AN ANALYSIS OF EMERGENT BEHAVIOR IN THE NORTH DAKOTA WATER DEPOT-BASED WATER ALLOCATION SYSTEM USING A DECENTRALIZED AGENT-BASED MODELING (ABM) APPROACH

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MASTER OF SCIENCE

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ABSTRACT

Water demand has increased exponentially since 2007 in western North Dakota. This increase can largely be traced to the advancement of technology in hydraulic fracturing (fracking) which has led to one of the largest oil booms in the country. Along with the recent oil boom, water depots have expanded and played a significant role in providing water for fracking.

Using decentralized agent-based modeling (ABM) to model water allocation among water depots, a scenario analysis obtains results for four scenarios. Policy suggestions, based on the scenario analysis, include allowing greater access to LSMR water sources and restricting SW and GW use for the oil industry to reduce water scarcity in the Bakken. These results support allowing greater access to LSMR water sources for the oil industry as desired by the North Dakota State Water Commission (SWC), and other elected officials in the past decade.

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CHAPTER I. INTRODUCTION

Water is one of the most precious natural resources in the world. Humans cannot live without it, and its presence separates Earth from the rest of the planets in the universe. North Dakota is home to many different water sources, but western North Dakota faces challenges in water management associated with the increased water demand as a result of the increased activity in the oil industry in recent years (Hearne & Fernanado, 2016).

Bakken shale oil activity in North Dakota has been around for decades. Exploratory drilling began during the 1970s in the Williston basin; however, it was overlooked by most oil producers. In fact, Bakken shale was discovered in 1951, but shale oil production was not economical at that time. Production levels in North Dakota hit a low point in 1974, but rebounded due to the oil boom in late 1970s (Gerhard & Anderson, 1979). This boom continued until the mid-1980s when oil prices fell again. However, oil production began again in the 2000s with another oil price spike. Development in fracking and horizontal drilling also lowered oil and gas extraction costs. As a result of the latest oil boom, population and other economic development projects increased dramatically. These changes have been most prominent in the "core" counties of North Dakota. These core counties are where most of the oil production in the Bakken occurs and these include Dunn, Mountrail, McKenzie and Williams Counties (KLJ, 2014).

A U.S. Geological Survey (USGS) report released in 2008 estimated recoverable oil levels in the Bakken formation to be the largest in the Continental United States with a mean around 3.65 billion barrels. An updated USGS report in 2013 found similar oil levels in the Bakken formation, but it also found a mean recoverable oil level of 3.73 billion barrels in the

Three Forks formation underlying the Bakken formation for an approximate 7.4 billion barrels of oil in the region. However, this expansion of the oil industry in North Dakota as a result of the hydraulic fracturing technology and favorable oil prices led to tremendous increases in the demand for water among other natural, physical, social and economic resources between 2008 and 2014.

Before the recent oil boom, rural users, such as ranchers and farmers in western North Dakota, struggled to access clean freshwater. North Dakota has a variety of surface and groundwater sources; although, most are not suitable for long-term use for various reasons. Many surface water sources are being used at full sustainable capacity, and groundwater sources may not be economically feasible to access; however, there is overwhelming agreement among many investigators and the North Dakota State Water Commission (SWC) that Lake Sakakawea and the Missouri River are dependable sources of water that could be used to keep up with demand (Schuh, 2010; Harms, 2010; Shaver, 2012; Horner et al., 2014; Hearne & Fernando, 2016). Conflict with the United States Army Corps of Engineers (USACE) over Surplus Water Policy on water distribution from these sources has prevented desired usage of these water sources (Best, 2013).

Trying to understand the complexities of the energy-water nexus with the rapid changes in North Dakota—especially with hydraulic fracturing—is difficult. North Dakota’s agricultural sector has always played a substantial role in its economy accounting for almost 14% of the state’s GDP in 2013 (Springer, 2014); it should be no surprise that irrigation accounted for over almost half of its consumptive water use in 2014 (Figure 2, Chapter 2). Data provided by the State Water Commission show how the fracking industry in North Dakota has grown in less than a decade accounting for about 5% of total consumptive water use in the state in 2013 (Sando, 2014). The exponential nature of growth is seen in Figure 2 comparing 5% of total consumptive water use in the state in 2013 to about 10% in 2014. Further comparison shows fracking accounted for under 1% of the total annual water use in the entire United States in 2011 and 2012 (EPA, 2015).

Because of the rapid growth in water demand in the Bakken region of North Dakota, research is needed to examine water consumption connected with the water depot-based water allocation system in this region. In the past couple of years, greater uncertainty regarding future levels of oil activity in the region also has developed. There is a vast amount of water in the Missouri River system; however, there is limited access to these waters. The United States Army Corps of Engineers (USACE) has limited the access to these sources under authority granted through the Flood Control Act of 1944 (Best, 2013). In addition to the prior water demand, the advent of the recent oil boom has generated even greater demand for water. Land owners and others with access to water realized the potential gains from selling water—assuming they could obtain proper water permits—and thus came the exponential growth in the number of water depots.

With a number of water depots selling water making large profits (Scheyder, 2013) there also is great incentive to pump and sell as much water as possible; however, the State Water Commission (SWC) has imposed fines for water violations in an attempt to curb illegal water sales (Springer, 2015). Knowing where water is being drawn from and protecting precious groundwater sources is vital for the health of North Dakota and its residents.

The water depot-based water allocation system in North Dakota is unique and provides an opportunity to examine the efficacy of this system. Outcomes associated with the analysis will improve understanding of agents' behavior in an autonomous environment.

Objectives

There is no question that the oil boom helped North Dakota remain one of the leaders in economic well-being during economic difficulties for the rest of the country, but it is important to recognize the potential negative impacts it has as well. Energy generation through power plants and other means also requires a substantial quantity of water. This research is intended to provide nascent knowledge on the water depot-based water allocation system present in western North Dakota. This is achieved by providing a new model framework that can be used and built upon using agent-based modeling (ABM) for the water depot-based water allocation system in western North Dakota.

Policy makers and other readers can be more informed on how water allocation in western North Dakota could be impacted by possible scenarios. Four scenarios are examined to address additional issues that could occur. ABM simulations provide a scenario analysis which allows for discussion of policy implications under each scenario. This research should help policy makers and the general public be better equipped to take action—when needed—to optimize precious water resource usage in the state.

Method

An agent-based model is capable of simulating the emergent patterns found in the water-depot based water allocation system in North Dakota. This model sheds light on expected behavior of water depot owners and helps forecast how water depots will affect the future water system through a scenario analysis. This model treats water depots as agents with autonomy in an attempt to resemble the real-world situation.

This research examines a few scenarios and the effects each could cause on water consumption from water depots. This research also provides a review of numerous water issues and advances basic principles of understanding in the field of water resource management along with further application of agent-based modeling (ABM) in the field of water resource economics. Further research could include a greater number of classifications for water depots or apply techniques used here in different water allocation studies as this is an exploratory study with potential changes to water allocation methods. Some factors that may change water allocation procedures include a change in behavior patterns for water depots, changes in the oil industry's behaviors, and other dynamic socioeconomic and environmental factors. Changes in oil prices would be a common factor to continue observing that is capable of impacting each of these factors.

Summary

Chapter 2 provides extensive background information on the Bakken area and the issues surrounding water specifically in North Dakota. A review of the literature follows in Chapter 3 looking at water valuation methods, water markets, and a comparison of the Bakken shale play to shale plays in other states. Chapters 2 and 3 also provide some background on the impact of the oil industry and what role oil plays in water management. After a general awareness of the issues surrounding the energy-water nexus in North Dakota is addressed, methodologies used in previous water management research and agent-based modeling (ABM) are reviewed in Chapter 4. In Chapter 5, ABM is applied to the water-depot based allocation system problem addressed in this thesis. Chapter 6 presents a discussion of the data related to North Dakota water, and Chapter 7 presents results and discussion stemming from this research. Finally, Chapter 8 offers a conclusion of overall contributions and findings from this research with suggestions for policy actions to provide a sustainable water supply through water practices in the Bakken region in North Dakota.

CHAPTER II. BACKGROUND

Understanding the complex environmental and socioeconomic factors connected to North Dakota provides background for this research. An extensive look at issues associated with the energy-water nexus focused on North Dakota are examined. These issues are separated into the following sections: (1) *Natural Resource Property Rights*, (2) *Water Sources*, (3) *Sectors of the Energy-Water Nexus*, and (4) *Water Depots*.

Natural Resource Property Rights

Countries and states have different ways of defining property rights of water, so this is an important distinction to consider when trying to understand water allocation systems.

North Dakota's state constitution makes clear that property rights of water resources belong to the state (Paulson, 1990). North Dakota water rights follow the doctrine of prior appropriation as well. In North Dakota citizens are required to apply for water permits if water use would exceed 12.5 acre-feet per year if used for irrigation or industrial uses (Schuh, 2010). Applications are not always accepted, and any complaints can be voiced and taken into consideration if received, typically in the first 30 days (Schuh 2010). If objections are not an obstacle—assuming the permit passes through a hydrologist and the State Engineer—the permit receives "conditional" status and can become a "perfected" permit after inspected at a later date to prove the water is meeting beneficial use standards (Schuh, 2010).

Water permits also have a priority listing dependent on the intended use of the water. Ranking from highest to lowest, the priorities are domestic, municipal, livestock, irrigation, industrial, and recreation (Schuh, 2010). There also is importance in noting that permits filed within 90 days of each other will be evaluated based on this priority level; if the total amount of water requested cannot be granted to all permits, higher ranking uses will be granted first (Schuh, 2010).

In places like North Dakota where there is also a great demand for water in obtaining oil, understanding mineral rights laws is important too. Mineral rights are attached with the land in North Dakota, so oil companies often obtain rights to the oil by buying or leasing those rights from various landowners (Banning 2013). In many other countries, the mineral rights are owned by the government; this has also played an important role in the development of the natural resources in the United States (Scanlon, Reedy, & Nicot, 2014a).

Water Sources in North Dakota

Awareness of the unique sustainability, political, and water access problems for a variety of users all contribute to the complex energy-water nexus in the state. Basic background on where and how the water is being used also is vital to effective water management in the state.

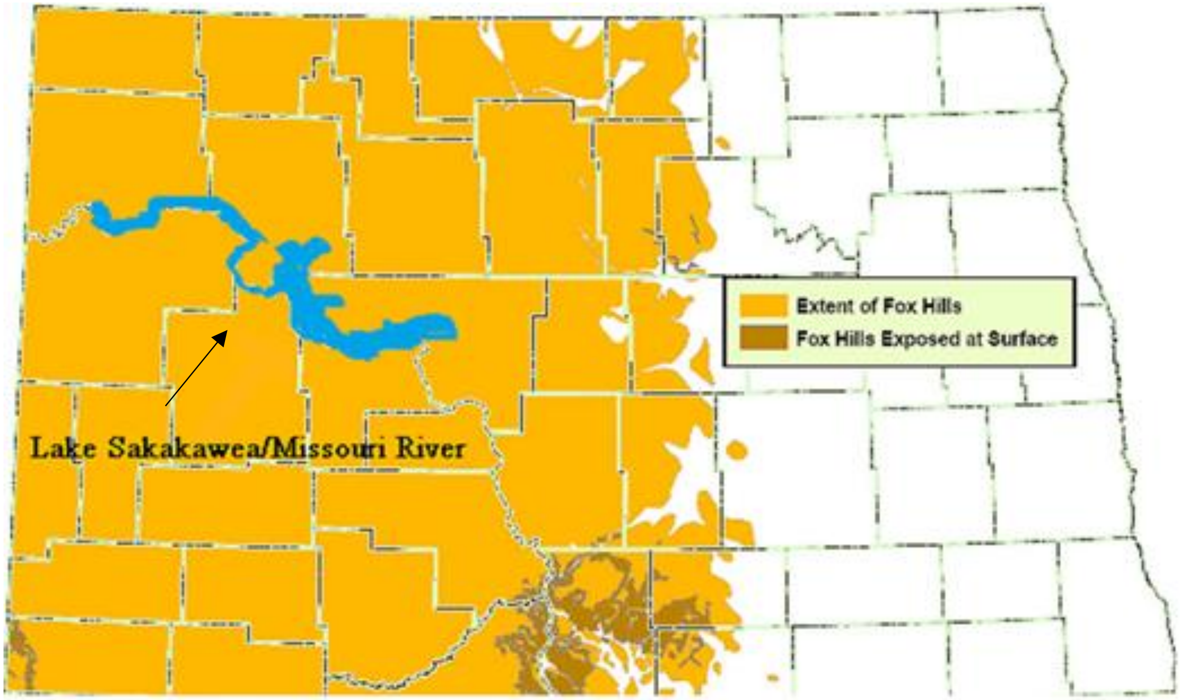

Figure 1. Fox Hills Aquifer in North Dakota. Source: Modified from Shaver (2012).

Fox Hills-Hell Creek (FH-HC) Aquifer

Western North Dakota heavily relies on the Fox Hills-Hell Creek (FH-HC) aquifer for its water needs. As seen in Figure 1, this aquifer is quite extensive. Water depths in this aquifer vary from being at the surface to 2,000 feet in the middle of the Williston Basin area (Schuh, 2010; Shaver, 2012). There is estimated to be around 346 million acre-feet of water throughout the aquifer (Schuh, 2010).

Farmers, ranchers, cities, and small industries are some of the users that rely on the freshwater available from the FH-HC aquifer (Schuh, 2010). Living in western North Dakota, these water users do not have many options with many areas being rural and isolated. Because of such dependence on this aquifer for water, pressure head declines in the aquifer of 1-2 feet per year has been observed since the 1980s (Harms, 2010; Gordon & Garner, 2014).

In Schuh's 2010 summary, he states the importance of withholding the FH-HC aquifer from large industrial uses pointing out that the water is already being mined meaning the water is being taken out faster than it can be recharged. At these levels of use, there are already concerns about the longevity of wells that draw water from the FH-HC aquifer (Gordon & Garner, 2014). Although the FH-HC aquifer is important for meeting many needs in North Dakota, it is unable to be used for drinking water in most cases due to its total dissolved solids (TDS) concentration of around 2,500 mg/L (Gordon & Garner, 2014).

Dakota Aquifer

Spanning nearly all of North Dakota, the Dakota aquifer is another tremendous source of water; unfortunately, most of this water cannot be used without treatment (Schuh, 2010). The Dakota aquifer ranges from 4,000-6,000 feet in the Williston Basin to 2,000-3,000 feet in north-central North Dakota, and is shallow in eastern North Dakota (Schuh, 2010). In oil drilling areas, this formation is often where produced water from hydraulic fracturing is injected to dispose of the wastewater that would otherwise need to be treated (Schuh, 2010).

Glacial Aquifers

Glacial aquifers play an important role in providing quality water. Most of these aquifers are shallow only going to depths of a few hundred feet (Gordon & Garner, 2014). This provides easier access to these groundwater sources compared to other aquifers in the state. Irrigation water often needs to come from these aquifers as well because qualities inherent to these aquifers result in lower concentrations of TDS than other water sources in the area (Gordon & Garner, 2014).

Missouri River System

The Missouri River and Lake Sakakawea are the largest sources of surface water in North Dakota. Lake Sakakawea covers more than 500,000 acres of flooded land (Harms, 2010), and the Sakakawea Reservoir has 7,800 billion gallons storage capacity (Scanlon et al., 2014a). The lake is capable of providing 10 billion gallons of water using one inch of the lake as estimated by the North Dakota Department of Mineral Resources (Hicks, 2010). This is why there is a desire for greater access to water from the lake for the oil and gas industry from the North Dakota State Water Commission (SWC), the governor, and the congressional delegation (Harms, 2010); however, the United States Army Corps of Engineers (USACE) controls the points of diversion to Lake Sakakawea.

Conflict with USACE

Restricted access to Lake Sakakawea began in May 2010 when the USACE "announced that a three to seven year storage availability study would be required before any additional water access permits could be approved from Lake Sakakawea" (Schuh, 2010, p. ES-8). In addition to the storage availability study, the USACE worked to calculate a value for "surplus water" storage fees (Schuh, 2010) so when the first study was completed there would be a price that could be charged to those who wanted to access this surplus water. This power of the USACE comes from the Flood Control Act of 1944 which the agency to charge fees for this water in its Surplus Water Policy (Best, 2013). Water from Lake Sakakawea is classified as surplus because there were authorized projects in the area that would have used this water, but were never finished (Best, 2013).

Little time was needed before 100,000 acre feet of water per year was made available for the next five years in December 2010 (U.S. Army Corps of Engineers, 2010). Because this supply was made available on a temporary basis, Gordon and Garner (2014) argue that without permanent availability, infrastructure to transport water for the oil industry will not be constructed.

Sectors of the Energy-Water Nexus

With background on basic problems and availability associated with the water sources in North Dakota, delving into the consumption of water throughout the different sectors of water use will provide some quantifiable data for water planning. Water demand can be gathered and seen mainly in a few different sectors in North Dakota. Most of the consumption comes in the form of irrigation, with industrial and municipal usage as the other major forms. However, fracking water use accounted for 43% of total water use in the four major oil-producing counties (Williams, Mountrail, McKenzie, and Dunn) in North Dakota in 2014, up from 0.7% in 2007 (Lin, Lin, & Lim, 2015). Examining some of these components will provide a better understanding of the role water depots play in the water allocation system present in North Dakota.

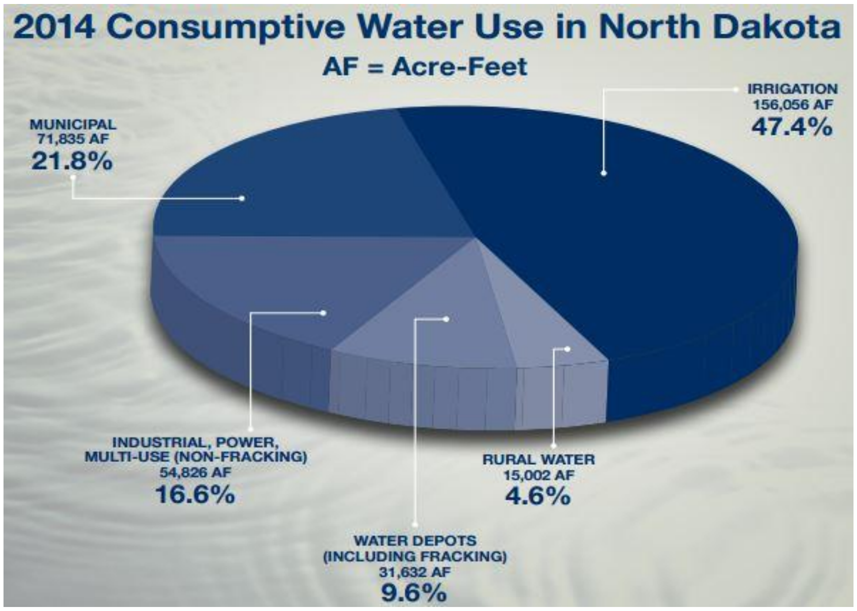

Figure 2. Water Consumption in North Dakota (2014). Source: North Dakota State Water Commission (2016).

Irrigation

Irrigation is by far the most extensive use of water in North Dakota. As previously mentioned, irrigation accounts for almost half of consumptive water use in North Dakota (Figure 2). But this water, even with the recent oil boom, is being used to support the agriculture industry which remains the largest industry in North Dakota (Hearne & Fernando, 2016). Farmers have always needed water for their crop production. Being a leading agricultural state, it is important to continue to make sure water is available in this sector as water demand grows in other areas.

