TRANSPORTING AND DISPOSING OF WASTEWATER FROM NORTH DAKOTA OIL PRODUCERS

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ABSTRACT

North Dakota’s oil boom is aided by a new technology, fracking. But this technology implies large amounts of wastewater. The methods of dealing with this wastewater are now an issue. Currently, North Dakota locks it into deep injection wells in the Bakken formation. With the development of membrane technologies to treat wastewater, it may be feasible treat the wastewater and reuse it.

This study uses a mathematical programming model to minimize the total cost of dealing with wastewater using three methods- deep well injection, on-site treatment and off-site treatment. The model results show it is cost-effective to use on-site and large capacity off-site treatment to treat the 20% of the wastewater flows back within first 30-60 days after a well is drilled.

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CHAPTER 1. INTRODUCTION

Since 1859 when the first oil well was drilled at Titusville, Pennsylvania, pollution problems relating to the disposal of oil-field brines and oil production wastewater have confronted both the petroleum industry and the general public. Practically every oil-producing state has enacted laws that regulate the drilling and plugging of wells and the disposal of brines and wastewater. Many of these laws are the direct result of ground-water or surface-water contamination (Pettyjohn, 1971).

North Dakota's oil boom was made possible through hydraulic fracturing, often referred to as fracking, a technology which allows for extraction of oil and gas from hydrocarbon rich oil shale. The process of fracking is to break through layers of rock with pressurized water to release oil and gas. This is a technology which leads to North Dakota's oil boom, but it remains controversial in the United States because of potential pollution problems (Cowan et al., 2010). Water and sand make up more than 99.5% of the fluid used to hydraulically fracture a well. Most water used in the process comes from surface water sources. For example, the water used in the process of fracking comes from lakes, rivers and municipal supplies. However, when it is available in sufficient quantities, groundwater can also be used, but the amount is small comparing to from other sources. But, producers consider not only the supply of fresh water for fracking, but also disposal of wastewater because once the process is finished; the water used for fracking turns out to be wastewater, which has to be dealt with ("Groundwater protection: Priority number one," 2011).

Once the formation fracturing is completed, the water flows back as the pressure in the well is released. In the Bakken, there is no need for pumping. The flowback is a mixture of sand, water, oil, and gas. Gas is separated from the liquid and then is utilized on-site, sent to a gas-processing facility, or flared. An American oil–water separator is used to separate water and oil. Before fracture event, the water is collected in a pit, sometimes in fracture tanks. The oil is sent to the production separators (heater–treaters) for removal and collected in tanks to prepare for shipping to a refinery. Any water collected with the oil over time is considered flowback. After sand removal and oil recovery, the frac flowback water is typically disposed of via deep-well injection.

Transportation costs, particularly for long haul distances, can be very high for both freshwater and flowback water (Cowan et al., 2010). Oil traffic consists largely of five types of movements: first, inbound movements of sand, water, cement, scoria, gravel, drilling mud, and fuel; second, inbound movements of chemical; third, outbound movements of oil and byproducts; fourth, outbound movements of saltwater flowback; fifth, movements of specialized vehicles such as workover rigs, fracturing rigs, cranes, and utility vehicles.

Fracking produces millions of gallons of wastewater that is handled as a hazardous mix of salt, metals and chemicals. Often this fluid is disposed of by pumping it more than a mile underground, below any drinkable groundwater. In North Dakota, the disposal method is to lock the fracking flowback wastewater into salt water disposal wells in the Dakota Formation. In 2010, there were 300 wastewater wells in North Dakota and 300,000 barrels of flowback were disposed of a day, which translates to 120 million barrels per year. The process of fracking and how the wastewater is produced is as follows. A well field service company comes to the field with large wastewater-holding tanks and pumps when wells have been drilled. Water is brought in by tanker truck to fill the water tanks. These tanker trucks are typically at the size of 7,500 to 8,000 gallon. The flowback water is injected at a high flow rate and pressure into the formation. The fluid pumped into the formation may be pumped in immediately or in one to several days' time.

Then, the fluid is shut in for a period before it is allowed to flow back. It takes as short as 4 hours to as long as 30 days to finish the fracturing process to the start of flowback (Cowan et al., 2010).

In North Dakota, instead of processing fracking wastewater in water treatment plants or recycling it, oil drillers lock it inside the Dakota Formation, a deep, brackish aquifer. Drillers in the Williston Basin region of North Dakota currently dispose of their drilling wastes primarily in deep injection wells and continually assess fresh water resources for their fracking operations. But researchers and some producers are also considering recycle and reuse technologies. The type of treatment technology is one issue and the percentage of flowback water to be treated is another issue. Because different technologies have different capacities and costs, not all the amount of flowback wastewater can be treated (Cowan et al., 2010).

The total number of rig-related truck movements is over 2,000 per well, with approximately half of them is transported with large amount load. But road conditions in North Dakota are not good for wastewater transportation. Trucks drive on highways, streets and roads will increase frequency of number of vehicles. In effect, high levels of traffic from a variety of vehicles is occurring on unpaved and paved roads, as oil trucks, water trucks, equipment trucks and passenger vehicles compete for the same road capacity. Additional roads investments are needed to support oil and gas production. But increasing traffic congestion is costly, which leads to high transportation costs (Upper Great Plains Transportation Institute, 2010).

The financial costs of fracking flowback wastewater disposal are not the only concern. Environmental issues are also important. Commercial oil field waste disposal facilities pose significant risks to wildlife. Reserve pits used to store drilling fluids during drilling operations can cause bird and wildlife mortality if they contain visible sheens or oil on the surface. Flare pits, earthen pits constructed below flare stacks used to vent hydrogen sulfide gas from production wells can also cause bird and wildlife mortality if they contain visible sheens or oil on the surface. Some oil operators still continue to use colored flagging at oil skim pits and reserve pits to deter birds. Thus, once this paper tries to find out the optimal way to deal with fracking flowback wastewater, environmental issues should also be considered (Trail, 2006).

Another concern is fracturing fluids contain numerous chemicals that could harm human health, water sources, and the environment. Currently, the oil and gas service companies use fracturing products containing 29 chemicals, which are components of 652 different products. Under the Safe Drinking Water Act, 53 of the products may have an adverse effect on human health and are likely to occur in public drinking water systems. Although what people do often is to lock the wastewater into Dakota Formation, this paper also considers environmental issues because there is still opportunity that the wastewater would enter into drinking water systems (United States House of Representatives Committee on Energy and Commerce Minority Staff, 2011).

The Problem

Wastewater disposal technologies

The boom in oil and gas exploration in western North Dakota is in large part due to the recent advancement of fracking technology. This new technology is critically dependent on large volumes of high quality fresh water. Water, in combination with sand and proprietary chemical gelling mixtures, is forced into various locations along an oil-slate formation to fracture the slate and allow the oil and gas to travel through the fractures into the well. The wastewater then emerges with the crude oil is made up of roughly half fracking water and half water that had been locked underground. The main ingredient in mixture of flowback is sodium chloride but it also contains sulfur, arsenic, ammonia, copper and manganese, as well as naturally occurring radioactive materials, such as uranium and thorium. The liquid usually contains some crude too. After this process, the fresh water will become wastewater, it produces millions of gallons of wastewater that is handled as a hazardous mix of salt, metals and chemicals and is disposed of by pumping it more than a mile underground, below any drinkable groundwater. Companies are required to report a spill of any size and must reclaim any harm to the affected soil, but the state does not get involved unless the accident is severe, nor does it have the staff to report to every reported incident (Cowan et al., 2010).

Over one thousand wells are being drilled in North Dakota every year. These wells require a large amount of fresh water, straining available water resources and produce additional large quantity of fracking flowback wastewater. In the United States, there are many oil shale deposits. The Three Forks formation and the Bakken formation are two large ones among them. Due to recent technology advances, the estimated 167 billion barrels (BBL) of oil are produced from these reserves. North Dakota was analyzed for its water related issues to the oil industry in the Bakken area. In the year 2010, an estimated 132 million barrels of produced wastewater and 48 million barrels of flow back water have been produced and that wastewater has to be disposed of. And the amount is increasing year by year. Currently, only 20% of the flow-back water is being recycled. Thus, dealing with the wastewater from the oil companies is a big issue for both the government and the companies ("Water key to N.D. oil patch growth," 2011).

Environmental issues

As mentioned before, no matter which kind of technology is used, dealing with fracking flowback wastewater will lead to environmental issues. Deep well injection may lead wastewater to enter groundwater aquifers and damage the groundwater. Wastewater from treatment plants may pollute land in that area. They all may lead to damage to human lives. Transportation would produce air pollution and dust on the road, which is also considered as an environmental issue. Fracking may cause earthquake if there is a fault underground. No matter how people think about it, it should be considered as an environmental factor. And at last, there is an issue that could not be gotten rid of. Drilling fluids can cause bird and wildlife, mortality if they contain visible sheens or oil on the surface, but no one could avoid it because when fracking, there it is still necessary to use pits.

Transportation technologies

Water for fracking is typically hauled to the well site in 7,500 to 8,000 gallon tanker trucks. Once the formation fracturing is completed, the wastewater flows back (fracing flowback) as the pressure in the well is released. After sand removal and oil recovery, the fracing flowback water is typically disposed of via deep-well injection or treated by treatment plants. Transportation costs, particularly for long haul distances, can be excessive for both freshwater and flowback water. And no matter how the wastewater could be dealt with, either be treated or disposed of, there is always transportation cost associate with it.

Objectives

The general objective of this study is to assess the most efficient way to transport and dispose of wastewater from North Dakota State's oil producers. Several technologies can be used, but they have different financial costs and different environmental impacts, the most effective combination of these technologies should be determined. The companies need to minimize financial costs, but environmental costs also need to be taken into consideration.

Specific objectives include:

i) Develop a mathematical programming model to find optimal solution to minimum financial cost.

ii) Choose from different types of treatment technologies to reach optimization and compare with wastewater disposal to see whether wastewater treatment and reuse is suitable.

iii) Take environmental costs into consideration as a factor that would have an influence on decision making.

In previous work, the issue has been discussed and many engineers compared the effectiveness of several treatment technologies and came up with a result of which one is better than others. Many studies focus on the Bakken area mentioned wastewater treatment technologies but never use it or give a percentage of the amount been treated and reused. It seems like although people know flowback wastewater can be treated for reuse, no one would do it.

So, this study will use mathematical programming model to see whether it is cost-effective to use treatment technologies to deal with flowback wastewater and if it is cost-effective, quantity of treatable wastewater will be given. Thus, it is easier for readers to look at the optimal way to deal with flowback wastewater.

CHAPTER 2. LITERATURE REVIEW

Review of Bakken Formation Wastewater Production

As the use of fracking for natural gas started to increase in the last decade, energy companies have faced mounting criticism over the environmental consequences of an extraction process that involves pumping millions of gallons of water into the ground for each well and can leave significant amounts of hazardous contaminants in the water that comes back to the surface. Thus, environmentalists and the press have paid more attention to drilling and its affects.

Cowan et al. (2010) provided an overall description of Bakken water issues in an unpublished consultant report. Treatment and recycling of frac flowback water is a means of reducing the demand for freshwater and supply near drilling and fracturing activities. The quantity and quality presented significant challenges for cost-effective water-recycling opportunities, but widespread recycling will not likely be economically viable. The article implied that the Northern Great Plains Water Consortium (NGPWC) identified an opportunity to reuse treated water that is used in the oil field to pressurize and fracture oil-bearing formations to enhance the flow and recovery of the oil economically. In North Dakota, multistage fractures are increasingly being employed because they generate fractures more effectively. The authors also discuss wastewater transportation. Fracking flowback as the pressure in the well is released once the formation fracturing is completed. The fracing flowback is typically disposed of via deep-well injection after sand removal and oil recovery.

Transportation costs, particularly for long haul distances, can be excessive for flowback water. So, in terms of transportation, Upper Great Plains Transportation Institute (UGPTI) (2010) gave a brief introduction of road condition in North Dakota. Currently, nearly 958 miles of paved roads are impacted by wastewater transportation. A total of 58% of these miles are in good condition, another 35% are in fair shape, only 7% of these miles are in poor or very poor condition. Unfortunately, because of the structural characteristics of the roads and the increasing amount of wastewater, the 35% of miles currently in fair condition will deteriorate quickly.

