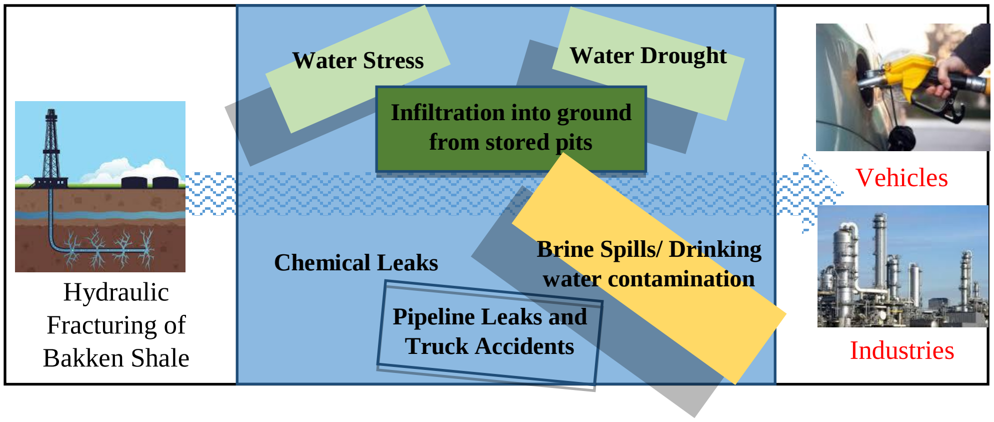
Graphical Abstract



POTENTIAL WATER RESOURCE IMPACTS OF HYDRAULIC FRACTURING FROM UNCONVENTIONAL OIL PRODUCTION IN THE BAKKEN SHALE

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Abstract

Modern drilling techniques, notably horizontal drilling and hydraulic fracturing, have enabled unconventional oil production (UOP) from the previously inaccessible Bakken Shale Formation located throughout Montana, North Dakota (ND) and the Canadian province of Saskatchewan. The majority of UOP from the Bakken shale occurs in ND, strengthening its oil industry and businesses, job market, and its gross domestic product. However, similar to UOP from other low-permeability shales, UOP from the Bakken shale can result in environmental and human health effects. For example, UOP from the ND Bakken shale generates a voluminous amount of saline wastewater including produced and flowback water that are characterized by unusual levels of total dissolved solids (350 g/L) and elevated levels of toxic and radioactive substances. Currently, 95% of the saline wastewater is piped or trucked onsite prior to disposal into Class II injection wells. Oil and gas wastewater (OGW) spills that occur during transport to injection sites can potentially result in drinking water resource contamination. This study presents a critical review of potential water resource impacts due to deterministic (freshwater withdrawals and produced water management) and probabilistic events (spills due to leaking pipelines and truck accidents) related to UOP from the Bakken shale in ND.

Keywords: Bakken, corrosion, energy use and resources, hydraulic fracturing, horizontal drilling

1.0 Introduction

The state of North Dakota (ND) in the upper Great Plains (UGP) region (South Dakota (SD), Montana (MT), Wyoming (WY), Nebraska (NE), and ND) has adopted unconventional drilling techniques, notably multi-stage horizontal drilling and hydraulic fracturing (HF) techniques, to extract crude oil from the previously inaccessible Bakken Shale Formation (Gaswirth et al., 2013). While the Bakken Shale Formation is located throughout MT, ND and the Canadian provinces of Saskatchewan and Manitoba, the majority of unconventional oil production (UOP) occurs in ND (U.S. EIA, 2016). "Pad drilling," the use of multiple horizontal wells (>4) in the same pad, has enabled a cost-effective route for oil production, allowing the UOP rate in ND to reach as high as 1,350 thousand bbl/d (North Dakota Industrial Commission, 2014). According to the ND Department of Mineral Resources (NDDMR), nearly 10,160 Bakken wells were horizontally drilled in the last 15 years (Murex Petroleum Corporation, 2014; North Dakota Department of Mineral Resources, 2015). UOP has strengthened oil industries and businesses (e.g., excavation equipment such as backhoes and front-end loaders, machinery for frack-sand mining) (Holloway and Rudd, 2013), creating new job opportunities and increasing the gross domestic product in ND by nearly 11% in 2012 (Horner et al., 2016). However, similar to UOP from other low-permeability shales, UOP from the Bakken shale can result in environmental issues related to altered land usage (Moran et al., 2015), stressed pipeline and railway infrastructure (Rahm et al., 2015), water shortages and environmental and human health risks (Kassotis et al., 2015; Stamford and Azapagic, 2014; Webb et al., 2014) due to water resource contamination (Entrekin et al., 2011).

As suggested by the Environmental Protection Agency (EPA) (U.S. EPA, 2015b), UOP from tight geological formations such as the Bakken shale affects regional water resources during the five stages of the HF water cycle (see Figure 1). Oil industries in ND acquire and transport large volumes of freshwater from the Missouri River or the water depots to well sites (Stage I) (Horner et al., 2016; Jiang et al., 2014). The over-extraction of freshwater may create water stress during drought periods and restrict water access for production of typical agricultural products (durum and wheat), special commodities (sunflowers, safflower, canola, flaxseed, lentils, dry beans, and honey), biofuel feedstock (corn and soybean) and energy (corn-based ethanol and coal-fired power) in ND (Torres et al., 2016). A recent study by Horner et al. (2016) concluded that existing ground water resources in ND are not adequate to meet anticipated increases in freshwater demand for UOP. In Stage II, water-based fracturing fluids are prepared by mixing freshwater with proppants and fracturing chemicals (Jiang et al., 2014). Pumping trucks are used to inject fracturing fluids at high pressures (0.75 psi/ft) (Murex Petroleum Corporation, 2014) to fracture oil-bearing rocks and carry proppants to hold open the fractures and stimulate UOP from the Bakken shale (Stage III). Chemical spills during Stages II and III can contaminate surface and groundwater resources (Torres et al., 2016). Well-casing failures and existing faults or fractures in geological formations between target formations and aquifers can potentially result in migration of toxic fracturing fluids into drinking water resources (Rogers et al., 2015).

UOP generates a significant amount of saline wastewater (flowback or produced water) (Stage IV), which is transported to disposal sites for subsequent injection into Class II injection wells (Stage V) (Figure 1) (North Dakota Department of Health, 2015b). In Stages IV and V,

truck accidents and pipeline breaks during transport of the saline wastewater have resulted in several brine spills (fracturing fluids, flowback water and produced water) (North Dakota Department of Health, 2015b) that threaten the land and water resources in ND (Lauer et al., 2016; Pichtel, 2016). For example, in 2014, an accidental spill contaminated 9,000 ft^2 of land in William County with 150 barrels of produced water (North Dakota Department of Health, 2014a). The UOP wells in ND are located throughout a range of agricultural lands (e.g., wheat and durum) and near water resources (Missouri River and aquifers) (Jacobson, 2015; Griswold, 2014), increasing risks for water and food contamination.

ND contributes 12.5% of the total crude oil production and accounts for only 0.6% of the total energy consumption in the United States (U.S.) (US EIA, 2014). Due to limited oil refining capacity in ND (92,860 $bbl.day^{-1}$ of crude oil), the bulk of the oil is exported to the east and west coasts using trucks, pipeline and railway infrastructure (U.S. EIA, 2014c). Inadequate transportation infrastructure to handle massive volumes of oil has been cited as a reason for the increasing number of transportation-related spills in ND (Federman, 2014; Gadhamshetty et al., 2015; North Dakota Department of Health, 2014b). Nearly 6.5% of transportation-related accidents in the Bakken region have been attributed to inadequate railway infrastructure (Bradley, 2014; Mitchell and Child, 2015). The roadways in a 17-county oil region of western ND have been experiencing sharp increases in traffic volume, shifts in traffic mix, and large increases in vehicle crashes in the past few years (Upper Great Plains Transportation Institute, 2015). The roadways previously used only for local access and agricultural purposes continue to be used at higher volumes to serve the oil industry, resulting in ongoing traffic safety issues (Upper Great Plains Transportation Institute, 2015). The number of rural road crashes involving

trucks in Bakken regions has increased by 109% from 2010 to 2014 (Upper Great Plains Transportation Institute, 2015).

From an oil exploration standpoint, the Bakken shale serves as an in situ geological laboratory for developing new assessment techniques for estimating recoverable oil volume from tight shales. From a commercial standpoint, the Bakken shale is the primary target for private industries exploring for crude oil in the UGP (U.S. EIA, 2014a; 2013b). From an environmental standpoint, the Bakken shale is a platform for establishing baseline data for environmental impacts due to UOP, for the reasons discussed below. Compared to oil and gas production in Colorado (CO), Nebraska (NE), Pennsylvania (PA), Texas (TX) and Wyoming (WY) that dates back to the late 19^{th} century (U.S. EIA, 2015a; 2014), UOP from the Bakken Shale Formation began only after the discovery of the Parshall field in 2007 (Bakken-Lodgepole, 2008; Higley and Cox, 2007). ND has a relative short industrial history compared to its eastern counterparts, and it is therefore easier to segregate environmental impacts due to UOP. However, there is a paucity of peer-reviewed information on environmental impacts due to UOP in ND (EERC, 2010; Gordon and Garner, 2014; Horner et al., 2016; Lauer et al., 2016; Smith, 2009). For example, since 2007, nearly 3900 brine spills have occurred during transportation of wastewater from well sites to Class II injection wells (Lauer et al., 2016) in ND, and there are very few studies that have investigated their environmental impacts. Lauer et al. (2015) have studied two brine spills in ND (the Bear Den Bay spill and the Blacktail Creek spill) and established that the affected sites accumulated a range of contaminants (salts, inorganic chemicals, and metals). The spill events can therefore be expected to influence water resources for several years after they occur (Lauer et al., 2016).

The literature suggests an increasing number of studies related on water resource impacts due to UOP from contemporary shales (Kahrilas et al., 2014; Stringfellow et al., 2014; Uddameri et al., 2014; Vengosh et al., 2014) including the Marcellus (Haluszczak et al., 2013) and Niobrara shales (Lester et al., 2015). Recent studies have established that spill sites in the Marcellus shale are characterized by elevated levels of halides (~28 mg/L iodide) and ammonia (~106 mg/L) (Harkness et al., 2015) that can impact stream ecosystems and result in the formation of brominated, iodinated, and nitrogen disinfection byproducts during chlorination at downstream water treatment plants. Their findings have indicated that discharges and accidental spills of produced water to waterways pose environmental and health risks. Vengosh et al. (2014) have identified and reviewed the following four potential water resource impacts due to gas production from the Marcellus, Haynesville, and Barnett shales: stray gas contamination; spills, leaks, and disposal of untreated shale gas wastewater; accumulation of toxic and radioactive elements in soil and stream sediments; and water shortages due to excessive freshwater consumption. However, the current literature lacks such a detailed studies on water resource impacts due to UOP in ND.

This paper presents a critical overview of recent studies (through September 2016) related to potential water resource impacts due to UOP in ND. This study focuses on the potential sources of water resource degradation during the HF water lifecycle described in Figure 1, which include the following: (1) high-volume freshwater withdrawals during water acquisition (Stage I) and (2) surface and ground water contamination due to spills associated with flowback and produced water management (Stages III and IV). We present a critical discussion on water

resources impacts due to both the deterministic (freshwater withdrawals and produced water management) and probabilistic events (oil spills, leaking pipelines, truck accidents) related to UOP in ND. We also present an overview of experimentally determined information (type and quantity) for fracturing contaminants detected in the following sources in ND: i) flowback and produced water and ii) sites affected by brine spills and pipeline accidents. The subsequent sections of the paper discuss the environmental oversight for UOP by the federal and ND state agencies. Due to the limited amount of peer-reviewed literature related to UOP in ND, the study is based on both scientific journal articles and the gray literature, including annual reports and technical documents from ND stage agencies (ND Industrial Commission (NDIC), NDDMR, North Dakota Department of Health (NDDH), ND State Water Commission) and oil industries.

2.0 Increase in crude oil production in the Bakken shale and consequences of existing crude oil infrastructure

The Williston Basin encompasses 135,000 square miles of flat, rolling land surface that extends into MT, ND, SD, and WY. Figure 2 shows a topographic map of the UGP region defining the boundaries of the Williston Basin (red), the Bakken Formation (blue), the prairie pothole region (yellow) and the Missouri River system. The Williston Basin is underlain by sedimentary rocks such as sandstone, coal, and shale. The Bakken shale in the Williston Basin contains coal/lignite, natural gas, and uranium. The U.S. Geological Survey (USGS) has confirmed that the Tertiary and Upper Cretaceous geologic units in the Bakken shale are major crude oil reservoirs (Figure 2). Horizontal drilling techniques have enabled oil extraction from the previously inaccessible (impermeable) Bakken formation (Gaswirth et al., 2013).

Figure 3 compares productivity information for UOP (i.e., crude oil production, natural gas production, rig count, and oil production per rig) for the Bakken shale with that of the Permian (TX), the Niobrara (CO, Kansas (KS), and WY) and the Marcellus shales (Ohio (OH), West Virginia (WV), PA, New York (NY)) through July 2016. As shown, the Permian shale produces the highest amount of oil compared to the Bakken, Niobrara, and Marcellus shales (U.S. EIA, 2015c). TX is the largest crude oil-producing state, and ND is the second-largest oil-producing state in the U.S. As of September 2015, 10,298 wells were extracting 1.1 million barrels (MMbbl) of crude oil daily (Figure 3) (North Dakota Department of Mineral Resources, 2015). Oil production volumes in ND and TX increased at average annual rates of 37% and 28%, respectively, from April 2010 to April 2014 (U.S. EIA, 2014b) (Figure 3). The emerging literature suggests a correlation between the increasing volume of oil production and the increasing number of water resource impacts (Horner et al., 2016; Lauer et al., 2016).

As shown in Figure 3c, a sharp decrease in rig counts in all four shale locations since January 2013 is attributed to declining oil prices (U.S. EIA, 2015b). When oil companies decide to reduce the number of rigs in an oil field, they begin the process by idling the oldest and least efficient rigs. Therefore, the impact of reducing the number of rigs on cumulative oil production depends upon the productivity of the remaining rigs. During the 2008-09 recession, decreasing oil prices resulted in reduced rig counts without affecting cumulative oil production (Figure 3). The decreased oil production due to reduced rig count was compensated by increased productivity of remaining rigs. The productive rigs facilitate well completion at faster rates, enhance initial production rates, and enable oil companies to drill multiple horizontal wells from a single pad (U.S. EIA, 2015b). However, the rapid production rates can result in higher truck

traffic and a higher probability of water stress, surface spills or leaks, truck traffic, and potential surface and groundwater contamination (Vengosh et al., 2014).

UOP from the Bakken shale has increased from 150 thousand bbl/d in 2007 to 1,350 thousand bbl/d in 2015 (North Dakota Industrial Commission, 2014). However, the transportation infrastructure has not been upgraded at a rapid enough pace to handle the high volumes of UOP and export the oil to neighboring states (Hamilton, 2008). The aged railways used to transport 700,000 barrels of oil daily to refineries have been reported as vulnerable to accidents (Shea et al., 2015). Trucks (56%) and pipelines (44%) used to transport the crude oil from well sites to rail terminals or pipelines (Lord et al., 2015) have also been considered vulnerable to accidents, resulting in regional oil spills (details in Section 4.0). The challenging climate of ND further influences the supply chain and lowers the UOP rate. During heavy snowstorms that are common in the area, once the onsite storage tanks are filled, the production of crude oil cannot resume until weather supports oil transportation. Nearly 80% of ND's crude oil production occurs in Dunn, Montrail, William and McKenzie counties, and harsh weather in these areas retards crude oil production and transportation rates (U.S. EIA, 2013a). For example, in 2014, unfavorable weather conditions were considered as the primary factor for 18% of vehicle crashes in the oil counties of ND (Upper Great Plains Transportation Institute, 2015).

