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Vulnerability Indices For Waterbodies Impacted By Theoretical Hydraulic Fracturing Spills Modeled Utilizing Gis

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VULNERABILITY INDICES FOR WATERBODIES IMPACTED BY THEORETICAL HYDRAULIC FRACTURING SPILLS MODELED UTILIZING GIS

by

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This thesis, submitted by Isaac J. Simon in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School and is hereby approved.

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Isaac J. Simon

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ABSTRACT

Hydraulic fracturing is a method used to extract oil or natural gas from unconventional sources. Within western North Dakota it is largely used to extract oil from the Bakken Formation since the low permeability of the Bakken shale makes conventional methods of oil extraction difficult. Hydraulic fracturing utilizes large volumes of frack fluid and this frack fluid is toxic to humans, animals including livestock, and vegetation including crops. Research is needed to provide a greater understanding of where frack fluid would travel if spilled, how much frack fluid could infiltrate into the soil, and how much frack fluid could impact waterbodies.

The spill pathways of frack fluid were modeled by integrating National Elevation Dataset (NED) Digital Elevation Models (DEMs) with well site locations in ArcMap 10.2. SSURGO datasets were utilized to estimate the volume of frack fluid that the soil was able to hold along the spill path. Twelve different scenarios based on spill volume and soil infiltration level were used to create vulnerability indices that were normalized between 0-1 in order to compare the vulnerability of different waterbodies and watersheds relative to the worst spill in the study area.

This study finds that spills of volumes that have occurred within North Dakota are large enough that, if unmitigated, water quality can degrade. Threatened waterbodies include both large waterbodies that are the water source for many North Dakotans such as Lake Sakakawea, and smaller waterbodies that may only be utilized by the landowner. Due to the ability of large waterbodies to dilute the impacts of spills, under certain

scenarios, the most vulnerable waterbodies are small ones as they can be severely degraded by small spills. This puts individual landowners who rely on a small waterbody within their property at risk from the impacts of spills. Additionally, spill pathways can, depending on the size of the spill, extend from areas where hydraulic fracturing is allowed to areas where it is banned making it difficult for landowners to protect their property from the impacts of spills.

CHAPTER I

INTRODUCTION

Hydraulic fracturing is a method to produce economically viable quantities of oil and or natural gas, usually from unconventional sources such as shale, tight sands, and coal beds. This occurs by injecting fluids at high pressure into previously drilled holes so the fluid can fracture the geologic formations that contain the oil and gas. These pores in the formation are held open by sands or ceramic beads that allow the oil and natural gas to flow from the pores into the production wells (EPA, 2012b). Before hydraulic fracturing, a wellbore must be drilled to reach the target formation. This drilling is done in parts. After each section of the wellbore is drilled, steel casings are placed around the wellbore hole. Cement is then placed in between drilled hole and the cement casing (Fracfocus, 2014b). The reason for the use of the steel casing and cementation is to prevent both the frack fluid that will eventually be pumped into the wellbore, and the oil and natural gas that will be extracted from the wellbore, from escaping and contaminating the environment (Fracfocus, 2014c). Occasionally the casings fail and can lead to frack fluid spills.

Why is Hydraulic Fracturing Important in North Dakota?

Hydraulic fracturing is not only allowed in North Dakota, but encouraged because of the large amount of money it brings into the state. For example, in 2009 the oil and gas industry had a $12.6 billion economic impact in North Dakota with a large portion of this impact came from hydraulic fracturing. The petroleum industry in North Dakota also supplied 18,328 full time jobs in 2009 and a large portion of those jobs were associated with hydraulic fracturing (Fershee, 2012).

At least 750 different chemicals are used in the over 2,500 products required for hydraulic fracturing. At least 29 of those chemicals are toxic to humans and those 29 chemicals are used in approximately 650 hydraulic fracturing products (Waxman et al., 2011). In 2013 there was one environmental incident for every six wells in North Dakota. Between 2006 and October 2014, 18.4 million gallons of oil and hydraulic fracturing chemicals leaked or misted into the air, soil, and water in North Dakota (Sontag and Gebeloffa, 2014). Hydraulic fracturing spills can cause varying levels of harm up to and including death to exposed organisms, including humans (Bamberger and Oswald, 2012). Both human and non-human residents of North Dakota have been harmed by contact with the toxic chemicals used in hydraulic fracturing. (Sontag, 2014; Sontag and Gebeloff, 2014).

Hydraulic Fracturing Regulation in North Dakota

Hydraulic fracturing in North Dakota is mostly regulated by the North Dakota Industrial Commission which consists of the governor, attorney general, and agriculture commissioner with the Department of Public Health having minimal regulatory authority (NDCC, 2011; NDCC, 2013A; NDIC, 2014B). The director of the North Dakota Industrial Commission's Department of Mineral Resources, Oil and Gas Division regulates the day to day hydraulic fracturing operations within North Dakota (NDCC, 2013A). Mineral development in North Dakota is regulated both via state laws in the North Dakota Century Code (NDCC) and via administrative rules in the North Dakota Administrative code (NDAC) (NDCC, 2016; NDLB, 2016). North Dakota regulators have chosen to collaborate with hydraulic fracturing companies in an attempt to minimize spills as opposed to penalizing them, and as a result, usually forgive spills as long as the process for cleaning the spill starts immediately (Sontag and Gebloff, 2014). Federally, regulation of hydraulic fracturing is largely limited to the Clean Water Act which allows the Environmental Protection Agency (EPA) to regulate the disposal of flowback fluids into surface water (EPA, 2014b). This is due to exceptions having been made in other environmental laws that weaken the EPA's ability to use them to regulate hydraulic fracturing (Brady and Crannell, 2012).

Bakken Formation

The hydraulic fracturing in North Dakota occurs in the Bakken Geological Formation. The Bakken Formation, situated on top of the Williston Basin, is located in northwestern North Dakota (Miller et al., 2008). The Bakken Formation lies within the Northern Great Plains region of the United States, a region that stretches between the foothills of the Rocky Mountains in the west to the 100th meridian on the east, and north from the North Platte River through Wyoming and Nebraska to the grassland and the Boreal Forest border in Alberta, Saskatchewan, and Manitoba. The dominant native vegetation are various species of wheatgrass and needlegrass above most of the Bakken Formation. The major exceptions to this are the riparian woodlands along water bodies such as the Missouri River (Barker and Whitman, 1988). North Dakota has a continental climate with cold winters and hot summers (Li and Merchant, 2013). Western North Dakota, the section of North Dakota that contains the study area, is approximately 127mm dryer than eastern North Dakota annually (Daly and Weisburg, 1997). Approximately 75 percent of the annual precipitation in the study area occurs between

April and September (McMahon et al., 2015). Excluding the oil industry, the dominant industry above the Bakken Formation is agriculture both in the form of cropland and ranchland (Enz, 2003; MDOA, 2014). Both intermittent and permanent waterbodies of a variety of sizes are above the Bakken Formation. The largest of these waterbodies are the Missouri River, the Little Missouri River, Lake Darling, and the combined Des Lacs lakes. The area above the Bakken Formation is sparsely populated. The largest city, Minot, North Dakota has a population over 46,250 people. Approximately 250,250 people live in the Bakken Formation (USCB, 2012; Cubit, 2014).

Hydraulic fracturing spills within the Bakken Formation can have negative environmental, economic, and human health consequences. Such spills can degrade the environment by elevating levels of toxic chemicals in both the air, soil, and water. Spills can cause illness in both humans and livestock. Livestock illness causes economic harm as the value of ranchers' herds decrease. Additionally, illness in humans decreases the economic productivity of the sick humans (Royte, 2012).

Study Objective

The overarching goal of this thesis is to produce a Vulnerability Index for each waterbody as well as for various hydraulic unit code 8 (HUC 8) watersheds within the study area, which display how vulnerable each area is to a frack fluid spill. The HUC is a code that identifies each watersheds and for HUC 8 watersheds, the HUC is eight digits. The number of digits in a HUC signifies the size of the watershed with fewer digits meaning a larger watershed. There are 2,264 HUC 8 watersheds in the United States (USGS, 2015). The results of this thesis may help policy makers and mitigation managers make decisions about which waterbodies are most threatened by hydraulic fracturing, where to test waterbodies for frack fluid contaminations, and the size of a hydraulic fracturing free buffer zone that should be utilized around waterbodies to minimize the likelihood of serious impacts.

This thesis investigates a worst case scenario where frack fluid spills are allowed to travel without remediation until they reach a surface waterbody. The definition of frack fluid used by this study is water-based fluids used in, or created by hydraulic fracturing that are toxic. The definition of waterbody used in this thesis is any body of water whether it be a lake, river, stream, reservoir, or pond. The objectives of this thesis are:

1. To model the pathway a frack fluid spill would take from the well site to a surface waterbody.
2. To model the entry points where spills would enter waterbodies, and the number of wells from which a spill would enter at that point.
3. To model the range of volumes of frack fluid that would infiltrate into the soil prior to reaching a surface waterbody. This is the volume of frack fluid that is required for a spill to impact a surface waterbody under a given soil infiltration scenario.
4. To model which surface waterbodies, entry points, and watersheds in North Dakota are the most susceptible to frack fluid spills via the associated Vulnerability Index given various spill volumes and soil infiltration scenarios.

Study Area

The study area of this thesis is the Missouri River watershed that is based off a pour point within the North Dakota portion of the Bakken Formation (Figure 2). The Bakken Formation itself is in parts of North Dakota and Montana within the United

States and within parts of Saskatchewan and Manitoba in Canada (Figure 1). The size of the study area is 40,625.0km^2 (Figure 2), and it contains many different waterbodies of varying sizes and types some of which are labeled in figure 3.

There are approximately 70 cities within the study area with the largest city being Williston with an approximate population of 24,562 (USCB, 2015). In 2000 the population of the study area was over 34,351 and the population of the study area has grown substantially since then to over 51,281 people (USCD, 2015).

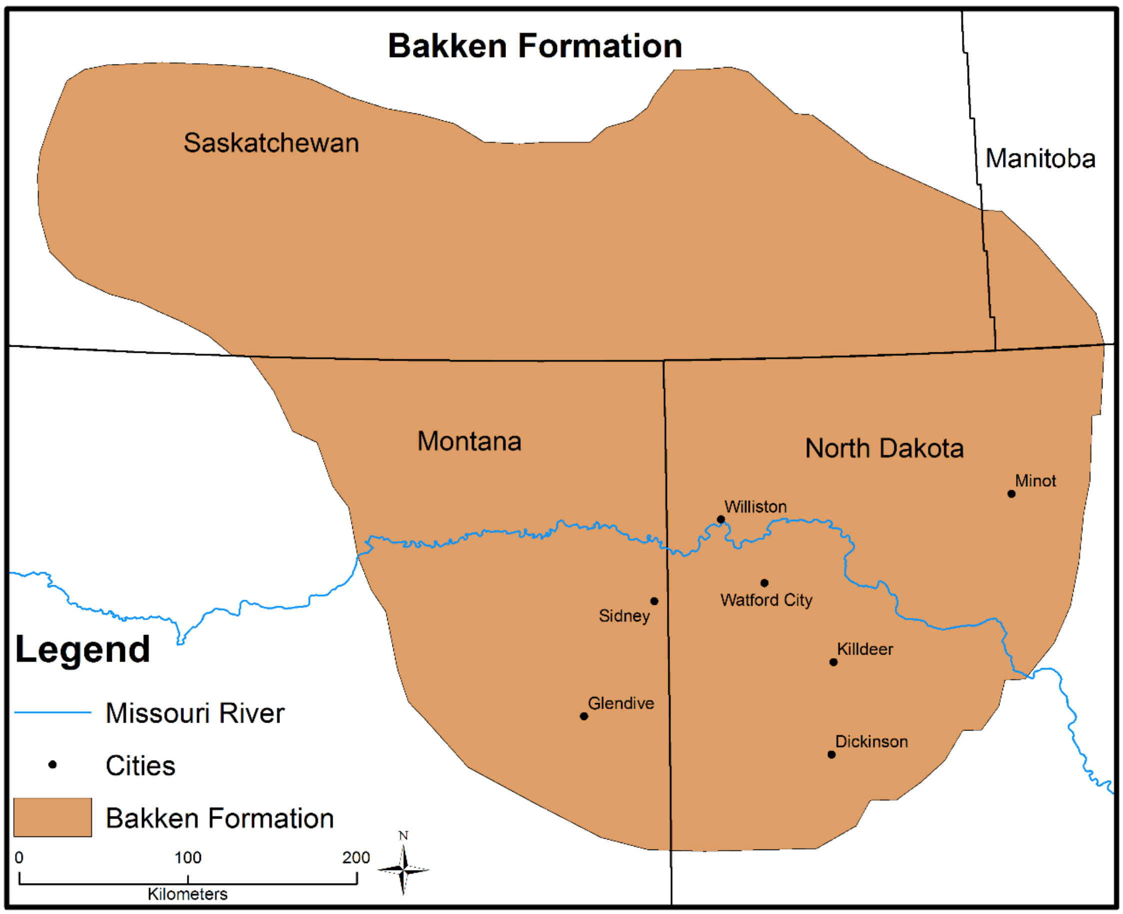

Figure 1 Location of the Bakken Formation

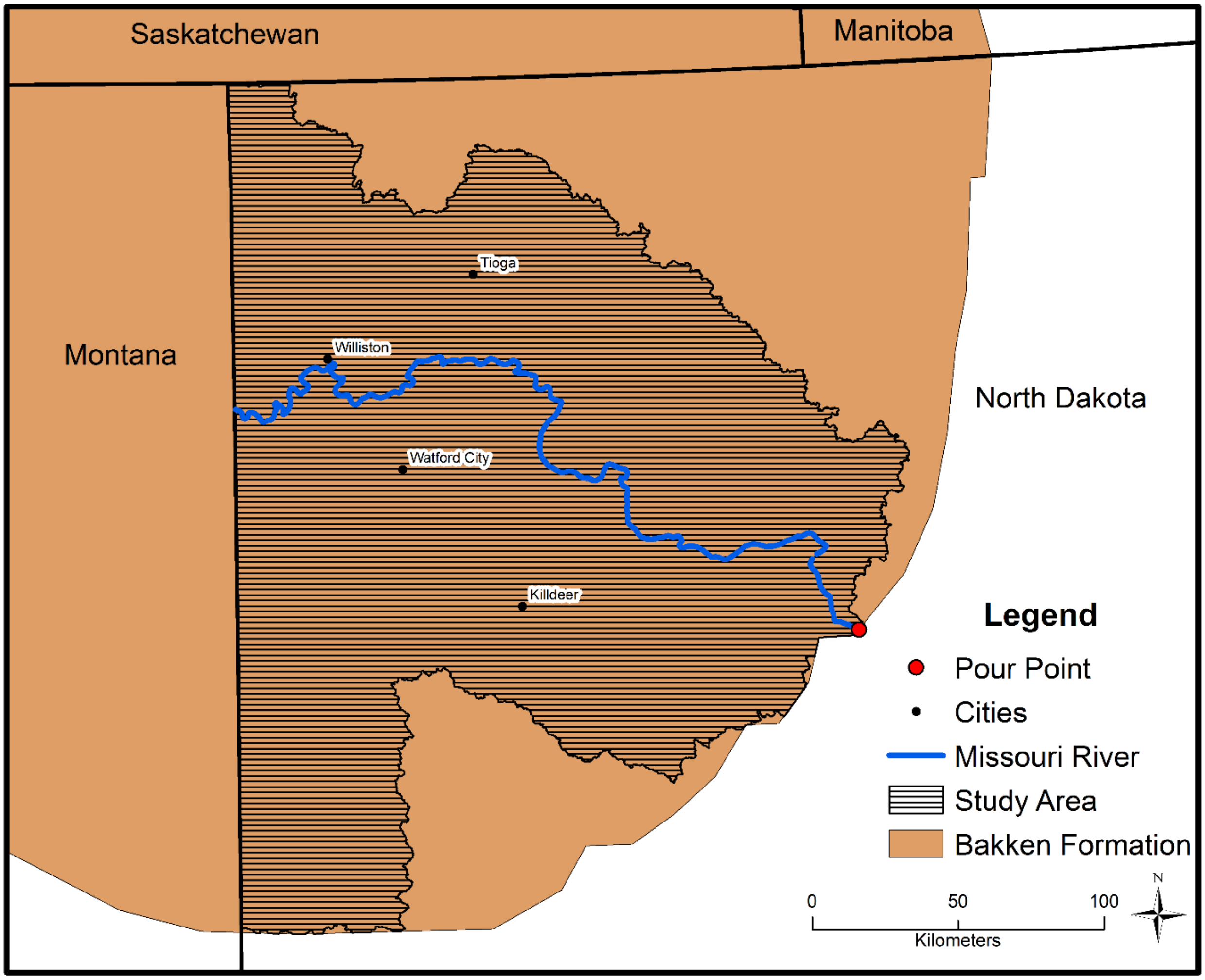

Figure 2 Study area and the pour point that was used to define the study area

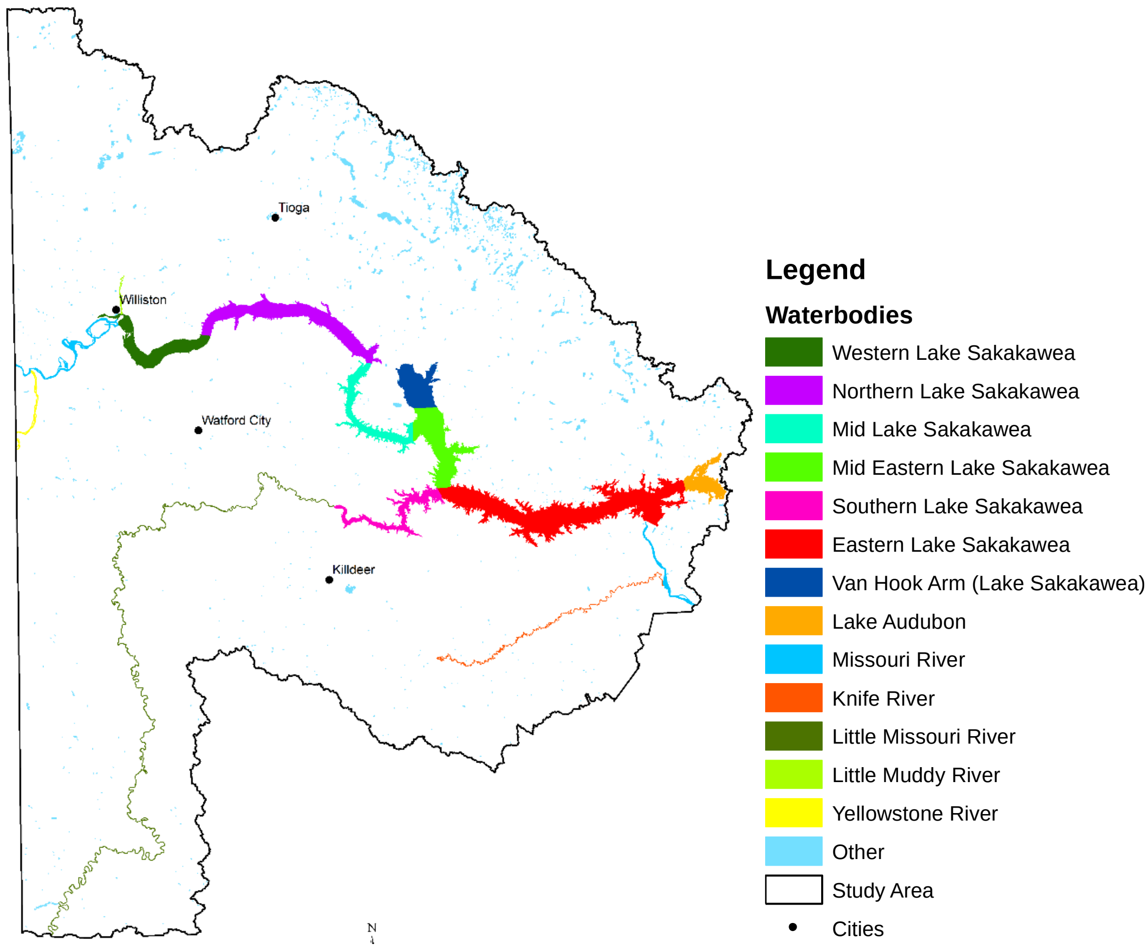

Figure 3 Waterbodies and cities that are in the study area

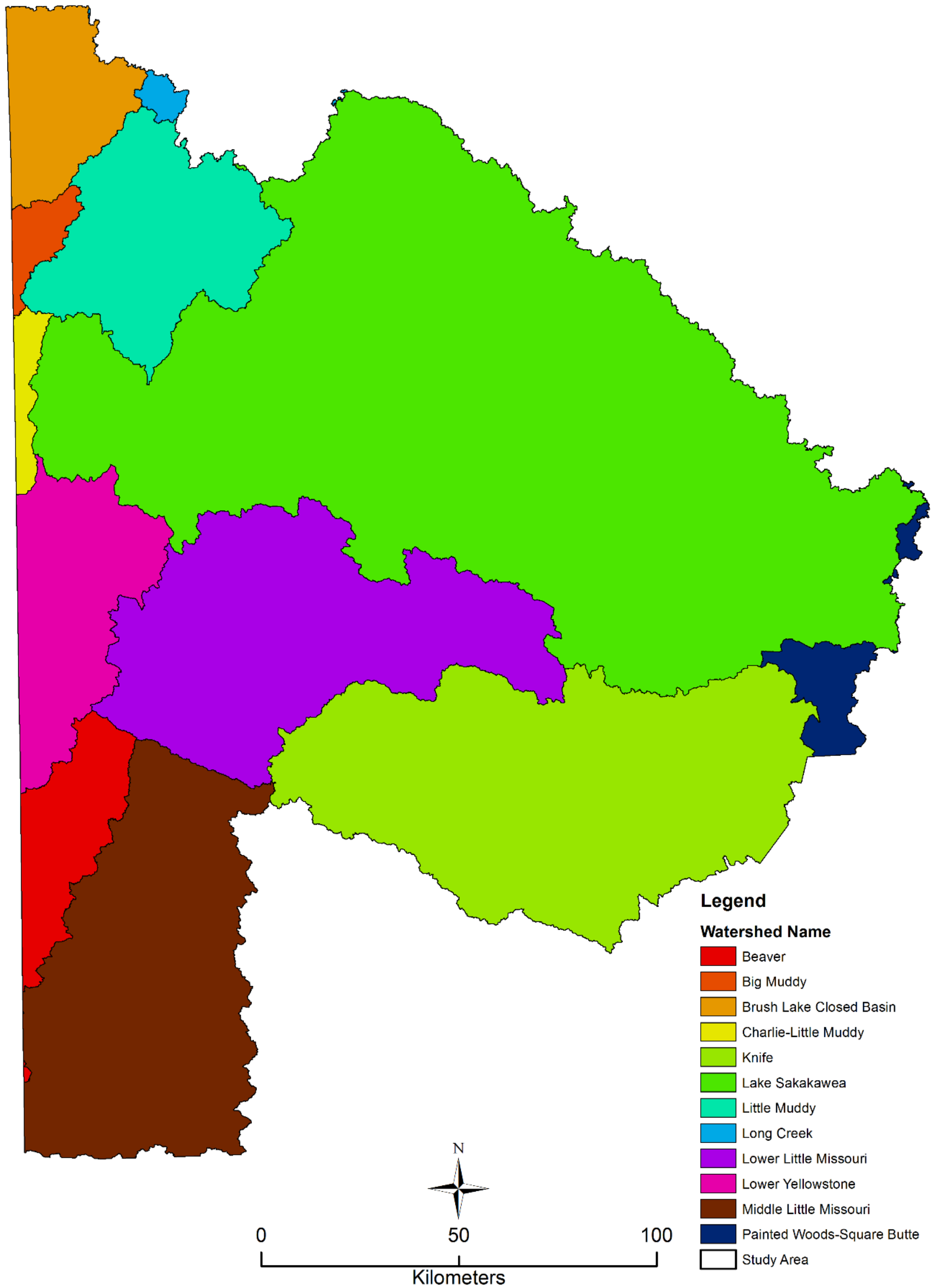

Figure 4 Names and locations of the watersheds within the study area.

The Missouri River enters North Dakota in the northwest near the border between Williams and McKenzie counties and flows southeast, leaving the state near the border between Sioux and Emmons counties (NDOGb, 2014). Recreation along the Missouri River and Lake Sakakawea contribute $85 million annually to the national economy. Popular forms of recreation on the Missouri River and Lake Sakakawea include boating, fishing, hunting, camping, sightseeing, and swimming. Lake Sakakawea, which is entirely in North Dakota, and Lake Oahe, which is partially in North Dakota, account for 30 percent of the annual recreation on the Missouri River area (NDSWC, 2008). Five North Dakota State Parks lie along the Missouri River and Lake Sakakwea: Cross Ranch State Park, Fort Abraham Lincoln State Park, Fort Stevenson State Park, Lake Sakakawea State Park, and Lewis and Clark State Park (NDPR, 2014). There are a number of recreational activities that people at these state parks can do such as hiking, camping, cross country skiing, birding, canoeing, kayaking (Oversen, personal communication). Within North Dakota, the water from the Missouri River and Lake Sakakawea has many uses such as municipal, domestic, industrial and irrigation uses as well as for stock ponds and recreation (NDSWC, 2008; NDSWC, 2014).

Within the study area itself there are five state parks, Fort Stevenson State Park, Little Missouri State Park, Sully Creek State Park, Lewis and Clark State Park, and Lake Sakakawea State Park. They provide opportunities for all previously mentioned activities and attract 390,618 tourists annually (Hodur and Bangsund, 2013; NDPR, 2014; Oversen, personal communication). Their economic impact on the localities around the state parks is $19,607,260 and their total economic impact on North Dakota is $33,516,684 (Hodur and Bangsund, 2013) (Table 1).

A national park and two national historic sites lie within the study area; Theodore Roosevelt National Park, Fort Union National Historic Site, and Knife River Indian Village National Historic Site. These sites attracted 669,242 tourists who spent $39,237,000 in the localities around those parks which created 528 jobs in 2012 (Andes, 2014). At the Theodore Roosevelt National Park people do a number of recreational activities such as camping, bicycling, canoeing, kayaking, cross country skiing, snowshoeing, fishing, hiking, horseback riding, and wildlife viewing (NPS, 2016C).

Table 1 Local spending, statewide economic effect, and visitation numbers of the state parks within the study area (Modified from Hodur and Bandsund, 2013).

State Park	Visitation Numbers (2009-2011 Averages)	Visitors Local Spending (2012) (USD)	Statewide Economic Effect (2012) (USD)
Fort Stevenson State Park	143,825	$6,965,769	$11,907,297.
Little Missouri State Park	17,160	$924,490	$1,580,325
Sully Creek State Park	50,343	$2,223,396	$3,800,677
Lewis and Clark State Park	71,620	$3,751,757	$6,413,260
Lake Sakakawea State Park	107,670	$5,741,848	$9,815,125
Total	390,618	$19,607,260	$33,516,684

At the Knife River Indian Village National Historic site people can engage in recreational activities such as exploring a museum or reconstructed Indian villages, hike, fish, and view wildlife (NPS, 2016B). At the Fort Union National Historic Site a reconstruction of Fort Union contains a visitor center (NPS, 2016A). These national parks attract tourists that provide revenue for both the locality and the state as a whole (Table 2).

Table 2 Visits, visitor spending and contributions to the local economy of the visitor spending in terms of jobs created and economic output for the national park and national historic sites within the study area. All datasets are in USDs and are from 2014 (Modified from Thomas et al., 2015).

Site Name	Visitation	Visitor Spending	Jobs	Economic Output
Theodore Roosevelt National Park	559,580	$33,959,900	470	$35,988,600
Fort Union National Historic Site	11,520	$883,600	10	$801,200
Knife River Indian Village National Historic Site	10,751	$603,000	9	$763,100
Total	581,851	$35,466,500	489	$37,552,900

CHAPTER II

LITERATURE REVIEW

Bakken Formation Geology

The Bakken Formation is a geological formation within the Williston Basin. The Bakken Formation is within eastern Montana and western North Dakota in the United States and within southern Saskatchewan and southwestern Manitoba in Canada (Meissner, 1978; Pitman et al., 2001). The Bakken Formation can be divided into three geological members. There is an upper shale member, a middle siltstone member, and a lower shale member (Meissner, 1978). The lower member of the Bakken was deposited in the late Devonian period over 359 million years ago. The middle member contains the Devonian-Mississippian boundary which occurred around 359 million years ago. The upper member was deposited in the early Mississippian period around 358 million years ago (Holland et al., 1987; Lefever, 1991). The Bakken Formation is surrounded by the Lodgepole Formation on top and the Three Forks Formation below and the depth of the Bakken formation varies between 1,070 meters and 3,200 meters, but the majority of the Bakken Formation is at a depth of around 2,950 meters (Meissner, 1978, Price et al., 1984; Lefever, 1991). The Bakken Formation ranges in thickness between 43 meters at its center to close to 0 meters on its eastern, southern, and southwestern edges (Meissner, 1978).

