree/SP20113421.pdf (accessed 9.25.14).
NDCC, 2012. Chapter 43-02-03 oil and gas conservation. http://www.legis.nd.gov/information/acdata/pdf/43-02-03.pdf?20150306121451 (accessed 3.5.15).
NDDMR, 2011. NDPC Annual 09/21/11. http://www.ndoil.org/image/cache/NDPCAnnual092111_2.pdf (accessed 3.5.15).
NDSWC, 2014. Facts about North Dakota: fracking & water usage. http://www.swc.nd.gov/4dlink9/4dcgi/getcontentpdf/pb-2419/factsheet.pdf (accessed 9.5.14).
Nicot, J.-P., Scanlon, B.R., Reedy, R.C., Costley, R.A., 2014. Source and fate of hydraulic fracturing water in the Barnett Shale: a historical perspective. Environ. Sci. Technol. 48, 2464–2471.
North, D.W., Stern, P.C., Webler, T., Field, P., 2014. Public and stakeholder participation for managing and reducing the risks of shale gas development. Environ. Sci. Technol. 48, 8388–8396.
NPC, 2011. Management of produced water from oil and gas wells. http://www.npc.org/Prudent_Development-Topic_Papers/2-17_Management_of_Produced_Water_Paper.pdf (accessed 1.14.15).
NRC, 1983. Risk assessment in the federal government: managing the process. http://www.nap.edu/openbook.php?record_id=366 (accessed 3.18.15).
Orem, W., Tatu, C., Varonka, M., Lerch, H., Bates, A., Engle, M., Crosby, L., McIntosh, J., 2014. Organic substances in produced and formation water from unconventional natural gas extraction in coal and shale. Int. J. Coal Geol. 126, 20–31.
Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc. Natl. Acad. Sci. U. S. A. 108, 8172–8176.
PADEP, 2009. State water plan principles. http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-76835/3010-BK-DEP4222.pdf (accessed 10.12.14).
PADEP, 2013. 2013 oil and gas annual report. http://www.portal.state.pa.us/portal/server.pt/community/annual_report/21786 (accessed 11.2.14).
PADEP, 2014. 2014 Pennsylvania integrated water quality monitoring and assessment report. http://www.portal.state.pa.us/portal/server.pt/community/water_quality_standards/10556/draft_integrated_water_quality_report_-_2014/1702856 (accessed 12.5.14).
PAPUC, 2014. Water: we all need it. We always need it. http://www.puc.state.pa.us/general/consumer_ed/pdf/waterbrochure.pdf (accessed 8.19.15).
Perry, S.L., 2012. Environmental reviews and case studies: addressing the societal costs of unconventional oil and gas exploration and production: a framework for evaluating short-term, future, and cumulative risks and uncertainties of hydrofracking. Environ. Pract. 14, 352–365.
Pidgeon, N., 1998. Risk assessment, risk values and the social science programme: why we do need risk perception research. Reliab. Eng. Syst. Saf. 59, 5–15.
Reilly, D., Singer, D., Jefferson, A., Eckstein, Y., 2015. Identification of local groundwater pollution in northeastern Pennsylvania: Marcellus flowback or not? Environ. Earth Sci. 73, 8097–8109.
Renn, O., Burns, W.J., Kasperson, J.X., Kasperson, R.E., Slovic, P., 1992. The social amplification of risk: theoretical foundations and empirical applications. J. Soc. Issues 48, 137–160.
Rich, A.L., Crosby, E.C., 2013. Analysis of reserve pit sludge from unconventional natural gas hydraulic fracturing and drilling operations for the presence of technologically enhanced naturally occurring radioactive material (TENORM). New Solut. 23, 117–135.
Rozell, D.J., Reaven, S.J., 2012. Water pollution risk associated with natural gas extraction from the Marcellus Shale. Risk Anal. 32, 1382–1393.
RRCT, 2013. Eagle Ford shale task force report. http://www.rrc.state.tx.us/media/8051/eagle_ford_task_force_report-0313.pdf (accessed 11.19.14).
RRCT, 2015a. Chapter III — pollution potential and statewide regulation. http://www.rrc.state.tx.us/oil-gas/applications-and-permits/environmental-permit-types-information/chapter-3-pollution-potential/ (accessed 3.6.15).
RRCT, 2015b. Crude oil, gas well liquids or associated products (h-8) loss reports. http://www.rrc.state.tx.us/oil-gas/compliance-enforcement/h-8/ (accessed 3.22.15).
Saba, T., Mohsen, F., Garry, M., Murphy, B., Hilbert, B., 2012. Methanol use in hydraulic fracturing fluids. http://www.methanol.org/Environment/Resources/Environment/Methanol-Fracking-Fluid-White-Paper-Aug-2011.aspx (accessed 10.20.14).
SARS, 2011. Applied R&M manual for defence systems part D - supporting theory. http://www.sars.org.uk/old-site-archive/BOK/AppliedR&MManualforDefenceSystems(GR-77)/p4c00.htm (accessed 1.6.15).
Scanlon, B.R., Duncan, I., Reedy, R.C., 2013. Drought and the water–energy nexus in Texas. Environ. Res. Lett. 8, 045033.
Scanlon, B.R., Reedy, R.C., Nicot, J.-P., 2014. Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. Environ. Sci. Technol. 48, 12386–12393.

Shonkoff, S.B., Hays, J., Finkel, M.L., 2014. Environmental public health dimensions of shale and tight gas development. Environ. Health Perspect. 122, 787–795.
Siegel, D.I., Azzolina, N.A., Smith, B.J., Perry, A.E., Bothun, R.L., 2015. Methane concentrations in water wells unrelated to proximity to existing oil and gas wells in northeastern Pennsylvania. Environ. Sci. Technol. 49, 4106–4112.
