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MARCELLUS SHALE NATURAL GAS DRILLING OPERATORS' CHOICE OF WASTEWATER DISPOSAL METHOD

A Thesis in

Agricultural, Environmental, and Regional Economics

by

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ABSTRACT

As natural gas drilling in the Marcellus Shale region moves forward, the issue of wastewater disposal has risen to the forefront. In 2010, the Pennsylvania Department of Environmental Protection (PA DEP) issued more stringent total dissolved solids (TDS) regulations effectively prohibiting the discharge of wastewater into Pennsylvania's surface waters. Then in April 2011, the PA DEP requested that drilling operators cease sending wastewater to municipal sewage treatment plants. These policies have increased the use of underground injection, particularly in Ohio, and recycling and reuse as wastewater disposal methods.

This thesis seeks to determine the factors that a drilling company considers in its choice of wastewater disposal method, through the use of a mixed logit model. In particular, the model includes price, distance, size, competition, distance to "nearest" large city, and river basin dummy variables. The model is then estimated using Stata 12 and the coefficient estimates obtained are then used to calculate the marginal effects of the variables on the probabilities that a brine or industrial waste treatment plant, an injection well, or recycling and reuse will be the disposal method chosen.

The results show that the marginal effects of the price and distance variables both have the expected negative signs, meaning that an increase in either of them will result in a decrease in the probability that the corresponding disposal method will be chosen. This represents rational economic behavior. Overall the price of the disposal method and, more importantly, the cost of transporting the wastewater from the gas production well to the disposal location (for which the distance variable is a proxy), have the largest impacts on the probability that a particular

alternative will be chosen. This indicates that policies that affect the price or location of disposal methods will be the most effective in influencing the use of a particular method.

The marginal effect of the size variable has a positive sign which can be explained through economies of scale. The competition variable also has a positive sign. An increase in competition would place a strain on the supply of freshwater withdrawals available for the fracing process which would then create a market for the treated water that is produced by the recycling facilities. Therefore the use of recycling and reuse facilities to treat wastewater would be encouraged.

The marginal effect of the "distance to nearest large city" variable has a negative sign which can be explained by access to valuable infrastructure, such as roads and pipelines, which is the result of being located close to a city. The marginal effects of the river basin dummy variables were not as intuitive and would benefit from a recalculation using a counterfactual simulation (as discussed in Section 4.4) instead of the method actually used.

The results of the model estimation are then used to calculate the marginal effects of the explanatory variables on the probabilities that the three disposal methods (brine or industrial waste treatment plant, injection well, and recycling and reuse) will be chosen by the drilling operators. Their interpretations can then be used to predict what the future of wastewater disposal will look like under three possible future scenarios (a business-as-usual scenario, a permanent moratorium in Youngstown, Ohio, and a scenario in which Pennsylvania takes primacy of its underground injection program).

The interpretations of the marginal effects of the variables, as well as the conclusions gleaned from the three presented scenarios, can then be considered by policymakers and utilized to influence future policies in the state of Pennsylvania.

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1. Introduction

Over the past several years natural gas drilling activity in the Marcellus Shale has increased, leading to concerns over its environmental implications, particularly as they relate to the disposal of the resulting wastewater. This is of particular concern because of the significant volumes of wastewater involved, along with the considerable monetary resources needed to dispose of it. It is predicted that the horizontal drilling and hydraulic fracturing of one gas production well costs approximately $3-4 million and uses approximately 4-5 million gallons of freshwater. Ten percent of the water will return to surface as flowback water in the first thirty days and more produced water will return to the surface over the life of the well. Thus, assuming that approximately 10-20 percent of the water used to fracture a well will return to the surface as wastewater, approximately 400,000 to 1 million gallons of wastewater per well will be produced (Sumi 2008). This equates to approximately 10,000 to 24,000 barrels of wastewater (1 barrel = 42 gallons). As mentioned in Section 3.2, the price of disposal ranges between $0.25 and $6/barrel (in 2012) which means the cost of wastewater disposal (not taking into account the significant transportation costs) ranges between $2,500 and $144,000. It is also predicted that it costs on average $4 to $6/barrel to transport the wastewater to its disposal location (GE Power and Water). That adds between $40,000 and $144,000 to the cost of wastewater disposal. Thus, in total, wastewater disposal costs are approximately $42,500-$288,000 per well. This is approximately equal to 1-7 percent of the amount of funds required to drill a well. While this might not seem like a large percentage, when you take into account that over 5,000 wells have been drilled to date, it means that close to $1 trillion has been spent on wastewater disposal since drilling began in the Marcellus Shale back in 2005 (Kelso). It is partly due to these enormous costs that make wastewater disposal such an important issue.

Recent policies enacted by the Pennsylvania Department of Environmental Protection (PA DEP) have caused a shift in the prevalence of the types of wastewater disposal methods used. In 2010, the PA DEP issued more stringent total dissolved solids (TDS) regulations effectively prohibiting the discharge of wastewater into Pennsylvania's surface waters, and in April 2011, the PA DEP requested that drilling operators cease sending wastewater to municipal sewage treatment plants. These policies have led to an increase in the use of underground injection, particularly in Ohio, and recycling and reuse as wastewater disposal methods. In light of these policies, it would therefore be beneficial to examine the determinants of the drilling operators' choice of disposal method.

This thesis will use a mixed logit model to determine the relative importance of the variables that affect a drilling operators' choice of disposal method. The results of the model estimation will then be used to calculate the marginal effects of the explanatory variables on the probabilities that a brine or industrial waste treatment plant, an injection well, or recycling and reuse will be the disposal method chosen. The interpretations of these marginal effects will then be applied to three possible future scenarios, including a business-as-usual scenario, a permanent moratorium in Youngstown, Ohio, and a scenario in which Pennsylvania takes primacy of its underground injection program, in order to develop future implications to be considered by policymakers and used to influence the implementation of future policies.

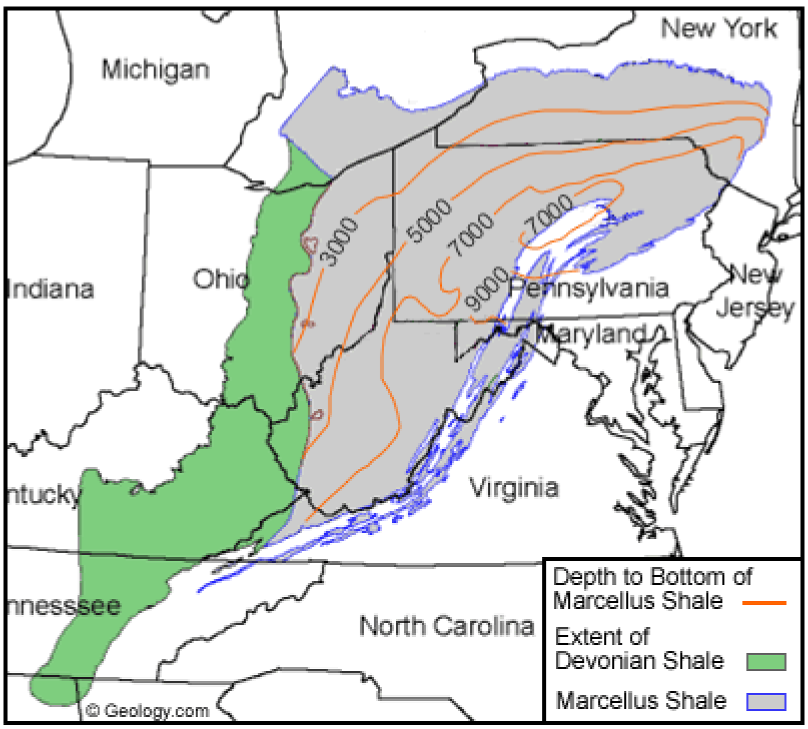
Based on relevant research and the goals of Pennsylvania at such a time as it may want to implement any of the findings presented in this thesis, policymakers can determine which disposal method(s) they want to promote and then use the findings of this thesis to decide on the best ways to encourage the use of said method(s). Ultimately, this thesis seeks to have policymakers consider the information gleaned from the interpretation of the marginal effects, along with the implications of the presented scenarios, and utilize them to influence future policies in the state of Pennsylvania.

The thesis is organized as follows: the remainder of Chapter 1 details the history and background of natural gas drilling in the Marcellus Shale in Pennsylvania and gives an overview of the types of wastewater disposal methods in use. Chapter 2 describes the research goals of this thesis and the methods used to accomplish these goals. The chapter then goes on to describe the econometric model (mixed logit) that will be used and provides a brief review of the existing relevant literature. Chapter 3 provides a description of the data and variables. Chapter 4 presents the estimation results and analysis. Chapter 5 describes several possible future scenarios and their policy implications. And Chapter 6 presents the conclusions of this thesis and suggestions for future study.

1.1. Background on the Marcellus Shale

The Marcellus Shale is a rock formation that exists primarily beneath Pennsylvania, New York, West Virginia, and Ohio but underlies very small areas of Maryland, Virginia, Kentucky, and Tennessee as well, spanning approximately 600 miles, north to south, and covering an area of approximately 54,000 square miles. It occurs at a depth of between 3,000 and 9,000 feet and is up to 250 feet thick or more in some areas (Sumi 2008).

Figure 1.1 Extent of and Depth to the Base of the Marcellus Shale



Source: http://geology.com/articles/marcellus-shale.shtml

It is a black shale that is part of the Middle Devonian Series, meaning that it originated approximately 350-415 million years ago when layers of clay and mud were compressed to form a sedimentary rock. Dead organic material was also caught in these layers and has since been converted into hydrocarbons, including natural gas (Sumi 2008). It is this reserve of trillions of cubic feet of natural gas that has caused the Marcellus Shale to attract considerable attention over the past few years. Many politicians and economists have cited this resource as part of a plan to end this country's dependence on foreign oil and create domestic jobs.

The exact estimates of the amount of natural gas contained in the Marcellus Shale formation have varied over the years due to changing geologic and engineering data and improvements in the technology used to recover this resource. They also differ in the terminology used to describe them[1]. In 2003, the United States Geological Survey (USGS) released its *Assessment of Undiscovered Oil and Gas Resources of the Appalachian Basin Province, 2002* in which it estimated that the Marcellus Shale contained a mean of approximately 1.9 trillion cubic feet (tcf) of undiscovered resources. In 2008, Terry Engelder, a professor of geosciences at the Pennsylvania State University, and Gary Lash, a professor of geology at the State University of New York at Fredonia, estimated that the Marcellus Shale contained approximately 500 tcf of gas-in-place, referring to the total volume of natural gas contained in the formation, not taking into account the technological capability to recover the resource. Production data from the Barnett Shale in Texas indicated that about 10 percent of its gas-in-place could be technically recovered. Applying this information to the Marcellus Shale, Engelder and Lash estimated that the Marcellus Shale would yield 50 tcf of technically recoverable resources, referring to the volume of gas that is actually able to be produced from either discovered or yet undiscovered reserves (Engelder and Lash).

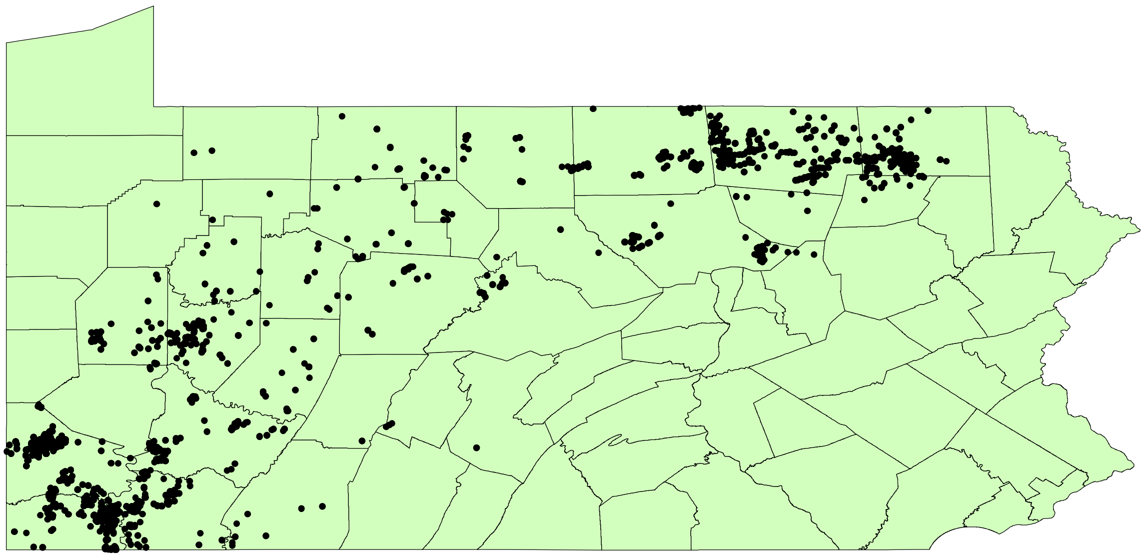
[1] The Penn State Extension informational sheet "How Much Natural Gas Can the Marcellus Shale Produce?"prepared by David Yoxtheimer of the Penn State Marcellus Center for Outreach and Research, gives a summary of the range of estimates of the amount of natural gas contained in the Marcellus Shale and compiles a list of the accepted definitions used to describe the resource.

In 2009, the U.S. Department of Energy's (US DOE) National Energy Technology Laboratory (NETL) estimated that the Marcellus Shale contained 1,500 tcf of original gas-in-place and 262 tcf of technically recoverable resources. The U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2011* estimated that the Marcellus Shale contained 400 tcf of technically recoverable resources. In August 2011, the USGS issued a new assessment estimating that the Marcellus Shale contained 84 tcf of undiscovered, technically recoverable resources, referring to gas that can be produced using secondary recovery methods, regardless of economic viability. Most recently, the EIA's *Annual Energy Outlook 2012* estimated that the Marcellus Shale contained 141 tcf of unproved, technically recoverable resources, referring to the volume of gas that is predicted to be recoverable in the future, given available geologic and engineering data, but has not actually been proven to exist based on accepted geologic information, such as actual drilling production data.

Range Resources – Appalachia, LLC, currently one of the largest natural gas producers in Pennsylvania, pioneered the development of the Marcellus Shale. In 2003, they drilled an experimental well in Washington County, Pennsylvania, and met with success through the utilization of the horizontal drilling and hydraulic fracturing methods that were previously successful in the Barnett Shale in Texas. Their first Marcellus well began producing in 2005 ("Marcellus Shale – Appalachian Basin"). As of May 2012, a total of 5,338 Marcellus wells have been drilled by 70 different operators, including 545 so far in 2012 (Kelso).

Due to data availability, Figure 1.2 shows the Marcellus Shale wells that were active and producing wastewater during the second half of 2011, according to the PA DEP Oil & Gas Reporting Website.

Figure 1.2 Active Marcellus Shale Gas Production Well Locations in Pennsylvania (Jul. – Dec. 2011)



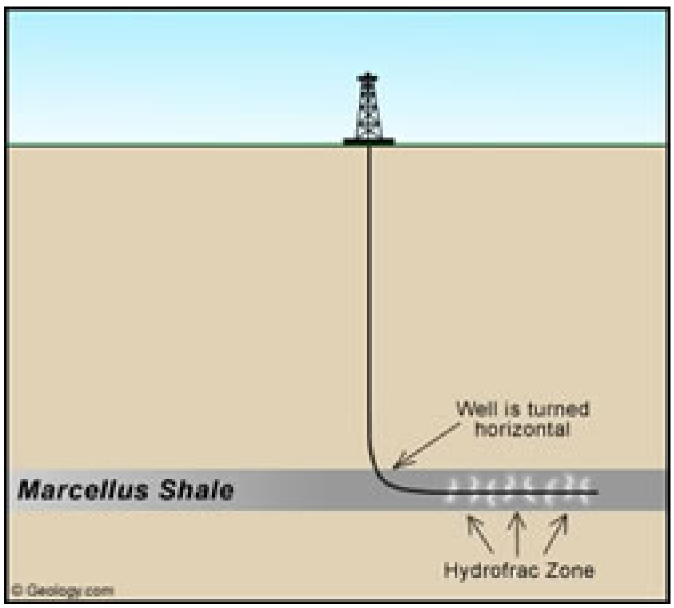
Source: data obtained from the PA DEP Oil & Gas Reporting Website (accessed May 23, 2012) and then input into GIS

1.2. Horizontal Drilling and Hydraulic Fracturing

The amount of natural gas that can be produced from the Marcellus Shale relies heavily on the technological capacity and economic viability of recovering the resource. The introduction of horizontal drilling and hydraulic fracturing, known as fracing, has greatly increased the amount of natural gas that can be recovered. Horizontal drilling involves drilling down vertically first to reach the Marcellus Shale formation and then turning the wellbore horizontally to cut through the formation itself. The natural fractures, containing the natural gas and allowing its movement, that occur in the shale are generally oriented vertically meaning that a wellbore will come in contact with a greater number of these fractures if it is oriented horizontally. It also allows more wells to be drilled from a single drilling pad, decreasing the footprint of the drilling operation (Sumi 2008).