The upper and lower shale members are very similar as both consist of hard brittle dark brown to black, non-calcareous, organic rich, hard shales (Alexandre, 2011). Both shales contain smaller amounts of clay, silt, and dolomite grains, but the upper shale contains less than the lower shale (Meissner, 1978; Lefever, 1991). Dolomite is a type of carbonate mineral (Smyth, 1997). The shales also contain type I and II kerogens and average a total organic carbon rate of 11.5 percent, but commonly exceeds 20 percent (Flannery, 2006; Alexandre, 2011). Type I and II kerogens are types of organic matter within a rock that are likely to generate oil if exposed to heat. Type I kerogen is mostly created from algal material with some bacteria, while type II kerogen is mostly created from zooplankton and phytoplankton with some bacterial debris (PDNCR, 2016). In addition to dolomite, the lower shale member contains a significant amount of quartz (Lefever, 1991). Quartz is silicon dioxide (SiO_2) and usually originates from igneous rock (Helper, 2009). The lower shale member contains less organic matter than the upper shale member and has a thicker depocenter (15.25 meters) than the upper shale member (7 meters) (Alexandre, 2011). The base of the lower shale member contains a lag sandstone deposit. The upper shale member has the greatest area of all three members and is flatter than the lower shale (Lefever, 1991).

The middle siltstone member varies from light to medium gray dolomitic siltstone to a silty crystalline dolomite (Meissner, 1978). It also contains sandstone (Pitman et al., 2001). The middle member contains high levels of lithologic variability which leads to various descriptions of the middle member (Alexandre, 2011). The middle member contains different minerals such as calcites, pyrite, and feldspar. It also varies in levels of bioturbation (Pitman et al., 2001).

Bakken Petroleum System

The Bakken petroleum system consists of the Bakken Formation, lower Lodgepole Formation, and upper Three Forks Formation (Sonnenberg and Pramudito, 2009). The oil in the Bakken Formation originated as kerogen within the formation that turned into oil (Sperr, 1991). Geothermal heat is necessary for the creation of hydrocarbons and the paleogeothermal heating of the Bakken Formation occurred was uneven. The uneven heating of the Bakken Formation caused the hydrocarbons within the Bakken Formation to be formed at different depths. In areas with greater paleogeothermal heating, hydrocarbons were produced at depths as little as 2,330 meters, while areas with less paleogeothermal heating hydrocarbons were produced at around 3,050 meters (Price et al., 1984). These reservoirs originated via continuous accumulation which allows hydrocarbons to be trapped in a relatively large area with poorly defined boundaries (Nordeng, 2009). Hydrocarbons that are economically viable to extract must be in a reservoir. There are four such types of these reservoirs within the Bakken Formation. The first type is located in the depositional edge of the upper Bakken shale in McKenzie, Billings, and Golden Valley Counties, North Dakota. In these locations the upper Bakken thins, which results in an increase in natural fractures that are capped by the Lodgepole Formation creating a hydrocarbon reservoir. The second type of reservoir occurs where the underlying Three Forks Formation fractures the lower Bakken. The third type of reservoir is where regional lineaments occur within the Bakken, where recurrent movement over geological time causes fractures. This process is especially effective in the Bakken due to the overpressureing of the Bakken shales. The fourth type of reservoir occurs in hotspots where greater paleogeothermal heating generated an increased volume of hydrocarbons, and also, fractures within the surrounding rock (Sperr, 1991).

The eastern edge of the commercial oil production of the Bakken Formation is due to shallower bedrock. Shallow bedrock increases the percentage of produced water that is extracted with the oil, and as a result, it is not commercially feasible to extract oil from those locations. Commercial extraction of oil is optimal when the total volume that is extracted consists of 40 percent or less produced water. In locations within the study area where hydraulic fracturing is not occurring, produced water consists of 60 percent or more of what would be extracted. This line, where the commercial extraction of oil stops being economically feasible, is commonly called the line of death (Bergin et al., 2012).

Diagenesis of the Bakken Formation

The upper and lower Bakken was formed in a stratified water column that was part of a large, epicontinental sea, which while not deep for a sea, had a depth of at least 46 meters (Webster, 1984; Flannery, 2006; Alexandre, 2011). This sea had productive surface waters and anoxic bottom waters that allowed for the deposition of large amounts of preserved organic matter. The anoxia of the bottom waters was enhanced by the Sweetgrass Arch which separated the Williston Basin from the Western Canada Sedimentary Basin. This prevented the waters from mixing with an open-marine environment that contained less anoxic bottom water (Flannery, 2006; Alexandre, 2011).

The middle Bakken formation was deposited in a shallow aerobic bay that had either limited or inconsistent connection to the sea (Alexandre, 2011; Angulo and Buatois, 2012). The higher energy facies of the middle Bakken were deposited in parts of the bay that were closer to the shore and therefore were impacted by waves and tides.

The lower energy facies of the middle Bakken were deposited further offshore and were not influenced by waves and tides. The energy level of facies is determined by whether they were deposited in a dynamic (high energy), or static (low energy) environment (Alexandre, 2011).

Diagenetic changes in the middle Bakken led to their current form. Though multiple authors propose differing diagenetic processes within the Bakken Formation, they all include the dolomite formation, which is then followed by dissolution of specific minerals. These two processes, along with natural fractures, are important for creating a quality hydrocarbon reservoir in the middle Bakken (Alexandre, 2011).

According to Pitman et al. (2001) the early diagenesis of the middle Bakken was associated with the lithification of the middle Bakken and involved the cementation and recrystallization or transformation of unstable detritus. This lithification was enhanced by mechanical compaction of the detritus. These processes involved the precipitation of calcite and dolomite cements from weakly basic solutions at temperatures less than 80°C. Other reactions precipitated other minerals. Pitman et al. (2001) also discussed the later diagenesis of the Middle Bakken. The late diagenetic changes included the dissolution of previously formed carbonate cements and the precipitation of ferroan dolomite overgrowth cement and K-feldspar grain overgrowths. The creation of petroleum in the middle Bakken occurred during the Late Cretaceous at which point the Bakken was already at its maximum burial depth of approximately 3,000 meters and a temperature around 115 °C. Natural fractures developed within the middle Bakken at the same time as the hydrocarbon generation. The diagenetic processes for the upper and lower Bakken members were very similar to the diagenesis of middle Bakken (Pitman et al., 2001; Pramudito, 2008).

Porosity and Permeability of the Bakken Formation

The porosity of the middle Bakken ranges from one to 16 percent, but averages around five percent. Depth, which was strongly correlated with thermal maturity with deeper areas having greater thermal maturity, impacts the porosity of the middle Bakken. Areas of the middle Bakken that were less than 3,000 meters deep have a porosity between five and seven percent, while areas of the middle Bakken that are deeper than 3,000 meters have a porosity between three and six percent (Pitman et al., 2001). The porosity of the Bakken shale members is usually between two to three percent (Burrus et al., 1996).

The permeability of the middle Bakken ranges from 0 to 20 millidarcies, but the average is 0.04 millidarcies. As burial depth increases permeability tends to decrease. At lesser depths the permeability usually ranges from 0.01 to 0.06 millidarcies, while at greater depths the permeability ranges from 0 to 0.01 millidarcies. The areas of the middle Bakken with the highest permeability tend to contain well developed fractures and oil reservoirs (Pitman et al., 2001). The permeability of the Bakken shale members range from 0.001 to 0.01 millidarcies (Burrus et al., 1996). The low permeability of the Bakken Formation prevents conventional methods of oil extraction from being able to extract oil by preventing the oil from being able to travel through the source rock and enter the production casing. Hydraulic fracturing increases the permeability of the Bakken Formation to allow for oil to travel through the source rock into the production casing (Miskimins, 2008; CSUR, 2012). Most conventional oil reservoirs have a permeability of at least 0.1 millidarcies with most having a permeability between 10 and 100 millidarcies (CSUR, 2012).

Hydraulic Fracturing

Hydraulic fracturing is a well stimulation process used to maximize the extraction of an underground resource. The oil and gas industry use hydraulic fracturing to create and enhance subsurface fractures that will allow oil and natural gas to move from the fractures in the rock to production wells. Prior to the use of hydraulic fracturing, site infrastructure including the well must be built (EPA, 2012a).

Well Construction

The drilling of the wellbore is done in sections and after each section is drilled the appropriate steel casing is placed in the well. Each full-length casing is commonly called a casing string. The casings are generally implemented from the largest in diameter to the smallest (FracFocus, 2014c). The first type of casing is the conductor casing which prevents the sides of the wellbore from caving in and prevents outside materials such as soil and gravel from filling the wellbore (PDEP, 2010; FracFocus, 2014c). Following the conductor casing, the surface casing is put in place. The surface casing should run from the surface to below the deepest groundwater baring formation (API, 2009; FracFocus, 2014c). The goal of the surface casing is to protect groundwater aquifers from being harmed by hydraulic fracturing. The next casing, the intermediate casing, is not always necessary (FracFocus, 2014c). The reason for using an intermediate casing is to protect subsurface formations and to protect the wellbore from pressures originating from the subsurface formation (API, 2009). The final casing is the production casing which either goes to the top of the target formation, or into the target formation (FracFocus, 2014c).

The goal of the production casing is to isolate the production formation from the other subsurface formations, pump the frack fluid into the target formation, and to contain the hydrocarbons that are produced (API, 2009).

The space between the casing and the wellbore is called the annulus. After each casing is put in place and before drilling continues, cement is placed in the annulus to cement the casing in place. The cementation is just as important as the casing in protecting water resources, because it creates a hydraulic barrier around the casings preventing fluid migration. There are different methods for cementation. An optimum method for cementation is called circulation. This method requires pumping enough cement into the annulus to fill it. This is followed by pumping fresh water into the casing until the cement returns to the surface of the annular space. Circulation is a bottom to top method of cementation (FracFocus, 2014c). Sometimes, when circulation cannot be done a top down cementation is possible (API, 2009).

There are two methods of hydraulic fracturing that are used: open hole and perforated hole. The open hole method has the production casing end right above the target formation and frack fluid shoots from the open whole into the target formation. The perforated hole has a steel casing with perforations traveling through the target formation. The perforated casing can travel through the target formation both vertically and horizontally. The frack fluid will shoot out of each perforation in the casing into the target formation (API, 2009).

Hydraulic Fracturing Process

After the wellbore is drilled and the casings are placed into the wellbore and cemented in place, the process of hydraulic fracturing can start. This process has four stages. The first stage is the acid stage. The acid stage contains an acidic solution that is shot down the wellbore to clear cement and other debris and to dissolve carbonate minerals in the wellbore. This is done to clear the wellbore for the next stages of hydraulic fracturing and to initialize the fractures in the target formation. The second stage is the pad stage. The pad stage shoots down large volumes of slickwater into the target formation. Slickwater is frack fluid that contains a friction reducing agent that reduces tubular friction by 50 to 60 percent. The pad stage helps facilitate the flow and placement of the proppant materials, defined below, that will be used in the next stage and increases the previously initialized fractures within the target formation. The third stage is the prop sequence stage. The prop sequence stage contains proppants in the slickwater that is shot down the wellbore. Proppants are materials such as sand or ceramic beads that enter the fractures in the target formation and hold them open to allow hydrocarbons to leave the target formation (PDEP, 2010). The final stage is the flushing stage where fresh water or recycled frack fluid is shot down the wellbore to clear the pipes. This cleans up excess proppants and ensures that the casings are open for hydrocarbons to travel through in order for them to reach the surface and be utilized (API, 2009; PDEP, 2010).

When the injection pressure is reduced or turned off altogether, the direction of travel reverses due to the internal pressure of the target formation pushing materials such as flowback fluid, produced waters, the hydrocarbons from within the formation, and anything else that previously resided in the target formation to the surface (EPA, 2012b). Most wellheads are outfitted with a collection of valves called a christmas tree that regulates pressure, controls flow, and allows access to the well, if the well requires additional work (OOGA, 2014).

Chemical Use

The previously mentioned stages of hydraulic fracturing each require a different composition of frack fluid. As a result, at least 750 different chemicals are used in hydraulic fracturing as a part of over 2,500 products that are combined in order to make frack fluid function (PDEP, 2009; Waxman et al., 2011). At least 29 of those chemicals are toxic to humans and those 29 chemicals are used in at least 650 products (Waxman et al., 2011). The different chemicals and products used in hydraulic fracturing all have a specific purpose. Acids are used to clean out cement debris from the wells. Biocides are used to prevent bacterial growth that can clog wells. Scale inhibitors are used to control precipitation of carbonates and sulfates. Iron control and stabilizing agents are used to keep iron from precipitating. Friction reducing agents are used to reduce tubular friction. Corrosion inhibitors are used to prevent the corrosion and degradation of the steel casings. Gelling agents are used to increase the viscosity of the solution used in the prop sequence stage, so that the solution can carry the proppants to the fractures in the target formation. Breaker agents are used to decrease the viscosity of the frack fluid to allow the flushing stage to be effective. Cross-linking agents are used to increase the effectiveness of both the gelling and the breaker agents (PDEP, 2009). Surfactants aid in the recovery of water used in hydraulic fracturing (Halliburton, 2014).

Causes of Hydraulic Fracturing Spills

Any time a well is drilled into the Earth it creates a potential pathway for the substances that are trapped underground to reach the surface. Wells used in hydraulic fracturing must be able to withstand higher pressure and larger volumes of water than traditional oil and gas wells. Frequently they must do so while curving laterally. If the integrity of these wells fails it will have negative consequences that are financial, environmental, and human health related due to the large number of toxic chemicals used during the hydraulic fracturing process (Jackson et al., 2014).

Sustained Casing Pressure

A needle valve is a type of globe valve where a long pin or needle that is tapered at the end moves in and out of a conical seat to regulate flow (DOC, 2014). It is a type of valve utilized to control and regulate fluid flow in hydraulic fracturing (Bourgoyne et al., 2000; DOC, 2014). Sustained casing pressure (SCP) occurs when there is pressure on the casing even though the needle valve is closed and therefore there should not be any casing pressure. SCP is measured with casing gauges that measure the pressure on the casing of a well (Bourgoyne et al., 2000). Having sustained casing pressure does not automatically mean that a well will spill, but unmitigated sustained casing pressure can cause a blowout (Bourgoyne et al., 2000).

Faulty Well Cementation

A variety of issues can cause a well to leak. During the construction of the well, if mud or spacer fluid is inadequately removed prior to cementation, the cementation will not provide zonal isolation. This lack of zonal isolation can cause leaks. If the slurry design of the cement is done incorrectly, flow can occur prior to the cement setting as a result of decreased hydrostatic pressure. If the formation pressure becomes greater than the hydrostatic pressure, the well will no longer be overbalanced and it will fail (Bruffato et al., 2003).

Post Cementation Issues

Cement can also be damaged after a successful cementation due to well activities. The stresses in the wellbore can cause microannuli and stress fractures in the cement that can create a pathway for leaks into the environment. These issues can be compounded by the fact that the cement and the steel casings react differently to the temperature and pressure changes that occur through hydraulic fracturing (Bruffato et al., 2003). Improperly abandoned wells can allow fluids to travel up and down the well and create a pathway for chemicals from within the well to reach the environment. This process can be expedited by nearby hydraulic fracturing which increases the reservoir pressures which can cause older wells, including old conventional wells, in depleted oil and gas fields to leak (Jackson et al., 2014).

Another cause of well failure is the corrosion of steel casings. This can occur due to regular use of a well, since some of the chemicals used in hydraulic fracturing, such as hydrochloric acid, are acidic and therefore can corrode steel (FracFocus, 2014d; Jackson et al., 2014). This was confirmed in Weld County Colorado, where 10 equipment failures that lead to spills that impacted groundwater were specifically due to equipment failure due to corrosion (Gross, et al., 2013). Bamberger and Oswald (2012) found that common causes of exposure to frack fluid were from compressor station malfunctions, pipeline leaks, and well flaring.

Considine et al. (2013) performed a study of notices of environmental violations issued by the Pennsylvania Department of Environmental Protection related to the hydraulic fracturing of the Marcellus Shale between 2008 and 2011. During the study period 3,533 wells were drilled and 2,988 violations were issued, but only 1,144 of the violations involved the environment. The other 1,844 violations were either administrative violations, or preventive violations. The environmental violations were divided into seven categories shown in table 3 below.

Blowouts and uncontrolled venting are both serious and dangerous due to the fact that the lack of control makes them difficult for operators to mitigate. They are commonly caused by excess pressure in the wellbore and therefore are commonly violent. They also have the potential for large environmental impacts as large amounts of fluids and or gases can be released in the environment. This loss of control commonly is associated with loss of well integrity that can reduce operators' ability to protect aquifers and their ability to prevent the release of fluids both at depth and near the surface. Blowouts can occur due to poor cementation, or incorrect casing (Considine et al., 2013).

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Spills that are contained to the drilling pads have limited environmental impacts, though Gross et al. (2013) found that they still can impact groundwater (Considine et al., 2013). In Pennsylvania between 2008 and 2011, 12 percent of these spills were contained to the drilling pad, 20 percent were unspecified and 68 percent reached the environment. Most spills were small (91.8 percent) and averaged less than 681 liters (Considine et al., 2013).

Table 3 Environmental violations from hydraulic fracturing of the Marcellus Shale in Pennsylvania between 2008 and 2011 (Modified from Considine et al., 2013).

Violation Type	Description	Number of violations	Percent of environmental violations
Cement and casing	Cement and casing job cited as defective and the cause of pollution	100	8.7
Blowout and venting	Citation for a blowout or hazardous Venting	10	0.9
Major spills on land	Citation for major (>1,514 L) spills of materials on land	46	4.0
Minor spills on land	Citation for minor (<1,514 L) spills of materials on land	236	20.6
Gas migration	Citation for migration of gas in underground aquifers or substrates	6	0.5
Site restoration	Citation for violations of site restoration regulations	400	35
Water contamination	Citation for tainted water as the primary focus of the citation	346	30.2

Natural Gas Migration

When hydraulic fracturing occurs in areas that contain natural gas, it can lead to natural gas migration into the environment where it can affect environmental resources such as freshwater aquifers. A common cause of gas migration is from flaws in the casings and or cement. These flaws can be repaired to mitigate the environmental impacts of gas migration; it is important that these flaws be repaired as sequestered methane can explode (Considine et al., 2013). While Considine et al. (2013) found gas migration to be a rare occurrence in Pennsylvania, Watson and Bachu (2009) report that where testing for surface casing vent flow and soil gas migration was legally required in Alberta, Canada, 9.2 percent of wells showed surface casing vent flow and 5.7 percent showed soil gas migration. Beyond location, the difference between the frequency of gas migration found by Watson and Bachu (2009) and Considine et al. (2013) may be due to the fact that a common cause for the release of gases is via incipient faults or fractures in well casings and cement (Vengosh et al., 2014). These faults may have been missed by the inspectors in Pennsylvania, but were found in Alberta where gas migration and surface casing vent flow was actively searched for.

The ecosystem impact of a spill depended both on the size of the spill and the sensitivity of the ecosystem where the spill occurred. The spills that contaminated subsurface drinking water in Pennsylvania were both due to gas migration into a well as opposed to a spill directly into a water body. The most severe spills were caused by operator error, negligence, or failure to follow procedure when drilling. Common causes of failures are leaks through steel tubing and casing, frequently due to faulty connections (Considine et al., 2013). In Weld County, Colorado the leaks that impacted groundwater were usually from either tank battery systems, or the production facility due to equipment failure (Gross et al., 2013).

Spills from Wastewater Ponds

In addition to spills coming from the wells themselves, they also can come from the ponds that store flowback fluids and produced waters. Flowback fluids are a mixture of hydraulic fracturing fluids, the natural fluids from within the formation, and toxic elements such as barium, strontium and radioactive radium. Produced waters are usually composed of hypersaline formation water, oil, bitumen, hydrocarbon condensates, high concentrations of total dissolved organic carbon and the organic chemicals that are contained in frack fluid. The salinity of flowback fluids and produced waters range from 25 to 180 g/L. These waters are typically stored in ponds near the drilling site. They can impact surface waters in three potential ways. Flowback and produced waters can reach a surface water body if they spill from the pond where they are being held, if they are illegally disposed into a surface water body, and if they are inadequately treated and then disposed into a surface water body while still toxic. The frequency of spills of flowback and produced water spills into surface waters increases when there is both a high density of wells (above 0.5 wells km^2) and the wells are close to surface waters. The discharge of improperly treated wastewaters into waterbodies increases the salinity, toxic metal concentrations, radioactive radium concentrations, and the concentration of toxic organics such as benzene and toluene in water (Vengosh et al., 2014).

Faulty Treatment of Frack Fluids

The toxicity of frack fluids is such that even after treatment at wastewater treatment facilities, they can still have a negative environmental impact upon release into a natural water body. Increases in the levels of total dissolved solids, chlorine, bromine, sulfates, magnesium, strontium, sodium, and barium were found downstream from a discharge site in Pennsylvania. Almost two kilometers downstream chloride had an enrichment factor of 16 and bromide had an enrichment factor of 37. The enrichment factor was based on how many times greater the concentration of the chemical was downstream from the wastewater discharge compared to upstream. Radium did not travel from the discharge site; instead, it contaminated the soils surrounding the discharge site. This radium could bioaccumulate starting with benthic organisms where it has the potential to reach lethal levels depending on the specific organism. Though benthic organisms have the greatest vulnerability to the bioaccumulation of radon, aquatic plants will also be impacted to a lesser extent (Warner et al., 2013).

Hydraulic Fracturing Regulation in North Dakota

Hydraulic fracturing in North Dakota is largely regulated by the North Dakota Industrial Commission which consists of the governor, attorney general, and agriculture commissioner (NDCC, 2013A; NDIC, 2014B). Working for the Industrial Commission is the director of the North Dakota Industrial Commission's Department of Mineral Resources, Oil and Gas Division who regulates the day to day hydraulic fracturing operations within North Dakota (NDCC, 2013A). In North Dakota, mineral development wells and associated facilities cannot be built in or hazardously near waterbodies, but in reality, the Industrial Commission allows mineral development facilities to be built within 25 meters of major surface waterbodies (Google Earth, 2014; NDOGb; 2014; NDCC, 2014). Starting on May 1, 2014, special consideration was mandated by the Industrial Commission for wells within certain distances from specified locations (Table 4). Despite the special consideration for wells within those buffer areas, the director can decide to allow wells within the buffer area (NDIC, 2014A). The NDAC requires that wells also cannot be within 152.4m from the boundary of the property line owned or leased by the operator of the well unless the Industrial Commission provides an exception (NDAC, 2013A; NDAC, 2013B).

Table 4 Areas of special consideration for wells permitted after May 1, 2014 as mandated by the Industrial Commission. These locations are a subset chosen based on their importance to this study (NDIC, 2014A).

Location	Buffer Distance (km)
Confluence of Yellowstone and Missouri River	3.2
Elkhorn Ranch State and National Park Sites	3.2
Lake Sakakawea	0.8 from the shoreline at 1850ft
Little Missouri River	1.6 from centerline of riverbed
Little Missouri River State Park	1.6
Theodore Roosevelt National Park	3.2

North Dakotan regulators have chosen to collaborate with hydraulic fracturing companies in an attempt to minimize spills as opposed to penalizing them, and as a result are usually forgiving of spills. As a result of the collaborative approach, the Industrial Commission frequently suspends 90 percent of the fines it levies contingent on the company not having any violations for the next year. This method has not been particularly effective as between March 31, 2015 and March 31, 2016 there have been 1,389 oilfield incidents where over 1,500m^3 of oil has as well as over 5,350m^3 of frack fluid has spilled (NDDH, 2016). Possibly due to the collaborative, as opposed to punitive regulatory atmosphere, the rate of environmental incidents from hydraulic fracturing increased from one incident for every 11 wells in 2006 to one incident for every six wells in 2013 (Sontag and Gebeloff, 2014). Additionally, multiple companies were associated with over 90 spills in 2013 such as Continental Resources (232), Hess Corporation (116), and Whiting Oil & Gas (92) (Sontag and Gebloff, 2014; NDDH, 2016). This hypothesis is supported by Considine et al., (2013)'s findings that between 2008 and 2011 while regulation of hydraulic fracturing increased, the percent of wells that had environmental violations dropped from 58.2 percent to 26.5 percent. Federally, the EPA regulate the disposal of fluids from hydraulic fracturing into surface waters under the Clean Water Act. The program that regulates the disposal is the National Pollutant Discharge

Elimination System (NPDES) permit program (EPA, 2014b). This program regulates point source discharge of pollutants into waters in the United States (EPA, 2014a).

When damage occurs due to hydraulic fracturing the mineral developer is liable and must pay the surface owner a sum of money equal to the damages sustained (NDCC, 2013B). When there is an obvious cause of property damage that is found within the six year statute of limitation, issues associated with landowner compensation are minimal. Problems for landowner compensation arise under two circumstances:

1. When there is a delay between the cause of the damage and the damage itself. In these situations the statute of limitations can make it difficult for a landowner to receive compensation. Depending on the cause of these delayed spills the liability for the spill can switch from the oil company to the landowner. In these situations a landowner can be liable if a contamination spills from his property into neighboring properties even if a mineral development company and not the landowner is the source of the original contamination (Neilan and Dooley, 2014).
2. When the cause of the damage is unclear. The general rule for causation is that the action or omission of action by the defendant must cause the plaintiffs injury. Frequently multiple operators will have multiple wells in close proximity to each other. In the event that a landowner finds their property degraded it may be difficult to prove which operator caused the damage in a manner that proves a specific operator liable for the damage (Neilan and Dooley, 2014). In other situations it may be difficult for the landowner to prove that hydraulic fracturing degraded his property even when the damage occurred right after hydraulic fracturing operations started (Royte, 2012; Knutson, 2014).

Situations where landowners are unable to receive compensation for damage to their property are especially harmful when they do not own their mineral rights and as a result they not only have no control over whether or not mineral development occurs on their property since mineral rights supersede surface rights, but also do not receive royalties for the mineral that are extracted from below their property. Landowners not owning their mineral rights is especially problematic in for hydraulic fracturing in North Dakota since 45 percent of the mineral rights in oil producing counties within North Dakota are owned by nonresidents (Knutson, 2014).

Negative Consequences of Hydraulic Fracturing Spills

In order to characterize these risks an understanding of the technical information related to the risk, such as what is the risk, must be determined (Stern and Fineberg, 1996). The following three subsections contains information that can be useful in understanding the environmental, financial, and human health consequences associated with hydraulic fracturing spills as the consequences of spills must be understood in order to understand the inherent risk associated with hydraulic fracturing. One of the risks associated with hydraulic fracturing is fluids from hydraulic fracturing reaching and contaminating a surface waterbody. Contaminated surface water can pose an environmental, human health, and financial risk by harming wildlife, humans, and livestock that use an impacted waterbody (Bamberger and Oswald, 2012). The results of this thesis on how frack fluid would travel to reach waterbodies within North Dakota can be used to help characterize the risk from hydraulic fracturing in North Dakota.

Environmental Consequences

Examples of the negative environmental consequences when frack fluids reach the environment were displayed in both West Virginia and Kentucky (Adams, 2011; Papoulias and Velasco, 2013). In June 2008, an experiment was conducted in West Virginia. Around 303,000 liters of frack fluids were applied to about 0.20 hectares of mixed hardwood forests in the Fernow Experimental Forest, West Virginia. A few days after the frack fluid was applied almost all the ground vegetation died. Within 10 days the trees started dropping their leaves. This caused the canopy openness to increase to 15 percent from a normal 7.2 percent. In late spring the following year 51 percent of the trees in the application area lacked leaves. Two years after the experimental application of the frack fluid 56 percent of the trees were dead. The frack fluids also increased the soil concentrations of calcium, magnesium, sodium, chloride, and carbon to nitrogen ratio. The experiment also caused a decrease in levels of aluminum, zinc, and manganese in the soil. After one year it caused the soil to become less acidic. The frack fluid was found to kill vegetation both by direct contact with leaves in ground vegetation and by uptake from the soil by trees when the frack fluid did not contact their leaves directly (Adams, 2011).

In 2007 frack fluid used in Knox County, Kentucky was spilled into Acorn Fork, a second order tributary of the Stinking Creek in the upper Cumberland River Basin. The frack fluid caused the stream to become more acidic and increased the stream's conductivity. The stream started to develop an initially suspended and later precipitated orange-red flocculent composed of an organo-colloidal complex of iron, aluminum, and other metals. In some locations the flocculent was several inches thick. The spill killed or displaced fish and aquatic invertebrates within a 2.7 kilometers section of Acorn Fork. Among the species harmed by the spill were *Chrosomus cumberlandensis* (Blackside Dace), a federally threatened fish species (Papoulias and Velasco, 2013).

Bamberger and Oswald (2012) looked at the 24 case studies where animals and or humans were harmed from spills from gas wells. Of the 24 case studies, 18 were from wells that were hydraulically fractured. The health impacts for the animals involved in those cases included issues such as reproductive, dermatological, musculoskeletal, neurological, gastrointestinal, urological, upper respiratory, respiratory, and death. In two cases there was direct exposure to hydraulic fracturing fluid. In one case the frack fluid reached an adjacent cow pasture which killed 17 cows in one hour. The necropsy found that they died from respiratory failure and circulatory collapse. In the second case a defective valve on a frack fluid tank caused hundreds of barrels of frack fluid to reach a pasture that contained goats and caused them to suffer reproductive issues for the next two years. The two most common pathways to exposure were affected water wells and springs followed by affected ponds and creeks. The most common symptoms were reproductive issues such as difficulty breeding and increased likelihood of stillborn calves. In one case, a creek in which wastewater was dumped was the water source for 60 cows, while another 36 cows did not have access to that creek. Of the 60 cows that were exposed to the creek, 21 died and 16 failed to produce calves the following spring. Of the 36 cows that did not have access to the spring only one failed to produce calves and none died. In a second case of 140 cows exposed to wastewater, 70 died and a high incidence of stillborn and stunted calves was observed. Sixty cows from the same owner were in another pasture and therefore were not exposed to wastewater and had no health problems.

