Risk Assessment of Groundwater Contamination from Hydraulic Fracturing Fluid Spills in Pennsylvania

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ABSTRACT

Fast-paced growth in natural gas production in the Marcellus Shale has fueled intense debate over the risk of groundwater contamination from hydraulic fracturing and the shale gas extraction process at large. While several notable incidents of groundwater contamination near shale gas wells have been investigated, the exact causes are uncertain and widely disputed.

One of the most frequently occurring and widely reported environmental incidents from shale gas development is that of surface spills. Several million gallons of fluid are managed on each well site; significant risk for spill exists at several stages in the extraction process. While surface spills have been primarily analyzed from the perspective of surface water contamination, spills also have the potential to infiltrate groundwater aquifers.

This thesis develops a risk assessment framework to analyze the risk of groundwater resource contamination in Pennsylvania from surface spills of hydraulic fracturing fluid. It first identifies the major sources of spills and characterizes the expected frequency and volume distribution of spills from these sources using results from a preliminary expert elicitation. It then develops a stochastic groundwater contaminant transport model to analyze the worst-case potential for groundwater contamination in local water wells. Finally, it discusses the range of risk perception and incentives from a wide-ranging stakeholder base, including industry, communities, environmentalists, and government. This thesis concludes that while the vast majority of shale gas operations do not result in large spills, the worst-case potential for groundwater contamination is high enough to warrant further attention; it also recommends increased inclusion of community stakeholders in both industry and government risk management strategies.

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Chapter 1: Introduction

1.1 Problem introduction

The emergence of shale gas as a major source of U.S. natural gas production has fueled widespread debate on the role of natural gas in the future of energy. While increased use of natural gas has the potential to create significant benefits for national security, the economy, and the climate, concerns about the environmental and water impacts of the extraction processes remain. The nature and severity of these concerns are hotly contested.

While domestic shale gas development began over a century ago, recent advancements in hydraulic fracturing technology have driven explosive growth in domestic production over the past decade. In 2000, shale produced 0.1 trillion cubic feet (Tcf) of natural gas, less than 1% of U.S. natural gas production. By 2009, shale output grew to 3.0 Tcf annually, almost 14% of domestic gas supply (MIT, 2011). Indeed, this increase in economically recoverable reserves has the potential to fundamentally change the energy mix of the future; it is widely stated that U.S. reserves have the potential to supply "100 years" of domestic energy consumption.

Natural gas plays an important role in our energy system today, supplying approximately a quarter of primary energy consumption within the United States (U.S. EIA, 2011). Natural gas consumption is pervasive across multiple sectors of the economy, providing energy for electric power generation, industrial production, and residential and commercial direct-use. The potential benefits of natural gas as a major resource in our energy future include improved national security as the result of a reliable, domestic source of energy as well as reduction in greenhouse gas (GHG) emissions by decreasing the use coal in electricity production. Additionally, natural gas may play an important role in reliably integrating intermittent renewable resources such as wind and solar into the electric power system at large scale.

Discussion surrounding the challenges and potential pitfalls of shale gas has been widespread. Uncertainty regarding the amount of economically recoverable reserves and opportunities for financial speculation launched an investigation by the U.S. Securities and Exchange Commission (Solomon, 2011). In recent months, major domestic gas producers have announced plans to significantly slow production as the result of oversupply (Gilbert & Dezember, 2012). Additionally, while natural gas is widely shown to have a lower lifecycle GHG footprint than oil or coal, there has been recent debate about the role of methane leakage from shale gas operations in overall global warming potential (Cathles, Brown, Taam, & Hunter, 2012; Howarth, Santoro, & Ingraffea, 2011).

Perhaps the most widely and heatedly discussed topic in the shale gas debate has been the risk of environmental and community impacts from the shale gas extraction process. While the majority of the growth in shale gas production in the past decade has been from production in the Barnett shale in Texas and other shales in the southwest, significant production activity has grown in the Marcellus shale in Appalachia since the end of 2009; nearly 1,500 wells were drilled in Pennsylvania in 2010 (PA DEP, 2011, MIT, 2011). Shale gas production activity in Pennsylvania often occurs in populated areas that have not previously been the site of significant oil and gas drilling operations.

Communities in the middle of this activity are affected in a variety of ways. The increased economic activity can lead to job creation and other benefits for the community. Likewise, the discovery of mineral rights increases property value to landowners. However, operations can also pose negative community impacts. Major community impacts have included heavy truck traffic leading to road damage and high noise levels from drilling. The primary environmental risks include water contamination from fracturing fluid and methane gas, hazardous air emissions from on-site chemicals, and excessive water withdrawals.

Of these various impacts, the focus of this thesis is the risk of water contamination. There are several exposure pathways in which fracturing fluid, drilling fluid or natural gas could contaminate water wells. The analysis presented here focuses on the risk of surface spills of fracturing fluid and flowback water. Several million gallons of fluid are managed on each well site; significant risk for spill exists at several stages in the extraction process. Indeed, one third of the widely-reported incidents involving gas well drilling between 2001 and 2010 involved surface spills (MIT, 2011). If spilled fluid is not recovered, it has the potential to either runoff into local surface water or infiltrate the ground and enter the groundwater system.

Significant technical analysis is needed to assess the risk from surface spills; however, the development of a legitimate risk management strategy additionally requires an understanding of the complex social, economic and political perspectives of a variety of stakeholders. Industry players are wide ranging in management practice, transparency of operation, and safety-culture in the face of powerful and complex economic incentives. Mass media attention has been pervasive and often highly polarized; information is presented to the public by a variety of stakeholder groups ranging from natural gas trade organizations to environmental NGOs. Indeed, public perception of shale gas extraction in these communities varies widely; local attitudes can be polarized (Brasier, 2010).The regulatory scheme, a complex mixture of federal, state, and municipal policy, is highly politicized and rapidly changing. Finally, the science underlying water contamination and public health is characterized by high levels of uncertainty.

1.2 Research questions and goals

The focus of this thesis is water contamination risk from fracturing fluid spills at shale gas extraction sites in the Marcellus shale in Pennsylvania. This is just one pathway through which fracturing fluid can contaminate a water well. This pathway has two components that must be addressed in order to assess the overall risk: the spill of fracturing fluid at the well site, and the fate and transport of the fluid in groundwater. As such, this thesis is guided by two central research questions:

1) What is the expected frequency and volume of fracturing fluid spills at shale gas well sites in Pennsylvania?

2) What is the potential for fracturing fluid spills to contaminate groundwater resources?

The objective is both methodological and results-driven: I aim to develop a risk assessment framework appropriate to address the above questions, and also to present some findings.

While the results of the technical risk assessment described above are critical to developing a risk management strategy, a credible and effective strategy must also take into consideration the concerns of relevant industry and community stakeholders. This leads to a final research question:

3) What factors should be considered in developing an effective risk management strategy for water contamination from fracturing fluid spills?

1.3 Structure and approach

This thesis is divided into four major sections. Part I provides an overview of the shale gas extraction process, focusing primarily on fluid management in order to identify the major opportunities for surface spills at the well-site. It then presents an overview of the relevant risk assessment tools, drawing from the probabilistic risk assessment, environmental risk assessment and risk perception literatures. The final outcome is the development of a risk assessment framework for analyzing the impact of fracturing fluid spills.

The second and third parts of the thesis comprise the technical analysis of groundwater contamination risk from fracturing fluid spills. Part II focuses on characterizing the likelihood and volume of fracturing fluid spills in Pennsylvania. Because necessary data is sparse and uncertain, expert elicitation is presented as a methodology for characterizing this risk. Preliminary results from an elicitation study are presented.

Part III develops a stochastic groundwater contaminant transport model to assess the potential of fracturing fluid spills to contaminate water wells. The model is applied to four hydrogeological scenarios representative of typical groundwater aquifers in Pennsylvania. Monte Carlo simulation, as well as a series of scenario and sensitivity analysis, is used to assess the range of possible transport outcomes.

Part IV discusses the development of an effective and credible risk management strategy to address fracturing fluid spills. It identifies a wide-ranging stakeholder base and analyses the varying risk perceptions and incentives of several stakeholder groups. Finally, it draws conclusions and makes recommendations for risk management based on the analyses presented in this thesis.