Although the Marcellus Shale does contain natural fractures, they generally are not porous enough to allow production in commercial quantities and thus fracing is used. This process, which involves creating artificial fractures, through the injection of millions of gallons of pressurized water, mixed with sand and chemicals, increases the flow of the natural gas out of the well (Sumi 2008).

Figure 1.3 Horizontal Drilling and Hydraulic Fracturing



Source: http://geology.com/articles/marcellus-leases-royalties.shtml

1.3. Wastewater Management

The use of millions of gallons of water per well in the fracing process requires that the drilling operators properly manage the wastewater that is inevitably produced as a result. Approximately ten percent of the water will return to the surface as flowback water within thirty days of fracing and must be disposed of or treated properly, as it contains high levels of total dissolved solids (TDS), fracing chemicals, sand, salt, metals, and even radioactive material from its contact with the shale. Produced water that will return to the surface, along with the natural gas, when a well is in production must also be properly managed (Abdalla et al. 2011)[2].

Discharge into Pennsylvania's rivers, streams, and lakes is not a disposal option unless the wastewater is treated first, due to its high levels of TDS that are toxic to the health of aquatic ecosystems. The Federal Safe Drinking Water Act does not include enforceable TDS standards, but the Pennsylvania Safe Drinking Water Act does, following new regulations issued by the PA DEP in 2010. A more stringent standard of 500 mg/L for TDS was introduced. As a result of this new standard, it has become necessary to utilize alternative treatment and/or disposal methods, including dilution at a municipal or industrial brine treatment plant, direct reuse without treatment by blending the flowback water with freshwater, on- or off-site treatment and reuse, or off-site disposal in an underground injection well (Abdalla et al. 2011).

In 2007 and early 2008, dilution at municipal treatment facilities and then discharge into surface waters was a fairly common disposal method because of its convenience and low cost ($0.05-$0.065/gal). However, municipal sewage treatment plants are not properly equipped[3] to remove the high levels of TDS found in Marcellus Shale wastewater (dilution is the only option at these facilities), which means that the discharged water is still quite briny (Abdalla et al. 2011). The PA DEP realized that Pennsylvania's surface waters would not be able to continue to absorb these still relatively high levels of TDS so in 2008 the PA DEP imposed a limit on municipal sewage treatment plants, allowing them to only accept 1% of their daily intake as natural gas drilling wastewater, and then in 2010 the PA DEP issued the new TDS regulations (as described above) ("Our Look"). Under these new regulations, 27 facilities that had

[2] According to Table 1.2, approximately 25.2 million gallons of wastewater, both flowback and produced water, was generated in 2011.

[3] The municipal sewage treatment plants are also not properly equipped to deal with the radioactive materials that are present in the wastewater due to the water's contact with the shale.

historically accepted natural gas drilling wastewater were allowed to continue doing so as long as their daily intake did not increase. Between 2010 and 2011, twelve of those grandfathered facilities voluntarily ceased accepting drilling wastewater. Then on April 19, 2011, the PA DEP issued a press release calling on all Marcellus Shale natural gas drilling operators to stop sending drilling wastewater to the remaining fifteen municipal sewage treatment plants that were still accepting it by May 19, 2011 (Commonwealth of Pennsylvania). Thus, as a result of the more stringent TDS regulations and the PA DEP request, drilling operators have turned to other disposal and/or treatment options. In particular, disposal in underground injection wells and the recycling and reuse of wastewater have become increasingly attractive alternatives to drilling operators.

1.3.1. Underground Injection

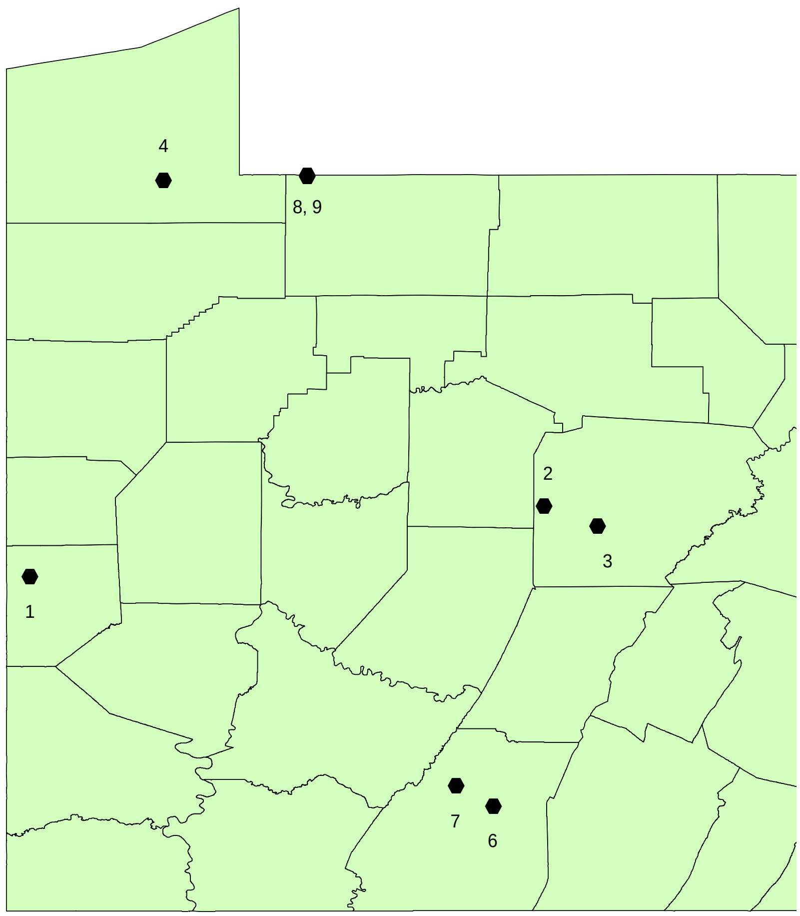
There are five classes of underground injection wells. Class IID wells dispose of brine and other liquid waste derived from the production of oil and natural gas ("Underground Injection"). There are currently six active (and currently two under review) Class IID underground injection wells accepting Marcellus Shale natural gas drilling wastewater in Pennsylvania[4] and four of them accepted wastewater in the second half of 2011. One of the active wells and the two under permit review are commercial facilities, meaning they can accept wastewater from any drilling company. The rest of the wells are private facilities, meaning they are only permitted to dispose of wastewater originating from gas production wells belonging to the operating company (Platt).

[4] XTO Energy's well located in Indiana County was recently plugged and abandoned. Also, according to Steve Platt of EPA Region 3, the Bear Lake Properties' two disposal wells are awaiting a decision by the Environmental Appeals Board, following a public hearing that resulted in a request to appeal the permit decision. Thus, only six of the eight wells are accepting wastewater at this time.

The permit for the Range Resources well, located in Erie County, was originally issued to NEA Cross Company in November 1985 and has since been transferred to several different operators. It is now operated by Range Resources. Its ten-year permit expired in January 2011 and a new one was issued following a public hearing in June 2011 (U.S. EPA, Region 3, *Range Resources*). The permit for the CNX Gas Company well, located in Somerset County, was originally issued to Dominion Exploration Production in May 2001. Then in April 2012 CONSOL Energy Holdings, LLC purchased Dominion and after corporate restructuring CNX Gas Company LLC took control in January 2011. Its 10-year permit expired in May 2011 and a new one was issued following a public hearing in June 2011 (U.S. EPA, Region 3, *Jenner Township, PA*). The permit for one of the two EXCO Resources wells, located in Clearfield County, was issued to EOG Resources in May 2005. It is a ten-year permit and therefore will remain in effect until May 2015. The permit was transferred to EXCO Resources in June 2008 (U.S. EPA, Region 3, *Consent Agreement*).

Figure 1.4 shows the location of the wells and Table 1.1 indicates their injection volume (bbls/month) and maximum surface injection pressure (psi). The injection volume refers to the maximum allowable volume of wastewater that can be injected into each well on a monthly basis. The surface injection pressure is the maximum allowable pressure at which wastewater can be injected (the pressure just below that which would fracture the rock). Once a well approaches its maximum surface injection pressure (or instantaneous shut-in pressure) it means the well is approaching its maximum capacity. Several wells have been in operation since the 1980s and have not yet approached their maximum capacity, indicating that the injection formations have good injectivity, transmissivity, and high capacity potential. This is contrary to the popular belief that Pennsylvania's geology is unsuitable for underground injection. Rather, the limited number of underground injection wells seems to stem from Pennsylvania's historical lack of interest in them due to the availability of other alternatives (before the introduction of the PA DEP's regulations) (Platt).

Figure 1.4 Underground Injection Wells in Western Pennsylvania[5]



Source: data obtained directly from Steve Platt, EPA Region 3, and then input into GIS

[5] Each hexagonal symbol on the above map represents an underground injection well in Pennsylvania. The numbers associated with each of the symbols correspond to the numbers describing each of the underground injection wells listed in Table 1.1. There is no #5 on the above map because, as indicated in Table 1.1., XTO Energy's underground injection well has recently been plugged and abandoned.

Table 1.1 Maximum Surface Injection Pressures and Injection Volumes

	Facility	County	Injection Formation	Maximum Surface Injection Pressure (psi)	Injection Volume (bbls/month)
1	Columbia Gas	Beaver	Huntersville/ Oriskany	1,300	21,000
2	Exco Resources Pa	Clearfield	Oriskany	3,240	4,260
3	Exco Resources Pa	Clearfield	Oriskany	1,450	4,200
4	Range Resources #	Erie	Gatesburg	1,570	45,000
5	XTO Energy *	Indiana	Balltown	1,930	3,600
6	Cottonwood	Somerset	Oriskany	3,250	27,000
7	CNX Gas	Somerset	Huntersville/ Oriskany	3,218	30,000
8	Bear Lake Properties #	Warren	Medina	1,726	30,000
9	Bear Lake Properties #	Warren	Medina	1,696	30,000

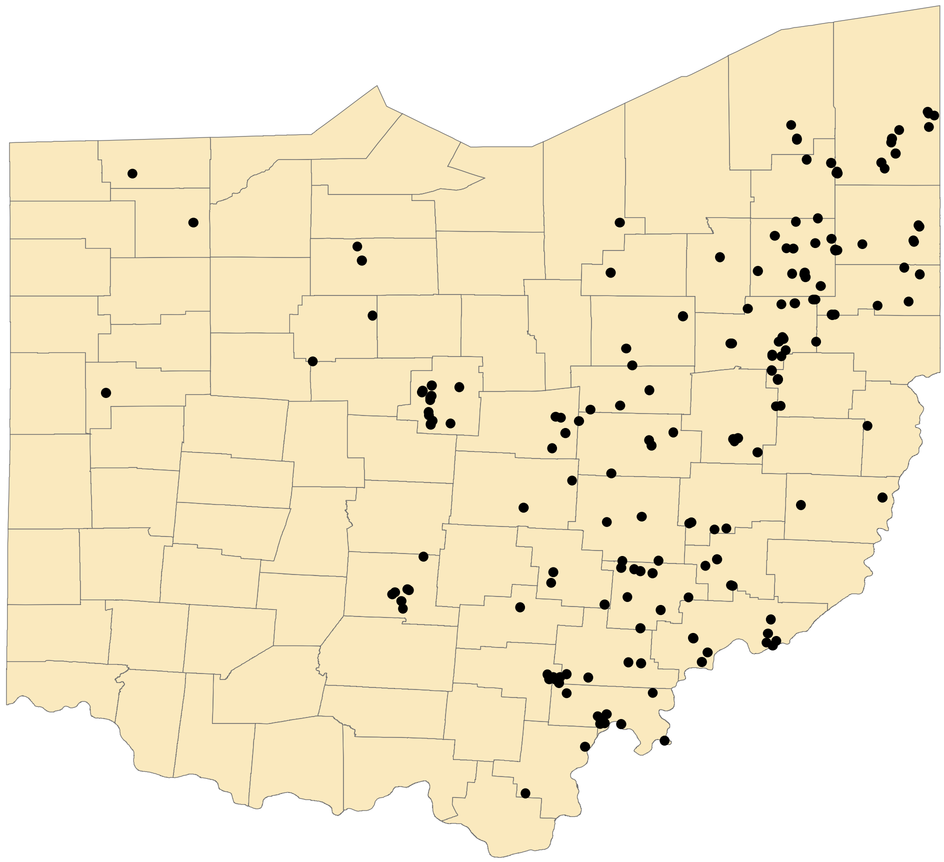
*** Recently plugged and abandoned; # Commercial facilities**
Source: data obtained directly from Steve Platt, EPA Region 3

In contrast to the small number of underground injection wells in Pennsylvania, there are close to 200 such wells in Ohio. Figure 1.5 shows the locations of these wells. After speaking with Steve Platt of EPA Region 3 and Tom Tomastik of the Ohio Department of Natural Resources (ODNR), it seems that whether the state has primacy is the main reason behind the difference in the number of wells. Injection wells are regulated by the Environmental Protection Agency (EPA) under the authority of the Underground Injection Control (UIC) program, as provided for by the Safe Drinking Water Act (SDWA) that was passed in 1974. An individual state, if it so chooses, can apply to the EPA to obtain primacy, or primary enforcement responsibility, over its own UIC program, meaning that it would be in charge of overseeing all injection activity and ensuring that all EPA requirements were being met ("Underground Injection"). Pennsylvania does not have primacy over its UIC program, meaning that EPA Region 3 is responsible for the implementation of the program, including issuing permit applications. Permits are issued jointly for construction, operation, monitoring, and reporting. Application processing and review, which could include a public notification and comment period and a hearing if necessary, typically takes about four to six months. Permits are issued for ten-year periods but can be renewed if operational history proves satisfactory. Steve Platt believes that monetary constraints play a large role in Pennsylvania's lack of primacy. An annual federal grant in the amount of approximately $11 million is allocated to support all of the UIC programs in the country. Thus, EPA Region 3 only receives about $200,000 to implement Pennsylvania's program. Platt believes that this is an insufficient amount to entice Pennsylvania to take responsibility for its own program (Platt).

On the other hand, Ohio does have primacy over its UIC program. It received primacy from the US EPA in 1983. Its allocation of the federal grant totals about $160,000 (down from about $300,000 previously). It also receives at least a 25 percent match from state funds which, according to Tom Tomastik, actually exceeds federal funding at this point. Ohio's Class II regulations are actually more stringent than federal standards and no sub-surface contamination[6] resulting from injection well operations has occurred since Ohio received primacy of its UIC program. This is just one of the benefits of a state having primacy according to Tomastik. He also cites a greater level of expertise and speed at which permits are processed. In contrast to the four to six months it takes EPA Region 3 to issue a permit, the turnaround for the ODNR is about 30-60 days. Also, the EPA contracts out its well inspections and only requires one per year, whereas the ODNR conducts unannounced inspections every 11-12 weeks by ODNR personnel (Tomastik).

[6] Surface spills and pipeline breaks have happened, but no leaks into aquifers have occurred.

Figure 1.5 Underground Injection Wells in Ohio



Source: data obtained directly from Tom Tomastik, ODNR, and then input into GIS

1.3.1.1. Seismic Activity

Underground injection has been in the news recently due to a collection of twelve earthquakes that occurred in eastern Ohio throughout 2011 that have possibly been linked to this disposal method. On December 31, 2011 a magnitude 4.0 earthquake occurred near an injection well in Youngstown, Ohio (Mahoning County). It was the twelfth earthquake to occur in the area since March 2011 and the strongest yet, as the others were about 2.1 to 2.7 in magnitude.

Following an earthquake on December 24, 2011, the director of the ODNR requested, on December 30, that D&L Energy Inc. halt injection at the Northstar 1 well; the company did so voluntarily. Then, following the latest, strongest earthquake on December 31, state officials instituted a moratorium on all injection activity within a five-mile radius of the Northstar 1 well. This moratorium applies to three wells in the area that were under construction at the time. It also resulted in the permit for another well in the area being put on hold (Ohio Department of Natural Resources).

In March 2012, the ODNR issued a preliminary report on the seismic activity that occurred in the vicinity of Youngstown, Ohio. Prior to the March 2011 earthquake, there had been no record of any earthquakes with epicenters located in Mahoning County, but now a series of seemingly coincidental events appears to point to evidence of injection activity at the Youngstown well inducing the recent seismic activity. The Northstar 1 well commenced injection activity in December 2010, three months before the first earthquake, and the subsequent earthquakes were all located in proximity to the wellbore. The focal depths of these seismic events were determined to be approximately 4,000 ft laterally and 2,500 ft vertically from the wellbore terminus once monitoring equipment was put in place. There also appears to be evidence of fractures within the Precambrian rock formation, the well's injection layer (Ohio Department of Natural Resources).