Financial Consequences

The financial costs of spills both in terms of fines and remediation can be expensive. Nami Resources Company was fined a total of $50,000 for violating the Clean Water Act and the Endangered Species Act for their aforementioned spill in Knox County, Kentucky (USAO, 2009). Consindine et al. (2013) looked at the fines associated with 16 major spills from hydraulic fracturing in Pennsylvania and found that the average fine was $249,675 with the highest fine being $1,912,000. In September 2014, the Pennsylvania Department of Environmental Protection fined Range Resources $4.15 million for releasing contaminants such as flowback fluid that impacted both soil and groundwater (PDEP, 2014). Costs of remediation of spills can vary significantly based on location, but one spill of 20,600 barrels of oil from a leaky pipe in Mountrail County North Dakota was estimated to cost $4 million to remediate (Gawel, 2006; Burnes, 2013). In one case 17 miles north of Killdeer, North Dakota, crude and engine oil along with surface water drained from the side of the road, around an oil well, across a hay field, and into a stock pond. Absorbents, water vacuuming, and dirt work were done to clean up the oil and a dam was built to prevent future contaminated water from flowing into the stock pond. This process cost $20,000, but heavy rains damaged the dam and it cost an additional $5,000 to repair making the entire cost of the remediation $25,000 (Oversen, Personal Communication).

There are numerous examples of spills associated with hydraulic fracturing harming both farmland and livestock to the extent that livestock have died and cropland has become sterilized (Bamberger and Oswald, 2012; Kusnetz, 2012; Royte, 2012; Sontag and Gebeloff, 2014). Such incidents have occurred in multiple states such as North Dakota, Louisiana, and Pennsylvania (Kusnetz, 2012; Royte, 2012; Sontag and Gebeloff, 2014). These spills have negative economic impacts on the landowners whose property is damaged by these spills both in terms of loss of property and extra effort required to maintain their property (Bamberger and Oswald, 2012; Kusnetz, 2012; Royte, 2012; Sontag and Gebeloff, 2014). A North Dakota landowner who previously allowed her cattle to drink from a possibly damaged creek spent $4,000 one summer to bring clean water to her ranch. This occurred after some of the landowner's cattle had died due to contamination of her property including a $5,000 bull and five cows (Royte, 2012). Bamberger and Oswald (2012) provide additional examples of where livestock was killed due to spills from hydraulic fracturing. In one example, 17 adult cows that were used for breeding, and 4 calves were killed. Though the exact weight of the deceased cattle were not provided, but a reasonable valuation for the calves is $948 and for the adults is $910 (Hildenbrant, 2012). As a result the frack fluid spill would cost the rancher approximately $19,262 in lost livestock and this valuation excludes any additional costs to the cattle's owner associated with trying to save his cattle, the loss of future cattle due to the premature death of his breeder cattle, and the difficulty that some of his surviving breeder cattle had in further breeding (Bamberger and Oswald, 2012). At a different farm 140 cows were exposed to a frack fluid spill and 70 died from the exposure at an estimated cost to the owner of $63,700, though Dutzik et al., (2012) valued of the loss from the death of the cattle at $112,000 (Bamberger and Oswald, 2012).

The threat of hydraulic fracturing spills can also harm landowners both by impacting the value of their property by decreasing property values in close proximity to where hydraulic fracturing occurs and by decreasing sales when buyers feel uncomfortable buying livestock that is raised near areas where hydraulic fracturing occur. An example of sales being impacted occurred when the Park Slope Food Co-op in New York threatened not to buy cows from farms close to where hydraulic fracturing occurs had hydraulic fracturing become legal in New York. This would have cost their suppliers $4 million in direct sales (Royte, 2012).

In Tioga and Antler, North Dakota two different spills contaminated 33 and 24 acres of farmland (Sontag and Gebloff, 2014). Tioga, North Dakota is located in Williams County where an acre of farmland is valued at approximately $553 per acre which leaves the loss of land due to the spill in Tioga at approximately $18,249 (NDDTL, 2014). Antler, North Dakota is located in Bottineau County where an acre of farmland is valued at approximately $978 per acre, leaves the valuation of the land damaged from the spill at $23,472 (NDDLTL, 2014).

Human Health Consequences

Hydraulic fracturing spills can negatively affect human health when people come in contact with chemicals from hydraulic fracturing. Gross et al. (2013) found levels of benzene, toluene, ethylbenzene, and xylene in groundwater to be above the national drinking water regulation’s maximum contaminant level (MCL). Symptoms of benzene exposure from ingesting food or water contaminated with benzene are vomiting, abdominal pain, dizziness, sleepiness, convulsions, irregular heartbeat and at very high levels, death. Benzene is also carcinogenic and can harm both the immune system and bone marrow upon long term exposure (NCBIa, 2014). Upon exposure, toluene targets the central nervous system, which can cause fatigue, sleepiness, headaches, and nausea. High levels of exposure can suppress the central nervous system enough to cause death (EPA, 2013). The ingestion of ethylbenzene can cause damage to the inner ear (ASTDR, 2011). The ingestion of xylene can harm the nervous system causing headaches, lack of muscle coordination, dizziness, confusion and in very high concentrations, death (NCBId, 2014).

Below are two examples of accidents associated with hydraulic fracturing and their health repercussions for humans. On January 1, 2009 there was an explosion in an outside, underground water well pit at a home in Dimock Township, Pennsylvania. It was found that the explosion was caused by combustible gas that was present due to the hydraulic fracturing activities of Cabot Oil and Gas Corporation (Lobins and Duffy, 2009). Cabot oil and Gas Corporation's hydraulic fracturing was found to have contaminated 18 drinking water wells with methane (Lobins and Duffy, 2010; Cooley and Donnelly, 2012). Though methane is not currently considered toxic to ingest, it can act as an asphyxiate and is explosive (Osborn et al., 2011). Methane can cause carcinogenic trihalomethanes (THMs) to be formed in ground water that also contains halogens such as chlorine and bromine (Vengosh et al., 2014). This problem is expedited by the high levels of chlorine and bromine found in frack fluids, which can become THMs when they come in contact with methane (Warner et al., 2013; Vengosh et al, 2014). Gas in drinking water wells can lead to the salinization of the water and decrease the water quality.

In Pavillion, Wyoming elevated levels of specific conductance, pH, methane, ethane, and propane, were found in ground water due to hydraulic fracturing though the specific mechanism of the spill was undetermined (Vengosh et al., 2014). Ethane is not considered toxic unless inhaled where it becomes an asphyxiate; propane harms the central nervous system and as a result can cause dizziness and confusion (NCBIb, 2014; NCBIc, 2014).

There are also chemicals that have toxic effects that have been associated with multiple hydraulic fracturing spills due to being commonly used in hydraulic fracturing. Some of these common hydraulic fracturing chemicals are endocrine-disrupting chemicals (EDC) (Kassotis et al., 2013). Kassotis et al. (2013) found 12 chemicals used in hydraulic fracturing in Garfield County, Colorado were EDC as they showed antiestrogenic, antiandrogenic, and estrogenic activities. They also found that water samples from sites in areas with hydraulic fracturing incidents in Garfield County, Colorado contained more chemicals that exhibited estrogenic, antiestrogenic, and antiandrogenic activities. Estrogenic chemicals decrease fertility, increase cancer risk, and can impair gonadal development. Antiandrogenic chemicals cause decreased sperm quality and quantity, hypospadias, cryptorchidism, and reproductive tract deformities. Antiestrogenic chemicals reduce both bone density and bone mineral content (Kassotis et al., 2013). Common symptoms of humans exposed to frack fluids are upper respiratory issues such as the burning of the throat and nose. Burning of the eyes is also common as well as headaches, gastrointestinal symptoms such as vomiting and diarrhea, and dermatological issues such as rashes. Nosebleeds are also common (Bamberger and Oswald, 2012).

The process of hydraulic fracturing releases toxic gases into the atmosphere that harms the people who live near the wells. These gases can be both carcinogenic and non-carcinogenic and change based on proximity to the well. The primary toxic non-carcinogenic gases inhaled by people who live within a half mile from the wells are trimethylbenzenes, aliphatic hydrocarbons, and xylenes (Mckenzie et al., 2012). Trimethylbenzenes, aliphatic hydrocarbons, and xylenes cause health issues that affect the central nervous system, the respiratory system, blood, fetal development, and bodyweight development (Mckenzie et al., 2012; NCBId, 2014). The primary toxic non carcinogenic gases inhaled by people who live more than half a mile from the wells are aliphatic hydrocarbons and trimethylbenzenes. The primary carcinogenic chemicals inhaled by people who live within a half mile from a well are benzene and 1, 3-butadiene. The primary carcinogens inhaled by people who live more than half a mile from a well are benzene and ethylbenzene. People who live less than half a mile from a well are 167 percent more likely to get cancer than those living more than half a mile from a well (Mckenzie et al., 2012).

North Dakota Waterbodies

Missouri River and Lake Sakakawea

The Missouri River Basin is the largest river basin in the United States covering more than 1,295,000 square kilometers and includes covering all or parts of 10 states (Montana, Wyoming, Colorado, North Dakota, South Dakota, Minnesota, Iowa, Nebraska, Kansas, and Missouri). Forty-six percent of wheat, 22 percent of grain corn, and 34 percent cattle produced in the United States is grown in the Missouri River Basin (Mehta et al., 2011). The length of the Missouri River is approximately 4,090 kilometers with about 590 kilometers within North Dakota where it starts in northwestern North Dakota near the border between Williams and Mckenzie counties, flows southeast leaving the state near the border between Sioux and Emmons counties (Kammerer, 1990; NDOGb, 2014). Recreation along the Missouri River contributes $85 million annually to the national economy. Popular forms of recreation on the Missouri River include boating, fishing, hunting, camping, sightseeing, and swimming. Lake Sakakawea, which is entirely in North Dakota, and Lake Oahe, which is partially in North Dakota, account for 30 percent of the annual recreation on the Missouri River (NDSWC, 2008). The five North Dakota State Parks along the Missouri River: Cross Ranch State Park, Fort Abraham Lincoln State Park, Fort Stevenson State Park, Lake Sakakawea State Park, and Lewis and Clark State Park allow for a number of recreational activities such as hiking, camping, cross country skiing, birding, canoeing, kayaking, and camping (NDPR, 2014; Oversen, personal communication).

Table 5 Local economic impact of visitors to the North Dakota State Parks near the Missouri River (Modified from Hodur and Bangsund, 2013).

State Park	Visitors Local Spending (2012) (USD)
Cross Ranch State Park	$2,156,077
Fort Abraham Lincoln State Park	$5,478,541
Fort Stevenson State Park	$6,965,769
Lake Sakakawea State Park	$5,741,848
Lewis and Clark State Park	$3,751,757
Total	$24,093,992

The total economic impact of the aforementioned state parks on the state of North Dakota is greater than the value shown in table 5, because there is also money spent to travel to and from the state parks which increased their impact on the state's economy to above the local economic impact displayed in table 5 (Hodur and Bangsund, 2013). The waters from the Missouri River and Lake Sakakawea have municipal, domestic, industrial and irrigation uses (NDSWC, 2008). The waters from the Missouri River and Lake Sakakawea are also extracted and used for irrigation, as rural water supplies, as municipal water supplies, for stock ponds, for recreation, for fish and wildlife, and for industry. For example, in 2013 Huff Hills Ski Resort in Mandan, North Dakota used 21,463m^3 of water from the Missouri River and the city of Bismark, North Dakota used 6,949,930m^3 of water from the Missouri River. In 2013 the city of Williston, North Dakota used 9,497,800m^3 of water from Lake Sakakawea (NDSWC, 2014).

Smaller North Dakota Waterbodies

The other waterbodies within North Dakota are also provide important ecosystem resources. The major waterbodies within North Dakota, such as the Little Missouri River and the Knife River, are extracted and used for irrigation, as rural water supplies, as municipal water supplies, for stock ponds, for recreation, for fish and wildlife, and for industry just like the Missouri River and Lake Sakakawea (NDSWC, 2014). Smaller waterbodies on private property are frequently important water sources for landowners, livestock and crops (Royte, 2012).

The smaller waterbodies, such as the ones a landowner may have on their property, have multiple sources. They can acquire water via precipitation, overland flow if a gulley drains into the waterbody, or from groundwater. Many gullies and small waterbodies become dry when their water loss is greater than their intake. Wet or frozen soil are the most conducive soil types for allowing surface water to travel though a gulley and reach a waterbody as if the soil is dry much of the water will infiltrate into the soil and not stay on the surface (Eisenlohr and Sloan, 1968).

Similar Studies

Though the author is unaware of another study that modeled spills associated with hydraulic fracturing, other studies have used GIS (Geographic Information Systems) and DEMs (Digital Elevation Models) to model river floods (Gichamo et al., 2011). DEMs are frequently used as a replacement for higher quality topographic data due to time and budget constraints (Sanders, 2007). Though the specific GIS software and sources of DEMs they used differed, Gichamo et al., (2011), Asante et al., (2008) Sanders (2007), Merwade et al., (2005), and Herath et al., (2003) all integrated GIS with DEMs to model river flooding (Gischamo et al., 2011). In a separate example, Brown et al., (2014) integrated DEMs, GIS, and other data sets to model streamflow from glaciers and snow melt in the Himalayas.

CHAPTER III

METHODS

This study used ArcMap 10.2 to create a generalized model of potential vulnerability of waterbodies and rivers to hydraulic fracturing spills of frack fluid. Specifically, this model calculates the volume of frack fluid that will infiltrate into the soil from any given well, given certain assumptions about the spill and the percentage of soil volume available for infiltration. To conduct this study, a series of steps integrated raster and vector data used with ArcMap 10.2's geospatial analysis tools. These steps are explained in detail in Appendix A.

For this study the following datasets were used: 1. A 1/3 arc-second DEM, 2. point well locations, 3. polygon surface waterbody locations 4. SSURGO datasets, 5. HUC 8 watersheds and 6. imagery from Google Earth.

Analytical Process

The general concept of the analytical process of this study is described as follows and is shown in Figure 5. The DEM was combined with the point well locations and the polygon surface waterbodies to generate a spill path line that modeled the pathway the frack fluid would follow from the hydraulic fracturing well where it originated to a surface waterbody. The spill path line was combined with the SSURGO datasets and the Google Earth imagery to model how much frack fluid could infiltrate into the soil prior to reaching a surface waterbody. This process allowed for analysis of the potential of frack fluid spills to impact waterbodies in order to achieve the objectives of this thesis.

Ultimately, a Vulnerability Index was produced that estimates the potential danger of frack fluid spilling into a waterbody based on the size of the waterbody, the number of wells that spill into the waterbody, and the volume of soil infiltration of frack fluid prior to reaching the waterbody.

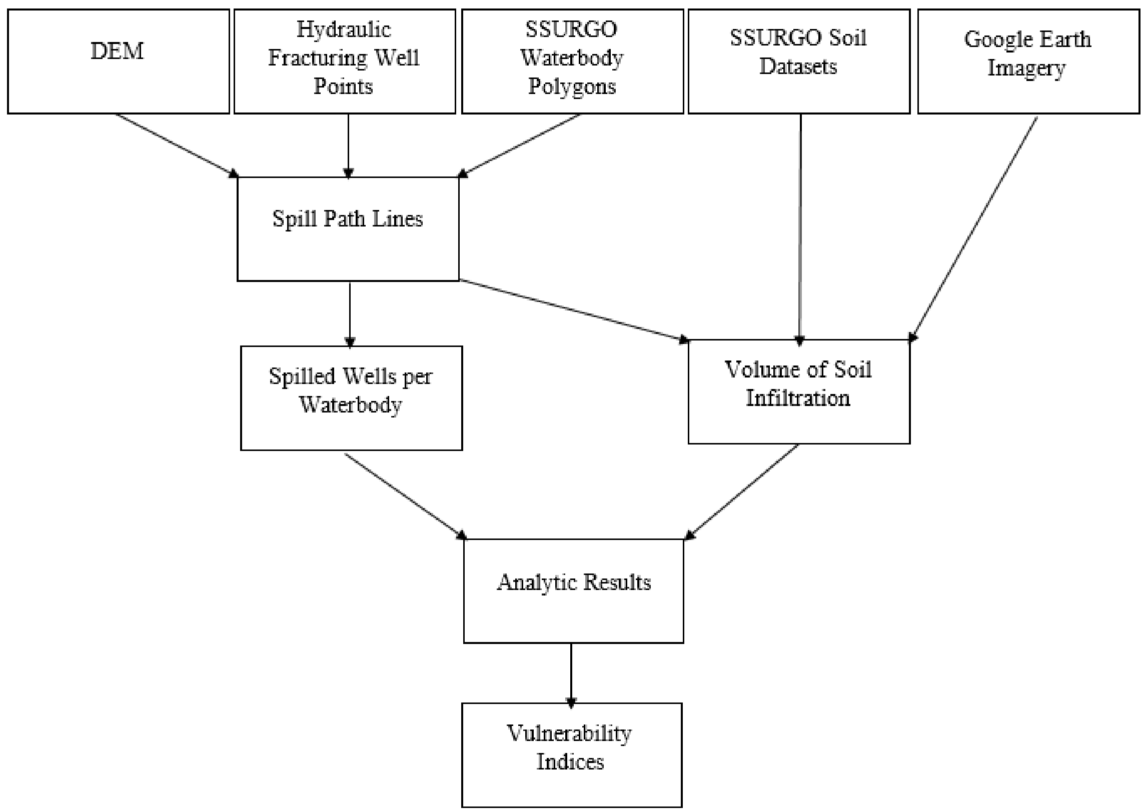

Figure 5 Flow diagram of analytical process

Data Collection and Processing

Table 6: Summary of data collection

Data	Type	Origin	Spatial/Temporal	Reference
15 USGS NED DEMs	Raster	Remote Sensing	N47W101 to N49W105 1/3 arc-second 03/06/2014	USGS National Map Viewer (http://viewer.nationalmap.gov/viewer/?p=ned)
Well Data	Point-based	Operating Companies	1 ft accuracy 02/18/2015	North Dakota Department of Mineral Resources (NDDMR) (https://www.dmr.nd.gov/OaGIMS/viewer.htm)
Bakken Formation	Raster	Geology.com	12/01/2014	(http://geology.com/articles/bakken-formation.shtml)
Soil and waterbodies	Polygon-based and Tables	USDA SSURGO	9/19/2014	United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (https://gdg.sc.egov.usda.gov/GDGOrder.aspx?order=QuickState)
Watersheds	Polygon-based	USGS	North Dakota 11/08/2015	USGS National Hydrography Dataset (NHD) (http://viewer.nationalmap.gov/viewer/nhd.html)
Real Spills	Table	NDDH	County Day	North Dakota Department of Health (NDDH) Tables 7 and 8 (https://www.ndhealth.gov/EHS/Spills/)

Table 7 Five largest well site frack fluid spills in North Dakota (Modified from NDDH, 2016).

Incident ID	Date Incident	Date Reported	County	Well Name	Spill Volume (M^3)
20130804194934	8/3/2013	8/4/2013	Billings	SKURUPEY 1-9H	639.9
20141111163046	11/10/2014	11/11/2014	Williams	ANDRE SHEPHERD 5501 14-7 2T	572.4
20060828134019	8/26/2006	8/26/2006	Dunn	MARLIN 24-12H	497.6
20140708090239	7/7/2014	7/8/2014	McKenzie	HELLING ALEXANDER SWD #1	447.2
20131107142914	11/7/2013	11/7/2013	McKenzie	SANDERS SWD #1	387.9

Table 8 Samples of frack fluid well site spills of 79.5 and 31.8 m^3 (Modified from NDDH, 2016)

Incident ID	Date Incident	Date Reported	County	Well Name	Spill Volume (M^3)
20110510162911	5/10/2011	5/10/2011	McKenzie	BOXCAR BUTTE SOUTH FEDERAL 1-26H	79.5
20140915132410	9/14/2014	9/15/2014	Mountrail	MANHATTAN FEDERAL 5792 11-2H	79.5
20150216144523	2/16/2015	2/16/2015	Williams	HELLAND 15-19H	79.5
20150215111437	2/14/2015	2/15/2015	Divide	ROBERT STEPHEN 5-8H	79.5
20110318104507	3/3/2011	3/3/2011	McKenzie	ABERCROMBIE 44-12H	79.5
NHE00000054	8/21/2009	8/21/2009	Mountrail	RS-FELDMAN-156-92- 1423H-1	31.8
20131202100606	12/1/2013	12/2/2013	Burke	MOBERG 29A-2-3H	31.8
20140516100630	5/15/2014	5/16/2014	Stark	ZENITH-NEWTON UNIT 5	31.8
20140620094241	6/18/2014	6/20/2014	Stark	KOSTELECKY SWD 1	31.8
20151124193325	11/24/2015	11/24/2015	Divide	SIOUX TRAIL 160-101-35-26H-1	31.8

The spill volumes used for the 12 Vulnerability Index scenarios (Table 9) were based on volumes of real frack fluid spills that had occurred in North Dakota during the current oil boom. The 509 m^3 was chosen to represent the high range of spill sizes since it is the average value of the five largest well site frack fluid spills in North Dakota (Table 7). Spills of 79.5 and 31.8 m^3 were chosen to represent medium and small sized spills and they were based off the volume of well site frack fluid spills that had occurred in North Dakota (Table 8).

Table 9 Name of each spill scenario with its associated spill volume and soil quartile.

Scenario Name	Spill Volume (m^3)	Soil Infiltration Quartile
1A	509	25
1B	509	50
1C	509	75
1D	509	100
2A	79.5	25
2B	79.5	50
2C	79.5	75
2D	79.5	100
3A	31.8	25
3B	31.8	50
3C	31.8	75
3D	31.8	100

All geographic data (Table 6) were subset to the study area using ESRI's ArcMap 10.2. The DEMs were mosaicked in the remote sensing software ENVI Classic prior to being utilized in ArcMap 10.2. A map of the Bakken Formation was acquired from http://geology.com/articles/bakken-formation.shtml, which was then georeferenced and digitized. The Intersect tool was used to find the intersected area where the Bakken Formation shapefile and a North Dakota state shapefile overlapped. After this was done, a series of steps were followed to create the Missouri River watershed shapefile that was used in this study and those steps are explained in Appendix A.

National Elevation Dataset DEMs

The author collected 15 DEMs from the United States Geological Survey's (USGS) National Elevation Dataset (NED). These DEMs have a spatial resolution of one-third arc-second and cover from 47°0'N, 101°0'W to 49°0'N, 105°0'W. That range was chosen, as it completely covered the area from which the study area was determined; the portion of the Bakken Formation that is within North Dakota. These DEMs were very important for this study, because they were the basis for the model. Frack fluid, like all liquids, have their movements controlled by topography. As a result, DEMs were used to determine the downhill path frack fluid could take to reach a surface waterbody.

These DEMs were imported into ArcMap 10.2 and converted from an overlay (ovr) file to a tagged image format (tif) file. The tif files were uploaded into ENVI Classic and the mosaic function was used to combine all 15 DEMs into one larger DEM. The mosaicked DEM was adjusted to the WGS 1984 datum and UTM Zone 13 projection using the Project Raster tool.

Hydraulic Fracturing Wells

The well locations and other information about mineral development wells were collected from the North Dakota Department of Mineral Resources' Oil and Gas Division's GIS Map Server (https://www.dmr.nd.gov/OaGIMS/viewer.htm). The wells shapefile that was used contained the information about all the past and present mineral development wells in North Dakota including wells that were not used for hydraulic fracturing and wells that are no longer active. The wells shapefile had been last updated on February 18, 2015 and contained 31,182 well sites. The Project tool was used to project all the wells to projected coordinate system WGS 1984 UTM Zone 13. The Clip tool was used to exclude the wells that were outside the study area and a total of 20,436 wells remained. The wells were sorted based on the category "well_type" and only the wells with well types either OG (oil and gas), or confidential were kept. The remaining wells were sorted based on the category "status" and only the wells with status A (active), confidential, or DRL (drilling) were kept and a total of 12,390 wells remained. This was done because this study focuses on the hydraulic fracturing that is currently occurring in North Dakota. Since hydraulic fracturing is a method used for well stimulation to facilitate the recovery of oil and gas, only the well types OG and confidential could be wells used in hydraulic fracturing. Since this study is looking at what is currently occurring, active wells are of interest since they are currently being used and wells that are currently being drilled are of interest since they may soon become active. Confidential wells are of interest, since wells cannot be confidential for more than six months and therefore confidential wells are most likely active, or wells that will soon become active (NDAC, 2012).

The well sites were required for this study, because they provided the point source locations for frack fluid spills. Wells were deleted if they were incorrectly digitized which was determined by the well location existing in an illegal area. Also, wells were deleted if they spilled outside the study area leaving 11,520 wells. The soil infiltration of frack fluid was only calculated for wells with spill paths that covered at least 95 percent of the total distance between the well and the waterbody. The deletion of the wells that did not meet this criteria resulted in 11,435 wells remaining.

SSURGO Datasets

The SSURGO datasets were used because they contain the locations of North Dakota's surface waterbodies, the depth of the soil, and the percentage of soil capable of holding frack fluid. The location of surface waterbodies is required to determine what wells could spill into them. The depth of the soil is required to calculate the volume of the soil. The percentage of soil capable of holding frack fluid is required to model how much frack fluid could infiltrate into the soil, with the remaining frack fluid reaching a waterbody.

The author acquired Soil Survey Geographic Database (SSURGO) data from https://gdg.sc.egov.usda.gov/GDGOrder.aspx?order=QuickState. The SSURGO dataset that was used in this study was downloaded on June 26, 2015. SSURGO datasets come in the form of a series of tables that can be joined to a polygon shapefile. The data used in the study was contained in three tables titled “muaggatt”, “chorizon”, and “component”. Each table contains multiple columns of datasets and titles of the columns used in the study were “muname”, “hzdepb_r”, “wsatiated_r”, and “cokey” with “muname” being from the “muaggatt” table, both “hzdepb_r”, and “wsatiated_r” from the “chorizon” table, and “cokey” from the “component” table. All terms are defined in the glossary. A series of steps were taken to organize the SSURGO datasets into a usable format. These steps are explained in Appendix A.

The Project tool was used to project the base SSURGO polygon shapefile to Projected Coordinate System WGS 1984 UTM Zone 13 and the Clip tool was used to eliminate the SSURGO polygons that were outside the study area.

Watersheds

The author downloaded the HUC 8 watersheds for North Dakota from USGS’s National Hydrography Dataset (NHD). These polygon shapefiles watersheds are the subwatersheds of the Missouri River watershed that were used in this study to determine which subwatersheds were more threatened by frack fluid spills within the study area. These watersheds were imported into ArcMap 10.2 and were converted to WGS 1984 UTM Zone 13 projection using the Project tool.

Specific Analytical Procedures

The following section provides a description of the methodological procedures and the purposes of each step so as to complete the objectives of this study. A detailed step-by-step explanation of the methodology including how every tool works and why every tool was used is explained in Appendix A.

In order to fulfill the first objective of this study and model the pathway a frack fluid spill would take from a well to a surface waterbody the data from the DEM, well site locations, and waterbody locations had to be integrated. Three main tools used in this process were the Flow Direction, Extract by Mask, and Flow Accumulation. The Flow Direction and Extract by Mask tools were used with the DEM and the waterbody locations to create a flow direction raster that would stop spill pathways at each distinct waterbody. This decision was made, because the first waterbody to be impacted by a frack fluid spill would be the waterbody most severely impacted by the frack fluid spill since the frack fluid would be most heavily concentrated within that waterbody. The Flow Accumulation tool was used with the flow direction raster to create the spill pathways, but these spill pathways were in raster format. For the spill pathways to be utilized to determine the number of wells that could impact a waterbody at a specific entry point they had to be converted into vectors and reorganized. This process involved using three main tools: Raster to Polyline, Multipart to Singlepart, and Dissolve. The

Raster to Polyline tool turned the raster spill pathways into vector spill pathways. The Multipart to Singlepart and Dissolve tools were used on the vector spill pathways to organize them into distinct spill pathways networks. Each spill pathway network was defined as the network of spill pathways that enter a waterbody at a single entry point. In order to calculate how many wells were associated with each spill pathway network and in turn how many wells were associated with a distinct entry point, the spill pathway networks were integrated with the wells utilizing the Spatial Join tool. The entry points were created by using two main tools on the spill pathway network and the waterbodies: Feature Point to Vertices and Intersect. This process created vertices of the spill pathway networks that intersect with the waterbodies. These points were the locations of the entry points and were joined with their spill pathway network using the Spatial Join tool so their attribute table would contain the number of wells that could spill into each entry point.

Objectives three and four both required the modeling of frack fluid soil infiltration. In order for this value to be calculated the length of each individual spill pathway was required and ArcGIS's Model Builder was used to automate this process. The wells and the flow direction raster that had previously been created from the DEM were input into Model Builder from which each individual flow path was extracted. The Merge tool was then used to combine all the spill pathways into a single shapefile that had a separate record for each spill pathway. Since these spill pathways had been created by integrating both raster and vector datasets, the spill pathways did not cover the entire distance between the well site and the waterbody due to differences in data spatial resolution. There was some distance between the well site and the start of the spill pathway as well as some distance between the end of the spill pathway and the waterbody. The wells, spill pathways, and waterbodies were combined with a Spatial Join to find the distances between the well site and the start of the spill pathway and the distance between the end of the spill pathway and the waterbody. The equation for the total distance of the spill pathway is calculated as follows:

$$TD_p = E_{WSp} + LS_p + E_{SPWp} \qquad \text{(EQ: 1)}$$

where TD_p equals the total distance of the spill path (p), E_{WSp} equals the Euclidean distance from the well site to the spill path (p), LS_p equals the length of the spill path (p), and E_{SPWp} equals the Euclidean distance from the spill path (p) to the surface waterbody. It was determined that if the spill pathway length was not at least 95 percent the length of the total distance it did not accurately display the spill pathway and those spill pathways and associated wells were removed from the study. The spill pathway percentage was calculated as follows:

$$SP_p = \frac{LS_p}{TD_p} \qquad \text{(EQ: 2)}$$

where LS_p equals length of spill path (p), TD_p equals total distance of the spill path (p), and SP_p equals the spill pathway percentage for spill path (p).