Chapter 2: Shale gas extraction in Pennsylvania

2.1 Shale gas extraction overview

2.1.1 Shale gas and hydraulic fracturing technology

Shale is a type of sedimentary rock that acts as both the source and reservoir for some natural gas deposits. Unlike conventional natural gas reservoirs, shale gas reservoirs are charcterized by low permeability. This means that the pore space in the rock is not well connected, so that natural gas does not flow readily. When a well is drilled into a conventional natural gas reservoir, natural gas flows readily up through the well. This is not the case in a shale gas reservoir; extra stimulation is required in order to extract the natural gas. As a result, economical natural gas extraction from shale is not possible without the use of hydraulic fracturing.

Hydraulic fracturing is a process in which large volumes of water are mixed with a proppant, usually sand, and chemical additives are injected at high pressure into shale rock. The high pressrue creates fractures in the rock, which are held open by the proppant. These fractures allow the natural gas in the shale to flow more easily to the surfrace. The development of horizontal drilling techniques allows hydraulic fracturing to be performed legnthwise along the shale formation, increasing the number of useful fractures; this technique has dramatically increased the amount of domestic economically recoverable reserves. A schematic of a horiztonal shale gas well is presented in Figure 1. The hyrdaulic fracturing process occurs in the production zone, depicted in grey at the bottom of the figure.

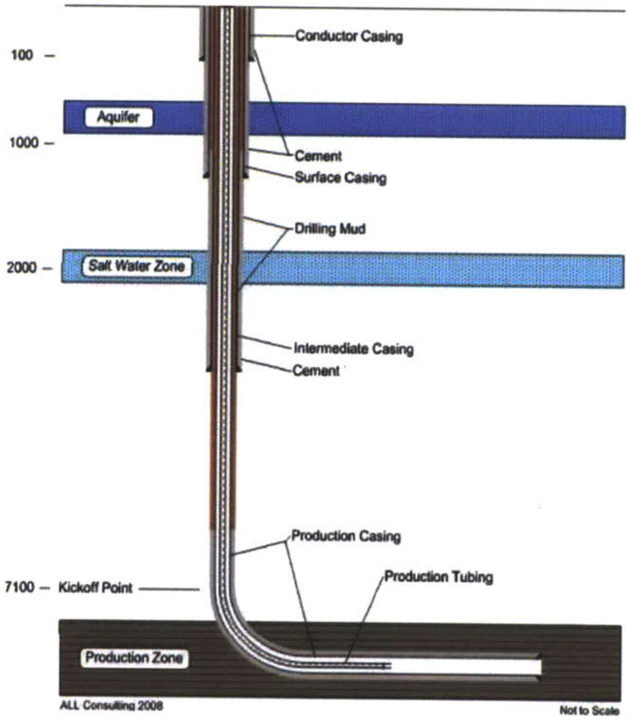

Figure 1: Diagram of typical shale gas well (not to scale). Source: (Groundwater Protection Council & ALL Consulting, 2009)

Because of the low permeability of shale rock and the need for hydraulic fracutring, shale gas wells often need to be spaced much more closely together than conventional gas or oil wells. This requires more drilling activity in areas that are unfamiliar with oil and gas production activity. However, the advancement of horizontal drilling has mitigated this problem. Drilling and fracturing takes place at a well pad, an area of land a few acres in size which is cleared to hold all the necessary extraction equipment. Using horizontal drilling techniques, as many as ten wells can be drilled on the same well pad. The vertical portion of the wells are drilled very close together; the horizontal sections then extend outward in different directions, chosen according to the stress pattern in the shale. A typical well pad might have horizontal wells layed out in a similar pattern to the diagram in Figure 2. In a ten-square mile area, vertical drilling techniques from a single pad could require up to 160 3-acre pads, disturbing a total of 480 acres of land. In contrast, horizontal drilling at multi-well sites would require only 10 5-acre pads, disturbing a total of 50 acres (NY SGEIS, 2009).

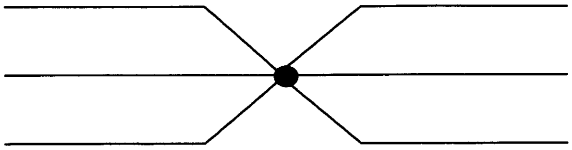

Figure 2: Schematic of horizontal well layout in a typical multi-well pad. The dot in the center is where the above-ground wellheads are located; the surrounding branches are the paths of the horizontal wells underground. Reproduced from (NY SGEIS, 2009).

Another unique characteristic of shale gas development in contrast to conventional gas production is the need for large volumes of fluid on the well site. The hydraulic fracturing process requires between 3 million and 5 million gallons of fluid. This fluid, a combination of water and chemical addditives, must be trucked to the well pad and properly mangaed on site. Similarly, a signifcant portion of the injected fluid returns back up the well; this waste fluid must be trucked off site and disposed.

2.1.2 Shale gas development in Pennsylvania

While the majority of shale gas development in the United States to date has taken place in the Barnett Shale in Texas and other shale plays in the southwest, the Marcellus Shale in the Appalachain basin has seen significant growth since 2009. Nearly 1,500 wells were drilled in Pennsylvania in 2010 and nearly 2,000 wells were drilled in 2011 (PA DEP, 2011). Drilling activity is geographically distributed throughout the state; both the northeast corner and southwest corner are drilling hotspots. Figure 3 shows the number of gas wells drilled throughout the state by county in 2011.

Much of this drilling activity occurs in areas not used to major oil and gas activity; many of these areas inlcude well-populated communities. Because conventional natural gas and oil reservoirs are not abundant in the state, little drilling activity took place before 2008. This has several important implications that make operations in Pennsylvania unique from those in Texas. First, there are limitiations in infrasturcture. Injection wells are widely used in Texas to dispose of waste fluid; no injection wells are available for fluid disposal in Pennsylvania. Likewise, the pipeline infrastrucutre necessary to transport natural gas has not previously been built; substantial pipeline construction has been necessary as drilling growth has continued. Similarly, the roads in many parts of the state were not built to withstand the heavy truck traffic necessary to transport the sand, chemicals and fluid needed. (National Park Service, 2009). Moreover, communities in the area are not familiar with the impacts of drilling. Public perpcetion studies in the region demonstrate that communities in and near development areas have mixed views about shale gas extraction, ranging from strongly negative, to neutral, to strongly positive (Brasier, 2010).

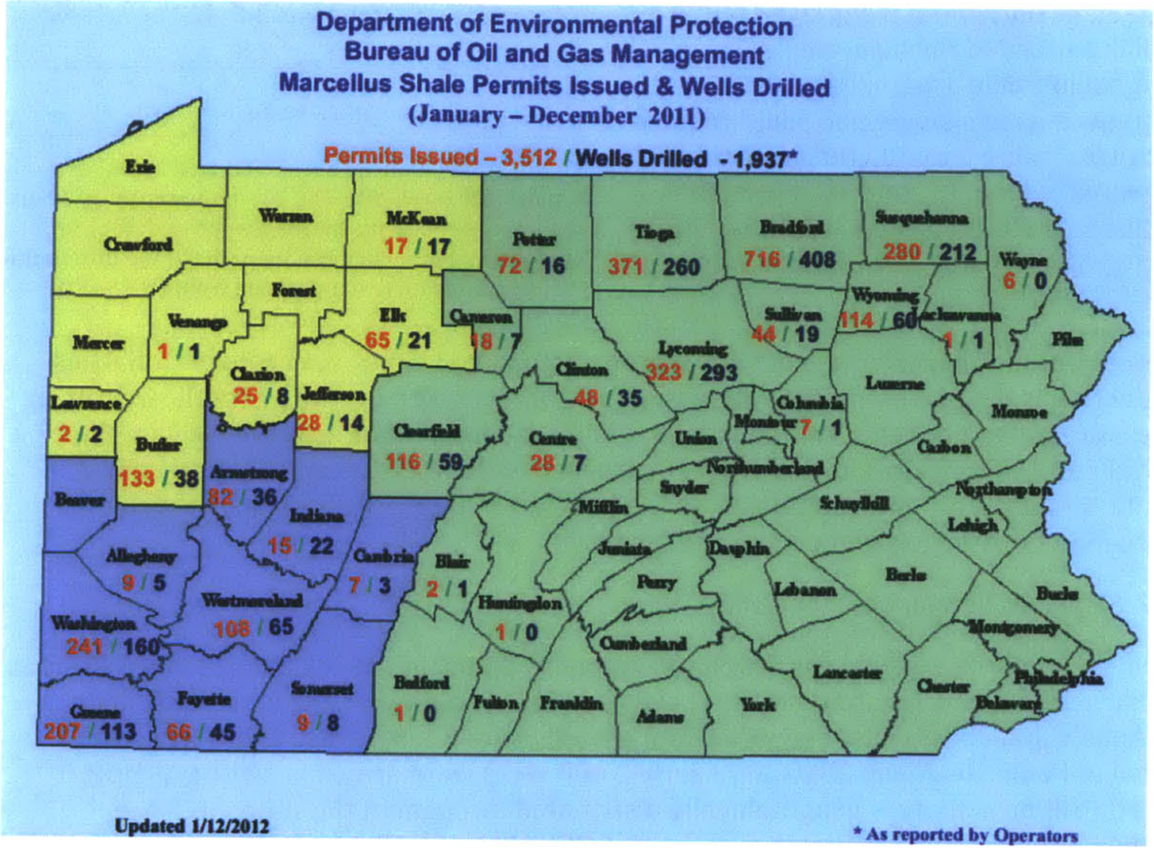

Figure 3: Wells drilled in the Marcellus Shale in Pennsylvania in 2011. Source: PA DEP.