Due to the evidence of possible induced seismicity from injection well activity, the report goes on to make recommendations to better monitor underground injection wells and protect the health and safety of Ohio's citizens. These changes, if adopted, would make Ohio's regulations the most stringent in the nation. The recommendations include not locating new injection wells within known faulted areas; submitting, at the time of permit application, any information regarding the existence of known faults within a certain radius of the proposed well; conducting seismic surveys; conducting an injection test, prior to initial injection, to determine the formation parting pressure and injection rates; requiring the installation of a continuous pressure monitoring system and an automatic shut-off system that would be activated if the maximum injection pressure were to be exceeded; and requiring the installation of an electronic data recording system to track all injection fluids from "cradle to grave"[7] (Ohio Department of Natural Resources).

Following these recommendations by the ODNR, Ohio Governor John Kasich issued an executive order on July 10, 2012, immediately enacting new state regulations on underground injection wells used to dispose of natural gas drilling wastewater. The order gives the ODNR the authority to implement their recommendations and gives the chief of the Division of Oil and Gas Resources Management authority to order preliminary tests at proposed well sites, prevent drilling at any sites that fail these preliminary tests, limit injection pressure, monitor for any leakages, and order the installation of automatic shut-off systems. This order does not affect the regional moratorium that was instituted following the recent earthquakes in the Youngstown area[8]. The order will remain in effect for ninety days, allowing the state's legislators to formally pass a law making the regulations permanent ("Kasich").

The case of Youngstown, Ohio, is not the first instance of the possibility of injection activity inducing seismic activity. In 2011, state officials in Arkansas shut down some injection wells and then instituted a permanent moratorium after a "swarm"[9] of earthquakes occurred in the north-central part of the state and was linked to the underground injection of wastewater

[7] This new requirement would also help in the comparison and verification of wastewater data from Pennsylvania and Ohio. This issue is discussed further in Section 6.1.1.

[8] In February 2012, D&L Energy, the Youngstown well's operator, sought permission from the state of Ohio to resume disposal operations at the injection well. As of April, though, it had not yet received such permission due to the ongoing nature of the moratorium ("Kasich").

[9] An earthquake swarm is defined as an event in which a local area experiences a sequence of earthquakes striking in a relatively short period of time; no earthquake in the sequence can be identified as the main event (Soraghan).

originating from the Fayetteville Shale. Since then a scientist at the Center for Earthquake Research and Information at the University of Memphis published a paper citing underground injection as the cause. Also, according to scientists at the University of Texas, Austin, several small earthquakes that occurred near the Dallas-Fort Worth International Airport in 2008 and 2009 were linked to an underground injection well drilled in September 2008. This resulted in two wells being shut down (Soraghan). In May 2012, two more earthquakes occurred in eastern Texas, near the Louisiana border, in an area home to several injection wells. Scientists are still determining whether these recent seismic events can be linked to underground injection as well (Kenworthy).

1.3.2. Recycling

The recycling and reuse of natural gas drilling wastewater is the management method that has experienced the largest increase in use over the past six months (beginning of 2011 to end of 2011) (a 150 percent increase, according to Table 1.2) and now represents 87 percent of the wastewater disposal/treatment total. In March 2012, the PA DEP announced the revised Residual Waste Beneficial Use general permit (the new WMGR123) that encourages the recycling of wastewater that results from oil and gas drilling. Previously there existed three different general permits, WMGR119, WMGR121 and WMGR123, but the new permit consolidates them into one that will improve institutional efficiency while better protecting Pennsylvania’s waterways through the minimization of surface water withdrawal and discharge. It promotes the use of a closed-loop process, meaning that after wastewater has been treated and processed at dedicated recycling facilities it is then sent back out into the field and reused at other drill sites (e.g. to frac other natural gas wells) because these facilities’ permits allow no liquid discharge into streams.

The permit also establishes water quality criteria, based on drinking water and in-stream water quality standards, which, if met, allow the treated and processed water to be stored and transported as freshwater. Water that does not meet these standards will continue to be stored in tanks or impoundment pits and transported as residual waste. There are currently ten facilities operating under one of the previous general permits and they will continue to operate under the new revised permit. There are also ten new facilities that have submitted permit applications to the PA DEP (Pennsylvania Department of Environmental Protection).

1.3.3. On-Site Treatment and Reuse

The reuse of wastewater is often done in the field and involves either a mobile treatment unit or dilution with freshwater. The mobile units can be dispatched directly to the drilling site (or might be stationed at strategic locations around the state) and are able to treat flowback water for frac additives and TDS, provide disinfection against bacteria, and generate a solids sludge that is safe for disposal at a landfill. The process could involve pretreatment (reduction of TDS and disinfection), evaporation to produce reusable freshwater, and crystallization to produce reusable salt products. On-site treatment and reuse reduces the volume of wastewater removed from and freshwater brought to the drilling site, reducing truck traffic (as well as the distances the trucks travel). If on-site treatment is not utilized, drilling companies will often just dilute the flowback water with additional freshwater before reusing it (Mittal).

1.4. Wastewater Numbers

According to the data sourced from the PA DEP Oil & Gas Reporting Website, summarized in Table 1.2, in the first half of 2011, 246,589 barrels (bbls, 1 bbl = 42 gallons) of wastewater were disposed of at nine municipal sewage treatment plants. That amount decreased to 408 bbls at two facilities in the second half of 2011, after the PA DEP requested that drilling operators cease sending drilling wastewater to municipal sewage treatment plants. This is an example of how policy can influence wastewater disposal.

Conversely, in the first half of 2011, only 866,023 bbls of wastewater were disposed of in 32 underground injection wells, but, by the second half of 2011, 1,951,293 bbls were injected in 51 wells, an increase of 125 percent. In the second half of 2011, four Pennsylvania underground injection wells accounted for 11,795 bbls of wastewater disposal or 0.6 percent of the share of wastewater that was disposed of in underground injection wells; five West Virginia injection wells accounted for 15,121 bbls or 0.8 percent of the injection total; and 42 Ohio injection wells accounted for 1,924,377 bbls or 98.6 percent of the injection total. Recycling and reuse also increased during this time period, from 5,833,704 bbls, in the first half of 2011, to 14,632,869 bbls in the second half of 2011, representing a 150 percent increase. Figures 1.6 and 1.7 demonstrate the change in the type and number of each disposal method being utilized between and first and second six-month periods of 2011.

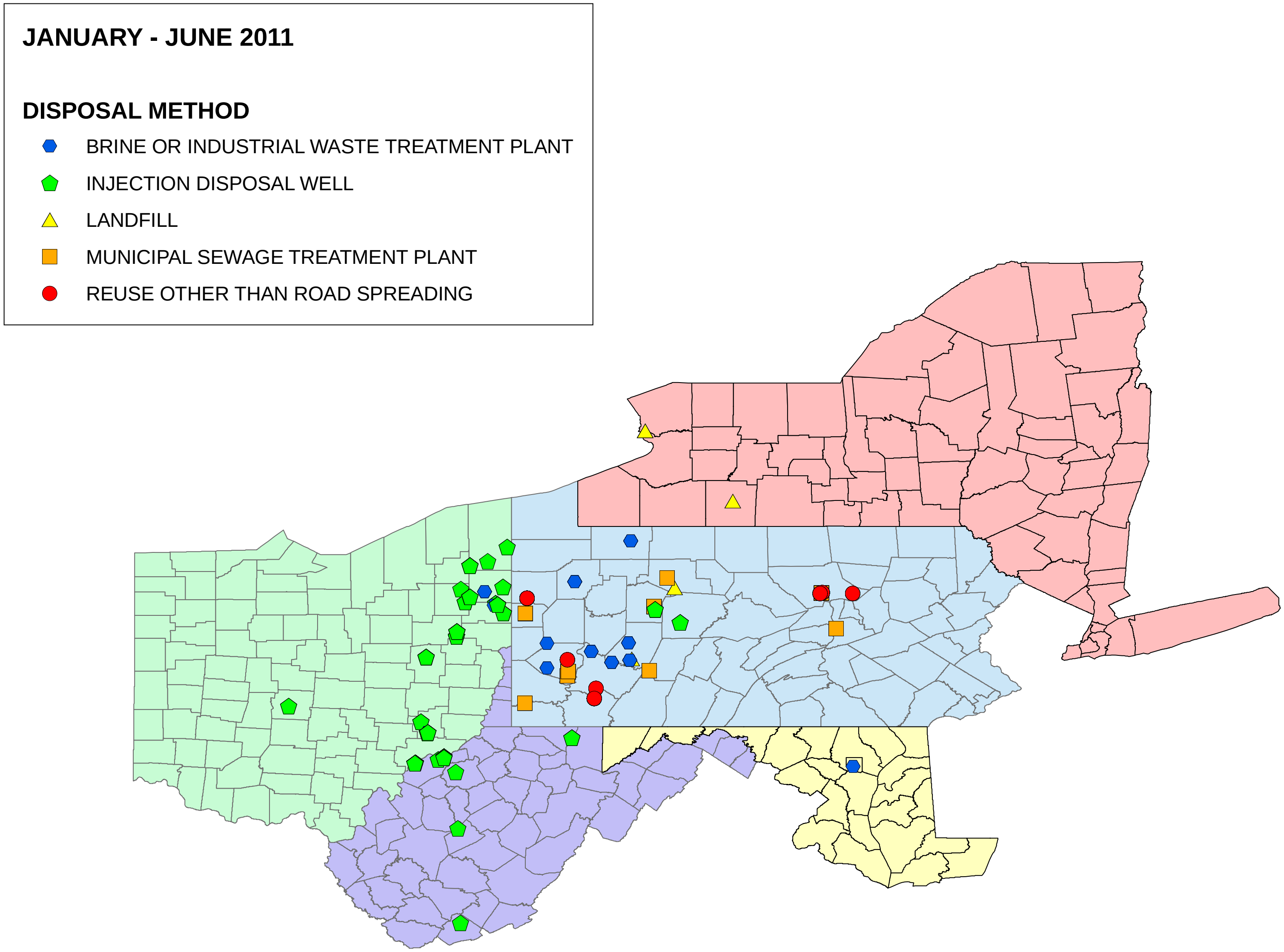
Table 1.2 Wastewater (Brine and Frac Fluid) Volumes (bbls) by Disposal Method

	Jan-Jun 2011	Jul-Dec 2011
Municipal Sewage Treatment Plant	246,589.21	408.00
Underground Injection Well	866,023.09	1,951,293.69
Recycling and Reuse	5,833,704.14	14,632,868.78
Brine or Industrial Waste Treatment Plant	1,151,480.03	169,108.35
Landfill	2,289.19	1,288.19
Other*	338,618.00	6,884.11
TOTAL:	**8,438,703.66**	**16,761,851.12**

*** "Other" refers to the category "Not Determined" because the wastewater is being stored, pending disposal or reuse**

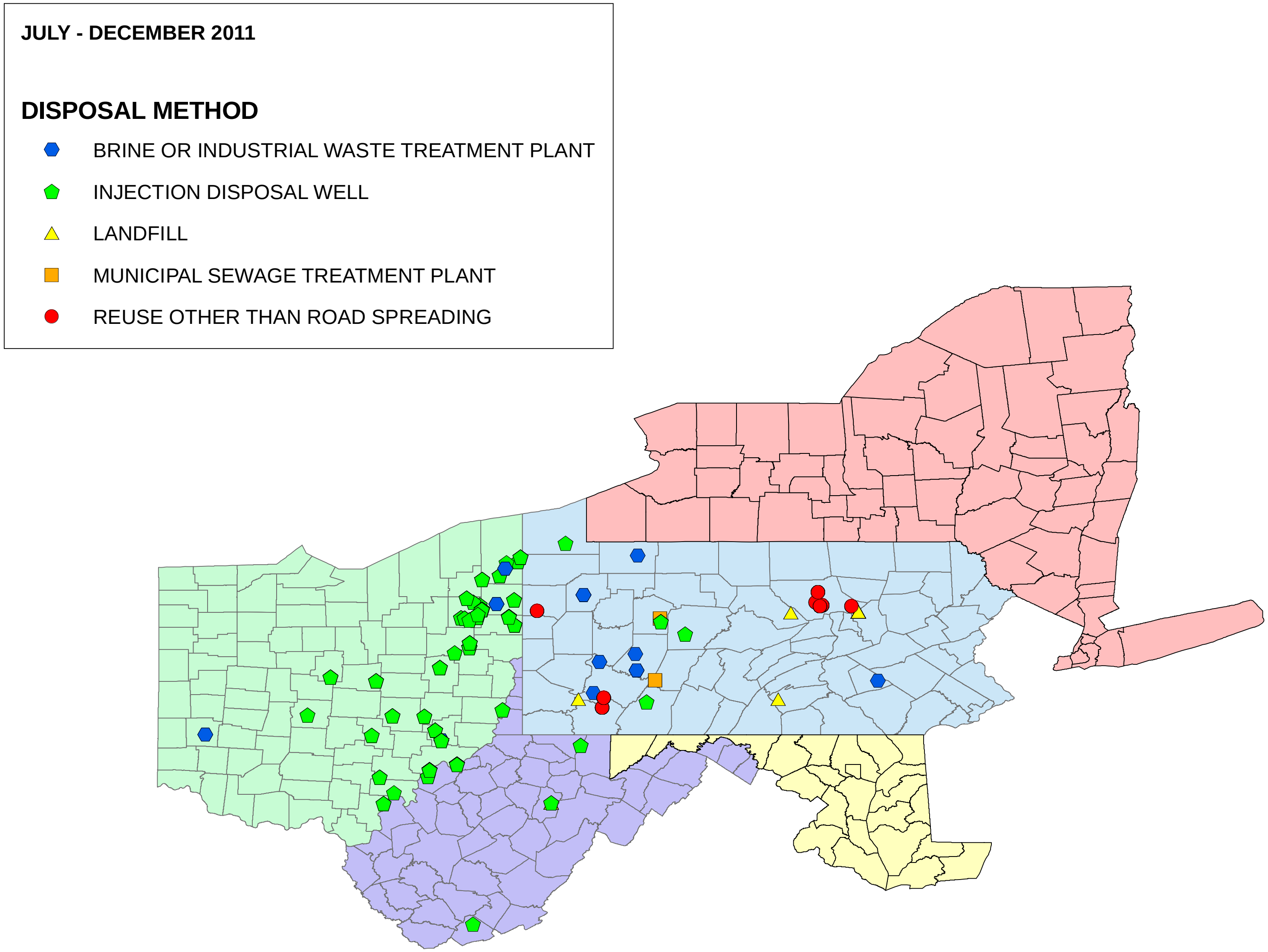
Source: data obtained from the PA DEP Oil & Gas Reporting Website (accessed May 23, 2012)

Figure 1.6 Wastewater Disposal Locations (Jan. – Jun. 2011)



Source: data obtained from the PA DEP Oil & Gas Reporting website (accessed May 23, 2012) and then input into GIS

Figure 1.7 Wastewater Disposal Locations (Jul. – Dec. 2011)



Source: data obtained from the PA DEP Oil & Gas Reporting website (accessed May 23, 2012) and then input into GIS

2. Research Goals and Methods

2.1. Research Goals

In light of the changing wastewater disposal landscape (due to recent policy changes, such as the PA DEP's issuance of more stringent TDS regulations and their request that drilling operators cease sending wastewater to municipal sewage treatment plants), this thesis seeks to

(1) explore the factors that a Marcellus Shale drilling operator might consider in its choice of wastewater disposal method;

(2) assess the importance of certain alternative-specific (characteristics of the disposal method choice) and individual-specific (characteristics of the drilling operators making the decisions) variables and how they affect the probability that the decision maker (the drilling operator) will choose a particular alternative (disposal method); and

(3) use the knowledge about the relative importance of the variables included in the model to develop implications of the results for policy-makers to consider in the future.

The following methods will be used to achieve the research goals described above:

(1) to achieve goals (1) & (2), a mixed logit model will be developed in the context of the Marcellus Shale natural gas drilling operators' choice of disposal method; data will be collected from the PA DEP Oil & Gas Reporting Website and cleaned so as to make

it usable for this study; then analysis will proceed using Stata[10];

(2) to achieve goal (3), the results of the mixed logit regression will be analyzed through the interpretation of the estimated coefficients as well as the marginal effects of the corresponding variables on the choice probabilities of the disposal methods; the results and these interpretations will then be used to develop implications for policy-makers through the use of three scenarios; these scenarios will be developed in the context of possible future policies and their implications will be interpreted using the results (estimated coefficients and marginal effects of the corresponding variables) of the mixed logit model.