United States Government Accountability Office (2012) provided a new report to the public on produced wastewater. Produced wastewater from oil and gas production has a poor quality and is hard to use for other purpose without prior treatment. The specific quality of produced water produced varies widely according to hydrocarbon, geography and production method. Although a number of practices to manage and treat produced wastewater can be chosen, underground injection is the predominant practice because it requires little or no treatment and is often the least costly option. Except for underground injection, a limited amount of produced water is managed by discharging to surface water, and a certain amount of the produced water is minimally treated. After all, cost is the primary driver in producers' decisions. For example, underground injection range from $0.07 to $1.60 per barrel. However, if the injection formation is far away, transporting the water via truck can significantly increase the cost. Another important factor is treatment cost, which depends on the technologies used, which in turn depends on the quality of the produced water being treated and the level of treatment. This article also talked about water quality. Produced water may contain a wide range of contaminants and most of them occur naturally in the produced water, but some are added through the process of drilling, hydraulic fracturing, and pumping oil and gas. Human health and environment may at risk if exposure to these contaminants at high levels.

Trail (2006) introduced contaminant issues of oil field waste pits. This report stated that commercial oil field waste disposal facilities pose significant risks to wildlife. Reserve pits and flare pits can cause bird and wildlife mortality if they contain visible sheens or oil on the surface.

Currently, an estimated 500,000 to 1 million birds are lost annually in oil field production skim pits and centralized oilfield wastewater disposal facilities.

Hammer at al. (2012) presented an overall review of environmental impacts of oil drilling wastewater. When wastewater is treated and discharged to water bodies, discharge of pollutants is allowed in amounts, but regulations are not enough to protect water quality. As human beings drink the water, it may be a risk to our health. There are also risks even to underground injection because the injection fluids may migrate into sources of drinking water, as well as a risk of triggering earthquakes. Another method to deal with the wastewater is to reuse for additional hydraulic fracturing. It brings numerous benefits, and is recommended by the authors. Also, there are regulations concerning treated water discharge. Federal water pollution legislation restricts wastewater plants, so that they do not discharge pollutants into waters unless the discharge is authorized. The Safe Drinking Water Act (SDWA) (2003) established the Underground Injection Control (UIC) program, which sets standards for safe wastewater injection practices and bans certain types of injection to prevent the infect wastewater into underground sources of drinking water. On the other hand, if shale gas wastewater is treated for the purpose of reuse, it is not subject to federal regulation. That is why the authors recommend this way.

Review of Wastewater Treatment and Recycling

Dealing with wastewater is not a new issue. A number of previous studies can be found. Baicker at al. (2011) reviewed two aspects of Marcellus shale development in Pennsylvania. Pennsylvania has similar condition as in North Dakota; development of the Marcellus has extended rapidly in recent years. Ten to thirty percent of the water used in fracking Marcellus wells is brought back to the surface after fracking. This wastewater contains 4% to 25% salts and several other constituents such as barium, strontium and naturally occurring radioactive material.

Because of the significant cost of treatment and transportation wastewater, operators are investigating all available options for on-site treatment such as using treatment technologies, recycling and underground injection control. But when dealing with wastewater, several regulations should be complied with. For example, the Clean Water Act (1972) requires National Pollutant Discharge Elimination System permits for any discharge of treated or produced flowback. It also requires states to identify waters for which technology-based effluent limits fail to achieve water quality necessary to protect designated and existing uses.

Baker et al. (2011) presented a brief introduction on technologies being used to deal with wastewater. In general, there are two kinds of technologies. One is membrane treatment, which is the most popular treatment technology in the world. The technology uses semipermeable membranes to separate suspended and dissolved solids from water. Another is thermal treatment. This technology uses distillation of high concentration brine containing water to produce clean water, and then a lower-volume brine concentrate comes and can be disposed in landfills. But, this technology is not economical for the treatment of fracking flowback water because the process requires high energy input. The authors also compare the two technologies including their cost, transportation cost and capacity. At last, they come to a conclusion that having a technology that can be transported to each well for on-site flowback treatment is of great significance. In other words, mobile treatment plants are the ones they are would like to use.

Frenkel (n.d.) in his water white paper presented information on technologies. In this article, he said although different kinds of technologies are useful to treat wastewater; membrane treatment is the newest commercial technology. It is the fastest growing technology with the greatest number of installations in the world. The percentage of membrane treatment in all the technologies being used is close to 80% and thermal occupies almost other 20%. In this paper, he also relates the cost of membrane treatment including capital cost, chemicals and labor costs based on capacity of the facilities.

Review of Wastewater Disposal Regulations

Helman (2012) presented a brief introduction of the effects and regulation of hydraulic fracturing. He also mentions that wastewater is eventually dumped in injection wells or saltwater disposal wells. But the disposal wells are not necessarily adjacent to the drilling site; operators often haul the water along busy roads, across crowded intersections and through residential neighborhoods, so transportation costs would be a significant factor. Besides, the wastewater does affect environment. Insufficient downstream water has negative impact on the quality and quantity of animal habitats and increases droughts. So, environmental cost is another factor. The author also talked about regulations- Clean Water Act, as mentioned above.

Campbell et al. (2011) presented a more detailed understanding of deepwater oil drilling regulation. Some impacts of drilling restrictions include: some bans on deepwater and ultradeepwater drilling will reduce domestic crude oil production. The impacts on the world oil price would be moderate to negligible. A reduction in offshore oil production under the policies is reflected in a reduction in domestic consumption. They also presented assessment of deepwater drilling and its alternatives. For example, deepwater drilling policies would affect jobs of high political importance, as well as economically important to those directly or indirectly affected. The authors also express that although deepwater oil drilling does have harm on human activities, but the damage should be divided by different types of drilling. Some oil releases have little impact on ecological resources or human activities but other may have a significant and long-lasting impact. Because of this, the oil release from natural seeps is not thought to pose an imminent threat to the natural ecosystems in the ocean.

Tucker (2011) discussed landowner protection from Marcellus Shale development. Although these landowners in the region stand to benefit financially from the production of natural gas form beneath their property, many will be saddled with the burden of drilling operations on the surface of their land. So the legal way is to address the environmental risks of Marcellus Shale drilling. Flowback water contains a large amount of pollutants; these contaminants can reach water supplies through improper well construction or surface spills, so it must be treated before being discharged into streams. The Pennsylvania Oil and Gas Conservation Law are the statutes that regulate the extraction of natural gas in the state. However, it does not apply to Marcellus Shale wells.

Review of Methodology

One method to analyze a wastewater transportation problem is to use linear programming. Dantzing and Thapa (1997) presented a general conception of linear programming in their textbook. In general, linear programming is a mathematical method for determining a way to achieve the best outcome in a given mathematical model for some list of requirements represented as linear relationships. Linear programming is a specific case of mathematical programming. More formally, linear programming is a technique for the optimization of a linear objective function, subject to linear inequality constrains. It is feasible region is a convex polyhedron, which is a set defined as the intersection of finitely many half spaces, each of which is defined by a linear inequality. Its objective function is a real-valued affine function defined on this polyhedron. A linear programming algorithm finds a point in the polyhedron where this function has the smallest or largest value of such point exists.

Several articles use linear programming methods to solve real-world problems. Barbier et al. (2006) used this method to simultaneously determine the cost-minimizing size and location of the processing plants of coffee production in Honduras. They introduced processing, quality, environmental impacts, technologies and regulations of coffee production first. Then, a methematical programming model was built. With good data and feasibility analysis, they came up with the conclusion that in order to increase river water quality, successful implementation of a centralized system should be used, but this needs all participants in the coffee market have financial incentive to support it.

Coffey (2001) analyzed the effects of feed ingredient price risk on the selection of minimum cost feed rations. Because feed expenses affect producers' net income greatly, usage of linear programming to select minimum-cost feed ratios is of great significance. The model used in the article was designed to choose optimal rations on a pound of per-day basis. In the model, the author's objective is to minimize cost and subject to price and quantity constrains. Ran this model, the author came up with a solution that minimize cost feed rations that are subject to an individual's risk aversion and thus represent utility maximization.

Conrad (1985) investigated disposal of sewage sludge in the New York Bight. This paper showed that sludge might be spread on pasture land and its organic matter will serve as a fertilizer, promoting plant growth. For the aforementioned coastal cities, ocean disposal seemed the preferred alternative, so as in New York. The author developed a dynamic model of sludge disposal to minimize the cost. The objective function is built on variable cost, transportation cost and environmental cost. Then constrains include cost and also time periods. With this model and analysis, the author get the conclusion that the optimal choice is to cease or reduce dumping at the nearshore site when the sum of marginal disposal and environmental costs equaled the marginal cost of disposal at the more distant offshore site.

Di (1994) researched multimedia waste disposal optimization under uncertainty with an ocean option. The author argues that waste management is a complex problem because it influences by many physical and finical factors, which means the costs and effects are location-specific. Because of this, the author analyzed the problems at community level. He made some assumptions like the number of waste management potions with liner cost functions. The objective function is maximum expected utility and the constraints are technology capacities. With the linear programming method, he at last analyzed data he had and did risk preferences. In the conclusion part, the author said managing waste at least cost is difficult because waste has some effects on human health and the environment, which may lead to uncertainties. This makes selection of the options more difficult. But at least, in general, the simulation results show that if a community is of high risk-averse, then the optimal strategy is to dispose of most of the waste. Besides, the empirical results show that based on available data the author got, the optimal strategy of a moderately risk-averse decision maker is to manage sewage sludge at land-based facilities. And, for more improvement, it is necessary to reduce uncertainty cost associated with different options by increasing data collection for research or increasing the waste planning and management information available to states, local communities, waste handlers, citizens and industry.

Ayalon et al. (2008) used a mathematical programming model to present a comprehensive economic analysis of recycling organic wastes through composting. The model is built to examine the optimal level of compost production from sources of organic municipal solid waste, livestock manure and wastewater-treatment sludge and they apply the model to the case of Iarael because now, despite of the high levels of organic material in solid waste, the scarcity of landfills and the low level of organic content in agricultural soils, only 37% of the composting potential is realized. Their model considers spatial distribution of the sources of organic wastes and takes in account 13 different agricultural regions of demand for compost based on the data. Then results show the percentage of different kinds of waste can be recycled. It also shows the total amount of compost produced and the value of the objective function, which expresses the financial return to the Israeli economy from the composting array relative to sending the organic wastes to landfills. Thus, the authors make the conclusion that the regulations potentially encourage disposal by compotation. And, composting is not worthwhile for all settlements. Also, the realization of aforementioned scenario depends on the agricultural demand for compost, which depends on the recognition by farmers of the benefits of compost application.

Linear programming is often used in water and transportation assessment. Mandal (2005) investigated water management in mountain ecosystem using linear programming method. Because population growth and growing population of livestock for the hill people in India, energy is demanded in the hills for cooking lighting and heating in the household. Technological interventions at micro-level have the capacity of producing hydroelectricity in abundance, so a large amount of water is needed. How to manage water to minimum water cost and maximize agricultural profit is a big issue. Then, a linear programming model was built to lead to a result. This analysis showed that making additional products of forestry in the mountain area would be the best choice.

Ayer and Hogan (1977) presented a model of solid waste disposal in rural areas. Solid waste disposal, especially in rural areas, is frequently done in an unsanitary, potentially dangerous and often unsightly manner. Because of the distance between rural areas and disposal sites, transportation cost has to be considered. The author built a least-cost model which led to the result that potential cost saving from site centralization.

Hartwick (1970) introduced the transportation problem in linear programming. There are m trucks supplies points geographically separated from each other and are n trucks demand points geographically separated from each other. The sum of supply endowments is as least as great as the sum of the demand requirements. There exist fixed transportation costs. The problem is to transport the supply endowments to the demand requirements so as to minimize total costs. To solve this kind of problem, linear programming is the best choice. This method can also be used to solve minimize wastewater transportation costs problem.