2.1.3 Environmental and community impacts

The rapid growth of drilling activity in Pennsylvania has raised concerns about a number of community and environmental impacts. The major impacts and risks cited widely in the literature include:[1]

- *Noise.* Noise pollution from drilling operations and transportation activities can disturb local communities.
- *Road use.* Each gas well requires between 320 and 1,365 truckloads of fluid and equipment (National Park Service, 2009). Rural roads in Pennsylvania are often not equipped to handle this kind of large truck traffic and suffer damage as a result.
- *Excessive water withdrawals.* Each shale gas well requires between 3 million and 5 million gallons of fluid in order to complete the hydraulic fracturing process. The annual water withdrawals for shale gas operations in the Marcellus are a small fraction of the water withdrawn for industrial uses and public supply (Groundwater Protection Council & ALL Consulting, 2009). However, the necessary water is

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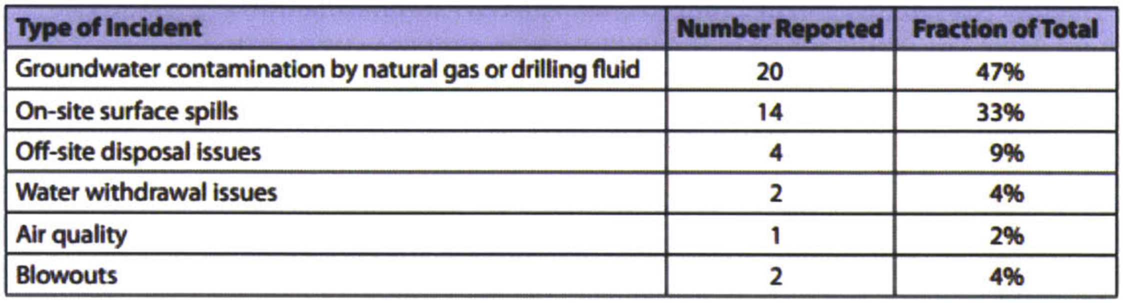
[1] The sources used to compile this list are: (Groundwater Protection Council & ALL Consulting, 2009), (National Park Service, 2009), (MIT, 2011) and (*NY DEC*, 2009).

withdrawn over a short time period; a few million gallons may be large relative to the amount withdraw over the course of a week. This increase in water withdrawal can pose a risk to water-stressed regions.

- *Air pollution.* The extraction process has significant potential to produce both GHG emissions and air pollutants. The potential GHG emissions from methane leakage are widely-debated. Diesel engines used on site and heavy truck traffic contribute to both GHG emissions and local air pollution. Retaining pits that expose wastewater with chemical additives to the open air also impact local air quality.
- *Surface water contamination.* Drilling and fracturing fluids can contaminate surface water from surface spills or improper wastewater disposal.
- *Groundwater contamination.* There have been several major reports of groundwater contamination from drilling and fracturing fluids and methane gas resulting from shale gas extraction operations (MIT, 2011). Poor drilling and well cementing in the shallow zones can lead to subsurface leaks that contaminate aquifers. This thesis assesses the potential for surface spills of fracturing fluid to contaminate groundwater resources.

The Future of Natural Gas study from MIT (2011) identified 43 "widely reported incidents" from shale gas operations between 2001 and 2010; these were identified by reviewing reports that assessed drilling-related incidents. While these incidents are not comprehensive of all the risks, they are a good representation of the types of incidents that have caused significant concern for communities. Of the major incidents, one third is surface spills, suggesting that major spills are a potentially significant risk from operation.



Type of Incident	Number Reported	Fraction of Total
Groundwater contamination by natural gas or drilling fluid	20	47%
On-site surface spills	14	33%
Off-site disposal issues	4	9%
Water withdrawal issues	2	4%
Air quality	1	2%
Blowouts	2	4%

Figure 4: "Widely reported incidents involving gas well drilling," 2001-2010. Source: (MIT, 2011).

2.1.4 Development and extraction process

Many steps are required to place a shale gas well into production. The major steps and their relative durations are as follows (Ground Water Protection Council, 2009; MIT, 2011):

1. *Mineral leasing.* Mineral owners, often private landowners in Pennsylvania, must grant production companies the right to develop. *Time: weeks to years.*
2. *Permitting.* Production companies must obtain a state permit in order to drill a well. The permitting authority in Pennsylvania is the Department of Environmental Protection (DEP). *Time: weeks to months.*

3. *Well site construction.* Access roads must be constructed and a few acres of land cleared. Often, retaining pits are excavated. *Time: days to weeks.*
4. *Drilling.* As the well is drilled, several layers of casing are set and cemented. These layers are depicted in Figure 1 above. *Time: weeks or months.*
5. *Hydraulic fracturing.* The horizontal portion of the well is perforated and the shale rock is fractured using fracturing fluid pumped at high pressures. This is usually performed in multiple stages. The fluid must then be flowed back out of the well. *Time: days.*
6. *Production.* The well is placed into production, and the natural gas is treated and sent to market. Excess equipment is taken off site. *Time: years.*
7. *Workovers.* Cleaning, reparation and maintenance of the well may be performed in order to improve the performance of the well. *Time: days to weeks.*
8. *Plugging, Abandonment and Reclamation.* After the well stops producing at an economic rate, it must be plugged and abandoned by Pennsylvania standards. The well pad and access road area is reclaimed. *Time: weeks.*

2.1.5 Fluid management

Each gas well requires between 3 million gallons and 5 million gallons of fluid for the hydraulic fracturing process. The fluid components are transported to the well pad by truck, stored on site, and mixed to create drilling fluid and fracturing fluid. Waste fluid from drilling and hydraulic fracturing may be recycled on site and is eventually transported offsite by truck for treatment and disposal.

Figure 7 below is a photograph of a typical well pad; the captions identify the common equipment used. The major stages in the fluid management process at a shale gas well are as follows:[2]

- *Truck transportation.* First, freshwater, sand and chemical additives are brought by truck to the well pad. See Figure 6 for a photograph of typical trucks used to transport water and acid.
- *Fluid storage.* Freshwater, or recycled water if previous fracturing jobs have been performed on the well pad, is stored in an open-air impoundment; see Figure 5 for a photograph of a freshwater impoundment. Chemicals are stored on trucks and sand is stored in tanks (see captions in Figure 7).
- *Blending.* Just before hydraulic fracturing begins, the freshwater and chemical additives are transferred by pipe to a blender, mounted on a truck, where they are mixed with sand to form fracturing fluid. Pumps attached to the blender then immediately send the fluid to the wellhead for fracturing; fracturing fluid is not stored (see blender trucks and pumps in Figure 7).
- *Hydraulic fracturing.* Fracturing fluid is pumped at high pressure down the cemented, cased wellbore.
- *Fluid return.* When pressure is released from the well, a large of volume fluid returns back up the well; this is known as flowback water. Additionally, some fluid returns mixed with gas after the well is placed into production over the course of a few

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[2] This description was compiled using (NY SGEIS, 2009) and personal correspondence with industry experts.

weeks; this is known as produced water. According to reports from wells in northern Pennsylvania, between 9% and 35% of the fluid pumped down the well returns (NY SGEIS, 2009).