2.2. Conditional Logit

According to Greene (2008), a conditional logit model is often employed in cases of migration decision or location choice in which the attributes of the alternatives figure prominently into the decision-making process. It requires alternative-specific explanatory variables and can also include individual-specific variables. A conditional logit model is an example of an unordered choice model and is based on a random utility model (RUM). For the ith individual facing J choices, the utility of choice j can be decomposed into an observable and unobservable component represented as

$$U_{ij} = z'_{ij}\theta + \varepsilon_{ij} \qquad (2.1)$$

where z_{ij} captures the components observed by the econometrician and the error term, ε_{ij}, captures the components that affect the utility but are only known to the individual decision-

[10] Stata is a statistical software package. A dataset is input into the software and then different types of regressions (of certain variables on others) can be run. Further statistical analysis can be performed following the model estimation.

maker and are thus unobservable to the econometrician. Individual *i* will choose alternative *j* if and only if

$$Prob(U_{ij} > U_{ik}) \text{ for all } k \neq j.$$

Utility depends on z_{ij} which includes alternative-specific as well individual-specific exogenous variables. Thus $z_{ij} = (x_{ij},\ w_i)$, where x_{ij} varies across alternatives, and possibly across individuals, w_i varies across individuals only (it is the same for all alternatives), and $\theta = (\beta',\ \alpha')$. Utility can therefore be expressed as

$$U_{ij} = x_{ij}'\beta + w_i'\alpha + \varepsilon_{ij}\ . \qquad (2.2)$$

The unobserved (to the econometrician) error terms are assumed to be independently and identically distributed (iid) and follow a type 1 extreme value distribution which gives rise to the traditional logit model

$$F(\varepsilon_{ij}) = ex\,p\big(-exp(-\varepsilon_{ij})\big)\ . \qquad (2.3)$$

Thus the difference of two error terms follows a logistic distribution.

Let Y_i be a random variable that represents the choice made by individual *i*. Thus, following the assumption about the distribution of the error terms, the probability that individual *i* chooses alternative *j* can be expressed in closed form given by

$$Prob(Y_i = j) = \frac{exp(x_{ij}'\beta + w_i'\alpha)}{\sum_{j=1}^{J} exp(x_{ij}'\beta + w_i'\alpha)}\ . \qquad (2.4)$$

Because w_i represents the individual-specific characteristics, it does not vary across choices and will therefore drop out of the probability expression because Equation (4) can be rewritten as

$$P_{ij} = \frac{\big[exp\big(x_{ij}'\beta\big)\big]exp(w_i'\alpha)}{[\sum_{j=1}^{J} exp\big(x_{ij}'\beta\big)]exp(w_i'\alpha)}\ . \qquad (2.5)$$

In order to incorporate individual-specific effects, the model must be modified. The problem can thus be rectified by creating a set of dummy variables, $\mathrm{A} = (A_1,\ A_2, \dots, A_J)$, for each of the choices and multiplying each of them by w_i

$$P_{ij} = \frac{exp\left(x'_{ij}\beta + (A_1 w_{il})'\gamma_{l1} + \cdots + (A_J w_{il})'\gamma_{l(J-1)}\right)}{\sum_{j=1}^{J} exp\left(x'_{ij}\beta + (A_1 w_{il})'\gamma_{l1} + \cdots + (A_J w_{il})'\gamma_{l(J-1)}\right)} \qquad (2.6)$$

where $w_{il} = (w_{i1},\ w_{i2}, \dots,\ w_{iL})$ and L is equal to the number of individual-specific characteristics. An estimated coefficient, γ_{lj}, will be obtained for each individual-specific interaction term, where $l = 1, 2, \dots, L$, L being the number of individual characteristics, and $j = 1, 2, \dots, J$, J being the number of alternatives. These interaction terms will correspond to the probabilities of an individual choosing each alternative relative to the alternative used as the reference (in this case the *J*th). This is in contrast to the estimated coefficients of the alternative-specific variables which demonstrate how these attributes affect the overall choice probabilities.

The non-linear nature of the conditional logit model means that the estimated coefficients cannot be directly interpreted as the marginal effects of the corresponding variables on the probabilities. In the case of the alternative-specific variables, the signs of the parameter estimates are indicative of the direction of influence of the explanatory variables, but the absolute values of the estimates are not cardinal in their interpretation. Instead, the marginal effects can be calculated by differentiating Equation (4) with respect to a particular alternative-specific variable, x_{ij}

$$\frac{\partial P_{ij}}{\partial x_{imk}} = \left[P_{ij}\left(\delta_{jm} - P_{im}\right)\right]\beta_k\ , \qquad (2.7)$$ [11]

$$\delta_{jm} = \begin{cases} 1\ , & if\ j = m \\ 0, & if\ j \neq m \end{cases}$$

[11] When $j = m$ Equation (7) is equal to the own-marginal effect, or the effect of a change in an attribute of alternative j on the probability of choosing alternative j. When $j \neq m$ Equation (7) is equal to the cross-marginal effect, or the effect of a change in an attribute of alternative m on the probability of choosing alternative j.

where $j, m = 1, \dots, J$ and $k = 1, \dots, K$ and represents the kth attribute of alternative m.

The nature of Equation (2.7) indicates that the cross marginal effects of a particular alternative's attributes on the probabilities that any of the other alternatives will be chosen exhibit the opposite sign from the attributes' own marginal effects on the probability that that particular alternative will be chosen. This means that if a change in a particular alternative's attribute results in an increase in the probability that that alternative will be chosen, that same change will also result in a decrease in the probabilities that any of the other alternatives will be chosen. The decrease in the probabilities that any of the other alternatives will be chosen compensates for the increase in the probability that a particular alternative will be chosen.

The error assumption that gives rise to the conditional logit model requires an independence of irrelevant alternatives (IIA) assumption. The IIA property means that the ratio $\frac{P_{ij}}{P_{ik}}$, for all j, k, is constant and is independent of the other remaining probabilities. Thus, if another alternative is added or if the characteristics of any of the other alternatives are changed the ratio between the two probabilities in consideration will not change. Additionally, this assumption precludes the ability to correlate errors across individual drilling operators who may appear multiple times in the dataset. The assumption of IIA simplifies the estimation process but is not realistic when applied to real-world situations. There is no reason to think that an individual decision-maker will not take into account the characteristics of all the alternatives when making his/her choice. In the case of drilling operators, it is reasonable to assume that each drilling operator will take into consideration the characteristics of each of the three disposal methods before deciding which method to utilize. Thus, a mixed logit model will be used to relax the IIA assumption. This approach will also allow tastes to vary across individuals (drilling operators), meaning that drilling operators will each weigh the explanatory variables differently when deciding which disposal method to utilize. This is a reasonable assumption.

2.2.1. Mixed Logit

According to Train (2009), the mixed logit model is flexible and can be used in conjunction with any RUM (in this case, a conditional logit model). It does not have the limitations of the standard logit models and instead allows for random choice variation, unrestricted substitution patterns, and correlation in unobserved factors over time. The probabilities of the mixed logit model can be expressed as follows:

$$P_{ij} = \int L_{ij}(\beta) f(\beta) d\beta \qquad (2.8)$$

where $L_{ij}(\beta)$ is the conditional logit probability, expressed in Equation (2.6), evaluated at parameters β, and $f(\beta)$ is a density function. The econometrician determines which density function will be used.

In a mixed logit model the β's are allowed to vary across individuals which means that the probabilities are weighted averages of the logit formula evaluated at different values of β, with weights determined by the density function $f(\beta)$. The use of a normal density function is common[12] and thus $f(\beta) = \phi(\beta | b, W)$ with mean b and covariance W. The integral in Equation (2.7) cannot be evaluated directly so it is estimated using simulation.

Because β varies across individuals, it can be thought of as

$$\beta = b + W_i \,, \qquad (2.9)$$

meaning it consists of its mean, b, and a deviation from that mean, W. Thus the utility, $U_{ij} = x_{ij}\beta + \varepsilon_{ij}$, becomes

[12] The use of a lognormal density function is common as well, particularly if the researcher wants to restrict the coefficient estimates to be positive (or negative if the variable is multiplied by -1).

$$U_{ij} = x'_{ij}b + x'_{ij}W_i + \varepsilon_{ij} \qquad (2.10)$$

and can be thought of as an error component specification. The unobserved components of utility are $\eta_{ij} = x'_{ij}W_i + \varepsilon_{ij}$. If $x'_{ij}W_i$ is nonzero, as in the case of the mixed logit approach, utility is correlated across alternatives and the IIA assumption is relaxed.

2.3. Literature Review

McFadden (1974) is credited with the development of the conditional logit model. It is a variation on the multinomial logit model with the main difference being that the conditional logit model incorporates attributes of the choices, rather than (or in addition to) characteristics of the individuals. McFadden then applies this new model to consumers' choice of shopping destination in Pittsburgh, incorporating both choice- and individual-specific characteristics. The model is estimated using three explanatory variables: a price index and an attractiveness index (both choice-specific variables) and an interaction of the price index and a socioeconomic variable, the number of preschool children (a variable that varies by both alternative and individual). This last variable deals with the issue that individual-specific variables are not identified in the model and thus the model must be modified (as described by Greene).

Davies, Greenwood, and Li (2001) use a conditional logit model in the context of state-to-state migration of individuals within the contiguous U.S. They use the model to determine the factors that affected interstate migration over a period of eleven years from 1986-1997. The model then allows for the calculation of cross-marginal effects and trade-offs. Cross-marginal effects can be interpreted as the effect of a change in an attribute of a particular alternative on the probability of choosing any other alternative. In this paper, the magnitudes of the cross-marginal effects turn out to be very small (as the authors expected). The authors then examine the trade-offs between per capita income and several explanatory variables in order to approximate the dollar value of those trade-offs, ceteris paribus. A one-unit increase in x_{ij1}, x_{ij2}(in this case per capita income) must increase by $\frac{\beta_1}{\beta_2}$ to compensate and hold the probability of choosing alternative j constant. The trade-off can be equated to the marginal rate of substitution (MRS) between the two variables in question while holding the utility constant. In this paper, the authors seek to demonstrate the use of a conditional logit model in studying state-to-state migration of individuals in particular. They envision that this approach can then be extended to location choice in general.

O'Keefe (2004) utilizes a county-level conditional logit model to determine the effects that influence migration of welfare recipients in California. She uses Equation (7) to demonstrate the relationship between the estimated coefficients and the marginal effects of the explanatory variables on the probabilities of moving between every pair of counties. The author notes that the large number of counties means that, for most pairs, the probabilities will generally be very small. She then divides both sides of Equation (7) by P_{ij} which results in a partial elasticity, the percentage change in probability as a result of a one-unit change in a particular variable, x_{ijk} . Because P_{ij} is usually small, β_k is an approximation for the partial elasticity. This interpretation for the estimated coefficients is only valid if it is assumed that the probabilities are very small. The author then goes on to note that the state of California should be aware of the factors affecting migration, as presented in her paper, and take current migratory trends into consideration when designing future welfare policies.

Bayoh, Irwin, and Haab (2006) use a conditional logit model in the context of location choice. They refer to their model as a "hybrid" conditional logit model because, in addition to considering the effects of choice-specific attributes (as a traditional conditional logit model does), it also considers the effects of individual-specific characteristics (by interacting the choice dummy variables with the household-specific variables to ensure that the household-specific variables are identified in the model). This model is then used to determine the relative effects of community (choice-specific attributes) versus household characteristics (individual-specific characteristics) on the determination of residential location choice. Bayoh et al. also note the need to incorporate a set of dummy interaction terms for each household variable that correspond to each alternative to ensure that the household variable does not drop out of the model. Because the nonlinear nature of the conditional logit model means that it will generate estimated coefficients that are not equal to the marginal effects of the corresponding variable, Bayoh et al. use the marginal effects, calculated by Equation (7), to compute partial elasticities, the effect of a one-percent change in a particular variable, x_{ijk} , on the probability that a household will choose one of the locations. The authors go on to conclude that household location decisions are most influenced by community attributes (alternative-specific variables) associated with a "flight-from-blight" process of suburbanization rather than one of natural evolution (largely due to changes in individual-specific variables). These results indicate that local policies could be used to increase the attractiveness of city attributes to encourage in-migration and discourage out-migration in order to revitalize city centers.

It is also common for a conditional logit model to be used in the case of brand choice because price, along with health and safety indices (alternative-specific variables), figure prominently into an individual's choice of which brand to purchase. Batte et al. use a conditional logit model to examine customers' willingness to pay for different levels (100%, 95%, 70%) of organic content in breakfast cereals. They found that the estimated coefficient on the price variable was significant and negative as expected, suggesting that as the price of the organic product rises relative to the price of the conventional one, the customer will be less likely to purchase the organic product. They also found that the estimated coefficient on the food safety index was significant and positive, suggesting that customers are more likely to purchase organic products over conventional ones to avoid pesticides and genetically modified organisms (GMOs). Individual-specific variables, such as income, race, and number of children in the household, were also included in the model. The authors then used the results of the conditional logit model to estimate customers' willingness to pay for organic products. They found that nutritional and food safety concerns were the primary motivators for purchasing organic products, outweighing the higher prices of these products. The results of their contingent valuation experiment suggested that changes in price do not significantly affect the probability of choosing an organic product. This suggests that customers are willing to pay a premium price for organic products in order to protect their health.

The use of a conditional logit model is also common in cases of recreation demand choice. As described by Train (1998), a prominent example is the application of a conditional logit model to fishing, in which anglers must decide whether to take a fishing trip during a specified period, which species of fish to target, and/or which fishing site to travel to. The nature of the conditional logit model allows characteristics of the alternatives (e.g. the time and cost of traveling to the site, the catch rate, the availability of campgrounds, etc.) as well as characteristics of the individual anglers (e.g. age, sex, and income, etc.) to be considered. As mentioned above in the case of the choice of organic vs. conventional cereal, the results of the conditional logit model are then used to estimate the anglers' willingness to pay for changes in site attributes. Train recognizes the limitations of the IIA assumption of the conditional logit model and instead utilizes a mixed logit model that allows the estimated coefficients to vary over individuals to account for taste differences across individuals. This also implies that the unobserved component of utility associated with any alternative is correlated over time for each individual. This property is included in the estimation when an individual encounters more than one choice situation within the data set.

Hynes and Hanley (2005) use a mixed logit model to examine taste heterogeneity in kayakers' choice of whitewater site. They discuss their attempted use of a lognormal density function for some of the coefficients. A lognormal density function is used if the researcher wants to restrict the coefficient estimates to be positive (or negative if the variable is multiplied by -1). The authors expected the trip cost coefficient to be negative for all kayakers in order for the model to exhibit rational behavior because one would expect that as the trip cost increased a kayaker would be less likely to visit that site. They also expected the scenery and water quality coefficients to be positive as one would expect that kayakers would prefer better quality scenery and water, not worse. However they found that using a lognormal density function did not allow the mixed logit model to converge. They go on to say that Brownstone and Train encountered this same problem in one of their papers. Thus Hynes and Hanley use a normal density function for all of the coefficients in the model.

Christiadi and Cushing (2007) discuss the use of a conditional logit model in the context of migration. Very early on in the paper the authors bring up the issue of the IIA assumption and say a violation of this assumption could lead to an incorrect prediction of the probability of different migration destinations being chosen. They use this concern as a stepping stone in their paper and devote its remainder to discussing other models that have been developed to relax the IIA assumption, including the mixed logit model. The authors go on to say that when they ran the conditional logit model with their data it only took a little over a minute to complete the regression whereas the mixed logit model took nearly 10 hours. Thus relaxing the IIA assumption necessarily results in significant time and computational costs. But on the positive side, the more complex mixed logit model results in a more efficient estimation and thus a higher likelihood value. They also found that, for the most part, the corresponding estimated coefficients in both the mixed and conditional logit models were of the same sign and statistical significance, but the magnitudes of the estimated coefficients in the mixed logit model were consistently higher. The authors conclude, as did Dahlberg and Eklof in one of their papers, that the mixed and conditional logit models are qualitatively very similar. Thus, the results of a conditional logit model can often be used as a general approximation of models, such as the mixed logit model, that relax the IIA assumption. They point out that if it is the researcher's goal to merely discover the individuals' average preferences, a violation of the IIA assumption of the conditional logit model is not of much concern. But if it is the researcher's goal to more accurately forecast the substitution patterns among alternatives due to changes in their characteristics, it is important to utilize a model that relaxes the IIA assumption, such as a mixed logit model.

Choi and Ishii (2010) estimate both a conditional logit model and a mixed logit model to examine the degree to which consumers' perception of a manufacturer's warranty is a signal of unobservable car quality. When comparing the two models, the authors found, as Christiadi and Cushing did, that they are qualitatively similar. They then conclude that the differences between the two models, namely the counterintuitive coefficients estimated by the conditional logit model, might be a byproduct of the restrictive IIA assumption. The authors go on to calculate the marginal effects of each of the exogenous variables on the choice probabilities. The basic equation is the same as Equation (2.7) but the authors modify it a bit. Instead of calculating the marginal effects of a “representative” individual, the average of the marginal effects of all the individuals is calculated as follows

$$\frac{1}{N}\sum_{i=1}^{N}\frac{\partial \hat{P}_{ij}}{\partial x_{ij}} = \frac{1}{N}\sum_{i=1}^{N}\hat{\beta}_{x_{ij}}\hat{P}_{ij}(1-\hat{P}_{ij}) \qquad (2.11)$$

where j is the product chosen by individual i, $\hat{P}_{ij}$ is the estimated probability that consumer i chooses product j, and $\hat{\beta}_{x_{ij}}$ is the mean of the estimated coefficient of x_{ij}. It makes sense to calculate the average of the marginal effects because the mixed logit estimation results report the mean of the estimated coefficients (in the mixed logit model the coefficient estimates vary across individuals).