Biomass – Ethanol Production

Biomass is one of these areas where there is a great deal of energy being generated. The importance of biomass to United States energy production is not difficult to see when in 2007, it was greater than that of hydropower (Schuh, 2010). When trying to meet our future energy demands, failing to take advantage of biomass would leave an incredibly valuable source of energy to waste. This is why it is important to recognize its connection to water consumption as well. There are five operating ethanol plants in North Dakota with a combined production of 465 million gallons of fuel ethanol per year as of July 2015 (Nebraska Energy Office, 2015).

Using a 3-3.5 gal of water/gal of ethanol ratio in North Dakota (Schuh, 2010) and an operating production of 470 million gallons of ethanol per year for July 2016 in North Dakota (Nebraska Energy Office, 2016), the industry's annual use ranges from about 4,330-5,050 acre-feet of water used in the state.

Municipal

A key area of municipal water use is domestic water demand. With populations increasing in North Dakota oil field regions, there is expected to be a correlated increase in water demand. Looking at population changes in the City of Williston where the recent oil boom has had an enormous impact, the U.S. Census Bureau (2014) estimated a change in population from 16,046 in 2010 to 24,562 in 2014 which would be a 50% increase in population. This is just one example of the growth in population the Bakken region of North Dakota. If population continues to grow at rates even close to this, municipal water demand will continue to increase at rates putting increased pressure on the already scarce quality water supply in the Bakken region.

Industrial & Electricity Generation (Non-Fracking)

Another water intensive industry is thermoelectric energy generation. Thermoelectricity in North Dakota uses water, but much of the water is reused. Using terms to differentiate between the water used is important, and Schuh (2010, p. ES-10) describes as those before him did, "Withdrawn water is returned to the source stream after it is used and has little effect on the source waters. Consumed water is not returned to the source stream after it is used."

The United States is quite reliant on thermoelectric energy generation as it accounts for about 90% of all electrical capacity (EERC, 2015). Thermoelectric plants using Missouri River water have the capacity to provide 15,000 Megawatts (MW) of energy (Hearne & Prato, 2016). This knowledge should help solidify the need and importance of some of these water intensive forms of energy generation. A couple other energy industries in North Dakota are natural gas and wind. Both of these industries use little water leading to little worry in being able to supply their water needs (Schuh 2010).

Hydraulic Fracturing

In the past decade, oil production has increased in North Dakota due to advances in hydraulic fracturing technology, or fracking. Fracking compliments horizontal drilling in North Dakota's Bakken play which is different from conventional oil production methods where there is only vertical drilling. Another distinction is that hydraulic fracturing does not occur until drilling of the well is completed. Fracking is the process used to create small fractures in the rock where oil can flow out and be recovered at the surface of the well. This is where the hydraulic part comes in because 98 to 99.5 percent of the fluid used to create these fractures is water and sand (FracFocus, 2015). This fracking fluid opens fractures by pumping a large volume of the fluid into the well at high pressures. Many precautions are taken throughout the drilling process to protect groundwater sources and other environmental resources.

Fracking is occurring in the Bakken and Three Forks Shale formations in North Dakota which hold an abundant amount of oil. To frack these formations, drills must reach depths around 10,000 feet. Based on estimations conducted by the North Dakota Industrial Commission's (NDIC) Department of Mineral Resources (DMR), there are 200-300 billion barrels of oil in the Bakken but only 1.4 percent would be recoverable (Harms, 2010); however, more recent recovery rates are in the 4-6 percent range (Stockdill, 2014). This shows just how plentiful oil is in North Dakota and why there is so much interest in the Bakken play.

Water required for hydraulic fracking is immense. Because fracking has grown quickly, finding sustainable water supplies to support the demand has been worrisome. There is common consensus in the state and literature that support the Missouri River system and Lake Sakakawea to be the best source of water to support hydraulic fracking's demand (Schuh, 2010; Harms, 2010; Horner et al., 2014; Shaver, 2012).

The amount of water for each frack varies greatly. A 2010 estimate by the North Dakota Department of Mineral Resources found 1.5-4 million gallons of water needed from start to finish per well (Hicks, 2010); whereas, another report estimated use in the 2-8 million gallon range per well or more (Clark, Horner, & Harto, 2013). However, the 2013 average water consumption per well due to the fracking process in the Bakken is estimated at 3.6 million gallons based on information provided by the North Dakota State Water Commission (2015b; Hearne & Fernando, 2016). Considering there were "about 8,000 still-active wells drilled between 2006 and 2014" (Gordon & Carter, 2014, p. 1), water demand will continue to grow, especially if new wells are drilled. Oil production over the lifetime of a well uses a similar amount of water as initially fracking a well (North Dakota State Water Commission (2015b). Water also is used during the drilling process, but most of the water is used in fracking and maintenance of the well (Gordon & Carter, 2014). Maintenance water can reach 100 barrels per day per well (G. Slick, cited in Geiver, 2014).

Water Depots

Water depots in North Dakota’s Bakken region make the water allocation system different from anywhere else in the world. Because many oil companies rely on these depots for their water needs, and with the increased role oil has played in the state and the world, understanding what water depots are, how they operate, why they have become popular, and how the state has been involved are questions for water resource managers to understand.

One way to think about the function of water depots is to consider a gas station where drivers pump gasoline; oil companies go to water depots to fill their trucks with water in a similar manner. Water depots often have only a small building with pumps that draw the water from a source and hookups to dispense the water to the trucks (Scheyder, 2013). Figure 3 below shows an image of a water depot.

Figure 3. Water Depot**.** Source: Tong Lin (NDSU).

There also are several reasons why water depots have continued to expand. One reason is the lack of tax or any other cost to selling the water; another reason is the incredible profits realized due to the demand for water (Scheyder, 2013; Kusnetz, 2012). A number of farmers have converted their irrigation water permits to sell water to the oil industry temporarily (Kusnetz, 2012). Figure 4 shows how the number of water depots has increased exponentially in recent years. From 2007 to 2010, the number of water depots nearly tripled increasing from 17 to 43; however, the number of water depots from 2010 to 2014 increased from 43 to 555 showing an increase of more than 1,000 percent. Water consumption from water depots also has increased over 800 percent from 2010 to 2014.

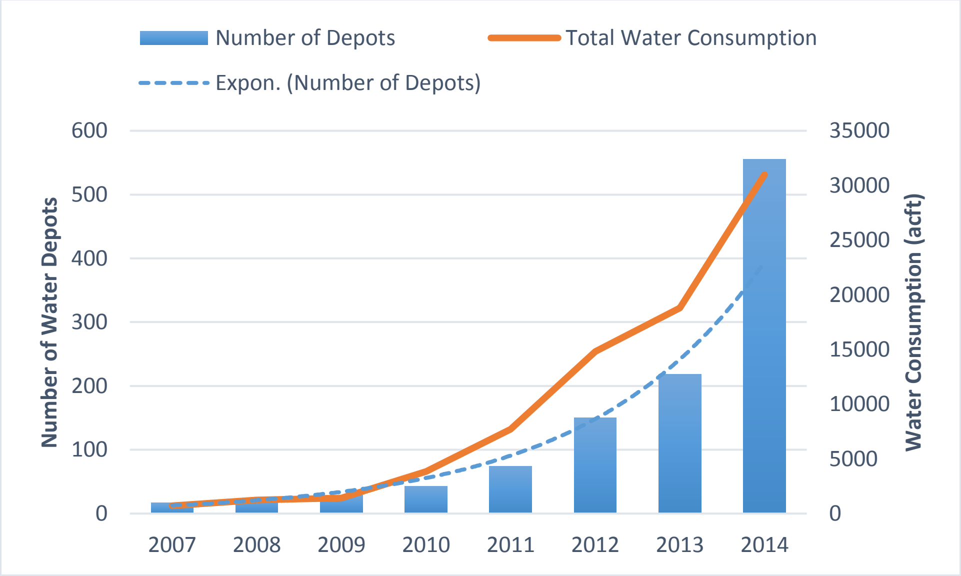

Figure 4. Number of Water Depots (2007-2014). Source: Author using data from North Dakota State Water Commission (SWC).

CHAPTER III. LITERATURE REVIEW

Introduction

Water management is an important task for every community around the world to address and prioritize. With growing global water availability concerns, effective policy and water management plans are becoming increasingly important. Supply and demand analysis is an essential part of addressing these issues. Therefore, work in economics and other disciplines has become increasingly important in providing timely solutions to these problems. Proper economic analyses of water supply and demand are needed to ensure demand for water is being met while water supplies also are being sustained.

Prior to the 1970s and 1980s, water management relied on supply-side solutions to meeting the needs of a population, but policy has since shifted to demand-side solutions (Chong & Sunding, 2006; Galán, López-Paredes, & del Olmo 2009). With more advanced economic methods and computational tools now available, water management issues can be more effectively countered from an efficiency standpoint.

An outline of the primary sections in this chapter is provided. *Water: A Private or Public Good?* examines the classification of water as a private or public good. *Non-Market and Market Valuation Methods* reviews different ways to value water. Without proper economic valuations of water, it can be difficult for policy makers to develop policy that not only protects water sources, but also allows for water to be used for other beneficial economic activities. *Water Supply and Demand in Other Shale Plays* examines water management in other shale plays.

Water: A Private or Public Good?

Classification of goods as private or public is critical to understanding how a good is valued. Different ownership characteristics (especially with public goods) requires different ways of valuing them. The following paragraphs highlight various classification characteristics water exhibits in different forms.

Water as a Public Good

Water has traditionally been identified as a public good (Grimble, 1999), but with different water management systems currently being used, there is cause to examine whether water is no longer a public good. Public goods are non-rival and non-excludable in nature; therefore, rivalry and excludability characteristics must be examined for water. This begs the question: is water a private good, public good, or both?

One characteristic of water that nearly all water resource managers have agreed on is that it is an economic good (Savenije & van der Zaag, 2002). As set out in the fourth principle of the Dublin conference on water and the environment: “Water has an economic value in all its competing uses and should be recognized as an economic good” (ICWE, 1992). This principle classifies water as an economic good, but the implication of this principle is unclear (Savenije & van der Zaag, 2002).

Savenije (2002) argues that water is a public good, but that it also is a special economic good with inherent properties that prevent it from being treated like other economic goods. In fact, it has been argued that water is “the quintessential public good” (Dellapenna, 2001, p. 1). This might be because water is essential to all people. To protect human rights, access to water must be provided to those who cannot afford it. If water consumption by high or middle-class income brackets exhibits characteristics of rivalry or if low-income groups can be excluded from the consumption of water, violations of basic human rights may occur. However, this does not entitle governments to provide water for free (Savenije, 2002). Citizens in Egypt and India also consider water to be a public good (Allen, Dávila, & Hofmann, 2006).

Water as a Private Good

Water also can have characteristics associated with private goods. Schouten & Schwartz (2006) note that water services are examples of private goods most of the time. This is because water services can be rival in consumption by one user leaving less for another and excludable by water service providers who are able to prevent access to consumers.

Another example of water as a private good is the case of water being privatized. Traditionally, water has been allocated using public companies as can be seen in many municipalities. However, private companies became significantly more involved in water resource management in the 1990s (Bakker, 2013).

Private versus public water management has now become a controversial issue. Anti-privatization advocates voice that privatization of water can lead to water acting like any other market good which is sold for profit without taking into account the ability of a consumer to pay. Fears also arise that the right to access water will not be adequate for all peoples if it is turned into a good used mainly for profit. The anti-privatization movement in Cochabamba in the early 2000s is one movement which sparked other anti-privatization movements throughout the world (Laurie & Crespo, 2007; Swyngedouw, 2013). As a result of a global movement, the United Nations General Assembly “adopted a resolution recognizing the human right to water and sanitation as human rights that are essential for the enjoyment of life and all other human rights”

(Baer, 2014, p. 145). Advocates of water privatization point to increases in economic efficiency of water use as a major motivation for privatization. Letting markets decide the price theoretically will move water from lower to higher uses with greater efficiency (Rosegrant & Binswanger, 1994). Water privatization also removes some power from centralized management. Even with privatization, state level involvement provides necessary provisions in providing the right to water for all peoples (Baer, 2014). Therefore, water privatization does not necessarily imply a water market system without regulation. As current water markets are further developed and new water markets are established, the benefits and costs of privatization should become clearer for both advocates of anti-privatization and privatization.

Water Markets

Acknowledging that water is typically seen as a public good, but that it also can exhibit the characteristics of private goods, markets have been developed attempting to maximize economic efficiency in the use of water resources. Looking at the different water allocation systems then sparks debate on issues similar to those discussed with water privatization issues.

Advocates of water markets believe markets can provide more efficient water management, but those opposed to water markets believe that environmental and water protection and conservation measures will be neglected in markets (Bakker, 2014). Both of these points should be addressed and balanced in any water allocation system. Neither advocacy group would disagree with trying to promote both efficiency and water protection; but with nearly all of life's problems, finding balance in issues is essential. Examining different characteristics and implementations of water markets will provide examples of how they work, a couple of different forms they take, and the larger issues they face.

Regulation is needed because of the essential role water plays in sustaining human and other life. Evidence points to the establishment of water markets with proper regulation actually increasing the value of water, but there is uncertainty on the environmental impacts of establishing water markets (Tietenberg, 2003). Issues of equity and sustainability are several other factors that have to be addressed within a proper market framework for water.

There are different criteria that may be included in best water management practices outside of economic efficiency (such as sustainability), but using markets also can be one way of removing a strong central authority that may be perceived as self-interested from having control over water allocation. The old Soviet Union’s strong central government exemplifies this type of central authority, and its management of the Aral Sea and surrounding area has left a lasting impact on the region. The Soviet Union had developed too many irrigation projects around the Aral Sea without proper water resource management. This resulted in the once great freshwater source in Central Asia being reduced to a fraction of the size it was in the 1960s. In fact, the volume of the sea decreased by 90% (Micklin, 2007). Other water planners around the world—including those in North Dakota—should recognize the importance of responsible, efficient water management in response to events like these and realize that the water resources they manage have great value.

Additional Costs Associated with Water Markets

The possibility for market failures should be examined in any market analysis as well. Because water is a complex economic good, there are a few different reasons market failures may occur such as its nature of being a public good, being bulky, and being a desirable environmental resource to live near (Savenije, 2002). Each of these characteristics corresponds respectively to the broader topics of transaction costs, transportation costs, and externalities. Additional problems faced in water markets include information burdens and establishing effective monitoring and enforcement (Garrick, Siebentritt, Aylward, Bauer & Purkey, 2009).

One source for market failures is the existence of transaction costs. Transaction costs make markets less than efficient. Whenever there are additional costs associated only with the process of exchanging goods or service (such as time or transaction fees), a transaction cost is present. Garrick, Whitten, & Coggan (2013, p. 196) explain how—in the case of water markets—transactions costs occur due to “the high cost and impracticality of perfectly defining private tradable water rights for a socially and physically interconnected resource.” Therefore, water market exchanges are only to be expected when benefits to both parties exceed the transaction costs.

There also are issues concerning the costs associated with transportation of water. This is because water is not cost-effective to transport. Water is bulky; it cannot be transported at a cost that would make its transportation profitable like other economic goods such as fuel and food (Savenije, 2002). In the context of water depots, transporting water is more expensive than the water itself (Kurz, Stepan, Harju, Stevens, & Cowan, 2011) which has incentivized oil companies to obtain water that is priced higher at closer distances to avoid an overall higher cost. This particular example highlights both problems of trying to exchange large quantities of water and exchanging water over greater distances.

Water markets face externalities too. Some of these externalities are commonly associated with any type of environmental resource. An example of a positive externality is the beauty of a nearby water source owned privately but still visible to others. This comes from the human desire to live near clean water (Savenije, 2002). There also can be negative externalities associated with the use of water in a market if property rights for water are not well-defined. These negative externalities occur when a water source has downstream flows or is used by multiple users. As one user may sell water from this source, other users will have less water available for uses such as recreation and fishing for which they do not receive compensation (White, 2015).

Externalities are a common problem in any market when property rights are not well-defined. The Coase Theorem addresses well-defined property rights as one of the essential characteristics for a market to operate efficiently. There also needs to be a means of enforcement through regulation in environmental markets (Garrick et al., 2009). Flowing water sources (such as rivers and streams) provide a greater chance for externalities to exist because of the integral connection between upstream water use and downstream water use. Failing to take into account externalities associated with water markets, if they exist, will result in some loss of economic efficiency in water allocation. Because water markets are to be used in an attempt to obtain more efficient use of water, externalities should not be excluded from any water market efficiency analysis.

Water Banks

Other water market tools have developed such as water banks. Water banks handle short-term water allocation transactions (Goemans & Pritchett, 2014) and less often permanent transfers of water (Ghosh, Cobourn, & Elbakidze, 2014). Most water banks are found in the western United States. They do have different forms of implementation, but they share a mission in moving water to areas of greatest need (Washington State Department of Ecology, 2016). Some differences include the organizational structures of federal, state, or other local level ownership (Goemans & Pritchett, 2014). Common processes water banks facilitate include setting water prices and determining who may participate in water banking (Ghosh et al., 2014), but pricing structures also can be determined through auctions (Goemans & Pritchett, 2014). Sellers lease the rights to water that they have to the water bank so that the water bank may find buyers to rent the water. In this way, a water bank acts as an intermediary in connecting buyers and sellers. This is one way that water banks can reduce transaction costs and provide a water exchange that benefits both buyers and sellers as is evident by continued participation in water markets.

Conjunctive administration (CA) is another component of management in water banking. This is where surface and groundwater rights are merged into one framework (Ghosh et al., 2014). CA also is compatible with the doctrine of prior appropriation for water rights which follows first come, first served and beneficial use criteria (Paulson, 1990; Best, 2013; Ghosh et al., 2014). A majority of the states in the western United States "(North Dakota to Texas and west)" follow the doctrine of prior appropriation for water rights (Saxowsky, 2016). The common doctrine of prior appropriation shared between North Dakota and other states in the west provides a similar framework for water rights. However, North Dakota has only begun to allow those interested in water banks to apply in June 2016 (North Dakota Department of Agriculture, 2016). With the use of water depots and little involvement using water banks in North Dakota at the present time, North Dakota separates itself from other states in the west in water allocation practices.

States with Water Banks

Examining water banks in California, Idaho, and Colorado provide background information and examples of water markets and water banks in contrast to the water-depot allocation system in North Dakota.

California

California faces a number of water issues like other western states. These issues have particularly been seen with California facing severe droughts in the past five years (USGS, 2016). One of the ways California has experimented with addressing water scarcity has been through the development of water markets. Because of major economic sector shifts in California's history, water markets have become an attractive option versus the alternative of accepting large costs associated with further development of water resources (Howitt, 2014). Water market buyers and sellers tend to stay local in exchanges to avoid high transactions costs, but there are various avenues of transportation including canals and infrastructure throughout the state that allow for a greater scope for water markets (Griffen, 2006). Water markets in California include long term and permanent transfers of water along with selling water itself in spot markets, but these spot markets have declined since 2000 (Howitt, 2014).

California water rights follow a combination of riparian and prior appropriation doctrines (Saxowsky, 2016). The riparian doctrine—unlike prior appropriation doctrine—focuses on who owns the land connected to a water source and assigns the water right this way (Clifford, Landry, & Larsen-Hayden, 2004; Saxowsky, 2016). Under riparian doctrine in California, water rights are also correlative meaning that riparian water rights holders share the same water source equally (Saxowsky, 2016). Water rights for surface water and groundwater also are regulated differently in California where surface water follows appropriative and riparian rights, and groundwater follows rule of capture and reasonable use doctrines (Clifford et al., 2004; Saxowsky, 2016). Rule of capture doctrine gives full ownership of groundwater to the landowner and reasonable use doctrine limits water use to beneficial purposes (Saxowsky, 2016).