CHAPTER 3. METHODOLOGY

Model Development

The problem is to simultaneously determine the cost-minimizing size and location of the treatment plants in North Dakota, given the need to dispose all produced wastewater from oil field and meet environmental standards. The problem is solved by mathematical programming. All of the wastewater generated at oil producers should be treated, recycled, or disposed of.

There are three options to deal with fracking flowback wastewater. First, treat it and reuse it. Second, treat it and put it back into water body such as back into a river. Third, dispose of it into disposal wells. However, North Dakota has never permitted disposal of fracking flowback into natural water resources. After all, it is not fresh water even after treatment. The cost to meet the requirements for surface water quality is high. Thus, two situations are being considered: the first is that fracking flowback wastewater is treated for reuse to fracking other wells and the second is that fracking flowback wastewater is disposed of in deep wells. Although fracking flowback water has not been recycled in North Dakota, this mathematical programming model will consider both on-site and off-site treatment and disposal methods dominate the management of produced wastewater (Baker, 2011).

Generally, Bakken flowback wastewater is highly saline, thus it requires robust treatment and recycling technologies. Based on the properties of the flowback water, two major technologies may be used- thermal treatment and membrane treatment. Of these two technologies, membrane treatment is the fastest and most popular worldwide. Almost 80% of the total desalination facilities worldwide utilize membrane technologies. Thermal treatment is used in most the other 20%. Thermal treatment needs high energy, which implies high fixed and variable costs. And because the fracking flowback wastewater is treated for reuse in fracking, it does not need to be treated to meet drinking water quality standards. Thus, membrane treatment is considered in this paper. There are several kinds of membrane treatment technologies. Reverse osmosis (RO) will be assessed in the thesis because it occupies 90% of membrane treatment and is more cost-effective (Frenkel, n.d.).

Membrane treatment removes dissolved minerals, such as salts, through a semipermeable membrane, from solution using filtration. Reverse Osmosis is a process in which a solvent passes through a semi-permeable membrane from lower to higher solute concentration and the solvent flows until equilibrium is established. RO is used for removal of high concentration of contaminants from the fracking water. Within the process, the separation of salt from the water is called desalination, which allows reuse and appropriate disposal of fracking wastewater. After the wastewater is treated, part of it with low- concentration is ready to reuse and the other part with high-concentration will be disposed of.

In general, the process of dealing with fracking flowback wastewater is as follows: It takes typically 1-2 weeks to frac a well. Three million gallons are used in average for a frac. Over the life of the well oil producers will eventually get all of the water to flow back. But in the first 30-60 days, 50% of that water will flow back. With all the amount of wastewater, the first 50% is considered as the quantity that could be treated because a mobile treatment plant could not wait so long until all the wastewater flows back and the cost of waiting the last 50% is high. Also the last 50% of wastewater has waited too long to be treated and there would be storage cost for that (Dustin Schultz, personal communication, September 19, 2012).

Then, among the first 50% of wastewater, 5%-45% could be recovered. After it is treated, a certain amount of water with low concentration could be reused and the other with high concentration should be disposed of. The process of RO treatment is shown in Figure 1. and the picture of dealing with wastewater is shown in Figure 2. Since RO is the appropriate treatment and recycling technology, several alternative kinds of plant sizes and capacities have been identified. Table 1. shows the features and costs of identified RO treatment plants.

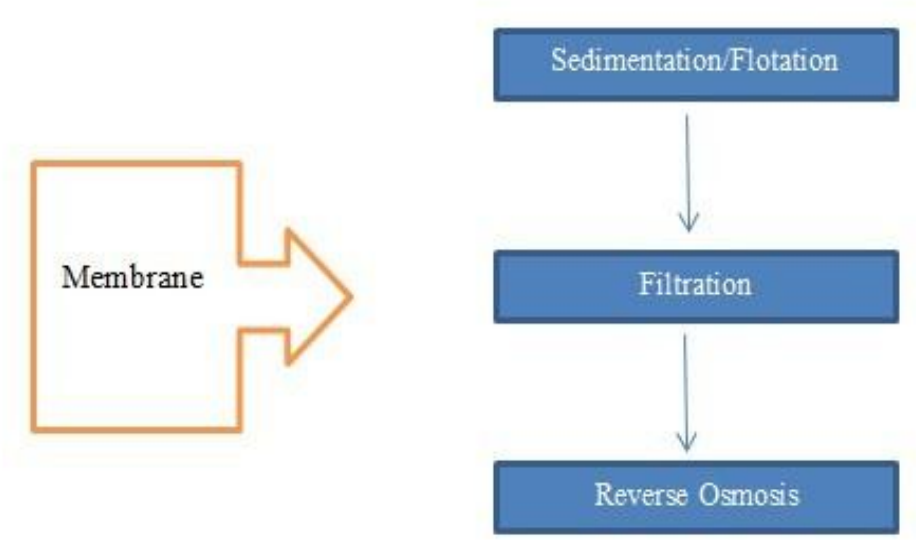

Figure 1. The process of RO treatment

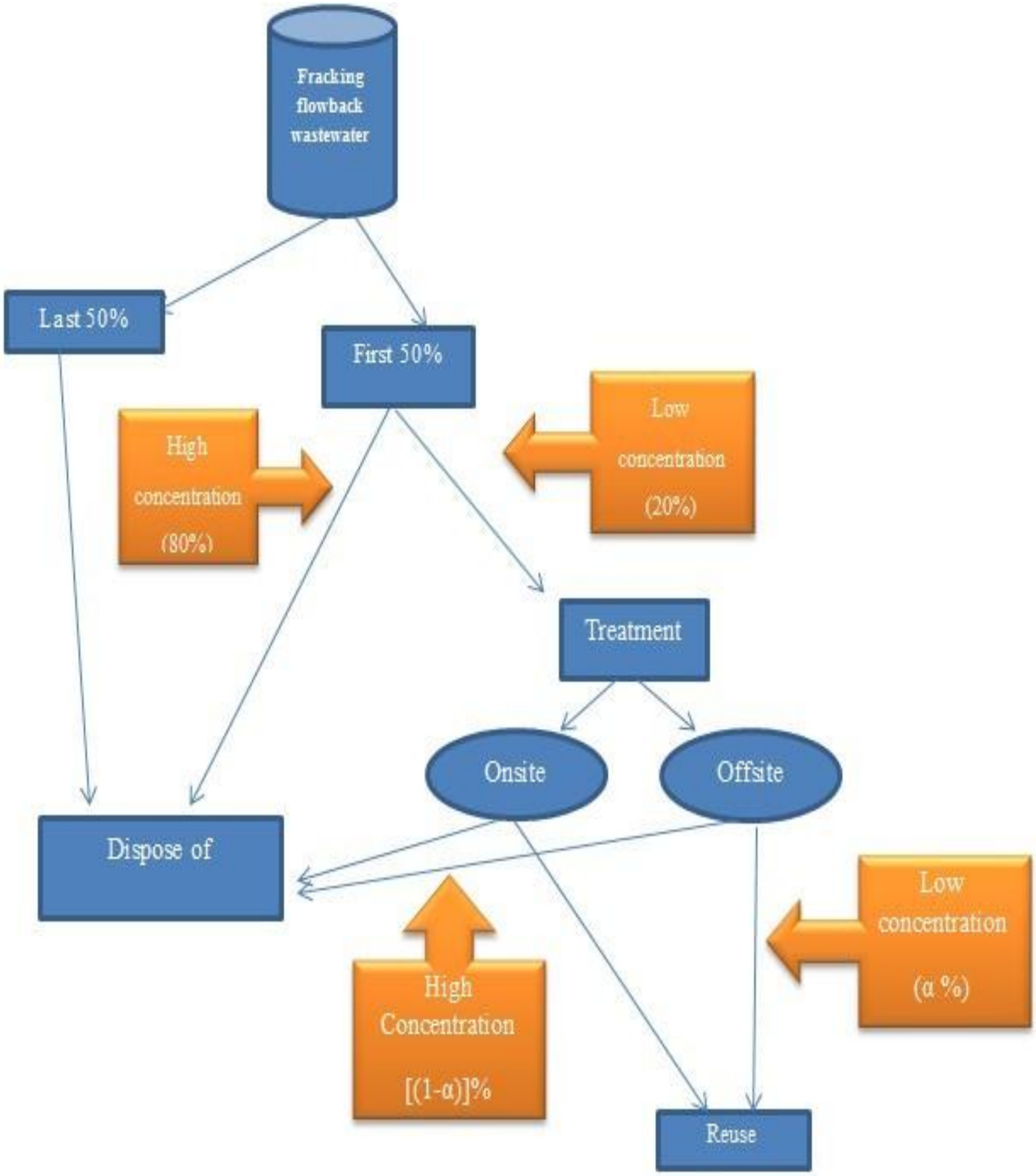

Figure 2. Fracking flowback wastewater disposal and recycling

Table 1. Capacities and costs of RO treatment

Name		Estimated	Unit
Treatment Cost (Capacity 20,000 m^3/day)	Capital cost for 20yrs at 6% (Fixed)	\$0.27/ m^3 or \$1.02/1000 gal	\$/ m^3 or 1000gal
	Energy cost at 4KW-H/ m^3, \$0.06/KW-H (Variable)	\$0.24/ m^3 or \$0.9/1000 gal	\$/ m^3 or 1000gal
	Chemicals + labor (Variable)	\$0.21/ m^3 or \$0.79/1000 gal	\$/ m^3 or 1000gal
	Total water cost (Variable)	\$0.72/ m^3 or \$2.73/1000 gal	\$/ m^3 or gal
	Capacity total	\$ 20M	
Treatment Cost (Capacity 95,000 m^3/day to 135,000 m^3/day)	Capital cost for 20yrs at 6% (Fixed)	\$0.32/ m^3 or \$1.21/1000 gal	\$/ m^3 or 1000gal
	Energy cost at 4KW-H/ m^3, \$0.06/KW-H (Variable)	\$0.12/ m^3 or \$0.45/1000 gal	\$/ m^3 or 1000gal
	Chemicals + labor (Variable)	\$0.219/ m^3 or \$0.83/1000 gal	\$/ m^3 or 1000gal
	Total water cost (Variable)	\$0.659/ m^3 or \$2.49/1000 gal	\$/ m^3 or 1000gal
	Capacity total	\$ 110M	
Treatment Cost (Capacity 165,000 m^3/day to 330,000 m^3/day)	Capital cost for 20yrs at 6% (Fixed)	\$0.17/ m^3 or \$0.64/1000 gal	\$/ m^3 or 1000gal
	Energy cost at 4KW-H/ m^3, \$0.06/KW-H (Variable)	\$0.24/ m^3 or \$0.91/1000 gal	\$/ m^3 or 1000gal
	Chemicals + labor (Variable)	\$0.117/ m^3 or \$0.44/1000 gal	\$/ m^3 or 1000gal
	Total water cost (Variable)	\$0.527/ m^3 or \$1.99/1000 gal	\$/ m^3 or 1000gal
	Capacity total	\$ 212M	

The cost of moving the treatment plants is not a major consideration. For example, assume the amount of wastewater produced in a well every day is 4,000 m^3, and then a dissolved air floatation machine could be used. This kind of machine can be either mobile or semi-permanent. If the plant operators choose it to be mobile, there is moving cost. Naturally, there are costs for piping to disconnect and reconnect the system. There are also the costs of mounting and dismounting the system for transport. After use, the membrane material needs to remain wet to avoid damage, so speed in transferring is very important. Should the system not be used for a long period of time, the system would also need to go through a simple disinfection process. But, if a company has engineers, there is no need to pay extra money to do this because the process is simple. The cost of moving the machine is transportation cost (Tian Jin, personal communication, September 12, 2012).

Traditional dual cost theory suggests total cost is composed of fixed cost and variable cost. But due to lake of current cost data, this paper focuses on per unit cost associated with the recycling of wastewater and assumes fixed cost is factored into per unit costs.