Arik Levinson (1996) uses a conditional logit model to examine the effect of differences in the stringency of state environmental regulations on the location choice of manufacturers. One of the issues he faces is quantifying the regulations in a significant way. There are currently three broad categories of ways in which to quantify these regulations: qualitative indicators of regulatory stringency, quantitative measures of the states’ enforcement efforts, and quantitative measures of the manufacturing plants’ compliance costs. Levinson develops and explores six environmental regulatory measures that fall into these three categories. He then uses a conditional logit model to determine the probability that a particular state maximizes profits for a particular plant. To overcome the IIA issue, regional dummy variables are included for the four Census regions explored in this study. The author found that environmental regulations do not significantly affect the opening of new manufacturing plants. The main implications of this particular article are the ways in which the environmental regulations can be quantified and applied within a conditional logit setting.

3. Data

3.1. Description

The data used in this thesis are sourced from the PA DEP Oil & Gas Reporting Website (https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Welcome/Welcome.aspx). This website allows the public to view oil and gas well production and waste data dating back to the year 2000. This information is reported to the PA DEP and then made publicly available in accordance with Pennsylvania law. An amendment to the 1984 Oil and Gas Act, signed into law on March 22, 2010, requires drilling operators to file semi-annual production data reports with the PA DEP on or before February 15th and August 15th of each year that include the data from the previous six-month period. Under the original act, the production data remained proprietary for five years, but under the amended act the PA DEP is required to make the reports publicly available on its website after six months (Oil & Gas Act of 2010, P.L. 169, No. 15). The law does not specifically mention the provision of waste data, but it is also included in the reports.

The "Marcellus Only" waste report for the period July-December 2011 was downloaded on May 23, 2012, for use in this thesis. Appendix A details how the data in the waste report was prepared and cleaned for use in this thesis. The report includes information such as gas production well location, operating company name, waste type (i.e. basic sediment, brine, drill cuttings, drilling, flowback fracturing sand, frac fluid, spent lubricant), disposal method (i.e. brine or industrial waste treatment plant, injection disposal well, landfill, municipal sewage treatment plant, reuse other than road spreading), waste quantity, waste facility name, and waste facility location. Because this thesis is only concerned with wastewater, the dataset is limited to the “brine” and “frac fluid” waste types. “Brine” refers to produced water, or the water that will return to the surface over the life of a producing well. “Frac fluid” refers to flowback water, or the water that will return to the surface immediately after fracing is completed.

One of the “Disposal Method” classifications is “Reuse Other Than Road Spreading” and includes both recycling and on-site treatment and reuse or dilution and reuse. The observations that include a Waste Facility Permit Number and/or an address can be identified as dedicated recycling facilities. The other observations are labeled as “Frac Water Reuse”, “Reuse of Brine to Frac a Well”, “Reused for UIC Class II”, or “Reused in Drilling or Plugging Job” but they cannot be positively identified as either on-site treatment and reuse or dilution and reuse (the labels are not descriptive enough) (Yoxtheimer)[13]. For this reason, those observations that are not identified as dedicated recycling facilities will be excluded from the data set.

The “Disposal Method” classification “Landfill” will be excluded from the data set because it is not technically (liquid) wastewater that is being disposed of in these facilities; the wastewater is solidified first before it is disposed of in landfills. The “Disposal Method” classification “Municipal Sewage Treatment Plant” will also be excluded from the data set. Firstly there are only four such observations, totaling only 408 bbls. And secondly, because of the PA DEP’s request for drilling operators to stop sending wastewater to municipal sewage treatment plants, this disposal method will not be a viable option in the future (the 408 bbls that were disposed of this way in the second half of 2011 were most likely residuals from before the PA DEP’s request).

After excluding the necessary observations from the original data set, the wastewater volume totals are as described in Table 3.1 (an amendment of Table 1.2). The recycling and

[13] David Yoxtheimer, of the Penn State Marcellus Center for Outreach and Research, offered guidance in the deciphering of the different labels applied to the “Reuse Other Than Road Spreading” classification.

reuse category experienced the largest impact. After excluding the necessary observations, its volume total decreased from 14,632,868 to 9,093,594 bbls, a decrease of 38%.

Table 3.1 Wastewater Volumes (bbls) by Disposal Method, After Excluding the Necessary Observations

	Jul-Dec 2011
Underground Injection Well	1,951,293.69
Recycling and Reuse	9,093,594.91
Brine or Industrial Waste Treatment Plant	169,108.35
TOTAL:	**11,213,996.95**

Source: data obtained from the PA DEP Oil & Gas Reporting Website (accessed May 23, 2012)

The July-December 2011 data set includes 2,933 observations. Wastewater produced from a particular gas production well may be included in two separate observations if it was sent to multiple disposal/treatment facilities. Thus the drilling operators of 1,278 unique gas production wells are making decisions about where to send their wastewater; the possible utilization of multiple disposal locations per gas production well brings the number of total observations in the data set to 2,933.

Table 3.2 Description of Data Set

	Number of Observations	**Probability**
Underground Injection Well	2,059	0.70
Recycling and Reuse	730	0.25
Brine or Industrial Waste Treatment Plant	144	0.05
TOTAL:	**2,933**	**1.00**

Source: data obtained from the PA DEP Oil & Gas Reporting website (accessed May 23, 2012)

3.2. Variables

Distance (*dbrine*, *dinjection*, *dreuse*) Using ArcGIS, a distance variable was created in order to determine the role location plays in an operator's choice of disposal method. The straight-line distance between each gas production well and the corresponding nearest disposal/treatment location of each type is calculated.

The minimum, maximum, and mean for the *dreuse* variable (distance to nearest brine and industrial waste treatment plant), as described in Table 3.3, are the smallest out the three alternatives. This means that the recycling facilities are more centrally located to all of the gas production wells than either of the other two disposal methods.

Conversely, the *dinjection* variable (distance to nearest injection well), also described in Table 3.3, has the largest minimum, maximum, and mean out of the three alternatives, meaning that the injection wells are not as conveniently located to the current gas production wells. This makes sense because most of the injection wells are located in Ohio, far from some of the gas production wells.

Costs (*pbrine*, *pinjection*, *preuse*) For each gas production well, the costs, in 2012 dollars, of the nearest disposal/treatment locations of each type are included. The cost for disposal in underground injection wells varies widely from pennies to upwards of $10/barrel. A presentation by Chesapeake Energy for the EPA reported a cost of $0.50-$2.50/bbl for commercial wells in Texas, as well as a cost of $0.25 for private wells (McCurdy). A report prepared by General Electric (GE) reported a cost of $1.50-$2.00/bbl for Pennsylvania drilling operators disposing of wastewater in Ohio wells (GE Power and Water). For the purposes of this thesis, a cost of $2.00 is used for underground injection because it is on the conservative end of the cost range reported by GE.

For wastewater exported from Pennsylvania to Ohio, an additional disposal fee of $0.20/bbl is added to the cost. The passage of Ohio's Senate Bill 165 in 2010 made some changes to the state's UIC program, including an additional disposal fee. The fee amounts to $0.05/bbl for wastewater originating in-district (within one of the three districts in which an Oil & Gas regional office is located) and $0.20/bbl for wastewater originating out-of-district (effectively meaning out-of-state). The fees are collected by the ODNR and are used to run the Division of Oil and Gas Resources Management (Tomastik).

Three of the four Pennsylvania underground injection wells utilized are private wells[14]. Using the estimate from Chesapeake Energy's report, a private-well cost of $0.25/bbl is used for the purposes of this thesis (McCurdy). The fourth Pennsylvania injection well is technically a commercial well[15] but the only drilling operator that sent wastewater to the well is the same company that operates the injection well, effectively making this well a private one for the purposes of this thesis. Thus, in this case, a cost of $0.25 will also be used (Platt).

According to Quay Shappell, the Chief Operating Officer of TerrAqua Resource Management, one of the main reasons recycling costs vary across Pennsylvania is the lack of consensus among the drilling operators as to the water quality standards for beneficial reuse. Because wastewater that is recycled at dedicated facilities is then sent back out into the field for reuse at other drilling sites, the drilling operators can determine the water quality treatment standards that need to be met by the recycling facilities. The prices charged by these facilities are related to the quality of both the wastewater input and the freshwater output and it is thus

[14] As mentioned in Section 1.3.1., private wells are operated by the same drilling company whose production wells produce the wastewater that is disposed of in these wells; they are only permitted to accept wastewater from their own production wells.

[15] As mentioned in Section 1.3.1., commercial wells are permitted to accept wastewater originating from any drilling company. They are able to set their own disposal fees.

difficult to make a generalization about the cost. If a company only wants the solids removed from its wastewater it costs less than $2/bbl. On the other hand, if a company wants almost all of the barium, a scale-forming element, removed it costs upwards of $6-$7/bbl. Now, on average, companies want the incidence of barium to be reduced from 6,000 to 3,000 parts per million (ppm) and for this they are charged $4.62/bbl (Shappell). The University of Pittsburgh Graduate School of Business economic impact study reports a cost of $3.50-$5.50/bbl and Reserved Environmental Services (RES) reports a cost of $3-$5.50/bbl (Hefley 2011; Kasey). Thus, for the purposes of this thesis, the cost of $4.62/bbl reported by Shappell will be used, as it also falls within the other reported ranges.

Treatment and disposal at brine or industrial waste treatment plants costs between $0.12 and $0.25/gallon, or $5.04 and $10.50/bbl (Abdalla et al. 2011). For the purposes of this thesis, a cost of $6.00/bbl is used (about $0.14/gallon)[16].

Size of Drilling Company (*size*) The number of unique gas production wells operated by a particular drilling company is used as a proxy for the size of the company. There are 22 companies that operate less than 10 wells, 16 that operate between 10 and 100 wells, and 6 companies that operate more than 100 wells. Thus, of the 44 companies represented in this dataset, 22 of them, or 50 percent, are small companies operating less than 10 wells. Range Resources Appalachia LLC is currently the largest drilling operator with 350 gas production wells across Pennsylvania. The other large companies are Talisman Energy USA Inc. with 268 wells, Chesapeake Appalachia LLC with 248 wells, Atlas Resources LLC with 207 wells, Chevron Appalachia LLC with 110 wells, and EQT Production Co. with 106 wells.

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[16] The DEP's new TDS regulations (500 mg/L, instituted in 2010) apply only to new or expanded TDS loads at facilities accepting wastewater. If they don't have to adhere to standards that are as stringent, they won't have to charge prices that are as high (Abdalla et al. 2011). Further research of the websites for the facilities included in the data set indicates that the facilities have been operating at their current levels for some time. Thus a lower price is used.

Competition (*comp*) For each of the gas production wells, a count of the number of other gas production wells within a 10-mile radius that utilize the same disposal method is used as a measure of competition.

Distance to Nearest "Large" City (*citydist*) In order to determine if a gas production well's proximity to a city has an impact on the disposal method chosen, a variable is included that indicates the distance to the closest "large" city/village/municipality/borough. In this case, a "large" city is any with a population greater than 10,000 people. This data was obtained from the U.S. Census Bureau's population estimates, released on June 28, 2012, for the period April 1, 2010 through July 1, 2011. With the exception of the cluster of wells located in the southwest of Pennsylvania near several "large" cities, including Pittsburgh, most gas production wells seem to be located in more rural areas of lower population.

A map of the location of these "large" cities can be found in Appendix B.

River Basin (*RB*) A dummy variable is included to indicate in which river basin a particular gas production well is located. There are eight river basins in Pennsylvania – Allegheny, Delaware, Erie, Genesee, Monongahela, Ohio, Potomac, and Susquehanna. The gas production wells are located in four of them – Allegheny, Monongahela, Ohio, and Susquehanna – and are pretty evenly distributed among them.

Table 3.3 Description of Variables

Variable Name	Variable Description	Minimum	Maximum	Mean
	Alternative-Specific Variables			
dist	the straight-line distance (in miles) between each gas production well and the corresponding nearest disposal location of each type			
	dbrine	1.05	115.18	41.54
	dinjection	4.31	218.02	65.24
	dreuse	0.10	88.35	34.41
price	for each gas production well, the cost (in $/bbl) of the nearest disposal method of each type			
	pbrine	6.00	6.00	6.00
	pinjection	0.25	2.20	2.00
	preuse	4.62	4.62	4.62

Table 3.3 Description of Variables (continued)

Variable Name	Variable Description	Minimum	Maximum	Mean
	Individual-Specific Variables			
size	the number of unique gas production wells operated by a particular drilling company	1	350	169*
comp	the number of gas production wells within a 10-mile radius of a particular gas production well that utilize the same disposal method	1	220	89
citydist	the straight-line distance (in miles) between each gas production well and the nearest "large" city	2.61	56.98	16.19
RB_all	a dummy variable equal to 1 if the gas production well is located in the Allegheny River Basin and 0 otherwise	0	1	0.2145
RB_mon	a dummy variable equal to 1 if the gas production well is located in the Monongahela River Basin and 0 otherwise	0	1	0.2444
RB_ohio	a dummy variable equal to 1 if the gas production well is located in the Ohio River Basin and 0 otherwise	0	1	0.2876
RB_sus	a dummy variable equal to 1 if the gas production well is located in the Susquehanna River Basin and 0 otherwise	0	1	0.2533

***** this mean does not accurately represent the data; a majority of the drilling companies operate fewer than 100 wells but the mean is inflated due to the 6 companies that operate a large number of wells

4. Results and Analysis

4.1. The Model

In the case of the research goals presented in this thesis, the Marcellus Shale natural gas drilling operators are the decision-makers and they must choose which of three disposal methods (brine or industrial waste treatment plant, injection well, or recycling and reuse) to utilize to dispose of the wastewater produced as a result of their drilling operations in Pennsylvania. Appendix C details how the data was organized in Stata in order for the model to run properly.

Each drilling operator *i* faces the following utility function in their choice of disposal method *j*

$$U_{ij} = V_{ij} + \varepsilon_{ij} \qquad (3.1)$$

where

$$V_{ij} = \beta_1 dist_{ij} + \beta_2 price_{ij} + \beta_3 size_i + \beta_4 comp_i + \beta_5 citydist_i + \beta_6 RB_{mon} + \beta_7 RB_{ohio} + \beta_8 RB_{sus} \qquad (3.2)$$[17]

and the variables are as described in Section 3.2 and delineated in Table 3.3; V_{ij} represents the observable component of the utility and ε_{ij} represents the unobservable component of the utility.

In order for the individual-specific characteristics (*size*, *comp*, *citydist*, *RB_mon*, *RB_ohio*, *RB_sus*) to be identified in the model they must be interacted with (in other words, multiplied by) the choice dummy variables[18]. Thus the conditional logit model is represented as

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[17] *RB_all* is used as the baseline and is thus not included in the model.

[18] The dummy variables are as such:

$$c_j = \begin{cases} 1 \; if \; alternative \; j \; is \; chosen \\ 0 \; otherwise \end{cases}$$

where *j = 1,2,3* and *1 = brine*, *2 = injection*, *3 = reuse*.

$$Prob(Y_i = j) = \frac{\exp(V_{ij})}{\sum_{j=1}^{3} \exp(V_{ij})} \qquad (3.3)$$

where

$$V_{ij} = \beta_1 dist_{ij} + \beta_2 price_{ij} + \beta_3(c_2 size_i) + \beta_4(c_3 size_i) + \beta_5(c_2 comp_i) + \beta_6(c_3 comp_i) + \beta_7(c_2 citydist_i) + \beta_8(c_3 citydist_i) + \beta_9(c_2 RB\_mon_i) + \beta_{10}(c_3 RB\_mon_i) + \beta_{11}(c_2 RB\_ohio_i) + \beta_{12}(c_3 RB\_ohio_i) + \beta_{13}(c_2 RB\_sus_i) + \beta_{14}(c_3 RB\_sus_i) \qquad (3.4)$$[19]

and $j = 1, 2, 3$, $1 =$ *brine*, $2 =$ *injection*, and $3 =$ *reuse*; and c_j = the dummy variables corresponding to each of the disposal methods.

The mixed logit model is represented as

$$P_{ij} = \int L_{ij}(\beta) f(\beta) d\beta \qquad (3.5)$$

where

$$L_{ij}(\beta) = Prob(Y_i = j) = \frac{\exp(V_{ij})}{\sum_{j=1}^{3} \exp(V_{ij})} \qquad (3.6)$$

and $f(\beta)$ is the normal density function[20].

Table 4.1 details the results of the model estimation in Stata, including the coefficient estimates and their standard errors.

[19] $c_1 =$ *brine* is used as the baseline and is thus all interaction terms that include it are not included in the model; the dummy variable *RB_all* is used as the baseline and is thus not included in the model.

[20] As Hynes and Hanley (2005) found, when the lognormal density function was used for the distance and price variables (because it was expected they would be negative), the mixed conditional logit model failed to converge. Thus the normal density function was used for all of the variables.