3.0 Water resource impacts

3.1 Overview of Bakken shale members and the Williston Basin

The Williston Basin in the north-central U.S. and south-central Canada has been a leading source of oil and gas during the past 50 years (USGS, 2014a). Unconventional drilling techniques have

enhanced UOP from the Bakken and Three Forks Formations in the Williston Basin. With widespread oil production in the Williston Basin, the USGS emphasizes the need for comprehensive research and development (R&D) studies to understand the effects of increased energy production on regional land and water resources. As shown in Figure 2, a major portion of the Williston Basin is overlain by the prairie pothole region known for its digressional wetlands that promote breeding and nesting habitats for North America's migratory waterfowl and miscellaneous wildlife (U.S.Geological Survey, 2015). The Tertiary and Upper Cretaceous geological units of the Bakken shale represent oil reservoirs (Figure 2). Overlying aquifers in the glacial sediments and Upper Cretaceous and Lower Tertiary systems are water resources in the Williston Basin (U.S.Geological Survey, 2015), representing a need to monitor and assess the impacts of HF activities (e.g., oil and produced water spills) on regional water resources (USGS, 2014b). In the following sections, existing knowledge about each stage of the HF water cycle will be summarized and its consequences for water resource impacts will be assessed.

3.2 Water Acquisition, chemical mixing and well injection (Stage I, II and III)

The water-based fracturing fluids used to stimulate UOP from the Bakken shale offer low frictional losses and effectively inject the proppants into fractures. However, water-based fluids consume significant amounts of freshwater for i) consumptive uses (e.g., chemical mixing and preparing drilling fluid) and ii) indirect sinks (e.g., well construction) (see Figure 1). HF contributes to nearly 4% of total freshwater consumption in ND (North Dakota State Water Commission, 2014), and the consumption rate is expected to increase by 85% in the next ten years (North Dakota State Water Commission, 2015a).

The ND State Water Commission has reported its concerns about declining pressure in aquifers and is hesitant to permit oil industries to extract potable groundwater, limiting oil industries in western ND to seeking freshwater from surface water, municipalities, or public and private water depots. The surface water resources in ND are primarily based on the Missouri River reservoir system that includes six dams and a reservoir that are managed by the U.S. Army Corps of Engineers (USACE) (Kurz et al., 2011; North Dakota State Water Commission, 2015b). Water depots obtain water from both groundwater reserves and surface water (Horner et al., 2016; Kurz et al., 2011). While ND may have adequate surface water reserves to meet freshwater demands for UOP, it has been reported that the USACE currently restricts Missouri River water usage for Bakken oil production (Horner et al., 2016; North Dakota State Water Commission, 2015b). The Western Area Water Supply Project (WAWSP)—a domestic water project that uses Missouri River water, treats it at the Williston regional water treatment plant, and supplements it with groundwater—is an alternate freshwater source for fracturing activities in ND (Western Area Water Supply Agency ((WAWSA, 2016). In addition to meeting municipal, rural and industrial water needs for five northwestern ND counties, WAWSA is expanding 20% of its current water supply to meet UOP needs. WAWSA sells water at nine water depots or transports the water to oil fields through dedicated pipelines (WAWSA, 2015). As discussed in later sections, unusual levels of salinity in wastewater in the Bakken fields prevent its reuse for UOP. This explains why the Marcellus oil field recycles 90% of its produced water (Clark et al., 2013), but none is recycled in the Bakken play (Horner et al., 2016).

A recent study by the Idaho National Laboratory and the Montana Bureau of Mines and Geology in 2015 estimated that the Bakken region may gain nearly 2,500 new oil wells per year in the next 15-25 years (Plummer et al., 2015). With anticipated growth in the oil industry, it is important to develop accurate estimates and predict whether adequate freshwater is available for increasing UOP in ND (North Dakota State Water Commission, 2014). Table 1 shows the total number of wells and annual total water consumption for UOP in ND. The freshwater consumption for UOP has increased 5-fold from 2008 to 2012 (Table 1). The lateral length in the Bakken has increased by 25% from 2009 to 2013 (Horner et al., 2016), and the corresponding water consumption has increased four-fold in this period (Table 1). The specific water requirements for a given Bakken well depend upon the type of fracturing technique and the number of fracturing stages (Kurz et al., 2011). Scanlon et al. (2014) estimated that the 7868 Bakken wells consumed 15.8 Mgal of freshwater from 2005 to 2013, and on average, each well consumed 4.8 Mgal water (Scanlon et al., 2014).

The freshwater consumption for UOP in ND can be expected to be at least 20% higher per well when water consumption for drilling and cementing are taken into account (Scanlon et al., 2014). Other indirect sinks for UOP are discussed below. Nearly 10-15% of the Bakken wells require maintenance water, or freshwater to minimize salinity buildup, and this quantity ranges as high as 5 Mgal per well. Due to high salinity, the maintenance water requirements for the Bakken play are significantly higher than for contemporary shales (e.g., Eagle Ford) (Horner et al., 2016). Further, the Bakken wells in the western region of ND require higher maintenance water compared to their eastern counterparts (Horner et al., 2016). The temporary workers (who come to the region only to take jobs related to UOP) in ND exerts significant freshwater

demands for their domestic needs. The freshwater demand for the temporary workers is equivalent to the regional water demand for all fracturing activities in ND. In 2010 to 2012, the domestic water requirements (2,190 Mgal) have exceeded 50% of the total freshwater used for the fracturing (4,270 Mgal) (Horner et al., 2016).

Slickwater (or water frac) is a commonly used fracturing fluid in the Bakken field. Slickwater uses freshwater that is typically mixed with chemicals from the classes of friction reducers, biocides, surfactants, breakers or clay-control additives. UOP from the Bakken shale using slickwater is 25% higher than that using non-slickwater fluids (Geiver, 2014). However, the slickwater has low viscosity (2 – 3 centipoise) and requires higher energy to pump the proppant. Gel-based fracturing fluids can also be used in tight oil formations such as the Bakken shale (U.S. Department of the Interior, 2015). Gel-based fracturing fluids can be based on cross-linked gel or hybrid cross-linked gel/slickwater. Cross-linked gel is water containing a gelling agent (e.g., guar), cross-linker (e.g., Zr) and additives such as buffers, biocides, surfactants, breakers, and clay controls. Compared to linear gels, cross-linked gels have a higher viscosity (100 – 1000 cP), and they are designed to improve proppant transport and achieve wider fractures. Hybrid cross-linked gel/slickwater uses slickwater followed by a linear gel or cross-linked gel during a HF process (Barati and Liang, 2014; Pearson et al., 2013; Scanlon et al., 2014). A typical frac system used in the Bakken shale consists of a gelling agent such as guar gum (0.45%), gel breaker (0.02%), biocide Phosphonium salt (0.02%), and a cross linker such as borate salt (0.08%) (Fracfocus, 2016; Purvis D, 2015). Guar gum and its derivatives are commonly used, as they are known to transport sand into the fractures in an effective manner (Torres et al., 2015).

Figure 4 compares the typical life cycle stages involved in water consumption for both conventional oil production (COP) and UOP. COP occurs in three different stages, as follows: i) the primary recovery stage that entails oil extraction using naturally occurring underground pressure and occasional pumping, ii) the secondary recovery stage (water flooding) that uses external energy (in the form of injecting fluids) to increase well pressure when natural pressure in a well fails to recover oil, and iii) the tertiary recovery stage (enhanced oil recovery) that uses thermal or steam-injection methods to recover oil (Wu and Chiu, 2011). As shown in Figure 4a, the majority of freshwater consumption for COP occurs during the primary recovery stage. During the secondary recovery stage, separate injection wells are drilled and the water is injected into the formation to increase the oil production. As the oil production matures beyond the secondary stage, the additional increase of injection water does not increase the oil production because the oil is trapped in the reservoir rock due to surface tension and viscosity effects. In such cases, the tertiary recovery method uses a combination of carbon dioxide (CO_2) and steam to extract oil. CO_2 injection reduces surface tension, while steam injection reduces viscosity, and both enhance oil recovery.

Table 2a and Table S1 compares the oil production rates and corresponding water usage during the primary, secondary, and tertiary stages for COP. As shown, the secondary stage of COP entails bulk of the oil production and the highest water usage. In contrast to COP, the majority of oil production in UOP occurs during the fracturing stage (i.e., primary stage) and to the lesser extent during the enhanced recovery stage (Wu and Chiu, 2011). Table 2a shows also shows average values for oil production rate and the water usage rate in the primary stage of UOP.

Table 2b ranks the individual stages of both the COP and UOP based on the following three different parameters: (i) basis of oil produced, (ii) basis of water usage, and iii) basis of ratio for water used for a unit of oil production.

In light of the increasing public perception of excessive freshwater demand for UOP, Scanlon et al. (2014) have reported a counter-intuitive finding that freshwater requirements for UOP are equivalent to, or lower than, those for COP. Using the data for UOP from the Bakken Formation in western ND and eastern MT and the Eagle Ford Formation in south TX from 2009-2013, Scanlon et al. (2014) have concluded that the water-consumption-to-oil-production ratio, WOR (vol water/vol oil), for UOP (0.2-1.4) is within the lower range of that for COP (WOR: 0.1-5). Further, their study concluded that the U.S. is using more water for UOP because fracturing has expanded oil production and not because the fracturing consumes more water per unit of oil production. However, Lampert (2015) noted that Scanlon's study failed to account for the differences in the maturity of unconventional and conventional wells, resulting in unfair conclusions related to lower freshwater consumption for UOP. For example, in Scanlon's (2014) study, the estimated values for WOR in COP were based on water consumption for all three stages (primary, secondary, and tertiary), while the WOR for UOP considered only the primary stage (Lampert, 2015).

The WOR analysis for COP in Scanlon et al. (2014) built upon a study by Wu and Chiu (2011) that used experimentally determined values from the literature to calculate water consumption profiles for different oil extraction technologies. Wu and Chiu (2011) have estimated that 8 gallons of freshwater (2.1-5.4 gallons of make-up water and the remainder from

recycled water) are required to extract a gallon of oil from a COP well. Figure 5 compares the volume-of-water/volume-of-oil requirements for the COP and UOP technologies. As shown in Figure 5, water consumption data for the COP and UOP is arranged according to the following two categories: i) primary recovery stage (drilling/fracturing) and ii) secondary/tertiary recovery stage (injection). Figure 5 indicates that the water consumption for the primary stage of COP is relatively lower than that for UOP. Readers are advised to read the relevant literature to gain a deeper insight about the controversy related to relative water footprints for UOP and COP (Lampert, 2015; Scanlon et al., 2014; 2015).

3.3 Flowback Water and Produced Water production (Stage IV)

Figure 6 indicates that, from 2007 to 2015, the increasing number of reported brine spills in ND matches with the increasing volumes of UOP from the Bakken shale. The majority of these brine spills are related to the accidental release of flowback water and produced water generated from the Bakken play. Flowback water is a portion of injected HF fluids that returns to surface after the HF process is complete. It contains a range of fracturing chemicals (e.g., added aliphatic and aromatic hydrocarbons such as solvents, biocides, and scale inhibitors) (Banerjee, 2015; U.S. EPA, 2015a) and detritus of the fractured well (e.g., salts, naturally occurring radioactive materials). In chemical terms, a liter of flowback water from a Bakken well contains 220,000 milligrams of total dissolved solids (TDS), 47,100-74,600 milligrams of sodium, 1,220 milligrams of carbon-rich organic matter (i.e., chemical oxygen demand) (Guerra et al., 2011), traces of heavy metals, carcinogens and toxins (Auers et al., 2014; Guerra et al., 2011; Stepan et al., 2010). On the contrary, produced water (fluids that are extracted together with the crude oil during production) is indigenous to the deeper earths where crude oil has been buried for

millions of years. Produced waters are composed of naturally occurring formation water, and can contains high concentrations of total dissolved organic carbon, in addition to the organic compounds typically reported in flowback waters (Vengosh et al., 2014). Both flowback and produced water from the Bakken shale contains toxic metals (barium and strontium) and radioactive radium along with the high levels of salinity (Gadhamshetty et al., 2015; Nelson et al., 2015). Based on the available studies, representative compositions for both of these waters from the Bakken shale are shown in Table 3 and Table S2. Readers are encouraged to read the relevant literature about typical chemicals (originating from injected fracturing compounds and natural shale formation) detected in the flowback and produced water from the contemporary shales (Elsner and Hoelzer, 2016; Getzinger et al., 2015; Gordalla et al., 2013; Harkness et al., 2015; Hoelzer et al., 2016; Maguire-Boyle and Barron, 2014; Orem et al., 2014; Parker et al., 2014; Rogers et al., 2015). For example, produced water from Marcellus, Eagle Ford, and Barnett shales are characterized with saturated (aliphatic) compounds and a small fraction of aromatic, resin, and asphaltine compounds (Maguire-Boyle and Barron, 2014). Some of the chemicals, such as benzene, toluene, and xylene, found in the produced water (Getzinger et al., 2015) are known carcinogens and they pose environmental and health concerns.

Figure 6 considers only the brine spills that were promptly reported to the NDDH. The brine spills result in an undesirable discharge of saline wastewater (TDS = 300 g/L; salinity = 47 g/L) into regional water bodies, especially surface waters including the Missouri River and lakes (e.g., Smishek Lake near the town of Powers Lake). It is clear that the increasing number of brine spills (Figure 6) threatens drinking water resources in ND (Lauer et al., 2016). However, the literature suggests that the volume of the reported brine spills represent an insignificant

portion of total brine generated from the Bakken shale. For example, in 2014, the volume of the reported brine spills (71,000 barrels) was only 0.016% of the total brine generated (432,000,000 barrels) during the UOP in ND (Energy & Environmental Research Center, 2015a; North Dakota Department of Health, 2014a). The environmental impacts due to spills in ND are amplified if the regional oil spills in the last decade (e.g., 1000 oil spills in 2011 in ND) are also taken into account (Propublica, 2012). Figure 6 does not include oil spills. Readers are encouraged to read the relevant information in the literature (de Santiago-Martín et al., 2015; Finkel and Law, 2011; Kingston, 2002; McLaughlin et al., 2016).

Figure 7 shows the typical accidents responsible for brine spills due to UOP in ND. As shown, the typical brine spill sources are related to vessel leaks, blowouts, equipment failure, fires, pipeline, pump, valve, and stuffing box leaks, and truck overflows. The pipeline leaks resulted in the highest number of spills (Fig. 7a) and the largest volume of spilled brine. The human and ecological health impact of such spills depends upon the spill volume, spill location and the specific composition of the produced and flowback water. Further, the quality of the produced water and flowback changes on both the spatial (one well to another) and the temporal scales (over time in the same well or one well to another) (Lyons, 2014). Regardless of the specific composition, these wastewaters are not amenable to conventional treatment technologies, due to their high values for chemical oxygen demand, TDS, salinity, and a suite of toxic and hazardous chemicals. Currently, there is a paucity of information about the potentially harmful constituents in flowback and produced water generated during UOP in ND and the specific effects of brine spills on the land and water resources (EERC, 2010; Horner et al., 2016;

Lauer et al., 2016). Relevant details about recent brine spills in ND are included in Section 3.4.2 of this study.

3.3.1. Chemicals involved and their toxicity

Table 3 provides a list of inorganic contaminants identified in produced waters and flowback water in ND. The Northern Great Plains Water Consortium (NGPWC) has analyzed flowback water samples from 89 different Bakken wells (Stepan et al., 2010) and reported the average salinity to be high as 220,000 mg/l, which is dominated by NaCl and contains traces of Ca, K and SO_4^{2-}. Figure S1 shows the sample collection locations of Bakken oil wells where flowback water data and information used in the assessment were collected. A recent report by Lauer et al. (2016) has provided comprehensive details on the composition of the produced water from the Bakken Formation. The produced water from the Bakken is highly saline and characterized by a typical Na−Ca−Cl composition. In addition to the elevated concentrations of Na, Cl, and Br, the produced water from the Bakken shale is rich in metals, metalloids, and miscellaneous contaminants (Se, V, Sr, B, Mn, Ni, Cd, Cu, Zn, Ba, Pb, Ra, and NH_4) (Table 3).