The resolution of the DEM made it impossible to utilize the DEM to find the widths of the gullies through which the frack fluid would travel, since many gullies within the study area are less than 10 meters wide. In order to estimate the width of the gullies Google Earth imagery was used to measure the width of 500 random points along the spill pathways. After measuring and recording the width at the 500 points, the median value of 2.775 meters, was used as the width of the spill pathways.

The spill pathways, the 2.775 meter value for their widths, and the SSURGO data that contained both the soil depth and the percentage of soil volume that can hold water were combined into a single shapefile using the Intersect tool. This was necessary in order to perform the calculations to determine how much frack fluid could infiltrate into the soil. The soil volume was calculated as follows:

$$SV_p = LS_p * WS_p * SD_p \qquad \text{(EQ: 3)}$$

where SV_p equals soil volume for spill path (p), LS_p equals length of spill path (p), WS_p equals the width of the spill path (p), and SD_p equals soil depth of spill path (p).

The calculated soil volume (SV) was then multiplied by the percentage of soil volume that can hold water in order to determine how much frack fluid could infiltrate into the soil. This was done, because the volume of frack fluid that soil is able to hold does not equal the volume of the soil and certain soil types are able to hold a greater percentage of their volume in water than others. The reason why it is valid to use the ability to hold water as a proxy for the ability of soil to hold frack fluid is because frack fluid is mostly water and therefore it will infiltrate into soil in a similar manner to water. This was calculated as follows:

$$MV_p = SV_p * PSV_p \qquad \text{(EQ: 4)}$$

where MV_p equals the maximum volume of frack fluid soil infiltration for spill path (p), SV_p equals the soil volume from (EQ 3) for spill path (p), and PSV_p equals the percentage of soil volume that can hold water along spill path (p).

In reality soil is usually not completely dry and the velocity of the spilling frack fluid may be at a rate that does not provide enough time to fully infiltrate into the soil. To calculate a range of values for potential volumes of frack fluid that could infiltrate into the soil the maximum volume of frack fluid infiltration (MV_p) was multiplied by 0.25, 0.50, and 0.75 in order to calculate the 25th, 50th, and 75th percentile values. The maximum infiltration volume (100th percentile) was also used. This calculation produced a volume of soil infiltration (SI) for the four percentiles (i)

Objective four required the creation of a Vulnerability Index for both waterbodies and watersheds as well as to calculate the volume that could spill into each entry point in order to determine how vulnerable the waterbodies are to a frack fluid spill. The Vulnerability Index for waterbodies is calculated based on 12 different scenarios of soil infiltration and spill volume from the wells (Table 9). To calculate the Vulnerability Index for each waterbody, first a total volume of frack fluid spilled into each waterbody was needed. This was calculated as follows:

$$VS_W = SP_{v,p} - SI_{i,p} \qquad \text{(EQ: 5)}$$

where VS_w equals the volume of frack fluid spilled into a given waterbody (w), $SP_{v,p}$ equals the amount of frack fluid spill for the three sample volumes (v) from tables 7 and 8 along a flow path (p), and $SI_{i,p}$ equals the amount of soil infiltration given the percentile

(i) along the flow path (p). The Vulnerability Index for the waterbodies was calculated as follows:

$$VI_W = \left(\frac{N_{i,v}}{A_W}\right) \times VS_{W,i,v} \qquad \text{(EQ: 6)}$$

where VI_w is the Vulnerability Index for a waterbody (w), N equals the number of wells that would impact a waterbody under a given scenario (i,v), A equals the area of the waterbody (w), and VS_w equals the volume of frack fluid spilled into a waterbody (w) under a given scenario (i,v). The reason for using the number of wells as a variable in the Vulnerability Index is that the greater the number of wells that can impact a waterbody the greater the likelihood that one of those wells will spill and impact the waterbody. As a result the greater the number of wells, the greater the Vulnerability Index. As well, the greater the area of the waterbody, the greater the ability of the waterbody to dilute and therefore mitigate the impact of a spill. As a result and in general, waterbodies which are larger in area and impacted by a smaller number of wells will have a smaller Vulnerability Index. Conversely, waterbodies which are smaller in area and are impacted by a large number of wells will have a greater Vulnerability Index. The Vulnerability Index will also vary dependent on the volume of frack fluid impacting the waterbody, with a larger amount of frack fluid leading to an increased Vulnerability Index and a smaller amount of frack fluid leading to a decreased Vulnerability Index.

The Vulnerability Index for the waterbodies was normalized on a 0-1 scale by taking the largest Vulnerability Index for each scenario and dividing all the vulnerability indices within the scenario by that number. This was done in order to standardize the

Vulnerability Index values since they lack units, so that the Vulnerability Index can be better compared between waterbodies. This is calculated as follows:

$$NVI_W = \frac{(VI_w - VI_l)}{VI_h} \qquad \text{(EQ: 7)}$$

where NVI_w is the normalized vulnerability index for a given waterbody (*w*), VI_w equals the vulnerability index for waterbody (*w*), VI_l equals the lowest vulnerability index of all waterbodies, and VI_h equals the highest vulnerability index of all waterbodies.

In order to determine which entry points were most threatened by frack fluid spills, the volume that entered at each entry point was calculated. This was done by combining the entry points with the spill pathway volumes using the Spatial Join and Dissolve tools. This associated each entry point with its associated spill pathway volumes, and summed those volumes per entry point. These spill volumes per entry point allowed for a comparison between points in order to determine which ones were associated with the greatest spill volumes.

Finally, the Vulnerability Index for the watersheds used a similar equations as the Vulnerability Index for waterbodies, but required the data at a watershed scale. The HUC 8 watersheds was used to delineate which watershed the entry points and the impacted waterbodies exist. The number of wells and spill volume per watershed as well as the sum of the area of all the impacted waterbodies within the watershed were calculated. These datasets were used to create the watershed Vulnerability Index which was calculated as follows:

$$VI_{WS} = \left(\frac{N_{i,v}}{A_{ws,i,v}}\right) \times VS_{WS,i,v} \qquad \text{(EQ: 8)}$$

where VI_{ws} is the vulnerability index for a given watershed (*ws*), $N_{i,v}$ equals the number of wells for a given scenario (*i,v*), $A_{wsi,v}$ equals the sum of the area of the all the waterbodies within the watershed (*ws*) that are impacted by a spill under a given scenario (*i,v*), and VS_{ws} equals the volume of frack fluid spilled for a given watershed (*ws*) under scenario (*i,v*). The watershed Vulnerability Index was normalized between 0-1 by dividing all the watershed vulnerability indices by the greatest watershed Vulnerability Index within each scenario just as was done with the waterbody Vulnerability Index. This was the final step in fulfilling the fourth and final objective.

Uncertainty Calculation

Uncertainty of the results largely lies with the soil volume as soil infiltration is critical in determining how much frack fluid will reach a waterbody. Soil infiltration has three variables as described in (EQ 3): gulley width, soil depth, and flow path length. While the most complete analysis of uncertainty would include a combined measured uncertainty of all three components, statistical analysis (and therefore a measure of uncertainty) exists for only the gulley widths. Individual measures of uncertainty for the soil depths is not available in the SSRUGO data, and the uncertainty of the spill length is negligible. Therefore, uncertainty was calculated by utilizing equation three, and replacing the width of the spill path with the standard error of all the measured widths (0.284). The result of this equation was divided by the result of equation three resulting in an uncertainty of 10.2 percent for all frack fluid volume spills in this study.

CHAPTER IV

RESULTS

Spatial Relationship of wells, spill pathways, and waterbodies

There are 11,520 hydraulic fracturing wells used to model waterbody vulnerability in this thesis. Of the 1,307 surface waterbodies in the study area, 280 individual surface waterbodies are threatened by potential spills. Spills from the wells are modeled to enter the waterbodies at 873 distinct locations. The spill pathways modeled in the study assume that the spill is not mitigated. If a spill is mitigated than the pathway of the spill will be impeded and will not reach a waterbody. The wells, spill pathways, and waterbodies that were modeled in this thesis are displayed in figure 6.

Of the 280 waterbodies into which frack fluid could spill, 64 waterbodies are threatened by only one well, while Northern Lake Sakakawea, is threatened by 2,294 (Figure 7). The mean number of wells spilling into any given waterbody is 41, while the median number of wells spilling into any given waterbody is four. The distribution of wells to waterbodies is skewed toward a small number of waterbodies. For example, a total of 629 (5.5%) wells threaten 196 (70%) waterbodies while 9,227 (80%) wells threaten 20 (1.5%) waterbodies.

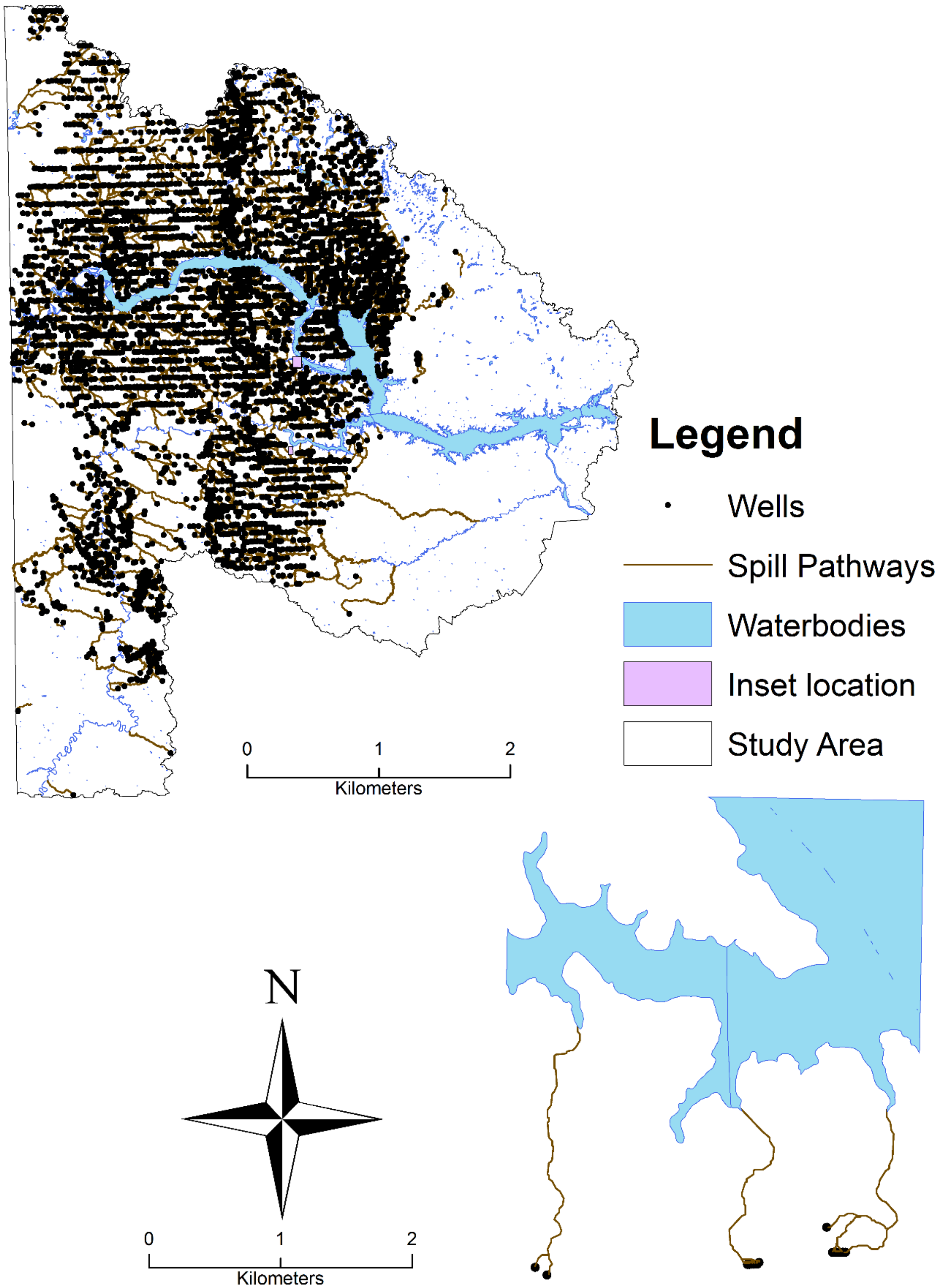

Figure 6 Hydraulic fracturing wells, their spill pathways and surface waterbodies for the entire study area including an inset zoomed in to a portion of Mid Lake Sakakawea.

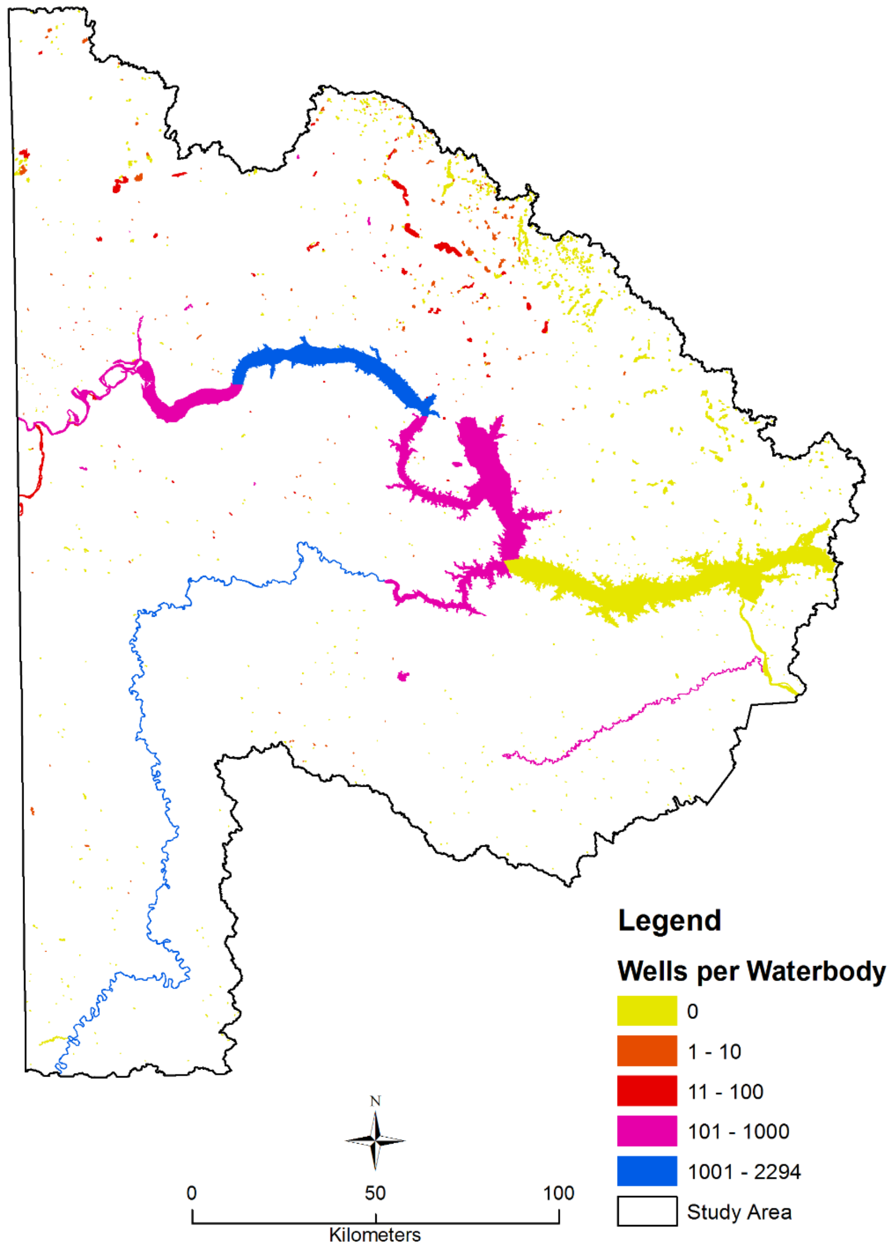

Figure 7 Number of wells that will spill into each waterbody within the study area.

The most threatened waterbodies based on number of wells that could spill into them are the northern and western sections of Lake Sakakawea as well as the Little Missouri and Knife Rivers.

The length of the spill pathways ranges from 40.60m to 155,134.54m. The mean length is 23,514.23m and the median length is 14,618.15m. The length of the spill pathways that could reach a waterbody under scenario 1A ranges from 40.60m to 18,916.09m. The mean length is 1374.17m and the median length is 1,148.28m. The Euclidean distance between the wells whose spills can reach a waterbody under scenario 1A ranges from 39.47m to 8,048m with a mean distance of 841.41m and a median of 663.57m. The spill path lengths are consistently greater than the Euclidean distance between the wells and the waterbodies, because the spill pathways are not straight lines from the well to the waterbody. This curvature in the spill pathways increase the length of the spill path and therefore the ability for frack fluid to infiltrate into the soil prior to reaching a surface waterbody.

Spill pathways and Spill Entry Points

There are 873 distinct locations where spills from a well can enter a waterbody, because frequently multiple spills flow together and enter a waterbody at a single entry point. The number of wells associated with each entry point ranges from 1 to 611 with a mean value of 13.20 and a median value of 3. This is because there is a greater number of entry points associated with a few wells. This skew in the statistics is exemplified by the fact that the mode is 1 and 278 (31.8%) entry points come from individual wells. The waterbodies that are associated with the five largest entry points (i.e. with the largest number of wells) are Northern Lake Sakakawea, Knife River, Cherry Creek, the Little Muddy River, and Bear Den Creek. These entry points are displayed in red in figure 8.

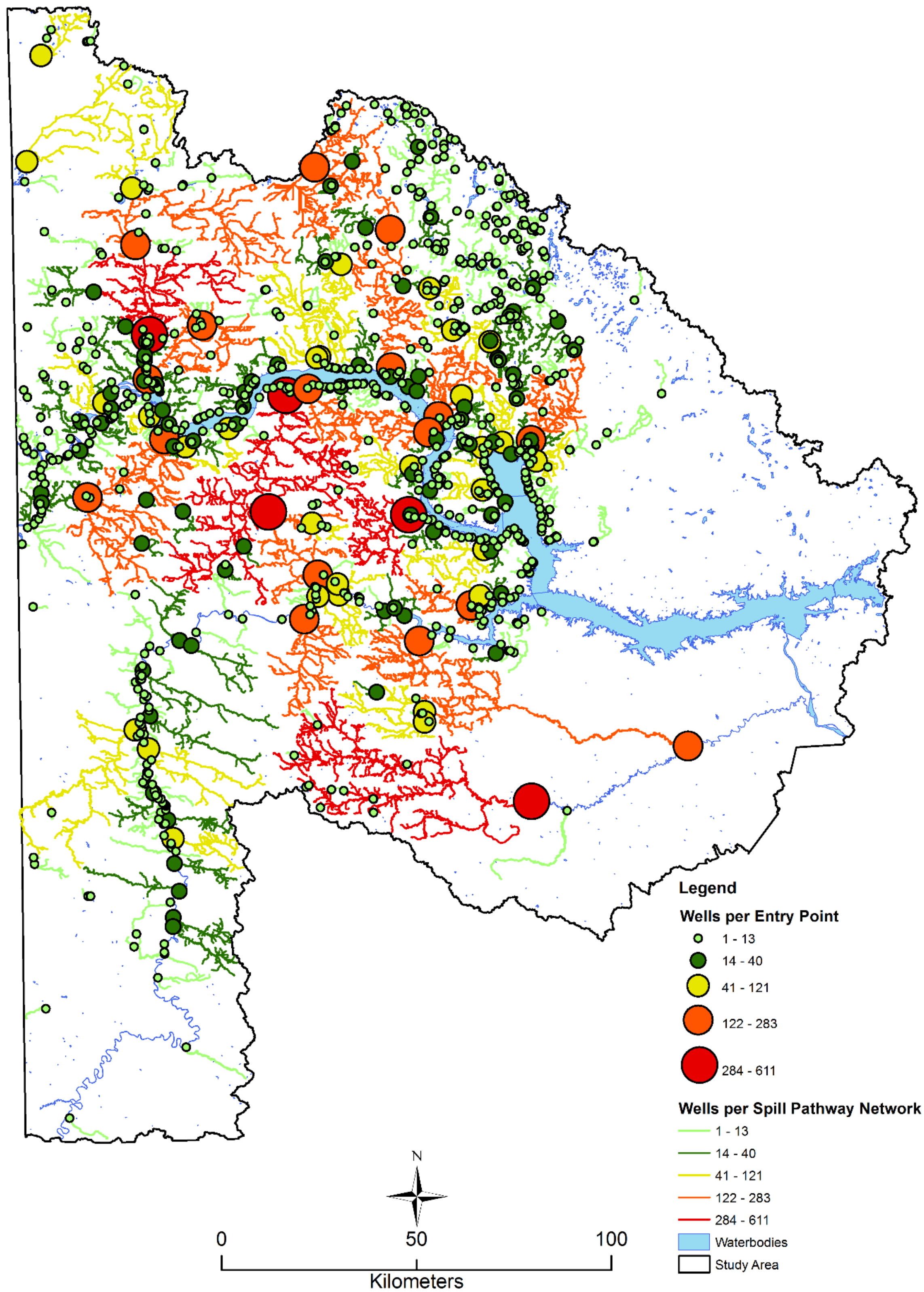

Figure 8 Location of spill entry points, spill pathways and the number of associated wells.

The 873 entry points are shared between 280 different waterbodies and range between 1 and 101 per impacted waterbody. The average impacted waterbody has 3 associated entry points, but the median value is one entry point as 192 (68.6%) waterbodies have only one entry point. The five waterbodies with the most associated entry points are Western Lake Sakakawea, Northern Lake Sakakawea, Mid Lake Sakakawea, Van Hook Arm Lake Sakakawea, and the Little Missouri River, which are displayed in blue in figure 9. These five waterbodies combine for 332 entry points, and 38 percent of the total entry points.

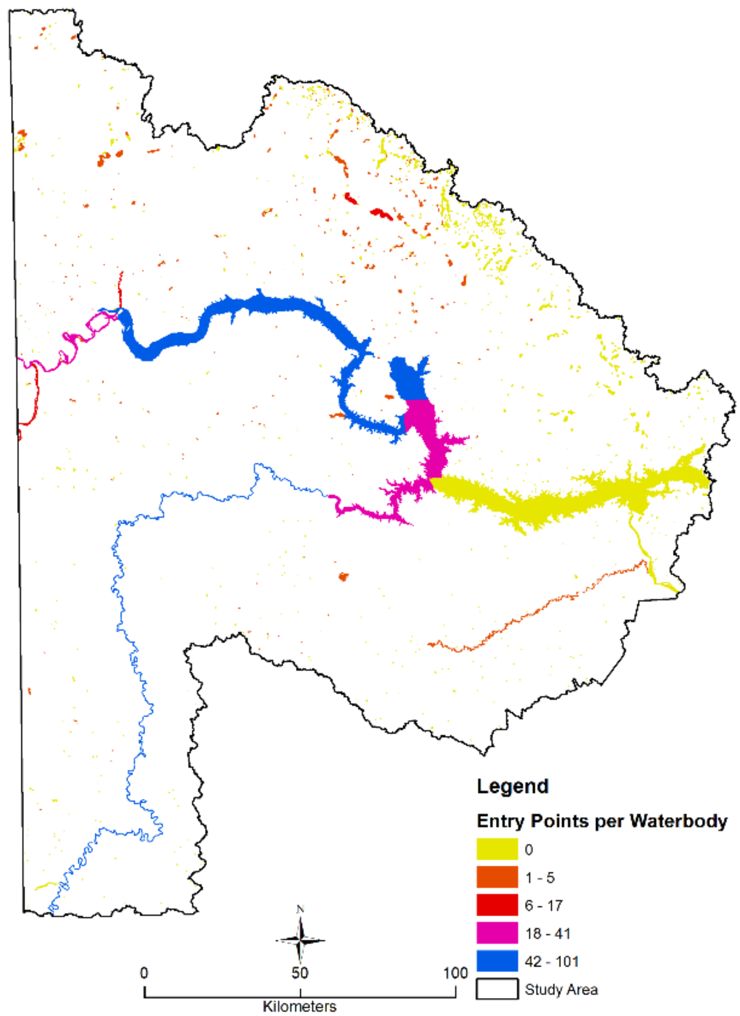

Figure 9 Number of spill entry point per waterbody.

Soil Infiltration of Frack Fluid

A significant factor in determining the risk a hydraulic fracturing spill poses to a waterbody is the volume of frack fluid that would infiltrate into the soil prior to reaching a surface waterbody. The greater the volume of soil infiltration the lower the risk to the associated surface waterbody. The soil infiltration associated with each spill path is displayed below in figure 10.

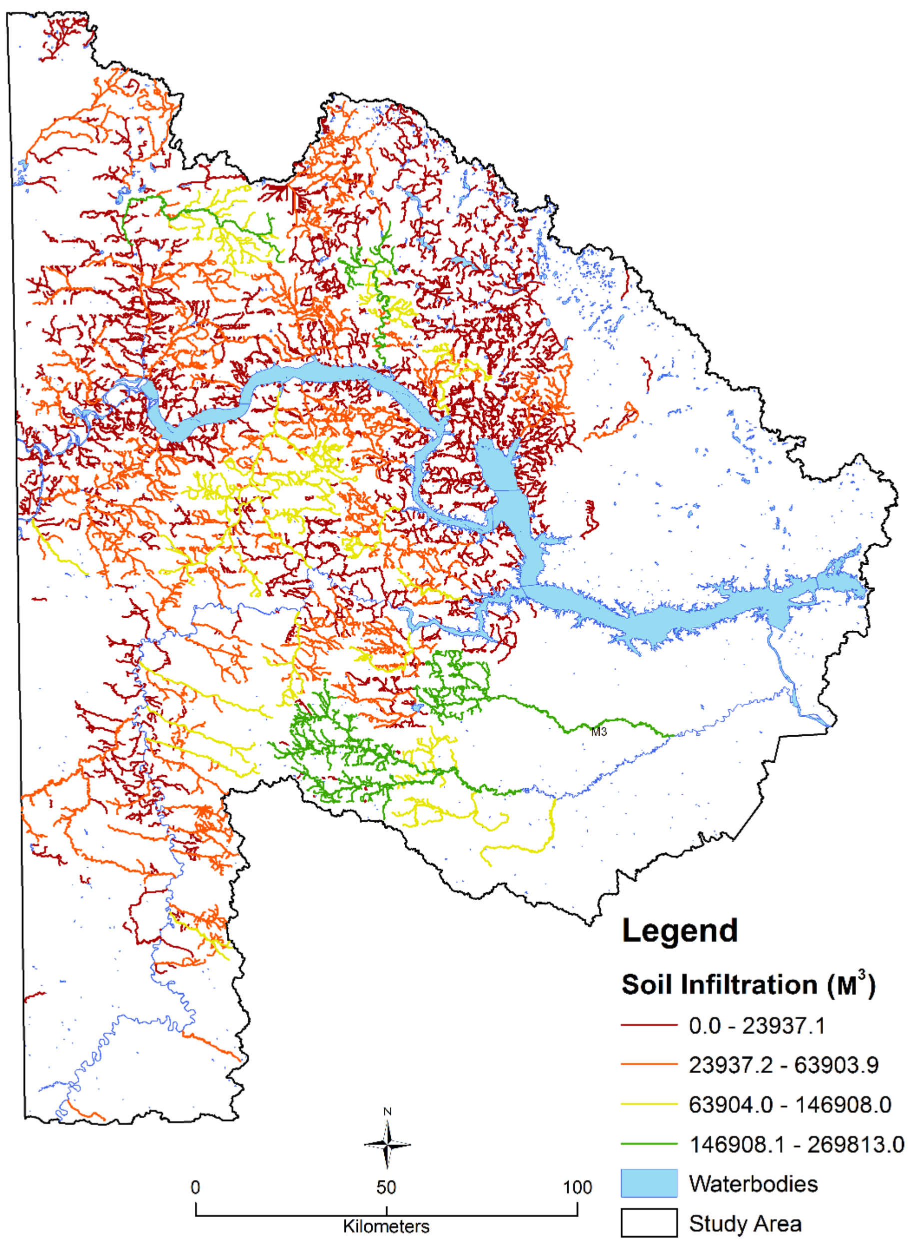

Figure 10 Maximum soil infiltration volumes for spill pathways in meters cubed.

The medians are substantially lower than the means because many of the spill pathways are short and there is a strong correlation ($r=0.97$; $p < 0.01$) between length of the spill pathway and soil infiltration. The median spill path is 14,618.15 meters while the longest spill path is more than 10 times longer 155,134.54 meters. This variation in soil infiltration is displayed below (Table 10).

Table 10: Descriptive statistics for soil infiltration volumes based on 11,109 spill pathways. The volumes are in meters cubed.