In California, conjunctive use of water also refers to “the temporary storage of water in a groundwater aquifer through intentional recharge and subsequent extraction for later use” (California Statutes, Water Code, §79171). Exchanges of both surface water and groundwater occur through water banks with CA. This includes stored water uses. Conjunctive management of water resources allows surface water to be stored during wet years so the same water may be pumped for use later in dry years.

The start of water markets making an impact in California began with the 1991 Drought Water Bank buying 821,000 acre-feet of water resulting in a successful project (Howitt et al., 1992 cited in Howitt, 2014; Coppock, Gray, & McBean, 1994 cited in Griffen, 2006). However, this success was not repeated with the 2009 Drought Water Bank which targeted a purchase of 600,000 acre-feet but only bought 82,000 acre-feet of water (Howitt, 2014). One of the reasons for differences in the success of these two projects was due to having a well-known and trusted leader working with the water bank in the 1991 Drought Water Bank (Howitt, 2014). These two examples show how water banks and water markets can succeed and fail to meet expectations in the same area. Different time periods and other factors obviously played a major role in these outcomes, but they still point out that water market implementation should be considered on a case-by-case basis.

Idaho

In Idaho, water markets mostly exist in the form of water banks. Active water banks in Idaho date back to 1932, but there was a lack of legislation regarding water banking until 1979 (Clifford et al., 2004). The primary avenue water rights are leased and rented through is the Idaho Water Supply Bank, but rental pools also exist for storage water transactions (Idaho Department of Water Resources, 2016). The Idaho Water Bank covers 18 regions across southern Idaho (Ghosh et al., 2014).

Water rights in Idaho follow conjunctive administration (CA) and CA allows for prior appropriation to be applied across surface and groundwater rights in the state (Ghosh et al., 2014). Surface water belongs to the state (Clifford et al, 2004) and the use of unappropriated surface waters is acquired only by appropriation under the application, permit, and license procedures of the state (Idaho Statutes, Water Code, §42-103).

Water banks have been active in Idaho. Water rented from water banks has increased from 2008 to 2013 starting with 12,000 acre-feet in 2008 and reaching 75,000 acre-feet in 2013 (Idaho Department of Water Resources, 2013). If averaged, water rented increased over the original volume by 12,000 acre-feet each year. This type of water usage makes it important to continue to be aware of water banks and their role in water markets.

Bulletin board markets often operate under the water bank title (Hadjigeorgalis, 2009). In bulletin board markets, transactions occur through buyers and sellers making offers using a bulletin board at a central location or through an electronic system rather than paying prices established by a water bank (Hadjigeorgalis, 2009). Bulletin board markets have been a simple mechanism used to conduct trades following the same goal of water banks in providing a means for buyers and sellers to reduce search and transaction costs.

Colorado

Like other western states, water in Colorado is conjunctively managed and has been since the 1960s (Blomquist, Heikkila, & Schlager, 2004). This combines water rights of surface water and groundwater sources. Colorado is different from other states like California in that it does not primarily use conjunctive management for long-term underground storage, but rather in protecting the water rights of senior water rights holders (Blomquist et al., 2004). Water in Colorado follows the doctrine of prior appropriation as well (Blomquist et al., 2004; Lepper & Freeman, 2010). Water rights issued through water courts begin with “conditional” status and obtain “absolute” status after the water has been put to beneficial use (Colorado Division of Water Resources, 2016). This process is similar to the one in North Dakota with “conditional” and “perfected” status for permits.

Other water markets have been functioning in the state since the late 1880s (Clifford et al., 2004), but Colorado’s water banking program was tested from 2001-2005 (Clifford et al., 2004; Lepper & Freeman, 2010). Legislation in 2003 (HB-1318) opened water banking to all river basins in Colorado and made the program operational (Clifford et al., 2004; Lepper & Freeman, 2010). However, due to many problems (including a lack of protection for senior water rights owners) and a lack of interest, the pilot program was decommissioned in 2005 (Lepper & Freeman, 2010). The Northern Colorado Water Conservancy District (NCWCD) is the current water bank in Colorado which operates a bulletin board market (Hadjigeorgalis, 2009).

Valuation Methods

Placing a value on water can be a difficult but important task. In North Dakota and around the world, it is difficult to know how important something is without placing some type of value on it. In North Dakota, this could include using water for energy generation, oil production, or irrigation to produce crops.

Strangely, the most essential resources can appear to have lower monetary values than others. This particularly holds true with water as a resource that is essential to the survival of humans, yet its market value is lower than that of many other goods that have no practical use to humans. This interesting phenomenon is an example of the water-diamond paradox explained in Adam Smith's *Wealth of Nations* (1776) pointing out how a diamond with little practical use is valued at a much greater level than water. This issue of scarcity in determining market value is particularly highlighted in the water-diamond paradox.

With this knowledge, one could reason that market prices alone do not always show the true value in use. This is true with water, and as explained later there is a non-use value to water that markets may not always reflect. Accounting for the opportunity cost of water is important in deriving the economic value of water as well. Savenije & van der Zaag (2002) explain that water has intrinsic values that provide greater benefits than the market value or willingness to pay for water. These additional considerations, however, should not undermine the importance of market mechanisms and water scarcity in determining water's true value. Awareness of these issues also points to the importance of being able to calculate the opportunity cost of water using non-market valuation techniques when such situations do not allow only for market valuation procedures.

Non-Market Valuation Techniques

Non-market valuation is used to obtain a dollar amount of economic value for water in areas where there is no market to determine the value of water (Loomis, 1997). Valuing water through non-market valuation methods is important because trying to place an approximate value on something like water in a situation without market factors for valuation becomes near-impossible. There are both revealed and stated preference methods used in non-market valuations.

One of two common revealed preference methods is the travel cost method (TCM). The TCM credits its foundation to Hotelling (1947, cited in Pearce, 2002) and development to Clawson (1959, cited in Birol, Karousakis, & Koundouri, 2006). It is an alternative method used when no market valuation system exists for ecological valuations. TCM valuations are computed using observed data such as travel distance, travel cost, and time costs (Pearce, 2002; Birol et al., 2006). This method faces limitations; however, in valuing water resources as TCM valuations cannot be used in determining the non-use value of water.

The other common revealed preference method is the hedonic pricing method. This method traces its origin to ideas Lancaster (1966) set forth on how people receive benefits from a good based on its characteristics rather than from the good itself. Hedonic pricing methodology used in the valuation of water quality (Poor, Pessagno, & Paul, 2007) shows continued applicability of non-market valuation related to water resources in the past decade. Limitations with this methodology are similar to the obstacles faced in using TCM for non-market valuation; i.e., hedonic pricing cannot be applied in non-use valuations either.

One popular stated preference method used for water and other environmental economic problems is the contingent valuation method (CVM). Its continued popularity in recent literature is evident with numerous applications such as valuing aquifers (Rupérez-Moreno, Pérez-Sánchez, Senent-Aparicio, & del Pilar Flores-Asenjo, 2015) and valuing willingness to pay for water (Roy & Chakraborty, 2014) among many other water-related uses that can be found with a Google Scholar search inclusive of the words “water” and “contingent valuation”. Studies using CVM rely on responses from individuals. Using stated preference methods is beneficial in the ability to obtain all types of information related to economic value (Pearce, 2002). However, a limitation apparent in these studies is obtaining useful information that comes from only truthful responses to questionnaires (Pearce, 2002).

Water Supply and Demand in Other Shale Plays

Examining other shale plays in the United States provide comparisons to North Dakota. Most of these are in semi-arid areas that have some type of water scarcity problems that have an impact on fracking in these regions as well. As seen in Figure 5, there are plays from California to New York, but the largest oil producing plays are the Eagle Ford (Texas), Bakken (mainly North Dakota), and Permian (mainly Texas), respectively accounting for 34%, 29%, and 23% of United States oil production in 2013 (Scanlon et al., 2014b). Examining the relationship between water supply and demand in these other plays should shed more light on the problems facing North Dakota in the Bakken shale play.

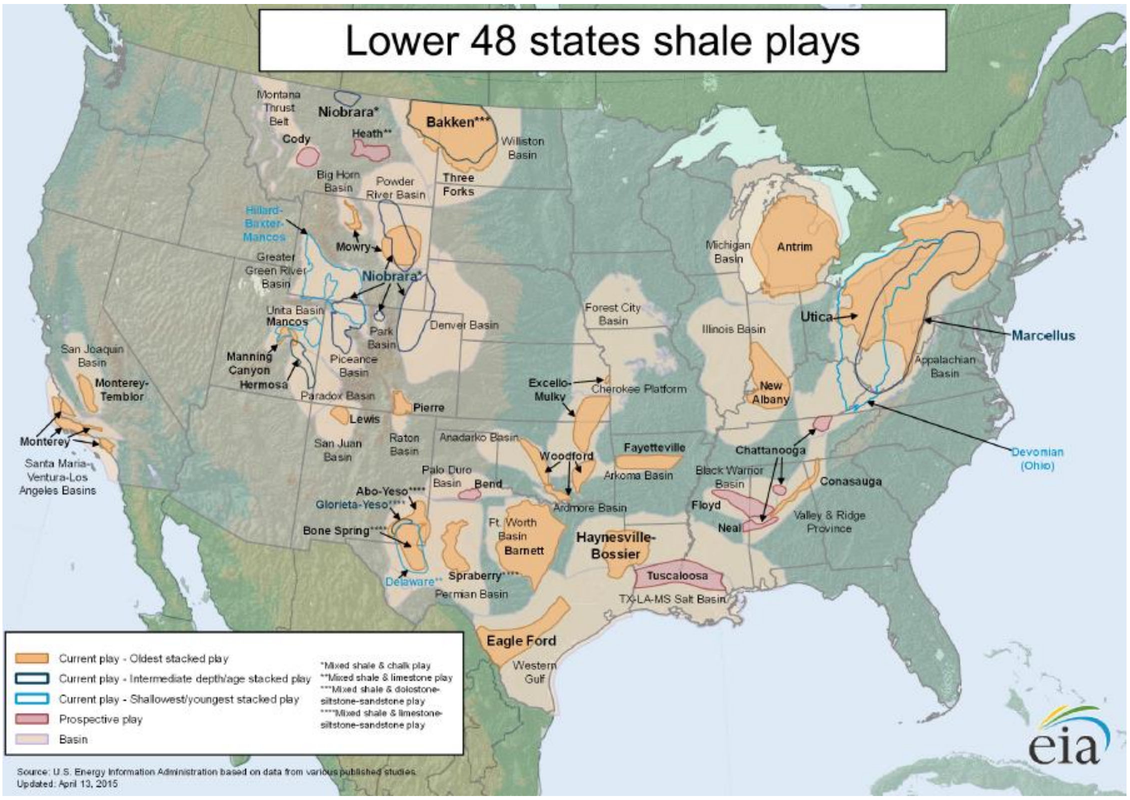

Figure 5. Shale Plays in the Lower 48 States**.** Source: EIA (2015).

Water Management in Other States

Texas and Pennsylvania’s shale plays each provide a different comparison to the Bakken shale play in North Dakota.

<u>Texas</u>

The Eagle Ford play in Texas produces both shale oil and gas, and unconventional production began in this region in 2008 (Scanlon et al., 2014a; Scanlon et. al, 2014b). Both types of production use large amounts of water, but the focus here will be on the oil component to make comparisons to the Bakken play where nearly all of the production is oil. About 18 billion gallons (approximately 55,240 acre feet) of water were used in the Eagle Ford play for fracking in 2013 (Scanlon et al., 2014a); more than 1.5 times greater than the water used for fracking in North Dakota (Figure 2, Chapter 2). Texas also is home to the Permian Basin where approximately 10.4 billion gallons (approximately 32,000 acre feet) of water was used for fracking between 2011 and mid-2013 (Scanlon et al., 2014a).

Water rights in Texas differ for surface water and groundwater. For groundwater, water rights follow English common law and follow previous court rulings which have consistently provided landowners the right to pump as much water from below their land that they desire, consistent with the rule-of-capture (Clifford et al., 2004; Texas A&M University, 2014). For surface water, however, it remains property of the state and users only acquire a right to the water (Texas Statutes, Water Code, §11.021; Saxowsky, 2016). Surface water rights also follow riparian doctrine (water rights are connected to the person who owns the land), prior appropriation doctrine, beneficial purpose, and historical use (Clifford et al., 2004; Texas A&M University, 2014). Prior appropriation doctrine in Texas follows "first in time, is the first in right" (Texas Statutes, Water Code, §11.027) in determining priority for water rights. Temporary permits issued for periods of one year or less can be issued like in North Dakota; however, permits in Texas cannot exceed 10 acre-feet if they are temporary (Texas Statutes, Water Code, §11.138).

Water supply is another factor that should be taken into consideration. Most of the water used for fracking in the Eagle Ford play comes from the Carrizo-Wilcox aquifer recharge and other groundwater sources, but some of the water also comes from the Rio Grande (Scanlon et al., 2014a). Looking at water demand versus water supply, production in the Eagle Ford play is not expected to be limited by water resources in the future (Scanlon et al., 2014a).

Oil wells in the Bakken play were found to use about half the water needed for those in the Eagle Ford play, which was largely based on differences in geology (Scanlon et al., 2014b). Some other factors that affect the amount of water used in fracking are “type of well (vertical vs horizontal); length of horizontal wells or laterals; number of HF [hydraulic fracturing] stages; and HF fluid types (e.g., slickwater, X-link gel, or hybrids)” (Scanlon et al., 2014b, pp. 12386-12387). In comparing the Bakken to Eagle Ford, other differences—besides geology—in fracking could come from the number of stages and the length of the laterals where both are about twice in the Bakken what they are in the Eagle Ford play (Scanlon et al., 2014b).

Comparing water issues in fracking between Texas shale plays and the Bakken play in North Dakota reveals key differences between the two states. A few of the water suppliers in the Barnett shale play in Texas include “self-suppliers, local landowners, municipalities, larger water districts, and river authorities” (Nicot et al., 2014). In the Bakken (referring to the North Dakota part of the Bakken), water for fracking is mainly supplied by water depots. These water depots are primarily owned by private individuals, but there also are water depots owned by the government and individual cities. Texas and North Dakota both regulate surface water withdrawals with a permitting system operating through a state commission (North Dakota State Water Commission (SWC) in North Dakota and Texas Commission on Environmental Quality (TCEQ) in Texas). However, in Texas groundwater is not regulated by this same permitting system since the water belongs to the landowner unlike North Dakota. Also, water is scarce in both states, so they both face constraints in accessing suitable water for fracking.

Pennsylvania

The Marcellus shale play extends from New York to West Virginia underlying most of Pennsylvania (Figure 5). This shale play primarily produces gas, unlike the Bakken which primarily produces oil (Scanlon, Reedy, & Nicot, (2014b). The first well in the Marcellus was completed in 2004, but greater media attention did not come to the play until late 2007 when research by Dr. Terry Engelder and Dr. Gary Lash was highlighted in press releases claiming the Marcellus could produce 50 trillion cubic feet of gas (Harper & Kolstelnik, n.d.). Swindell (2016) estimated the number of wells in the Marcellus shale play in June 2014 at over 5,400, but Kondash and Vengosh (2015) estimated 8,307 wells in the Marcellus shale play.

Water rights in Pennsylvania follow riparian and common law (previous court decisions) doctrine with landowners owning the water beneath their land as well (Abdalla, 1997). Water is further classified into four types: (1) surface water, (2) diffuse surface water, (3) percolating groundwater, and (4) groundwater with "separate, inconsistent rules" (Bishop, 2006). However, there is not full ownership of water in any classification as the state owns the water (Bishop, 2006).

Shale gas wells use large amounts of water. Water consumption from hydraulic fracturing shale gas wells ranges from 2 to 5 million gallons (6 to 15 acre-feet) per well (Arthur, Uretsky, & Wilson, 2010; Ground Water Protection Council & ALL Consulting, 2009). Over a well's life cycle, water consumption is estimated at 20,000 m^3 (approximately 16.21 acre-feet) for an average well excluding final gas utilization (Jiang, Hendrickson, & VanBriesen, 2013).

Comparing Pennsylvania and North Dakota water issues in their shale plays further highlights the unique issues faced in the Bakken. Water used for fracking in Pennsylvania must be approved by either the Susquehanna River Basin Commission (SRBC) or the Delaware River

Basin Commission (DRBC) (depending on withdrawal site) and the state, but in the case of a water withdrawal outside of the jurisdiction of either of these commissions, water is handled by state regulations (Koncelik, 2016; Abdalla & Drahan, 2010). A guideline for areas outside of river basins in Pennsylvania limits water withdrawals during low water flow for streams, but allows them in high or normal flow (Abdalla & Drahan, 2010).

In North Dakota, the State Engineer working with the SWC approves permits throughout the state. Most of the water used for fracking in the Marcellus comes from operators withdrawing it directly from surface water sources, but also it comes from public suppliers and reused (produced) water (Mitchell, Small, & Casman, 2013). Operators have had to submit water management plans (WMP) to the Pennsylvania Department of Environmental Protection (PADEP) since 2009 (Mitchell et al., 2013). In the Marcellus play, approximately 85% of the water used for fracking is surface water (Mitchell, et al., 2013). However, water shortages are not problematic in the Marcellus region (Rodriguez & Soder, 2015).

CHAPTER IV. REVIEW OF METHODOLOGY

Methods for Addressing Water Demand, Policy, and Management

A variety of demand models have been developed to address issues surrounding water resource management. Table 1 summarizes various models and offers comparisons of methodologies examined in this chapter.

Forecasting water demand has been one of the fundamental methods used for water management since water management shifted to a demand-side approach. Forecasting is done by looking at future populations and growth to estimate future water demand using statistical models. These models can be useful in helping water policy makers or other water management officials establish proper measures to maintain and provide water necessary for residents and other water users in the region they are presiding over.

One particular statistical method commonly used in economic literature to examine demand-side water management is econometrics. The regression models formed from using econometric techniques often are used in studies that aid city or other regional water planners in estimating the amount of water they will need to supply residents and other users in the future. Multiple examples of municipal water demand are seen in forecasting using econometrics (Martinez-Espiñeira, 2002; Babel, Gupta, & Pradhan, 2007; Qi & Chang, 2011). This is further illustrated by Arbués, García-Valiñas, & Martínez-Espiñeira (2003) and Milutinovic (2006) who provide reviews of water demand studies.