The accidental discharge of flowback or produced water provides a potential pathway for contamination of affected soils, sediments of rivers and lakes, and shallow groundwater (Vidic et al., 2013) with organics, salts, metals, and other constituents shown in Table 3. The reported TDS in Bakken flowback and produced water vary in the ranges of 150,000-220,000 mg/L (Stepan et al., 2010) and 35000-632689 mg/L (Lauer et al., 2016; Torres et al., 2016), respectively. Considering that salinity in the flowback and produced waters from Bakken shale is several-fold higher than that in typical surface waters (<1000 mg/L), small discharges can

degrade freshwater quality. Compared to the wastewater from the Niobrara and Marcellus shales, the flowback and produced waters from the Bakken possess exceptional amounts of total dissolved solids and high salinity (Abualfaraj et al., 2014; Haluszczak et al., 2013; Hayes, 2009; Lester et al., 2015; Stepan et al., 2010). Health concerns arise if brine spills introduce these fracturing compounds to drinking water resources at levels higher than the maximum contaminant level (MCL) defined by the EPA. The MCL for sodium is 20 mg/l, beyond which there are increased risks for kidney damage, increased blood pressure, and irritation of the skin, eyes, nose and throat.

Benzene at an MCL above 0.005 mg/L has been reported to increase cancer risks, promote anemia, and decrease blood platelets in the affected people (Lenntech, 2015). Consumption of toluene-contaminated water (MCL = 1 mg/L) increases risks for kidney and liver damage. Similarly, consumption of xylene-contaminated waters (drinking water MCL = 10 mg/L) is known to cause headaches, dizziness, lack of muscle coordination, confusion and changes in the sense of balance (ATSDR, 2007). Upon inhalation, xylene irritates eyes, nose, throat, and gastrointestinal tissues. Long-term inhalation exposure to xylene affects the human central nervous system (U.S. EPA, 2015c). A train derailed in Lac-Mégantic carrying Bakken crude oil has been reported to contain the following diverse organic compounds in varying proportions: polycyclic aromatic hydrocarbons; volatile aromatic hydrocarbons such as benzene, toluene, ethyl benzene and xylene; trace metals and metalloids; alcohols, biocides, surfactants, acids/bases, and corrosion inhibitors (de Santiago-Martín et al., 2015). According to Globally Harmonized System of classification of chemicals (1-4, 1 being the most dangerous), Bakken crude oil is ranked under each category of the health effects as follows: Aspiration Hazard

Category 1 (most toxic); Specific Target Organ Toxicity, Single Exposure, Category 3 (slightly toxic); Specific Target Organ Toxicity, Repeated Exposure, Category 2 (moderately toxic); Carcinogen, Category 1B (highly hazardous); Hazardous to the aquatic environment, long-term, chronic, Category 2 (moderately toxic) (ConcocoPhillips, 2014).

The potential health hazards due to different constituents in flowback or produced water are outlined in Table 4. The typical inorganic contaminants in the produced and flowback water (shown in Table 3) belong to classes of reproductive (Golub, 2005), immunological (Berlin et al., 2012), and neurological toxicants (De Vries, 1996; Zatta, 2003) and endocrine disruptors (Kassotis et al., 2015; Webb et al., 2014). The volatile organic compounds (e.g., benzene, toluene, and xylene) and heavy metals (e.g., arsenic, cadmium and lead) in the flowback water are known carcinogens that increase risks for acute myeloid leukemia, acute lymphocytic leukemia, chronic lymphocytic leukemia, multiple myeloma, and non-Hodgkin lymphoma (Webb et al., 2014).

As reported for the Niobrara and Marcellus shales, the brine spills in ND can also pose environmental risks (Table S2). Flowback waters from the Bakken, Marcellus and Niobrara shales are all characterized by metals such as Ba, Sr, Cd, Pb, Cr and Hg that cause physiological toxicity, skin and eye irritation, lung and kidney problems, and carcinogenic effects (Lenntech, 2015; U.S. EPA, 2016). Naturally occurring radioactive materials (e.g., Cs, Ra, and U) found in the flowback water pose cancer risks (Lenntech, 2015; Tchobanoglous and Burton, 1991; U.S. EPA, 2016). The endocrine disruptors reported to be found in the flowback water can cause miscarriages, birth defects and impaired fertility (Kassotis et al., 2015; Webb et al., 2014).

Biocides used during fracturing are reported to contain carcinogens including bronopol and methylisothiazolinone (Elsner and Hoelzer, 2016; Kahrilas et al., 2014). A recent study in 2012 reported that residents living in Colorado within ≤ 0.5 mile distance from unconventional gas wells are at a greater risk of cancer (McKenzie et al., 2012).

3. 4 Management of Flowback Water and Produced Water (Stage V)

Using wastewater production data from the Oil and Gas Division of the NDDMR, Horner et al. (2016) compared average volumes of flowback water, produced water, and total wastewater (flowback and produced) per well in the first year and the first 3 years of oil production (Figure 8). As shown in Table 1, on average, a Bakken well annually consumed 2.37 Mgal in 2012, which corresponds to the total wastewater generated by a well in the first year of oil production shown in Figure 8.

The wastewater volume generated by a Bakken well has been reported to be higher than that for its counterparts (Horner et al., 2016). Further, the average wastewater production per well in the Bakken play has been increasing. This trend can be attributed to the increasing amount of freshwater consumption, which is primarily due to the increasing later lengths (the lengths of the well bores extending horizontally within the reservoir) requiring higher numbers of fracturing stages (Horner et al., 2016). Based on the first year of the oil production data in Figure 8, the average volume of produced water per oil well has increased 3.5-fold from 2008 to 2012. The average volume of produced water in the first year of production was 0.655 Mgal/year for wells completed in 2008; this value had increased to 2.31 Mgal/year by 2012. Similarly, flowback water increased 1.2-fold from 2011-2012. This increasing trend in wastewater

production in ND can be expected to result in relevant wastewater management challenges, especially due to increasing risks for brine spills during the transportation of brine to Class II injection wells. The literature suggests the following five different options for managing the produced water from oil fields:

i) ***Avoid production of water onto the surface***: Polymer gels can be used to block the water contributed from fissures or fractures, separate water from the crude oil and gas streams downhole, and reinject water into suitable formations (Igunnu and Chen, 2012).

ii) ***Inject produced water into the same formation or another formation***: Produced water can be injected into the same formation or another suitable formation. This option involves transportation costs for moving produced water between different sites.

iii) ***Treat and discharge produced water***: Use physical, chemical, or biological processes, or a combination of these processes, to treat produced water and achieve the national pollutant discharge elimination system (NPDES) standards (Warner et al., 2013). The treated water can then be discharged into surface water bodies.

iv) ***Reuse produced water in oil and gas operations:*** Reuse treated water for stimulation, drilling, and workover operations after appropriate treatment. Further, relevant treatment options are required to reduce fouling, scaling, and biological growth on metal surfaces of drilling infrastructure.

v) ***Consume in beneficial use:*** Reuse the treated, produced water for irrigation and for consumption by cattle and other animals (Arthur et al., 2005).

High levels of TDS (especially high salinity: 60,000-200,000 ppm (Stepan et al., 2010)), organics, and miscellaneous constituents (e.g., metals) in produced water from the Bakken

reduce its amenability to treatment processes (Stepan et al., 2010). The NGPWC has recently investigated the feasibility of reverse osmosis (RO) for treating and recycling the Bakken flowback water. While RO has been reported to yield 90% ion-removal efficiency and 70% water recovery, the expenditure for an off-site 1.5 MGD RO system was estimated to reach as high as $39-47 million (Stepan et al., 2010). In ND, it is currently economical to dispose the wastewater into Class II injection wells (e.g., depleted oil formations and deep saline water reservoirs) (Kurz et al., 2011). Nearly 400 Class II injection wells are in operation to dispose of the wastewater from Bakken oil fields in ND (Horner et al., 2016; North Dakota Department of Mineral Resources, 2014). The wastewaters are piped or trucked to the disposal sites where they are stored in containers prior to injection into Class II wells. A study in 2010 attributed 56-84% wastewater handling costs to transportation expenditure (Cypress Energy Partners, 2015), including the operational cost for fuel, labor, and insurance coverage. According to the ND Industrial Commission, the cost for transporting freshwater or wastewater in ND ranges from $0.63-$9.00 per bbl. (Stepan et al., 2010).

If produced water treatment technologies become viable in the near future, the water may be treated and reused in agriculture, industries, and livestock feeding. Oil companies may take initiatives to develop strategies that minimize the freshwater consumption and reduce volumes of flowback water. Long-term studies are required to identify viable technologies for enabling produced water reuse in the Bakken play (Stepan et al., 2010). It is important to assess environmental, energy, and economic aspects of both the conventional (flocculation, coagulation, sedimentation, filtration, and chemical precipitation) and advanced options (membrane process, thermal distillation, and crystallization) for treating produced water (Boschee, 2014). In shale

plays such as the Haynesville and the Marcellus, the oil industries have already developed successful strategies for reusing wastewaters in diverse applications (Clark et al., 2013) (Auers et al., 2014). Further research is required to develop similar strategies in the Bakken play. For example, high salinity of produced water may prevent its reuse in certain applications (e.g., dust suppression or deicing on roads), indicating the need to assess potential health and environmental impacts.

3.4.1 Disclosure rule for hydraulic fracturing chemicals

In 1986, Congress enacted the Emergency Planning and Community Right to Know Act (EPCRA) requirements for federal, state and local governments, tribes, and industry regarding emergency planning and the public's right-to-know reporting on hazardous and toxic chemicals (Fracfocus, 2015; U.S. EPA, 2015a). Many states including WY, PA, AR, TX, CO, NM, MN, WV, ID and ND have mandated the public disclosure of HF chemicals (Fracfocus, 2015; U.S. EPA, 2015a). Table 5 provides a summary of HF chemicals disclosure requirements for seven states including AR, CO, LA, MT, ND, WY and PA (Department of Natural Resources: State of Louisiana, 2011). ND requires the owner, operator, or service company to post, on the Fracfocus chemical disclosure website within sixty days after the hydraulic fracture stimulation is performed (North Dakota Industrial Commission Oil and Gas Division, 2015). This disclosure rule informs the public about potential health and environmental risks caused by HF chemicals (McFeeley, 2012). A study by Colborn et al. (2011) investigated 944 different chemicals, including 632 compounds typically used in fracturing, and concluded the following: (a) 75% of these chemicals affect the skin, eyes and other sensory organs and the respiratory and gastrointestinal systems, (b) 40-50% of these chemicals can affect the brain/nervous system, the

immune and cardiovascular systems and the kidneys, and (c) 37% of these chemicals can affect the endocrine system and 25% cause cancer and mutations (Colborn et al., 2011). According to the National Institutes of Health, handling of the fracturing compounds and contaminated wastewater increases the health risks (NIH, 2014).

The FracFocus database (www.FracFocus.org) provides pertinent information on chemical additives and the freshwater volumes used in fracturing. However, the FracFocus database users can request information only for one well at a time. New organizations such as SkyTruth (skytruth.org) and PackWest (pacwestcop.com) have compiled comprehensive databases for all wells. For example, the SkyTruth database contains records for over 27,000 fracking operations across 24 different states in the U.S. and includes details for the following two major categories: i) fracking operation (location, date, well depth, and volume of water) and the ii) fracturing chemicals (name, quantity, and Chemical Abstract Service (CAS) number) (Skytruth, 2016). Similarly, the Information Handling Services (IHS) database (www.ihs.com) is comprehensive in nature and includes information related to well characteristics (depth and length of the lateral) and production data (crude oil, associated gas, condensate liquid, and water) (Scanlon et al., 2014). The IHS well database has been reported to account for every well in the U.S., retrieving information from wells dating back to nearly 1859. In November 2014, IHS acquired PacWest Consulting Partners, and the company is currently known as IHS PacWest (IHS, 2016).

These databases have been widely used in several studies to assess the water resource impacts due to UOP. For example, Scanlon et al. (2014) used the information from the

FracFocus and IHS websites to determine the water use for HF for unconventional oil development. In another study, Kondash and Vengosh (2015) used the data from the FracFocus website, along with that from the U.S. EPA, state databases and the literature (e.g., a report from Chesapeake Energy) to develop an integrated and comprehensive evaluation of flowback and produced water generated due to unconventional oil and gas production throughout the United States (Kondash and Vengosh, 2015). Based on their study, the annual freshwater consumptions for unconventional oil and gas production were 17,000 Mgal and 31,000 Mgal, respectively. A recent study by Horner et al. (2016) used information from the FracFocus database and the NDDMR and confirmed that the freshwater consumption for UOP from the Bakken shale in ND grew from 770 Mgal in 2008 to 4,300 Mgal in 2012. Based on their analysis, they concluded that the first-year wastewater volumes from UOP in ND grew in parallel, from an annual average of 1.135 Mgal per well in 2008 to 2.905 Mgal in 2012, surpassing the typical 4-year wastewater totals for the Barnett, Denver, and Marcellus shales.

Because each phase of the HF process (e.g., drilling, fracturing, and wastewater transportation) used to recover oil from the Bakken shale poses human health risks, it is important to inform the public about the risks associated with use, transport and storage of the fracturing chemicals (McFeeley, 2012). ND discloses the following information about fracturing chemicals to the public: i) base fluid type and volume; ii) additive trade name, vendor, concentration and function; and iii) chemical name, concentration, chemical abstract number (CAS) and chemical family CAS (Table 5). However, the HF disclosure rule exempts the reporting requirements when companies claim confidentiality and trade secrets about the chemicals used for HF (Table 5). Generally, comprehensive knowledge about HF chemicals

becomes beneficial in events during which human beings and other living organisms are exposed to fracturing chemicals, resulting in medical treatment. For example, it is important for medical professionals to obtain information about the type and concentration of the HF chemicals that affected a patient's health (McFeeley, 2012). In an event where agricultural lands are contaminated with HF chemicals (e.g., toxic metals and radioactive substances), prior knowledge of the physiochemical characteristics of HF chemicals facilitates an impact assessment of the affected crops and affiliated food chains (McLaughlin et al., 2016; Ridlington and Rumpler, 2013; Shaffer, 2001). A study by McLaughlin et al. 2016 has established that, after a spill event, the interaction between fracturing fluids and produced water constituents alters the fate, transport and toxicity of fracturing compounds in the affected soil. For example, the glutaraldehyde (a biocide used in fracturing fluids) was found to hinder the transformation of the poly(ethylene glycol) (PEG) (a surfactant) which would normally be degraded in agricultural topsoil within 71 days. The high salinity in the produced water was also found to inhibit the biodegradation of the PEG (McLaughlin et al., 2016).

3.4.2 Brine Spills

Table 6 provides the list of relevant brine spills during 2015-2016 in ND. Table 6a includes information on contained brine spills (contained within the production site) and Table 6b provides information on uncontained brine spills (occurred outside the production site), which are all based on the reported data available in the NDDH database. However, as evident from the literature, many of the reported spills lack retrospective studies that investigate the specific cause for the spill and subsequent risk to the land and water resource contamination, both on the spatial and temporal scales. For example, during 2001-2014, 1892 brine spills were related to pipeline

leaks, and to date, only 48 of them have been further investigated to discern the specific root causes and the subsequent recommendations related to the operational protocols and regulations (Energy & Environmental Research Center, 2015b).

3.4.2.1 Potential groundwater contamination

The contamination of aquifers due to HF chemicals can occur during their exposure to leaking of oil wells and unprocessed fracturing fluids (Vengosh et al., 2014). Groundwater contamination is often attributed to inadequate well structural design, well casing failure, and drilling site spills (Rozell and Reaven, 2012) (Figure 7). According to a U.S. EPA survey for the period of 2000 to 2013, approximately 9.4 million people lived within a mile of a hydraulically fractured well, and approximately 6,800 public drinking water sources were located within a mile of at least one hydraulically fractured well (Kaden and Rose, 2015). A recent USGS study has indicated the absence of HF impacts on shallow groundwater quality in the vicinity of the Bakken Shale Formation (McMahon et al., 2015). However, the potential land resource contamination from spills related to UOP can pose long-term risks to the groundwater. In this study, this potential will be exemplified in case studies related to the spills in the Williston and Powder River Basin. For instance, due to pipe leakage, 865,200 gallons of oil spilled over 7.3 acres of land in Williams County on September 29, 2013 (Horn, 2013). Williams County is located in northwestern ND and lies at the center of the Bakken oil field. On January 6, 2015, an accidental pipeline leak discharged 3 Mgal of HF fluids onto the land surface, the largest spill of its kind in ND during the last decade (Jacobson, 2015). In an incident in McKenzie County, 1,260 gallons of oil spilled, resulting in the contamination of an oxbow of Charbonneau Creek, which is a tributary of the Yellowstone River (North Dakota Department of Health, 2015a). The

groundwater impacts due to these spills are yet to be corroborated with groundwater sampling and scientific experiments. Media and newspaper articles suggest an increasing number of minor and major oil and brine spills in ND that have never been reported (Earthjustice, 2015; The Guardian, 2015).