Model

Based on dual cost theory, cost is function of input prices and quantities. To evaluate the relationship between cost and prices of input and output quantities, traditional econometric techniques are used. However, if the objective is to estimate the least cost as well as the number of trucks needed to meet the least cost combination of input to achieve a exocenous output, it is appropriate to lay of the cost function as total cost, i.e., the summation of fixed and variable cost. This can be represented as

$$\text{Total cost} = \text{Fixed cost} + \text{Variable cost}$$

Given the intent to minimize the total cost, total cost (TC) is composed of two parts, variable cost (VC) and fixed cost (FC). The FC cost is the cost of the investments made on building treatment plants. The VC is the cost of transporting and treating reusable water on the truck for each mile. This cost is based on transportation cost of truck per mile. So the common factor for FC and VC is the number of trucks, which is the decision variable of the network model. The combination of fixed and variable cost forms the parameter coefficients of the network model.

In the model, the costs of on-site treatment with small capacity plants and off-site treatment with medium and large treatment plants will be included and they all compared with wastewater disposal.

Notations

Decision Variables

K_i^{off} = number of truckloads to three types of off-site treatment plants and their locations;

$K_i^{off\text{-}B}$ = number of truckloads moving from off-site treatment plants to reuse wells;

$K_i^{off\text{-}SWD}$ = number of truckloads moving from off-site treatment plants to SWD wells;

K_j^{on} = number of truckloads moving to on-site treatment plants;

$K_j^{on\text{-}B}$ = number of truckloads moving from on-site treatment plants to reuse wells;

$K_j^{on\text{-}SWD}$ = number of truckloads moving from on-site treatment plants to SWD wells;

K_n^{dis} = number of truckloads moving to SWD disposal sites;

Parameter Coefficients

$C = C_i^{off}, C_j^{on}, C_n^{dis}$;

C_i^{off} = cost of transporting wastewater to off-site treatment plants;

$C_i^{off\text{-}B}$ = cost of transporting treated water from off-site treatment plants to reuse wells;

$C_i^{off\text{-}SWD}$ = cost of transporting treated water from off-site treatment plants to SWD wells;

C_j^{on} = cost of transporting wastewater to on-site treatment plants;

$C_j^{on\text{-}B}$ = cost of transporting treated water from on-site treatment plants to reuse wells;

$C_j^{on\text{-}SWD}$ = cost of transporting treated water from on-site treatment plants to SWD wells;

C_n^{dis} = cost of transporting wastewater to SWD wells;

The parameter coefficients, C above for the mathematical model are constructed from the following constants. For example $C_i^{off} = (TD_i^{off} + P_i^{off})$. The details of all the parameter coefficients used in the mathematical model are presented in detailed in equation (2) and equation (3).

Constants

T = transportation cost per truckload mile;

K = truckloads of wastewater produced at the first 60 days;

D_i^{off} = distance from the wastewater source location to off-site treatment plants location;

D_i^{off-B} = distance of treated water from off-site treatment plants to reuse wells;

$D_i^{off-SWD}$ = distance of treated water from off-site treatment plants to SWD wells;

D_j^{on-B} = distance of treated water from on-site treatment plants to reuse wells;

D_j^{on-SWD} = distance of treated water from on-site treatment plants to SWD wells;

D_n^{dis} = distance from the wastewater source location to SWD wells;

P_i^{off} = cost per truckload for three types of off-site treatment plants;

P_j^{on} = cost per truckload for on-site treatment plants;

P_j^{rep} = cost per truckload for fresh fracking water;

P_n^{SWD} = cost per truckload for disposal sites;

Let

i = 1, 2, 3……I = number of offsite treatment plants;

j = 1, 2, 3……J = number of onsite treatment plants;

n = 1, 2, 3……N = number of disposal wells and sites;

The social planner's problem is to select truckloads K_i^{off}, K_j^{on}, K_n^{dis}, plants' locations that travel between them in order to minimize total costs according to the equation below to minimum total cost.

The mathematical programming model of alternative routes or movement of wastewater is presented below. This model is for the water discharged from one well to: a) onsite treatment plant and reuse in a new well; b) three alternative offsite treatment plants based on capacity; and c) disposal wells for a single well. However, the empirical mathematical model involves all possible wells. Thus for all wells the minimum cost set of flows is derived from the following:

(1) min TC = components 1 + components 2 + components3

(Offsite) (Onsite) (Disposal)

$$(2)\quad \min TC = \sum_{i=1}^{I}(TD_i^{off} + P_i^{off})\,K_i^{off} + \sum_{i=1}^{I}(TD_i^{off-B} - P_i^{rep})\,K_i^{off-B}$$

$$+ \sum_{i=1}^{I}(TD_i^{off-SWD})\,K_i^{off-SWD}$$

$$+ \sum_{j=1}^{J}(P_j^{on})\,K_j^{on} + \sum_{j=1}^{J}(TD_i^{on-B} - P_j^{rep})\,K_j^{on-B}$$

$$+ \sum_{j=1}^{J}(TD_j^{on-SWD})\,K_j^{on-SWD}$$

$$+ \sum_{n=1}^{N}(TD_n^{dis} + P_n^{dis})\,K_n^{dis}$$

$$(3)\quad \equiv \sum_{i=1}^{I} C_i^{off}\,K_i^{off} + \sum_{i=1}^{I} C_i^{off-B}\,K_i^{off-B} + \sum_{i=1}^{I} C_i^{off-SWD}\,K_i^{off-SWD}$$

$$+ \sum_{j=1}^{J} C_j^{on}\,K_j^{on} + \sum_{j=1}^{J} C_j^{on-B}\,K_j^{on-B} + \sum_{j=1}^{J} C_j^{on-SWD}\,K_j^{on-SWD}$$

$$+ \sum_{n=1}^{N} C_n^{dis}\,K_n^{dis}\,.$$

It is subject to the following constraints.

First, the total treatment capacity of the treatment plants and disposal sites are should equal to all the wastewater produced at the first 60 days in the location.

$K_i^{off} + K_j^{on} + K_n^{dis} = K$

Second, quantity of treated wastewater can be reused and quantity for disposal should be equal to the amount of treated wastewater.

$K_i^{off\text{-}B} + K_i^{off\text{-}SWD} = K_i^{off}$

$K_j^{on\text{-}B} + K_j^{on\text{-}SWD} = K_j^{on}$

Third, after treated, α percent of wastewater will go to reuse wells and others will go to disposal sites.

$K_i^{off\text{-}B} = \alpha K_i^{off}$ assume $\alpha=0.67$

$K_j^{on\text{-}B} = \alpha K_j^{on}$ assume $\alpha=0.67$

Fourth, the capacities of the three off-site treatment plants are large enough, if one capacity plant is chosen; there is no need to choose other two plants with different capacities.

Parameters and assumptions

Not all the amount of fracking flowback wastewater can be treated. In the first 30-60 days, 50% of the flowback come back and this amount is considered as the base case. Among the first 50%, a total of 20% is considered as the amount for treatment (Jacob Strombeck, personal communication, September 19, 2012).

There are many reported figures of the quantity of fracking water used in North Dakota petroleum wells. The quantity ranges from 2.4 million gallons per well to 8 million gallons per well (Cowan et al., 2010). Based upon these figures the base case figure for fracking water used will be 3.5 million gallons fresh water for drilling. Given the reported figure that 50% of frack flowback will return to the surface the first 30-60 days, 1.75 million gallons of wastewater will be the base case as the amount of flowback water to be considered per well (Jacob Strombeck, personal communication, September 19, 2012). Of these 1.75 million gallons, only a certain amount with low-concentration can be treated. The remaining high-concentration flowback should be disposed of directly. It has been reported that 20% of the wastewater is treatable (Cowan et al., 2010). This 20% is the only quantity of wastewater to be considered in this analysis. The remaining 80% will be transported to deep injection wells in all scenarios. And after treated, again water with low-concentration can be reused and other have to be disposed of. In Figure 1. the percentage of treated wastewater with low-concentration can be reused is α, and treated wastewater with high-concentration is $1-\alpha$. In the assumption, the percentage of treated wastewater can be reused is 67% and other 33% should be disposed of.

The current data shows there is no capacity constraint for both treatment plants and SWD wells. In the model, the program will choose the optimal flow that leads to minimum cost. But in reality, when an off-site treatment plant is selected, the fixed cost of building it is high and the variable costs of running it is based on the amount going to the plant. It is effective to run it within even over its capacity, but if it is ran under its capacity, the variable cost will be high, which is not cost effective. Thus, the assumption in this analysis is, once an off-site treatment plant is selected, the wastewater will go to this plant. There is no need to choose other plants even if the program shows lower cost.

A standard truckload of volume 8,000 gallons is selected in this paper and all the costs and prices will be calculated into truckloads. As shown in Table 1. capacities of the three off-site treatment plants are large enough, which can be considered as plants used in stations. But there are still smaller treatment plants which are mobile. But no information on the smaller plants has been collected, and then the assumption is, a smaller treatment plant has a cost of $\$1/m^3$, which equals $30.32/truckload. Due to the lack of environmental cost for trucks, the current per mile environmental cost available is for cars shown in Table 2.

Table 2. Environmental cost for cars per mile

Air Pollution Damage (health costs, crops, trees, materials,	4.0 ¢ per mile
Road Noise (property value decrease and abatement)	1.1 ¢ per mile
Water Pollution and Hydrologic Impacts	1.4 ¢ per mile
Transportation Diversity and Equity	0.7 ¢ per mile
Land Use Impact Costs	6.6 ¢ per mile
Roadway Land Value	3.4 ¢ per mile
Total	$0.172/mile

A similar environmental cost for trucks was not found from published reports. Because of the lack of a published parameter for environmental cost, the assumption is it is a portion of transportation cost. The total transportation cost for automobiles, as reimbursed by the State of North Dakota in November 2012, is $0.51/mile and the environmental cost is approximately $0.17/mile. The transportation cost for trucks is $1.62/mile. With calculation, the environmental cost for trucks is about $0.54/mile. This is a base case assumption because the environmental costs change with many factors such as the weight of cars and trucks, the years they are made and how dirty they are (“The true cost of driving”, n.d.).

Study Area

The study area is in the area of North Dakota where oil wells exist. This included portions of 19 countries: Adams, Billings, Bottineau, Bowman, Burke, Dicide, Dunn, Golden Valley, Hettinger, McHenry, McKenzie, McLean, Mercer, Mountrail, Renville, Slope, Stark, Ward and Williams. This area is in western North Dakota. Figure 3. shows the locations of all the wells (“About Us,” 2012).

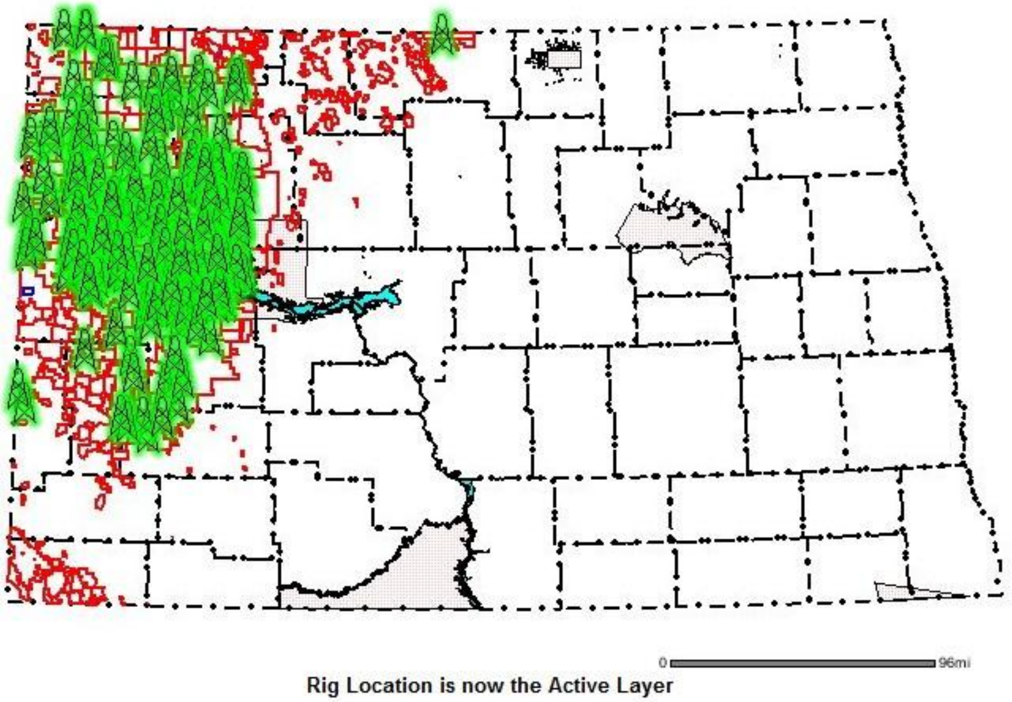

Figure 3. Well locations in North Dakota

In general, this area is a part of the Bakken formation, which is rich in oil and gas. The Bakken formation lies at the boundary of the Mississippian and Devonian area. The Bakken formation, a rock unit from the late Devonian to Mississippian, occupies about 200,000 square miles (520,000 km^2) of the subsurface of the Williston Basin. It lies in three political jurisdictions: the states of Montana and, North Dakota, and the Canadian province of Saskatchewan. The formation is named after Henry Bakken, a farmer who owned the land where the formation was initially discovered (“Bakken Formation,” n.d.).