Silvianita, S., Khamidi, M., Kurian, V., 2011. Critical review of a risk assessment method and its applications. 2011 International Conference on Financial Management and Economics. IACSIT Press, Singapore, pp. 83–87.
Skalak, K.J., Engle, M.A., Rowan, E.L., Jolly, G.D., Conko, K.M., Benthem, A.J., Kraemer, T.F., 2014. Surface disposal of produced waters in western and southwestern Pennsylvania: potential for accumulation of alkali-earth elements in sediments. Int. J. Coal Geol. 126, 162–170.
Skogdalen, J.E., Vinnem, J.E., 2011. Quantitative risk analysis offshore—human and organizational factors. Reliab. Eng. Syst. Saf. 96, 468–479.
Skogdalen, J.E., Vinnem, J.E., 2012. Quantitative risk analysis of oil and gas drilling, using Deepwater Horizon as case study. Reliab. Eng. Syst. Saf. 100, 58–66.
Soeder, D.J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A., Capo, R., 2014. An approach for assessing engineering risk from shale gas wells in the United States. Int. J. Coal Geol. 126, 4–19.
Standards Norway, 2010. Norsok standard: risk and emergency preparedness analysis, Z-013. http://www.govmin.gl/images/stories/petroleum/norsok/z013u3_Risk_and_Emergency_preparedness_assessment.pdf (accessed 4.19.15).
Stern, P.C., Webler, T., Small, M.J., 2014. Special issue: understanding the risks of unconventional shale gas development. Environ. Sci. Technol. 48, 8287–8288.
Strzepek, K., Yohe, G., Neumann, J., Boehlert, B., 2010. Characterizing changes in drought risk for the United States from climate change. Environ. Res. Lett. 5, 044012.
Summers, A.E., 2003. Introduction to layers of protection analysis. J. Hazard. Mater. 104, 163–168.
TAC, 1977. Title 16, Part 1, Chapter 3: oil and gas division. http://texreg.sos.state.tx.us/public/readtac$ext.TacPage?sl=T&app=9&p_dir=N&p_rloc=7489&p_tloc=&p_ploc=1&pg=7&p_tac=&ti=16&pt=1&ch=3&rl=8 (accessed 3.6.15).
Theodori, G.L., Luloff, A.E., Willits, F.K., Burnett, D.B., 2014. Hydraulic fracturing and the management, disposal, and reuse of frac flowback waters: views from the public in the Marcellus Shale. Energy Res. Soc. Sci. 2, 66–74.
USDOE, 2013a. Natural gas from shale: questions and answers. http://energy.gov/sites/prod/files/2013/04/f0/what_is_shale_gas.pdf (accessed 10.18.15).
USDOE, 2013b. U.S. energy sector vulnerabilities to climate change and extreme weather. http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather (accessed 4.30.15).
USDOE, 2014. Environmental impacts of unconventional natural gas development and production. http://www.netl.doe.gov/research/oil-and-gas/publications (accessed 4.24.15).
USGS, 2014. U.S. Geological Survey national produced waters geochemical database v2.1. http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data (accessed 8.18.15).
Vengosh, A., Jackson, R.B., Warner, N., Darrah, T.H., Kondash, A., 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environ. Sci. Technol. 48, 8334–8348.
Vicente-Serrano, S.M., 2007. Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region. Nat. Hazards 40, 173–208.
Wachinger, G., Renn, O., Begg, C., Kuhlicke, C., 2013. The risk perception paradox-implications for governance and communication of natural hazards. Risk Anal. 33, 1049–1065.
Warner, N.R., Christie, C.A., Jackson, R.B., Vengosh, A., 2013a. Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. Environ. Sci. Technol. 47, 11849–11857.
Warner, N.R., Jackson, R.B., Darrah, T.H., Osborn, S.G., Down, A., Zhao, K., White, A., Vengosh, A., 2012. Geochemical evidence for possible natural migration of Marcellus formation brine to shallow aquifers in Pennsylvania. Proc. Natl. Acad. Sci. U. S. A. 109, 11961–11966.
Warner, N.R., Jackson, R.B., Vengosh, A., 2013b. Tracing the legacy of accidental spills and releases of Marcellus wastewater in Pennsylvania. 2013 Geological Society of America Annual Meeting. Denver, Colorado, 27–30.
WEF, 2013. Considerations for accepting fracking wastewater at water resource recovery facilities. http://www.wef.org/uploadedFiles/Access_Water_Knowledge/Wastewater_Treatment/FrackingFactsheetFinal(1).pdf (accessed 1.14.15).
Wilson, J.M., VanBriesen, J.M., 2012. Oil and gas produced water management and surface drinking water sources in Pennsylvania. Environ. Pract. 14, 288–300.
Wiseman, H.J., 2014. The capacity of states to govern shale gas development risks. Environ. Sci. Technol. 48, 8376–8387.
Wu, H., Wilhite, D.A., 2004. An operational agricultural drought risk assessment model for Nebraska, USA. Nat. Hazards 33, 1–21.
Yan, J.Y., 2010. Drought risk assessment: mapping the vulnerability of agricultural systems. http://www.wamis.org/agm/meetings/slovenia10/S5-3a-GRIP_Understanding_Vulnerability.pdf (accessed 4.29.15).
Zielinski, R.A., Otton, J.K., Budahn, J.R., 2001. Use of radium isotopes to determine the age and origin of radioactive Barite at oilfield production sites. Environ. Pollut. 113, 299–309.
Ziemkiewicz, P.F., Quaranta, J.D., Darnell, A., Wise, R., 2014. Exposure pathways related to shale gas development and procedures for reducing environmental and public risk. J. Nat. Gas Sci. Eng. 16, 77–84.