Table 1

Economic methods for water demand and optimization

Method	Comments	Scope	Sources
Econometric Regression	Early model using regression in water demand. This research provided a foundation for a growth of research in the following decades focused on using regression techniques in residential water demand forecasting.	Multi-city	Howe & Linaweaver (1967)
	Two-stage least squares (2SLS) regression used in forecasting domestic water demand. This study uses panel data at the household-level.	Two communities	Renwick & Archibald (1998)
	Scenario analysis is used in a log-linear regression model. This research does not focus on forecasting or predictions like most of prior research.	Multi-county	Dziegielewski & Chowdhurry (2012)
Artificial Neural Network (ANN)	The model forecasted water demand using artificial neural network (WDF-ANN) which combines ANN and econometrics. Forecasting with ANN is also relatively new at this time in its application to domestic water forecasting. This study focuses on water demand in Weinan City, China.	Weinan City, China.	Liu et al. (2003)
	The model used incorporates methods of determining "more realistic assessment of parameter and model prediction uncertainties" (Cutore et al., 2008, p. 125). This model shifts away from previous trends in models which used a deterministic context. This study focuses on daily water consumption in Catania, Italy.	Catania, Italy.	Cutore et al. (2008)
	This study finds using different methods together can be useful in short-term forecasting of water demand. Univariate time-series models used include the Holt-Winters exponential smoothing, ARIMA, and GARCH models along with a random walk model for basic comparisons. This study uses daily water demand in Spain.	Spain	Caiado (2010)
Economic-Engineering Optimization	Large-scale optimization model used in California water management. Builds on detail and scope of previous optimization models. Results show potential for water markets in California.	Multi-region (California)	Draper et al. (2003)
Agent-Based Modeling (ABM)	A decentralized agent-based model (ABM) is used to simulate behavior of agents in a watershed. This allows self-interested optimizations rather than system level optimization criteria. This study also includes a hypothetical case study in its application. A scenario analysis looking at different water levels is included.	Watershed	Yang et al. (2009)
	This study follows the work of Yang et al. (2009). It applies the decentralized ABM to the Yellow River Basin in China and analyzes 3 management scenarios.	Yellow River Basin	Yang et al. (2012)

Forecasting in any time period is subject to error. Some of these errors can occur due to unexpected changes in political or physical environments, which cause supply, demand, or both supply and demand-side shocks to the system; however, long-term forecasts are even more susceptible to errors. This is one reason statistical approaches in forecasting are not always reliable on their own. In addition, statistical methods use correlation which does not always identify causality.

Mathematical models have been used as well in forecasting water consumption. Artificial neural network (ANN) models are mathematical models with variant types. A model combining econometrics and ANN was used by Liu, Savenije, & Xu (2003) to forecast water demand in Weinan City, China when application of ANN to water demand forecasting was relatively new. Later ANN models have separated themselves from others modified by a unique algorithm (Cutore, Campisano, Kapelan, Modica, & Savic, 2008) to predict daily water consumption in Catania, Italy and using combined forecasts which improved short-term forecasting (Caiado, 2010). Using forecasting models together with other more sophisticated models is appropriate for situations where water demand may not follow a predictable trend (Galán et al., 2009).

Significant advances in computational power have led to sophisticated models using simulation and optimization as other methods to assist demand-side water solution efforts. Economic models focusing on water policy, planning, and management have been increasingly seen in academic literature. One example is an economic model using an optimization framework to maximize net benefits in irrigation practices (Reca et al., 2001). Other models are integrated with ideas from other disciplines as well. In addressing water management issues in California, optimization methods in both economics and engineering have been applied (Draper et al., 2003; Jenkins et al., 2004). Optimization techniques also have been used in an integrated three-model framework, which was designed for evaluating options associated with the Central Valley Project Improvement Act (CVPIA) in California (Sunding, Zilberman, Howitt, Dinar, & MacDougall, 2002). The California Agriculture and Resource Model (CARM), agroeconomic, and rationing models presented by Sunding et al., (2002) address several goals associated with the water issues concerning agriculture in California, including farmer profit, water productivity, and measuring how changes in water supply policy impact crop production in water districts (Chong & Sunding, 2006).

Other researchers have developed models that use techniques that focus on the behaviors of individual actors, players, or firms in a given water management problem. These models are dynamic, rather than previous static models, allowing for more intensive computational analysis. However, dynamic models also face problems in becoming too complex to the point that other suitable forecasting methods may be preferred depending on the scenario (House-Peters & Chang, 2011). Agent-based models or agent-based modeling (ABM) are dynamic models that use optimization and simulation to assess individual agents' behaviors and the impact their choices have on a water management region.

Agent-based Modeling

Agent-based modeling (ABM) is a tool that can use a "bottom-up" approach in comparison to classical modeling techniques that use a "top-down" approach (Tesfatsion, 2010). In ABM, the analysis focuses on the individual or micro level first and allows defined behavior and attributes at the micro level to translate into a macro result. Using a bottom-up approach allows the modeler to avoid some assumptions that cannot be avoided in top-down approaches. ABMs, in contrast, make no assumptions about the existence of efficient markets or general equilibrium ("Agents of Change", 2010). In this thesis, using a bottom-up approach allows the water depots (agents) to act according to their behaviors without constraint at the system level.

Agents are the individuals or objects within the model with defined attributes and behaviors. Another defining characteristic of agents is that they are autonomous. ABM relies on the independence of agents so they follow individual rules and behaviors unlike a model where rules may be applied universally to the entire system (Wilensky & Rand, 2015).

This independence allows for many more real-world applications such as agents representing humans as citizens in a computational model of Tiebout competition (Kollman, Miller, & Page, 1997). In this model, multiple institutions are examined and differences are found to exist between them. Agents in this model follow utility maximization behaviors. Albin & Foley (1992) also used agents in a simulated decentralized exchange system with bargaining. Agents in this model maximize utility between two goods. Exchanges are made by advertising, which includes a cost, accounting for communication or search costs. These studies provide sources of ABM application in economics using utility function maximization theory.

Another distinction is that ABM always starts at the micro level—the level of the agent—and outcomes and properties at the macro level rely on how agents are defined and how they behave (Wilensky & Rand, 2015). This is what is meant when ABM is described as using a "bottom-up" approach. This approach allows users to examine complex systems and the phenomena of emergence.

Complex systems with interacting agents cause the system to exhibit properties and behaviors that are not found in the properties and behaviors of the individual agents. These interaction effects have a large influence on the final outcome of the system. Wilensky and Rand (2015) noted several real-world examples of complex systems occurring in the flight of birds in a

"V" formation and in traffic flows. Complex systems are formed from each bird or driver of vehicles acting independently and randomly according to the rules and behaviors for each bird or driver, but from these random actions, an ordered system emerges. The result of randomness leading to order is the phenomenon of emergence.

Emergent behavior and properties can be useful in deepening knowledge at macro and micro levels of a system. Sometimes research results will focus on the final outcome (macro level) while neglecting careful examination of how the micro level decisions led to the macro level result. Without the analysis of micro level behaviors, there is the possibility of making false inferences about how the micro level explains and leads to the macro level results. This can be seen in the example of birds flying in a flock where looking at a stable "V" formation can lead to the false inference that each birds remains in the same place when in reality, birds will occupy different places throughout flight (Wilensky & Rand, 2015). This leads to an understanding that macro properties do not always translate to properties of those at the micro level. Research is not expected to be flawless, but taking extra steps to support each level involved in reaching conclusions is an effective way to minimize the possibility of errors.

To uncover the more intricate details of the water depot-based allocation system in western North Dakota, ABM will be an effective means of examining the emergent behaviors present in the region. Through the use of ABM, deeper insight into the driving factors for water depots in the Bakken will be revealed. Examining emergence in complex systems is the main goal of agent-based models, and this is one reason ABM will be used to examine water depot behavior.

Adam Smith and Principles of ABM

One of Adam Smith's most important ideas in the *Wealth of Nations* (1776) stems from people acting in regards to their own self-interest. Smith wrote, "It is not from the benevolence of the butcher, the brewer, or the baker, that we expect our dinner, but from their regard to their own interest" (1776, I.2.2). We also see in perhaps, a more startling fashion, "By pursuing his own interests he frequently promotes that of the society more effectually than when he really intends to promote it" (Smith, 1776, IV.2.9). People acting in complete disregard for others—only looking upon themselves—often is what is best for society, but there is still the question of how and why this works.

Smith also introduced the idea of the invisible hand in markets. By the work of the invisible hand, free markets efficiently distribute goods and services such that actors in the market will change their supply and demand of goods and services, especially based on price mechanism. This is all completed without outside regulation or influence, i.e., the invisible hand dictates the process.

Smith's ideology runs parallel with the principles of ABM which assumes no outside intervention, and agents acting in accord to their own goals can lead not only to a functional result, but also to a stable equilibrium in the result. This also relates to decentralized actions where there is no central planner involved.

Welfare Economics and The Walrasian Auctioneer

Adam Smith's invisible hand is a way of expressing the first fundamental theorem of welfare economics before the theorem was formally contrived (Blaug, 2007). Other economists, such as French economist Leon Walras, also played a large role in advancing toward this theorem and in advancing the field of welfare economics. This is evident as many scholars may refer to competitive equilibriums as Walrasian equilibriums, but Vilfredo Pareto is credited with the formal derivation of the first theorem of welfare economics in 1906 (Blaug, 2007). Walras's model continues to have a large impact today as it is still the foundation used by many economists attempting to model economic systems (Tesfatsion, 2005).

Competitive (Walrasian) equilibriums occur when prices are allowed to fluctuate and when the existence of a market containing other consumers and producers creates a competitive environment where a market equilibrium is reached. This type of equilibrium requires some assumptions be made about price and market competition; prices must be flexible and there needs to be market competition. An example where there would not be a competitive equilibrium and therefore an improper application of the first fundamental welfare theorem would be in the case of a market dominated by a monopoly or any competition-restricting markets. If assumptions about price and competition hold, the competitive equilibrium is Pareto-optimal as well, i.e., in a market no one can be made better off at the expense of the other. Reaching a competitive equilibrium and therefore also reaching a Pareto-optimal point signifies a market clearing point many economists and general observers may agree to be good benchmarks for price and quantity in many markets.

Determining how prices fluctuate and are determined in such competitive environments is another issue that is vitally important to competitive equilibrium models. This analysis examines additional assumptions about the pricing mechanism.

In analyzing the invisible hand, how the market arrives at equilibrium prices and quantities that benefit everyone is not recognized, but the Walrasian Auctioneer's role is to carry out a sequence that allows a decentralized market to lead to an efficient outcome. In order to transition to ABM, the Walrasian Auctioneer is replaced by an agent-driven procurement process (Tesfatsion, 2005). Also, Tesfatsion (2005, p. 5) warns, “It [Walrasian equilibrium] does not address, and was not meant to address, how production, pricing, and trade actually take place in real-world economies through various forms of procurement processes”. Keeping these ideas in mind, the auctioneer calls out prices and, essentially, gathers bids from both the demand and supply sides. If there is excess supply or demand, prices will continue to be adjusted—rising if there is excess demand and falling if there is excess supply—until supply is greater than or equal to demand (Tesfatsion, 2005).

When using this mechanism, goods and services are not exchanged until the equilibrium is reached which is one of a few assumptions that must be made when using the Walrasian Auctioneer. Additional assumptions that can be gleaned are the lack of interaction between agents prior to exchanges and knowledge of the auctioneer in knowing demand and supply functions of those in the market. Because of the lack of interaction between market agents, this prevents strategic behavior and collaboration from occurring between these market agents (Tesfatsion, 2005). These characteristics and assumptions simplify a real-world problem (as a model typically does), but oversimplification can be overdone as well.

ABM & The Market Mechanism

Using ABM, one can attempt to fill the void of the auctioneer with methodology that simulates a more realistic mechanism for reaching equilibriums. Modeling Walrasian equilibrium without using the Walrasian Auctioneer is nearly impossible, if not impossible, in many cases (Tesfatsion, 2005). Using ABM in this context is often referred to as agent-based computational economics (ACE). Tesfatsion (2005) simulates this process of replacing the

Walrasian Auctioneer, and suggests that a similar process can be applied to other economic theories with assumptions that may be constraining.

ABM vs Other Models

A key difference between ABM and other traditional models is that "ABM is simulation based, not equilibrium based" (Nolan et al., 2009, p. 419). ABM can be modeled using sets of equations, and the equations describe agents separately (Bonabeau, 2002). At times, equation-based modeling takes a centralized approach which makes the modeling techniques significantly different. When comparing decentralized approaches in ABM to centralized approaches, a centralized approach often requires more assumptions. Some assumptions that can be relaxed in economic applications include assuming rational agents, homogeneous agents, decreasing returns to scale in economic processes, and looking at long-run equilibrium as the main focus in the system (Arthur, Durlaf, & Lane, 1997; Macal & North, 2010). Relaxing several assumptions can result in a more representative model of how agents—particularly human agents—behave because the model has fewer obstacles if agents do not exhibit the previous properties in the real world. Econometric and theoretical models are limited as well in addressing scenarios of heterogeneous decision-making units and heterogeneous environments, but ABM is suitable for these scenarios (Nolan et al., 2009; Parker et al., 2003).

Issues in using ABM

Agent attributes, behaviors, and states must be well understood to generate an accurate model. Models with a centralized approach do not require understanding every individual in nearly as much detail, but that also comes at the cost of losing accuracy or even unrealistic results if agents should be modeled heterogeneously (Wilensky & Rand, 2015); if a system can be modeled with homogeneous agents, ABM may not be important to use.

Although technology continues to grow, another problem ABM can encounter is the issue of computation. Bonabeau (2002) pointed out how one could possibly model a system using only a few equations if looking at the aggregate level of the system. In contrast, ABM requires so much information at the agent level that running simulations would use a great deal of computation and time, especially if there is a large number of agents.

Benefits of ABM

ABM has many benefits that make it more useful than other modeling techniques. Bonabeau (2002) concisely states, “The benefits of ABM over other modeling techniques can be captured in three statements: (i) ABM captures emergent phenomena; (ii) ABM provides a natural description of a system; and (iii) ABM is flexible” (2002, p. 7280). In a time when we do not know what the macro result will look like—especially in an economic context—having a modeling technique that does not require assumptions about the macro system is important.

ABM in the context of modeling the economy at the macro level could complement current models. After the recent financial crisis of the late 2000s, criticism of traditional economic models in macroeconomic forecasting opened investigation into the possible application of ABM for macroeconomic forecasting (“Agents of Change”, 2010). This type of modeling could theoretically model consumers, producers and many other agents. Agents could be modeled with unique attributes, behaviors and states that reflect how each would behave in the real-world environment. ABM does not keep strong assumptions of rational expectations on agents either, which has been criticized in other economic models ("Agents of Change", 2010). This is because ABM allows for behavioral uncertainty in agents (Tesfatsion, 2005).

ABM allows for modeling flexibility as well by the ability to adjust the number of agents or characteristics for each agent as conditions may change. Bonabeau (2012) suggests that ABM may be used if there is uncertainty regarding the complexity of a model, and experimenting with different variables can help determine that complexity.

Using ABM in water management scenarios is beneficial as it avoids some drawbacks faced in older forecasting methods such as problems presenting underlying hypotheses, problems integrating significant geographical features, and problems forming a model that considers multiple socioeconomic factors (Galán et al., 2009). Another benefit of ABM is the more realistic feedback system because ABM operates iteratively which can prevent immediate actions from agents that would not react immediately to water management changes (House-Peters & Chang, 2011). ABMs also fall under the category of a multiple agent system (MAS) framework and have been used to simulate agent behavior in watershed basins in an attempt to more effectively model the real world behaviors of actors. Presenting a water management analysis in North Dakota using optimization and simulation in an ABM framework will provide contributions for further research to be conducted in both North Dakota water management and ABM.

CHAPTER V. A DECENTRALIZED ABM APPROACH

Theoretical Framework for a Decentralized ABM

Decentralized Optimization

Following the decentralized optimization method used by Lim et al. (2016) and Yang et al. (2012), an agent-based model will be used to simulate water depot behavior using equations based on utility maximization theory. Utility maximization in a multiple agent system (MAS) has been applied in watershed management scenarios before (Yang, Cai, & Stipanovic, 2009; Yang, Zhao, & Cai, 2012). Following this example, the methodology with adjustments is applied to fit the unique water depot allocation system in western North Dakota. Each water depot attempts to maximize its benefit by selling as much water as it can subject to a set of constraints. The constraints reflect the limits set by either water permits issued to the water depots and the supply of water available to all water depots. These can change each year based on different political and environmental factors.

Agents behave autonomously and do not necessarily follow the same behavior as other agents. Environmental constraints on water source, in themselves, are not an issue for water consumption. The amount of water permitted from the water sources is the constraint associated with the regulations imposed.

Using a penalty-based decentralized optimization method, water depots balance maximizing their benefit functions with facing penalties associated with their penalty functions. This can be seen by the objective of each agent in Equation 1:

$$\max_{x_i} \Pi_i(x_i, \beta_i | \{x_r\}_i) = \max[\beta_i \cdot \pi_i(x_i) - P_i(x_i | \{x_r\}_i\ )], \tag{1}$$

$\forall i \in M = \{1, \dots m\}$ agents, where Π_i is the objective function for agent i, x_i is a decision variable for *i* with permits to draw water, β_i is a local interest parameter with $\beta_i > 0$, $\{x_r\}_i$ is a set of actions by agents in the relative area that affect i, π_i is the benefit function without application of any penalties, and P_i is the penalty function which accounts for any violation of the constraints. If $P_i > 0$, the agent is penalized for violating a constraint and its benefit from selling water is reduced by $-P_i$; otherwise, $P_i = 0$. Larger values of β_i correspond to larger values for the benefit function of agent *i*; however, agent *i* will be more likely to incur larger penalty values as well. The benefit function will measure profit by representing water sales. Marginal costs are also insignificant for water depots, so costs are assumed to be zero. Penalty functions penalize agents when water consumption is greater than water permitted to individual agents or groups of agents consuming from the same water source acting in the place of fines imposed on unregulated water use.

Local Optimization

When looking at local optimization, agents are assumed to attempt to maximize their benefits given the actions of other agents in their relative area. The decentralized optimization problem for each agent is defined in Equation 2:

$$\max_{x_i} \Pi_i(x_i, \beta_i | \{x_r\}_i), \tag{2}$$

with the solution in Equation 3:

$$[x_i^* | \beta_i, \{x_{\sim i}\}] = \arg\max_{x_i} \Pi_i(x_i, \beta_i | \{x_r\}_i) \tag{3}$$

The optimal solution x_i^* is the optimal water quantity for water depot *i* to consume. This water quantity will provide water depot *i* with the greatest benefit given the constraints placed by its neighboring agents' water consumption.

Global Optimization

The penalty function P_i in Equation (1) contains all the constraints associated with x_i at the system level and is shown in Equation 4:

$$P_i(x_i|\{x_r\}_i) = P_{li}(x_i) + P_{gi}(x_i|\{x_r\}_i), \tag{4}$$

where $P_{l_i}(x_i) = \sum_{q=1}^{q_i} P_{l_i,q}(x_i)$ is the sum of all local constraints associated with x_i, and $P_{g_i}(x_i|\{x_r\}_i) = \sum_{s=1}^{s_i} P_{g_{i,s}}(x_i|\{x_r\}_i)$ is the sum of all constraints associated with x_i and $\{x_r\}_i$. The second half of Equation 4 therefore is the interconnecting penalty function

The penalty function for local constraints applies to individuals consuming water above individual permits and the global penalty function incorporating the system constraints applies when agents drawing water from the same source have higher combined water consumption than these same agents' total permitted water amounts from that source. Global constraints with source violations are based on permits as the SWC runs a model that calculates and allows a certain quantity of water to be permitted encapsulating this global constraint already (M. Hove, personal communication, June 28). All constraints are permit constraints rather than physical constraints.

The global objective function is presented in Equation 5:

$$\Pi(x, \beta|\{x_r\}_i) = \sum_{i=1}^{m} \left(\beta_i \cdot \pi_i(x_i) - P_{l_i}(x_i)\right) - \sum_{s=1}^{s_i} P_{g_{i,s}}(x_i|\{x_r\}_i), \tag{5}$$

where m is the number of agents. Equation (5) obtains a global performance metric (İnalhan et al., 2002). Also, the sum of the objective functions in Equation 5, measures the benefits of all agents given the permit constraints, while the sum of the global constraints measures the system violation.