As Figure 4. shows, the red line is the Williston Basin Province boundary, the blue line is the Bakken- Lodgepole Total Petroleum System. Most well locations in Figure 3. are in the area of Bakken in North Dakota, thus, Bakken formation in North Dakota is the study area in this paper.

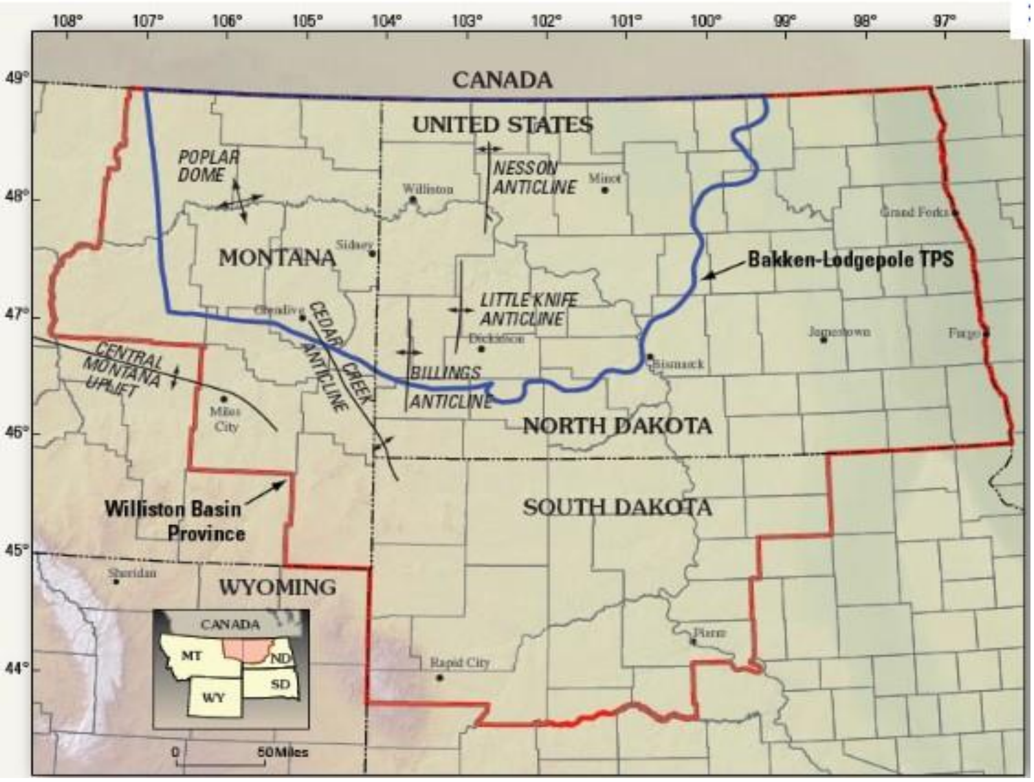

Figure 4. Bakken Formation ("Assessment of undiscovered oil Resources in the Devonian-Mississippian Bakken Shale Formation, Williston Basin Province, Montana and North Dakota," 2008)

Major cities in this area include Sidney, Terry, Williston, Parshall and Dickinson. The population of this area is around 16,000. Williston's median income was under $30,000 when the drilling started. But it has jumped to over $50,000 a year in 2012 (Collins, 2012).

Oil boom leads to the fastest growth in personal income, jobs and home prices. In 2012, North Dakota has the nation's lowest unemployment rate and oil boom also pushes rural North Dakota's housing, electric, and water, police and emergency services to unprecedented high. Meanwhile, the three-year-old boom brings thousands of workers to the western countries, which puts pressure on an already tight housing market (Oldham, 2012).

Freshwater for oil production is provided through groundwater and surface water system. Some comes from the Missouri River system. But groundwater sources in North Dakota are not sufficient to continue robust development of oil production, an alternative water supply is necessary. Lake Sakakawea is one of the alternatives but more is need for North Dakota oil and gas industry now and in the future (Harms, 2010).

Environmental issues are also important factors in this area. Frist, when fracking wastewater is disposed, there are fears that the wastewater may enter groundwater system and damage water quality. Then, human health maybe a problem because human beings still use it for drink and daily life. Even the chance is not large; people still have to pay certain attention to it. In addition, dispose of fracking flowback wastewater may pollute certain area of land, which would be another issue.

Second, when do wastewater treatment, membrane treatment plants should be used, which should place somewhere on certain area. Then, no matter how careful, the wastewater would pollute land in that area.

Third, transportation is an important part in the whole process of both wastewater disposal and treatment. Trucks are used to transport wastewater from well locations to disposal or treatment locations. But using trucks will cause air pollution and also produce dust on the road, which is also an environmental issue should consider.

Forth, fracking may cause earthquakes. On Christmas Eve and again on New Year's Eve, 2011, Youngstown, Ohio, received extra surprise- earthquakes, 2.7 to 4.0 on the Richter scale. It is determined that the likely cause was fracking. The disposal of wastewater from those operations, done by pumping it back into deep sandstone caused these earthquakes. Then why fracking could incur an earthquake is a focus. In general, if there is a fault in the earth, if the water content around the fault is change, the fault might slip. If the water gets into the fault itself, it can lubricate the fault and trigger a quake. Hydraulic fracturing pumps a lot of water underground, where it's used to crack the rock and liberate gas. This may cause tiny quakes, but fracking goes on for a day or two, and the quakes are small. Some people think that fracking in North Dakota would never trigger an earthquake. No matter what people are thinking, it is an environmental issue (Fischetti, 2012).

Fifth, whatever method is used to dispose wastewater, trucks have to be used to transport the wastewater from drilling locations to treatment or disposal locations. Then, road dust, which is earthen material or dusts that, becomes airborne, primarily by tries moving on unpaved dirt roads and dust covered paved roads, is produced. Road dust does affect human health because it can aggravate heart or lung-related conditions. Besides, food exposed to road dust would be eaten by people. Thus, road dust caused by trucks is also an environmental issue (United State Environmental Protection Agency, 2010).

Sixth, oil and gas exploration and production is an important industry in North Dakota. During production, the process of separating oil and produced water using heat treaters is often ineffective because heat treaters course 7,500 to 8,000 gallon of wastewater, only 20% of it is recycled. Production skim pits or open-topped tanks are used to further separate oil from produced water. In North Dakota, oil drillers lock it inside the Dakota Formation, a deep, brackish aquifer (Cowan et al., 2010). Drillers in the Williston Basin region of North Dakota currently dispose of their drilling wastes primarily in deep injection wells and continually assess fresh water resources for their fracking operations. Commercial oil field waste disposal facilities also pose drilling fluids can cause bird and wildlife mortality if they contain visible sheens or oil on the surface. Currently, an estimated 500,000 to 1 million birds are lost annually in oil field production skim pits and centralized oilfield wastewater disposal facilities. No one could sacrifice these birds and wildlife to fulfill the needs for ourselves, thus, maybe in the future, there will be a certain technology that does fewer harm to birds and wildlife (Trail, 2006).

Data and Parameters

Wastewater quantity and kinds of wells

A 2010 report from the Energy & Environmental Research Center (EERC) provides information on the amount of fracking water used as four to eight million gallons per well, depending on the depth and width of the wells. 2012 engineers' experiences present it usually needs 3 to 3.5 million of water to drill a well (Jacob Strombeck, personal communication, September 19, 2012). Three and one half million is used as the base case in this analysis. This can be adjusted to see whether the results would be different (Cowan et al., 2010).

Data on wells is from the North Dakota Industrial Commission, Department of Mineral Resources, Oil and Gas Division. This website provides information on all kinds of wells. Then choose "oil and gas (OG)" wells under the status of "drilling (DRL)" as wells produce wastewater. Meanwhile, "salty wastewater disposal (SWD)" wells under "active (A)" status as disposal wells. A number of oil and gas (OG) wells are being drilled at any time and there are other active wells. In order to account for current drilling wells that would release fracking flowback water and the number of wells that would potentially receive recycled flowback water, 16% of the drilling wells are randomly selected as wells B and others as wells A, where wells A are the ones producing wastewater and Wells B are the ones that need freshwater. With this kind of data, distance can be calculated for later use. Meanwhile, there are also active drilling wells on the website, which can be used as destination wells where treated water can go ("Oil and gas subscription: ArcIMS viewer," 2012).

Treatment plant costs

This analysis uses both treatment plants and disposal wells to deal with fracking flowback wastewater. The only available information on treatment plants costs presents fixed cost as \$/gallon, then instead of use fixed cost, a total variable cost includes fixed cost could be used in this paper. As discussed before, treatment technology has been narrowed down to Membrane treatment, but there are different capacities of off-site treatment plants can choose from. Three kinds of capacities and their costs can be found in IDS-Water –White paper. That is what will be used as parameters. The locations of the plants will selected by GIS, the location will be selected at intersections at distance of 10 miles long and 10 miles wide. Among them, the ones nearest the wells locations which lead to lowest transportation costs will be selected by GIS as candidate locations for later calculation (Frenkel, n.d.). In addition to off-site treatment, smaller plants with higher cost could also be used as on-site treatment plants. The cost is assumed as \$1/m^3.

Disposal capacities and costs

In terms of wastewater disposal, disposal wells have to be used. Then there are disposal capacities and costs. In order to dispose wastewater, oil companies or operators would either drill wells or buy disposal wells from other operators. The capacities would be different and also fixed and variable costs for buying disposal wells are different. But it was not possible to get data on drilling a disposal well, which is considered as fixed cost. But still, there is variable cost of disposal. One company, quantify a price of 75 cents per barrel. One oil barrel equals 42 US gallons. Then the cost is \$0.0179/gallon or \$143.2/ truckload (PowerFules, 2012). There are no binding capacity constraints for SWD wells on in North Dakota in 2012. Then in the model, disposal capacity will not be a constraint.

Distance and transportation cost

Transportation is a main factor in the whole process of dealing with fracking flowback wastewater. Either treat the wastewater or dispose it, wastewater has to be transported from oil well locations to reuse locations or dispose locations. As data of active OG wells and SWD wells is available, GIS could be used to calculate distances. When do treatment, there are two options: on-site treatment and off-site treatment. If on-site, GIS would help calculate distances to reuse sites and disposal sites. GIS can also be used to calculate distances when do off-site treatment once the location of the treatment plants have been selected. In GIS process, road network can be downloaded and be used for selection of off-site treatment location.

In 2010, the total number of truck movements for each well is estimated to be 2,024 and approximately half of them representing loaded trips. The average traffic on major country roads in oil-producing countries is 145 vehicles per day, among which 61 are trucks. But road condition in North Dakota is not so good for the large amount of trucks. In a survey of 958 miles of impacted paved roads, only 58% of these miles are in good conditions and 35% are in fair sharp and 7% are in poor condition. But the 35% of the miles currently in fair condition will deteriorate very soon (Upper Great Plains Transportation Institute, 2010).