4.2. Estimation Results

Table 4.1 Mixed Conditional Logit Estimation Results[21]

	LR chi2(14) =	203.09	
	Prob > chi2 =	0.0000	
	Log Likelihood =	-1321.2883	
choice	**Coef.**	**Std. Err.**	
mean			
dist	-0.0530	0.0048	*
price	-0.6135	0.0817	*
c2size	0.0126	0.0027	*
c3size	0.0125	0.0026	*
c2comp	0.0856	0.0096	*
c3comp	0.0628	0.0091	*
c2citydist	-0.0357	0.0164	**
c3citydist	-0.0429	0.0100	*
c2rb_mon	-3.6875	0.3816	*
c3rb_mon	-2.3563	0.3090	*
c2rb_ohio	-2.3495	0.3848	*
c3rb_ohio	-4.1397	1.2538	*
c2rb_sus	-0.3851	0.7184	
c3rb_sus	1.3416	0.6183	**
SD			
dist	0.0318	0.0033	*
price	0.0125	0.0753	
c2size	0.0000	0.0010	
c3size	0.0001	0.0011	
c2comp	0.0005	0.0017	
c3comp	0.0001	0.0019	
c2citydist	0.0490	0.0126	*
c3citydist	0.0125	0.0109	
c2rb_mon	0.0075	0.1859	
c3rb_mon	0.0407	0.2896	
c2rb_ohio	0.0326	0.3523	
c3rb_ohio	1.8360	1.0324	***
c2rb_sus	2.2827	0.4873	*
c3rb_sus	1.3114	0.5279	**

***** significant at the 1% level, ** significant at the 5% level, *** significant at the 10% level

[21] The conditional logit estimation results are reported in Appendix D.

4.3. Marginal Effects

As mentioned in Section 2.2, the signs of the estimated coefficients indicate the direction of impact of the corresponding variables, but the absolute values of the estimates are not indicative of the magnitude of the impact. In order to determine the magnitude, the marginal effects must be calculated; Equation (2.12) is used to do so. As done by Christiadi and Cushing (2007), the average marginal effect is calculated for each variable (because the mixed logit approach calculates the mean of the coefficient estimates).

Table 4.2 details the marginal effect of each explanatory variable. As mentioned in Section 2.2, the marginal effects of the alternative-specific variables will indicate the direction and size of the impact of each variable on the overall choice probabilities (regardless of which alternative is chosen). But the marginal effects of the interaction terms (the individual-specific variables multiplied by the alternative dummy variables) indicate the direction and size of the impact of each of the interaction terms on the probability of choosing the corresponding alternative relative to the alternative used as the baseline (in this case, brine is used as the baseline).

Table 4.2 Marginal Effects of the Variables

Variable	Marginal Effect
Alternative-Specific Variables	
dist	-0.0048
price	-0.0556
Individual-Specific Interaction Variables	
c2size	0.0034
c3size	0.0034
c2comp	0.0233
c3comp	0.0171
c2citydist	-0.0097
c3citydist	-0.0117
c2rb_mon	-1.0024
c3rb_mon	-0.6405
c2rb_ohio	-0.6387
c3rb_ohio	-1.1253
c2rb_sus	-0.1047
c3rb_sus	0.3647

4.4. Discussion of the Results

The marginal effect of the price variable has the expected negative sign. One would expect that as the price of a disposal method increases the probability of choosing that alternative would decrease; this is rational economic behavior. The magnitude of 0.0556 means that a $1/bbl increase in the price of the disposal method will result in a 5.56 percentage point decrease in the probability that that alternative will be chosen. Out of all the continuous variables, the price variable has the largest absolute value impact. It is rational to expect that the financial aspect of the decision-making process would have the largest impact on the probability that an alternative would be chosen.

The distance variable also has a marginal effect with a negative sign which is expected. One would expect that as the distance between the gas production well and the disposal location increases the probability of choosing an alternative would decrease. The magnitude of the distance variable is equal to 0.0048, meaning that a one-mile increase in the distance between the gas production well and the disposal location will result in a 0.48 percentage point decrease in the probability that that alternative will be chosen.

The distance variable is also tied to the price variable because the distance variable can be thought of as a proxy for the transportation cost. Thus as the distance between the gas production well and the disposal location increases the transportation cost also increases. And, as the sign of the marginal effect of the price variable indicates, as the cost of an alternative increases the probability of choosing that alternative will decrease. On average, the transportation cost amounts to about $1/bbl/hr. If it is assumed that the trucks transporting the wastewater travel, on average, approximately 45 mph[22], a distance increase of 45 miles will result in a $1/bbl increase in transportation costs. The magnitude of the coefficient of the distance variable indicates that a one-mile increase in distance will result in a 0.48 percentage point decrease in probability, and thus a 45-mile increase in distance will result in an approximately 22 percentage point decrease in probability. By extension a $1/bbl increase in transportation costs (equivalent to a 45-mile increase in distance), will also result in a 22 percentage point decrease in the probability that an alternative will be chosen. Thus, an increase in the transportation cost will have a larger magnitude of impact (22 percentage points) on the

[22] While wastewater disposal trucks can most likely average 60 mph on the interstate highways, many of the production wells are located a considerable distance from the interstates and thus must be accessed by smaller, back roads that require the trucks to travel at lower speeds, closer to 30 mph. Thus, the trucks were estimated to travel at an average of 45 mph.

probability of choosing an particular disposal method than an increase in the price of the disposal method itself (6 percentage points).

Both of the marginal effects of the size variables have a positive sign and the magnitudes indicate that the addition of one more gas production well to a drilling company's operation translates into a 0.34 percentage point increase in the probability that either an injection well or recycling and reuse will be the disposal method chosen, as compared to the effect of an additional gas production well on the probability that a brine or industrial waste treatment plant will be the disposal method chosen. The magnitude of impact is very small which indicates that size is not as important to the drilling operators' choice of disposal method. The positive impact of size on the disposal method chosen could have something to do with economies of scale. For example, if a drilling company is large enough to completely fill the trucks required to transport the wastewater to the disposal locations its transportation costs will be the lowest possible, making transportation more economical. The $1/bbl/hr transportation cost was originally calculated from a more general cost of $100/hr/truck and thus depends on the truck being filled to capacity. If a drilling company does not produce enough wastewater to completely fill a truck, their per barrel transportation cost will actually be higher[23].

Both of the marginal effects of the competition variables have a positive sign. An increase in competition (an additional gas production well within a 10-mile radius of a particular gas production well) will cause a 2.33 percentage point increase in the probability that an injection well will be the disposal method chosen and a 1.71 percentage point increase in the

[23] The per barrel transportation cost could also be higher if the wastewater disposal trucks idle at the drill sites while waiting to be filled up. Tomastik was consulted regarding this issue. He said that there could be a short wait time at the drill pad before collecting the frac fluid. The trucks are connected to a frac tank via a hose that transfers the wastewater into them. On the other hand, at the production pad there is generally no wait time. The trucks collect the brine directly from a tank called a knockout tank. It seems that the wait time isn't significant enough to affect the per barrel transportation cost to a great degree.

probability that recycling and reuse will be the disposal method chosen, as compared to the effect of an increase in competition on the probability that a brine or industrial waste treatment plant will be the disposal method chosen. An increase in competition might have a greater impact on the choice of an injection well for wastewater disposal due to the higher daily/monthly capacity for some of them as compared to the other disposal methods. There are also 51 injection wells accepting wastewater, almost five times as many as either of the other alternatives, meaning that the total capacity of all of the injection wells combined will be much greater than either of the other alternatives. An increase in competition might have a positive impact on the choice of recycling and reuse as the disposal method because it will create a market for the treated wastewater. The process of recycling and reuse means that the treated wastewater will be sent back out into the field and used to frac other wells. If there is not a market for this treated water, the recycling and reuse method will no longer be a viable option. In the long run, if demand for treated wastewater for fracing continues to increase (a possible result of an increase in competition because of the limitations placed on freshwater withdrawals), recycling facilities might be able to lower their per barrel prices, further increasing the probability that recycling and reuse will be the disposal method chosen.

Both of the marginal effects of the “distance to nearest large city” variables have a negative sign. As the distance to the nearest “large” city increases by one mile, the probability that an injection well will be the disposal method chosen decreases by 0.97 percentage points and the probability that recycling and reuse will be the disposal method chosen decreases by 1.17 percentage points, as compared to the effect of an increase in the distance to the nearest “large” city on the probability that a brine or industrial waste treatment plant will be the disposal method chosen. This result could indicate the importance of the infrastructure that goes along with proximity to a city in the wastewater disposal process. Cities have access to better and more roads usable by large volumes of large truck traffic. They also have the resources to potentially build pipelines and rail lines for the purposes of transporting large volumes of wastewater more easily over long distances.

Because injection wells are generally located further from more populated areas than are recycling facilities, one would expect the distance to the nearest “large” city to matter less (have a smaller magnitude of impact) for injection wells because as gas production wells are located further from the cities they might be located closer to the injection wells at which they will dispose of their wastewater. And, as the negative marginal effect of distance indicates, as the distance between a gas production well and disposal location decreases, the probability of choosing that disposal location increases. This slight positive effect would possibly cancel out some of the negative effect of the distance to the nearest large city, meaning the magnitude of impact of “distance to nearest large city” on the choice of injection well would be less than the magnitude of impact of “distance to nearest large city” on the choice of recycling and reuse, as the results indicate. But the marginal effects are pretty close in magnitude indicating that this possible effect is not likely to be very strong.

All of the coefficients on the river basin dummy variables are negative, except the coefficient on the interaction between the recycling and reuse alternative and the Susquehanna River Basin. This means that, as compared to the gas production well not being located in its current river basin, being located in its current river basin results in a smaller probability of choosing either an injection well or recycling and reuse, as compared to choosing a brine or industrial waste treatment plant. The magnitudes of impact are, in general, larger for the Monongahela and the Ohio River Basins. This would seem to indicate that any regulations governing water withdrawal and discharge (and ultimately reuse) are more stringent in the Monongahela and Ohio River Basins, but there is no indication that this is the case in actuality. This could then indicate the existence of other, as of yet unobservable as well as unfavorable attributes of these river basins. In this case, “unfavorable” refers to the fact that the signs of the marginal effects of some of the river basin dummies are negative, indicating that being located in these river basins means that drilling operators are less likely to choose either an injection well or recycling and reuse as the disposal option.

The ambiguity in the interpretation of the magnitudes of the marginal effects of the river basin dummies seems to indicate that the river basin boundaries on their own don’t paint a complete picture. The boundaries of the PA DEP districts, and possibly of Pennsylvania’s municipalities, could also play a role in the choice of disposal location. Thus the “unobservable” attributes mentioned above may not truly be unobservable; instead, the issue might simply be that the study presented in this thesis was not broad enough to include dummy variables for all of the possibly relevant boundaries.

On the other hand, being located in the Susquehanna River Basin has a positive impact on the choice of an injection well as the disposal method. The Susquehanna River Basin Commission (SRBC) is active in regulating water withdrawals and discharges within its boundaries. Because most of the injection wells are located farther from this river basin, which is located farther east than the other three river basins, drilling companies might utilize this disposal method in order to escape the regulations put in place by the SRBC.

The coefficients on the interaction terms between injection well and Monongahela River Basin and between recycling and reuse and Ohio River Basin are greater than one, which would mean that the difference in choice probability, as a result of being located in either of those river basins as compared to not, would be greater than 100 percentage points. A change in probability that is greater than 100 percentage points does not make sense nor is it intuitive. This is an indication that there might be a problem with the way the marginal effects of the river basin dummy variables were calculated and interpreted. According to Choi and Ishii (2010), Equation (2.12) should only be used to calculate the marginal effects of continuous variables. The marginal effects of binary (dummy) variables should be calculated as the averages of the differences of the actual estimated probabilities for the observed choices and the counterfactual estimated probabilities for the observed choices.

An economic counterfactual simulation involves predicting the new estimated probabilities of choosing the alternatives when a certain variable is changed. According to the method employed by Choi and Ishii (2010), when a binary variable is involved, a counterfactual simulation assumes that the value of the binary variable in question is zero. After performing the counterfactual simulation (by changing the values of the necessary binary variables to zero and running these new values back through the previously-estimated model), the marginal effect[24] of the binary variable in question can be determined by averaging the actual estimated probabilities for the observed choices and the estimated probabilities determined by the counterfactual simulation.

Because a binary variable can only ever equal zero or one, a probability difference provides a more natural interpretation than a probability derivative. Unfortunately the limitations of the Stata command "mixlogit" did not allow for the data to be modified and then run back through the previously-estimated model and thus this kind of analysis could not be performed.

[24] For observed choices whose original value of a binary variable is zero, the contribution to the marginal effect will be zero because the actual and counterfactual probabilities will be same (Choi and Ishii 2010).

5. Future Scenarios

5.1. Business-as-Usual

Under the "business-as-usual" scenario, natural gas drilling activity in the Marcellus Shale will continue to increase, along with the amount of wastewater that must be disposed of. According to Considine (2010), the regulatory policies of the states involved in natural gas drilling must be considered when discussing the trajectory of its development. Development prospects in Pennsylvania continue to remain the strongest of the states in the Marcellus or Utica Shale regions. The signing of Act 13 of 2012 (amending Title 58 of the Pennsylvania Consolidated Statutes) which provides for an unconventional gas well fee (also known as a drilling impact fee) could have an effect on future drilling activity though (Act 13). On the other hand, West Virginia has already imposed a severance tax and faces limited pipeline capacity and high pipeline construction costs as a result of the mountainous terrain that must be negotiated. Ohio, while not involved in drilling in the Marcellus Shale to any great extent, looks to become more involved in drilling in the Utica Shale (Considine 2010).

Currently in New York there exists an effective moratorium on horizontal drilling and hydraulic fracturing due to the limitations placed on the amount of water that can be used in the fracing process. But the large potential economic benefits that natural gas drilling could bring to the state are encouraging legislators to consider withdrawing this moratorium. Governor Andrew Cuomo has proposed a plan that would limit fracing to several struggling counties along the Southern Tier of the state, and only if the communities in which it would be used express their support for this process (Hakim). If the moratorium were to be lifted, these southern New York counties could expect to experience a substantial level of drilling activity, if the level of activity just south in Pennsylvania is any indication. All of these policies as a whole must be considered when trying to predict the overall level of natural gas development in the future.

Considine goes on to posit three development scenarios, extending through 2020, based on the aforementioned policy considerations. Under the low development scenario, Pennsylvania will drill close to 1,500 wells per year by 2020 and New York will continue to drill no wells as the moratorium will still be in effect. Under the medium development scenario, Pennsylvania will drill close to 2,500 wells per year and New York will drill approximately 300 wells per year by 2020. Under the high development strategy, Pennsylvania will drill close to 3,600 wells per year and New York will drill approximately 500 wells per year by 2020. Considine states that the rising importance of natural gas as part of our nation's energy future (as a way to end dependence on foreign oil and create domestic jobs) coupled with the vast growth in activity in the Barnett Shale in Texas, as well as in other shale plays across the country and throughout the world, indicate that the actual level of development might fall between the medium and high scenarios, if the moratorium in New York is lifted. On the other hand, if the moratorium in New York remains, if regulatory and tax policies are imposed, and/or if the price of natural gas remains low, the actual level of development might fall closer to the low scenario. Because there are so many factors to consider, it is extremely difficult to predict exactly what will happen (Considine 2010).

If the wastewater numbers from the last half of 2011 are any indication, the prevalence of the use of injection wells and recycling and reuse as disposal methods will continue to grow. From the first half of 2011 to the second half of 2011, the amount of wastewater disposed of in injection wells increased from 10% of the total to 11%[25] and the amount of wastewater disposed

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[25] While the percentage increase isn't that great, the volume increase from 866,023 bbl to 1,951,293 bbl indicates an increase in the prevalence of the use of this disposal method.

of through recycling and reuse increased from 69% of the total to 87% while the amount of wastewater disposed of in brine or industrial waste treatment plants decreased from 14% of the total to 1%. Because it is expected that the level of natural gas drilling will continue to increase, and, by extension, the amount of wastewater that must be disposed of, there is reason to believe that this trend in the prevalence of the use of disposal methods will continue in the immediate future.

Particularly if the moratorium in New York is lifted, a large increase in competition for wastewater disposal can be expected[26]. As the marginal effects of the competition variable indicate, an increase in competition will result in an increase in the probability that an injection well or recycling and reuse will be the disposal method chosen, as compared to a brine or industrial waste treatment plant. As mentioned in Section 1.3.1, most of the injection wells currently in operation, particularly in Pennsylvania, have been in operation since the 1980s and have still not reached their maximum capacity. They have also not seen very significant and intense levels of activity to date[27]. This is an indication that the Pennsylvania underground injection wells will continue to be able to accept the increasing volumes of wastewater that can be expected, at least in the short term (Platt; Tomastik). Information gleaned from both Platt and

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[26] If the moratorium in New York was lifted and the state began drilling, and thus producing wastewater, the wastewater would have to be disposed of somewhere. There is no indication to suggest that New York possesses any major capacity to handle large volumes of wastewater and thus drilling operators in New York would most likely be competing with those in Pennsylvania for the use of disposal methods in the short term (at least during the beginning stages of drilling activity in New York, before it could potentially develop its own disposal/treatment facilities and technologies).

[27] As compared to the injection activity that might be expected as drilling activity continues to increase.