First-Order Necessary Condition and Second-Order Sufficient Condition for Decentralized Optimization

Solving for the optimal solution in (1), and based on Inalhan, Stipanovic, & Tomlin (2002) and Yang et al. (2009), the first-order necessary condition and the second-order sufficient conditions are shown in Equation 6 and Equation 7, respectively. The negative definite matrix in Equation 7 shows that the value from the first derivative in Equation 6 is a true local maximum.

$$\frac{\partial}{\partial x_i} \Pi_i(x_i^*, \beta_i^* | \{x_r\}_i) = 0, \forall i \in M, \tag{6}$$

$$\frac{\partial^2}{\partial x_i^2} \Pi_i(x_i^*, \beta_i^* | \{x_r\}_i) < 0, \forall i \in M, \tag{7}$$

where < 0 indicates the matrix is negative definite in Equation 7.

Differentiable Inexact Penalty Format

Equation 6 also represents differentiating Equation 1 and setting the derivative equal to zero. This finds the maximum of the objective function, and the first-order necessary condition can also be written as:

$$\begin{aligned}\frac{\partial}{\partial x_i} \Pi_i(x_i^*, \beta_i^* | \{x_r\}_i) = \beta_i \cdot \frac{\partial \pi_i(x_i)}{\partial x_i} - \frac{\partial P_i(x_i | \{x_r\}_i)}{\partial x_i} \Bigg|_{x=x^*, \beta=\beta^*} \\ = 0, \forall i \in M.\end{aligned} \tag{8}$$

The penalty function allows for negative profits in the profit function incorporating both local and global constraints as follows:

$$P_i(x_i|\{x_r\}_i\ ) = \sum_{k=1}^{k_i} \max(\ 0, g_i(x_i|\{x_r\}_i\ )^2),$$

(9)

where k_i denotes the number of constraints associated with agent i; $g_i(x_i|\{x_r\}_i\ )$ is squared to ensure second-order differentiability as seen in Equation 7, and $g_i(x_i|\{x_r\}_i\ )$ is the constraint function that accounts for agent i's local constraints ($g_{li}(x_i)$) and global constraints ($g_{gi}(x_i|\{x_r\}_i\ )$):

$$g_i(x_i|\{x_{\sim i}\}) = \begin{cases} g_{li}(x_i) \leq 0 \\ g_{gi}(x_i|\{x_r\}_i) \leq 0 \end{cases}.$$

(10)

global constraints, $g_{gi}(x_i|\{x_r\}_i)$, interconnect agent i to other agents within the system.

The decentralized agent-based model does not obtain a system-level optimal solution, and this is because agents do not have an awareness of system level factors. The agents are only aware of themselves and the factors in their related areas. Also because agents are self-interested, they are not concerned with maximizing system level benefits, but rather with maximizing their own benefits. They do this taking into consideration individual constraints along with the system level constraints that apply to them.

Water Depots in North Dakota

In this thesis, agents are nine different types of water depots based on identifying characteristics such as organizational structure, permit type, and water source (see Table 2). Each type of water depot has a description and water source. The descriptions reflect the most common owners of water depots in western North Dakota or the permit type associated with the water depot. These were decided based on the literature and communication with people actively involved with water depots including members of the North Dakota State Water Commission (SWC). These combinations of permit types and water sources were selected based on general knowledge gathered from the two sources just mentioned as well through examination of the data provided by the SWC. When analyzing the data, if there were a sufficient number of water depots or amount of reported water consumption, these types of water depots would be compared with the general knowledge to prevent the addition of water depot types that only came from looking at the data. The time period from 2007-2014 was chosen based on available completeness and reliable data from the SWC. These criteria are fitting to provide a representative sample of water depots to be used for the purposes of this study. Future studies on water depots in North Dakota could analyze the individual water depots rather than sorting them into types for a greater in-depth analysis.

Agent Equations & Constraints

Agent types exhibit unique equations and constraints. Table 2 provides an overview for each agent type.

Table 2

Agent definitions for different types of water depot (WD)

Agent	WD type	Definition
1	Industrial – Fox Hills	Privately owned WDs with perfected permits for withdrawing water from the Fox Hills aquifer.
2	Industrial –GW	Privately owned WDs with perfected permits for withdrawing water from shallow groundwater (GW) aquifers.
3	Industrial – LSMR	Privately owned WDs with perfected permits for withdrawing water from Lake Sakakawea (LS) or the Missouri River (MR).
4	Industrial –SW	Privately owned WDs with perfected permits for withdrawing water from surface water sources other than LS or the MR.
5	Government-Enacted – LSMR	Government owned WDs with permits for withdrawing water from LS or the MR.
6	City –GW	City owned WDs with permits transferred from municipal water use permits withdrawing water from shallow GW aquifers.
7	Irrigation transferred – GW	Privately owned WDs with yearly permits temporarily transferred from irrigation permits withdrawing water from shallow GW aquifers.
8	Temporary – LSMR	Privately owned WDs with temporary permits (less than 1 year) withdrawing water from LS or MR.
9	Temporary –SW	Privately owned WDs with temporary permits (less than 1 year) withdrawing water from surface water sources other than LS or MR.

Agent 1: Permanent-Fox Hills (Water Depot Type 1)

This agent is a water depot that sells industrial water sourced from the Fox Hills (FH-HC) aquifer. This is a particularly important groundwater source in North Dakota, and provides water for many farmers and ranchers (Shaver, 2012).

The benefit function given the constraints for agent 1 is given in Equation 11:

$$\max_{x_{1t}} f_1(x_{1t}) = a_1 x_{1t}^2 + b_1 x_{1t} + c_1 + \delta_1 T, \tag{11}$$

$$\text{Subject to} \begin{cases} x_{1t} - WP_{1t} \leq 0, \\ n_{1t}x_{1t} - FH_t \leq 0 \end{cases}$$

where the subscript 1 denotes agent 1; $f_1(x_{1t})$ is the objective function for agent 1 deriving benefit from the amount of water consumption of agent 1 in year *t* (x_{1t}) and $a_1, b_1, c_1,$ and δ_1 are the coefficients of the objective function for agent 1 where T is a year variable with the base year in 2007.

The first constraint in (11) means water consumption for agent 1 (x_{1t}) should not exceed the amount of water permitted to be used by agent 1 in year *t* (WP_{1t}). In the second constraint in (11) n_{1t} is the number of type 1 water depots in year *t*. Total water consumption of all type 1 water depots in year *t* ($n_{1t}x_{1t}$) should not exceed the total water available from the FH-HC aquifer in year *t* (FH_t).

Agent 2: Permanent-Other Groundwater (Water Depot Type 2)

This agent is a water depot with a conditional or perfected water permit which obtains its water from a groundwater source other than the FH-HC aquifer.

The benefit function given the constraints for agent 2 is given in Equation 12:

$$\max_{x_{2t}} f_2(x_{2t}) = a_2 {x_{2t}}^2 + b_2 x_{2t} + c_2 + \delta_2 T, \tag{12}$$

$$\text{Subject to} \begin{cases} x_{2t} - WP_{2t} \le 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \le 0 \end{cases}$$

where the subscript 2 denotes agent 2; $f_2(x_{2t})$ is the objective function for agent 2 deriving benefit from the amount of water consumption of agent 2 in year *t* (x_{2t}) and $a_2, b_2,$ and $c_2,$ and δ_2 are the coefficients of the objective function for agent 2.

The first constraint in (12) means water consumption for agent 2 (x_{2t}) should not exceed the amount of water permitted to be used by agent 2 in year *t* (WP_{2t}). The second constraint in (12) implies that total water consumption by type 2, 6, and 7 water depots in year *t* should not exceed the total water available from shallow aquifers (GW) in year *t* (GW_t).

Agent 3: Permanent-Lake Sakakawea/Missouri River (Water Depot Type 3)

This agent is a water depot with a conditional or perfected water permit which obtains its water from Lake Sakakawea or the Missouri River. There is an abundance of water from these sources, but there has also been conflict between the state and federal governments over access to these water sources.

The benefit function given the constraints for agent 3 is given in Equation 13:

$$\max_{x_{3t}} f_3(x_{3t}) = a_3 {x_{3t}}^2 + b_3 x_{3t} + c_3 + \delta_3 T, \tag{13}$$

$$\text{Subject to} \begin{cases} x_{3t} - WP_{3t} \le 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \le 0 \end{cases}$$

where the subscript 3 denotes agent 3; $f_3(x_{3t})$ is the objective function for agent 3 deriving benefit from the amount of water consumption of agent 3 in year *t* (x_{3t}) and a_3, b_3, c_3, and δ_3 are the coefficients of the objective function for agent 3.

The first constraint in (13) means water consumption for agent 3 (x_{3t}) should not exceed the amount of water permitted to be used by agent 3 in year *t* (WP_{3t}). The second constraint in (13) implies that total water consumption by type 3, 5, and 8 water depots in year *t* should not exceed the total water available from LSMR in year *t* ($LSMR_t$).

Agent 4: Permanent-Other Surface Water (Water Depot Type 4)

This agent is a water depot with a conditional or perfected water permit which obtains its water from a surface water source other than Lake Sakakawea or the Missouri River. Typically, these water depots source their water from tributaries of rivers.

The benefit function given the constraints for agent 4 is given in Equation 14:

$$\max_{x_{4t}} f_4(x_{4t}) = a_4 x_{4t}^2 + b_4 x_{4t} + c_4 + \delta_4 T, \tag{14}$$

$$\text{Subject to} \begin{cases} x_{4t} - WP_{4t} \leq 0, \\ n_{4t}x_{4t} + n_{9t}x_{9t} - SW_t \leq 0 \end{cases}$$

where the subscript 4 denotes agent 4; $f_4(x_{4t})$ is the objective function for agent 4 deriving benefit from the amount of water consumption of agent 4 in year *t* (x_{4t}) and a_4, b_4, c_4, and δ_4 are the coefficients of the objective function for agent 4.

The first constraint in (14) means water consumption for agent 4 (x_{4t}) should not exceed the amount of water permitted to be used by agent 4 in year *t* (WP_{4t}). The second constraint in (14) implies that total water consumption by type 4 and 9 water depots in year *t* should not exceed the total water available from SW in year *t* (SW_t).

Agent 5: Coop-Lake Sakakawea/Missouri River (Water Depot Type 5)

This agent is a water depot which is a part of a cooperative agency. These agencies include the Southwest Water Authority (SWA) and the Western Area Water Supply Authority[1] (WAWSA). The depots included in this grouping obtain their water from Lake Sakakawea or the Missouri River. Agent 5 accounts for the largest amount of water consumed by the different agents (Table 3).

The benefit function given the constraints for agent 5 is given in Equation 15:

$$\max_{x_{5t}} f_5(x_{5t}) = a_5 x_{5t}^2 + b_5 x_{5t} + c_5 + \delta_5 T, \tag{15}$$

$$\text{Subject to} \begin{cases} x_{5t} - WP_{5t} \le 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \le 0 \end{cases}$$

where the subscript 5 denotes agent 5; $f_5(x_{5t})$ is the objective function for agent 5 deriving benefit from the amount of water consumption of agent 5 in year *t* (x_{5t}) and $a_5, b_5, c_5,$ and δ_5 are the coefficients of the objective function for agent 5.

The first constraint in (15) means water consumption for agent 5 (x_{5t}) should not exceed the amount of water permitted to be used by agent 5 in year *t* (WP_{5t}). The second constraint in (15) implies that total water consumption by type 3, 5, and 8 water depots in year *t* should not exceed the total water available from LSMR in year *t* ($LSMR_t$).

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[1] The Western Area Water Supply Authority (WAWSA) was primarily formed to provide more accessible drinking water for the population in this region (Western Area Water Supply Authority, 2011). Funding came in the form of a \$110 million loan from the state with another \$40 million that would be received at a later date (Western Area Water Supply Authority, 2011; Kusnetz, 2012). By 2013 the WAWSA owned nine water depots and planned to pay back the state by selling 20 percent of the water it owned for fracking purposes (Scheyder, 2013).

Agent 6: City-Other Groundwater (Water Depot Type 6)

This agent is a water depot owned by a city. These water depots access their water from groundwater sources that do not include the FH-HC aquifer. Many of these depots have transferred previous permits to industrial use in lieu of the oil boom and have done so on a temporary basis.

The benefit function given the constraints for agent 6 is given in Equation 16:

$$\max_{x_{6t}} f_6(x_{6t}) = a_6 x_{6t}{}^2 + b_6 x_{6t} + c_6 + \delta_6 T, \tag{16}$$

$$\text{Subject to} \quad \begin{cases} x_{6t} - WP_{6t} \leq 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \leq 0 \end{cases}$$

where the subscript 6 denotes agent 6; $f_6(x_{6t})$ is the objective function for agent 6 deriving benefit from the amount of water consumption of agent 6 in year *t* (x_{6t}) and a_6, b_6, c_6, and δ_6 are the coefficients of the objective function for agent 6.

The first constraint in (16) means water consumption for agent 6 (x_{6t}) should not exceed the amount of water permitted to be used by agent 6 in year *t* (WP_{6t}). The second constraint in (16) implies that total water consumption by type 2, 6, and 7 water depots in year *t* should not exceed the total water available from shallow aquifers (GW) in year *t* (GW_t).

Agent 7: Irrigation Transferred-Other Groundwater (Water Depot Type 7)

This agent is a water depot which originally had a water permit for irrigational use and has temporarily transferred it to industrial use. This transfer was allowed because of increased demand for water from the oil industry. However, these transfers will no longer be allowed after September 2016 according to Mike Hove from the SWC **(**personal communication, June 28, 2016**).**

The benefit function given the constraints for agent 7 is given in Equation 17:

$$\max_{x_{7t}} f_7(x_{7t}) = a_7 {x_{7t}}^2 + b_7 x_{7t} + c_7 + \delta_7 T, \tag{17}$$

$$\text{Subject to} \quad \begin{cases} x_{7t} - WP_{7t} \leq 0, \\ n_{2t}x_{2t} + n_{6t}x_{6t} + n_{7t}x_{7t} - GW_t \leq 0 \end{cases}$$

where the subscript 7 denotes agent 7; $f_7(x_{7t})$ is the objective function for agent 7 deriving benefit from the amount of water consumption of agent 7 in year *t* (x_{7t}) and $a_7, b_7, c_7,$ and δ_7 are the coefficients of the objective function for agent 7.

The first constraint in (17) means water consumption for agent 7 (x_{7t}) should not exceed the amount of water permitted to be used by agent 7 in year *t* (WP_{7t}). The second constraint in (17) implies that total water consumption by type 2, 6, and 7 water depots in year *t* should not exceed the total water available from shallow aquifers (GW) in year *t* (GW_t).

Agent 8: Temporary-Lake Sakakawea/Missouri River (Water Depot Type 8)

This agent is a water depot with a temporary water permit. In order for this agent to continue selling water, it must reapply for a new temporary permit every year. This agent only uses water from Lake Sakakawea or the Missouri River.

The benefit function given the constraints for agent 8 is given in Equation 18:

$$\max_{x_{8t}} f_8(x_{8t}) = a_8 {x_{8t}}^2 + b_8 x_{8t} + c_8 + \delta_8 T, \tag{18}$$

$$\text{Subject to} \quad \begin{cases} x_{8t} - WP_{8t} \leq 0, \\ n_{3t}x_{3t} + n_{5t}x_{5t} + n_{8t}x_{8t} - LSMR_t \leq 0 \end{cases}$$

where the subscript 8 denotes agent 8; $f_8(x_{8t})$ is the objective function for agent 8 deriving benefit from the amount of water consumption of agent 8 in year *t* (x_{8t}) and a_8, b_8, c_8, and δ_8 are the coefficients of the objective function for agent 8.

The first constraint in (18) means water consumption for agent 8 (x_{8t}) should not exceed the amount of water permitted to be used by agent 8 in year *t* (WP_{8t}). The second constraint in (18) implies that total water consumption by type 3, 5, and 8 water depots in year *t* should not exceed the total water available from LSMR in year *t* ($LSMR_t$).

Agent 9: Temporary-Other Surface Water (Water Depot Type 9)

This agent is a water depot with a temporary water permit. This agent must also apply for a new temporary permit every year to continue operating. This agent uses water from surface water sources other than Lake Sakakawea and the Missouri River. Often these agents use creeks, ponds, and other small water sources.

The benefit function given the constraints for agent 9 is given in Equation 19:

$$\max_{x_{9t}} f_9(x_{9t}) = a_9 {x_{9t}}^2 + b_9 x_{9t} + c_9 + \delta_9 T, \tag{19}$$

$$\text{Subject to} \quad \begin{cases} x_{9t} - WP_{9t} \leq 0, \\ n_{4t}x_{4t} + n_{9t}x_{9t} - SW_t \leq 0 \end{cases}$$

where the subscript 9 denotes agent 9; $f_9(x_{9t})$ is the objective function for agent 9 deriving benefit from the amount of water consumption of agent 9 in year *t* (x_{9t}) and a_9, b_9, c_9, and δ_9 are the coefficients of the objective function for agent 9.

The first constraint in (19) means water consumption for agent 9 (x_{9t}) should not exceed the amount of water permitted to be used by agent 9 in year *t* (WP_{9t}). The second constraint in

(19) implies that total water consumption by type 4 and 9 water depots in year t should not exceed the total water available from SW in year t (SW_t).

Coefficients

Coefficients a, b, c and δ in equations (11) through (19) are adjusted in a trial and error process to model agent behavior and simulate water consumption values matching those from the data. This results in different values for the coefficients depending on the agent type. Different signs are also used in coefficients so that the benefit function for each agent will have the shape of a concave parabola—coefficients a and c are negative while b and δ are positive.

The shape of the parabola is shown in Figure 6 with two important values on the graph. Point *I* is negative profits in the concave optimization equation for the ABM model, which occurs at a zero water consumption level. Point *II* is the optimization point for profits. The use of a quadratic benefit function ensures the existence of a maximum. In this thesis, agents' benefits are measured by their profit functions.

The water demand curve facing each water depot is downward sloping because the water depot industry is spatially or monopolistically competitive, since some water depots have a location advantage over their competitors. For example, a water depot near the oil field has a location advantage over another water depot farther away. The total cost is assumed to be constant. Thus, the assumptions provide a profit function that is quadratic.

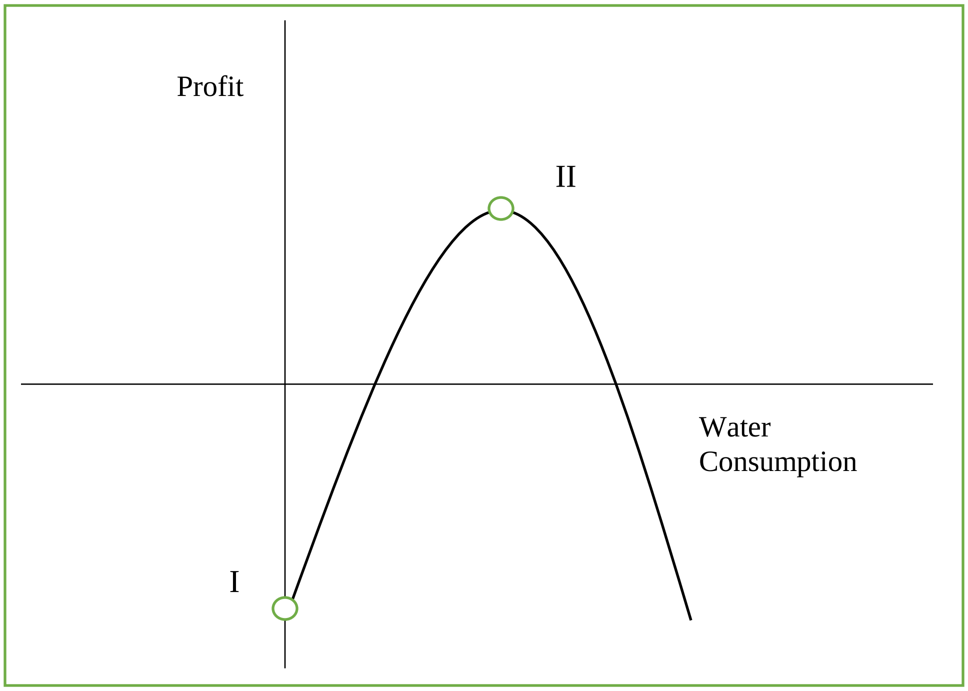

*Figure 6***.** Graph of Profit Function.