For a conventional tanker trailer at 55 mph, the variable cost per mile is estimated to be $1.62. But this is a weighted average for all miles. That is, if the destination is 50 miles away from the origin, it would be a total of 100 miles. The cost of this trip would be $162.

Environmental cost

As talked before, whatever technology be used, there will always be environmental cost such as air pollution, land pollution, damage to wildlife and human beings and earthquake. But the environmental cost could only include in the model, quantify it is impossible. Thus, when running the model, environmental cost is not included. As a whole, all the parameters are shown in Table 3.

Table 3. Cost

Name	Cost	Estimate	Unit	Reference
Small	Wastewater treatment	$30.32/truckload	$/truckload	
Medium 1	Wastewater treatment	$21.84/truckload	$/truckload	Frenkel, (n.d.).
Medium 2	Wastewater treatment	$19.92/truckload	$/truckload	Frenkel, (n.d.).
Large	Wastewater treatment	$15.92/truckload	$/truckload	Frenkel, (n.d.).
Disposal cost		$143.2/ truckload	$/truckload	PowerFules, (2012).
Transportation cost		$1.62/mile	$/mile	Alan Dybing, personal communication, October 5, 2012.
Fresh water cost		$120/truckload	$/truckload	"Industrial Water in High Demand in North Dakota," (2012).

Optimization Procedure

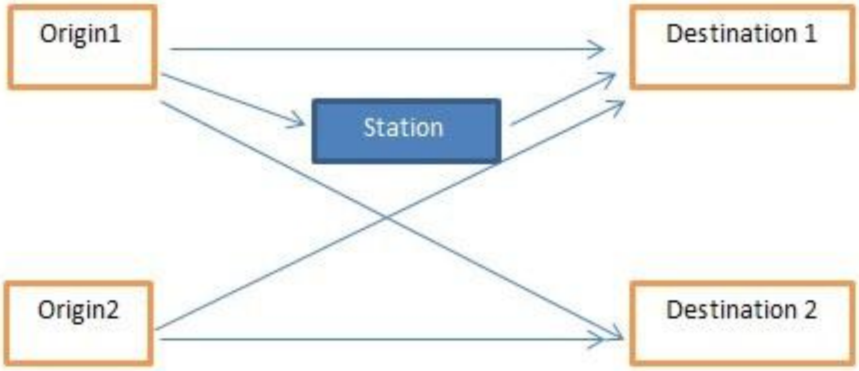

Figure 5. Netflow procedure

In the fracking flowback wastewater particular case, origins are drilling wells, stations are on-site or off-site treatment plants and destinations are disposal wells. Then the model built can be rewritten as one can be read by SAS.

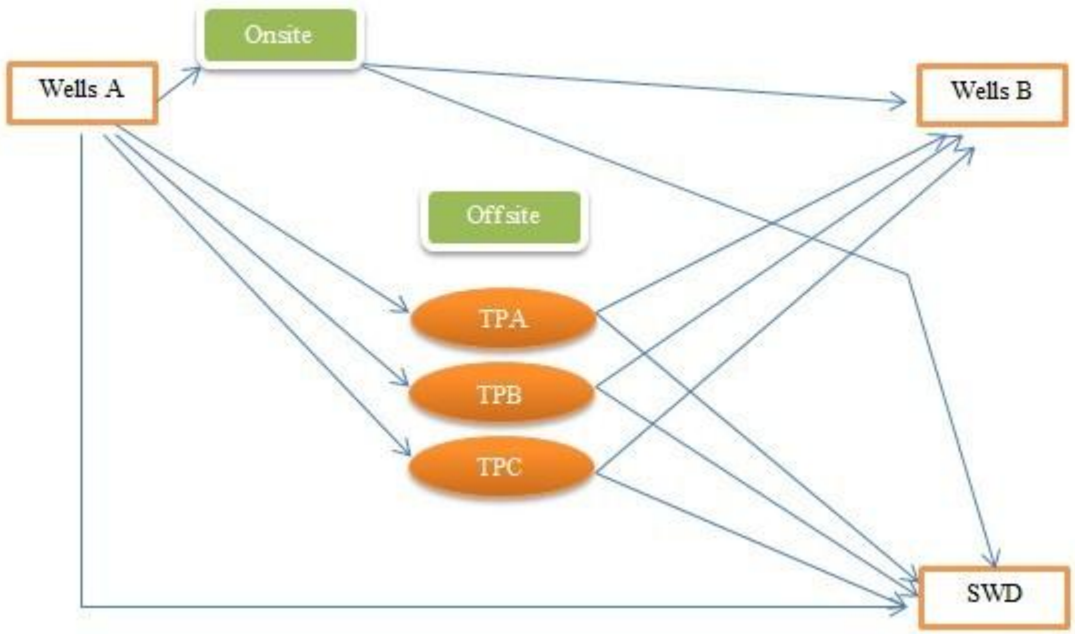

Figure 6. Netflow used for wastewater disposal

Table 4. Model used in Netflow procedure

number of truckloads	flow		cost
X_1	Wells A	SWD	$C_1 = X_1$[(T*dis)+SWD cost]
$X_{2,a}$	Wells A	cand	$C_{2,a}= X_{2,a}$[(T*dis)+treatment cost A]
$X_{2,b}$	Wells A	cand	$C_{2,b}= X_{2,b}$[(T*dis) treatment cost B]
$X_{2,c}$	Wells A	cand	$C_{2,c}= X_{2,c}$[(T*dis)+treatment cost C]
X_3	cand	SWD	$C_3= X_3$[(T*dis)+SWD cost]
X_4	cand	Wells B	$C_4= X_4$[(T*dis)-replacement cost]
X_5	Wells A	Wells B	$C_5= X_5$[(T*dis)+treatment cost D- replacement cost]
X_6	Wells A	SWD	$C_6= X_6$[(T*dis)+SWD cost]

Objective function

Min $[(C_1), (C_{2,a} + C_3 + C_4), (C_{2,b} + C_3 + C_4), (C_{2c} + C_3 + C_4), (C_5 + C_6)]$

Constraints

Total $X=X_1+X_{2,a}+X_{2,b}+X_{2,c}+X_5$

$X_{2,a}+X_{2,b}+X_{2,c}=X_3+X_4$

$X_3=\alpha X_4$

$X_6=\alpha X_5$

Parameter estimates and assumptions

Total X= 44

α=0.67

T＝$1.62/mile (average over all trips including backhauling empty)

SWD cost＝$143.2/truckload

Treatment cost A＝$21.84/truckload

Treatment cost B＝$19.92/truckload

Treatment cost C＝$15.92/truckload

Treatment cost D＝$30.32/truckload

Replacement cost＝$120/truckload

The model just uses one-way transportation cost because there are many reasons that the trucks will not return to the origin places. For example, the contracts for the trucks would be only one-way; the trucks may go to other wells to outside the model. Thus, it is better to use one-way transportation cost in this analysis. With the above costs and Netflow procedure, SAS can work out the optimal result which leads to minimum costs.

CHAPTER 4. RESULTS

Results of Simple Model and Discussion

The mathematical programming model is formulated on SAS files, which are converted from DBF database files, with the distances coming from GIS system, and run by means of SAS, using the Netflow method. In the simple model, the amount of wastewater that comes from each well is set at 3.5 million gallons per well which is 438 truckloads. Of these, 44 truckloads are considered to be treatable and is the base case for treatment. After treated, 67% is suitable for reuse in newly drilling wells.

The analysis indicates that after the 274 drilling wells have been drilled, the wastewater produced will be 12,056 truckloads, among which about 4,455.026 truckloads will go to treatment plant C, which is set as the large capacity treatment plant in this study for treatment and reusing. Another 7,600.973 truckloads will go to treatment plant D- small (on-site) treatment plant for treatment and reusing. There is 0.001 truckload that will go to SWD well directly to be disposed of. However, 0.001 truckload is not feasible in reality; thus, it can be considered that 7,601 truckloads will go to small on-site treatment plants for treatment and 847 truckloads go to large off-site treatment plants. After the wastewater is treated, 5,092.652 truckloads of treated water of low concentration from small on-site treatment plants will go to reuse wells and the remaining 2,508.321 truckloads of treated water of high concentration will be disposed of in SWD wells. 2,984.876 truckloads of treated water from large off-site treatment plants will go for reuse and 1,470.159 truckloads will be disposed of. The minimum cost is negative under this scenario. Because recycled water is valuable to drillers, this option implied 134,381.22 dollars in saving to drillers.

Comparing on-site treatment and three off-site treatment alternatives, on-site treatment plants have a higher treatment cost, but the distance is shorter, which leads to lower transportation costs. As a result, if the transportation costs and treatment costs of on-site treatment together is lower than the costs of off-site treatment; the flows will go to on-site treatment. Otherwise, the flows will go to off-site treatment. So, in this base case, approximately 7,601 of the total 12,056 truckloads go to on-site treatment plants because these wells are closer.

There is still 0.001 truckload that goes directly from drilling wells to a SWD well because this well is close enough to a SWD well. So, the cost of either the flow going to on-site treatment plants or to off-site treatment plants is higher than disposing of it. The program selects the optimal way. But the amount is too small to operate in reality, so it can be considered as going to on-site treatment plants for treatment. The numerical network model is shown in Figure 7. The maps show the flows are Figure 8. and Figure 9.

Table 5. Results of simple model

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	None	-134,381.22	Before treatment and disposal 7,600.973 to small plants (on-site) 4,455.026 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 5,092.652 from small to Wells B (reuse) 2,508.321 from small to SWD (disposal) 2,984.876 from large to Wells B (reuse) 1,470.159 from large to SWD (disposal)