- *Produced water storage.* Flowback water is often stored in lined pits similar to the freshwater impoundments shown in Figure 5. Produced water is stored in tanks after it has been separated from produced natural gas. As the result of problems with fluid spills from pits, many operators are also beginning to store flowback water in tanks instead of pits.
- *On-site water treatment.* Some operators treat wastewater on site in order to reuse it in future hydraulic fracturing jobs. On-site treatment removes enough of the dissolved solids and metals to reuse in fracturing, but does not treat it for final disposal.
- *Transportation off-site.* Wastewater is removed from site by truck for treatment and disposal.
- *Treatment and disposal.* Wastewater is treated at an offsite wastewater treatment plant and disposed.

Figure 5: Photograph of a freshwater open-air impoundment. Source: (NY SGEIS, 2009).

Figure 6: Transportation trucks for water (top) and acid (below). Source: (NY SGEIS, 2009).

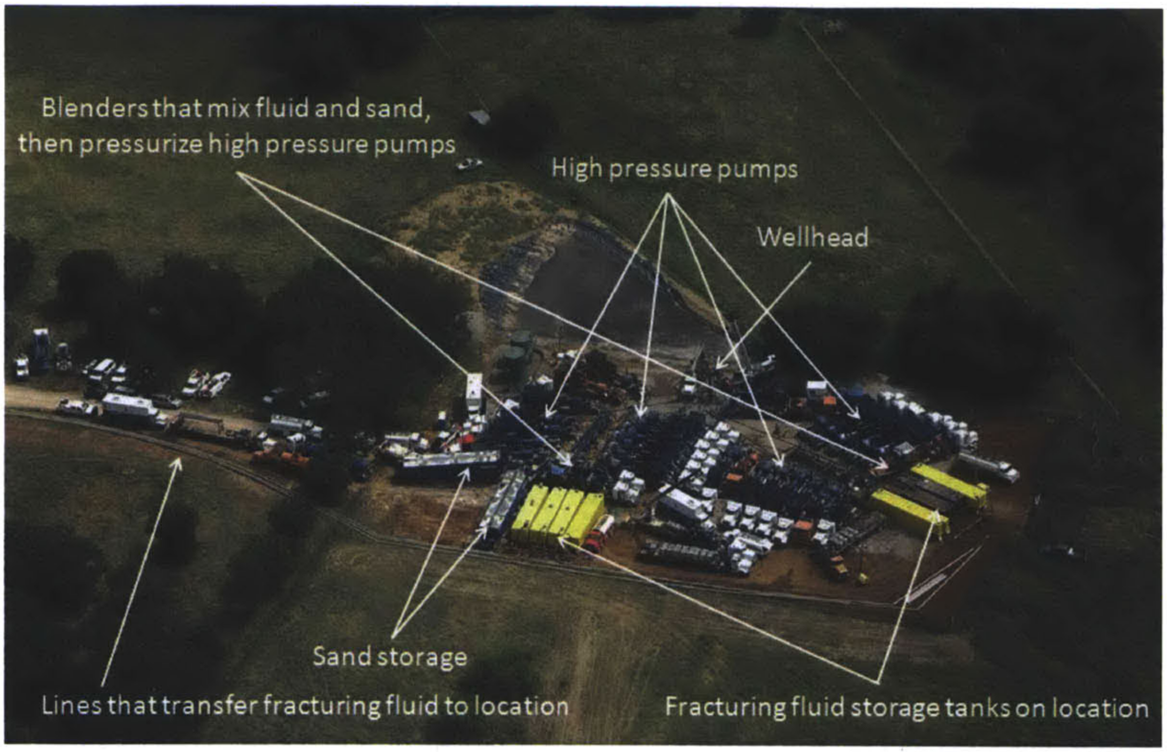


Figure 7: Photograph of a well pad. Courtesy of Schlumberger.

The management of such large volumes of fluid requires great care and presents several opportunities for spills to occur. There are six types of fluids that have the potential to be spilled on the well site. These fluids, and the stages in the development process at which they could be spilled, are summarized below:

- *Freshwater.* Freshwater is trucked in and stored in large open-air impoundments before it is mixed with sand and chemical additives. A freshwater spill would pose no risk to the environment.
- *Chemical additives.* Because chemical additives are trucked to site separately before they are added to the fracturing fluid, chemical spills can happen before fracture fluid is blended.
- *Drilling mud.* Vertical and horizontal wells are drilled using special muds as a drilling fluid. While most drilling mud is water-based, drilling mud for horizontal wells can also be polymer-based or synthetic oil-based (NY SGEIS, 2009). Drilling mud can be spilled before it enters the well, during drilling, or after it returns as waste.
- *Fracturing fluid.* Fracturing fluid, comprised of water, sand and chemical additives, can be spilled after it is mixed on site, on its way to the well-head for fracturing, or during hydraulic fracturing.
- *Produced water.* After the well is fractured, produced water comes back up the well. This fluid is a combination of fracturing fluid, solids and metals mobilized from the shale formation, and any new compounds resulting from chemical reactions (NY

SGEIS, 2009). Produced water can be spilled as it returns from the well, during transportation by pipes or hoses to a retaining pit or tank, or from leaks or overflows in retaining pits or tanks.

- *Recycled water.* Produced water is sometimes treated on site and reused in subsequent fractures. Recycled water may still contain chemical additives used in fracturing fluid. Recycled water replaces freshwater in the extraction process, and can be spilled similarly.

The analysis in this thesis focuses on fracturing fluid and produced water; these two categories have the greatest potential for large volume spills containing contaminants. The composition of these fluids is discussed in greater detail below.

Typically, about 90% of fracturing fluid is water and 8% is sand. The sand acts as a "proppant" to hold fractures in the shale rock open to allow gas to flow. Chemical additives typically comprise less than 2% of the total fracturing fluid by mass. They are necessary to ensure effective fracturing takes place; chemical additives both ensure that corrosion, rust, bacteria and precipitates do not build up in the well and also optimize the viscosity of the fluid suspending the proppant (NY SGEIS, 2009). Figure 9 below, reproduced from (NY SGEIS, 2009), describes the main types of additives used in fracturing fluid and their purpose in the hydraulic fracturing process.
Figure 8 depicts the relative concentration of these additives in the fluid as a whole.