Scenarios

The baseline scenario is the current practices going on in the Bakken with the water depots. Permits are allowed for each water depot and water source as reported by the SWC. In the other scenarios, permits are restricting based on a specific criteria involved with a real scenario in which it could occur.

Scenario 1 looks at the effects of restricting water consumption from LSMR sources. This involves the permit constraints for agents 3, 5, and 8. This could occur if continued conflict between USACE and the state of North Dakota escalates to much larger restrictions on LSMR water access.

Scenario 2 looks at the effects of restricting water consumption from GW sources. This involves the permit constraints for agents 2, 6, and 7. This could occur in the case of droughts where surface water is lacking and water depots turn to groundwater sources for available water.

Scenario 3 looks at the effects of restricting water consumption from SW sources. This involves the permit constraints for agents 4 and 9. This could occur if a drought occurs and, in an effort to conserve water, the SWC reduces the amount of surface water that is allowed to be extracted for use by water depots.

Scenario 4 looks at the effects of restricting water consumption from both GW and SW sources. This is a worst-case scenario for a lack of water resources. This could be the case where water levels are so low from a severe drought that only LSMR sources are allowed to be used by water depots.

CHAPTER VI. DATA

Looking at the location and quantity of water depots from a geographical standpoint helps in becoming aware of how water depots have developed. Looking at Figure 7, one can note the increase in water depots especially beginning in 2007. Many farmers starting selling water from water depots with temporary permits rather than conditional or perfected permits in 2008, so this is one contributing factor in the increasing number of water depots in the past decade. Conditional and eventually perfect permits were still being received and used by applicants, but temporary permits allowed more people the ability to create water depots. Figure 7's other purpose is to show how the number of water depots has increased in separate time periods. There were water depots prior to 2007 as far back as 1965. These water depots, however, supplied only small amounts of water. The next six years from 2007-2012 show a large number of new water depots established due to the oil boom. Then, the years 2013-2014 show how fast the number of water depots grew in only two years. This separation for the years 2013-2014 also demonstrates how the increase in the number of water depots remained strong.

Figure 8 examines the amount of water consumption by individual water depots and the total water consumption amounts of water depots for each county in the western portion of North Dakota. The four counties with the highest water depot consumption amounts (Williams, Mountrail, McKenzie, and Dunn) also are the core oil producing counties in North Dakota. Williams County's water depots have accounted for most of the water consumption of all water depots in the state using approximately 71,500 acft from 2007-2014 (Figure 8). This map also notes that there are a number of water depots that have obtained water permits, but they have not reported any water use.

Table 3 provides information about the different agents. Agent 1 draws water from the FH-HC aquifer and this agent type uses the smallest amount of water accounting for 0.65% of total water withdrawn by water depots between 2007 and 2014. This could be because water from the FH-HC aquifer is being preserved for use by ranchers and farmers. Agent 5 draws water from Lake Sakakawea or Missouri River (LSMR) water sources; this agent withdraws more water than any other agent (23.84%). Agent 5 water depots also withdraw the largest amount of water on average—almost 1,500 acre-feet from 2007 to 2014. Even though agent 5 uses LSMR water, GW accounts for the majority of water withdrawn by water depots over the 8-year study period.

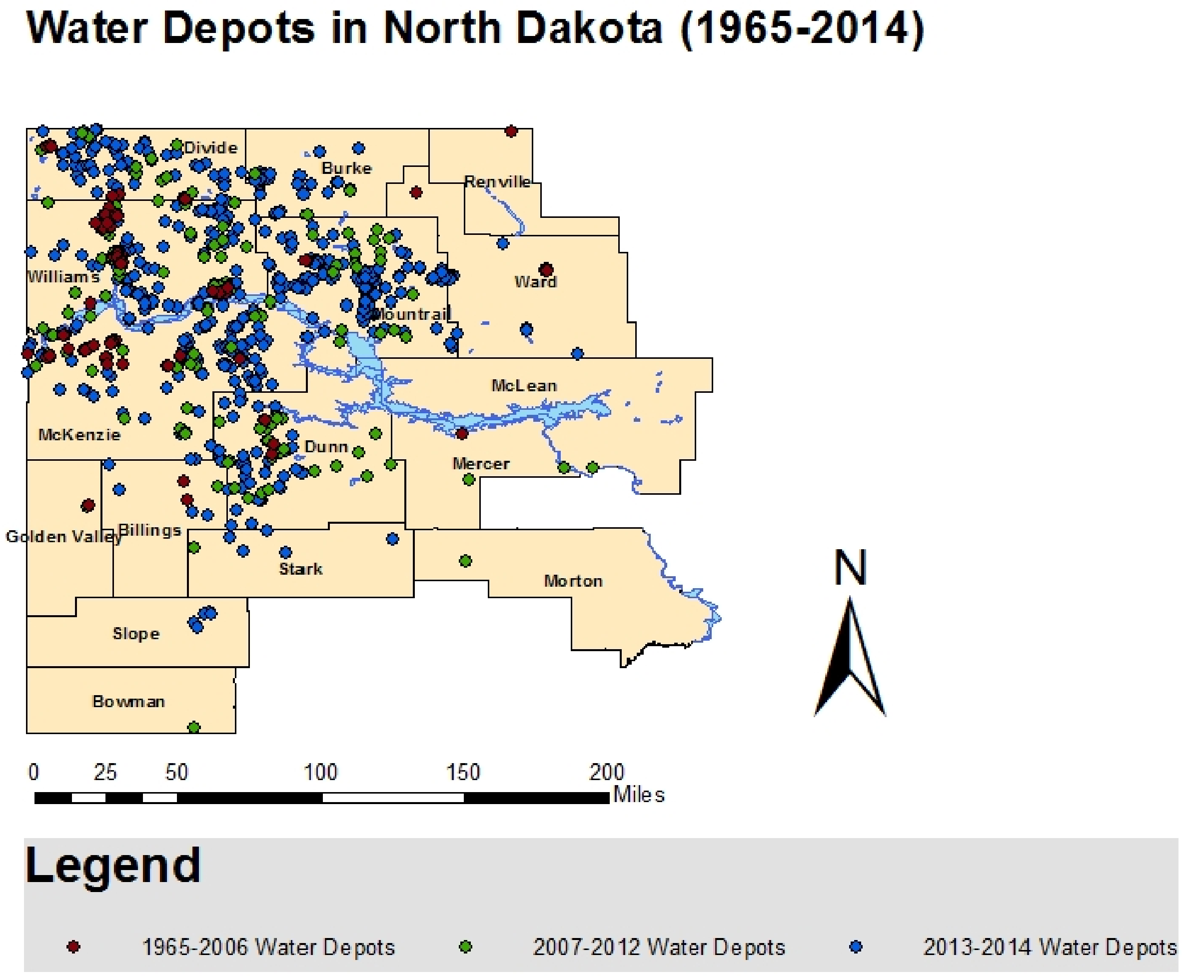

Figure 7[2]. Growth of Water Depots over Time. Data from North Dakota State Water Commission (SWC).

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[2] In Figure 7, all water depots are included. Also, some of the water depots from the later 2 sub-groups (2007-2012 & 2013-2014) are hidden under the 1965-2006 and 2007-2012 sub-groups respectively, since some of the same water depots have remained from previous years.

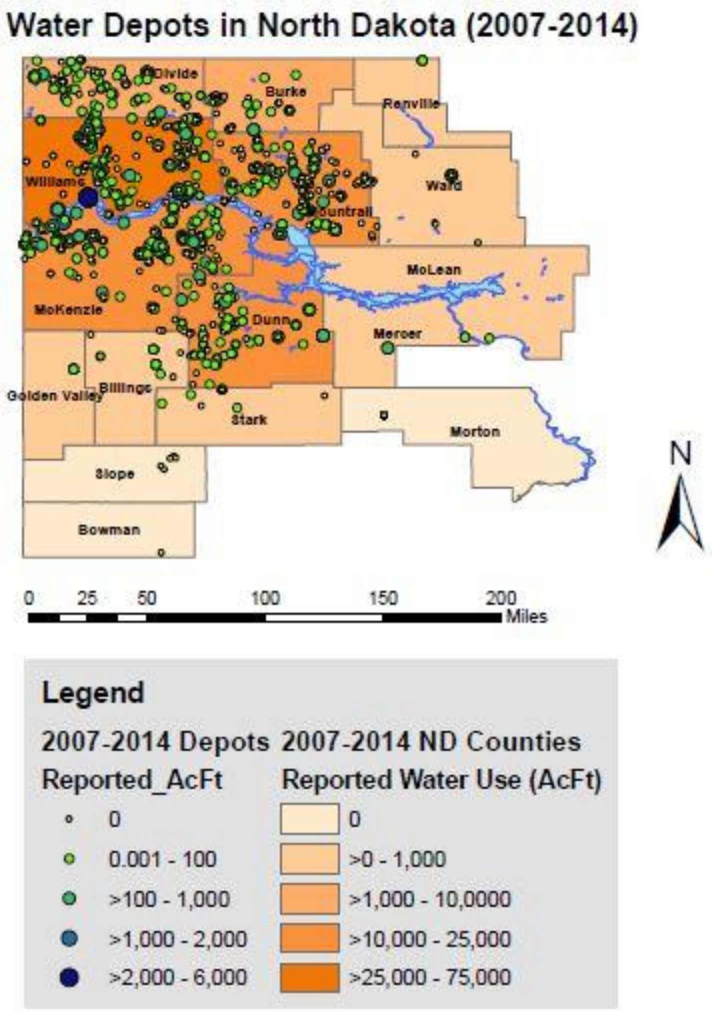

Figure 8[3]. Water Use by Water Depots (2007-2014). Data from North Dakota State Water Commission (SWC).

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[3] In Figure 8, all water depots are included. Counties with Reported Water Use of 0 contain water depots that have permits for water but did not use any water. Only water depot water consumption amounts are included in the county level water consumption values. The county level data contains the water use of the same water depots in different years. (e.g., the same water depot using 100 acre feet/year for five years would report 500 total acre feet towards the values in this figure)

Table 3

Summary of the water withdrawn by and approved water permits for different types of water depot (2007-2014)

Agent	WD type	Total water withdrawn (ac-ft)	Percent total water withdrawn (ac-ft)	Average water withdrawn (ac-ft)	Water withdrawn range (ac-ft)	Total approved water permit (ac-ft)	Average approved water permit (ac-ft)	Approved water permit range (ac-ft)
1	Industrial – Fox Hills	515.40	0.65%	16.11	0-60.36	1,040.00	32.50	20-60
2	Industrial – GW	10,865.90	13.66%	50.54	0-291.21	40,646.40	189.05	19.40-2,588.50
3	Industrial – LSMR	5,741.53	7.22%	249.63	0-1,946.90	548,728.00	23,857.74	1,950-90,000
4	Industrial – Other SW	2,789.74	3.51%	174.36	6.80-930.40	20,332.00	1,270.75	100-9,000
5	Government -Enacted – LSMR	18,961.80	23.84%	1,458.60	372.30-5,854.30	232,315.00	17,870.38	1,130-40,325
6	City –GW	3,484.76	4.38%	84.99	0-292.80	12,229.50	298.28	19-750
7	Irrigation transferred – GW	16,928.32	21.28%	132.25	0-783.70	82,837.10	647.16	20-4,182
8	Temporary – LSMR	3,441.16	4.33%	118.66	0-1,126.30	62,078.74	2,140.65	10.31-6,000.00
9	Temporary – SW	16,814.73	21.14%	27.48	0-1,183.89	108,498.60	178.45	0.46-10,000

CHAPTER VII. RESULTS & DISCUSSIONS

Utility maximization for each agent is accomplished using an iterative process following the equations previously outlined (Equations 11-19 in Chapter V). Each agent is interconnected in its consumption looking at the consumption of the other agents in determining an optimum consumption level for itself. An iterative process is used to find convergence in optimal consumption values for each agent. Simulated violations of the system water constraints along with permit constraints are measured. Each of these indicates the boundary was exceeded when the values are positive. When violations are present, they indicate areas where water depots might overuse water if left unchecked. Examining the violations provides policy makers with key areas to monitor if different scenarios occur.

Four scenarios are examined which provide possible future outcomes based on different precipitation and political factors. Each scenario simulates slightly different outcomes that can provide an additional resource for policy makers to consider before making adjustments to current water management policy. These scenarios are outlined and a baseline is provided for water depot water consumption in western North Dakota.

Scenario Results

Simulated violations and benefits are tracked in these scenarios. The violations are identified as two types: the permit violation of an individual water depot (V1) and the water source violations (V2). Constraints V2 violations are based on the SWC using a model to establish the total amount of water it will approve in water permits for each water source. This information is used to establish the constraint used in calculating V2 violations. V2 violations in each scenario are further analyzed to quantify the water use violation for each water source.

Benefits are the profits of the water depots, and total benefits is used to show total simulated profits gained by water depot water sales each year. Violations in acre-feet are shown on the left vertical axis while profits in millions of dollars are shown on the right vertical axis in Figures 9-17.

Baseline

As seen in Figure 9, violations decrease over time while benefits increase over time. TotalV1 is the aggregate individual water depot permit violation and TotalV2 is the aggregated water source violations. Total benefits or profits have been increasing each year with the greatest increase occurring from 2013 to 2014. With additional time, water depot owners have been able to build a larger customer base as oil production has increased (Figure A.2 in the appendix).

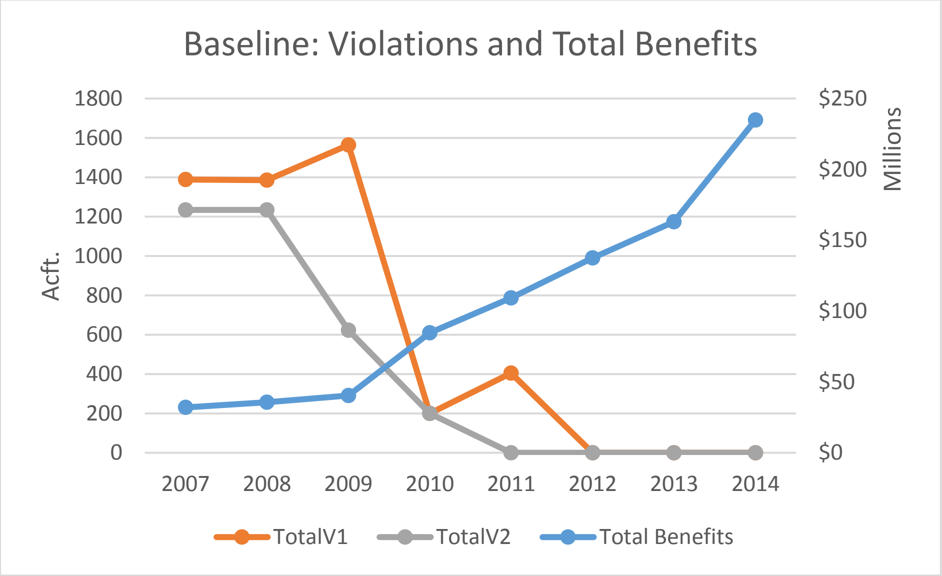

Figure 9. Baseline Violations and Profits.

Table 4

Percentage total water use/total water permitted for water depots (2007-2014)

Year	2007	2008	2009	2010	2011	2012	2013	2014
Total Water Use (Acft.)	716.5	1,242.7	1,420.7	3,850.8	7,709.8	10,223.3	18,804	30,988.5
Total Water Permitted (Acft.)	1,915.7	3,025.7	4,691.2	141,410.7	162,723.8	171,432.5	246,855.7	343,331.6
Use %	37.4%	41.1%	30.3%	2.7%	4.7%	6.0%	7.6%	9.0%

Scenario 1

Scenario 1 looks at the effects of restricting access to LSMR water sources. As seen in Figure 10, total violations by type of violation change because of different reasons around 2010. Individual total violations (TotalV1) decreased due to the substantial decrease in the ratio of total water used by water depots to the total water permitted in 2010 (Table 4); this decrease is seen in each scenario. However, the system violation for water withdrawn from LSMR water sources increased because of the constraint imposed in addition to constraints placed by the USACE in the same time period. These are the largest system violations of any scenario and again illustrate the role that LSMR sources play in providing water for water depots. Benefits continue to rise at a rate lower than the baseline in each scenario.

Figure 11 shows how nearly all of the violations relate to LSMR violations, as is expected since this is the water source being restricted. However, some SW violations occur from 2007-2010 as well.

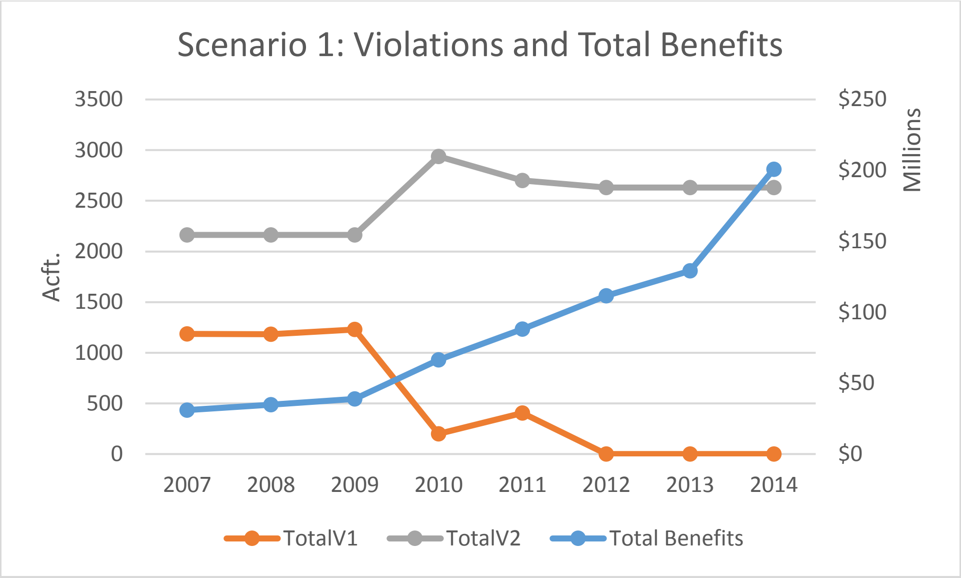

Figure 10. Scenario 1 Violations and Profits.