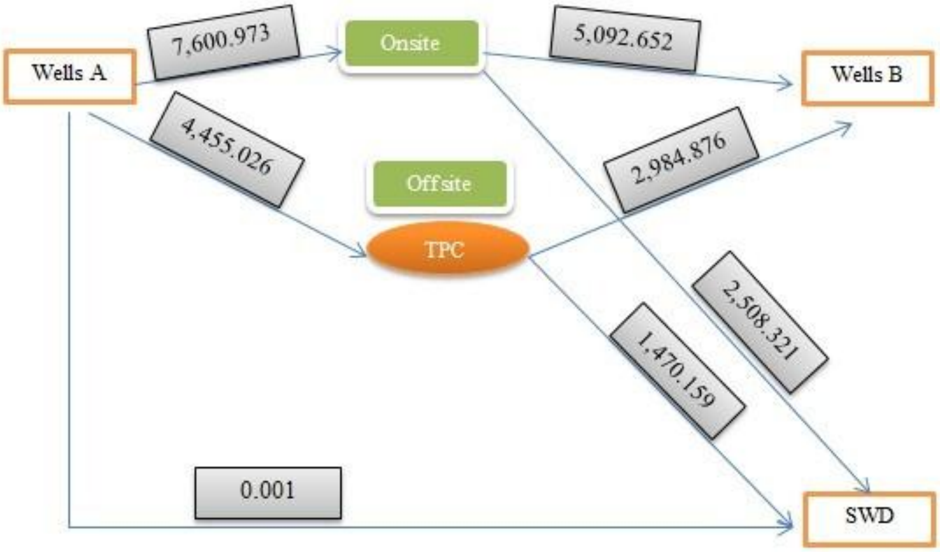

Figure 7. Numerical network model

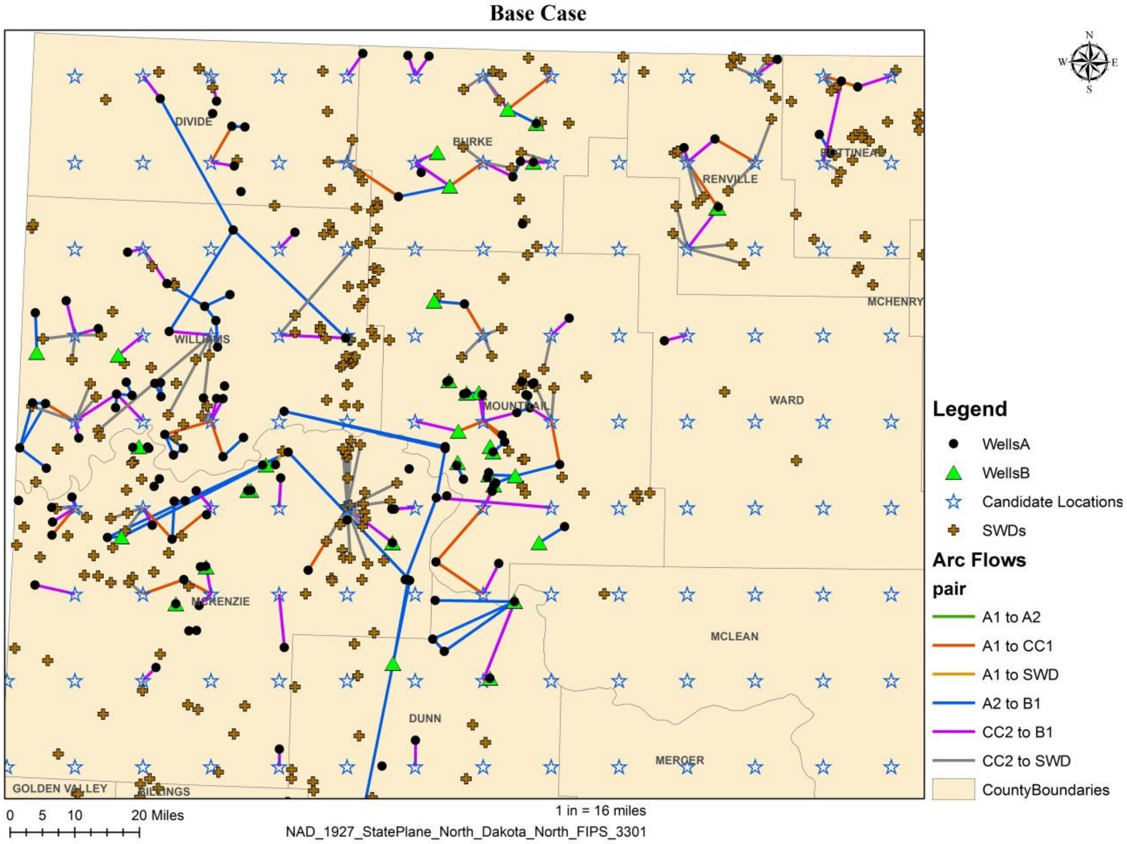

Figure 8. Optimal flows

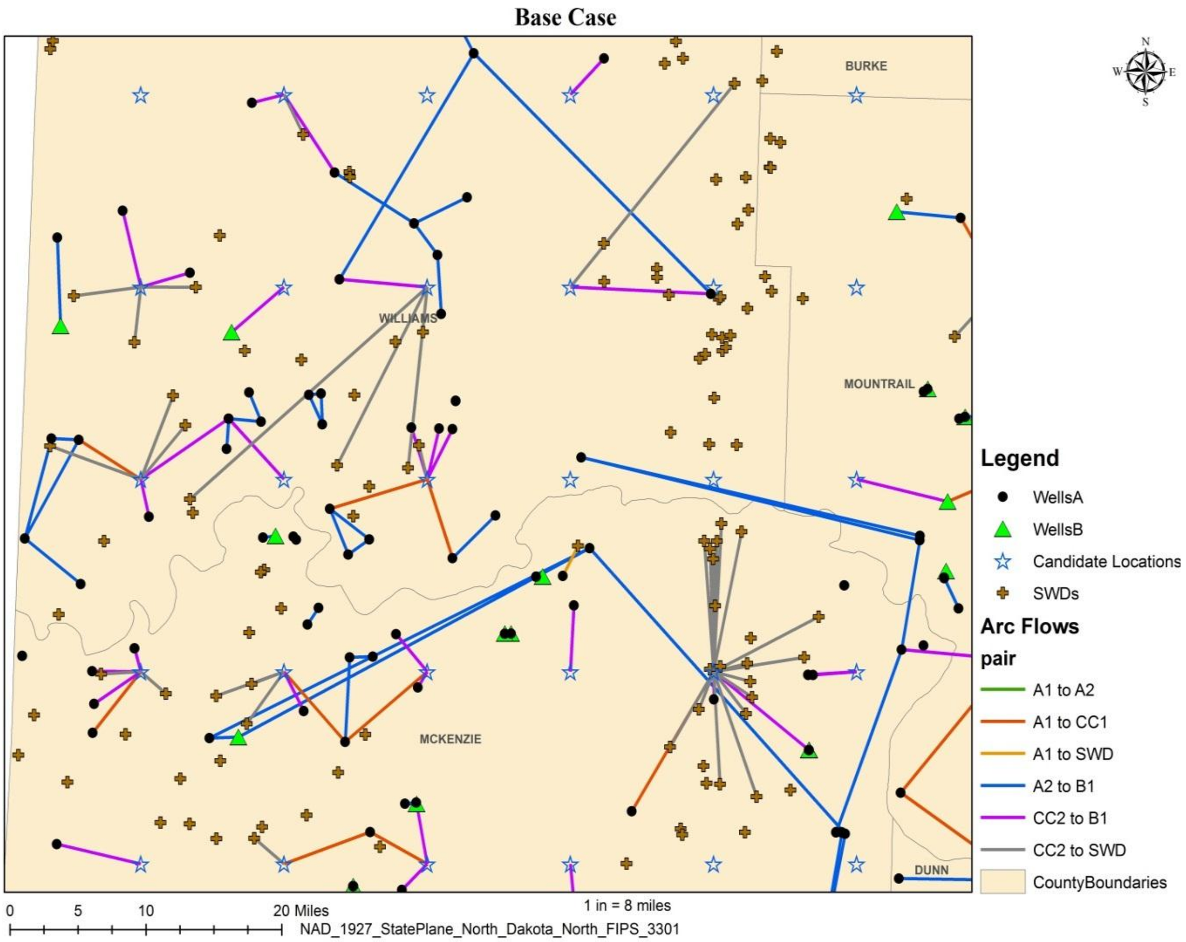

Figure 9. Optimal flows with details

Results of Model with Changed On Site Recycling Costs and Discussion

The data in the model used includes an assumed on-site treatment cost. Because it is an assumed number, it will be changed to see the differences in results.

First, as shown in Table 2. the difference in financial cost for large and medium treatment plants is close to \$5/truckload, but the assumption of the cost for small treatment plants is based on the assumption of \$1/m^3. Assuming the difference is linear, the cost for small plants is \$25/truckload. When the model is run again, the results show the number of truckloads going to large treatment plants (off-site treatment, large capacity) decreases to 2,772.039 and the number of truckloads going to small treatment plants (on-site treatment) increases to 9,283.96 and the

0.001 truckload going to SWD remains the same. After treatment, 6,220.253 truckloads of treated water from small on-site treatment plants are going for reuse and 3,063.707 truckloads are disposed of. For large off-site treatment, 2,022.267 truckloads are going for reuse and 749.772 truckloads are disposed of. The minimum cost changes to -$179,263.9 because with a lower treatment cost, the gains from replacing fresh water with treated water increases.

With a decreased small treatment plant cost, and the distances remain the same, transportation cost and treatment cost of small plants together decreases. Then the program will choose more flows to small plants that have lower transportation cost and treatment cost. That is the reason more truckloads go to on-site treatment plants this time.

Second, the breaking even point of minimum cost from negative to positive for small (on-site) treatment plants are $93/truckload. At this stage, the minimum cost becomes $656.99. A total of 802.999 truckloads are going to small treatment plants, 11,253 truckloads are going to large off-site treatment plants and 0.001 truckloads are going to SWD. And after the wastewater is treated, 538.009 truckloads are going from small on-site treatment plants to reuse locations and 264.99 truckloads for disposal. 7,539.51 truckloads from large off-site treatment plants are going for reuse and 3,713.49 truckloads are disposed of.

The above results show that with increasing cost of on-site small treatment plants, the truckloads keep going from on-site small treatment plants to large off-site plants because the program chooses the minimum of the total of transportation cost and treatment cost. If the total of on-site treatment cost is lower than off-site treatment, the flows will go to on-site treatment plants. Otherwise, they will go to off-site treatment plants. The program keeps choosing the large plant because it has a lower treatment cost than the two medium ones and there is no capacity constraints.

Table 6. Results of model with decreased on site recycling costs

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Treatment cost D: $25/truckload	-179,263.93	Before treatment and disposal 9,283.96 to small plants (on-site) 2,772.039 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 6,220.253 from small to Wells B (reuse) 3,063.707 from small to SWD (disposal) 2,022.267 from large to Wells B (reuse) 749.772 from large to SWD (disposal)

Table 7. Results of model with increased on site recycling costs

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Treatment cost D: $93/truckload	656.99	Before treatment and disposal 802.999 to small plants (on-site) 11,253 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 538.009 from small to Wells B (reuse) 264.99 from small to SWD (disposal) 7,539.51 from large to Wells B (reuse) 3,713.49 from large to SWD (disposal)

Results with Decreased Replacement Cost and Discussion

As shown above, the results always show negative minimum costs because the replacement cost is so high that none of the on-site or off-site treatment costs can exceed it. The program always chooses treatment instead of disposal. The replacement cost at present is published fresh water cost, but the reused water is treated water, the quality is different from fresh water. In order to see whether there is a difference in minimum cost with decreased replacement cost, the assumption is made that replacement cost changes to $60/truckload. The result does not change the route that 4,455.026 truckloads going to large off-site treatment plants, 7,600.973 truckloads going to on-site small treatment plants. 0.001 truckloads are going to a SWD well to be disposed of. The truckloads going to reuse locations and SWD wells after wastewater treatment also remain the same. Because the replacement cost is still higher than treatment cost and SWD cost remains high, the routes remain the same. But the minimum cost increases to 586,338.72 dollars with the decreased replacement cost.

Table 8. Results with decreased replacement cost

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Replacement cost: $60/truckload	586,338.72	Before treatment and disposal 7,600.973 to small plants (on-site) 4,455.026 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 5,092.652 from small to Wells B (reuse) 2,508.321 from small to SWD (disposal) 2,984.876 from large to Wells B (reuse) 1,470.159 from large to SWD (disposal)

Results with Increased Environmental and Transportation Cost and Discussion

The above models are running without environmental costs. But as mentioned before, whatever method of treatment or disposal is used, there will always be environmental costs. With the increase of environmental costs, the results would be different.

In the assumption section, environmental cost is considered as a portion of transportation cost, with calculation, environmental cost for trucks per mile is approximately $0.54/ mile, which converts to $2.16/mile of transportation cost. With the changed transportation cost, the result shows the minimum cost is -$94,919.64. A total of 3,245.015 truckloads are going to large off-site treatment plants, 8,810.984 truckloads are going to on-site small treatment plants and 0.001 truckloads are going to a SWD well. Among the treated water 5,903.359 truckloads from small on-site treatment plants are going to reuse locations; 2,907.625 remaining truckloads are disposed of. A total of 2,174.405 truckloads from large off-site treatment plants are ready for reuse and 1,070.55 should be disposed of.

The reason is, with a higher transportation cost, longer distances will lead to higher transportation costs, and then the program chooses more on-site treatment with lower costs to reach minimum cost. As a result, if the transportation cost keeps increasing, the flows that lead to minimum total cost will keep going to on-site treatment plants instead of going to any kind of off-site treatment plants.

If the environmental cost is doubled to be $1.08/truckload, the transportation cost becomes $2.7/mile. Then, the truckloads going to off-site treatment plants decreases to 2,596.018 and on-site treatment increases to 9,459.981 truckloads because of the increased transportation cost. And 6,338.187 truckloads of on-site treated water are reused in other drilling wells and 3,121.794 truckloads are disposed of. A total of 1,739.332 truckloads of large off-site treated water is reused, 856.686 truckloads for disposal. The minimum cost increases to -$58,755.13. So, if transportation cost keeps increasing, the flows will keep going from off-site treatment to on-site treatment.