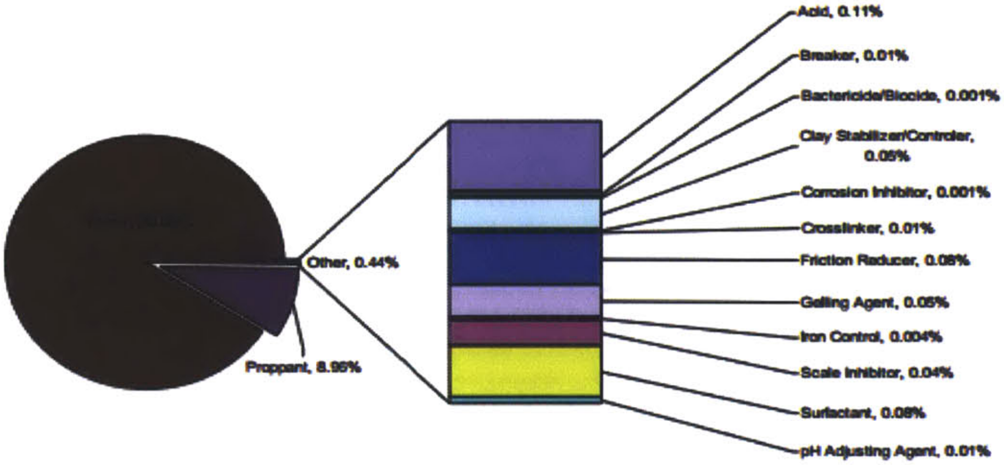
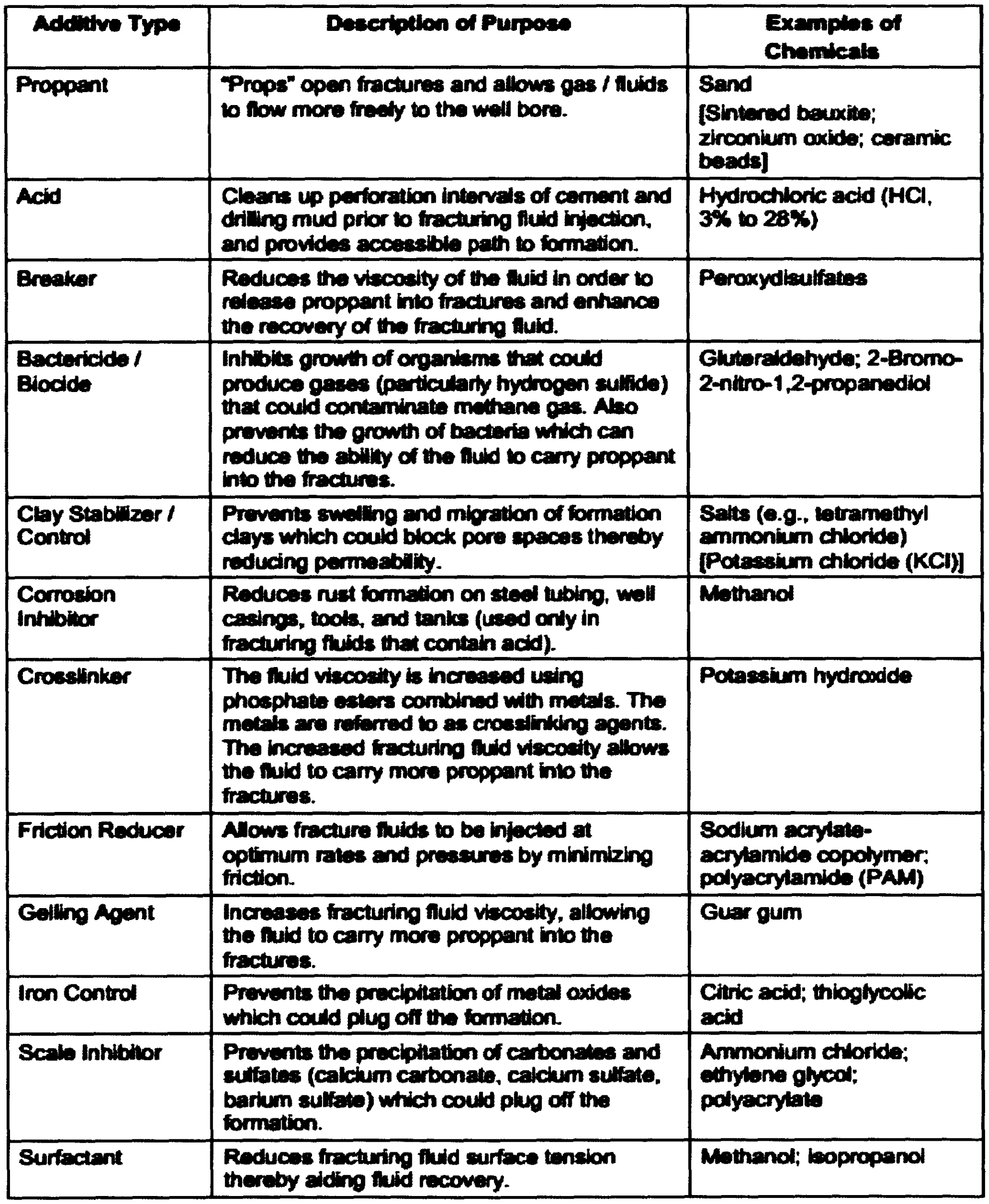


Figure 8: Typical fracturing fluid composition, by weight. Source: (NY SGEIS, 2009).

Produced water varies more greatly in composition; it is a combination of the engineered fracturing fluid and also components from the shale formation. As such, it varies greatly depending on the geology of the particular formation. (NY SGEIS, 2009) compiled produced water composition analysis from several production companies and service providers in Pennsylvania. The major categories of components were found to be (NY SGEIS, 2009):

- Dissolved solids: chlorides, sulfates, calcium
- Metals: calcium, magnesium, barium, strontium

- Suspended solids
- Mineral scales: calcium carbonate, barium sulfate
- Bacteria
- Friction reducers
- Iron solids
- Dispersed clay
- Acid gases: carbon dioxide, hydrogen sulfate



Additive Type	Description of Purpose	Examples of Chemicals
Proppant	"Props" open fractures and allows gas / fluids to flow more freely to the well bore.	Sand [Sintered bauxite; zirconium oxide; ceramic beads]
Acid	Cleans up perforation intervals of cement and drilling mud prior to fracturing fluid injection, and provides accessible path to formation.	Hydrochloric acid (HCl, 3% to 28%)
Breaker	Reduces the viscosity of the fluid in order to release proppant into fractures and enhance the recovery of the fracturing fluid.	Peroxydisulfates
Bactericide / Biocide	Inhibits growth of organisms that could produce gases (particularly hydrogen sulfide) that could contaminate methane gas. Also prevents the growth of bacteria which can reduce the ability of the fluid to carry proppant into the fractures.	Gluteraldehyde; 2-Bromo-2-nitro-1,2-propanediol
Clay Stabilizer / Control	Prevents swelling and migration of formation clays which could block pore spaces thereby reducing permeability.	Salts (e.g., tetramethyl ammonium chloride) [Potassium chloride (KCl)]
Corrosion Inhibitor	Reduces rust formation on steel tubing, well casings, tools, and tanks (used only in fracturing fluids that contain acid).	Methanol
Crosslinker	The fluid viscosity is increased using phosphate esters combined with metals. The metals are referred to as crosslinking agents. The increased fracturing fluid viscosity allows the fluid to carry more proppant into the fractures.	Potassium hydroxide
Friction Reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimizing friction.	Sodium acrylate-acrylamide copolymer; polyacrylamide (PAM)
Gelling Agent	Increases fracturing fluid viscosity, allowing the fluid to carry more proppant into the fractures.	Guar gum
Iron Control	Prevents the precipitation of metal oxides which could plug off the formation.	Citric acid; thioglycolic acid
Scale Inhibitor	Prevents the precipitation of carbonates and sulfates (calcium carbonate, calcium sulfate, barium sulfate) which could plug off the formation.	Ammonium chloride; ethylene glycol; polyacrylate
Surfactant	Reduces fracturing fluid surface tension thereby aiding fluid recovery.	Methanol; isopropanol

Figure 9: Typical chemical additives in hydraulic fracturing fluid. Reproduced from (NY SGEIS, 2009).

2.2 Regulatory framework

The shale gas extraction process in Pennsylvania is governed by a combination of federal and state laws and regulations. When analyzing the relationships between federal and state policy, it is important to understand the concept of primacy. Federal authority to regulate the oil and gas industry comes from federal statute; federal regulations required by federal statute are implemented by federal agencies. When it designs a regulatory program, a federal agency can either execute the program itself or in some cases give states the option of primacy, in which the state develops and implements a regulatory program instead. In general, state regulations must be as stringent as federal law requires and can be more stringent if the state desires. State legislatures can also pass state statutes, which grant state agencies the right to develop regulation.

The primary federal agency responsible for regulating environmental standards for the oil and gas industry is the U.S. Environmental Protection Agency (U.S. EPA). The U.S. Department of Transportation (U.S. DOT) regulates transportation-related activities for the oil and gas industry. In Pennsylvania, the primary state regulatory agency in charge of the oil and gas industry is the Pennsylvania Department of Environmental Protection (PA DEP).

2.2.1 Federal statute

Federal authority to regulate fluid management in the oil and gas industry comes from a few federal statutes: the Clean Water Act (CWA); the Safe Water Drinking Act (SWDA); the Oil Pollution Act (OPA) of 1990; the Resource Conservation and Recovery Act (RCRA); the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA, also known as the Superfund Act); and the Emergency Planning and Community Right to Know Act (EPCRA).[3]

The Clean Water Act regulates fluid discharge from point sources such as pipes into surface water and also storm water runoff. In order to discharge wastewater into a waterway, a shale gas operator must obtain a National Pollutant Discharge Elimination System (NPDES) permit. U.S. EPA sets effluent limits that require a minimum water quality threshold for discharge. PA DEP has primal authority to implement the program and approve permits for the oil and gas industry in Pennsylvania. CWA also contains an NPDES permitting provision for stormwater runoff from industrial and construction sites; however, a broad exemption is granted for the oil and gas industry. Instead, Pennsylvania state statute gives PA DEP authority to implement an NPDES permitting provision for stormwater.

The Safe Water Drinking Act sets health-based standards for drinking water and also developed the Underground Injection Control (UIC) program which regulates injection of fluids from shale gas operations underground. While "Class II" injection wells include most types of underground fluid injection in the oil and gas industry, fracturing fluid has a statutory exemption; it cannot be regulated by U.S. EPA under the UIC program. PA DEP

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[3] In addition to the statutes themselves, I used the following sources to compile this summary: (Nicholas A. Ashford & Caldart, 2008), (Groundwater Protection Council & ALL Consulting, 2009), (Marcellus Shale Advisory Commission, 2011), (State Review of Oil and Natural Gas Environmental Regulations Inc. (STRONGER), 2010), (Natural Resources Defense Council, n.d.).

does not have primacy for the UIC; it is instead implemented by U.S. EPA. Seven Class II underground injection wells, including one commercial well, are currently operational in Pennsylvania (STRONGER, 2010).