Statistic	Max Soil Infiltration	75% Soil Infiltration	50% Soil Infiltration	25% Soil Infiltration
Maximum	269,812.98	202,359.73	134,906.49	67,453.24
Minimum	0	0	0	0
Mean	33,290.46	24,967.85	16,645.23	8,322.62
Median	17,270.67	12,953.00	8,635.34	4,317.67
Standard Deviation	47,083.46	35,312.59	2,3541.73	1,1770.86

Three scenarios for spill sizes were modeled based on real spills that have occurred in North Dakota. A spill of $509m^3$ (Scenarios 1A, 1B, 1C, and 1D) was based on the median of the top five frack fluid spills in North Dakota (Table 7). Spills of $79.5m^3$ (Scenarios 2A, 2B, 2C, and 2D) and $31.8m^3$ (Scenarios 3A, 3B, 3C, and 3D) were chosen as representatives of medium and small spills as these are common volumes of frack fluid spills which have occurred since 2006 (Table 8).

Frack Fluid Volume at Entry Points

The volume of frack fluid that could enter into a waterbody at a single entry point varied based on the scenario, with the greatest volume being 4,770 m^3 under the scenario 1A. This entry point is shown as a red point in figure 11. There are 13 different wells that spill into that entry point. The reason why so few wells were able to spill such a large volume at a single entry point is because they are all wells that are close to (within 1,625 meters) Southern Lake Sakakawea and their associated soil infiltration volumes are low enough that a spill from all of those wells under scenario 1A will impact Southern Lake Sakakawea. The volumes of frack fluid that could enter a waterbody at each entry point are displayed below for three scenarios 1A, 2B, and 3D (Figures 11-13).

The number of entry points with spill volumes greater than zero increases as the spill size increases. Table 11 displays this by showing 12 scenarios and the associated number of threatened entry points and largest potential spill volume per entry point. As a result spill scenario 1A has the greatest range of volumes. The spill scenario 2B values are skewed towards the smaller volumes with only a single value above 79.5m^3. The spill scenario 3D only has two entry points that are threatened.

Table 11 Number of entry points that are impacted by spills under each scenario and the maximum volume in meters cubed of spills reaching each entry point.

Scenario Name	Number of Impacted Entry Points	Largest Volume per Entry Point (m^3)
1A	479	4770
1B	284	3431
1C	185	2357
1D	117	2294
2A	57	335
2B	25	272
2C	14	210
2D	8	147
3A	17	96
3B	6	35
3C	3	32
3D	2	32

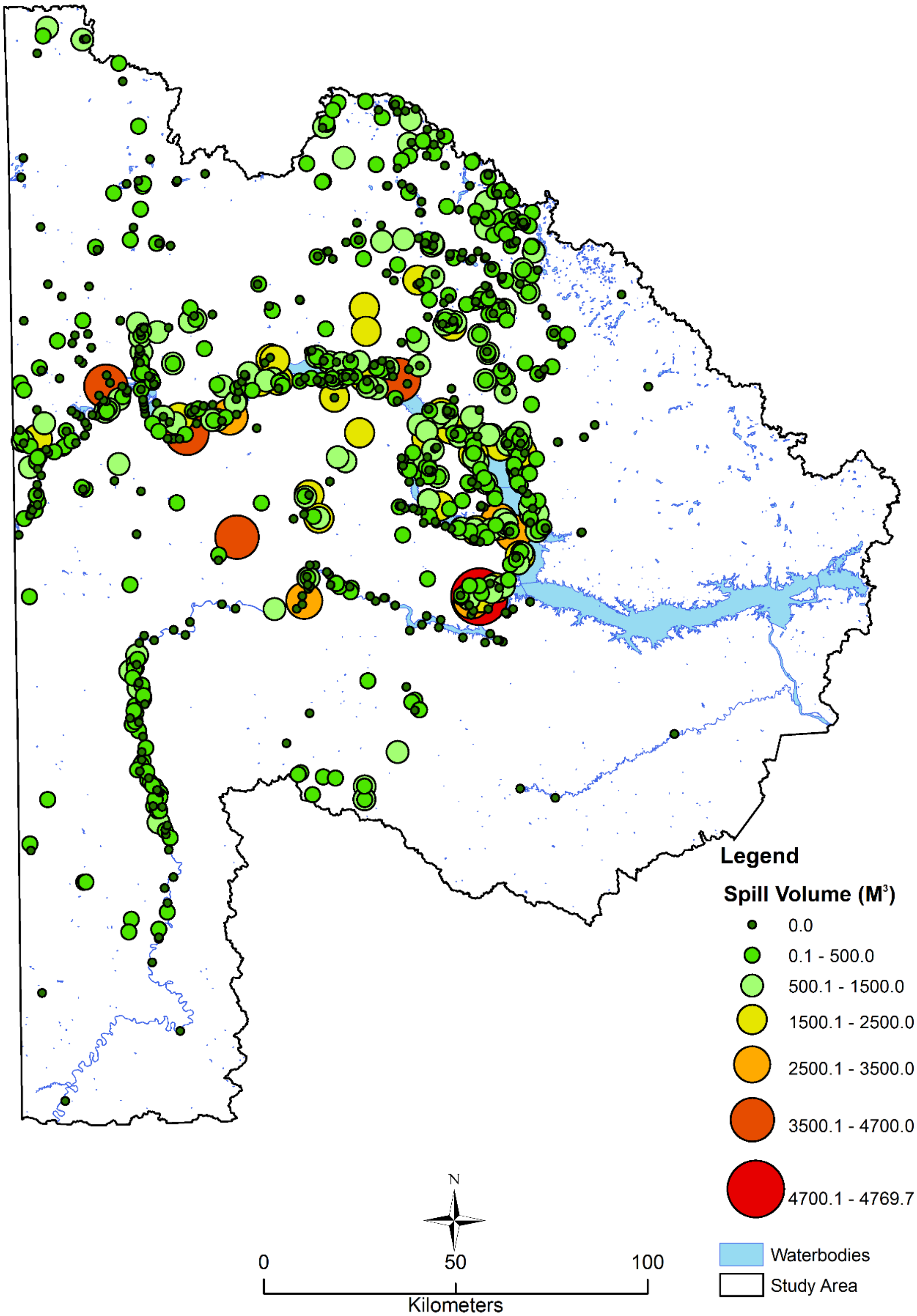

Figure 11 Normalized Vulnerability Index values for the entry points given scenario 1A.

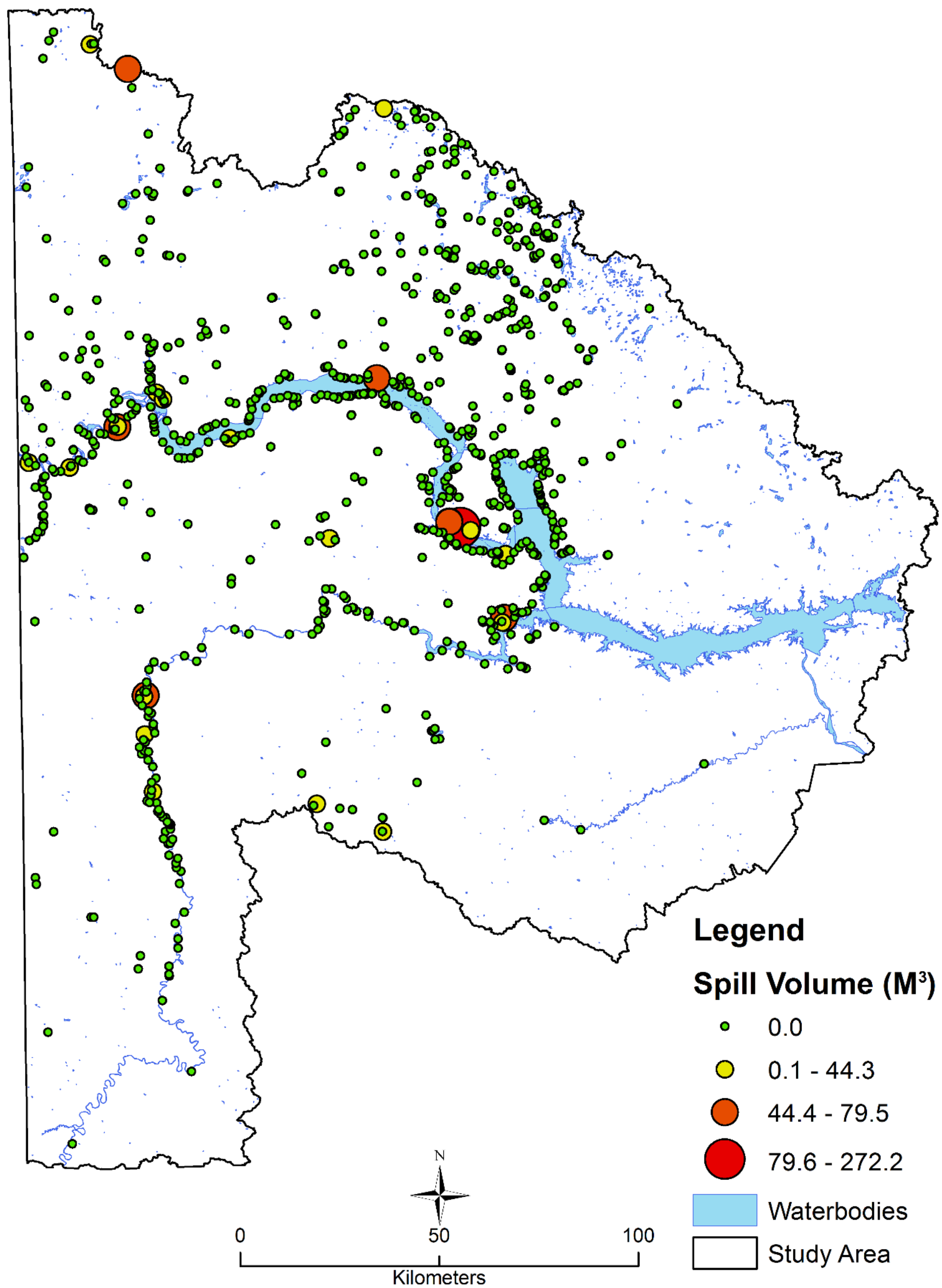

Figure 12 Normalized Vulnerability Index values for the entry points given scenario 2B.

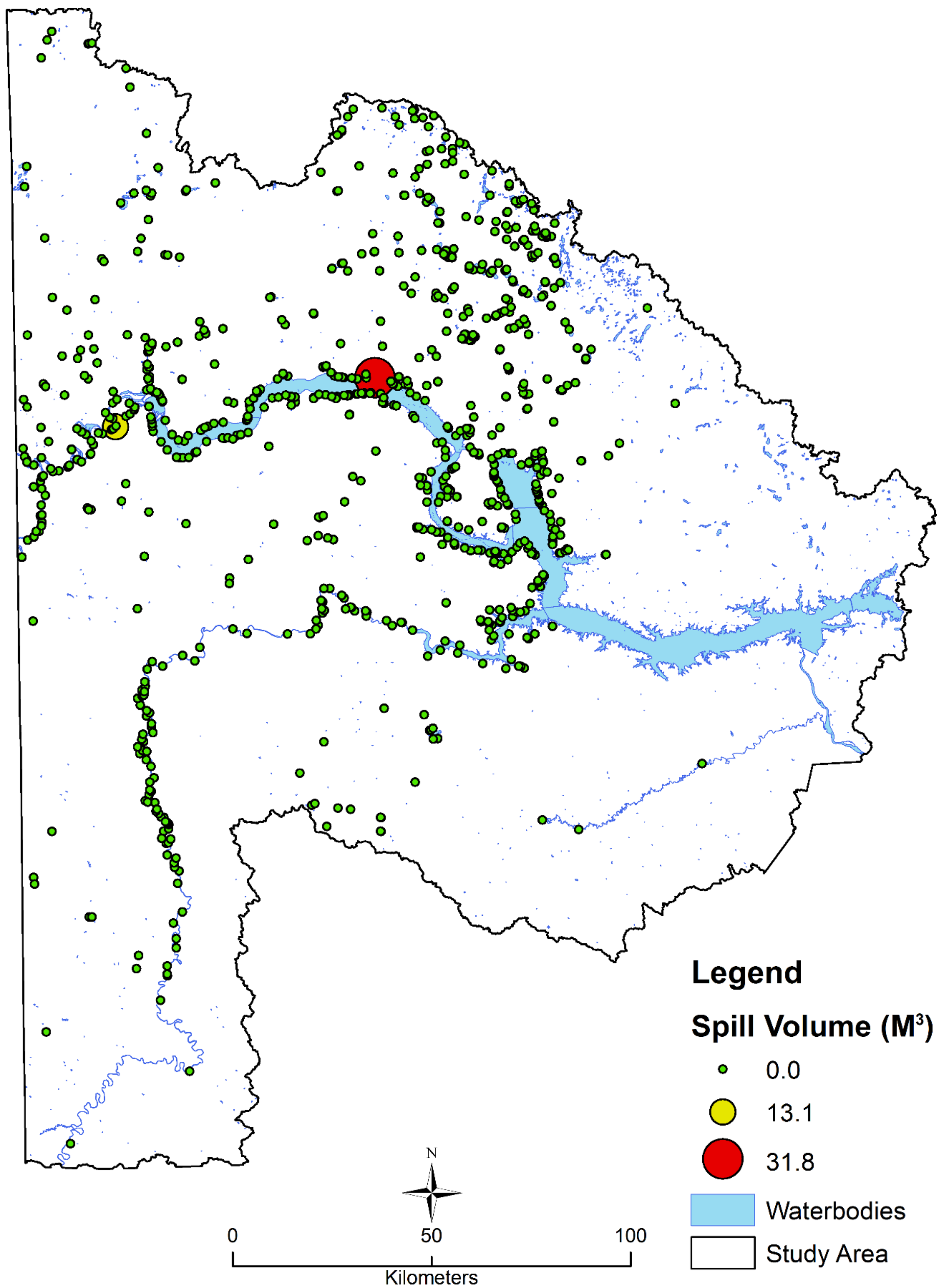

Figure 13 Normalized Vulnerability Index values for the entry points given scenario 3D.

Vulnerability Index

The Vulnerability Index results are shown for the three spill volume scenarios: 1A, 2B, and 3D (Figures 14-16).

The spill scenario 1A (Figure 14) had the greatest number of waterbodies with vulnerability indices above zero. The most dangerous spills, in terms of spill volume impacting waterbodies, were associated with scenarios 1A, 1B, 1C, and 1D. Under scenarios 1A and 2B the waterbody with the largest NVI was small with a size of $0.012km^2$ and $0.028km^2$ respectively (Figures 14 and 15). The impacts of spills are more severe on smaller waterbodies than larger waterbodies since the spills can be diluted in larger waterbodies. For scenario 3D both of the impacted waterbodies were larger waterbodies, the Missouri River and Northern Lake Sakakawea (Figure 16). The smaller of the two impacted waterbodies, the Missouri River, had the greater NVI, because even when dealing with larger waterbodies, the size of the waterbody and associated dilution is still very significant in determining how severely spills threaten a waterbody. Table 12 below displays the variability in number of wells and waterbodies that could be impacted by spills based on the scenario. It ranges from 2 to 1,168 for wells and from 2 to 180 for waterbodies. The largest waterbody Vulnerability Index value, which was under scenario 1A was 1.26 and was based off a waterbody with an area of $0.012km^2$ being impacted by 6 wells and $2,553.03m^3$ of frack fluid.

Table 12: Number of wells and waterbodies that could be impacted by spills under each scenario

Scenario Name	Number of wells whose spills Reach Waterbodies	Number of waterbodies with NVIs above 0	Volume Reaching Waterbodies M^3
1A	1,168	180	283,080.8
1B	562	122	119,325.7
1C	348	81	63,576.9
1D	202	56	37,748.0
2A	85	31	2,766.5
2B	34	12	1,104.0
2C	20	4	587.4
2D	12	7	389.2
3A	23	9	312.1
3B	9	6	109.7
3C	3	3	53.2
3D	2	2	44.9

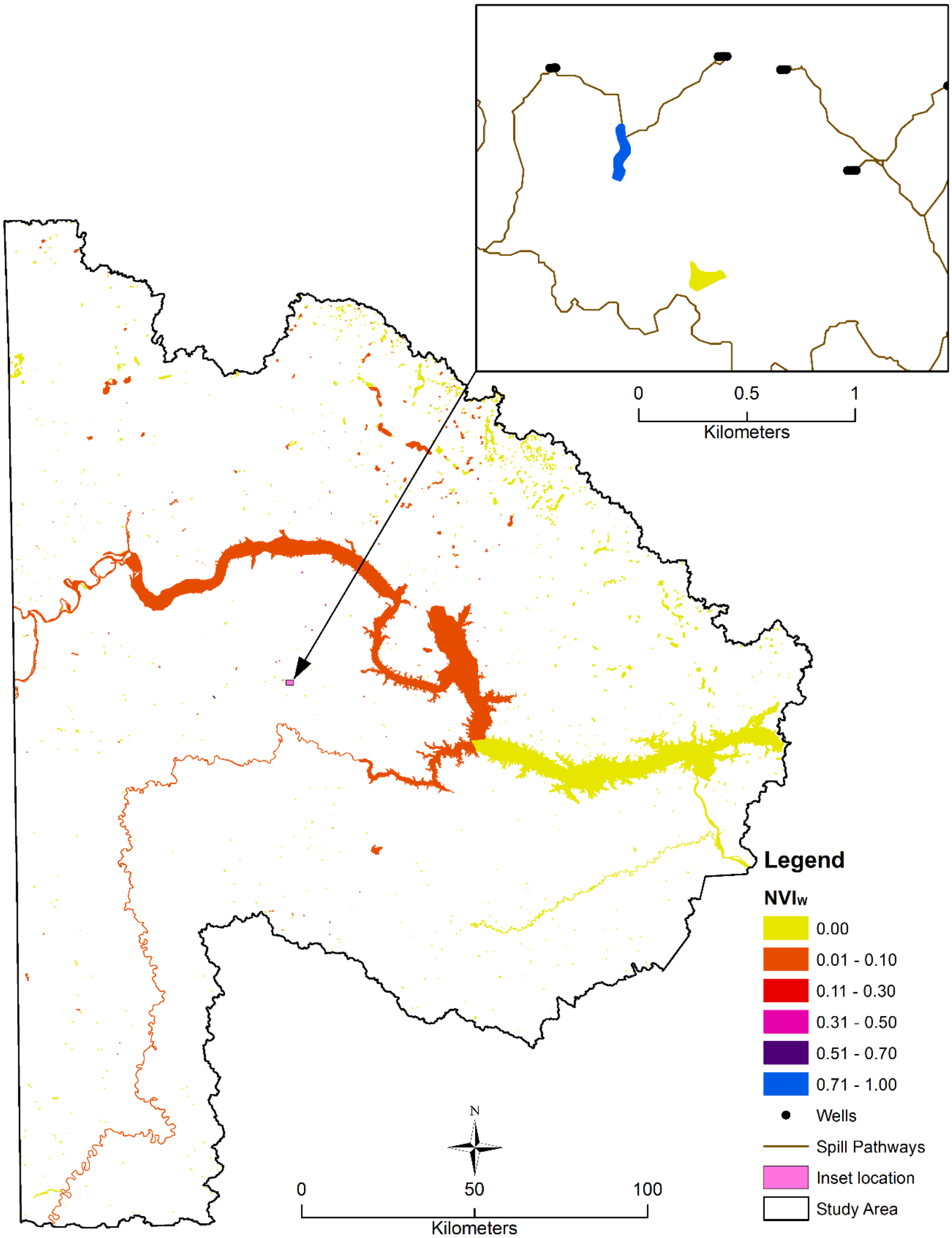

Figure 14 Normalized Vulnerability Index values for the waterbodies given scenario 1A including an inset showing the most vulnerable waterbody.

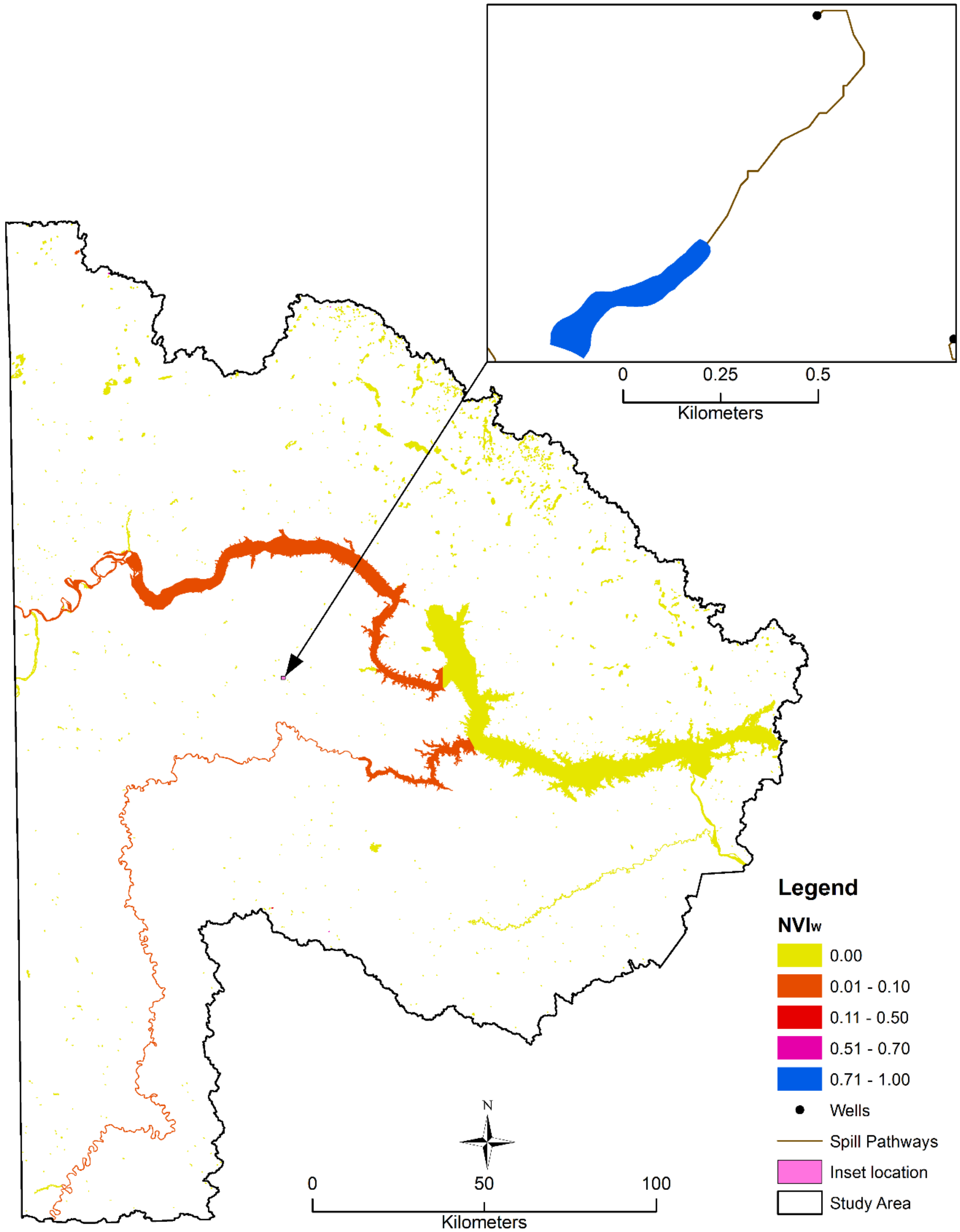

Figure 15 Normalized Vulnerability Index values for the waterbodies given scenario 2B including an inset showing the most vulnerable waterbody.

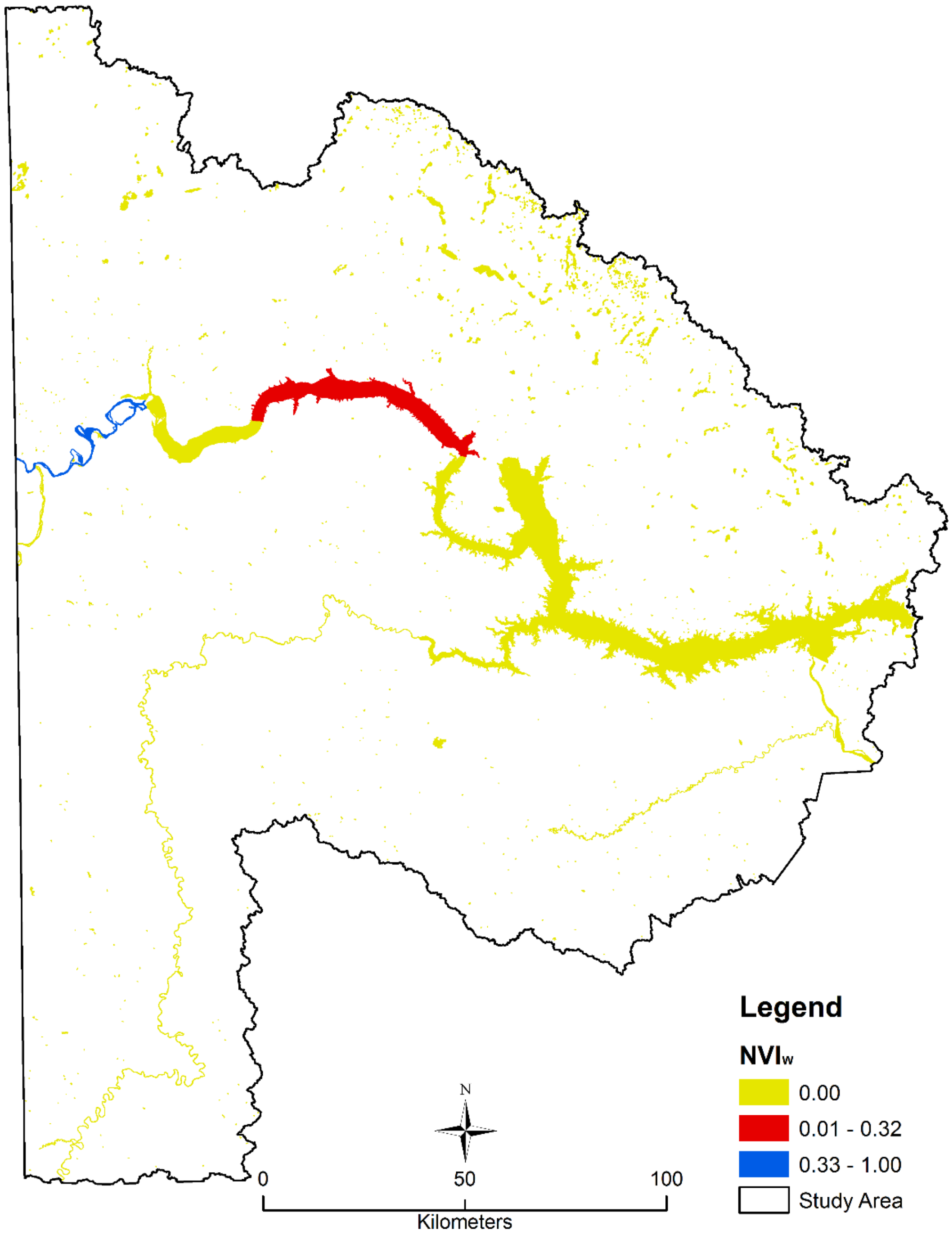

Figure 16 Normalized Vulnerability Index values for the waterbodies given scenario 3D.

Watersheds

Based on the USGS NHD there are 12 HUC 8 watersheds within the study area. Only one of the 12 watersheds, the Lower Little Missouri, is completely within the study area and some of the other watersheds such as the Lake Sakakawea and Little Muddy watersheds are mostly encompassed within the study area (Figure 4). The fact that some of the watersheds leave the study area, including the Lower Yellowstone which encompasses parts of Montana, displays that spills within the study area may impact localities outside of the study area including outside of North Dakota. Ten of the 12 watersheds contain wells that would spill into waterbodies within the watershed, ranging from 5 wells within the Big Muddy to 7,127 wells within the Lake Sakakawea watershed (Figure 17). The mean number of wells within an impacted watershed is 1,152 and the median is 330. The majority (61.9%) of the wells are within the Lake Sakakawea watershed, which is also the largest watershed within the study area (17,037 km^2; 41.9%).

In order to determine the potential threat to the different watersheds from spills, the volume of frack fluid that could reach a waterbody within each watershed under scenario 1A was determined. Nine of the watersheds were impacted by spills given the scenario ranging from 621.4 m^3 spilling into the Beaver watershed to 209,265.0 m^3 spilling into the Lake Sakakawea watershed. The mean volume of frack fluid spilling into waterbodies within a watershed is 31,453.4 m^3 and the median value is 6,003.9 m^3. The majority of the spilling (73.9%) would impact waterbodies within the Lake Sakakawea watershed. A Vulnerability Index for scenarios 1A, 2B, and 3D were produced using Equation 8, were normalized, and are displayed in figures 18-20. The largest watershed Vulnerability Index value, which was under scenario 1A was 0.22 and was based off a watershed with an impacted area of 854km^2 being impacted by 900 wells and 209,265m^3 of frack fluid.