In order to get rid of the negative cost, the replacement cost is set as $60/truckload again, minimum cost becomes $661,964.81, and flows remain the same.

Table 9. Result with increased environmental and transportation cost

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Transportation cost: $2.16/mile	-94,919.64	Before treatment and disposal 8,810.984 to small plants (on-site) 3,245.015 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 5,903.359 from small to Wells B (reuse) 2,907.625 from small to SWD (disposal) 2,174.465 from large to Wells B (reuse) 1,070.55 from large to SWD (disposal)

Table 10. Result with changed transportation cost and replacement cost

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Transportation cost: $2.7/mile	-58,755.13	Before treatment and disposal 9,459.981 to small plants (on-site) 2,596.018 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 6,338.187 from small to Wells B (reuse) 3,121.794 from small to SWD (disposal) 1,739.332 from large to Wells B (reuse) 856.686 from large to SWD (disposal)
	Transportation cost: $2.7/mile Replacement cost: $60/truckload	661,964.81	Before treatment and disposal 9,459.981 to small plants (on-site) 2,596.018 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 6,338.187 from small to Wells B (reuse) 3,121.794 from small to SWD (disposal) 1,739.332 from large to Wells B (reuse) 856.686 from large to SWD (disposal)

Results with Decreased Disposal SWD Costs and Discussion

The above results always show the optimal route to reach minimum cost is chosen by a certain number of treatment plants and only one of the flows going to a SWD well. The reason is, with the data at hand, treatment plants have high capacities, low costs and high replacement cost. On the other hand, SWD cost is too high for the program to choose from.

The replacement cost was set as \$10/truckload, SWD cost as \$30/truckload. The result shows 2 truckloads go to SWD, 649.02 truckloads go to off-site large treatment plants and 11,404.98 truckloads go to on-site small treatment plants. Then 7,641.337 truckloads of treated water from small on-site treatment plants are reused and 3,763.643 truckloads are disposed of. 434.843 truckloads of treated water from large off-site treatment plants are reused. The remaining 214.177 truckloads of water are disposed of. The minimum cost is \$983,607.48. If the SWD cost keeps decreasing and treatment cost keeps increasing or replacement cost keeps decreasing, more flows will go to SWD wells.

Table 11. Results with decreased disposal SWD costs

Base case	Changed part	Minimum cost (\$)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: \$1.62/mile SWD cost: \$143.2/truckload Treatment cost A: \$21.84/truckload Treatment cost B: \$19.92/truckload Treatment cost C: \$15.92/truckload Treatment cost D: \$30.32/truckload Replacement cost: \$120/truckload Capacity: none	SWD cost: \$30/truckload Replacement cost: \$10/truckload	983,607.48	Before treatment and disposal 11,404.98 to small plants (on-site) 649.02 to large plants (off-site) 2 to SWD well (disposal)
			After treatment and disposal 7,641.337 from small to Wells B (reuse) 3,763.643 from small to SWD (disposal) 434.843 from large to Wells B (reuse) 214.177 from large to SWD (disposal)

Results of Model with Changed Truckloads and Discussion

In the above example, the amount of wastewater coming from each well is set as 3.5 million gallons, but in reality, each well requires different amounts for fracking water which ranges from 2.4 million gallons to 8 million gallons, which translates to 30 truckloads to 100 truckloads. It is possible to change the truckloads in the program and see any differences in results.

After choosing 25% upper and lower of the 44 truckloads as upper and lower bounds, the model was run twice with 55 truckloads and 33 truckloads to see the differences. With decreased truckload to 33, the total truckloads of the 274 drilling wells change from 12,056 to 9,042. With the changed truckloads, the optimal route also changes. 5,697.98 truckloads are going to small on-site treatment, 3,344.019 truckloads are going to large off-site treatment and 0.001 truckloads to be disposed of. After treated, 3,817.647 truckloads of the on-site treated water are suitable to reuse and the other 1,880.333 truckloads are disposed of. 2,240.493 truckloads of large off-site treated water for reuse, the other 1,103.526 truckloads are disposed of. The minimum cost increases to -$107,908.79 because profit gains from replacement cost decreases with the decreased truckload.

With increased truckload to 55, total truckloads increases to 15,070. With the new total truckloads, 9,509.971truckloads go to small on-site treatment, 5,560.028 truckloads for large off-site treatment and 0.001 truckloads are disposed of. After treated, 6,371.681 truckloads from on-site treatment and 3,725.219 truckloads from off-site treatment are reused. 3,138.29 truckloads from on-site treatment and 1,834.809 truckloads from off-site treatment are disposed of. The minimum cost increases to -$146,695.63 because the profit gains from replacement cost increases with the increased truckload. The model is suitable to use different numbers of truckloads to see the difference in total minimum costs and the number of truckloads go to each wells to disposed of or treated.

Table 12. Results of model with changed truckloads

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Truckload = 33 Total truckload =9,042	-107,908.79	Before treatment and disposal 5,697.98 to small plants (on-site) 3,344.019 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 3,817.647 from small to Wells B (reuse) 1,880.333 from small to SWD (disposal) 2,240.493 from large to Wells B (reuse) 1,103.526 from large to SWD (disposal)
	Truckload = 55 Total truckload =15,070	-146,695.63	Before treatment and disposal 9,509.971to small plants (on-site) 5,560.028 to large plants (off-site) 0.001 to SWD well (disposal)
			After treatment and disposal 6,371.681 from small to Wells B (reuse) 3,138.29 from small to SWD (disposal) 3,725.219 from large to Wells B (reuse) 1,834.809 from large to SWD (disposal)

Result with Capacity Constraints

The above results always show the optimal flows reach the minimum cost by using on-site small treatment plants, off-site large treatment plants and SWD wells. The two kinds of medium-size treatment plants have never been selected. The main reason for this is because the capacities of all kinds of treatment plants and SWD wells are high enough to consider as there is no capacity constraints. Then the flows will always go from the lowest treatment cost with shortest distance to higher treatment costs with longer distance. Thus, among all four kinds of treatment plants, on-site small treatment cost always associates with shorter distances which leads to lower transportation costs and large off-site treatment plants have lower treatment cost. The flows will never go to medium treatment plants.

In order to see when the flows will go to medium plants, the capacity of on-site small treatment plants was set as 5 truckloads and large off-site treatment plants capacity as 10 truckloads. The result shows that 10, 125.953 truckloads go to medium-2 off-site treatment plants and after treated, 6,784.389 truckloads go for reuse and 3,341.564 truckloads are disposed of. A total of 710.047 truckloads go to large off-site treatment plants and 475.892 truckloads of treated water are reusable, the other 234.155 truckloads are disposed of. A total of 1,220 truckloads go to small on-site treatment plants and 817.4 truckloads of water after treated are reusable, the other 402.6 truckloads are disposed of. None of the flow goes to SWD wells. The minimum cost is $38,818.12. Because of the capacity constraints, the number of truckloads going to on-site treatment plants is limited. Flows should not go there when capacity constraints are reached. Meanwhile, SWD cost is higher than treatment cost; the flows will not go there. So, when the large off-site treatment plants' cannot meet the quantity of wastewater, the flows will go to the second lowest treatment plants medium-2 for treatment. If capacity constraints are added to medium-2 treatment plants, flows will also go to medium-1 plants, which have higher cost than the other two off-site treatment plants.

Table 13. Result with capacity constraints

Base case	Changed part	Minimum cost ($)	Flows (truckloads)
Truckload = 44/well Wells A=274 Wells B=46 Total truckload =12,056 Transportation cost: $1.62/mile SWD cost: $143.2/truckload Treatment cost A: $21.84/truckload Treatment cost B: $19.92/truckload Treatment cost C: $15.92/truckload Treatment cost D: $30.32/truckload Replacement cost: $120/truckload Capacity: none	Treatment capacity D: 5 truckloads Treatment capacity C: 10 truckloads	38,818.12	Before treatment and disposal 1,220 to small plants (on-site) 710.047 to large plants (off-site) 10,125.953 to medium-2 plants (off-site)
			After treatment and disposal 817.4 from small to Wells B (reuse) 402.6 from small to SWD (disposal) 475.892 from large to Wells B (reuse) 234.155 from large to SWD (disposal) 6,784.389 from medium-2 to Wells B (reuse) 3,341.564 from medium-2 to SWD (disposal)

Discussion on Parameters

The above results are based on parameters described in Chapter 3. The estimates on the quantity of wastewater produced and the 20% that is treatable are from published reports and is transferred into truckloads. There should be a lot of variability expected in these figures. Disposal costs come from a telephone quote from a large disposal company. This parameter may reflect high costs due to imperfect markets in SWD wells. Distances are calculated through GIS software (Cowan et al., 2010).

The three kinds of treatment plants' costs and capacities are from a company's report. Compare with other market costs, these are considered as non-market costs, which have very high capacities and very low costs. So in the program, it is considered as no capacity constraints of the three kinds of technologies, which leads to the results that flows always go from the cheapest cost to highest. Meanwhile, there is no available data that show either capacity or cost of the small treatment plants, and then all the parameters of small plants are assumptions (Frenkel, n.d.).

Replacement cost is also from published newspaper report. This is the imperfect market price of fresh water for fracking. This replacement value may be artificially high because of the imperfect market in transportation, and the imperfect market for water permits in western North Dakota. Although the opportunity cost of recycled water is different from higher quality fresh water, this is the only data available. With the high replacement cost, the program always shows negative total costs. But when the replacement cost is decreased, total cost will become positive ("Industrial water in high demand in North Dakota," 2012).

Estimates for environmental costs were not found. This cost would be expected to vary from place to place. The environmental cost used in this paper is calculated from similar costs in the environmental costs of automobile transportation.

Summary

Results of the mathematical model were presented. In general, the wastewater flows back within the first 30-60 days is considered as treatable wastewater, but only 20% of that amount with low concentration is considered as the base case. The results show that based on different parameters and assumptions, all the three kinds of on-site treatment, off-site treatment and SWD wells are used to deal with wastewater. But the amount of the treatment plants and SWD wells being used changes with parameters and assumptions.

CHAPTER 5. CONCLUSION

In general, there are three methods to deal with wastewater from oil producers: 1) deep well injection; 2) on-site treatment; and 3) off-site treatment. Currently, oil producers in North Dakota lock the wastewater into deep injection wells instead of treating it for reuse. With development of treatment technologies, it is possible to use treatment plants to treat the wastewater for reuse.

This study develops a mathematical programming model to see whether wastewater treatment is an appropriate way.

Based on information from the Bakken formation, the results show it is cost-effective to use treatment plants to treat the 20% of the wastewater flows back within 30-60 days after a well is drilled. The main reasons are as follows: First, the current data shows high capacities and low costs of the treatment plants. Compared with disposal cost, the costs of treatment plants are low enough to imply that they will be cost-effective. Second, in North Dakota, both drilling wells and reuse wells are very close, so transportation cost is not high. Compared with SWD disposal, the total costs of transportation and treatment are lower than disposal cost. Third, when doing treatment, the treated water will go to another drilling well for reuse, and then there is replacement cost for the fresh water. The replaced fresh water has a relatively higher value than on-site treatment cost, which may help gain profits if the replacement cost is high.

The main factors that influence these flows are distances, costs, transportation costs and capacities. First, when distances change, transportation costs will change, which leads to change of the optimal number of truckloads in each flow. Second, in the analysis, treatment costs are low, replacement cost and SWD costs are high. This implies that the flows always go to treatment plants. But with lower replacement and SWD costs, more flows will go directly to

SWD wells for disposal. Third, if transportation cost increases, the total costs of transportation and treatment will change, which also leads to change of flows. Fourth, the present data shows high capacities of all the treatment plants, there are no reported capacity constraints, so the flows always go from the lowest to highest. When capacity constraints for treatment plants with lower costs are added, the flows also go to higher cost treatment plants.

The above analysis is a case based on the Bakken formation because wells in the Bakken formation are so close that the distance from one well to another is not very long. If the dataset changes, the result also changes. But the model and program is suitable to be used with other data and will lead to optimal results.

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