The Oil Pollution Act governs spill preparedness in the oil and gas industry. It places requirements for spill prevention, spill reporting, and spill response planning on regulated oil and gas operations. The key requirement is the development of a Spill Prevention, Control and Countermeasure (SPCC) plan. However, while SPCC planning is widely required for onshore oil production operations, it is not applicable to most shale gas operations; the Act targets spills of petroleum products specifically. As an alternative, PA DEP implements spill prevention, reporting and response requirements (discussed below) under state statutory authority from the PA Oil and Gas Act.

RCRA and CERCLA are the federal statutory basis for the prevention, management, and cleanup of solid and hazardous waste; however, the oil and gas industry has exemptions from many of the important provisions. RCRA developed a program for the management of solid waste and hazardous waste. Subtitle C of RCRA created a "cradle-to-grave" system for the management of hazardous waste with comprehensive reporting and permitting requirements for the transportation, treatment, storage and disposal of hazardous waste. This system has dramatically improved the handling of hazardous waste in industry by effectively creating a tax on hazardous waste (Ashford & Caldart, 2008). Wastes from oil and gas exploration and production, however, are exempt from hazardous waste regulation under Subtitle C. Oil and gas wastes could instead be regulated under the significantly less stringent RCRA subtitle D requirements for solid waste, or under authority from state statute. Indeed, PA DEP regulates solid and hazardous waste under the PA Solid Waste Management Act.

CERCLA, the Superfund Act, created a fund for the cleanup of spills of hazardous waste. It also requires notification of the National Response Center whenever a regulated hazardous substance is spilled in an amount above the reportable quantity and creates strict liability provisions for responsible parties. However, section 101(14) exempts petroleum and natural gas products from the definition of hazardous waste. Some hazardous materials on site, such as hydrochloric acid, qualify as hazardous but typically not in large enough quantities to trigger CERCLA requirements.

EPCRA is the most widely applicable federal statue governing hazardous materials for shale gas extraction. EPCRA requires all manufacturers of dangerous chemicals to produce Mineral Safety Data Sheets (MSDS) describing the health effects of each chemical. Facilities, including shale gas operations, which use MSDS chemicals must notify state officials and make chemical inventory information available to the public. EPCRA also gave authorization for the creation EPA's Toxics Release Inventory (TRI) which is a public database that contains reports of spills and releases of toxic chemicals. The oil and gas industry is not among the industries EPA requires to make TRI reports; however, the oil and gas industry does not have a statutory exemption as in RCRA and CERCLA, so it is possible that EPA could require TRI reporting from shale gas operators in the future.

2.2.2 Pennsylvania statute

As mentioned in many of the federal statute descriptions above, Pennsylvania state statute fills in several of the gaps left in federal statutes. Below is a description of the major statutes that govern well permitting and fluid management for shale gas operations in PA.[4]

- The *PA Oil and Gas Act* requires that all shale gas operators obtain a permit from PA DEP in order to drill a new well; all wells must be registered with the state. PA DEP is given authority to deny permits for well sites that are in violation of the environmental requirements in the Oil and Gas Act or other environmental laws. The Oil and Gas Act also sets specific requirements for reporting, drilling, casing construction, operating, plugging and abandonment of all oil and gas wells.
- The *PA Clean Streams Law* provides PA DEP with authority to prevent and mitigate pollution of surface water and groundwater in Pennsylvania. It authorizes PA DEP's NPDES permitting program and Water Quality Program; it also grants DA DEP authority to fine violators of water pollution regulation.
- The *PA Solid Waste Management Act* authorizes PA DEP to regulate storage, transportation, treatment, and disposal of waste from oil and gas exploration and production with a permitting program. This Act gives statutory authority to the Preparedness, Prevention and Contingency (PPC) Planning program regulated by PA DEP.
- The *PA Storage Tank and Spill Prevention Act* governs the cleanup of spills from storage tanks. It authorizes the Spill Prevention Response (SPR) Plan implemented by PA DEP.

2.2.3 Pennsylvania regulation

The PA statutes above give PA DEP statutory authority to implement a series of regulatory programs. The major state regulatory programs relevant to fluid management at shale gas wells are described below.

- *Well permitting.* All new gas wells must be permitted by PA DEP before they are drilled. Obtaining a permit requires that the well be properly bonded and located. Siting restrictions set minimum distances to nearby water resources. A well site cannot be within 100 feet of a stream or wetland more than an acre in size. Similarly, a well site cannot be within 200 feet of a water supply or a home or workplace.
- *NPDES permitting.* In order to discharge wastewater into a surface waterway in Pennsylvania, a NPDES permit must be obtained, setting effluent limits on all discharge. This prevents shale gas operators from directly discharging produced water into surface water at the well site before treatment.
- *Preparedness, Prevention, and Contingency (PPC).* PPC planning regulates fluid used in oil and gas operations as well as waste from oil and gas operations. The program is designed both to prevent spills from occurring and also to manage spills that do

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[4] In addition to the statutes themselves, I used the following sources to compile the summary on Pennsylvania statute and regulation: (STRONGER, 2010), (Marcellus Shale Advisory Commission, 2011), (PA DEP, 2001).

occur. It is required for all oil and gas drilling operations under the Clean Streams Law. The plan must include provisions for preventive maintenance and training, equipment requirements, spill containment, inspections, and notification and evacuation requirements for spill emergencies.

- *Spill Prevention Response (SPR) Plan.* SPR plans are an additional requirement for facilities with >21,000 gallons of above ground storage; this is applicable to most shale gas operations. The requirements are the same as the PPC with the addition of downstream notification requirements.

The above section is an overview of the major federal and Pennsylvania state statutes and regulations that govern fluid management at shale gas well sites. Additional more specific regulations related to the risk scenarios analyzed in Part II of this thesis are detailed in the scenario description in Chapter 4.

Chapter 3: Risk Assessment

As Chapters 1 and 2 describe, the assessment of groundwater contamination risk from hydraulic fracturing fluid spills in Pennsylvania is a complicated problem that requires a technical assessment of shale gas operations, a scientific analysis of groundwater contaminant transport, and a more qualitative analysis of the perceptions and values of a variety of stakeholders. Therefore, in order to assess this risk thoroughly, I develop a three-part framework. The first step is to analyze the likelihood and consequence of fluid spills on the well site; the second is to analyze the potential for such spills to contaminate groundwater. The third step is analysis of the stakeholder perceptions and concerns. The final recommendations for risk management presented at the end of this thesis draw from all three components of the assessment.

In this section, I present some of the theory and frameworks used in risk analysis that are relevant to this problem. I then describe in greater detail the risk assessment framework developed and used in this thesis.

3.1 Risk theory and frameworks

Broadly defined, a risk is an uncertain event that carries a threat of negative consequence. At the core of this concept is the notion of uncertainty: risks are quantities which we have limited ability to observe and whose occurrence we can describe probabilistically at best. Depending on the nature of the uncertainty and its impacts, and its role in decision-making processes, different methodologies for assessing risk are appropriate.

3.1.1 Risk assessment

In general, risk assessment is the process of identifying, analyzing, evaluating and managing risk; some variant of this process is common to the majority of the risk literature.[5] This framework is broad enough to capture the breadth of risks from a variety of technologies; however, it describes the design choices that tailor the analysis to the specific question of interest. First a set of risks must be identified in a context that is useful to relevant stakeholders. Then these risks are analyzed; this is the objective, technical part of the assessment. Finally, risks are evaluated and a management mechanism produced. The evaluation of a risk is a subjective process that varies by stakeholder; effective risk management strategies should take into consideration a variety of stakeholder perspectives.

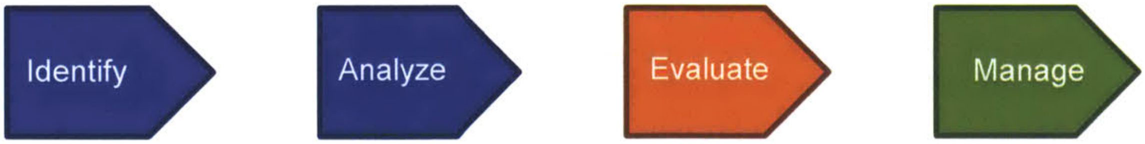

Figure 10: Elements of risk assessment.