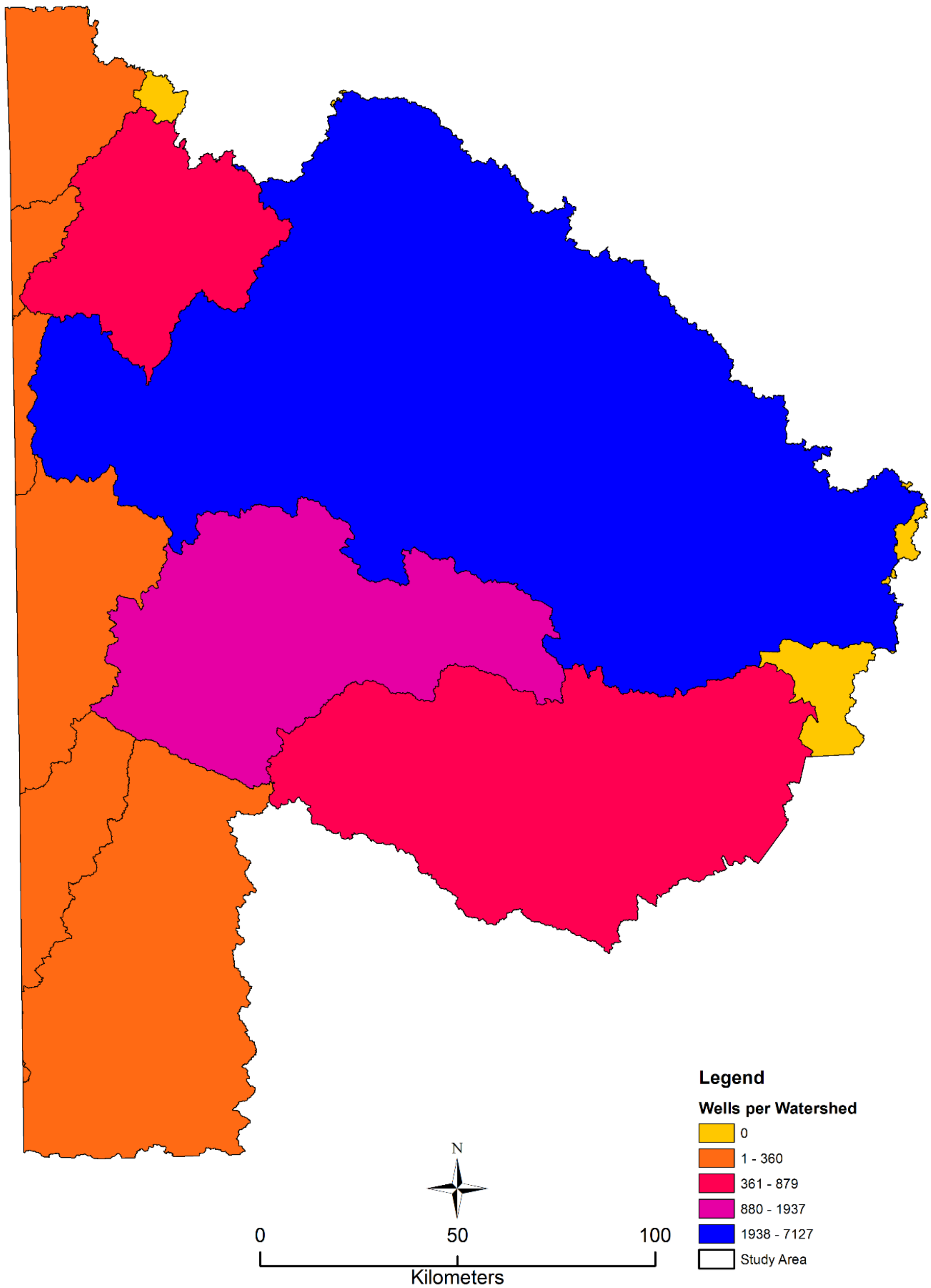

Figure 17 Number of wells spilling into waterbodies within each watershed.

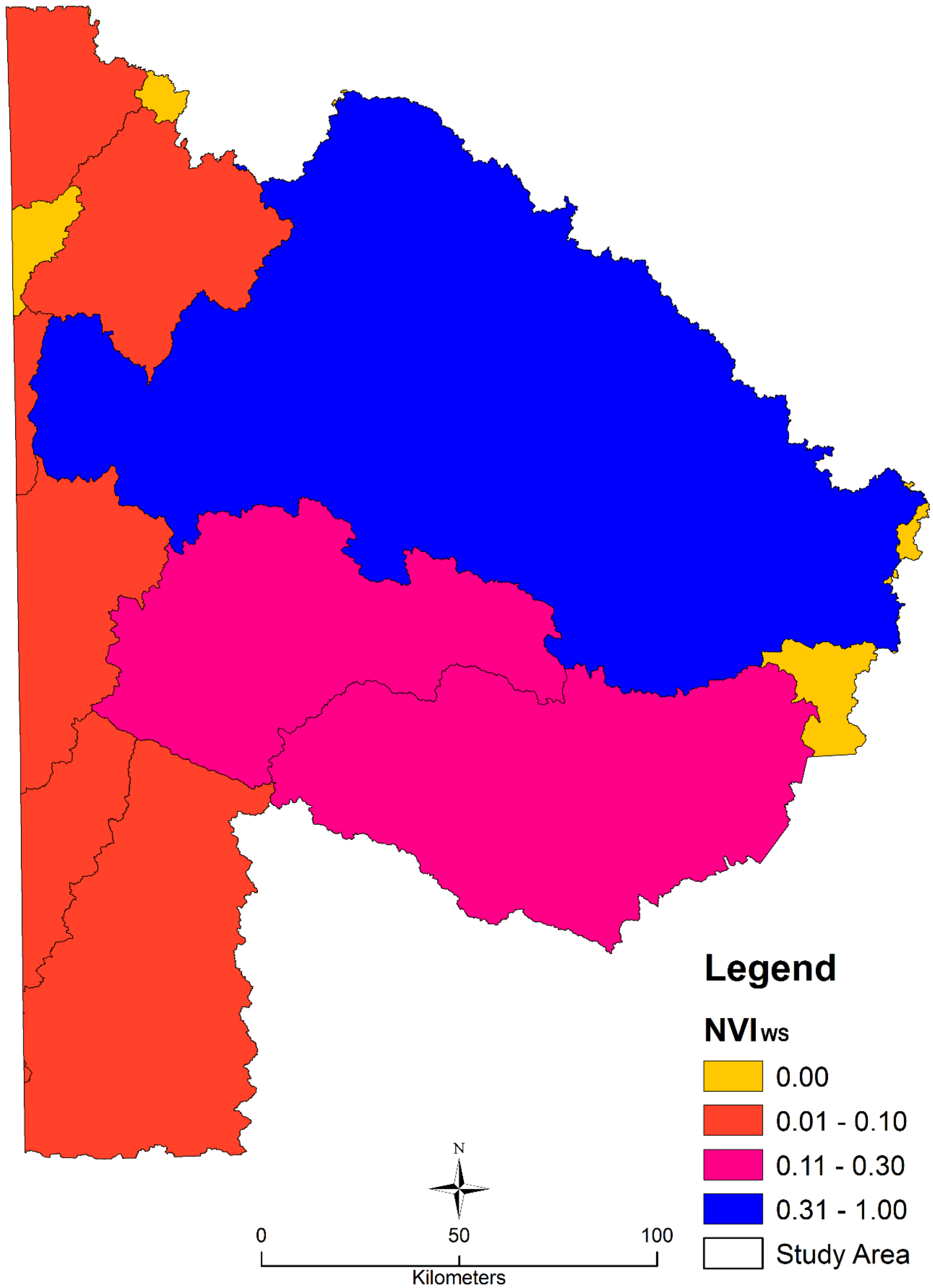

Figure 18 Normalized Vulnerability Index for watersheds given scenario 1A.

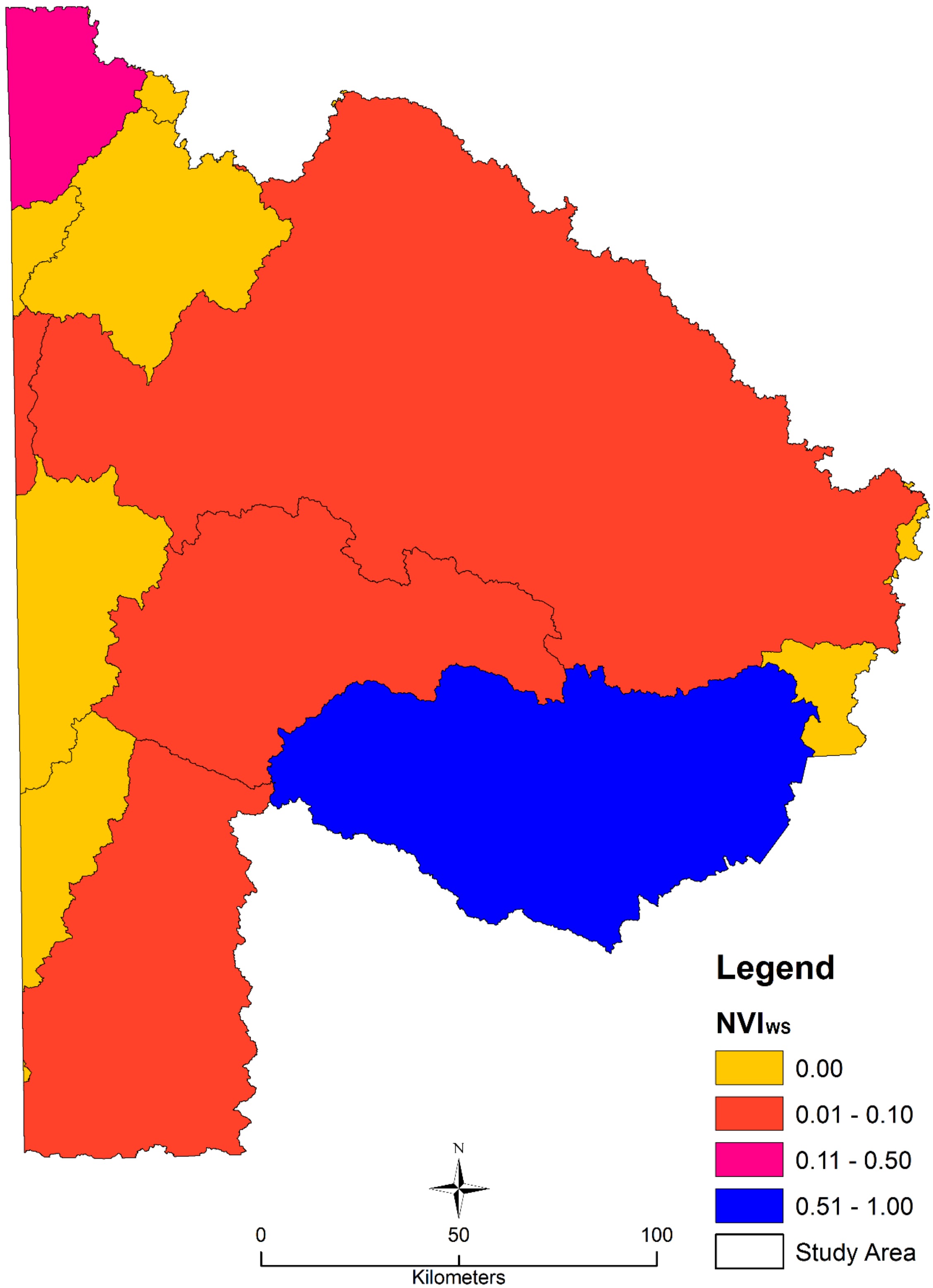

Figure 19 Normalized Vulnerability Index for watersheds given scenario 2B.

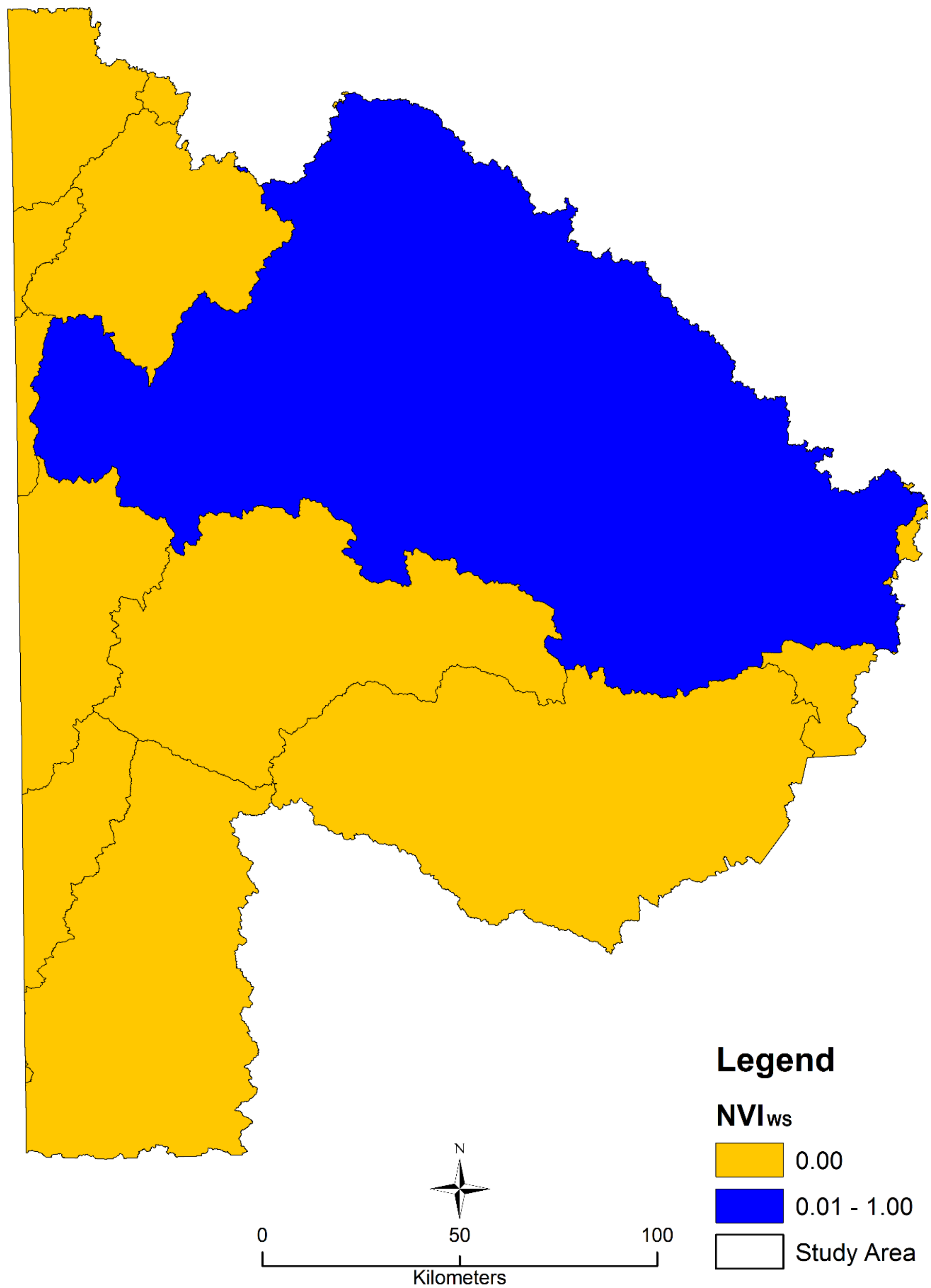

Figure 20 Normalized Vulnerability Index for watersheds given scenario 3D.

In figures 18 and 20 Lake Sakakawea is the most vulnerable watershed, while in figure 19 Lake Sakakawea is the third most vulnerable watershed after the Knife and Brush Lake Closed Basin watersheds. This displayed how the comparative vulnerability of watersheds can change based on the scenario. The number of impacted watersheds decreases with a decrease in spill size. In scenario 1A (figure 18) the Lake Sakakawea watershed has the greatest vulnerability (1.00) and is substantially more vulnerable compared to the next most vulnerable watershed which is the Lower Little Missouri watershed (0.29). This is different from scenario 2B (figure 19) where the Knife River watershed is the most threatened (1.00) and the next most threatened watershed is the Brush Lake Closed Basin watershed (0.47). All the other watersheds, including the Lake Sakakawea watershed, are not highly threatened under this scenario as they have a NVI_{WS} under 0.1. Under the scenario 3D (figure 20) only the Lake Sakakawea watershed is vulnerable due to the small size of the spill. Thus the spill would impact few waterbodies and have a low magnitude impact on this particular watershed ($VI_{ws} = 3.21 \times 10^{-7}$).

CHAPTER V

DISCUSSION

Sontag and Gebloff (2014) discuss three forms of spill that have occurred in North Dakota: leaking, spilling, and misting. The North Dakota Department of Health display in their Oil Field Environmental Incident Summaries that wells and facilities sites are a common location of origin for spills associated with oilfields (NDDH, 2016). There are some types of spills that are not modeled in this thesis; however, well site spills of frack fluid are a common spill type as evidenced by the many such incidents that can be found by searching though North Dakota Department of Health's Environmental Incident Summaries.

This thesis shows that several factors determine the impact of frack fluid spills. Waterbody size alters their vulnerability to frack fluid spills. Both the volume of a spill and the volume of frack fluid that infiltrates into the soil are important variables for determining the ability of spills to impact waterbodies. The topography of a landscape is also important for determining which waterbody will be impacted by a spill as spills may not impact the closest waterbody from a spill site.

Spill Pathways and Spill Entry Points

The spill pathways from independent wells often merge together as they get closer to the location where they will enter a waterbody. This is significant, because it allows for a single location to be the theoretical entrance point for frack fluid spilled from multiple wells. The entry points that would be impacted by spills from a high number of wells are more likely to be a location where frack fluid from a spill is most concentrated, regardless of waterbody size. These data can help optimize the location of water quality tests to search for contamination from frack fluid.

The length of the spill pathway is an important factor in determining the volume of soil infiltration along a spill path and therefore the likelihood that frack fluid from a specific well will reach a waterbody. This is important for determining the buffer distance between a well and a waterbody in order to protect the waterbody from a spill of a specific volume. There is variability in the buffer distance depending on the scenario of the spill. For a small enough spill any buffer can be sufficient, but a large spill would require a buffer that would potentially prevent all hydraulic fracturing. The successful buffer requirement ranges from 374m for a small spill to 8,048m for a large spill in this study. The variability of how the optimum buffer changes with the spill scenario combined with the fact that the larger the buffer the smaller the area allowed for hydraulic fracturing makes determining an optimum buffer size to legislate around every waterbody difficult. A large buffer would effectively protect waterbodies from most spills, but if it a large buffer was required around all of North Dakota's waterbodies, there would be very little area for hydraulic fracturing. A small buffer would allow hydraulic fracturing almost everywhere, but would largely be ineffective at protecting waterbodies from spills (Table 13).

Table 13 Buffer distance, percent of spills that waterbodies would be protected from, and the percentage of the study area outside the buffer zone under scenario 1A.

Buffer Distance (m)	Protected Waterbodies from spills (%)	% Area Available for Hydraulic Fracture
8,048	100	4.7
3,200	99.2	41.4
1,600	91.6	69.0
800	62.3	83.3
152.4	1.5	93.5
0	0	95.7

Vulnerability Index

The Vulnerability Index suggests that the largest variable in determining how vulnerable a waterbody is to the impacts of a frack fluid spill is its size. This is because there is greater variability in the size of waterbodies than variability in number of wells whose spills would impact a waterbody under any of the spill scenarios, or volume of spill. The area of waterbodies with Vulnerability Indexes above zero range from 4,537m^2 to 248,330,148m^2. This variability is much larger than the range between the greatest (163) and lowest (1) number of spilling wells associated with each waterbody, or the range between the largest (36,595m^3) and the smallest (12m^3) spill volumes associated with a single waterbody. This variability between the different components of the vulnerability indices utilized in this thesis are what mathematically makes the size of the waterbody have the largest impact on the associated Vulnerability Index. The size of a waterbody in determining how threatened a waterbody is to a frack fluid spill is important, because the results show that a small waterbody threatened by a single well can be more vulnerable than a larger waterbody threatened by a great number of wells. The vulnerability of small waterbodies is important for ranchers above the Bakken Formation in North Dakota. Bamberger and Oswald (2012) and Royte (2012) both discuss incidents where frack fluid contaminated small waterbodies used by ranchers for their livestock and the contamination resulted in injury and death to the impacted livestock. This loss of livestock and the use of the waterbodies on their property was financially expensive to the landowners whose waterbody was impacted. Though some small waterbodies are not used by North Dakotans, the impacts of frack fluid spills on small waterbodies can be very harmful to the people who use them.

The Vulnerability Index for the watersheds has a different result than the Vulnerability Index for the waterbodies since the largest watershed, Lake Sakakawea watershed, has the largest Vulnerability Index under two of the three displayed scenarios. In figure 20 under scenario 3D Lake Sakakawea is the most vulnerable watershed since it is the only threatened watershed. This is not surprising since it is the largest watershed and therefore under the scenario 3D where only two waterbodies are impacted by a spill, it is statistically likely that the impacted waterbodies will be within the Lake Sakakawea watershed.

In figure 18 the Lake Sakakawea watershed (1.00) is the most vulnerable watershed and has a substantially greater vulnerability than the next most vulnerable watershed, the Lower Little Missouri (0.29). The large volume of the waterbodies within the Lake Sakakawea watershed allows for the greatest dilution of spill, but it also allows for the greatest volume of spills and number of wells falling within its borders. The high vulnerability of the Lake Sakakawea watershed under the large spill scenario shows how a large enough spill volume and large number of wells can make up for the dilution ability within the Lake Sakakawea watershed and as a result even a large waterbody, or watershed as in this case, can be severely threatened by a large enough spill.

Figure 19 displays the spill scenario 2B where the most vulnerable watershed is the Knife River watershed and the Lake Sakakawea watershed is largely unthreatened with an NVI_{WS} under 0.1. This is different from the two scenarios displayed in figures 18 and 20, and is due to the ability of the Lake Sakakawea watershed to dilute spills that have a smaller volume. This is supported by the fact that the volume that impacts waterbodies under spill scenario 2B is 0.4 percent of the volume that impacts waterbodies under scenario 1A.

The size of the watersheds within the study area are variable due to a number of reasons. Some watersheds are larger than other watersheds. For example, despite the Lower Little Missouri watershed being the only watershed completely contained within the study area, the area covered by the Lake Sakakawea watershed within the study area is 365 percent greater than the Lower Little Missouri Watershed. It is also variable, because of the location of the study area contains varying percentages of the total size of a watershed. For example, only 3.1 percent of the Little Muddy watershed is contained within the study area while 96.9 percent of the Lake Sakakawea watershed is contained within the study area. One of the reasons why some watersheds are largely contained within the study area and others are not is due to the fact that the study area is limited by state and national boundaries in addition to natural ones. For example, the Lower Yellowstone watershed contains area above the Bakken Formation in both North Dakota and Montana; however, since the study area is limited to North Dakota the area of the Lower Yellowstone watershed outside North Dakota is excluded. A result of the variability of the size of watersheds within the study area is that there is a strong correlation ($r = 0.93$ $p > 0.01$) between the size of a watershed and the number of wells that can spill into the waterbodies within the watershed under scenario 1A. This is significant in relation to the watersheds that have large percentage of their area outside of the study area, because they may also be severely threatened by spills, but the majority of the threat to the watershed may occur outside the study area and therefore not be included in this thesis. As a result, this study may underestimate the vulnerability of watersheds that are largely outside of the study area.

The largest watershed contained the greatest number of spilling wells and the largest volume of spilled frack fluid due to its large size and location. The largest waterbody, Eastern Lake Sakakawea, was not threatened by spills from any wells due to being east of the line of death. The second largest waterbody, Northern Lake Sakakawea, received the greatest volume of frack fluid from the greatest number of spilling wells and is compared to the Lake Sakakawea watershed in Table 14. A much larger percentage of the total volume of frack fluid that could be spilled and total number of spilling wells is associated with the Lake Sakakawea watershed compared to Northern Lake Sakakawea; Northern Lake Sakakawea is better able to dilute spills than the Lake Sakakawea watershed under spill scenario 1A. Additionally, there are smaller waterbodies that are heavily impacted by spills within the Lake Sakakawea watershed as exemplified by the fact that six of the 10 waterbodies with the greatest NVI_W are within the Lake Sakakawea watershed and three of the remaining 10 most threatened waterbodies are within the Lower Little Missouri watershed, which has the second highest NVI_{WS}. This is why, despite its large size, the Lake Sakakawea watershed is unable to dilute its associated spills and has a large NVI_{WS}, while Northern Lake Sakakawea can dilute its associated spills and has an NVI_W under 0.1.

Table 14 Comparison of spilling wells and volume of frack fluid spilled between the largest threatened watershed and the largest threatened waterbody.

Name	Spilling Wells	Percentage of Total Spilling Wells	Spilling Volume (m^3)	Percentage of Total Spilling Volume
Lake Sakakawea watershed	900	77.0	209,265	73.9
Northern Lake Sakakawea	163	14.0	36,595	12.9

State and National Parks

North Dakota contains state parks, national parks, and national historic sites. Within these lands hydraulic fracturing is prohibited and as a result they do not contain any hydraulic fracturing wells within their boundaries. That does not prevent these lands from being vulnerable to spills. In four separate locations, spill pathways enter the Theodore Roosevelt National Park and three of those four spill pathways enter the Little Missouri River within the national park. The fourth spill pathway enters the Little Missouri River approximately 260m outside the national park. The three spill pathways that end within the national park are associated with 60 wells, though none of the wells are modeled to impact the Little Missouri River under any of the 12 modeled spill scenarios. The fourth spill pathway is associated with four wells as it travels through the national park though it too is not modeled to impact the Little Missouri River under any of the 12 modeled spill scenarios. Two of the spill pathways enter the Little Missouri River in the North Unit and two enter in the South Unit of the Theodore Roosevelt National Park (Figures 21 and 22).

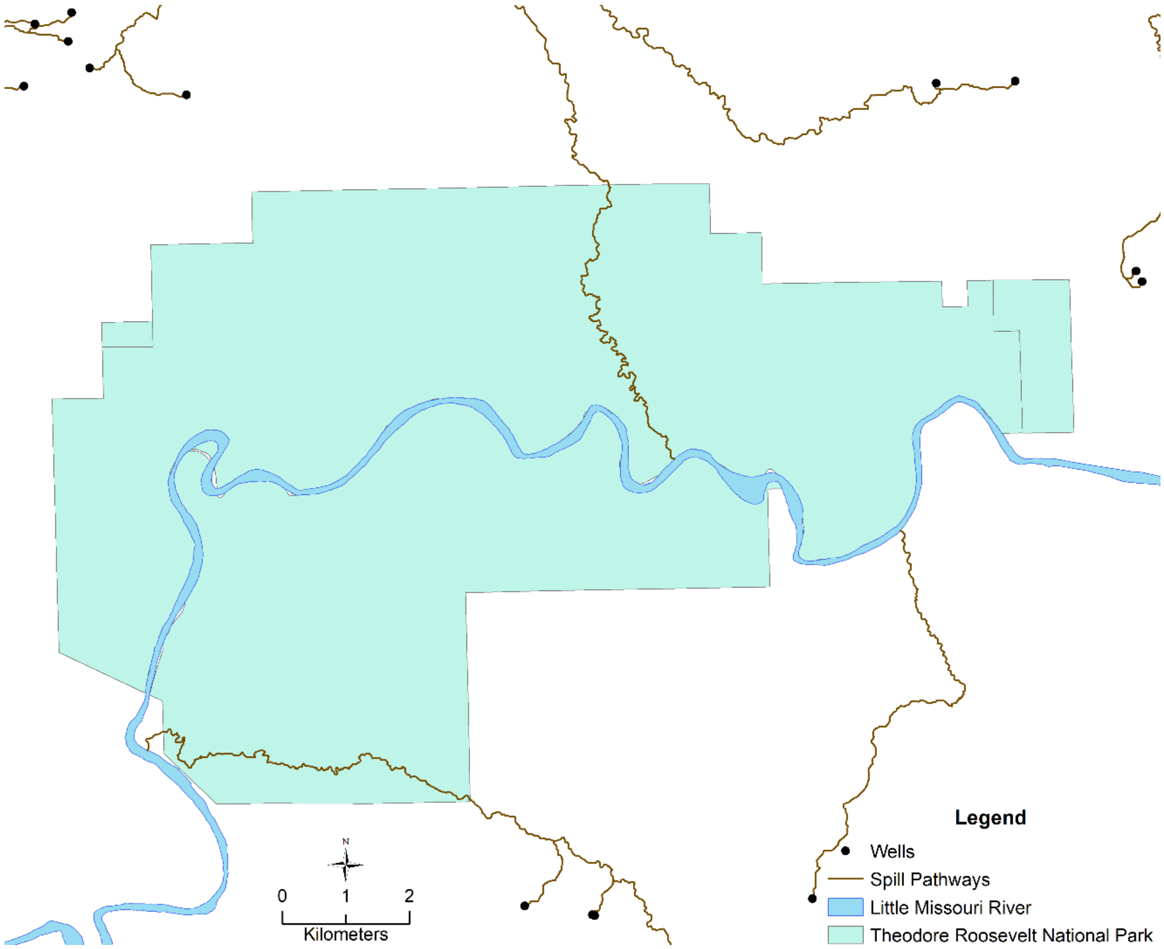

Figure 21 Wells and spill pathways around the North Unit of Theodore Roosevelt National Park and the Little Missouri River.