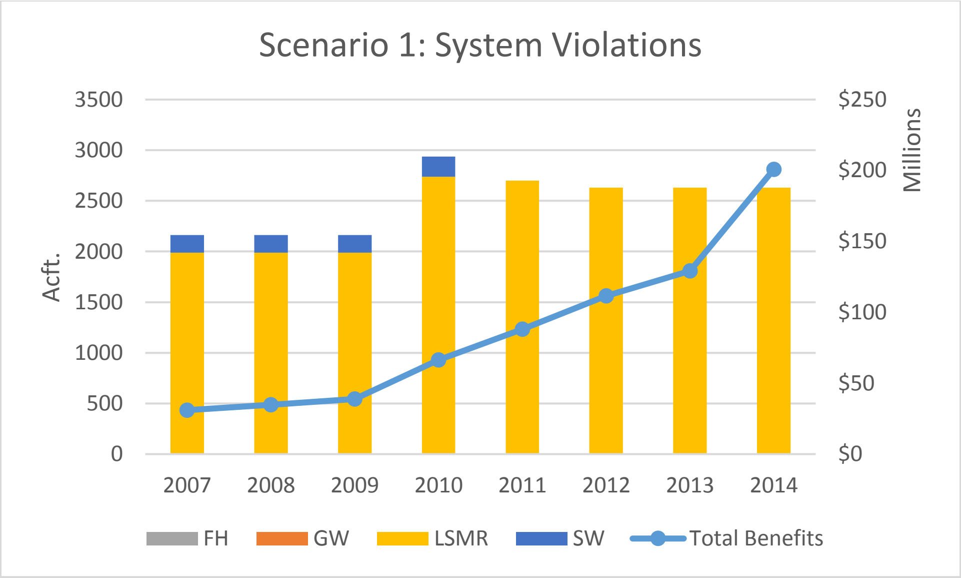

Figure 11. Scenario 1 System Violations Breakdown and Profits.

Scenario 2

Scenario 2 looks at the effects of restricting access to GW water sources due to a drought. As shown in Figure 12, both violations decrease around 2009 and 2010. Benefits continue to rise, but at a slower rate than the baseline.

Figure 13 shows a large number of violations coming from LSMR violations from 2007-2009, but all of the violations come from GW violations when water consumption is greater in 2011-2014. However, some SW violations occur from 2007-2010 as well.

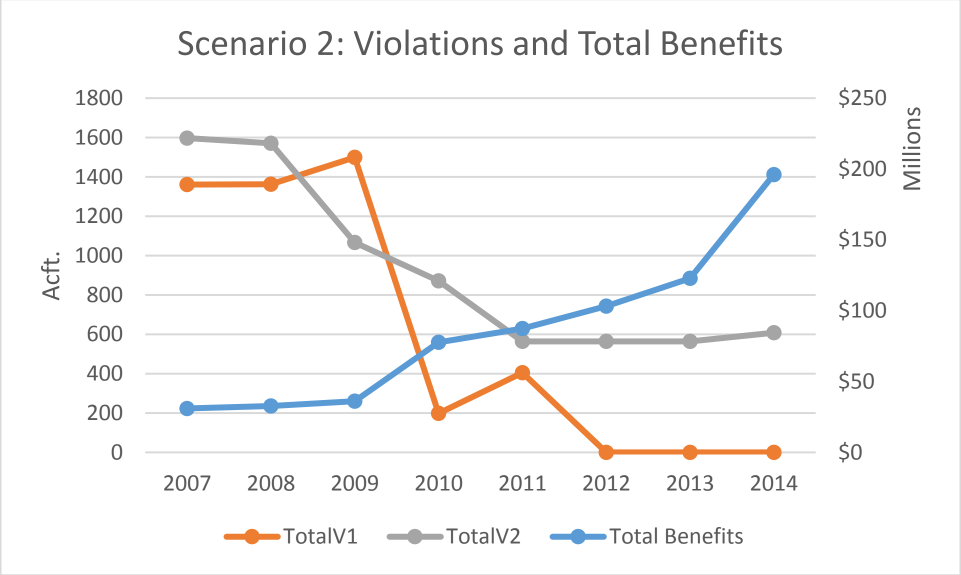

Figure 12. Scenario 2 Violations and Profits.

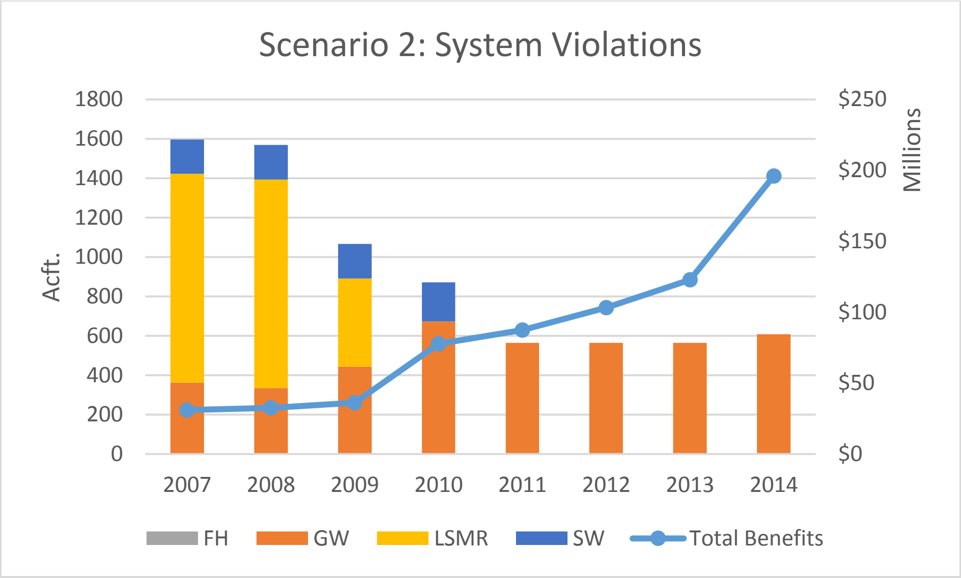

Figure 13. Scenario 2 System Violations Breakdown and Profits.

Scenario 3

Scenario 3 examines the restriction of SW sources due to drought. As seen in Figure 14, TotalV2 violations decrease around 2009 and TotalV1 violations decrease around 2010. Benefits continue to rise, but at a slower rate than the baseline and actually reach a lower peak than the previous scenarios.

Figure 15 shows large violations from LSMR violations from 2007-2009, but SW violations also are occurring. From 2010-2014, only SW violations are occurring.

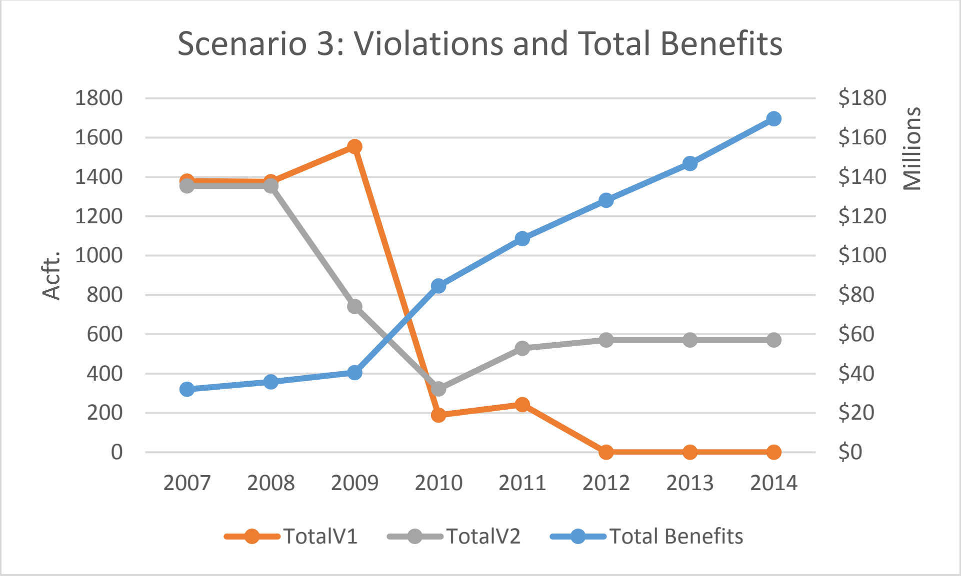

Figure 14. Scenario 3 Violations and Profits.

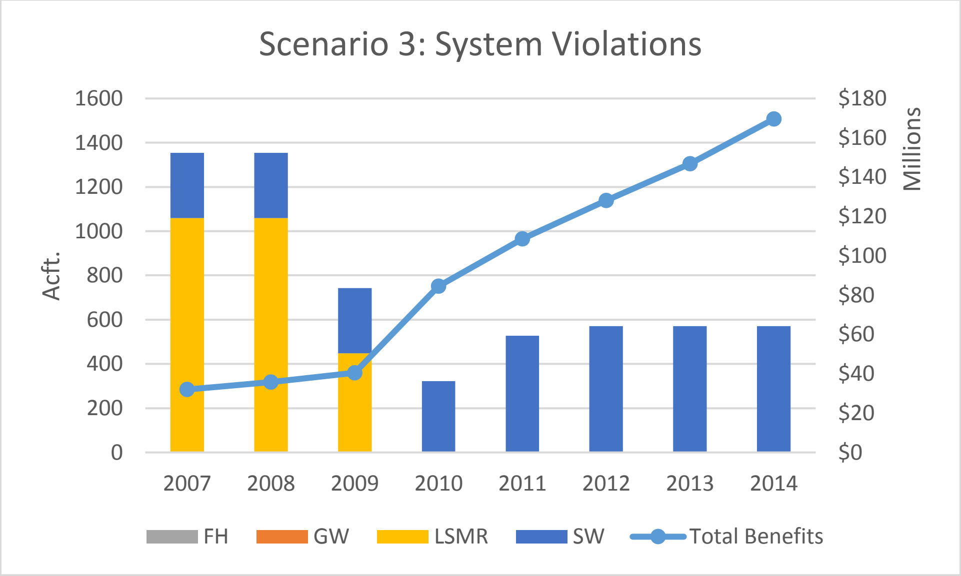

Figure 15. Scenario 3 System Violations Breakdown and Profits.

Scenario 4

Scenario 4 examines the situation of a severe drought where both SW and GW sources are restricted. As seen in Figure 16, TotalV2 violations decrease around 2009 and TotalV1 violations decrease around 2010. Benefits continue to rise, but at a slower rate than the baseline and have the lowest peak of all the scenarios.

Figure 17 shows how much of the violations in 2007-2009 result from LSMR violations, but GW and SW violations also are occurring. In the other years, GW and SW violations are nearly equal which shows no preference for either water source as well as the interconnectedness of GW and SW.

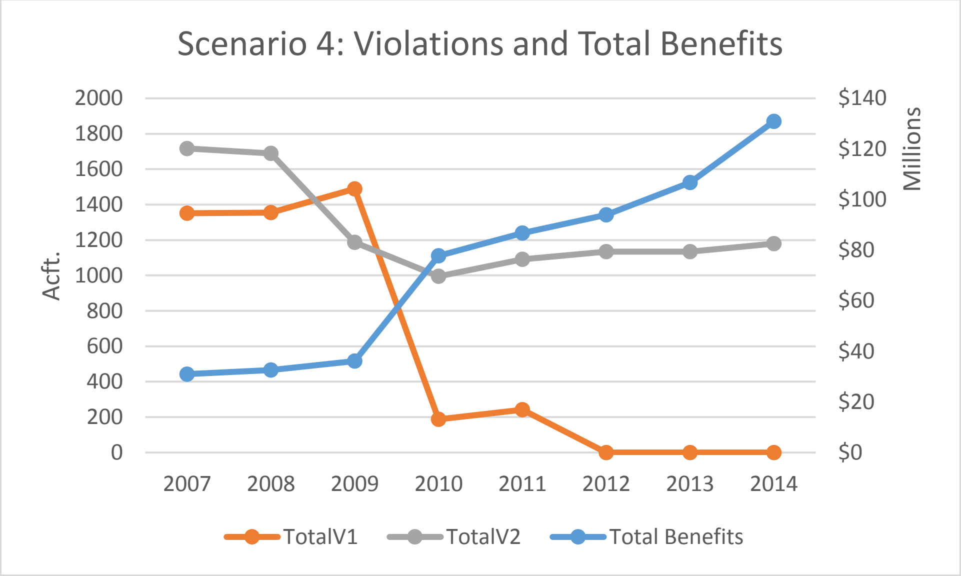

*Figure 16***.** Scenario 4 Violations and Profits.

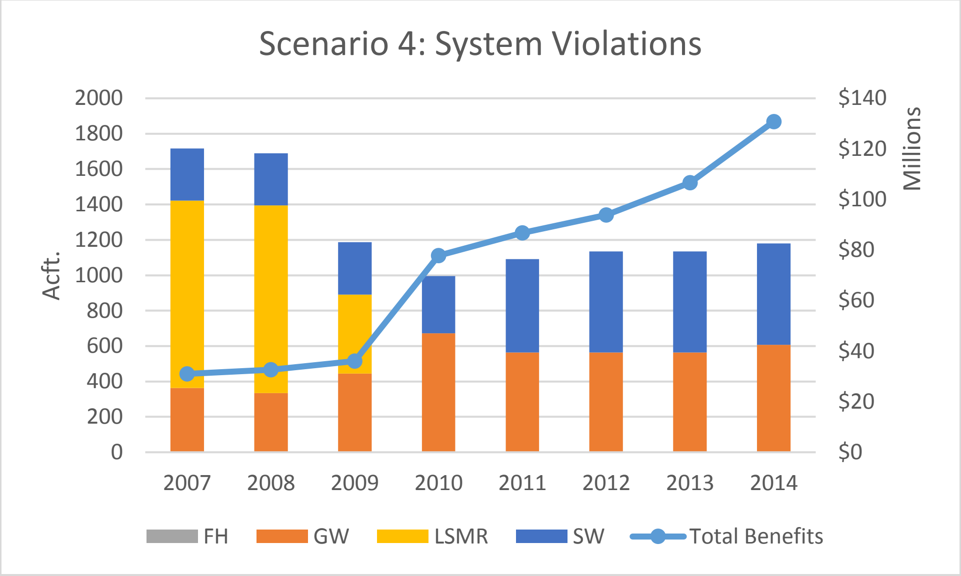

Figure 17. Scenario 4 System Violations Breakdown and Profits.

Scenario Comparisons

Comparing the scenarios provide useful insight into the behavior of water depots.

Figure 18 looks at the differences in benefits between the baseline case and each scenario. The baseline has the highest total profits among water depots, and scenario 4 has the lowest over most of the years. This shows that restricted access to both surface water and groundwater in a severe drought will have the largest impact on water depot profits.

Figure 19 looks at the differences in V1 violations in each scenario. Individual permit violations by water depots remain almost the same in every scenario showing that these violations hardly change by restricting water resources.

Figure 20 looks at the differences in V2 violations in each scenario. The LSMR restriction in scenario 1 has the highest system (V2) violation of each scenario. The system violation for water withdrawn from LSMR water sources increases due to the constraint imposed on top of the contemporary USACE constraints. These large system violations also show the role that LSMR sources play in providing water for water depots.

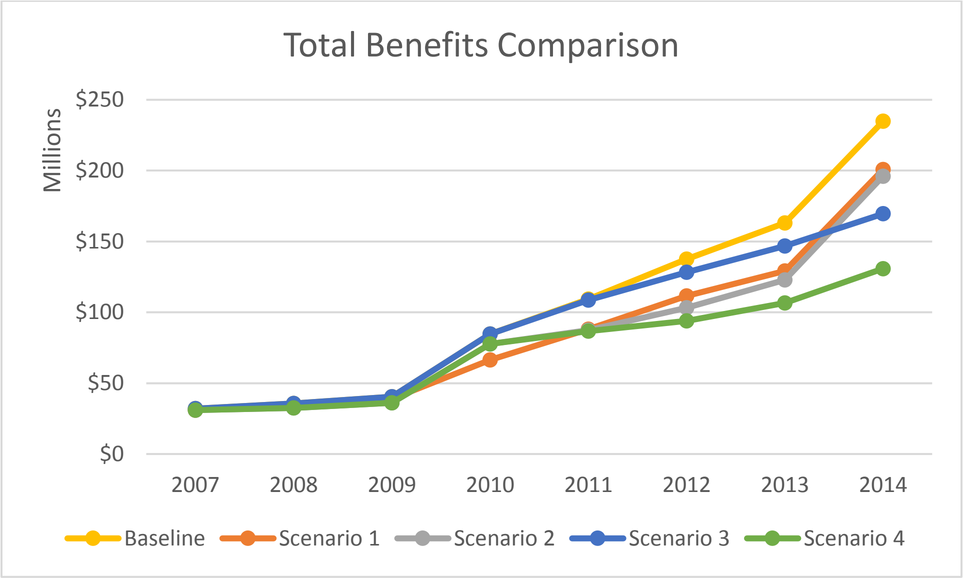

Figure 18. Total Benefits Comparison between Scenarios.

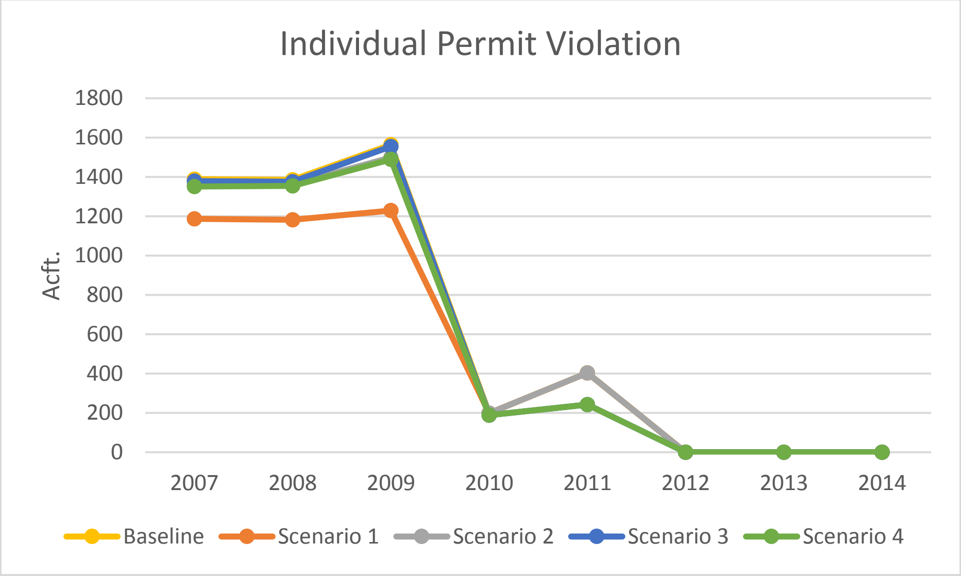

Figure 19. Violation 1 Comparisons between Scenarios.

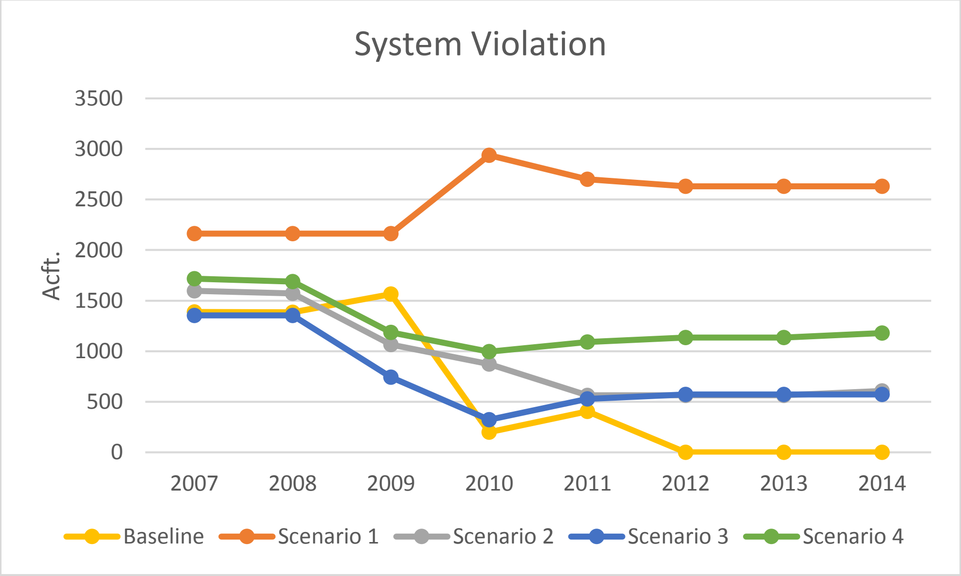

Figure 20. System Violations between Scenarios.