A recent study reported that UOP from the East Poplar oil field resulted in the contamination of a huge groundwater aquifer (~15,000-37,000 Mgal) in East Poplar on the Fort Peck Indian Reservation in MT (Thamke and Smith, 2014). Consequently, this forced the tribal government to construct a new drinking water pipeline to draw water from the Missouri River (Mordick, 2014). The Bakken crude oil characteristics are similar to those of the East Poplar field (Griswold, 2014). Due to similarities in crude oil handling and disposal practices, water resource impacts from UOP in the Williston Basin may be anticipated as similar to those of the recent East Poplar oil field incident (Griswold, 2014). These studies suggest that it is important to incorporate long-term groundwater monitoring strategies and track the potential movement of the HF chemicals from unconventional oil fields. A modeling study by Michie and Koch suggested that it is important to extend the surface casing of Class II injection wells below the bottom of drinking water aquifers to minimize contamination risks in the Williston Basin (Frohlich et al., 2014; Michie and Koch, 1991). This simple and yet effective recommendation is expected to minimize the aquifer contamination risks due to leaking wells by a thousand-fold (Michie and Koch, 1991).

Table 7 provides a list of ongoing studies that investigate landscape effects and environmental impacts due to oil production in the Williston Basin (USGS, 2013). For example,

a USGS study is investigating the effects of brine contamination near the East Poplar oil field on the Fort Peck Indian Reservation (Table 7) (Thamke and Smith, 2014). Another ongoing study is investigating whether brine water originating from storage tank facilities, oil wells, brine injection wells, pipelines, and impoundment pits in the oil fields contributes to groundwater contamination (USGS, 2014a). As shown in Figure 7, brine spills in ND are typically attributed to the infrastructure failures (e.g., vessel leak, blowout, pump leak, equipment failures) and accidents (e.g., pipeline leaks, fire, tank overflow, truck overflow). The USGS aims to establish a water-energy nexus, especially in the context of regional groundwater availability, and assess the long-term water needs and groundwater availability for the widespread crude oil production in the Bakken region. The USGS water-quality characterization studies will provide a detailed understanding of current groundwater and surface quality conditions due to oil and gas production from tight shales. The USGS intends to carry out diverse studies to address explicit ecological effects of oil field operations on the prairie pothole region that serves as habitat for native and migratory wildlife (Table 7). The USGS study "A GIS-Based Vulnerability Assessment of Brine Contamination to Aquatic Resources from Oil and Gas Development in Eastern Sheridan County" is designed to analyze whether the regional aquatic resources are vulnerable to oil exploration and production, based on oil field parameters (age and density of oil wells) and hydrogeological characteristics (surficial geology, wetland area, and length of streams) (Preston et al., 2014) (Table 7). The following sections provides a summary of results from the case studies related to potential ground water contamination due to brine spills in Killdeer region, and near Williston and Powder River Basin in ND.

3.4.2.1.1 Retrospective Case Study in Killdeer, North Dakota: This section provides the results for a retrospective case study in Dunn County, North Dakota, conducted near Killdeer, North Dakota. This is one of the five retrospective case studies conducted by the U.S. EPA to assess the potential impacts of a blowout incident, related to UOP from the Bakken shale, on drinking water resources. The blowout occurred at the Franchuk 44-20 SHW well site (Franchuk well) during the fifth stage of the 23-stage HF and released fracturing fluids, oil, and flowback water onto the land surface and possibly into the Killdeer aquifer in September 2010. Sixteen representative water quality samples were collected from 2 supply wells, 3 domestic wells, a municipal well, 9 monitoring wells and a state well, during a total span of three years. Specifically, the samples were collected in July 2011, October 2011, and October 2012 (U.S. EPA, 2015b). The study concluded that the water samples were free of detectable methane, organic compounds (except tertiary-butyl alcohol), and sulfates. Table S3a shows the concentration and major chemistry of groundwater sources impacted by the Franchuk well blowout in Killdeer. Location details for the samples collected near the well blowout are shown in Table S3b. The authors further concluded that the measured data for the specific HF contaminants were comparable to the historical data from the Killdeer aquifer and all wells (except for two wells), implying that the Franchuk incident did not influence the groundwater resources. Based on this study, the Franchuk 44-20 SWH well blowout was the potential source for contamination in only two of sixteen wells considered. However, long-term studies may be required to monitor the true impact of such incidents.

3.4.2.1.2 Quality of shallow groundwater near the Bakken Formation Production Area: As a part of the USGS investigation of ground water availability in the Williston and Powder River

Basins, a study was designed by McMahon et al. (2015) to study the effects of the UOP, especially from surface spills and subsurface leaks (imperfectly cemented wells) on the regional ground water quality. While the study did not include any specific details about sources of surface spills and subsurface leaks, they have collected the water samples from 30 randomly distributed domestic ground wells in the upper Fort Union formation at the median distance of 4.6 km from the nearby oil and gas wells. The study area included the wells in the Williston Basin in western North Dakota including the southeastern extent of the Bakken Formation and northeastern Montana (McMahon et al., 2015). The 100,600 km^2 study area in the Upper Fort Union Formation was divided into 30 equal-area and a domestic well from each area was sampled from August through September, 2013. Unlike the case Study in Killdeer, ND, inorganic and organic chemical concentrations of the samples analyzed in this study indicated no potential effect of oil and gas HF activities on the groundwater. However, it was cautioned that their results be considered in the context of ground water age. For example, the majority of groundwater used for domestic supply in the upper Fort Union Formation is based on pre-1950s in age, and the domestic wells used in their study are not well suited for detecting contamination due to recent spills related to the UOP in ND (McMahon et al., 2015). Based on the slow groundwater velocities in the Upper Fort Union Formation, contaminants from the wells will be less than 0.5 km from their source, while the median distance between the oil and gas wells and water sampled in their study is more than 4.6 km (McMahon et al., 2015). Their study suggests that further ground water monitoring should be done closer to the UOP activities. Table 4 shows the concentration and major chemistry, and traces metals in the ground near oil and gas well in the upper Fort Union Formation of the Bakken (McMahon et al., 2015).

3.4.2.2 Surface Water Contamination due to Brine Spills

The potential pathways for surface water contamination due to crude oil production from the Bakken shale can be attributed to accidental spills or leakages during crude oil storage, mixing and pumping of fracturing fluids, chemicals and wastewater, transportation of crude oil and produced water, and injection of produced water into Class II injection wells (Figure 7). The magnitude and the impact of spills on the water resources depend upon the nature of the spills (quantity and chemical composition of spilled liquid) and the transport and toxicity characteristics of the chemicals. Further, discharge of unprocessed produced and flowback water can contaminate the receiving surface water bodies. For instance, the effluent from the brine treatment facility for Marcellus shale produced water in western Pennsylvania contained higher concentrations of chloride, bromide, strontium, and radium than the threshold regulations (Warner et al., 2013). Another study investigating the contribution of HF wastewater from the Marcellus Shale and the Fayetteville Shale to river waters found that HF wastewater as low as 0.01% resulted in significant alterations to disinfection byproducts formation upon chlorination, chloramination, or ozonation (Parker et al., 2014).

It is clear that a potential brine spill in the Bakken region could contaminate the soil in affected agricultural fields with salts, heavy metals, and hydrocarbons (Rebhun, 2004), hindering the growth of the affected crops by limiting their ability to consume water (McLaughlin et al., 2016; USDA, 1998). In the study by Lauer et al. (2016), it was concluded that brine spills can contaminate the surface water (or soil) with elevated levels of inorganic contamination that can last as long as 4 years following the spill events (Lauer et al., 2016). The subsequent sections provide the details of three retrospective case studies involving recent brine spills in ND. All

three of the brine spill events were investigated by Lauer et al. (2016) to study their impacts on the receiving surface water sources. Relevant samples were collected to analyze the following: (1) major anions, (2) major cations, (3) trace metals, (4) strontium isotopes, (5) oxygen and hydrogen isotopes, (6) alkalinity, (7) dissolved organic carbon, and (8) dissolved radium (Lauer et al., 2016).

3.4.2.2.1 Bear Den Bay Spill and Blacktail Creek Spill: The Bear Den Bay spill and the Blacktail Creek spills represent the two largest brine spill events in the history of ND. In July 2014, an underground pipeline leaked and discharged nearly 24000 barrels (1 Mgal) of brine into a ravine and into Bear Den Bay (approximately 0.4 km upstream of the drinking water intake in Lake Sakakawea) (Lauer et al., 2016). Another spill occurred in Blacktail Creek in January 2015, which was also attributed to a pipeline leak that released 70000 barrels (3 Mgal) of brine into Blacktail Creek that flows into Little Muddy River, which is a tributary of the Missouri River. The GPS coordinates for the spill sites are shown in Figure S2. In both spill events, the chemical composition of the spill water samples showed that the impacted sites were potentially mixed with the brine that originated from the Bakken shale, as evident from the values for Br/Cl, B/Cl, Sr/Cl, and Li/Cl (Figure S3) ratios that exceeded the values for the background water. The sample analysis further indicated that the values for the Li/Cl, B/Cl, and Sr/Cl in the spill waters were comparable to those brines, indicating the potential of impact due to the spills. As shown in Table 8a and 8b, the defined background waters in the study were relatively saline, which is consistent with the findings from other literature sources (Lauer et al., 2016). It was concluded that the high salinity in the spill waters could not confirm that contamination was due to the brine spills. The study therefore recommended using strontium (Sr) isotopes as an independent tracer for the origin of the spills. They reasoned that, unlike the ionic ratios (Br/Cl) that are affected by

salt dissolution and differ from the expected Bakken brine composition, the Sr isotope ratios remain unaffected by the precipitation and the dissolution of secondary minerals (Table 8a and 8b).

Based on the analysis by Lauer et al. (2016), the magnitude of the contamination for the two sites depends upon the relative mixing proportions of the brine and the impacted surface waters. To study the effect of evaporation on the spill site, specifically the precipitation of relevant contaminants, they simulated the evaporation of the spill water and the saturation index (SI = log[Ionic-activity-product/Apparent-equilibrium-solubility-product]) of relevant minerals using the Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations (PHREEQC) software and showed that calcite and barite minerals can be expected to be supersaturated in the two spill sites. They concluded that the spill sites subjected to extensive evaporation would result in supersaturation and secondary mineral precipitation and subsequent soil salinization. There were 1.8- to 3.6-fold increments in Ra activities and 1-fold lower $^{228}Ra/^{226}Ra$ activity ratios in soil samples collected at the Bear Den Bay spill site (Table 8a). In the Blacktail Creek spill, Ra activities were 190-fold lower in the spill water compared to the brines (Table 8a). Such variation in radioactivity and isotopic ratios can provide useful information in the study of the potential impacts of the spills. These retrospective case studies suggest that brine spills with sizes equivalent to those of the Bear Den Bay spill and the Blacktail Creek spill can likely result in surface water contamination in ND.

3.4.2.2.2 Bottineau County Spill: In Bottineau County in northern ND, two separate cases of 300-barrel (12,680 gallons) brine spills occurred in February 2011 and in July 2011. These spills were comparatively smaller than the spills discussed in section 3.5.2.2.1. These spills occurred at a distance from water sources, and it is likely that these spills would undergo evaporation and result in the precipitation of minerals. In the study by Lauer et al. (2016), they found that the chemical composition of the spill water was different from that of Bakken brines mixed with background saline water. However, they attributed the distinctively low Br/Cl of the Bottineau County spill to the evaporation losses that resulted in secondary mineral precipitation and redissolution.

Based on the above retrospective case studies investigated by Lauer et al. (2016), surface waters impacted by brine spills can result in surface water contamination with trace metals. Their results suggest that the metal concentrations in the impacted spill site can reach 1 to 2 orders of magnitude higher than the average concentrations reported in the background surface water. Their results indicate that brine spills can result in raised levels of salts and trace elements at the spill sites and that elevated contaminant levels, especially for the inorganic contaminants, can persist for as long as 4 years. Lauer et al. (2016) recommended future research to evaluate additional spill sites, analyze organic and inorganic contaminants, assess the downstream areas of spill sites for possible risk, and perform a comprehensive assessment of long-term ecological and possible human health impacts (Lauer et al., 2016).

3.5 ND Water Regulations – hydraulic fracturing impacts on regional water resources The North Dakota Industrial Commission (NDIC) oil and gas division is primarily responsible for

minimizing environmental impacts due to oil and gas drilling and production in ND. As described in the NDIC website, the NDIC strives to minimize waste during drilling and production, enhance economic recovery, and protect the rights of the landowner, producer, royalty owner and the public. The NDDH environmental health section (EHS) is responsible for monitoring the quality of air, land and water resources. The NDDH water quality division monitors water resource impacts due to the oil industry. It ensures water quality protection through the processes of permitting, inspection, sampling, and analytical and monitoring services, enabling the oil industry to adhere to the regulations prescribed under the U.S. EPA's Clean Water Act and the Safe Drinking Water Act (SDWA). The NDDH water quality division monitors the effects of oil drilling and pollution on water resources under four different categories including surface water quality and management, water quality special projects, groundwater protection, and wastewater facilities and permits. The specific ND water quality standards are described in ND administrative code (NDAC) Article 33-16. For example, according to NDAC 33-16-02.1-11, the unprocessed wastewater from oil exploration cannot be directly discharged into ND state water. According to Water Code Section 13050-13051, the state water includes surface, ground and saline water within the ND boundaries. NDAC 43-02-03-19.3 mentions that HF wastewaters should be processed, stored and disposed of without affecting ND water bodies. ND uses the U.S. code 33 USC 1342 and 40 Code of Federal Regulations (CFR) 122 to establish a wastewater facility/permits program under the NPDES to regulate the discharge of oil waste into ND waters. However, a permit is not required to discharge the storm water runoff from oil and gas exploration activities, if the runoff is composed of water flows that are not exposed to oil waste. If the runoff is likely to pick up

undesirable oil pollutants and transport them to ND water, then an NPDES permit is required to meet 40 CFR 122.26(b)(14)(i)-(xi) Code of Federal Regulations.

The 40 CFR PART 435 subpart C and subpart E regulations of the U.S. EPA oil and gas extraction wastewater effluent limitation guidelines and standards are applicable to waste discharges from the exploration, drilling, treatment and completion activities for UOP. There are specific pretreatment requirements described by the U.S. EPA for indirect dischargers that treat wastewater before discharging into Publicly Owned Treatment Works (POTWs) (Natural gas extraction portal, 2015). However, discharges from POTWs are subject to 40 CFR PART 437 Code of Federal Regulations.

A state-approved permit (NDAC 43-02-05) and U.S. EPA federal regulations (SDWA guidelines for underground injection control (UIC)) are required for the injection of brine, produced and flowback water discharge from the Bakken oil fields into Class II injection wells. ND works closely with the U.S. EPA to implement SDWA, depending upon geological conditions, and facilitates the protection of drinking water aquifers.

4.0 Transportation Hazards and Corrosion Problems

The Bakken oil produced in ND is transported to refineries by railcar, truck and barge (New York State Department of Health, 2014). The high volatility of the Bakken oil poses unique fire hazards during its transportation. In 2013-2014, three major Bakken oil spills were reported to have caused fire accidents; two of these three incidents were related to rail cars, and the third incident was due to barge transport. The Lac-Mégantic Quebec railway fire incident resulted in

soil and river water contamination and caused forty-seven human deaths. The Louisiana barge incident in 2014 resulted in accidental discharge of 30,000 gallons of crude oil into the Mississippi River, resulting in an abrupt cessation of drinking water supply (New York State Department of Health, 2014). The NDDH website provides a list of the major truck incidents related to crude oil spills in ND (North Dakota Department of Health, 2015c).