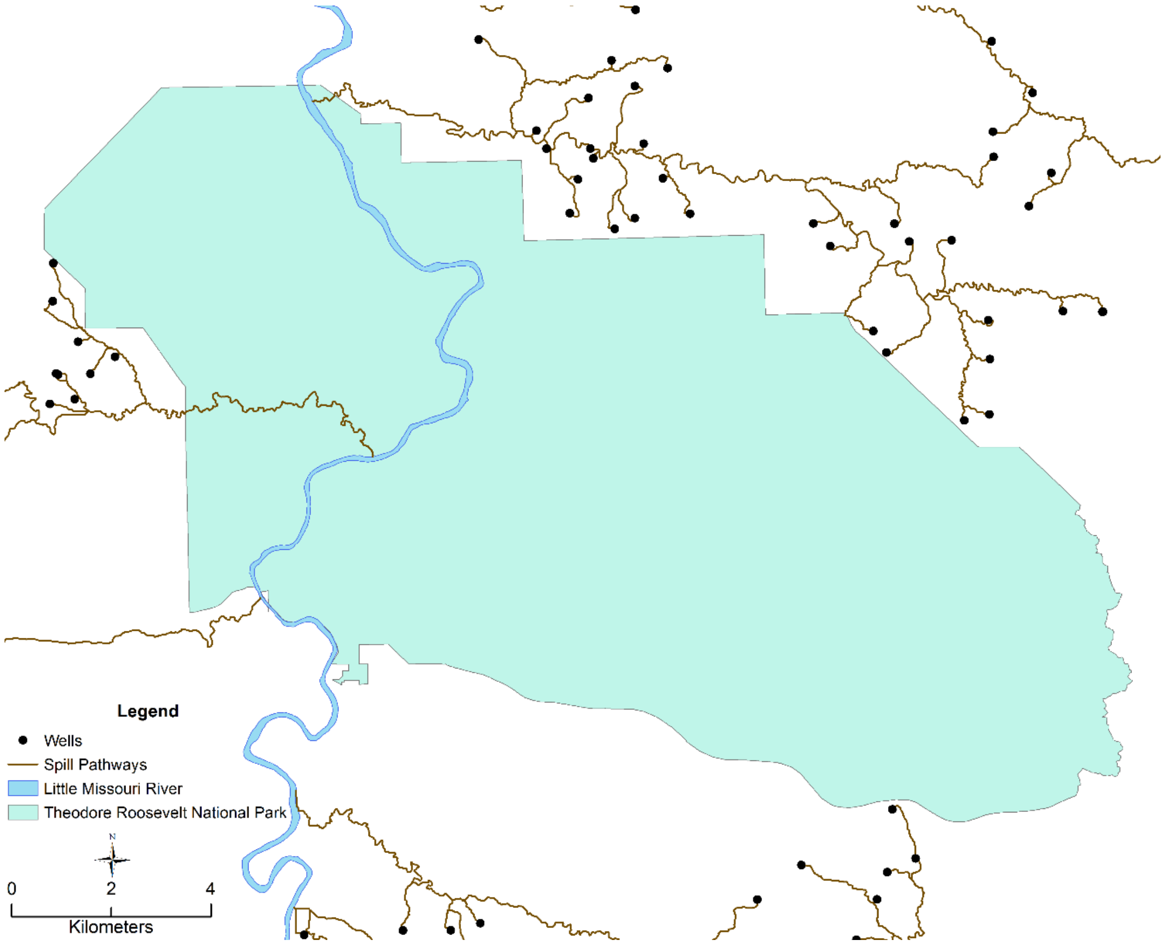

Figure 22 Wells and spill pathways around the South Unit of Theodore Roosevelt National Park and the Little Missouri River.

There are seven different spill pathways that travel through state parks; four travel through Lewis and Clark State Park, two travel though Little Missouri State Park, and one spill pathway travels through Sully Creek State Park. Three of the spill pathways end within a state park, twice within Lewis and Clark State Park and once within Sully Creek State Park. The spill pathway that ends within Sully Creek State Park ends at the Little Missouri River, is associated with 31 wells, and would not impact a waterbody under any of the 12 modeled spill scenarios. The two spill pathways that end in Lewis and Clark State Park, end within Northern Lake Sakakawea and are associated with 12 wells, none of which of would impact Northern Lake Sakakawea under any of the 12 modeled spill scenarios. The remaining two spill pathways that impact Lewis and Clark State Park both end within 230m from Northern Lake Sakakawea and are associated with 43 wells (Figure 23). Wells spilling along one of those spill paths could impact Northern Lake Sakakawea under scenarios 1A and 1B. The two spill pathways within the Little Missouri River State Park are associated with 241 wells, none of which would impact Sothern Lake Sakakawea under any of the 12 modeled spill scenarios.

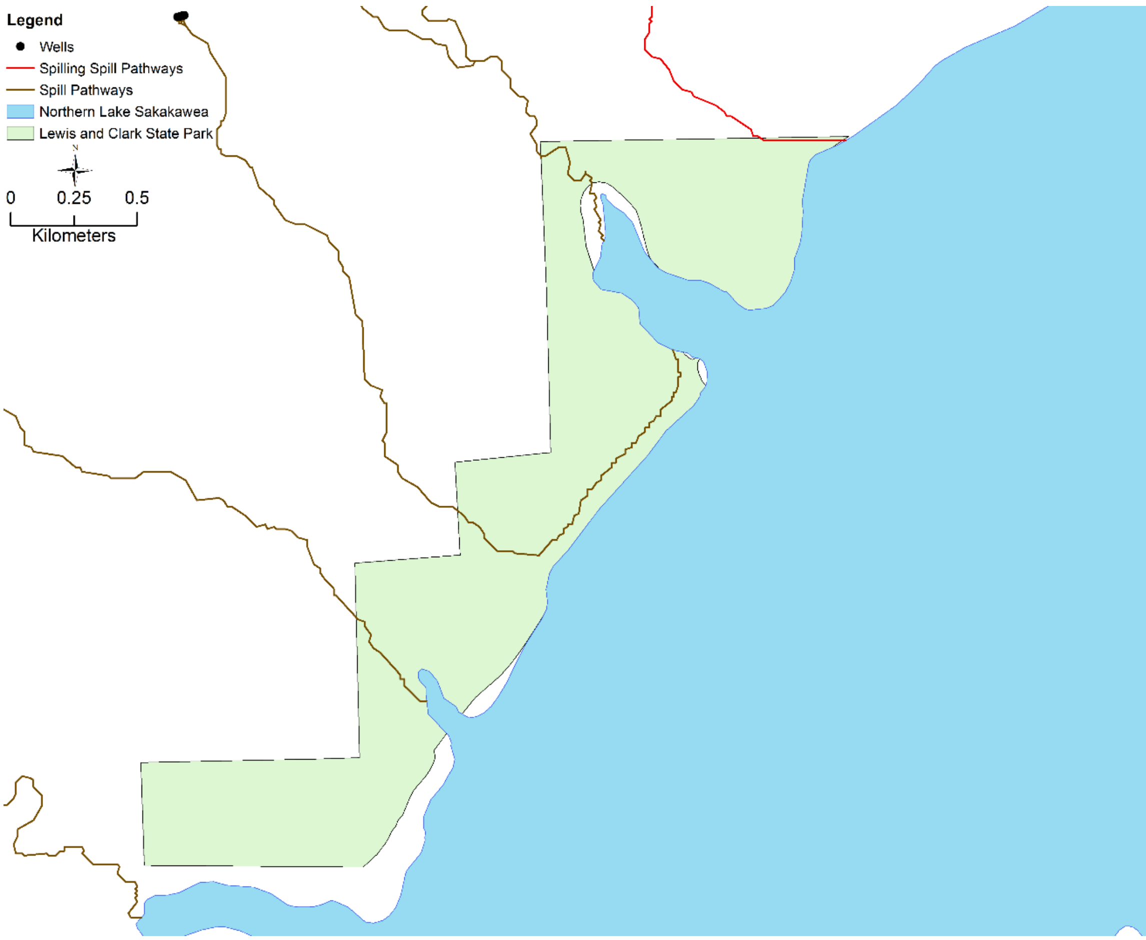

Figure 23 Wells and spill pathways around Lewis and Clark State Park including Northern Lake Sakakawea.

Policy Recommendations

The results of this study can be used to facilitate policy decisions related to hydraulic fracturing. Small waterbodies are more vulnerable to spills, but larger waterbodies are more likely to be impacted by a spill since a greater number of wells have the ability to threaten a larger waterbody. The larger waterbodies in North Dakota, such as Lake Sakakawea, are used by more people and therefore spills that impact them may cause harm to more people. There is also more support for people who are harmed by spills into large waterbodies that many people use. This was exemplified in Montana when 190m^3 of crude oil spilled into the Yellowstone River near Glendive, Montana and impacted municipal water systems that utilized the Yellowstone River as its water source. The owner of the pipeline that spilled provided pallets of clean bottled water to the impacted areas to mitigate the impacts of the spill on the local residents (Schweber, 2015). The emergency services that were provided to the localities that were impacted by the aforementioned spill, are not usually provided to individual landowners who have a small waterbody on their property for their use as a water source for themselves and their livestock. For example, when Jacki Schilke was concerned about hydraulic fracturing spills making a creek on her property toxic for her cattle to drink, she was forced to spend $4,000 of her own money to buy safe water (Royte, 2012).

Areas that are protected from hydraulic fracturing within their boundaries can still be impacted by hydraulic fracturing. This is displayed in figures 21-23 which show spill pathways that travel through Theodore Roosevelt National Park and Lewis and Clark State Park prior to reaching a waterbody. Frack fluid spills also impact the land they travel over, so any property through which a spill pathway travels can theoretically be impacted by a spill from outside its boundaries. This concept of the ability of spills to travel from areas where hydraulic fracturing is allowed into areas where it is forbidden is also significant for landowners within North Dakota. Even in situations where a landowner both chooses to and is able to completely prevent any hydraulic fracturing from occurring on his property, his property can still be harmed by hydraulic fracturing spills that occur on neighboring properties.

This leads to two policy recommendations:

1. Legislate a large buffer around the large waterbodies that are used as municipal water sources and do not allow anyone the ability to override these buffers as is currently allowed (NDIC, 2014A). This study finds that buffer of a minimum of eight kilometers is optimum in order to provide the maximum protection for waterbodies; however, a 3.2 kilometer buffer is sufficient to protect waterbodies from 99 percent of spills. Though these waterbodies are large enough that they can dilute most spills, lowering the quality of those waterbodies potentially harms large numbers of people.
2. Give landowners additional protections from damages done to their property by eliminating any laws, such as statute of limitations, that limit the liability of the mineral developers who cause the damage. For situations where it is impossible to pinpoint which specific well is the source of degradation to a landowner's property, allow the liability to be shared by all possible mineral developers who may have caused the spill as opposed allowing the mineral developers to escape liability due to being able to claim it may have been a different mineral developer who caused the damage. After a landowner proves via independent testing that chemicals that are utilized in hydraulic fracturing have degraded their property require nearby hydraulic fracturing companies to prove they are not the cause of the toxic chemicals on the landowner's property in order to avoid liability for the degradation of the property. This will make it easier for landowners to receive compensation for damage to their

property and especially their waterbodies since these waterbodies are frequently small, a small spill can do severe damage to the water quality of these waterbodies. This is especially important in North Dakota since mineral rights and land rights are separate, so a landowner may not receive royalties associated with a spill that damages his waterbody.

The ability to model how frack fluid spills travel and where they will enter into a waterbody is very useful for policy. The locations where greater volumes of frack fluid are able to enter a waterbody, especially a major waterbody, are the locations that should be tested for spills. In large waterbodies a spill can easily be diluted and if the wrong location is tested, a false negative may be produced that hides the damage that was done to a waterbody. This method can also be used when testing soil for spills since the likely pathway that a spill will take is known. The theoretical spill pathways can also be utilized in order to manage the risk associated with allowing each well on a case by case basis. By modeling where a theoretical spill from a well is likely to travel the Industrial Commission can perform a risk characterization for each well site to avoid permitting wells in areas where spills are likely to impact important waterbodies, or valuable agricultural land.

CHAPTER VI

CONCLUSION

Waterbody vulnerability changes depending on the various spill scenarios described in this thesis, under spill scenario 1A the most vulnerable waterbody is a small waterbody approximately 21km west of Mid Lake Sakakawea and 12km north of the Little Missouri River (Figure 13). The waterbody most likely to be impacted by any given spill was Northern Lake Sakakawea. The entry point with the largest associated spill volume impacts Southern Lake Sakakawea and the most vulnerable watershed was the Lake Sakakawea watershed. Under the scenario 1A, despite it being the largest spill scenario, only 10.2 percent of the wells were modeled to impact a waterbody though that 10.2 percent consists of 1,168 wells (Figures 24-25). This exemplifies one of the issues associated with hydraulic fracturing in North Dakota, that due to the large number of wells being utilized, even a small percentage of them equates to over 1000 wells potentially causing problems due to spilling.

Pathways traveled by frack fluid spills from different well sites will intersect prior to reaching a waterbody. This will make some entry points more vulnerable to a spill than others and these more vulnerable points will make optimum testing points to determine if a frack fluid spill has impacted a waterbody.

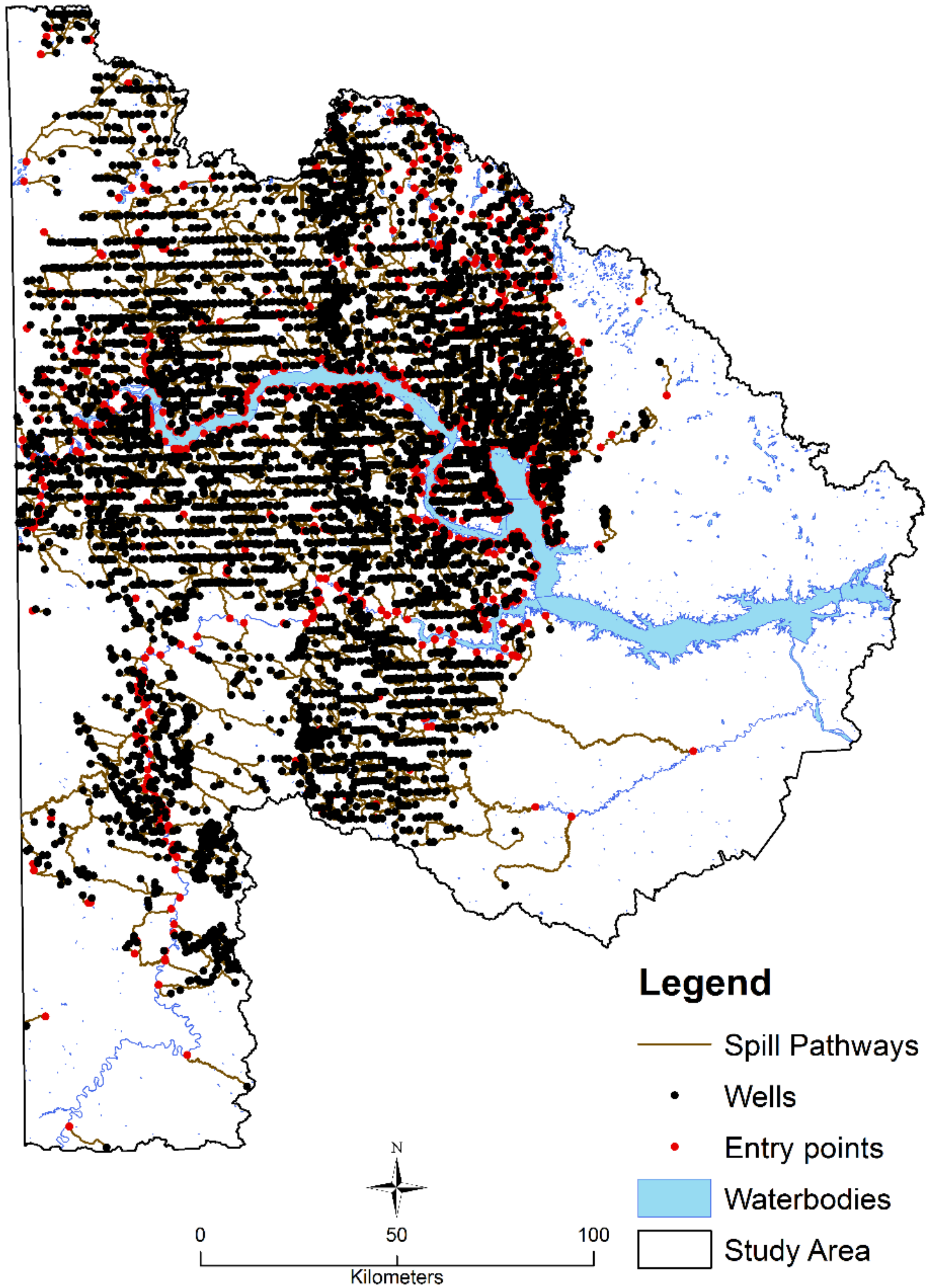

Figure 24 Spill pathways, wells, entry points, and waterbodies within the study area.

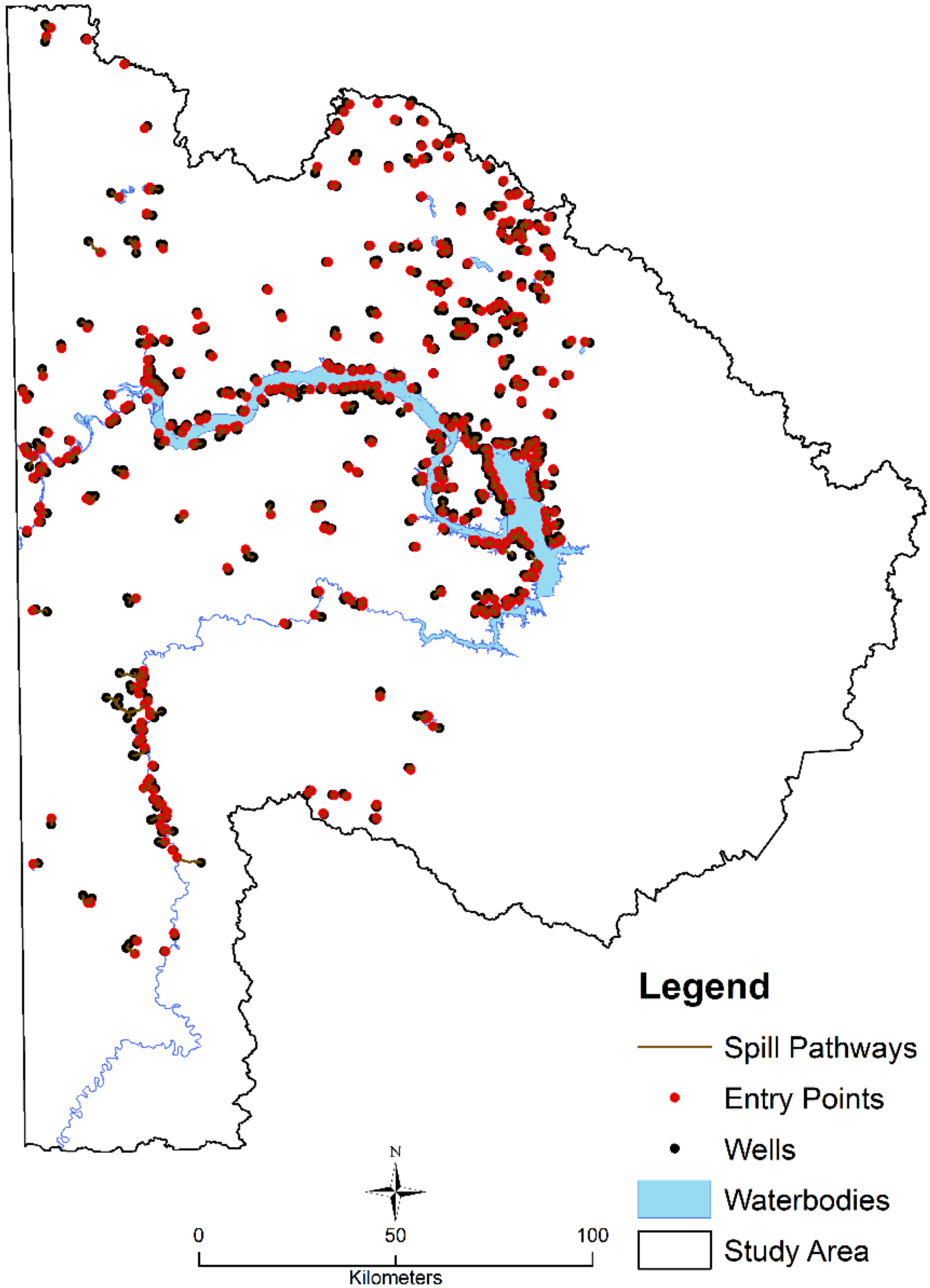

Figure 25 Spill pathways, entry points, wells, and waterbodies that would be associated with spills under scenario 1A.

The ability of soil to hold frack fluid is significant for determining if a frack fluid spill is likely to reach a waterbody. The greater the ability of the soil along a spill path to hold frack fluid the less likely it is for a spill to impact a waterbody. However the soil that the frack fluid infiltrates into will be degraded by the frack fluid. Additionally, any ground water near the spill path may also be impacted, although this study did not take that into account.

Large waterbodies are more likely to be impacted by a spill due to more wells being likely to spill into a large waterbody; however, small waterbodies are more vulnerable to the impacts of a spill since they have less ability to dilute spills. The ability of small spills to do substantial harm to a small waterbody makes landowners who utilize small waterbodies on their property especially susceptible to economic and health issues.

Limitations

Due to the resolution of the available data a generalized model was created for this thesis as opposed to a high resolution model. The model was heavily based off a 1/3 arc-second DEM. This resolution was used, because it was the best resolution available for the entire study area. If a DEM with a greater resolution had been available it would have allowed for the spill pathways to be more accurate. This increased accuracy would not only include the path the spills travel, but also their widths. A high resolution DEM would have been able to be used to find the widths of the spill paths in a much more accurate manner than was used. If a reader wishes to perform a similar study it is recommended to acquire a DEM of a greater resolution than was used in this study.

The actual percentage of soil volume that is able to hold frack fluid can be less than 25 percent of the maximum value for soil infiltration though 25 percent was the lowest value calculated in this study. For example, the soil can be saturated with water from rain preventing the soil from being able to hold frack fluid, or the ground can be frozen and a layer of snow and ice will buffer the soil from frack fluid preventing soil infiltration of frack fluid.

Relying on soil infiltration of frack fluid as a method to protect waterbodies is not safe, not only due to the variability of soil characteristics in holding frack fluid, but also because of the harm frack fluid does to soil and groundwater. Frack fluid can kill both natural and agricultural species of vegetation and situations have occurred where spills have rendered cropland useless in North Dakota (Adams 2011; Sontag and Gebloff, 2014). As a result, the best method for protecting waterbodies from spills is a regulatory structure that prevents spills from occurring.

The waterbody shapefiles used in this study were acquired from SSURGO. Despite the quality of the SSURGO waterbodies, there were areas where there are waterbodies in reality that were not displayed in the SSURGO dataset. Some of these waterbodies may be impacted by spills from wells, but as they were not displayed in the SSURGO data they were not included in this study. This created false positives where waterbodies were only impacted by spills in this study because the waterbody that would be impacted by a spill was not displayed. This is especially impactful for the smaller waterbodies that are associated with a smaller number of wells and the wells that have longer spill paths who may be associated with a waterbody that is not displayed by SSURGO. Additionally, some of the waterbodies that were displayed may be ephemeral which could lead to different results on a seasonal scale. If a reader wishes to perform a similar study it is recommended to acquire high resolution areal imagery of the study area and to digitize, or classify all the waterbodies to create more accurate shapefiles for the locations of waterbodies as of the date the areal imagery was taken.

There were limitations associated with the study area definition. There were wells that were deleted due to spilling outside of the study area. These wells were modeled to spill into Montana, Canada, and areas of North Dakota outside of the study area, though a well spills outside of the study area it may still impact North Dakota. For example, some of the wells that spill into Montana may impact the Yellowstone River which flows into North Dakota.

The soil infiltration of frack fluid is an important component of this study and it relied on the SSURGO data to find the depth of the soil and the percentage of soil volume that could hold frack fluid. Though these values can neither be confirmed nor denied by the author, it is likely that there is some level of error within the values that were used. If a reader wishes to perform a similar study it is recommended to acquire independent data about the depth of the soil and the ability of the soil to hold frack fluid that is at a greater resolution and more accurate than the SSURGO data.

There were also technology based limitations associated with creating the length of the spill pathways. These limitations were both associated with the quality of the computers utilized in this study and the quality of ArcMap 10.2. Running an individual spill pathway from each well site to its associated waterbody is a very time consuming process utilizing the technology the author had available. This limitation made it difficult for the author to double check results from these spill pathways and these spill pathways were important parts of this study. Had the author had access to technology that would allow for the creation of the spill pathways at a much faster speed it would have allowed for processes to be completed to increase the accuracy of the spill paths. The time it took to run the process that created the spill pathways would have been even longer with a higher resolution DEM. If a reader wishes to perform a similar study the reader should be aware of the processing time associated with creating individual spill pathways and the higher the resolution of the DEM that is used to create the individual spill pathways the longer the process will take.

The author recognizes the limitations associated with how this study was conducted and the data used within this model. The author also stands by the accuracy of the general conclusions of this study such as which waterbodies are vulnerable to the spills from the greatest number of wells, that smaller waterbodies, due to their small size and associated lack of ability to dilute spills, are the most vulnerable to the impacts of a spill should a spill occur, and that spills that occur on properties where hydraulic fracturing is permitted can degrade properties where hydraulic fracturing is forbidden.

As a result of these limitations the uncertainty was calculated focusing on the width of the spill pathways as that dataset contained the greatest level of uncertainty. The volumes calculated in this study had an uncertainty of 10.2 percent.

Future Research

Multiple types of related research can be done based on this study. Future investigators could use better technology and data than are currently available. Applying this methodology 10 years from now using high resolution DEMs and more accurate soil and waterbody data that will hopefully be created within that time frame would create a more accurate model of the spill pathways, soil infiltration, and vulnerability indices based on the wells that will be active 10 years from now.

Other studies could apply this method to currently available data to assess frack fluid spills from pipelines, as pipelines are also a source for spills. The largest frack fluid spill on record in the North Dakota Department of Health's list of Oilfield Environmental Incidents occurred on January 7, 2015. It was a spill of 11,129m^3 from a pipeline in Williams County, North Dakota (Stockdill et al., 2016). Pipeline spills are fairly common and can be of greater volumes than well site spills (NDDH, 2016). A study investigating the impact of pipeline spills on waterbodies may produce useful results to be used in determining where to safely lay pipelines that are to carry hazardous materials.

Future studies performed with the Vulnerability Index from this study can compare the vulnerability of the waterbodies and watersheds in this study to the vulnerability of waterbodies and watersheds at other times and places. Such comparisons will help determine if the waterbodies and watersheds that have the highest Vulnerability Index in this study have high vulnerability relative to other locations and time periods.

While frack fluid is a common product that can spill due to hydraulic fracturing, crude oil has also spilled. For example, 3,275m^3 of oil leaked from a pipeline in Williams County, North Dakota on September 29, 2013 (Harries, 2013). Oil does not infiltrate into the soil in the same manner as a water-based solution such as frack fluid. As a result, a separate methodology would have to be created by a future researcher to model how much oil could infiltrate into the soil in order to determine how vulnerable different waterbodies are to oil spills. Modeling oil spills in a similar manner to how this study modeled frack fluid spills would provide results that could be utilized to help protect waterbodies from oil spills.

Sontag and Gebeloffa (2014) indicated that large volumes of frack fluid and oil mist into the air. A study modeling how mists associated with hydraulic fracturing spills, especially from wastewater ponds, would travel could protect air quality. Such a study could lower the chances that hydraulic fracturing will degrade the air quality around a sensitive area such as a school, or hospital.

If a well or pipeline spills, whether it be frack fluid or oil, it threatens the surrounding area. A study that models the areas where a spill, could occur would be useful in determining what areas are most vulnerable to a spill. Such modeling is important to minimizing threats from spills associated with mineral development to important agricultural areas in North Dakota.

Under the current regulatory structure over 1,300 spills occurred within the last year. A study on how to improve the regulatory structure in a manner that maximizes the state's compensation for spills and minimizes the likelihood of spills would help protect North Dakotans from suffering the consequences of spills from hydraulic fracturing.

GLOSSARY

Calcite: Calcite is calcium carbonate ($CaCO_2$) and is a mineral that is usually lightly colored such as white (UMDOG, 2014a).

Chorizon: The name of a table from the SSURGO dataset that contained the columns hzepb_r and wsatiated_r.

Cokey: A column from the SSURGO table component which was the key required to join the SSURGO polygons with the chorizon table.

Component: The name of a table from the SSURGO dataset that contained the column cokey.

Confidential wells: Confidential is a legal status for a well in North Dakota that means for six months following the completion of the well the only information about the well that can legally be released by the state is name the operator, the well name and location, the spacing or drilling unit description, spud date (when they commenced drilling), the rig contractor, and any production runs (oil sold) from the well (NDOGa, 2014).

Cryptorchidism is a birth defect where one or both testicles have not moved into the scrotum prior to birth (Mayo Clinic Staff, 2013).

Depocenter: Depocenter is the area of a formation with the maximum deposition, or the thickest portion of a stratigraphic unit in a depositional basin (Jackson et al., 2005).

Feldspar: Feldspar is a class of aluminum containing silicates which are the most common mineral on the Earth (Hyperphysics, 2014).

Field Capacity: Field capacity is the volume of water that remains in soil a few days after it is wetted and after drainage has stopped (Cornell, 2010).