CHAPTER VIII. CONCLUSIONS

Scenario Analysis

Four scenarios were selected to be examined—each dealing with political or environmental factors that affect the levels of water being used by water depots. The scenarios placed restrictions on Lake Sakakawea and Missouri River (LSMR) water, groundwater (GW), surface water (SW), and both surface water and groundwater. LSMR water was found to play an important role in providing water for water depots. This is seen as the largest violations occurred in scenario 1 where LSMR sources were restricted. This further illustrates the importance of allowing greater access to LSMR sources in North Dakota.

Based on the simulated violations seen throughout each of the scenarios, there also is increased potential for illegal water use by water depot owners if water is restricted. Violations did occur in the baseline, indicating there could have been overuse of water. However, some of these simulated violations suggest there were illegal water sales even without water source restriction. In either case, increased efforts to monitor water meters could help identify illegal water use and reduce the possibility of undetected water resource use.

Profits or benefits realized by water depot owners show incentives for water depot owners to participate in illegal water sales. The baseline results estimate profits from water sales eclipsing $200 million, and the average water depot can generate over $700,000 per year (Scheyder, 2013). These profits could outweigh a risk-reward ratio.

From 2012-2014, all the violations at the system level came from the water source being restricted. These are expected results, and many LSMR violations occurred at the system level in the years 2007-2009 for many of the scenarios.

Restricted access to SW values resulting from a drought in scenario 3 result in the lowest system violations. LSMR sources make up most of the violations from 2007-2009, but the remaining years are all violations from SW.

In scenario 4, SW and GW sources are both restricted due to a severe drought. From 2007-2009, LSMR violations dominate individual SW and GW violations. In the remaining years from 2010-2014, SW and GW violations are nearly the same. The combined SW and GW violations increase each year from 2010-2014.

Total benefits or profits are found to increase every year in the baseline and in each scenario. This shows an increase in water sold each year by the water depots to meet water demand. The consumer base also increases each year for water depot owners as the location of the water depot is known and as more oil wells are developed.

Policy Implications

Restricting access to LSMR water is not a reasonable option. In scenario 1, violations of LSMR water use show that water would continue to be used by water depots even if the LSMR water supplies were restricted. Water depots established to use LSMR water would not have easy access to other water sources. There were some SW violations in the years 2007-2010, but this was minimal. System violations also are greater in scenario 1 than in the other scenarios. The violations for LSMR sources alone in scenario 1 are measured at nearly 3,000 acre-feet or more each year—surpassing the violations of other sources restricted in their respective scenarios. The violations of both GW and SW in scenario 4 range from 1,000-1,200 acre-feet per year, so LSMR violations are nearly triple the next largest violations. LSMR violations also occur more frequently in the other scenarios at larger levels than any other water source.

Conservation of groundwater and surface water for uses outside of the oil and gas industry should be considered. In the case of a severe drought, water resources should be carefully managed. Scenario 4 examines the situation where both SW and GW resources are restricted, and results in combined simulated violations surpassing 1,000 acre-feet for SW and GW. The violations occur at nearly the same levels in each year for SW and GW, showing the nexus between surface water and groundwater.

Conserving SW and GW water resources would be advisable even in moderate droughts. Scenario 2 restrictions on SW and scenario 3 restrictions on GW sources result in fewer violations of these resources than in scenarios 1 or 4. Lack of SW or GW from a drought is examined in scenarios 2 and 3. The violations seen for GW in scenario 2 and SW in scenario 3 remain under 700 acre-feet. In the other scenarios, violations for the water sources being impacted are at 1,000 acre-feet or more. These results show that a moderate drought could be handled, but will impact the water sources. A report produced by the Harms Group in 2010 stated "groundwater will not meet future demands for oil development" (Harms, 2010) showing support for conservation of GW resources. Because the results and previous literature show that SW and GW are hydraulically connected (Ghosh et al., 2014, p. 6929), surface water may not meet future demands either.

Thesis Focus/Limitations

In this thesis, agents are used to simulate human behavior or water depot's behavior in the water allocation system at the Bakken. The main problem addressed in this thesis is not trying to maximize agent profits, but rather trying to examine future scenarios that would change current water allocation and use patterns. Agent benefit (or profit) maximization provides a realistic framework of modeling agents which allows analysis of how agents respond in changing circumstances.

Because this thesis focuses on analyzing a broad spectrum of water depot types while at the same time trying to keep the model simple, the number of water depot type classifications is not too large. The goal of this thesis is to provide a pioneer model using an adaptable framework that others can build upon. A simple model including most of the water depots in the state allows for a larger number of scenarios to be tested more easily in further research. Further research also could expand the number of classifications to test different scenarios.

Water Price and Transportation Cost

In this thesis, prices are not formally assigned to water depots. Prices in this thesis are calculated by dividing total profits by total annual water consumption and vary from $23 to $31 per 1000 gallons by. These prices are generally above the observed price range of $5.95 to $25 per 1000 gallons (Kurz et al., 2013). These higher prices should be considered when examining profits at a strictly quantitative viewpoint. This model focused more on simulating accurate water consumption values for water depots than obtaining accurate prices.

There is a location dependency with prices as well because water depots selling water closer to an oil well site can charge a higher rate. Location of water depots is not integrated into the model in an effort to maintain model simplicity. Transportation costs are another variable that is not included. Adding location and transportation costs variables in further research could provide more accurate quantitative results.

Water depots located close to oil well sites are likely to experience larger profits than those farther away. At these locations, water depots can charge higher prices because the cost of transportation decreases for oil companies. With transportation costs much larger than the price of water itself (water cost ranging from $0.25 to 1.05/bbl and transportation cost ranging from $0.63 to $5.00/bbl) (Kurz et al, 2011), minimizing distances between water depots and oil well locations is vital for minimizing costs and maximizing profits.

The Western Area Water Supply Authority (WAWSA), however, has its price for water set at $0.84/barrel (WAWSA employee, personal communication, June 29, 2016; Western Area Water Supply Authority, 2015). Although there is a set price for water sold by the WAWSA, it still brings increased competition among water depots. Because the WAWSA is government-owned, it has faced opposition in selling water from independent sellers who have invested in their own water depots at an average start-up cost of $200,000 (Mortenson, 2011; Scheyder, 2013). The conflict between these two parties along with the stable prices set for the WAWSA further show how the model would lose simplicity with the addition of a more stringent price application.

Oil Price

The impact of oil prices is not included in this model. Sustained changes in oil prices would probably affect simulated profits and violations. Decreasing oil prices could have affected water depot water consumption from 2008 to 2009. As seen in Figure 21, water consumption by water depots increased approximately 180 acre-feet from 2008 to 2009 compared to an increase of over 500 acre-feet from 2007 to 2008. From 2008 to 2009, oil prices also experienced a large decline (Figure 21); however, oil prices increased substantially the following year. This example shows only minor changes in water consumption associated with a substantial change in oil prices. From 2009 to 2014, a relatively sustained increase in oil prices (Figure 21) and an increase in water sales in each scenario (Figure 18, Chapter 7) supports following sustained changes in oil prices to see changes in water sales. However, policy implications would not be expected to change if oil prices were a factor in the model. There could be quantitative changes in simulated profits and violations, but the quantitative changes should not affect the severity of simulated violations in each scenario—scenario 1 should continue to experience the largest simulated system violations followed scenarios 4, 2, and 3.

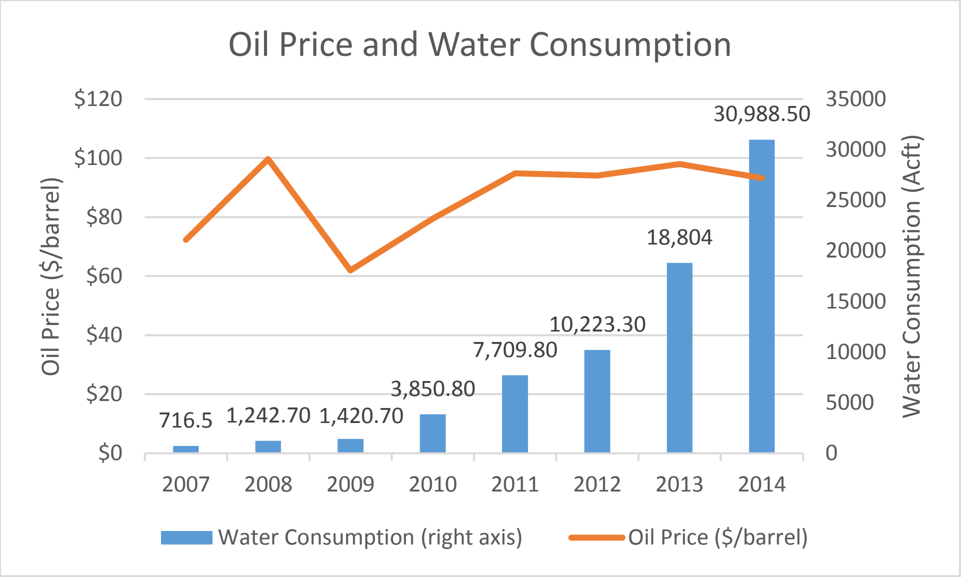

Figure 21. Oil Price and Water Consumption. Source: Author using data from North Dakota State Water Commission (SWC) and EIA.

General Conclusions

Oil in the Bakken formation has become an enormous asset for the state of North Dakota; however, hydraulic fracturing and other steps required to access this oil have led to greater concerns for the water supply in the state. There is no doubt about the importance of continued and expanded energy development to keep up with an ever-growing energy demand but this development also brings a faster growing water demand. Carter (2011) observes this relationship between water and energy by assessing shifts in meeting energy demand across the nation to shifts in intensity of water practices to produce energy. Finding a balance between preservation of the water supply and meeting the water demand for continued growth and stability throughout the state will be of utmost importance at all times. Without this balance there could be either a stagnation of growth or a depletion of water in the future leading to even more serious consequences.

Restricting consumption of groundwater sources should be further examined. Conservation of groundwater for uses outside of the oil and gas industry should be considered. Further access to the Missouri River system and Lake Sakakawea appears to be the best resource for meeting future water demand. However, most of the water being drawn by water depots is drawn from GW sources (Table 3, Chapter 7). Water depots have been able to supply a large amount of water to energy companies thus far, but reliance on water depots may not be the best long-term solution. Proper care and preservation of natural resources and the environment must always take precedence in any decisions that may cause negative impact on them as well.

The role of water depots in North Dakota must continue to be examined because of the uncertainty facing the future of the oil industry in the state. Oil activity in the region was growing exponentially until 2015, but oil production continues to exceed one million barrels per day as of June 2016 (U.S. Energy Information Administration, 2016). Predictions of continued levels of growth experienced prior to 2015 have not been realized for the past two years, resulting in the need to re-evaluate expected growth levels for the oil industry. If more predictable levels of oil activity are experienced in the region, clearer water management policy could be implemented as well. The Bakken region also is unique in having a much lower population density than other shale plays (Raimi & Newell, 2016). The continued role that water depots play will largely hinge on the oil industry’s activity for the future, demonstrating a greater need to continue research in this area as developments occur.

Water depots play an integral role in the water allocation system in western North Dakota. With fracking water use accounting for 43% of total water use in Williams, Mountrail, McKenzie, and Dunn counties in 2014 (Lin, Lin, & Lim, 2015), special attention needs to follow water depot activity. Because of the relatively short time period that water use by water depots has been significant, conducting future research will be important for managing water resources in the state.

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APPENDIX

Additional information on population, oil activity, oil prices can provide further insight into the circumstances in the Bakken. As one might expect, there is a general growth in water consumption and population in North Dakota over time. However, data does show unpredictably sharp increases and decreases in total water consumption and population throughout the state. Figures are included at the end of the appendix.

Figure A.1 shows how water consumption and population have increased at different rates in North Dakota the past 40 years. From 2000 to 2013 there has been an approximate 17% increase in water consumption and 13% increase in population across the state. This makes continued studies on water consumption important in planning for water demand, especially with the volatility of water consumption and population in the state shown in Figure A.1. Knowing how much water consumption to expect makes a large difference in how cities and other water suppliers plan to store and distribute water for the future. Being aware of population changes also plays a role in determining future water demand. If water consumption is higher than expected, there is the problem of trying to provide enough water to meet the demand, but if it is lower than expected, there could be storage costs to keep the water available.

Oil production in North Dakota has increased rapidly in the past decade. Figure A.2 shows that 2008 marked the highest level of oil production ever seen in North Dakota and how oil production continued to increase at a rate never experienced before in the state. Oil production in 2015 throughout the state was nearly ten times greater than that in 2007. Average daily oil production also surpassed one million barrels a day for 2014. This growth can be attributed to the technological advances in the oil industry, especially in fracking.

Following the impacts of changing technology in fracking may provide additional information into the future of oil activity in the Bakken as well. Greater technological advancements could point to higher levels of optimism for the future of oil prices leading to larger oil activity, leading to increase water consumption and a larger role for water depots. This chain of effects demonstrates the importance of understanding each part of the water-energy nexus as each sector is so interconnected that the impacts in one will be experienced in the other. The chain of effects also will bring clarity to an uncertain future for increased confidence for water resource planners, policy decisions, and even looking ahead at the impacts of whatever direction the oil industry may follow.

Oil prices will continue to have a major impact on the future of the Bakken. If prices continue to remain low for an extended period of time, past estimates and other projections for the future will need to be adjusted even further. Tracking behavior of oil industry leaders in the Bakken will be important in forming policy and other estimates in regard to the energy-water nexus in North Dakota.

High oil prices have also been a contributing factor to the rapid expansion and investment in oil in North Dakota, but oil prices plummeted in mid-2014 (Figure A.3). However, despite falling oil prices production has remained strong. For the first seven months of 2015, oil was still being produced at about 1.2 million barrels per day, but has been slowly falling since then sitting closer to 1 million barrels per day in June 2016 (U.S. Energy Information Administration, 2016). However, with lower oil prices many are forced to find additional ways of cutting costs. Some companies are doing this by finding ways to cut down the time it takes to drill a well and even drilling wells but waiting to frack them until the price of oil rises again (Krauss, 2015). Companies are completing wells, but they are waiting to stimulate them.

The period of low oil prices has been a blessing for development of infrastructure. Infrastructure among many other things had not been able to grow fast enough to support the tremendous growth in areas due to the oil industry. This period of lower oil prices and a lower numbers of oil rigs in the fields should allow some needed time for everything else citizens need in the towns near oil hot spots to develop and sustain the influx of people in the future (Brooks, 2015).

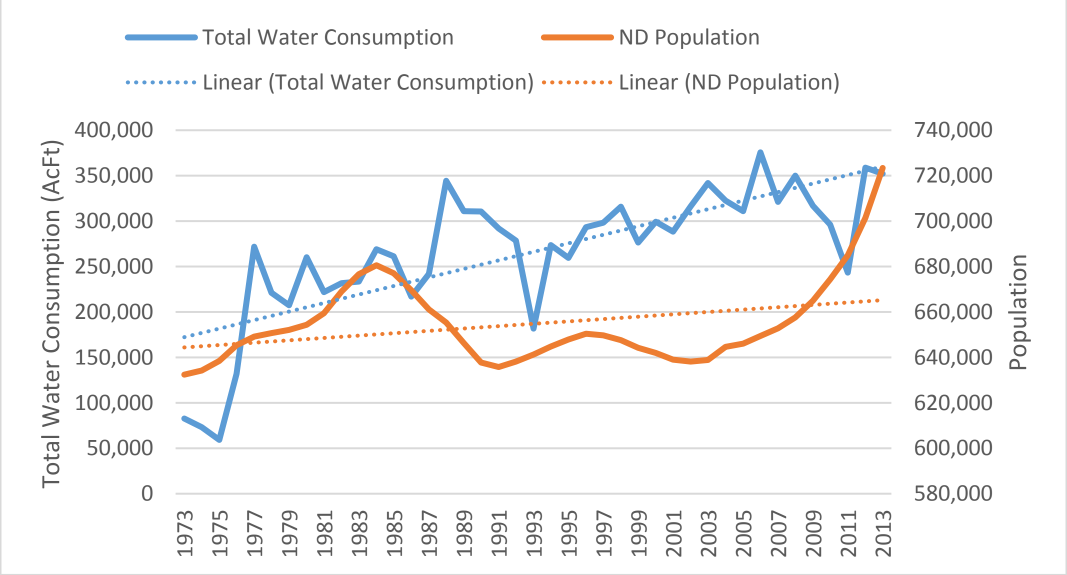

Figure A.1. North Dakota Water Consumption and Population**.** Data from North Dakota State Water Commission (SWC) and Bureau of Economic Analysis (BEA).

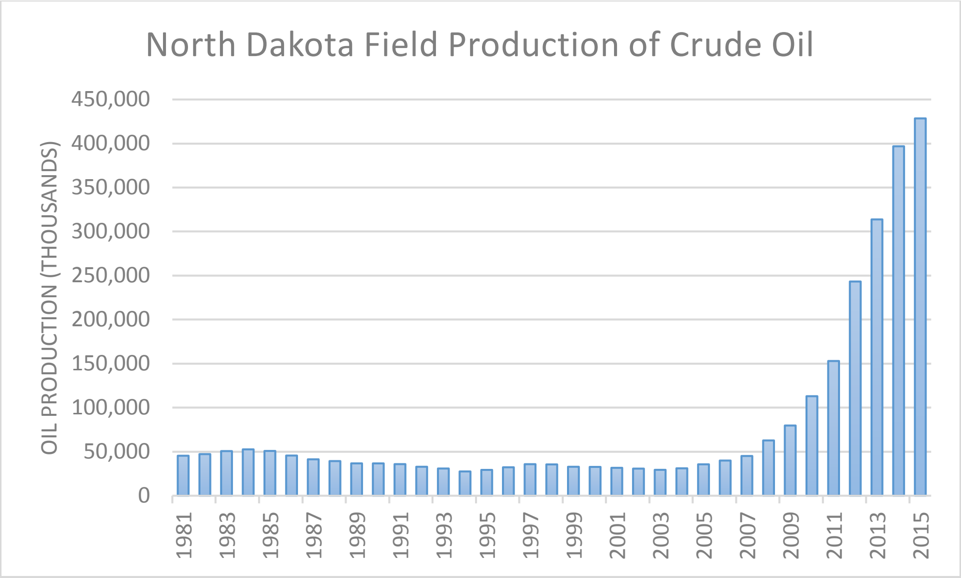

Figure A.2. North Dakota Annual Oil Production. Data from U.S. Energy Information Administration (EIA).

Figure A.3. Historical Crude Oil Prices**.** Source: http://www.macrotrends.net/1369/crude-oil-price-history-chart.