The shipping of Bakken oil by rail has increased from 30% in 2011 to 55% in 2014. The increasing use of railways for oil transport in ND has been attributed to the lack of adequate pipeline infrastructure for crude oil (Frittelli et al., 2014). Compared to gasoline, the Bakken crude oil is highly volatile due to its low flash point (32 ^{O}F) and high vapor pressure (7-15 psi). The high levels of dissolved methane (CH_4) in the Bakken oil tend to bubble out of the liquid and exist in the vapor phase above the liquid surface. The United States Department of Transportation (USDOT) classifies the Bakken crude oil as a Class 3 flammable liquid with Packing Group 1 (PG 1), categorizing the Bakken crude oil as the most dangerous fluid in the PG 1 category. The increasing rates of ND railcar incidents have been attributed to increased crude oil volume being transported in DOT-111 rail cars (New York State Department of Health, 2014). The natural gas liquid (NGL) in the Bakken crude oil has also been reported to increase the risks to the carrying pipelines. The NGL in the crude oil results in the emission of flammable gases in the case of a leaking crude oil pipeline. Ruptured oil pipelines represent 16% of pipeline failures but account for 80% of fatality incidents (Hill et al., 1993).

The steel pipelines carrying crude oil or produced water are vulnerable to corrosion. The high total dissolved solids (notably, chloride and sulfate) in the produced water have often been

reported to result in the failure of the corrosion inhibitors (Roscoe Moss Company, 1990). The high salinity in the produced water can also result in the pitting corrosion of the exposed pipelines, increasing the risks for groundwater contamination. Higher levels of hydrogen sulfide (H_2S) (~1,200 ppm) in the Bakken oil (Andrews, 2014) imply that the corresponding oil pipelines are prone to sulfide stress corrosion (Kemp, 2013). Media reports have highlighted a series of pipeline accidents in the Bakken region during the past five years. For example, a recent pipeline accident introduced nearly 3 Mgal of produced water from the Bakken shale into the Missouri River (Dawson, 2015). The corrosion deposits (e.g., goethite (α-FeOOH) (Gerke et al., 2010) typically found on interior surfaces of pipes can adsorb and accumulate heavy metals and radioactive constituents present in produced water. A pipeline accident can therefore release significant amounts of fracturing contaminants into regional land and surface waters (Gerke et al., 2013). The oxidizing biocides such as N-bromosuccinimide (NBS) used to arrest biological growth can promote corrosion of pipelines carrying produced water (Kahrilas et al., 2014). A detailed set of R&D studies may be required to quantify corrosion and material degradation aspects of pipelines exposed to the oil or produced water from the Bakken shale.

5.0 Conclusion

This study reviews the major risks to water resources (WR) due to UOP from the ND Bakken shale. The UOP from the ND Bakken shale results in following unique WR impacts compared to other plays in North America: (i) water demand due to large volumes of maintenance water to avoid salinity buildup; (ii) excessive domestic water consumption due to temporary oilfield workers; (iii) unusual levels of salinity in produced water that minimize its recycling options; (iv) intense pressure of the existing infrastructure (trucking and piping) to

transport produced water from oil wells to deep injection wells; (v) large brine spills due to truck accidents and pipeline breaks during transport of produced water; (vi) high flammability of Bakken oil that poses explosion risks. Other potential WR risks in ND and the recommended solutions are outlined in Table 9. The first WR risk is the water stress that can be developed due to excessive withdrawals of freshwater from arid regions, especially during drought periods. Potential limitation of freshwater resources for UOP can be minimized by developing alternative WR such as brackish ground water or produced water, marginal waters (e.g., acid mine drainage from abandoned coalmines that is unfit for domestic and agricultural use), or alternate liquids (e.g., gel) for fracturing. The second risk is related to WR contamination due to the migration of fracturing fluids or saline water due to well casing failure or inadequate well structural design, which can be mitigated with well-integrity tests and engineering controls. The brine spills due to the infrastructure failure (e.g., pipeline leaks) can be minimized by recycling produced water for UOP and reducing the need to transport water to injection wells (Table 8).A third risk is related to the spills sites in ND that accumulated a range of toxic and radioactive elements, implying that the spill events affect the WR impacts for several years after they occur. A series of retrospective studies are required to evaluate WR impacts in the spill sites, especially near the oil wells, rather than the aquifers and surface water away from the contamination. A detailed investigation of hydrology and hydrogeology and water chemistry using the recently developed geochemical and isotopic tracers (e.g., $^{87}Sr/^{86}Sr$) are required at multiple spill sites to confirm or refute the evidence for WR contamination due to UOP in ND.

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Table 1

Table 1. Annual Total Water Consumption for Hydraulic Fracturing in the North Dakota Bakken Play (Adapted from Horner et. al., (2016))

	Total water consumed (millions of gallons)	Total water consumed (millions of litres)	number of wells	average volume per well (millions of gallons)	average volume per well (millions of litres)
2008	770	2914.45	401	NA	NA
2009	894	3383.79	465	NA	NA
2010	1457	5514.745	758	NA	NA
2011	2304	8720.64	1199	1.92	7.27
2012	4274	16177.09	1801	2.37	8.97

Table 2

Table 2a. Comparison of the oil produced and water used in the individual stages of the COP and UOP

	COP			UOP		
	Oil production (Million litres/d)	Water used (Million litres/d)	Litres of water used per litre of oil produced	Oil production (Million litres/d)	Water used (Million litres/d)	Litres of water used per litre of oil produced
Primary	308.4	7.6	0.02	789.4	181.7	0.23
Secondary	411.6	3531.4	8.6	NA	NA	NA
Tertiary	103.2	893.3	8.7	U	U	U

Table 2b. Ranking of COP and UOP based on oil produced and water used in different stages

	Ranking		
	On basis of Oil produced	On basis of water used	On basis of litres of water used per litre of oil produced
Primary COP	3	4	4
Secondary COP	2	1	2
Tertiary COP	4	2	1
Primary UOP	1	3	3
EOR UOP	U	U	U

Note1: Table 5a is based on data from Wu and Chiu (2011), Kondash and Vengosh (2015).

Note2: Table 5b: Ranking 1-highest contribution; Ranking 4-least contribution

Note3: NA: Not applicable; U: Data is unavailable; COP-Conventional oil production; UOP- Unconventional oil production; EOR-Enhanced oil recovery

Note4: COP involves primary, secondary and tertiary stages (See Fig. 4)

Note5: UOP involves primary and enhanced recovery stages only (See Fig. 4)

Table 3

Table 3. Major Chemistry, Isotopic Ratios and Trace Metals of Produced water (Adapted from Lauer et al., (2016)) and Flowback water in Bakken (Adapted from Stepan et al., (2010) and Strong et al. (2013))

Note: PWn refers to produced water sample collected at site n (e.g., PW1 refers to the first sample), Specific locations for PW_1-PW_4 were not provided in the original source; FWn refers to Flowback water samples collected from the location n, Specific location detail for FW1 sample is shown is Figure S1; FW2 and FW3 samples were obtained in July 2012 from wells producing oil, Specific location details was not provided in original source

Constituent	Concentration (mg/L) found in Bakken produced water at different location						
	Produced water				Flowback water		
	PW1	PW2	PW3	PW4	FW1	FW2	FW3
Cl	119,989	75,892	21,728.0	136,220	118,666.7	125,818	903
Br	558	384	91.6	601	-	576.8	37.5
SO4	128	102	-	293	650	532.9	360.4
HCO3	35	169	856	-	290.7	-	-
Ca	12,033	8,573	372	15,346	9,683.3	15,543	9,208
Mg	1,001	741	118	1,299	1,273.3	-	-
Sr	774	551	33.1	970	764	915.8	57.2
Na	47,217	34,745	12,271	60,571	61,466.7	-	-
NH4	2,110	1,200	44.8	2,520	-	-	-
$^{87}Sr/^{86}Sr$	0.7	0.7	0.7	0.7	-	-	-
Li	31.5	19.7	2.9	37	-	34.7	0.7
B	225.3	142.8	25.0	260.1	-	-	-
Al	0.2	0.9	0.3	1.1	<1	-	-
V	1.0	0.6	0.1	1.0	-	-	-
Mn	16.7	13.1	0.2	15.8	7.1	-	-
Co	0.1	0.2	0.003	0.2	-	-	-
Ni	0.5	0.6	0.009	0.8	-	-	-
Cu	0.1	0.015	0.013	0.4	0.2	-	-
Zn	12.5	3.8	0.0	17.1	6.7	-	-
Se	0.9	0.6	0.1	1.0	-	-	-

Rb	11.7	7.4	0.3	12.9	-	-	-
Tl	0.2	0.1	0.0	0.2	-	-	-
Fe	19.2	30.2	0.7	22.3	96	-	-
Ba	9.2	12.4	26.3	6.4	10.5	9.6	1.3
Pb	0.6	0.1	0.0	3.5	-	-	-
Cd	0.021	0.022	0.001	0.031	-	-	-

Table 4

Table 4. Major Chemistry, and Trace Metals in the ground water at the median distance of 4.6 km from the nearest oil and gas well in the upper Fort Union Formation of the Bakken (Adapted from McMahon et al., (2015), Tchobanoglous and Burton, (1991))

Potential Contaminant	**Concentration in nearby ground water sources (Upper Fort Union Formation) (µg/l)**	**Potential Health hazard**
TDS	$3{,}590 * 10^3$	Hardness, Deposits, Colored water, Staining ,Salty taste but no health hazard
Conductivity (mS/cm)		Especially for fish and other aquatic species
COD		Especially for fish and other aquatic species
pH		Especially for fish and other aquatic species
Na		Kidney damage, Increases in blood pressure, Skin, Eyes, Nose and Throat irritation
Ca		Kidney stones, Reproductive toxicity
K		Fluid in the lungs, Eyes irritation, Nose and Throat Irritation
Mg		Fever, Chills, Nausea, Vomiting & muscle pain, Irritation of upper respiratory tract irritation upon inhalation
Fe	4,460	Conjunctivitis, Choroiditis, and Retinitis, Neurological disorder
P		Kidney damage, Osteoporosis ,Nausea, Stomach cramps and Drowsiness
NO_3^--N	6.47	Harmful to infants, Shortness of breath and blue-baby syndrome
NO_2^--N		Harmful to infants, Shortness of breath and blue-baby syndrome
Si		Fibrosis in lung tissue, Skin and eyes irritation, Renal system diseases
Mn	1090	Hallucinations, Forgetfulness, Parkinson, Lung embolism, Bronchitis, Nerve damage, Endocrine disruptor.
Al		Severe trembling, Listlessness, Loss of memory, Damage to the central nervous system, Dementia
B		Infection in stomach, liver, kidneys and brain
Ba	223	Flammable at room temperature in powder form, Long term- Increased blood pressure and nerve block
Cd		Flammable in powder form, Toxic by inhalation of dust or fume, A carcinogen. Soluble compounds of Cd are highly toxic. Long term- concentrates in the liver, kidney, pancreas, and thyroid, Hypertension suspected effect
Cu		Gastrointestinal distress, Liver or kidney damage, Neurological disorder
Cr		Hexavalent Cr compounds are carcinogens and corrosive on tissue. Long term- skin sensitization and kidney damage, Reproductive toxicity
Li		Corrosive to the eyes, skin and respiratory tract

Pb		Toxic by ingestion or inhalation of dust or fumes, Long term-brain and kidney damage, Birth defects, Reproductive toxicity, Neurological disorder, , Immunological disorder
Sr		Problems with bone growth, Anaemia and carcinogenic
Rb		Skin and eye burns, Failure to gain weight, Ataxia, Hyper irritation, Skin ulcers, and Extreme nervousness
V		Cardiac and vascular disease,Damage to the nervous system, Dizziness, Eye, nose and throat irritation
Tl		Hair loss, Changes in blood and Kidney, Intestine, or liver problems
Se	42.8	Long term- red staining of fingers, teeth and hair, General weakness, Depression, Irritation of nose and mouth
Ti		Pain in chest, Skin and eye irritation
Zn		Loss of appetite, Decreased sense of taste and smell, Slow wound healing and Skin sores, Endocrine disruptor, Neurological disorder
Hg		Kidney damage, Reproductive toxicity, Immunological disorder
Ag		Toxic metal, Long term-permanent gray discoloration of skin, eyes, and mucous membranes
Ni		Lung cancer, Nose cancer, Larynx cancer, Prostate cancer, Asthma and chronic bronchitis, Heart disorders and Allergic reactions such as skin rashes
Be		Kidney damage
Cl^-	$162*10^3$	Irritates skin and eyes, Chest pain, Water retention in the lungs
Br^-		Malfunctioning of the nervous system and disturbances in genetic materials
Mo	<0.2	Hyperbilirubinemia, Gout and Joint pains
F	4.22	Dermal, Musculoskeletal, Ocular (Eyes), Respiratory (From the Nose to the Lungs)
SO_4^{2-}	<59	Dehydration, Laxative effect, Decrease in gastrointestinal retention of food
CN^-		Nerve damage or thyroid problem
As	11.5	Carcinogen and mutagen, Long term- sometimes can cause fatigue and loss of energy, Dermatitis, Endocrine disruptor, Reproductive toxicity.
Ammonia		Skin, eyes, respiratory tract and lungs irritation
Sulfide		Dermatitis and burning eyes
Sulfate	$1,830*10^3$	Salty taste but no health hazard
Sb		Increase in blood cholesterol, Decrease in blood sugar
Benzene	<0.026	Anemia; decrease in blood platelets, Increased risk of cancer, Disrupt endocrine systems
Toluene	<0.69	Nervous system, Kidney or Liver problems, Disrupt endocrine systems
Bicarbonate		No health hazard
Phenol		Systemic poison and constitutes a serious health hazard, Weak endocrine disrupters
Ethylbenzene	<0.036	Liver or kidneys problems, Disrupt endocrine systems

Xylenes		Toxic on inhalation, Disrupt endocrine systems
Cs		Nausea, Vomiting, Diarrhea and Bleeding
U	23.2	Increased risk of cancer, Kidney toxicity
Ra		Increased risk of cancer
Methane	$32*10^3$	Headache, Dizziness, Weakness, Nausea, Vomiting, and loss of coordination

Table 5

Table 5. Comparison of State Hydraulic Fracturing Chemical Disclosure Regulations in Arkansas, Colorado, Louisiana, Montana, Wyoming, North Dakota and Pennsylvania (Adapted from Department of Natural Resources: State of Louisiana (2011))

	Arkansas	**Colorado**	**Louisiana**	**Montana**	**Wyoming**	**North Dakota**	**Pennsylvania**
Base Fluid Type	Yes	Yes	Yes	Yes	Yes	Yes	No
Base Fluid Volume	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Additive Trade Name	Yes	Yes	Yes	Yes (trade secret only)	Yes	Yes	No
Additive Vendor	Yes	Yes	Yes	Yes	No	Yes	No
Additive Function	Yes	Yes	Yes	Yes	No	Yes	Yes
Additive Concentration	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Chemical Names	Yes (Unless trade secret)	Yes (Unless trade secret)	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)	Yes (unless trade secret)	Yes	Yes	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)
Chemical Concentration	No	Yes (Unless trade secret)	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)	Yes (unless trade secret)	Yes	Yes	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)
Chemical Abstract Service (CAS) Number	Yes (Unless trade secret)	Yes (Unless trade secret)	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)	Yes (trade secret only)	No	Yes	Yes (if subject to 29 CFR 1910.1200 and unless trade secret)
Chemical Family CAS Number	Yes (trade secret only)	Yes (Unless trade secret)	Yes (trade secret only)	Yes (unless trade secret)	No	No	No
Effective Date	January 15,2011	April 1,2012	October 20,2011	August 27,2011	October 17,2010	September 11,2011	February 5,2011

Table 6

Table 6a. Representative, reported brine spills that occurred between 2015-2016 in North Dakota (Contained spills)

(Adapted from North Dakota Department of Health (2016))