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[5] See (National Research Council, 1983) as an example one of first widely-used paradigms for risk assessment.

3.1.2 Probabilistic risk assessment

One technical tool that is useful in the analysis step in the risk assessment process is probabilistic risk assessment (PRA). PRA is a quantitative, systematic methodology for the analysis of risk in complex technologies.[6] In PRA, the risk of a hazard is measured using two components:

- *Likelihood*. This is a probabilistic measure of the frequency of the event's occurrence.
- *Consequence*. This is a measure of the severity of the hazard, if and when it does occur.

Once likelihood and consequence are defined quantitatively, the risk of the hazard can be measured as the product of likelihood and consequence:

*Risk = likelihood * consequence*

Quantifying the likelihood and consequence of a hazard in a complex technological system can be challenging; a variety of techniques of varying complexity can be used. Likelihood quantification can be based on standard statistical analysis from past data. Fault trees and event trees are useful tools for quantifying the likelihood of a risk that depends on the combination of multiple failures. Monte Carlo sampling and Markov processes can also be used to quantify more complex probabilistic relationships. Quantifying consequences can be even more challenging because consequences can span a range of categories: health, safety, environment, economic, community, etc. Quantifying and comparing risk consequences across categories requires additional techniques; a large literature exists on risk categorization and ranking.[7] If only one category of consequence is relevant, quantitative comparison is easier.

One of the major advantages of PRA is that it allows for a quantitative measure of risk to be derived by analyzing a complex technology component by component; it is commonly used in the nuclear power industry to ensure that power plants are properly designed to prevent catastrophic failure, for example (Wu & Apostolakis, 1992). However, equating a low-probability high-consequence event with a high-probability low-consequence event may not be a useful method of comparing risks. Some techniques, such as the use of risk matrix, intentionally keep the evaluation of likelihood and consequence separate (Haimes, Kaplan, & Lambert, 2002).

3.1.3 Environmental risk assessment

Environmental risk assessment is a tool commonly used to characterize the nature and magnitude of threats to human health or the environment from chemical exposure. It has a long history of use by the U.S. EPA. Under this paradigm, risk is defined as:

*Risk = toxicity * exposure*

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[6] Probabilistic risk assessment is described in a variety of textbooks and other references. The main reference used in this description is (Sutton, 2010).

[7] See (Morgan & Florig, 2000) for a good overview.

In order to characterize the final health risk from a specific chemical, it is necessary to analyze both the dose that comes into contact with humans through a variety of pathways in the environment and also the impact of that dose on human health (National Research Council, 1983). (Ashford et al., 1980) analyze toxicity and exposure using the "biological impact pathway" which is depicted in Figure 11 below. Exposure is depicted by the horizontal line in the figure: industry releases a contaminant into the environment, the contaminant is acted on by a variety of fate and transport processes in the environment, and eventually some amount of contaminant comes into contact with a biological organism. Toxicity is defined by the dose-response relationship of the organism in question; each organism responds to a certain dose of a toxic chemical in a different way.

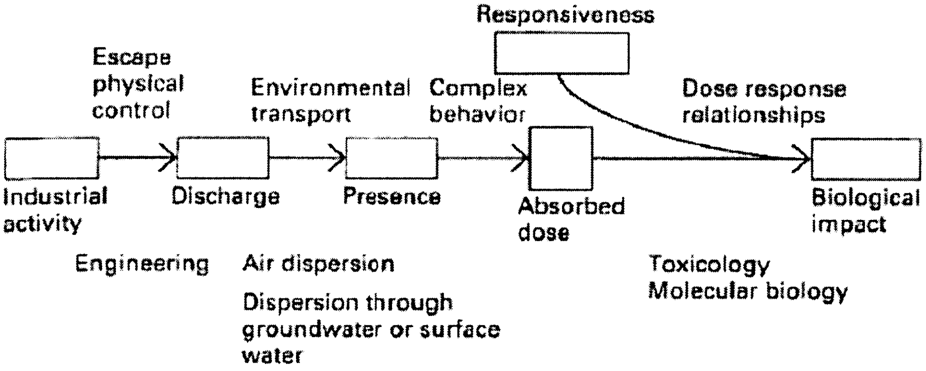

Figure 11: The Biological Impact Pathway. Source: (Ashford et al., 1980).

3.1.4 Risk perception

While objective, technical analysis, to the extent that it is possible, is essential to a credible and legitimate risk assessment, it is important to understand how different people perceive the risk. It is widely agreed in the literature that perception of risk is dependent on more than its quantitative, probabilistic characterization. Different individuals and groups of people may view the same risk very different, depending on their exposure to media coverage, their personal experiences, and their aversion to risk (Slovic, 1987).

It has been demonstrated that the degree to which a risk is undertaken voluntarily with control and also the degree to which a risk is uncertain or poorly understood has a large effect on its perception (Morgan, 1993; Slovic, 1987). (Slovic, 1987) defines two main factors: "unknown" and "dread" risk which influence the perception of risk; the public generally demands greater management of risks that are high on both scales. The characteristics which contribute to a risk being "unknown" or dread" are depicted in the vertical and horizontal categories in Figure 12 below.

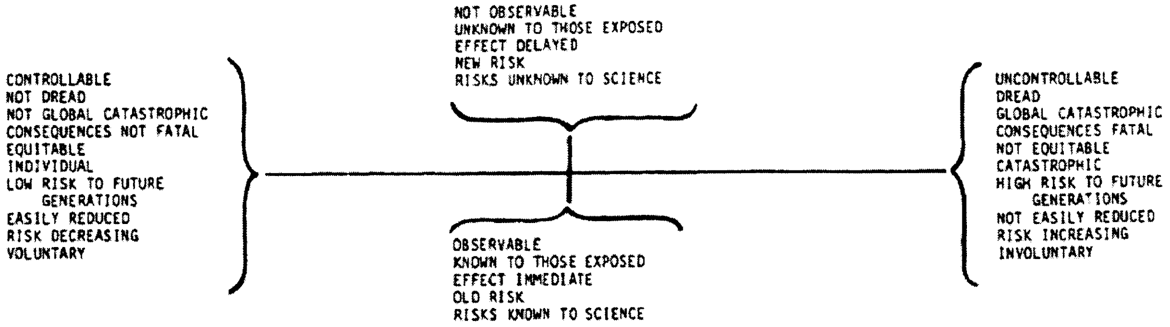

Figure 12: Unknown (vertical) and dread (horizontal) risk scales. Source: (Slovic, 1987).

Based on survey data, (Slovic, 1987) evaluated a series of risks on these two factors; the results are illustrated in Figure 13 below. Risks associated with mining and fossil fuels are rated high on the dread risk scale, and vary across the unknown risk scale. Because shale gas extraction is new to Pennsylvania, it is likely higher than other mineral extraction activities on the unknown risk.

Other factors that contribute to perception of risk include social pressures, trust, and extreme events. Perception of risk can be negatively influenced if information about the risk is transferred from sources that are not trusted (Slovic, 1993). Similarly, perceptions of risk can be amplified if they are widely socialized by the media, personal networks, etc. (Kasperson et al., 1988). Finally, the risk of extreme events is often overestimated as a result of misperception about their frequency (Tversky & Kahneman, 1974). (FACS, 1995) summarizes these factors as "emotive attributes" that influence perception in Figure 14 below.