Tomastik helped to form these assumptions[28]. Also, there are almost five times as many injection wells accepting wastewater as either of the other disposal methods, another indication of sufficient capacity at present.

In the case of recycling and reuse, the effect of competition might be two-fold. An increase in competition could place a strain on the amount of freshwater available for withdrawals used in the fracing process. This in turn could create a market for treated water sourced from recycling facilities to be used in the fracing process instead, therefore encouraging the use of existing and the development of new recycling and reuse facilities to dispose of/treat drilling wastewater.

As drilling activity and the volume of wastewater increase, if the state were to further encourage recycling and reuse as a disposal method[29], it could decrease the need for additional freshwater withdrawals and the amount of wastewater that must be disposed of. This would increase water use efficiency and help protect Pennsylvania's environment and waterways.

5.2. Permanent Moratorium in Youngstown, Ohio

As mentioned in 1.3.1, following the twelve earthquakes that occurred in Ohio in 2011, that have since been linked to an underground injection well in the Youngstown area, state officials issued a temporary moratorium on all underground injection activity within a five-mile

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[28] For example, in the short term in Ohio there is also sufficient capacity, but, according to Tomastik, there are currently 29 new permit applications pending, an indication that the high level of drilling activity is putting a strain on current capacity. He believes that in the long term a greater emphasis will be put on the recycling and reuse of wastewater to relieve the strain placed on underground injection capacity (as well as to decrease the amount of freshwater withdrawals needed in the fracing process and to cut down on disposal costs).

[29] This could perhaps be accomplished through some sort of subsidy because, as its marginal effect indicates, a decrease in price results in an increase in the probability that the alternative in question will be chosen. Incentives for recycling facilities to be built close to where the production wells are located would be another way to accomplish this because, as the marginal effect of the distance variable (a proxy for the transportation cost) indicates, the transportation cost plays a large role in the probability that a disposal method will be chosen.

radius of the injection well in question. Since then a determination has not yet been made as to the permanency of the moratorium. A permanent moratorium could be a possibility though – one was put in place in Arkansas following a swarm of earthquakes in the north-central part of the state that was linked to underground injection.

The way the data is currently defined (the distance variable is defined as the distance between the gas production well and the nearest disposal location of each type) it is not possible to model directly the effect of the Youngstown, Ohio, wells being removed from the data set because none of the Pennsylvania gas production wells have any of the Youngstown wells as their nearest injection well option. This scenario can be considered by applying the results of the model estimation and the interpretation of the marginal effects to it, though. The drilling operators of the 60 Pennsylvania gas production wells that utilize the Youngstown injection wells will have to reevaluate their disposal method choice. If the next closest injection well is closer than the Youngstown well, the drilling operator might start using this new injection well. On the other hand, if the next closest injection well is farther away than the Youngstown well, the drilling operator might consider utilizing a different disposal method because, as its marginal effect indicates, an increase in the distance variable will result in a decrease in the probability that a disposal method will be chosen.

The permanent moratorium will also affect wastewater produced in Ohio. According to Tomastik, natural gas development in the Utica Shale in Ohio is on track to increase in the coming years. Ohio anticipates drilling 200 Utica wells in 2012 and even more in the future (they are at the same stage of development that Pennsylvania was at in 2007 in the Marcellus Shale). Due to the potential increase in drilling activity in Ohio, and the inevitable increase in wastewater, Ohio may feel the effects of a permanent moratorium on some of its injection wells in the form of overall reduced injection capacity. As a result, they may feel the need to protect their supply of injection disposal capacity for their own future use, potentially accomplishing this by increasing the out-of-district disposal fee (currently set at $0.20/bbl in 2012). If the price of underground injection in Ohio increases, the probability of Pennsylvania drilling operators choosing it as a disposal method will decrease, causing drilling operators in Pennsylvania to turn to disposal methods within-state, including Pennsylvania's own underground injection wells, or, more likely, recycling and reuse. Thus a permanent moratorium on underground injection in Youngstown, Ohio, coupled with an increase in drilling activity in the Utica Shale in Ohio, could cause an even greater increase in the recycling and reuse of wastewater by drilling operators in Pennsylvania[30], as compared to the current trajectory of this disposal method.

5.3. Pennsylvania Takes Primacy

The increase in drilling activity in the Utica Shale in Ohio could also influence Pennsylvania's decision to take primacy of its underground injection program. As mentioned in Section 1.3.1, an individual state, if it so chooses, can apply to the EPA to obtain primacy, or primary enforcement responsibility, over its own UIC program, meaning that it would be in complete control of the program and in charge of overseeing all injection activity and ensuring that all federal and state requirements were being met ("Underground Injection"). As mentioned in the previous scenario, an increase in Utica Shale drilling could lead Ohio to attempt to protect its own supply of injection wells through an increase in the out-of-state disposal fee (currently set at $0.20/bbl in 2012). An increase in the price of underground injection, as evidenced by the

[30] It will be interesting to view the production and waste reports for the first half of 2012 when they are published by the DEP on their Oil & Gas Reporting website on August 15th. The data can be analyzed to determine the effect the temporary moratorium on underground injection has had on the probabilities of choosing each of the three disposal methods.

marginal effect of this variable, will lead drilling operators to reevaluate their choice of disposal method. Because most of Pennsylvania's injection wells are private facilities, recycling and reuse would be the natural next choice, but if Pennsylvania wanted to encourage underground injection within its borders, it would need to obtain primacy of its own program.

Primacy would allow Pennsylvania to permit more wells in a shorter period of time (as evidenced by how primacy allows Ohio to more efficiently operate its program[31]). It would also help if these potential new underground injection wells were located closer to the gas production wells that utilize them. As the marginal effect of the distance variable indicates, a decrease in the distance between the gas production well and the disposal location would result in an increase in the probability that it would be the method chosen. The marginal effect of the distance variable also indicates the large effect that transportation cost (for which the distance variable is a proxy) has on the choice of disposal method.

Previous, and now inactive, oil and gas production wells can be converted and used as new underground injection wells, cutting down on the required construction time. Thus the injection wells could also be located closer to the gas production wells they serve. This option comes with its own potential problems, though. Groundwater contamination could occur if the previous, inactive wells were improperly plugged, but primacy would allow Pennsylvania to institute its own regulations, more stringent than the federal standards, in order to control for this potential situation (Tomastik). Pennsylvania taking primacy of its underground injection program would be a potential solution to an increase in drilling in the Utica Shale in Ohio and thus Ohio increasing its disposal fee to protect its own supply of underground injection capacity.

[31] According to Tomastik, primacy eliminates the many bureaucratic hurdles that are present when the EPA is in charge of administering a state's UIC program. This allows a state to more efficiently operate their program, including permitting more wells in a shorter period of time.

6. Research Limitations

6.1. Data Limitations

As noted in Section 3.1, the "Reuse Other Than Road Spreading" observations labeled as "Frac Water Reuse", "Reuse of Brine to Frac a Well", "Reused for UIC Class II", or "Reused in Drilling or Plugging Job" could not be positively identified as either on-site treatment and reuse or dilution and reuse (the labels are not descriptive enough) and thus those observations were excluded from the data set. But for future research and analysis, it would be helpful to be able to make the distinction between on-site treatment and reuse or dilution and reuse (a more interactive form, as discussed in Section 6.1.1, could help with this). It would be interesting to examine the determinants of choosing on-site treatment and reuse as a disposal method, in particular the size of the drilling company. According to a University of Pittsburgh Graduate School of Business economic impact study, purchasing a mobile wastewater treatment unit can cost upwards of $4 million and renting it can cost about $80,000 per month, with a $73,000 operating cost (that covers fuel and labor) (Hefley 2011). Probably only larger companies, with many gas production wells that will benefit from the services of such a unit, would be willing or able to incur these huge fixed costs.

The data required some clean-up in order for it to be useable for the analysis conducted in this thesis. This was done as indicated in the following description. In the PA DEP waste report the drilling operators are required to provide the waste disposal method, but the method often does not match with the actual facility that is also provided. Many operators mistakenly chose "Brine or Industrial Waste Treatment Plant" when they should have chosen either "Injection Disposal Well" or "Reuse Other Than Road Spreading." The Waste Facility Permit Number was examined in order to correct this error. The permit numbers that take the form xx-xxx-xxxxx are underground injection wells and those that take the form WMGR119NC001 or WMGR123NC001 are dedicated recycling facilities. If a Waste Facility Permit Number was not provided, the names of the waste facilities were examined. If the name itself did not give an indication as to the type of facility, the descriptions provided by the facilities' websites were examined in order to make the distinction (Yoxtheimer)[32].

Another data problem was that latitude and longitude coordinates were lacking for some of the waste facilities in the PA DEP data set. In these cases, if a valid/complete street address was provided, a geocoding tool was used to convert the address to latitude and longitude coordinates. If a valid/complete street address was not provided, Christopher Tersine at the PA DEP and Tom Tomastik at the ODNR provided the missing coordinates.

The PA DEP also does not indicate when it updates the waste reports (other than on February 15th and August 15th). Apparently it will sometimes update the reports in the interim period if additional information becomes available (presumably if drilling companies submit new or updated data after the deadline). It would be helpful to know when and if these updates occur (i.e. a new version should be created each time an update is made) so that research using this data can easily be confirmed and replicated.

[32] David Yoxtheimer, of the Penn State Marcellus Center for Outreach and Research, offered guidance in the identification of the dedicated recycling facilities.

6.1.1. Future Improvements

As natural gas drilling activity and the volume of wastewater continue to increase it is imperative to the state and researchers alike that both are properly tracked. Only production data is currently covered under the amendment to the 1984 Oil and Gas Act, but if waste data were also specifically included in the act the quality of the data might improve by removing some of the inconsistencies. Performing a quick double-check of submitted data to verify they make sense might be a beneficial practice to institute by the PA DEP, to be performed by its employees upon reception of the data. Also, if the form used by the drilling operators to report their data is easier to use or includes more detailed instructions, the quality of the data might improve as well. For instance, a more interactive form might be able to catch some of the inconsistencies (e.g. if an operator chooses “Brine or Industrial Waste Treatment Plant” the form will not allow a Waste Facility Permit Number in the form of xx-xxx-xxxxx or WMGRxxxNC001 to be entered and the operator would be informed that one of the entries must be changed).

Since a large percentage of wastewater is sent across state lines for disposal (particularly to underground injection wells), future collaboration between states would be beneficial in order to be better able to track wastewater from production to disposal. In the course of conducting the research for this thesis, waste reports for Pennsylvania (found on the PA DEP website) and Ohio (provided by Tom Tomastik at the ODNR) were examined and it was found that their formats are not compatible. Pennsylvania reports waste data by the gas production well at which it originates and the waste facility destination is included. Ohio’s disposal well reports are broken down by the trucking company and indicate the amount of wastewater each hauler sends to each underground injection well. But there is no indication as to which gas production wells the wastewater originated from. Tom Tomastik said the ODNR can request that information (the haulers are required to keep logs) but it is only done if there is a major issue. Having that information readily available in order to verify that both states are receiving accurate data and to be able to conduct further research and analysis in the future would be useful. Potentially, some sort of national reporting standard could be implemented.

6.2. Model Limitations

As was discussed in Section 4.4, the calculation of the marginal effects of the river basin dummy variables requires the use of a counterfactual analysis because a probability difference provides a more intuitive interpretation of the marginal effects, as compared to the probability derivative that was calculated using Equation (2.7). The marginal effects should be calculated as the averages of the differences of the actual estimated probabilities for the observed choices and the counterfactual estimated probabilities for the observed choices. The limitations of the Stata command "mixlogit," due to it being a user-created command, did not allow for this kind of analysis. The use of a different statistical software package, such as MATLAB, would allow the data to be modified and then run back through the previously estimated model in order to perform a counterfactual simulation. This in turn would allow the marginal effects of the river basin dummy variables to be calculated correctly and ultimately allow for a better interpretation of said marginal effects.

6.3. Lessons Learned

This thesis shed light on several methodological issues and offered the opportunity to learn more about the model estimation process. At the same time it suggested ways in which these issues could be resolved as the study moves forward.

One of the most significant lessons learned involved the limitations of Stata's "mixlogit" command. Stata was the statistical software package of choice because, at first glance, it seemed to offer the best, most intuitive way to estimate the mixed logit model required for this thesis. But ultimately its user-created "mixlogit" command did not correctly allow the original data to be modified and run back through the original estimated model, thus performing the counterfactual simulation necessary to calculate the marginal effects of the river basin dummy variables and to evaluate the scenario in which there is a permanent moratorium on underground injection in Youngstown, Ohio. This issue sheds light on the need to explore the ability of other statistical software packages, such as MATLAB, to correctly manipulate the data and perform the necessary counterfactual simulation.

This thesis strove to use a counterfactual simulation to evaluate the scenario in which there is a permanent moratorium on underground injection in Youngstown, Ohio. But the use of an alternative statistical software package will only solve part of the problem this issue presents. The way the data is currently defined (for consistency reasons, the distance variable is defined as the distance between the gas production well and the nearest disposal location of each type) it is not possible to model directly the effect of the Youngstown, Ohio, injection wells being removed from the data set because none of the Pennsylvania gas production wells have any of the Youngstown wells as their nearest injection well option. This thesis instead used the results of the model estimation and the interpretation of the marginal effects to evaluate the permanent moratorium scenario. In order to be able to directly evaluate this scenario, the distance variable needs to be redefined. One possibility is defining each disposal location as its own unique choice alternative (instead of the type of disposal method being the choice alternative). This would allow the Youngstown, Ohio, injection wells to be successfully removed from the data set (because it is to be easier to remove a choice, as under the proposed new definition of each disposal location as a unique choice, as compared to a choice subset, as under the current definition of each disposal location as a subset of the broader disposal method choice set) in order to directly evaluate the permanent moratorium scenario.

7. Conclusions

The goals of this thesis were to:

(1) explore the factors that a Marcellus Shale drilling operator might consider in its choice of wastewater disposal method;

(2) assess the importance of certain alternative-specific (characteristics of the disposal method choice) and individual-specific (characteristics of the drilling operators making the decisions) variables and how they affect the probability that the decision maker (the drilling operators) will choose a particular alternative (disposal method); and

(3) use the knowledge about the relative importance of the variables included in the model to develop implications of the results for policy-makers to consider in the future.

Goal (1) was achieved through the development of a mixed logit model in the context of drilling operators' choice of wastewater disposal method. It included price, distance, size, competition, distance to "nearest" large city, and river basin dummy variables. The model was then estimated using Stata 12 and the coefficient estimates were obtained. These were then used to calculate the marginal effects of the variables on the probabilities of choosing each of the three disposal method alternatives (brine or industrial waste treatment plant, injection well, recycling and reuse). The marginal effects were then interpreted and the relative influence of each variable on the probabilities of choosing the corresponding alternative was determined, thus accomplishing goal (2). The marginal effects of the price and distance variables both have the expected negative signs, meaning that an increase in either of them will result in a decrease in the probability that the corresponding disposal method will be chosen. This represents rational economic behavior. Overall the price of the disposal method and, more importantly, the cost of transporting the wastewater from the gas production well to the disposal location (for which the distance variable is a proxy), have the largest impacts on the probability that a particular alternative will be chosen. This indicates that policies that affect the price or location of disposal methods will be the most effective in influencing the use of a particular method.

The marginal effect of the size variable has a positive sign which can be explained through economies of scale. The competition variable also has a positive sign. At first glance this result might seem counterintuitive. One might expect that competition would decrease the probability that an injection well or recycling and reuse would be the disposal method chosen. But after giving this result some thought it can be explained, particularly in the case of recycling and reuse. An increase in competition would place a strain on the supply of freshwater withdrawals available for the fracing process which would then create a market for the treated water that is produced by the recycling facilities. Therefore the use of recycling and reuse facilities to treat wastewater would be encouraged.

The marginal effect of the "distance to nearest large city" variable has a negative sign which can be explained by access to valuable infrastructure, such as roads and pipelines, which is the result of being located close to a city. The marginal effects of the river basin dummy variables were not as intuitive and would benefit from a recalculation using a counterfactual simulation (as discussed in Section 4.4) instead of the method actually used. The addition of variables to the model to capture other unobservable attributes of the river basins, including the stringency of the regulations governing the withdrawal and discharge water, would also be helpful.

These marginal effects were then used to predict what might happen under three possible future scenarios, accomplishing goal (3). This thesis explored a business-as-usual scenario, a permanent moratorium on underground injection in Youngstown, Ohio, and a scenario in which Pennsylvania takes primacy of its underground injection program. Under the business-as-usual scenario, that includes lifting the effective moratorium on natural gas drilling in New York, a further increase in the use of both underground injection and recycling and reuse as disposal methods beyond the current trends could be expected. This could be due to the increase in competition for wastewater disposal as a result of the commencement of natural gas drilling activity in New York.