Date Incident	County	Well Name	Spill water volume (Barrels)	Spill water volume (Litres)	Other Contaminant	Contained
6/19/2016	Burke	CATHY EDWARDS FEDERAL 5992 31-2H	150	23845.50	Produced water	Yes
6/13/2016	Mountrail	TIOGA-MADISON UNIT N-140D	770	122406.90		Yes
6/12/2016	Billings	BSMU 1701 CTB	180	28614.60		Yes
6/9/2016	Bottineau	ALICE-JEAN 33-30	190	30204.30		Yes
5/26/2016	Billings	TR MADISON UNIT 21-14H	210	33383.70		Yes
5/24/2016	Mckenzie	WEST CLARK SECTION 1 CENTRAL FACILITY	150	23845.50		Yes
5/19/2016	Mckenzie	PM SWD 5198 13-18	115	18281.55		Yes
5/7/2016	Mountrail	AUSTIN SECTION 26 CENTRAL FACILITY	259	41173.23		Yes
5/4/2016	Mckenzie	GUNDER T. 151-101-30A-31-1H	80	12717.60		Yes
5/1/2016	Mckenzie	GRIZZLY 146-99-3-3-10-14H	73	11604.81		Yes
4/29/2016	Mckenzie	Leiseth SWD #1	240	38152.80		Yes
4/24/2016	Dunn	MASTERS ENTERPRISES 1	640	101740.80		Yes
4/21/2016	Billings	UVI FEDERAL 1-33	80	12717.60		Yes
3/29/2016	Billings	NERU 29-01 CTB	320	50870.40	No other substances were released.	Yes
3/13/2016	Bowman	ABRAHAMSON D-8	75	11922.75	NA	Yes
3/11/2016	Mckenzie	MOEN 1-35 SWD	190	30204.30		Yes
3/7/2016	Mckenzie	HYSTED 5200 11-30 CTB	80	12717.60		Yes
3/1/2016	Mckenzie	GRIZZLY 1-25 SWD	160	25435.20		Yes
2/25/2016	Mckenzie	FORT BERTHOLD 152-93-19D-18-4H	77	12240.69		Yes
2/3/2016	Billings	NORTH ELKHORN RANCH UNIT 2105	136	21619.92	N/A	Yes
1/17/2016	Mountrail	SAUBER 1-17H	170	27024.90		Yes

1/15/2016	Williams	P HOVDE 8-20 SWD	745	118432.65	Melted snow (freshwater)	Yes
12/28/2015	Billings	BSMU 1701 CTB	150	23845.50		Yes

Table 6b. Representative, reported brine spills that occurred between 2015-2016 in North Dakota (Uncontained spills)

(Adapted from North Dakota Department of Health (2016))

Date Incident	County	Well Name	Spill water volume (Barrels)	Spill water volume (Litres)	Other Contaminant	Contained
6/14/2016	Renville	TRURO MADISON UNIT	210	33383.70		No
6/8/2016	Dunn	FORT BERTHOLD 148-94-33D-28-6H	5	794.85	Brine due to vandalism.	No
6/5/2016	Burke	SCHULTZ 1 SWDW	5	794.85		No
5/9/2016	Bottineau	JOHNSON 24-19	5	794.85		No
5/1/2016	Dunn	LIKES EAGLE #2-31H	50	7948.50	An estimated 50 bbls of produced water was illegally dumped by an unknown party on property adjacent to our well pad.	No
4/28/2016	Burke	RMU BATTERY 4	40	6358.80		No
3/27/2016	Williams	P EVITT 12-12 SWD	2	317.94		No
3/6/2016	Williams	CHEETAH 10-10H & LION 1-14H	2733	434465.01		No
2/22/2016	Dunn	RECKARD SWD #1	149	23686.53		No
2/18/2016	Golden valley		20	3179.40		No
2/12/2016	Dunn	BOREJAKS SWD 2	78	12399.66	NA	No
2/6/2016	Williams	Stokke SWD	10	1589.70		No
1/23/2016	Bowman	BRADAC CTB	4	635.88		No
1/11/2016	Renville	V. HARRIS-MONTANA 1	50	7948.50		No

1/7/2016	Williams		187	29727.39	N/A	No
12/11/2015	Divide		0.24	37.85	Salt Water	No
12/7/2015	Mckenzie	JONES USA CTB	90	14307.30		No
12/6/2015	Divide		5	794.85		No
12/5/2015	Burke	CHREST 22-26	6	953.82		No
12/5/2015	Mountrail	BURKE 100-20H	10	1589.70		No
11/23/2015	Mountrail	Evans SWD #1	15	2384.55		No
10/10/2015	Dunn		0.48	75.70	Brine Water	No
10/3/2015	Dunn	ECKELBERG 14-23TFH	60	9538.20		No
9/30/2015	Billings	FRYBURG HEATH-MADISON UNIT F-812	70	11127.90		No
8/5/2015	Divide	NOVA 4-9-163-98H	4260	677212.20		No
7/24/2015	Bottineau	KING SWD SYSTEM D01	50	7948.50	Also recovered 100 bbls of standing water from ditch area.	No
7/20/2015	Williams	CHARLESTON 4-22H1	3	476.91		No

Table 7

Table 7. U.S. Geological Survey, recent and ongoing studies in the Williston Basin. November 2013 (Adapted from USGS (2013))

Year	Project Title	Relevant Publication/Reports
2003-present	Delineation of brine contamination in and near the East Poplar oil field, Fort Peck Indian Reservation, northeastern Montana	(Thamke and Smith, 2014) http://pubs.usgs.gov/sir/2014/5024/
2008-present	Brine Contamination to Prairie Potholes from Energy Development in the Williston Basin	(Smith, 2009) https://gsa.confex.com/gsa/2009AM/finalprogram/abstract_163310.htm
2010-present	Water Balances for Energy Resource Production	On-going study, publication in preparation http://energy.usgs.gov/HealthEnvironment/EnergyProductionUse/ProducedWaters.aspx
2011-2012	A GIS-Based Vulnerability Assessment of Brine Contamination to Aquatic Resources from Oil and Gas Development in Eastern Sheridan County, MT	(Preston et al., 2014) http://www.sciencedirect.com/science/article/pii/S0048969713010656
2012-2015	Williston and Powder River basins groundwater availability	South Dakota School of Mines Theses 2013, USGS publications in preparation http://mt.water.usgs.gov/projects/WaPR/
2012-present	Investigating the biological impacts of brine contamination on wetlands of the Prairie Pothole Region: Developing maps depicting conditions in the ecosystems	On-going study
2012-present	Spatial characterization of wetland surface water contamination risk from oil development in the Prairie Pothole Region of North Dakota	On-going study, publication in preparation
2012-present	Baseline Chemical and Isotopic Data for Produced Water from the Bakken Formation, Williston Basin	Data available in USGS National Water Information System at http://mt.water.usgs.gov/
2012-2015	Effects of oil and gas development on grassland birds	On-going study
2013-2014	Presence and Abundance of Invasive Species and Non-Native Perennial Grasses Related to Energy Development in Montana and North Dakota	On-going study
2013-2014	Comprehensive Wetland Assessment and Monitoring Program within the Lost wood Complex of Northeast Montana and Northwest North Dakota	Final report to U.S. Fish & Wildlife Service in preparation
2013	Williston Basin Baseline Water-Quality Assessment	On-going study
2013-2014	Quantifying water-use requirements for the variable conditions and processes associated with hydraulic fracturing within North Dakota, South Dakota, and Montana	On-going study

2014	Updating, gathering and serving datasets relevant to oil and gas development and fish and wildlife management within the Williston Basin and Bakken Formation	On-going study
2014	Evaluating recent and future land-use changes related to energy development in the Williston Basin and Bakken Formation	On-going study
2014	A Web-Based Tool to Evaluate Potential Saline Contamination to Aquatic Resources in the Williston Basin from Energy Development	On-going study

Table 8

Table 8a. Major Chemistry, Isotopic Ratios and Trace Metals of the impacted surface water due to the Bear Den Bay Spill and Blacktail Creek Spills related to the unconventional oil production from the Bakken shale (Adapted from Lauer et al., (2016))

Note: Details on the geographical location of the spill site is provided in Figure S3.

Constituent	Concentration (mg/L) found in different locations of Bear Den Bay Spill and Blacktail Creek Spill					
	Background water	Bear Den Bay Spill site (ND102*)	Bear Den Brine Spill, (ND103*) uphill of ND102	Brine Spill adjacent to plant (ND113*)	Blacktail Creek (ND123*,10 m downstream of spill)	Blacktail Creek spill site (ND126*)
Cl	21	14,795.000	16,032.000	996.000	1,487.000	1,900.000
Br	0.73	72.500	74.000	5.500	5.200	5.900
SO4	1658	1,713.000	3,210.000	4,090.000	3,025.000	3,117.000
HCO3	687	279.000	247.000	668.000	880.000	941.000
Ca	121	1,953.000	1,773.000	576.000	156.000	212.000
Mg	104	684.000	902.000	376.000	235.000	258.000
Sr	1.41	52.600	51.100	5.670	3.480	4.700
Na	733	6,003.000	6,754.000	1,513.000	2,029.000	2,282.000
NH4	0.93	9.140	42.400	0.620	21.000	17.000
$^{87}Sr/^{86}Sr$	0.7082	0.710	0.710	0.708	0.710	0.710
Li	0.103	3.244	3.490	0.478	0.476	0.542
B	0.502	13.140	15.501	0.511	3.217	3.995
Al	0.087	0.202	0.137	0.028	0.026	0.041
V	0.0036	0.148	0.171	0.012	0.022	0.025
Mn	0.304	3.418	0.839	1.924	0.598	0.811
Co	0.0009	0.009	0.005	0.001	0.001	0.001
Ni	0.0043	0.044	0.025	0.004	0.001	-
Cu	0.0036	0.021	0.025	0.004	0.003	0.003
Zn	0.0068	0.088	0.052	0.010	0.012	0.025
Se	0.0011	0.095	0.132	0.008	0.007	0.007

Rb	0.0035	0.211	0.236	0.022	0.056	0.071
Tl	0	0.006	0.005	-	0.000	-
Fe	0.335	2.673	2.468	0.771	0.211	0.079
Ba	0.052	0.392	0.274	0.054	0.062	0.070
Pb	0.0002	0.008	0.008	0.001	0.001	0.001
Cd	0.0001	0.003	0.003	-	-	0.001

Note: Background water is the surface water

*Sample (Latitude, Longitude): ND102 (47.78302, -102.65152), ND103 (47.7827, -102.651147.7827), ND113 (47.86885, -102.95044), ND123 (48.39835, -103.62457), ND126 (48.39835, -103.62457),

Table 8b. Major Chemistry, Isotopic Ratios and Trace Metals of the impacted surface water due to the Bottineau County Spill related to the unconventional oil production from the Bakken shale (Adapted from Lauer et al., (2016))

Constituent	Concentration (mg/L) found in different locations of Bottineau County Spill					
	Background water	Bottineau County Spill (ND120*, Located adjacent to well pad)	Bottineau County Spill site (ND128*,0.1 mile away from storage tanks)	Bottineau County Spill site (ND129*, 0.25 mile away from spill)	Bottineau County spill (ND130*, 0.25 mile away from spill site)	Bottineau County spill site (ND131*, Located in ditch on side of road next to rig)
Cl	21	207.000	269.000	5,833.000	189.000	18,703.000
Br	0.73	0.220	0.560	5.800	0.170	20.500
SO4	1658	464.000	946.000	856.000	387.000	2,739.000
HCO3	687	306.000	466.000	116.000	345.000	110.000
Ca	121	111.000	187.000	1,225.000	109.000	1,381.000
Mg	104	101.000	148.000	475.000	91.000	2,220.000
Sr	1.41	0.460	0.890	5.940	0.490	8.530
Na	733	102.000	298.000	1,876.000	99.300	6,829.000
NH4	0.93	0.760	0.400	<0.01	0.190	0.320
$^{87}Sr/^{86}Sr$	0.7082	0.710	0.710	0.709	0.710	0.710

Li	0.103	0.067	0.213	0.804	0.079	1.196
B	0.502	0.224	0.193	5.358	0.039	1.155
Al	0.087	0.012	0.009	0.017	0.009	0.086
V	0.0036	0.005	0.010	0.073	0.005	0.218
Mn	0.304	0.107	1.555	1.984	0.306	0.725
Co	0.0009	0.001	0.002	0.002	0.000	0.003
Ni	0.0043	0.003	0.005	0.014	0.001	0.028
Cu	0.0036	0.002	0.002	0.005	0.001	0.028
Zn	0.0068	0.015	0.004	0.012	0.003	0.024
Se	0.0011	0.001	0.001	0.049	0.001	0.172
Rb	0.0035	0.004	0.008	0.044	0.003	0.005
Tl	0	-	-	0.000	-	0.000
Fe	0.335	0.161	0.271	1.517	0.148	1.901
Ba	0.052	0.110	0.078	0.512	0.117	0.194
Pb	0.0002	0.000	0.000	0.003	-	0.006
Cd	0.0001	-	0.000	-	-	0.001

Note: Background water is the surface water

*Sample (Latitude, Longitude): ND120 (48.47578, -102.8269), ND128 (48.77762, -101.31268), ND129 (48.79811, -101.34384), ND130 (48.80805, -101.19978), ND131 (48.73949, -101.23452)

Table 9

Table 9.Recommendation on Bakken crude oil production

#	Water cycle stage	Problem statement	Environmental Concern	Possible solution	Reference
1	**Water acquisition (Stage I)**	Increasing freshwater water demand and water stress	Excessive withdrawals of freshwater from arid regions can stress the regional water resources and affect existing sectors including agriculture, hydropower, recreation	Develop novel technologies for recycling and reusing produced water. Such technologies should be capable of separating high dissolved solids from produced water typical to Bakken Shale. Such innovative technologies include: i) Microbial capacitive deionization (Forrestal et al., 2016), ii) Microbial mats (Akyon et al., 2015), and iii) Marginal waster (e.g., Acid-mine drainage) for produced water treatment (Vengosh et al., 2015). Develop alternate water sources for fracturing	(Igunnu and Chen, 2012) (Vengosh et al., 2014)
		Large volumes of maintenance water to avoid salinity buildup in Bakken shale	Excessive withdrawals of freshwater	Develop alternate water sources (brackish to saline groundwater, treated domestic wastewater) for fracturing	(Vengosh et al., 2014)
		Existing groundwater resources are inadequate to meet the increasing freshwater demand	Inability to meet increased water demands in Bakken for direct (fracturing and brine dilution) and indirect uses (domestic water use by the temporary oilfield services population)	Surface water resources (e.g., Missouri river) may be used provided that access is available	(Horner et al. 2016)
		Limited information on water utilization data for hydraulic fracturing (HF) in ND	Extrapolated or conservative conclusions related to water stress issues	More case studies are required to investigate water usage on the spatial and temporal scale	(Gordon and Garner, 2014)

2	**Produced and Flowback water Production (Stage IV)**	Limited data on physiochemical properties, toxicity of the chemicals used in fracturing	Inadequate data to carryout health and environmental impacts risk assessment due to brine spills and wastewater leaks into drinking water resources	Develop analytical methods to determine a suite of organic, inorganic and other chemicals. More peer-reviewed studies to investigate chemicals in produced and flowback water from Bakken shale Learn from the existing studies available from contemporary shales	(Stringfellow et al., 2014)
		Energy-development activities in Bakken can potentially affect groundwater resources	Inorganic chemical, organic chemical, noble-gas and brine can accumulate in the groundwater and can remain undetected for several years	Long-term monitoring of groundwater using a new geochemical and isotopic tracers that are suitable for proving or refuting the evidence for water contamination due to ND Bakken shale development Studies near the oil wells, rather than further away from contaminated sites	(McMahon et al., 2015)
		Contamination of agricultural soil due to the migration and spills related to flowback and produced water (e.g. Brine spill)	Fracturing fluid and wastewater from the Bakken shale can reach and accumulate in the soil and remain unnoticed Fracturing contaminants can accumulate in food chain	Soil characterization on Bakken's agricultural yields needs detailed study	(Ridlington and Rumpler, 2013), McLaughlin et al., 2016
3	**Wastewater (Flowback and Produced water) management**	Wastewater handling, storage and transportation	HF wastewater spills can contaminate water and soil. No containment management protocols in place. HF wastewater underground pipeline database is not comprehensive and monitoring of underground pipeline is challenging. Unnoticed pipeline leaks can gradually contaminate ground water sources	Prompt reporting of spills to the statutory agency HF water tankers going to class II injection well should be required to carry certificate of analysis with details of all constituent chemicals to help predict. This will aid in containing the potential spills. Pipeline monitoring should be in place to detect leaks	(Gordon and Garner, 2014)