Flocculent: Containing or made up of small particles that have been aggregated together (Farlex, 2011).

Hypospadias is a birth defect in males where the opening of the urethra (the tubes that carries urine from the bladder to outside the body) is not located at the end of the penis (CDC, 2014).

Hzdepb_r: A column from the SSURGO table chorizon that contained the representative value for the distance from the top of the soil to the base of the soil horizon and was the soil depth.

Lineament: Lineaments are topographic features that is believed to reflect the underlying geologic structure (Dictionary.com, 2014).

Microannulus is a small gap that can form between a casing and the surrounding cement (Schlumberger, 2014).

Muaggatt: The name of a table from the SSURGO dataset that contained the column muname.

Muname: A column from the SSURGO table Muaggatt that contained the soil type for each polygon. Among the soil type categories were water, water intermittent, and water miscellaneous, these were the polygons that were used as waterbodies in this thesis.

Pour Point: The lowest point in a watershed that all the fluid within the watershed travels towards.

Pyrite: Pyrite is iron sulfide (FeS_2) and is the mineral that has been called fool's gold due to being gold colored when untarnished (UMDOG, 2014b).

Second order tributary is what is created by the combination of two small streams into one larger stream (WJU, 2004).

Sweetgrass arch: The sweetgrass arch was a large structural complex located in northwestern Montana, southeastern Alberta, and southwestern Saskatchewan that was active at the time the upper and lower Bakken members were formed (Kent and Christopher, 1994).

Wsatiated_r: A column from the SSURGO table chorizon that the contained the representative value for the estimated volumetric soil water content at or near zero bar tension, expressed as a percentage of the whole soil.

Zonal isolation is the exclusion of substances such as water or gas in one section from mixing with the substances in another section (BLT, 2014).

APPENDIX

APPENDIX A

Study Area Creation

1. Preparing the DEMs for analysis

A. The Fill tool was used on the DEM to find and correct any inaccuracies. The Fill tool removes sinks in the DEM which are areas of the DEM that have artificially low elevations. Had the sinks not been filled they could have impacted the analysis of the spill pathways by causing the spill pathways to take an incorrect path following a faux sink, or even ending the spill pathways early in a faux sink.

B. The Flow Direction tool was then used on the filled DEM. The Flow Direction tool finds the direction that a liquid would flow from each pixel on a DEM based on the elevation of that pixel and the elevation of the surrounding pixels. Knowing where a liquid would travel from one pixel to the next was a requirement for this study, because that information was used to model how the spill pathways would travel from the pixel containing the well sites, pixel by pixel, to the pixel containing the surface waterbodies.

2. Determining the Missouri River watershed within the North Dakota Bakken Formation

A. The Flow Accumulation tool was used with the flow direction raster for the entire study area. The Flow Accumulation tool creates a raster where each pixel is given the value of the sum of all the pixels combined whose flow reach that pixel. For example, if three pixels flow into one pixel and that pixel flows into another pixel, that last pixel would have a value of four. This was done in order to find the location within the North Dakota Bakken Formation that had the largest flow accumulation pixel value. That point was required, because it was the optimum pour point location to delineate the Missouri River watershed within the North Dakota Bakken Formation. Once that point was found a new pour point created by the author at that location.

B. This pour point, along with a flow direction raster of the entire study area, was input into the Watershed tool to create the Missouri River watershed that was used for this research. The Watershed tool operates by taking the pour point, which is the point that the entire watershed flows into, and creates a raster file for the entire area that flows into that pour point.

C. The Raster to Polygon tool was used to convert the Missouri River watershed from raster to vector format. The shapefile of the Missouri River watershed was used to establish the study area for this section of the study.

D. The Intersect tool was used to find the areas where the Bakken Formation, North Dakota, and Missouri River watershed shapefiles overlapped. This shapefile was the shapefile of the study area that was used throughout this thesis. Intersect tool combines shapefiles where they overlap into a single shapefile that has the attributes of both shapefiles in its attribute table.

SSURGO Organization

1. The first Join done was of the component table to the polygons, because the component table contained both a “mukey”, which allowed for it to join with the SSURGO polygons, and a “cokey” which is required for the “chorizon” table to join with the SSURGO polygons.

2. The “muaggatt” table was joined to the SSURGO polygons using its “mukey”. The “muname” column, which was contained in the “muaggatt” table, provided soil type and included the categories of water, water intermittent, and water miscellaneous. The SSURGO polygons that were associated with these water files were exported and used as the surface water polygons for this study.
3. The “cokey” that joined with the SSURGO polygons from the component table was used to Join the “chorizon” table with the SSURGO polygon. The “chorizon” table contained the “hzdepb_r” column which was the representative value for the distance from the top of the soil to the base of the soil horizon and was the soil depth that was used in this study. The “chorizon” table contained the “wsatiated_r” column which was the representative value for the estimated volumetric soil water content at or near zero bar tension, expressed as a percentage of the whole soil; this is the percentage of soil volume that could hold frack fluid that was used in this study.

Modeling Entry Points of Spills into Waterbodies

The spill pathways were modeled in this study twice. The methodology for modeling the spill pathways below was done in order to fulfill one of the objectives of this study: to model the pathway a frack fluid spill would take from the well site to a surface waterbody and to model the number of wells which would enter a waterbody at each entry point.

1. Preparing the DEMs for analysis

A. The Extract by Mask tool was used on the DEM with the study area shapefile to extract the areas of the DEM that were within the study area. The Extract by Mask tool extracts pixels from a raster file that are overlapped by another file. This was done, because the DEM was larger than the study area and the portions of the DEM that were outside the study area served no purpose for the study. Additionally, by subsetting the DEM to the study area it increased the speed of the ArcMap tools that utilized the DEM which saved time.

B. The Erase tool, a vector based tool that allows one vector to be used to delete the overlapping area from a different vector file, was used to erase the waterbodies from the study area shapefile to create a shapefile that contained the study area with the waterbodies deleted from it. This new shapefile was necessary in order to create a flow direction raster that did not contain any surface waterbodies.

C. The Extract by Mask tool was then used on the flow direction raster to extract the areas of the study area that were dry land by using the previously created shapefile (from part B). This created a flow direction raster with null values where the waterbodies occurred. The removal of the waterbodies from the flow direction raster prevented the modelled spill pathways from flowing through multiple waterbodies and instead ended the spill pathways at the first waterbody the spill pathway contacted. In reality a frack fluid spill could spill from one surface waterbody into another surface waterbody; however, the surface waterbody that would sustain the highest concentration of frack fluid would be the first surface waterbody impacted. As a result, the first waterbody was the only surface waterbody that was considered to be impacted by a spill in this study. The Flow Accumulation tool used the flow direction raster to create spill pathways and when it reached a null flow direction value it stopped running. If the spill pathways have been allowed to travel through surface waterbodies it would have caused an error in this study as it would have allowed individual wells to spill into multiple waterbodies. This new flow direction raster is the one that was used throughout this study.

2. Calculating spill pathways from wells to waterbodies

A. The Extract by Mask tool was used with the wells shapefile on the filled DEM to extract the location of the wells in raster format in order to be used in the Flow Accumulation tool.

B. The Flow Accumulation tool was used on the flow direction raster with the raster well locations used as the input weight raster. Using the raster wells as the input weight raster made the Flow Accumulation tool start its count of how many pixels would flow into another pixel from the well locations and excluded every other pixel from its analysis. This process created the first set of spill pathways used in this study: the Flow Accumulation tool started from the well site and modeled, pixel by pixel, what pixel the previous pixel would flow into until it reached a null value in the flow direction raster. The null value corresponded to the location of a surface waterbody. This was one of the key pieces of information for this study.

C. The Raster to Polyline tool was used to convert the spill pathways from raster to vector format. This was done, because the spill pathways were needed in vector format in order to perform further analysis such as computing how many wells would spill into each surface waterbody. This satisfies a portion of the first objective of this study.

3. Organizing the spill paths

A. The Buffer tool was then used to create a polygon file around the spill pathways that contained all the spill pathways as one object. The Buffer tool creates a polygon file around other vector files and also allows the new polygon file to be formatted as a single object regardless of the number of objects in the vector file that were buffered. This was done because the vector spill pathways created by the raster to polyline tool had many more objects than there were spill pathways. Performing the buffer on the spill pathway polylines was the first step in the process of converting each individual spill pathway into a single object within the spill pathway shapefile. The buffer was required specifically, because the polylines needed to be converted to polygons for later use.

B. The polygon created by the Buffer tool was then input into the Multipart to Singlepart tool which separated out each individual spill pathway as separate objects and provided a distinct number for each spill pathway. The Multipart to Singlepart tool takes a polygon that has individual objects that contain multiple polygons that do not intersect and makes each polygon a single object.

C. The Intersect tool was used with the original spill pathway shapefile and the polygon that contained each distinct spill pathway from the Multipart to Singlepart tool. This was done to combine the spill pathways with the result of the Multipart to Singlepart tool, so that each object that was a segment of a spill pathway had in the attribute table a corresponding number associated with its distinct spill pathway from the single to multipart polygon. This was done to create a new polyline file that could be dissolved and have each spill pathway be a distinctive object.

D. The Dissolve tool was used based on the corresponding numbers associated with each spill pathway that originated from the Multipart to Singlepart tool to create a line shapefile that had each individual spill pathway as a separate object. The Dissolve tool combines objects within a single shapefile together based on a specific attribute. This was the final step in creating a shapefile where each spill pathway was a distinct object in order to analyze how many wells would spill into each surface waterbody.

4. Calculating the number of wells that flow into waterbodies

A. A Spatial Join was used to connect each spill pathway to the associated wells and count the number of wells associated with each spill pathway. The Spatial Join took each spill path and looked for all the wells that were closer to that spill path than any others and then summed all those wells together to provide the total number of wells that were associated with each spill path. This was done, because the number of wells associated with each spill pathway was needed to calculate how many wells would enter into each waterbody at a single point and the total number of wells that would spill into each waterbody within the study area. It was also used to determine which wells would spill outside of the study area and those 869 wells and associated spill pathways were deleted.

B. The Polygon to Line tool was used to convert all the waterbodies into lines. The Polygon to Line tool converts polygon shapefiles into lines by taking the outline of the polygon file and converting that into a line shapefile. The Polygon to Line tool was used to prepare data for the Extend Line tool, since the Extend Line tool requires all the data it uses to be in line format.

C. The Merge tool, which combines multiple shapefiles into a single shapefile, combined the waterbody lines with the spill path lines. This was done because the Extend Line tool needed both shapefiles to be combined into a single line shapefile in order for it to extend the spill path lines until they intersected with the surface waterbody lines.

This was due to the fact that since the surface waterbodies were vectors and the spill pathway lines were created using rasters, many of spill pathway lines did not intersect with the surface waterbody polygons.

D. The Extend Line tool was used on the merged waterbodies and spill pathways line shapefile to make the spill paths intersect with the surface waterbodies. The Extend Line tool takes line objects and lengthens them in a straight line until they reach a perpendicular line. This was done, because in order for a Spatial Join to be run between the spill pathways and the surface waterbodies, the spill pathways had to intersect with the surface waterbodies. The waterbodies were deleted from this shapefile to create a new spill pathway shapefile after the Extend Line was completed. This was done as the waterbodies were no longer needed in that shapefile, since the objective of that shapefile was to create spill pathways that intersected with the original surface waterbodies shapefile.

E. A Spatial Join was used to find the distance between each spill pathway and the waterbody to which it is closest. Any spill pathway that was found to still not intersect with a waterbody had its end manually extended to intersect with the waterbody into which it would spill. This was done for 80 different spill pathways. The intersections between the spill pathways and the waterbodies they would spill into was necessary, because in certain cases a spill pathway would flow very close to one waterbody before ending in a different waterbody.

F. A Spatial Join was used to join the spill pathways to the waterbodies to find if any of the lines intersected with multiple waterbodies. The spill pathway that did intersect with multiple waterbodies were split into two spill pathways by the author based on the direction they appeared to be traveling, so that each spill pathway only intersected with a single waterbody. This was done for three different spill pathways. This was done to keep wells from being double counted as spilling into multiple waterbodies as this would be inaccurate.

G. A Spatial Join was then used to connect the spill pathways and their associated waterbodies using the one to many join operation and the intersect match option to associate each waterbody with its associated spill pathways. The one to many join operation was used, because it allowed multiple spill paths to be associated with a single waterbody. This was done, because frequently multiple spill pathways ended in a single waterbody.

H. The Dissolve tool was used to dissolve all the spill pathways that spill into a single surface waterbody and sum the number of wells associated with each of the spill pathways together. The result from this step provided the number of wells that could potentially spill into the waterbodies, which satisfies a portion of the first and second objectives of the study.

5. Creating the points where the spills entered the waterbodies

A. The Feature Vertices to Points tool was used on the spill pathways shapefile. The Feature Vertices to Points tool operates by taking all the vertices of a shapefile and converting them into a point shapefile. This created a point on all the vertices of the spill pathways which included the end of the spill pathways where they entered the waterbodies.

B. The Intersect tool was used with the points and the waterbodies with a half meter tolerance. This was done to create a shapefile that just had the vertices that were close to the surface waterbodies because those were the only vertices that could be the locations where the spill pathways would enter the surface waterbodies.

C. A Spatial Join was run to find the distance between each spill pathway and its associated entry point. If the distance between the spill pathway and its associated entry point was more than three meters it was determined that the spill pathway did not have an associated entry point, and an entry point was digitized.

D. A Spatial Join was run to determine how many entry points were closest to each spill pathway. Where the number was zero an entry point was digitized. Where the number was greater than one the extra entry points were deleted. This process was run until each spill pathway only had one associated entry point.

E. A Spatial Join was run to add the attribute table from the spill pathway shapefile to the entry points shapefile. This was done because the attribute table from the spill pathway shapefile contained the number of wells that would enter into the waterbody at the entry point. The result from this step provided the number of wells that could potentially spill into the waterbodies at each entry point, which satisfies a portion of the second objective of this study.

Modeling Frack Fluid Soil Infiltration

The spill pathways were modeled a second time in this section in order to create an individual spill pathway for each well. This was done, because the length of the spill pathway was required in order to answer the question: how much frack fluid could infiltrate into the soil from each well and therefore not reach a surface waterbody? This soil infiltration value was important for achieving the third and fourth objectives of this study.

1. Creating individual spill paths in ArcMap Model Builder

A. In order to produce individual flow paths from the wells to the water bodies, the Split tool was used to separate the wells into individual shapefiles. The Split tool requires a buffer around each well of which a one meter buffer was produced and contained individual object ID's corresponding to each well. The distinct object ID values allow the Split tool to separate the wells into individual shapefiles. Once the Split tool was run it produced 11,520 individual shapefiles containing one well. The wells were needed in that format for use in the ArcMap Model Builder

B. The ArcMap Model Builder is an application that allows the user to input a sequence of geoprocessing tools and run them sequentially with the output of one tool becoming the input in the next tool. The Feature Classes loop for the Model Builder was turned on and set to point in the folder that contained all 11,520 well in 11,520 separate shapefiles. The Feature Classes loop causes the model builder to look in a folder for a shapefile and run the model for each shapefile in the folder. The first tool input into the Model Builder was the Extract by Mask tool. The Extract by Mask tool extracted the pixel based on the flow direction raster that had the waterbodies erased. The Flow Accumulation tool used the raster well location created by the Extract by Mask tool as the input weight raster in conjunction with the flow direction raster that had the waterbodies erased to create the spill pathways from the well site to the surface waterbodies. The result of the Flow Accumulation tool is a raster of value zero except where the spill path exists. Finally, the Raster to Polyline tool was used to create a vector line of the spill pathway from the flow accumulation raster. These polyline shapefiles were the spill pathways that were used to model how much frack fluid could infiltrate into the soil.

2. Preparing spill pathway shapefiles for frack fluid soil infiltration calculations

A. ArcMap Model Builder's Feature Class loop was set to line and pointed at the folder that contained all the spill pathways. The Dissolve tool was the only tool that was input into the Model Builder and set to dissolve based on grid code. This use of the Dissolve tool made it so that each spill path shapefile contained a single object.

B. The Merge tool was then used to combine all the individual spill pathways into a single shapefile with each spill pathway as separate object. This was done, because this was the format that the spill pathways needed to be in, in order for them to be used for frack fluid soil infiltration calculations.

C. At this point all the spill pathways are in a usable format, but there are inaccuracies related to integrating raster and vector data as was done in this study. One of the issues was that in situations where well sites were located in close proximity to each other multiple wells would have the exact same spill pathway. Since there was no need to have the exact same spill pathway twice, duplicates had to be deleted. A second issue was that there was a space between the well site and the start of the spill pathway and there was also space between the end of the spill pathways and some of the waterbodies. In order to decrease the inaccuracy in the calculation of the volume of frack fluid soil infiltration, it was necessary to eliminate the spill pathways that covered less than 95 percent of the total distance between the well and the surface waterbody.

D. The Calculate Geometry tool within the attribute table of the spill pathways was used to calculate the length of the spill pathways in meters to 0.000001. The Delete Identical tool, deletes identical features based on an attribute, and in this case that attribute was length. This reduced the number of spill paths from 11,520 to 11,181.

E. Two consecutive Spatial Joins were run; the first was between the spill pathways and the wells and the second was between the result of the first Spatial Join and the waterbodies. The joins were done in this manner to create a single spill pathway shapefile that contained both the Euclidean distance from between the wells and their associated spill pathways and from the spill pathways and their associated surface waterbodies.

F. The Field Calculator was then used to calculate the percentage of the total distance (Equation 1) versus the spill pathway (Equation 2). The in the equations in this step are calculated as follows:

$$TD_p = E_{WSp} + LS_p + E_{SPWp} \qquad \text{(EQ: 1)}$$

$$SP_p = \frac{LS_p}{TD_p} \qquad \text{(EQ: 2)}$$

where TD_p equals the total distance of the spill path (p), E_{WSp} equals the Euclidean distance from the well site to the spill path (p), LS_p equals the length of the spill path (p), E_{SPWp} equals the Euclidean distance from the spill path (p) to the surface waterbody, and SP_p equals the spill pathway percentage for spill path (p). The spill pathways that were less than 95 percent of the total distance were deleted decreasing the total spill paths from 11,181 to 11,109. The deletion of these spill pathways caused the total number of wells modeled to decrease from 11,520 to 11,435. The reason why there was a different number of spill pathways (11,109) than wells models (11,435) was that, due to the use of raster datasets in the model, identical spill pathways were created for different wells that were in close proximity to each other.

3. Determining spill pathway widths.

A. In order to calculate the volume of frack fluid that could infiltrate into the soil it was first required to calculate the volume of the soil (Equation 3). Although the pathway lengths were previously calculated and the soil depth was obtained from SSURGO data, the widths of the spill pathways still needed to be determined. The soil volume was calculated as follows:

$$SV_p = LS_p * WS_p * SD_p \qquad \text{(EQ: 3)}$$

where SV_p equals soil volume for spill path (p), LS_p equals length of spill path (p), WS_p equals the width of the spill path (p), and SD_p equals soil depth of spill path (p).

B. The Buffer tool was used to create a 15 meter buffer around all the spill pathways and simultaneously combine all the spill pathways into a single object. This was done, because otherwise the Create Random Points tool would create a set of random points for each object which would be more random points than were required.

C. The Create Random Points tool used the dissolved buffer shapefile to create 500 random points throughout the spill paths. Five-hundred random points were chosen, because that was a large enough sample to include the variability of the gully widths within the study area, while being a small enough number that the author could manually measure them in a timely manner. The Create Random Points tool operates by taking a polygon and creating as many random points within the polygon as the user requests.

D. Gulley widths were manually measured off of recent Google Earth air photos at the locations of the random points using Google Earth's ruler tool. Where the widths of the spill paths were less than two meters, or could not be determined, a default value of two meters was used (Personal Communication, Vanlooy). All the widths were input into Microsoft Excel and the median width was calculated (2.775 meters) which was used in this study's soil volume calculations.

4. Modeling soil infiltration of frack fluid along spill pathways

A. The Intersect tool was used to combine the SSURGO polygons with the joined data to the spill pathways. This allowed for the calculation of the length of each spill pathway within each SSURGO polygon which was important because the SSURGO polygon contained the depth of the soil and the percentage of soil volume that could contain frack fluid.

B. The Field Calculator was used to calculate the volume of the soil for each line segment (Equation 3). Once the soil volume was calculated it was necessary to use the percentage of liquid that the soil could hold to calculate how much frack fluid could be contained by the soil (Equation 4). This was calculated as follows:

$$MV_p = SV_p * PSV_p \qquad \text{(EQ: 4)}$$

where MV_p equals the maximum volume of frack fluid soil infiltration for spill path (p), SV_p equals the soil volume from (EQ 3) for spill path (p), and PSV_p equals the percentage of soil volume that can hold water along spill path (p). In reality soil is usually not completely dry and the velocity of the spilling frack fluid may be at a rate that does not provide enough time to fully infiltrate into the soil. To calculate a range of values for potential volumes of frack fluid that could infiltrate into the soil the maximum volume of frack fluid infiltration was multiplied by 0.25, 0.50, and 0.75 in order the calculate the 25^{th}, 50^{th}, and 75^{th} percentile values. The maximum infiltration volume (100^{th} percentile) was also used. This satisfies the third objective of this study.

Creating a Vulnerability Index

In order to compare the vulnerability of different waterbodies to frack fluid spills a Vulnerability Index was created. The Vulnerability Index is based on a scenario where the spill consists of a specific volume minus the specific soil infiltration volume. Based on this scenario a larger spill volume with a smaller soil infiltration volume increases the Vulnerability Index. The Vulnerability Index also takes into account the area of the waterbody; a larger waterbody area decreases the Vulnerability Index, as the larger the waterbody the greater the dilution of the spill therefore decreasing the spill's impact on the waterbody. Lastly, the Vulnerability Index takes into account the number of wells from which a spill could reach the waterbody; a greater number of wells increases the Vulnerability Index due to a greater probability of a spill.

There are variables that are difficult to model that decrease the ability of frack fluid to infiltrate into soil. For example, the higher the volume of water being held in the soil prior to a spill the lower the volume of soil available to hold frack fluid. As well, a spill with a high velocity will decrease the time the frack fluid has to infiltrate into the soil therefore leading to a greater chance the frack fluid will reach a waterbody. This variability is the reason for the use of soil infiltration quartiles in the vulnerability indices. In total 12 scenarios were utilized to calculate the vulnerability indices in this thesis by combining the four soil infiltration quartiles with the three spill volume scenarios (Table 9).

1. Preparing datasets to calculate the Vulnerability Index

A. In order to create a Vulnerability Index the spill pathways with the soil infiltration data had to intersect with their associated waterbodies, because the soil infiltration data needed to be associated with a waterbody to determine how much frack fluid would infiltrate into the soil and therefore not reach the waterbody. The Snap tool was used to snap the waterbodies to the spill pathways. The Snap tool modifies shapefiles to intersect with a different shapefile within a distance set by the user.

B. A Spatial Join was used to measure the distance between the spill path and the waterbody and the spill pathways that did not intersect with their waterbody were selected and the Snap tool was run until all the spill pathways intersected their waterbodies.

C. A Spatial Join was then used to connect the spill pathways and their associated waterbodies using the one to many join operation and the intersect match option to associate each waterbody with its associated spill pathways.

2. Calculating and normalizing the waterbodies Vulnerability Index

A. Three different sized spills were used in the Vulnerability Index; 509, 79.5, and 31.8 m^3. A spill of 509 m^3 was chosen to represent the high range of spill sizes since it is the average value of the five largest well site frack fluid spills in North Dakota (Table 7). Spills of 79.5 and 31.8 m^3 were chosen to represent medium and small sized spills and they were based off the volume of well site frack fluid spills that had occurred in North Dakota (Table 8).

B. These spill volumes were input into the Field Calculator to calculate the volume of frack fluid spilled into a waterbody (Equation 5) as follows:

$$VS_W = SP_{v,p} - SI_{i,p} \qquad \text{(EQ: 5)}$$

where VS_w equals the volume of frack fluid spilled into a given waterbody (w), $SP_{v,p}$ equals the amount of frack fluid spill for the three sample volumes (v) from tables 7 and 8 along a flow path (p), and $SI_{i,p}$ equals the amount of soil infiltration given the percentile (i) along the flow path (p). Once this calculation was made all the wells that had positive volumes of frack fluid spilled into a waterbody were kept and all negative values were changed to zero since the volume spilling from that well into a surface waterbody would be zero.

C. The Dissolve tool was then used to sum the volumes of frack fluid that spilled into each waterbody and the number of wells that spill into each waterbody and the mean of the surface area of the waterbody. This provided the number of wells and volume of frack fluid spilled into each waterbody values along with the surface area of the waterbody in one shapefile. These data were then input into the Field Calculator to calculate the Vulnerability Index as follows:

$$VI_W = \left(\frac{N_{i,v}}{A_w}\right) \times VS_{W,i,v} \quad \text{(EQ: 6)}$$

where VI_w is the Vulnerability Index for a waterbody (*w*), *N* equals the number of wells that would impact a waterbody under a given scenario (*i*,*v*), *A* equals the area of the waterbody (*w*), and VS_w equals the volume of frack fluid spilled into a waterbody (*w*) under a given scenario (*i*,*v*).

D. The Vulnerability Index for each waterbody was calculated and normalized on a 0-1 scale. All the Vulnerability Index values were divided by the greatest Vulnerability Index Value within the same spill scenario to create Normalized Vulnerability Index for the waterbodies (NVI_W) (Equation 7) which was calculated as follows:

$$NVI_W = \frac{(VI_w - VI_l)}{VI_h} \quad \text{(EQ: 7)}$$

where NVI_w is the normalized vulnerability index for a given waterbody (*w*), VI_w equals the vulnerability index for waterbody (*w*), VI_l equals the lowest vulnerability index of all waterbodies, and VI_h equals the highest vulnerability index of all waterbodies.

3. Calculating the spill volume that could enter a waterbody at an entrance point.

A. A Spatial Join was run between the spill pathways that contained the soil infiltration volumes and the entry points. This was done to associate the spill pathways with their associated point of entry into a waterbody.

B. Equation 5 was used in the Field Calculator to the shapefile created in step A to calculate the volume of frack fluid that could enter each waterbody under each scenario.

C. The Dissolve tool was then used to sum all the spill volumes based on the object ID of the entry point. This created a line shapefile that contained the volume that could enter into a surface waterbody at each entrance point.

D. A Tabular Join was used to join the attribute table from the previously created shapefile (step C) to the entry points shapefile. A Tabular Join is a join that associates a shapefile with a table based on a shared value. The Tabular Join was done based on the object IDs of the spill entry point and created an entry point shapefile that contained the volume of frack fluid that could spill into a waterbody at each entrance point.

4. Calculating spill volumes and wells per watershed

A. The Clipping tool was used to subset the HUC 8 watershed shapefile for North Dakota to the study area.

B. The Intersect tool was then used to combine the watersheds entry points that contained the number of wells and volume of frack fluid that could spill into a waterbody at that entry point. This was done to have the number of wells and volume of frack fluid spill separated by watershed.

C. The Dissolve tool was then run based on the object ID of the watershed and it summed all the wells and spill volumes by watershed. This created a file that contained the volume of frack fluid that could spill into each watershed.

D. The results of the Dissolve were manually entered into the watershed shapefile, so that the watershed shapefile contained the number of wells that were within a watershed and the volume of frack fluid that could spill into each watershed.

5. Calculating the area of impacted waterbodies per watershed

A. The Intersect tool was used to combine the waterbodies with the watersheds shapefile. This was done to have the waterbodies separated by watershed.

B. A Spatial Join was run between the spill pathways that would impact a waterbody under the 12 scenarios (Table 9) and the intersected waterbodies. Some waterbodies were in multiple watersheds, so a spill would impact the waterbody in one watershed and not the others. The distance between the spill pathways and the waterbodies was used to find the portions of waterbodies that were outside of the watershed where they are impacted by a spill and these waterbodies were then deleted.

C. A Dissolve was run to sum the area of the impacted waterbodies by watershed. This was done to acquire the area of the waterbodies impacted by spills for each watershed in order to use these data to calculate the watershed Vulnerability Index.

D. The results from step C were manually input into the watershed shapefile in order to have the area of impacted waterbodies, number of spilling wells, and the volume of frack fluid spillage in a single shapefile which was necessary to calculate the watershed Vulnerability Index.

6. Calculating and normalizing the watershed Vulnerability Index

A. For all the scenarios (Table 9) the volume of frack fluid that could spill into waterbodies within each watershed, the number of wells that could spill into waterbodies within each watershed and the area of the impacted waterbodies were input into the Field Calculator using equation 8 to calculate the watershed Vulnerability Index as follows:.

$$VI_{WS} = \left(\frac{N_{i,v}}{A_{ws,i,v}}\right) \times \, VS_{WS,i,v} \qquad \text{(EQ: 8)}$$

where VI_{ws} is the vulnerability index for a given watershed (*ws*), $N_{i,v}$ equals the number of wells for a given scenario (*i,v*), $A_{wsi,v}$ equals the sum of the area of the all the waterbodies within the watershed (*ws*) that are impacted by a spill under a given scenario (*i,v*), and VS_{ws} equals the volume of frack fluid spilled for a given watershed (*ws*) under scenario (*i,v)*.

B. The watershed Vulnerability Index was normalized between 0-1 by dividing all the watershed vulnerability indices by the greatest watershed Vulnerability Index within each scenario. The process of calculating the various indices satisfies the fourth and final objective of this study.

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