In the case of a permanent moratorium on underground injection in Youngstown, Ohio, coupled with an increase in drilling activity in the Utica Shale in Ohio, an even greater increase in the recycling and reuse of wastewater by drilling operators in Pennsylvania, as compared to the current trajectory of this disposal method, could be expected. This could be due to a decrease in Ohio's overall underground injection capacity and its desire to protect its supply of underground injection for use when drilling activity in the Utica Shale region increases. It could accomplish this by increasing its out-of-state disposal fee, thus decreasing the probability that drilling operators in Pennsylvania will choose this disposal method. As a result, the probability that recycling and reuse would be the disposal method chosen would increase.

An increase in drilling activity in the Utica Shale could also play a role in the scenario in which Pennsylvania takes primacy over its underground injection program. The factors considered above, that could lead to a decrease in the probability that drilling operators in Pennsylvania would utilize Ohio injection wells, could also lead Pennsylvania to take primacy of its program if it wanted to instead encourage underground injection within its borders. Primacy would allow the state to permit more wells within a shorter period of time and adopt its own, more stringent regulations to prevent possible groundwater contamination. This scenario presents a counter solution to that presented in the second scenario (an alternative solution to the issues related to an increase in drilling activity in the Utica Shale in Ohio).

Based on relevant research and the goals of Pennsylvania at such a time as it may want to implement any of the findings presented in this thesis, policymakers can determine which disposal method(s) they want to promote and then use the findings of this thesis to decide on the best ways to encourage the use of said method(s). For example, current trends indicate that the level of natural gas drilling activity will continue to increase into the future and for recycling and reuse to be a viable option there needs to be a market for the treated water sourced from recycling facilities to be used in the fracing process, encouraging the use of existing and the development of new recycling and reuse facilities to dispose of/treat drilling wastewater. It therefore might make sense to encourage recycling and reuse in the short term, while the level of natural gas drilling activity continues to increase and the market for treated water for use in the fracing process is robust. Then, in the long term, it might make sense to encourage underground injection once the level of natural gas drilling activity, and thus the market for treated water for use in the fracing process, start to decline. As the level of natural gas drilling activity starts to decline, there will also be many inactive gas production wells that could potentially be used as underground injection wells.

The marginal effects indicate that the price and location of the disposal method have the largest impacts on the probability that a particular alternative will be chosen. Thus, policies that incentivize the price of recycling and reuse or encourage the location of recycling and reuse facilities central to the gas production wells that will utilize them will be most effective in influencing the use of this particular method. Then, to encourage the use of underground injection, Pennsylvania could take primacy of its underground injection program. Every indication seems to suggest that this could take some time, but, if recycling and reuse is encouraged in the short term, underground injection in Pennsylvania might not be needed as an alternative for many years. This would also allow the process of underground injection to improve, reducing the possibility of resulting water contamination.

Ultimately, this thesis seeks to have policymakers consider the information gleaned from the interpretation of the marginal effects, along with the implications of the presented scenarios, and utilize them to influence future policies in the state of Pennsylvania.

7.1. Suggestions for Future Research

Arik Levinson (1996) uses a conditional logit model to examine the effect of differences in the stringency of state environmental regulations on the location choice of manufacturers. The main implications of this particular article are the ways in which the environmental regulations can be quantified and applied within a conditional logit setting. It might be interesting to explore the differences in state regulations and policies (e.g. Pennsylvania vs. Ohio) and how they affect Marcellus Shale natural gas drilling operators' choice of wastewater disposal method. Section 1.3 details the recent PA DEP regulations that effectively prohibit municipal sewage treatment plants from accepting drilling wastewater, and Section 1.3.1 mentions that one of the factors that might be responsible for the difference in number of underground disposal wells between Pennsylvania and Ohio is whether the state has primacy. It would be interesting to develop variables that would represent these policy differences and then incorporate them into the mixed logit model. This way, the marginal effects of the regulatory differences can be quantified, thus demonstrating which policies are most effective in influencing the use of certain disposal methods.

This concept could also be applied to regulatory differences among the river basins in Pennsylvania. As the marginal effects of the river basin dummy variables indicate, there do exist systematic differences across the river basins that lead to differences in the probabilities that any of the three disposal methods will be chosen when a gas production well is located within one of four river basins. It would be interesting to develop variables that would better capture these differences and integrate them into the model. It would also be interesting to develop variables that capture differences across other boundaries, such as the PA DEP districts and municipalities, as well (as mentioned in Section 4.4).

The mixed logit model presented in this thesis explores the effect that quantitative variables, such as price and distance, have on the probabilities that different wastewater disposal methods will be chosen. Moving forward, it would be extremely interesting to incorporate non-market variables, such as those that represent regulatory stringency, into the mixed logit model in order to capture more of the factors that might influence natural gas drilling operators' choice of wastewater disposal method.

Taking this research a step further, it would be interesting to calculate not only the changes in the probabilities of choosing a particular alternative under the three scenarios presented above, but also the change in welfare of the drilling operators as a result of the change in probability. This would offer a monetary quantification of the changes, making them easier to interpret and compare across scenarios.

APPENDIX A

Preparing and Cleaning the Data Found in the PA DEP Waste Report

The original waste report was downloaded from the PA DEP Oil & Gas Reporting Website on May 23, 2012. This original data file was saved separately and can be accessed. A subsequent file was saved and then used to make the necessary changes as per the steps listed below. The final file was then also saved and can be accessed as well.

1. The July – December 2011 waste report was downloaded from the PA DEP Oil & Gas Reporting Website on May 23, 2012.
2. The "Brine" and "Frac Fluid" entries were separated out from the original data set to focus on wastewater.
3. The "Disposal Method" classifications "Landfill," "Municipal Sewage Treatment Plant," and "Not Determined" were excluded from the data set.
4. The "Disposal Method" classification "Reuse Other Than Road Spreading" includes both recycling and on-site treatment and reuse or dilution and reuse. The observations that include a Waste Facility Permit Number and/or an address can be identified as dedicated recycling facilities. The other observations are labeled as "Frac Water Reuse", "Reuse of Brine to Frac a Well", "Reused for UIC Class II", or "Reused in Drilling or Plugging Job" but they cannot be positively identified as either on-site treatment and reuse or dilution and reuse (the labels are not descriptive enough). For this reason, those observations that are not identified as dedicated recycling facilities were excluded from the data set.
5. Because many drilling operators mistakenly chose "Brine or Industrial Waste Treatment Plant" as the disposal method when they should have chosen either "Injection Disposal Well" or "Reuse Other Than Road Spreading." The Waste Facility Permit Number was examined in

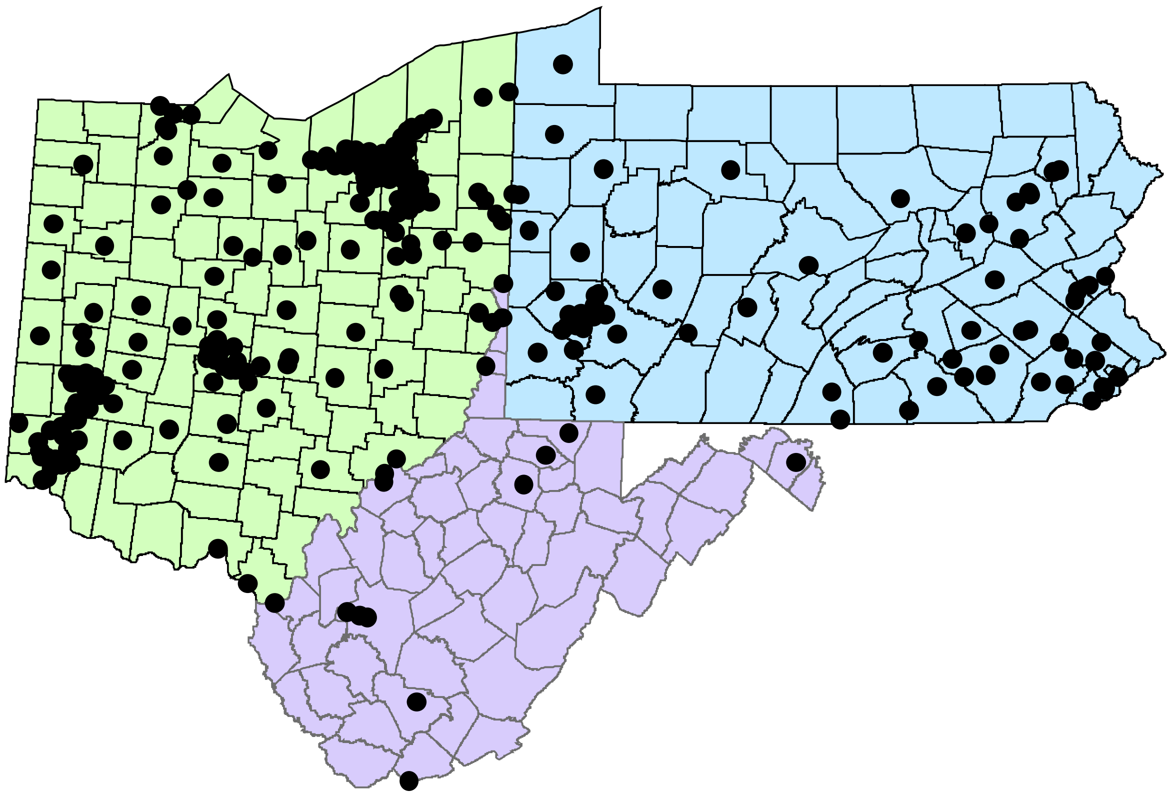
order to correct this error. The permit numbers that take the form xx-xxx-xxxxx are underground injection wells and those that take the form WMGR119NC001 or WMGR123NC001 are dedicated recycling facilities. If a Waste Facility Permit Number was not provided, the names of the waste facilities were examined. If the name itself did not give an indication as to the type of facility, the descriptions provided by the facilities' websites were examined in order to make the distinction. The "Disposal Method" classification was changed where necessary.

6. The data set ultimately included 2,933 observations.
7. Some of the waste facilities lacked latitude and longitude coordinates necessary for mapping in GIS. If a valid/complete street address was provided, a geocoding tool was used to convert the address to latitude and longitude coordinates. If a valid/complete street address was not provided, Christopher Tersine at the PA DEP and Tom Tomastik at the ODNR provided the missing coordinates.
8. The latitude and longitude coordinates of the gas production wells and the waste facilities were input into ArcMap 10 to determine the straight-line distance between each gas production well and the corresponding nearest disposal/treatment location of each type. These distances were added to the data set.
9. Several sources were used to determine the costs of the different disposal methods and these prices were added to the data set.
10. For each of the gas production wells, a count of the number of unique gas production wells operated by a particular drilling company is used as a proxy for the size of the company. These numbers were added to the data set.

11. For each of the gas production wells, a count of the number of other gas production wells within a 10-mile radius that utilize the same disposal method were used as a measure of competition. These numbers were added to the data set.
12. Data on the cities/villages/municipalities/boroughs in Pennsylvania, Ohio, and West Virginia with a population greater than 10,000 people were obtained from the U.S. Census Bureau. They were released on June 28, 2012, for the period April 1, 2012 through July 1, 2011. The latitude and longitude coordinates of these cities were input into ArcMap 10 to determine the straight-line distance between each gas production well and its nearest "large" city. These distances were added to the data set.
13. Dummy variables were included in the data set to indicate in which river basin a particular gas production well is located.
14. The variables were input into Stata 12 and then the "mixlogit" command was utilized to estimate a mixed logit model.
15. The coefficient estimates obtained as a result of the model estimation were used to calculate the marginal effects of each of the variables.

APPENDIX B

Map of Locations of "Large" Cities in Pennsylvania, Ohio, and West Virginia



APPENDIX C

Organizing the Data in Stata

According to Hole (2007), in order to be able to run the model in Stata, the data must be in long form – this means that there must be a separate observation that corresponds to each of the alternatives for each of the individuals. In this case, there will be three observations per drilling operator corresponding to each of the three possible disposal methods (brine, injection, reuse). Thus, there must be a dummy variable to indicate which of the three disposal methods was chosen by each operator. The three distance and price variables that were calculated for each gas production well will then be combined to form one distance and one price variable, respectively, as shown in the following example:

Short Form of the Data

Observation	Choice	dbrine	dinjection	dreuse	pbrine	pinjection	preuse
1	brine	5	30	15	6	2.2	4.62
2	injection	20	15	40	6	0.25	4.62
3	reuse	15	30	10	6	2	4.62

Long Form of the Data

Observation	Alternative	Choice	Distance	Price
1	brine	1	5	6
1	injection	0	30	2.2
1	reuse	0	15	4.62
2	brine	0	20	6
2	injection	1	15	0.25
2	reuse	0	40	4.62
3	brine	0	15	6
3	injection	0	30	2
3	reuse	1	10	4.62

APPENDIX D

Results from the Conditional Logit Model

	Wald chi2(14) =		726.04
	Prob > chi2 =		0.0000
	Log Likelihood =		-1377.0651
choice	**Coef.**	**Std. Err.**	
alternative			
dist	-0.0138	0.0016	*
price	0.3766	0.1254	*
c2size	0.0120	0.0026	*
c3size	0.0194	0.0027	*
c2comp	0.0629	0.0081	*
c3comp	0.0567	0.0082	*
c2citydist	-0.0131	0.0115	
c3citydist	0.0104	0.0124	
c2rb_mon	-1.9024	0.2267	*
c3rb_mon	-1.8772	0.2950	*
c2rb_ohio	-1.0655	0.3302	*
c3rb_ohio	-4.7687	0.5588	*
c2rb_sus	1.2775	0.3642	*
c3rb_sus	1.4878	0.3904	*
brine	(base alternative)		
injection			
cons	2.5501	0.6457	*
reuse			
cons	-0.8360	0.3839	**

***** significant at the 1% level, ** significant at the 5% level

In comparing the conditional logit model and the mixed logit model, a few significant differences are noted, the most glaring of which is that the coefficient of the price variable is positive (an irrational result) under the conditional logit model and negative (the expected and rational result) under the mixed logit model. Most of the coefficients have similar magnitudes between the two models, with the exception of the interaction between injection well and Susquehanna River Basin (it has a magnitude of 1.2775 under the conditional logit model and a magnitude of 0.3851 under the mixed logit model). The interaction variable between recycling and reuse and the "distance to nearest large city" (*c3citydist*) and the interaction variable between injection well and Susquehanna River Basin (*c2rb_sus*) are positive under the conditional logit model but negative under the mixed logit model. Also, under the conditional logit model, the two "distance to nearest large city" variables are not significant, the interaction variable between injection well and Susquehanna River Basin (*c2rb_sus*) is significant, and the interaction variable between recycling and reuse and Susquehanna River Basin (*c3rb_sus*) is less significant, whereas the converse is true under the mixed logit model. Unlike Christiadi and Cushing (2007), the two models are not qualitatively similar. This is an indication that the IIA assumption is incorrect.

As mentioned in Section 2.2, the conditional logit model relies on the assumption of IIA. According to Davies, Greenwood, and Li (2001), a Hausman specification test can be used to test for the validity of this assumption. Because the IIA assumption states that the ratio of the probabilities of choosing two of the alternatives does not depend on the probabilities of any of the other alternatives, the Hausman test is conducted by removing one alternative at a time from the choice set and reestimating the model. If the estimated coefficients from the restricted model are not significantly different from those from the full model then the IIA assumption holds. The test statistic is

$$\chi^2 = \left(b_r - b_f\right)'\left(V_r - V_f\right)^{-1}\left(b_r - b_f\right)$$

and is distributed χ^2 with *k* degrees of freedom, where *k* is the rank of $\left(V_r - V_f\right)$. The estimated coefficients from the restricted model are represented by b_r and the estimated coefficients from the full model are represented by b_f. V_r and V_f represent the estimates of the covariance matrices of the restricted and full models respectively.

In the case of the conditional logit model estimated in this thesis, the following is the result of the Hausman test that was conducted[33]:

	(b) reduced	B full	(b-B) difference	sqrt (diag(V_b-V_B)) S.E.
alternative				
d	0.0179	-0.0138	0.0316	0.0077
p	-0.6394	0.3766	-1.0161	0.3018
c2size	0.0173	0.0120	0.0053	0.0017
c2comp	0.0910	0.0629	0.0281	0.0065
c2citydist	0.0224	-0.0131	0.0355	0.0066
c2rb_mon	-2.0551	-1.9024	-0.1526	0.4333
c2rb_ohio	0.4516	-1.0655	1.5171	0.3778
c2rb_sus	1.3009	1.2775	0.0234	0.1611
injection				
cons	-4.2860	2.5501	-6.8361	1.5656

b = consistent under Ho and Ha

B = inconsistent under Ha, efficient under Ho

Test: Ho: difference in coefficients not systematic

$$\chi^2_9 = (b - B)'(V_b - V_B)^{-1}(b - B) = 113.72$$

Prob > χ^2 = 0.0000

($V_b - V_B$ is not positive definite)

Thus the hypothesis that there is no systematic difference in the coefficients is rejected and the IIA assumption does not hold. For this reason, a mixed logit model was used in this thesis.

[33] This test was conducted by removing the reuse alternative from the choice set. When each of the other alternatives (brine and injection) was removed and the model was reestimated, the model failed to converge.

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