	Discharge of untreated wastewater can contaminate water resources	Accumulation of metals and radioactive elements in water resources	Treat the wastewater to meet the discharge regulations	(Igunnu and Chen, 2012)
	Lack of continuous monitoring and database	Injection of brine water into class II wells can alter the geological formation and lead to ground water contamination	Spatial and temporal distribution of seismic measurements can be early indicators for major catastrophic failure of class II wells	(Frohlich et al., 2014)
	Inorganic contamination associated with brine spills in ND is remarkably persistent, up to 4 years following the spill events	The spill sites can threaten surface and ground water resources for several years after the spill	Future research should evaluate additional spill sites, analyze organic contamination in addition to inorganic elements, assess the impacts downstream of spill sites, including risks to drinking water sources, and conduct acomprehensive assessment of long-term ecological and possible human health impacts.	(Lauer et al.,2016)
	Pipeline breaks and brine spills	Contamination of the groundwater and surface water resources	More data on the fate and transport of fracturing fluid organic constituents and their transformation products are needed	(Rogers et al.,2015), (Parker et al.,2014)
	Lack of follow-up studies on brine spills site in the Bakken	Transport of contaminants can continue to impact the land and groundwater longer than expected	More retrospective studies should be done to collect data on transport of fracturing fluid constituents for longer monitoring duration	(Rogers et al.,2015)

Figure 1

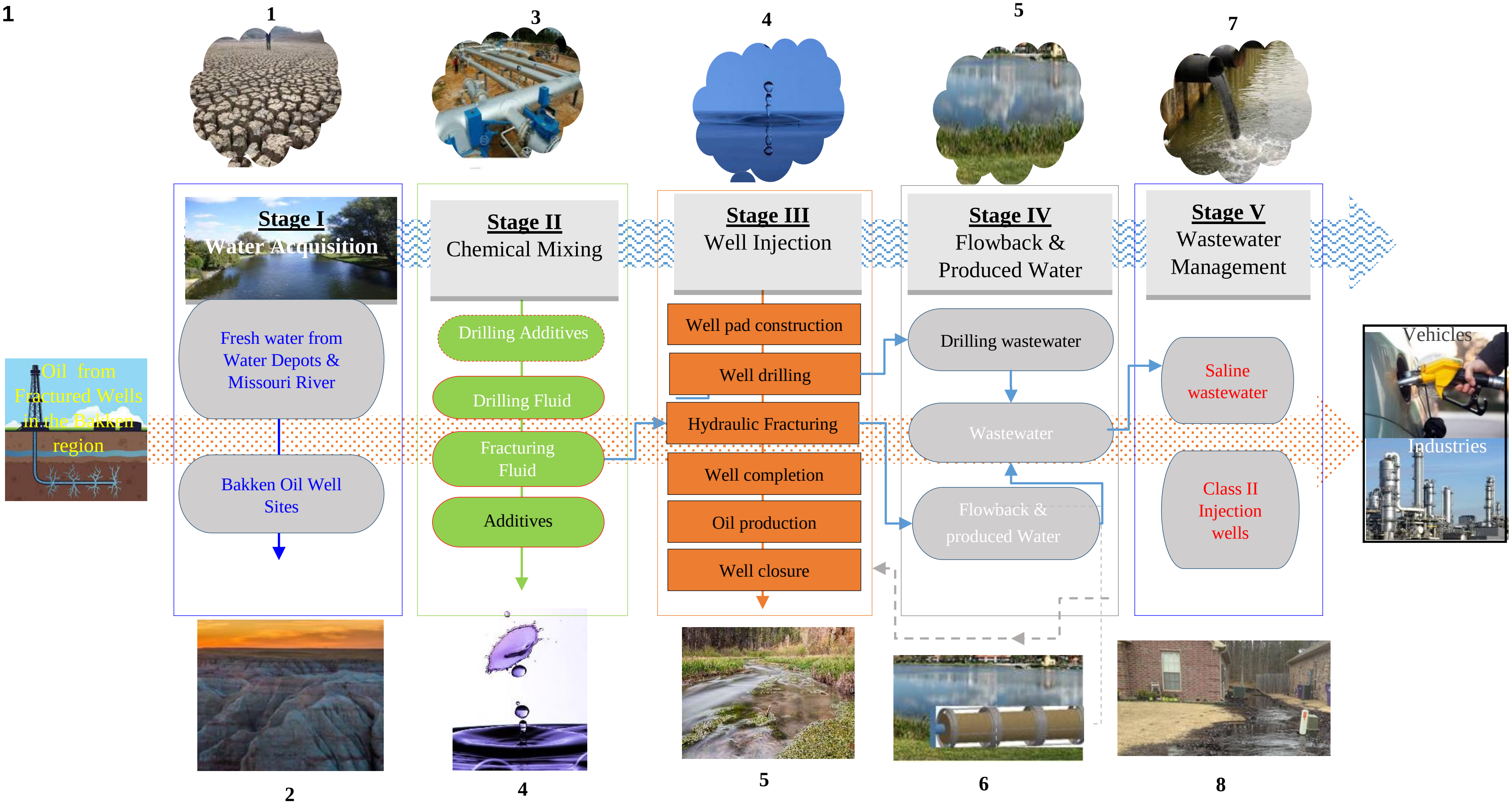

Figure 1. Potential water resource impacts due to the consumptive and non-consumptive water use for crude oil production from the Bakken shale (Hydraulic fracturing water lifecycle information adapted from U.S. EPA (2015), Chemical mixing and well injection sequence adapted from (Jiang et al., 2014)).

Note: Schematic illustration of possible modes of water resource impacts due to the ND Bakke shale oil development reviewed in this paper include: (1) Water stress due to excessive use of freshwater that can decrease the freshwater availability for agriculture, hydropower, drinking water and recreation; (2) Droughts due to overuse of freshwater in water-scarce areas; (3) Chemical leaks during mixing can water resources; (4) Chemical spills during mixing can contaminate water resources; (5) Infiltration of chemicals and wastewater into ground from stored pits due to poor well casing/ storage design; (6) Pipeline breaks during wastewater transporting can contaminate water and land resources; (7) Discharge of untreated wastewater can contaminate receiving water bodies; and (8) surface spills and leakage during treatment, storage and treatment can result in surface water and shallow groundwater contamination

Figure 2

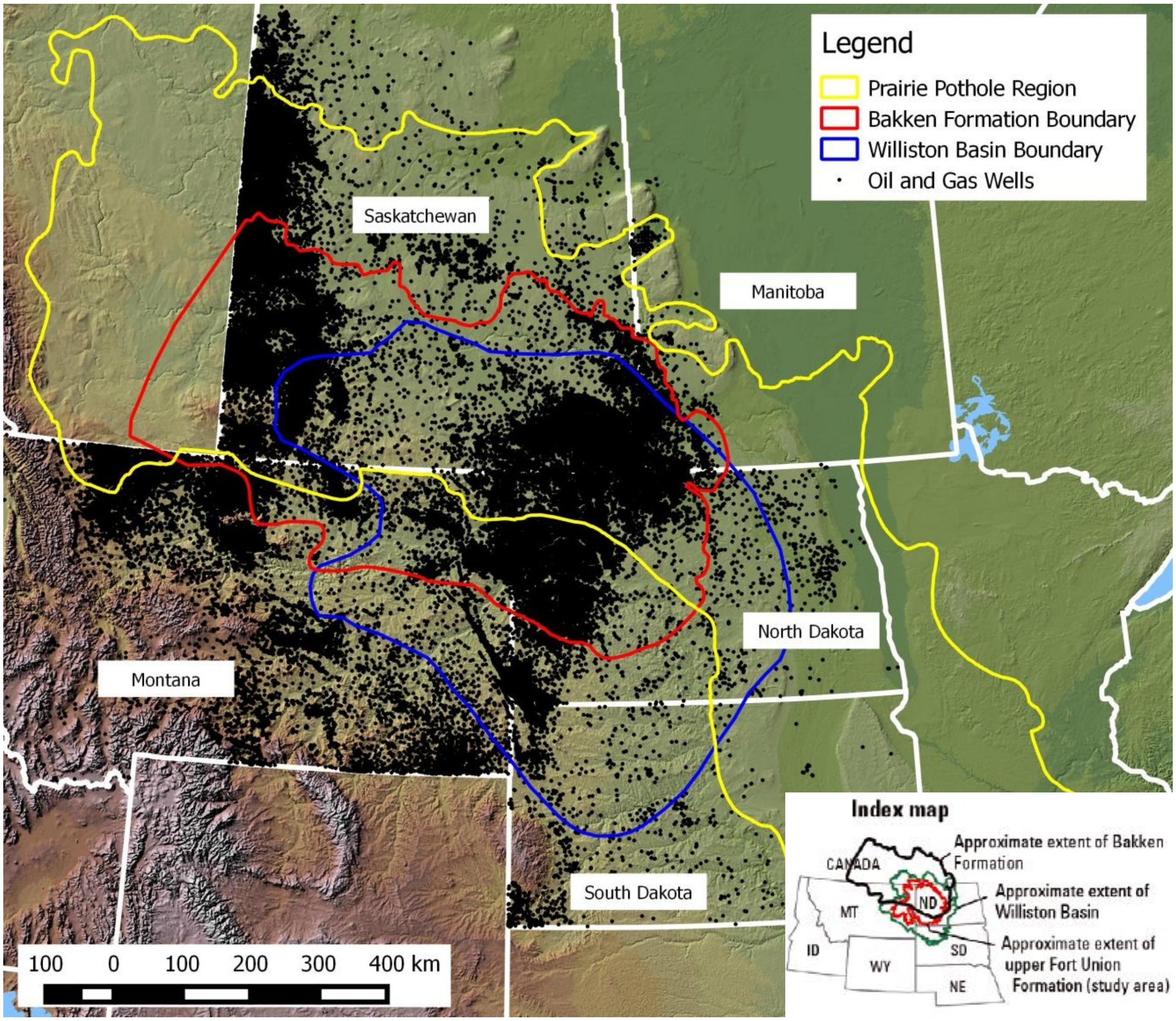

Figure 2. Topographical map showing the Williston basin boundary (highlighted in blue), the prairie pothole regions (highlighted in yellow), the Bakken formation boundary (highlighted in red), and the oil and gas wells (highlighted in black) (With permission from (U.S.Geological Survey, 2015)).

Note: Inset shows the extent of Williston basin, and Bakken and upper Fort union formation in the Upper Great Plain (UGP) regions including SD, ND, MT, WY, and NE.

Figure 3

B

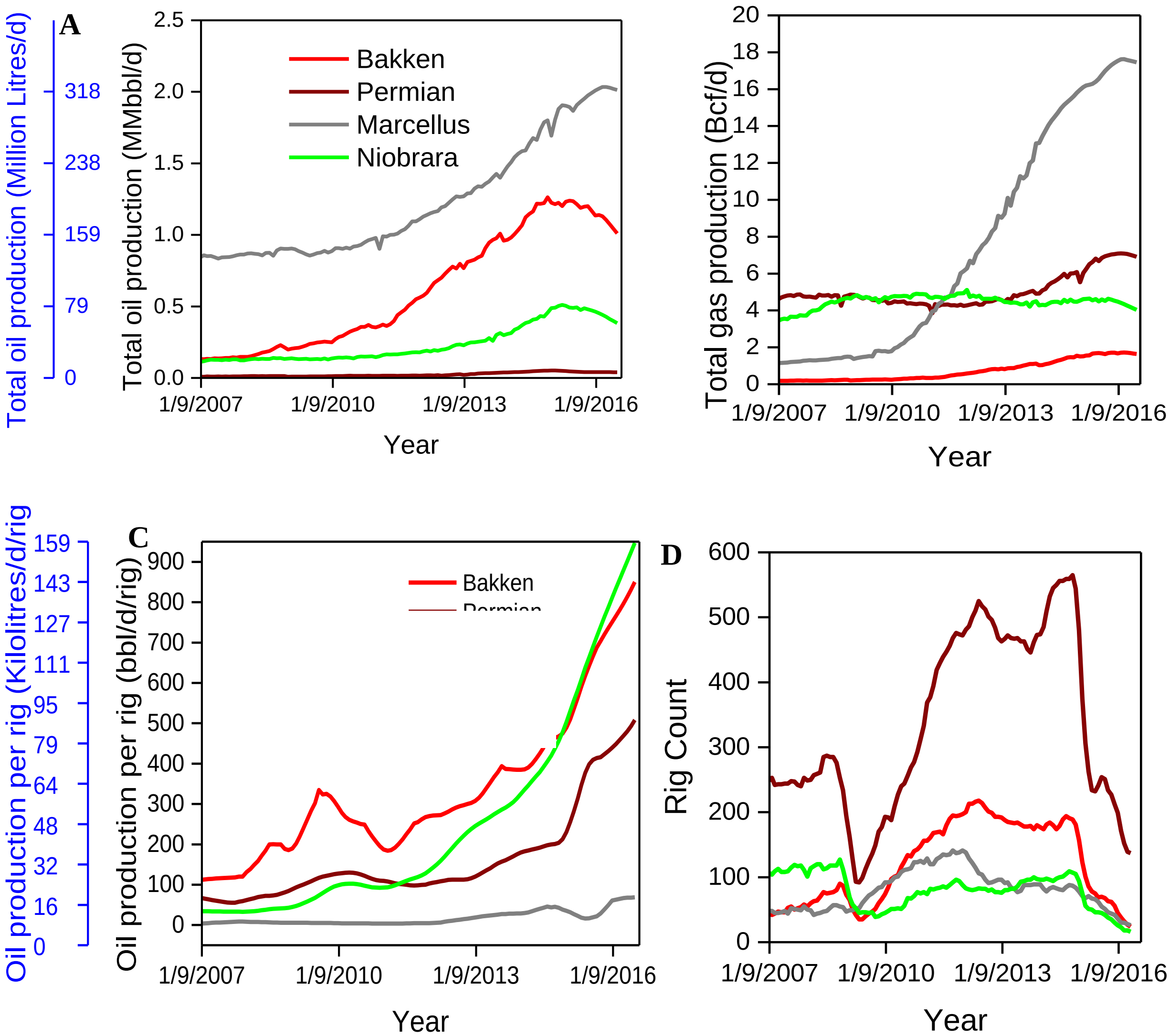

Figure 3. Comparison of drilling productivity for the Bakken shale with the Permian, Marcellus, and Niobrara shales from 2007 to 2016: a) Total crude oil production (MMbbl/d) or (Million Litres/d), b) Total natural gas production (Bcf/d), c) oil production per rig (bbl/d/rig) or (Kilolitres/d/rig), and d) Rig count (Adapted from (U.S. EIA, 2015))

Figure 4

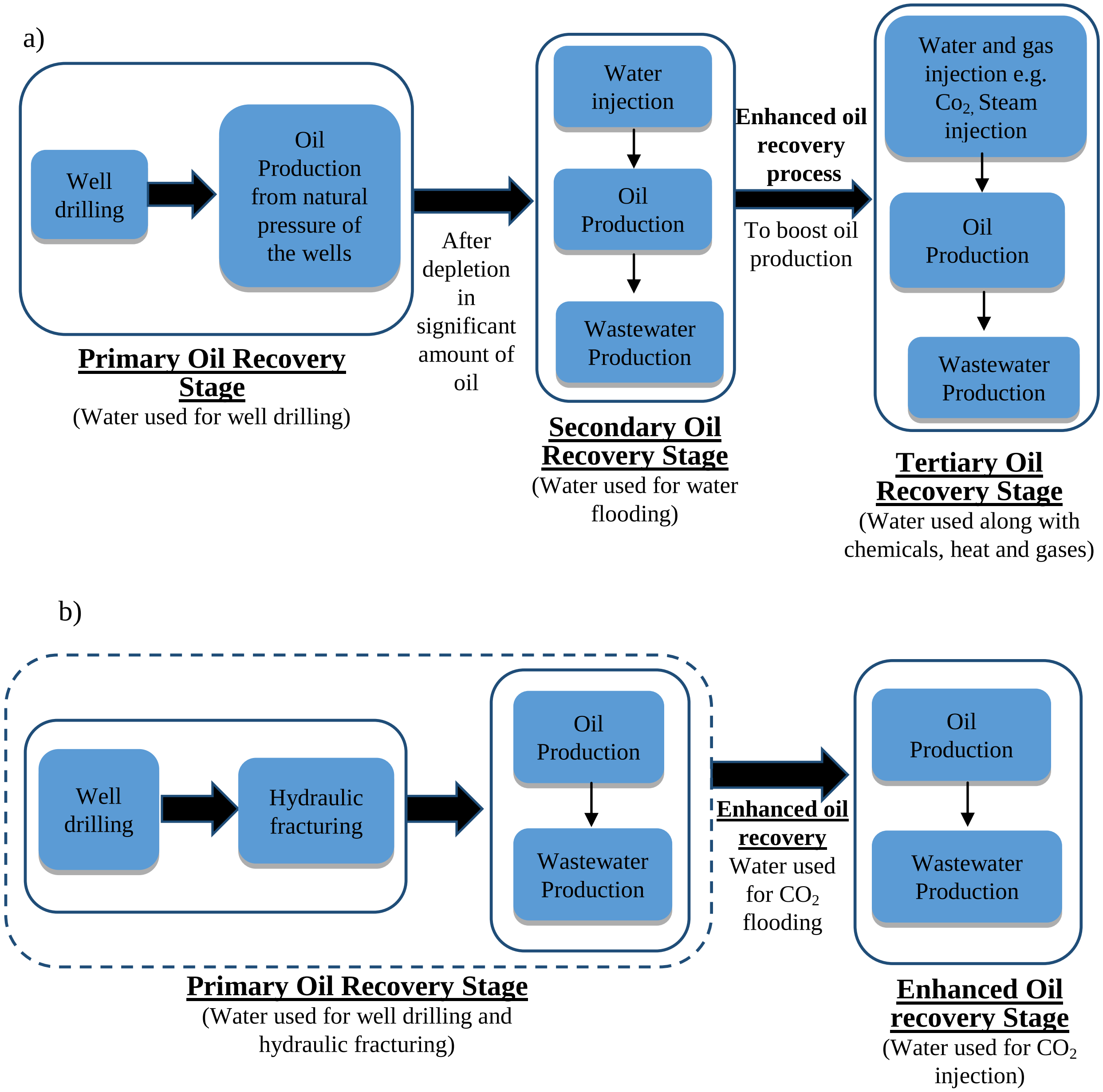

Figure 4. Water consumption during the three different stages of the crude oil recovery: a) Conventional Oil Production b) Unconventional Oil Production (Adapted Wu and Chiu (2011))

Figure 5

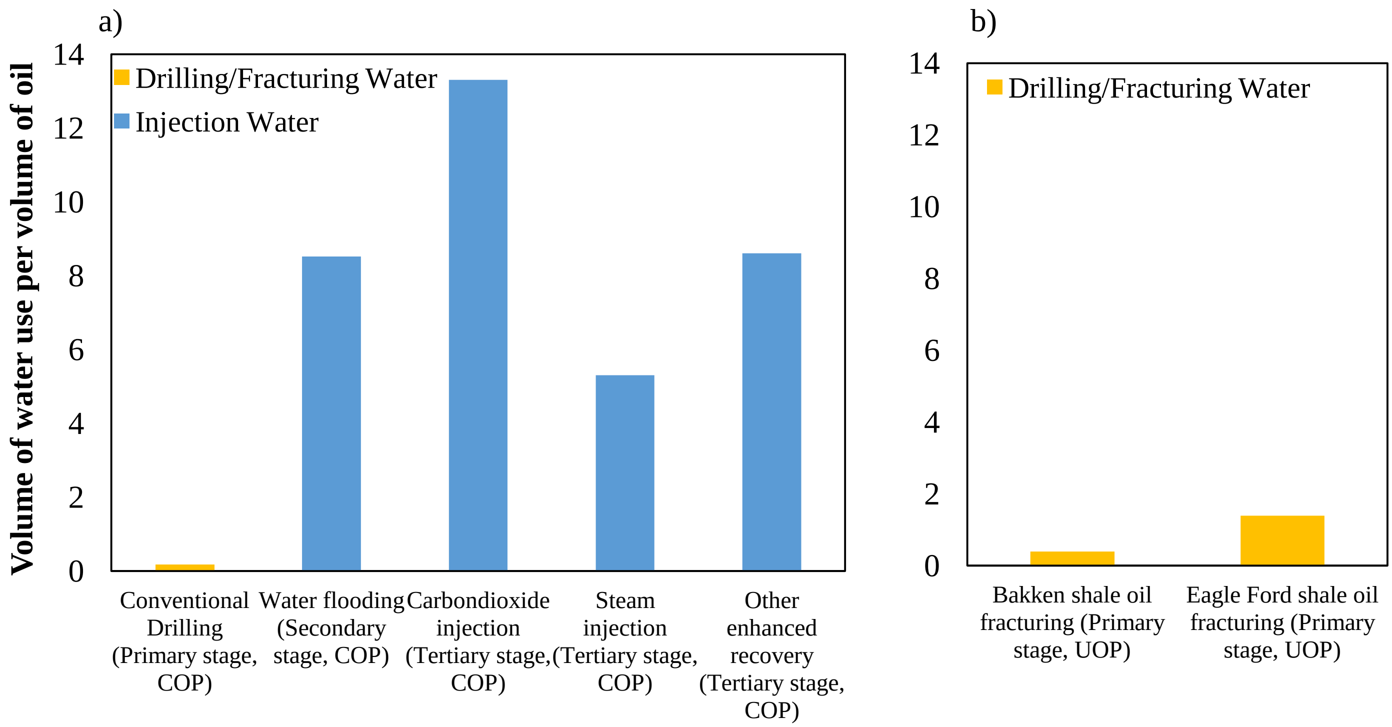

Figure 5. Comparison of water injection for three different oil recovery stages throughout the lifecycle of petroleum reservoirs. a) Water consumption for COP b) Water consumption for UOP (Adapted from Lampert (2015), Wu and Chiu (2011)

Note: COP refers to conventional oil production, UOP refers to unconventional oil production

Figure 6

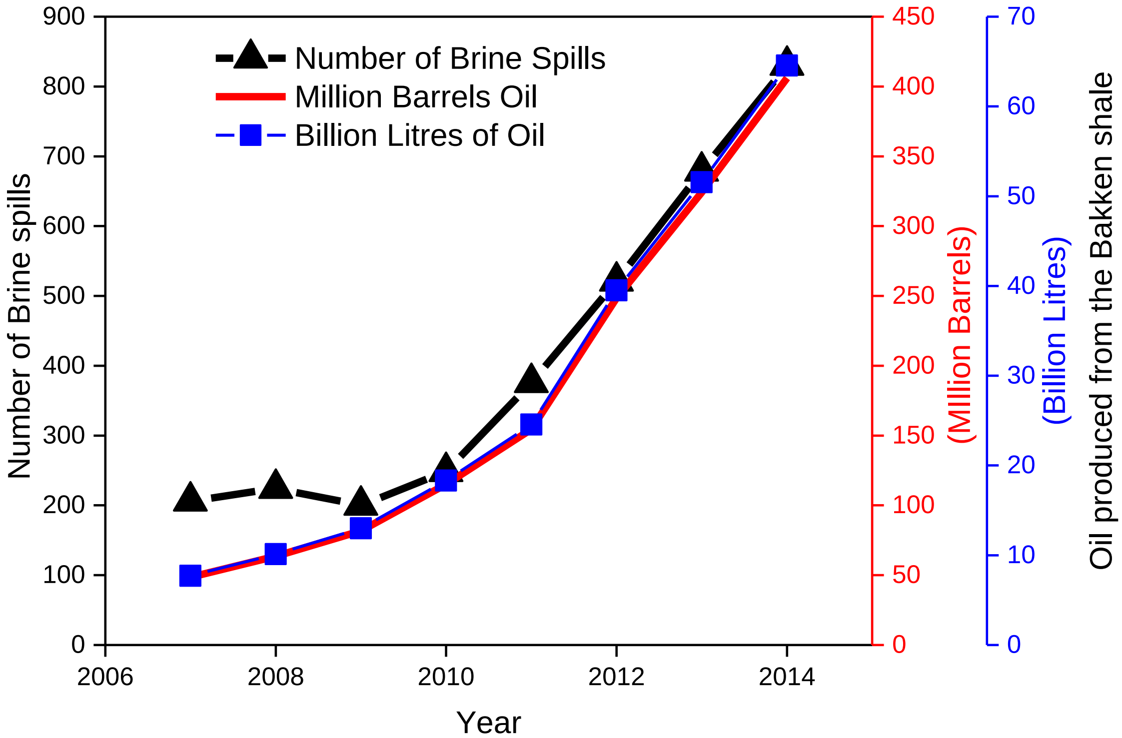

Figure 6. Parallel rise of annual Bakken oil production and number of spills in North Dakota from 2007 to 2014. Data compiled from North Dakota Department of Health and Lauer et al., (2016)

Figure 7

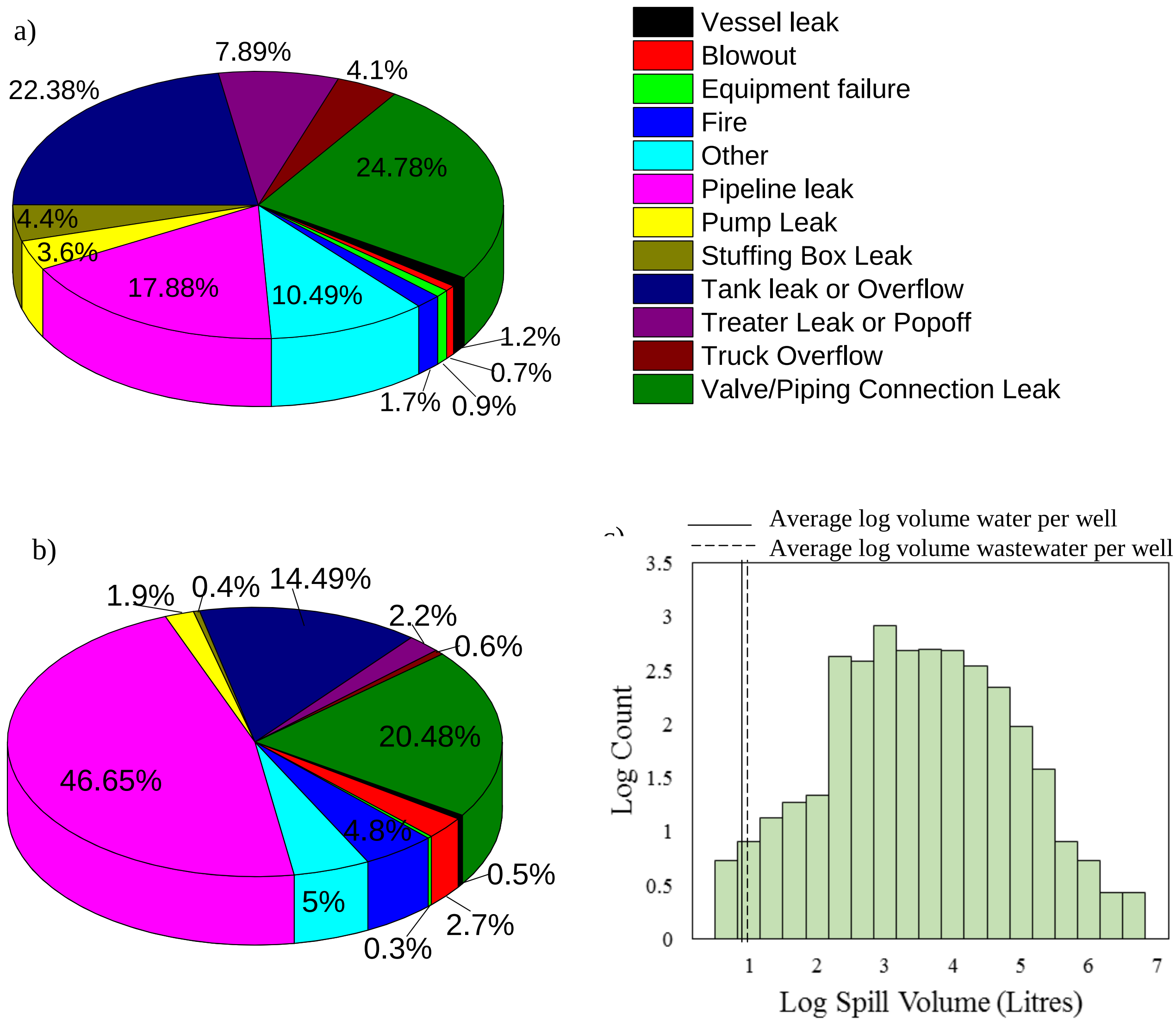

Figure 7. The distribution of brine spills sources in North Dakota based on (a) the number of spills and, (b) the volume of spilled brine. Data were compiled from North Dakota Department of Health: Environmental Releases & Investigations c) Brine spills volumes in North Dakota since 2007. Data were compiled from North Dakota Department of Health: Environmental Releases & Investigations. (https://www.ndhealth.gov/WQ/GW/spills.htm) and Lauer et al., (2016).

Note: The figure includes only brines spill during year 2006-2014. Oil spills during the given year are not considered.

Figure 8

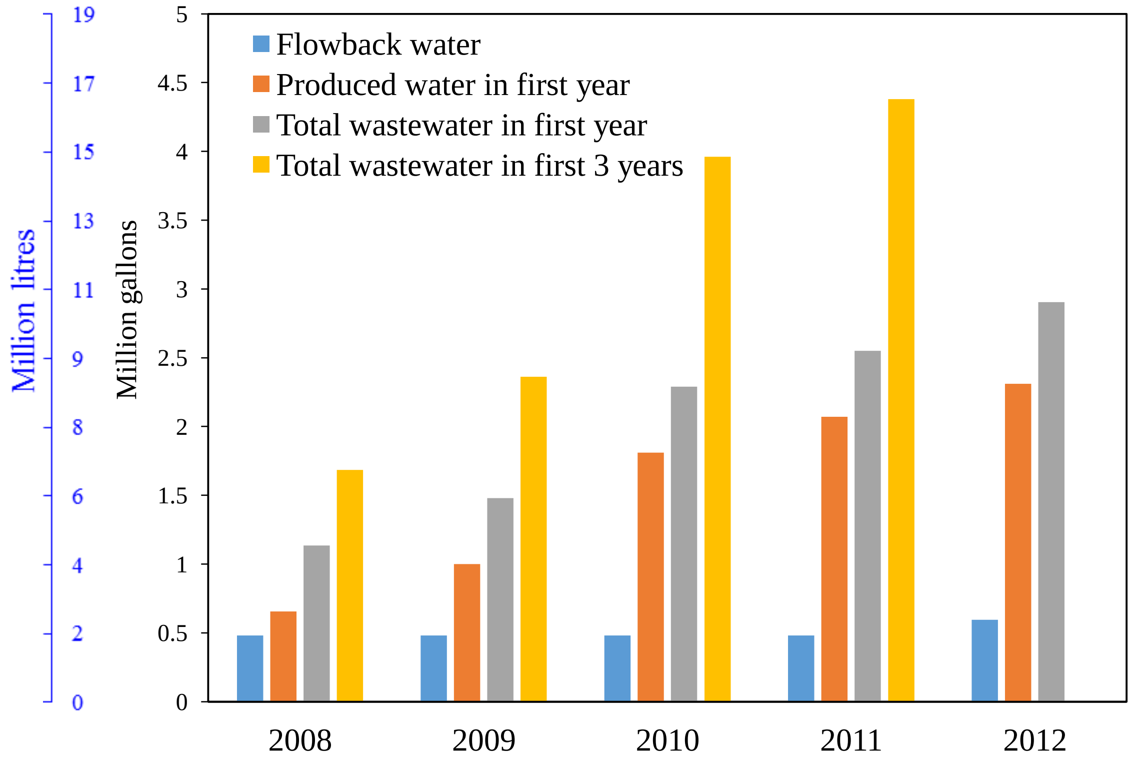

Figure 8. Average Flowback and Produced Water per Well in the First 1 and 3 Years of Production. Adapted from Horner et al., (2016)