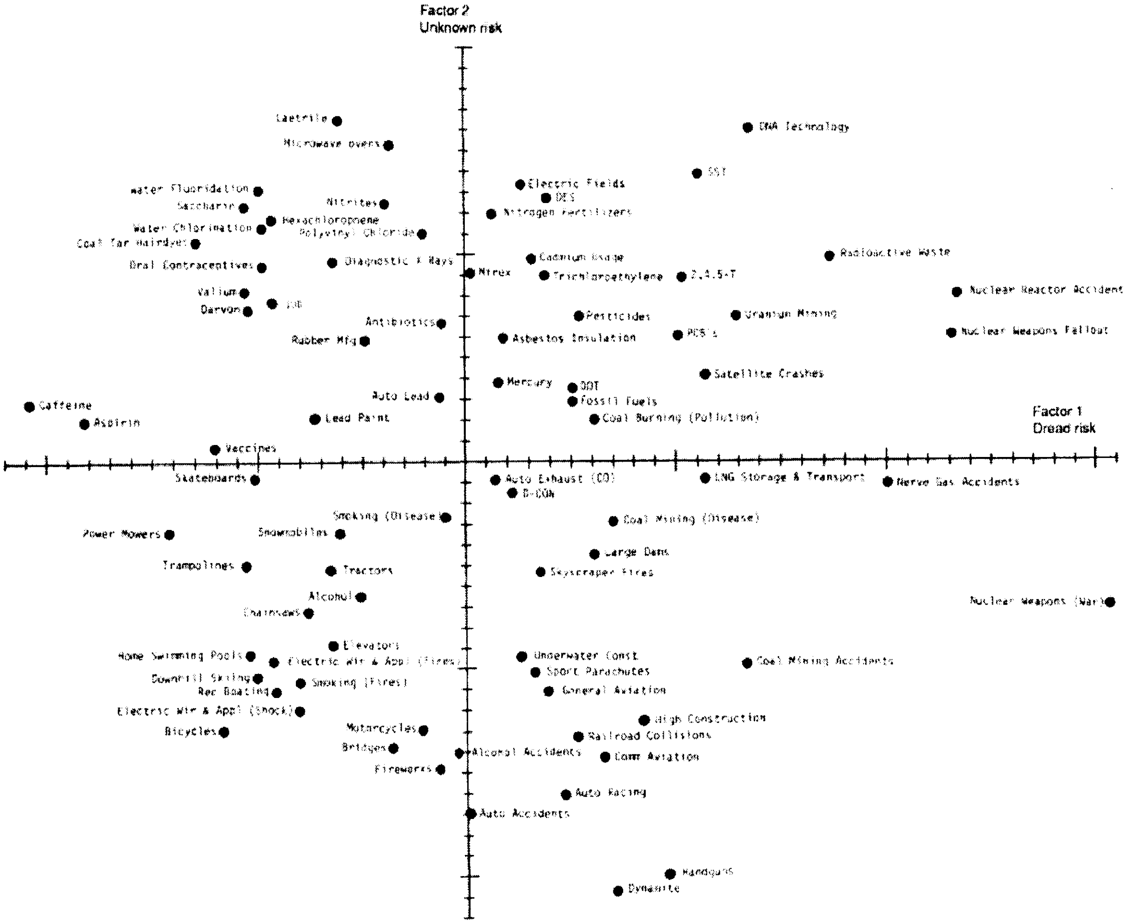

Figure 13: Risks assessed by the factors "Unknown" and "Dread." Source: (Slovic, 1987).

Emotive Attribute	Basis of Risk Perception
Involuntary	A risk one is forced to take
Uncontrollable	The inability to personally influence an event
Immoral	Something that is viewed as evil
Unfamiliar	A new and unnatural (manufactured) risk
Dreadful	A risk relates to a fearful consequence
Uncertain	Scientists are unable to exactly define the hazard and its associated risk
Catastrophic	Large scale disastrous events
Memorable	Risk is associated with a embedded, remarkable event with dramatic risk outcomes
Unfair	Exposure to risk with no clear benefit
Untrustworthy	No confidence in the source of risk analysis

Figure 14: Emotive attributes of risk perception. Source: (FACS, 1995).

3.1.5 Risk management

Risk management is the last part of the risk assessment process; management strategies are developed to prevent or mitigate the risks identified, analyzed and evaluated in the earlier stages of the risk assessment. Effective risk management strategies must take into consideration both the outcome of the technical, probabilistic risk assessment as well as the perceptions and values of stakeholders; many risk managers make the mistake of not engaging the public in the risk management process (Morgan, 1993). Stakeholder analysis can be a powerful tool in developing risk management strategies that are credible and legitimate to society. Stakeholder analysis can be helpful either in facilitating the implementation of a predetermined policy or in developing an appropriate policy for the future (Varvasovszky, 2000).

Expert analysis of a technical problem can play an important role in developing strategies to mitigate risk most efficiently, but reliance on experts may pose a conflict with democratically-selected solutions (Munger, 2000). Effective risk managements strategies require the trust of citizens; powerful technological change has great potential to destroy this trust (Slovic, 1993).

One paradigm frequently used in environmental risk management is the precautionary principle. Because the science of environmental risk assessment is often uncertain, risk managers must frequently make decisions about how, or whether, to mitigate a risk before the severity of the risk is well-understood. Under the precautionary principle, a risk manager should take preventative action at the earliest warning signs in order to avoid damage in the future. The opposite approach is to delay action, which often imposes high, immediate costs, until the nature of the risk is better understood. The decision to use the precautionary principle vs. a wait-and-see approach is often a political decision; in general, Europeans more regularly take a precautionary approach when facing environmental risks, while the U.S. does not (European Environment Agency, 2002).

A related paradigm that has gained traction in environmental management in the U.S. in recent decades is that of pollution prevention. Pollution prevention suggests that increased effort should be used to prevent pollution by using less chemicals or designing safer systems. This is a shift from the pollution control method, in which pollution is recovered and remediated after it has been released into the environment. Some pollution prevent techniques may impose an upfront cost; others, such as using fewer chemical additives, may not. Pollution prevention can also prevent the imposition of cleanup costs. (Ashford & Caldart, 2008)

Pollution prevention and the precautionary principle are more appropriate for risks in which the prevention is relatively cheap and easy, while the damages or cost of cleanup have the potential to be high.

3.2 A risk framework for hydraulic fracturing fluid spills

3.2.1 Central questions and approach

While a full environmental risk assessment, such as those performed by EPA, of shale gas extraction should go through this entire process, the bulk of the thesis is focused on the analysis stage. A literature review provided an identification of one primary risk, hydraulic fracturing fluid spills, in the shale gas extraction process; the rest of the process focuses only on this pathway. The analysis provides an objective characterization of the likelihood and consequence of the spill, in which the consequence is analyzed using the toxicity-exposure paradigm from environmental risk analysis. The evaluation of a risk varies by stakeholder; I provide a brief stakeholder analysis to describe the potential for differing evaluations of the risk of fracturing fluid spills. Finally, based on the outcome of the objective technical risk analysis and the stakeholder analysis, I provide some recommendations for factors to consider in an effective risk management strategy.

The central questions considered in this thesis are:

1. What is the risk of groundwater contamination from fracturing fluid spills in the Marcellus Shale in Pennsylvania?
2. What factors should be considered in developing an effective risk management strategy for water contamination from fracturing fluid spills?

Both quantitative risk analysis frameworks discussed above, probabilistic risk assessment and environmental risk assessment, divide the analysis into two components. PRA uses a likelihood-consequence paradigm, and environmental risk assessment uses toxicity-exposure. Therefore, I also subdivide the first question of risk analysis into two components. The first research question now becomes:

1.1 What is the expected frequency and volume of fracturing fluid spills at well sites in Pennsylvania?
1.2 What is the potential for fracturing fluid spills to contaminate water wells?

Under the PRA paradigm, question 1.1 assesses the likelihood of the hazard: the number of spills that are expected across a range of spill volumes. The ideal goal would be to develop a histogram of spills that probabilistically characterizes the expected number of spills for a particular range of volumes. Question 1.2 then assesses the consequence of the hazard, where water contamination is the consequence of concern. In reality, fracturing fluid spills have the potential to cause a variety of consequences: environmental degradation of nearby land and surface water resources, health and safety concerns for workers and families nearby, economic effects for property owners, and community outcry. In order to avoid comparing consequences across multiple categories, I focus solely on groundwater contamination as it relates to human health; this is a consequence that is both readily quantifiable and also of utmost importance to community stakeholders.

From an environmental risk assessment perspective, these two questions address only the exposure aspect of risk. A toxicity assessment would require an identification of all the chemicals in fracturing fluid and evaluation of their dose-response relationships for humans. Such an assessment is outside the scope of this thesis; I provide an order of magnitude analysis of one component to illustrate the methodology.

A full risk assessment should provide a comprehensive toxicity assessment as well as a complete characterization of likelihood of spills from all spill points. This thesis develops a methodology for such an assessment but does not undertake every aspect. A complete risk assessment on the risk of hydraulic fracturing to ground water resources is currently being undertaken by U.S. EPA; it began in 2011 and aims to publish results in 2014. I aim to both provide some preliminary results and also provide some methodological insights that could be useful in such an assessment.

3.2.2 Scenario analysis

As described in chapter 2, there are many steps in the shale gas extraction process in which fracturing fluid or flowback water spills could occur. In order to confine the risk analysis to a well-defined, manageable set of hazards, four hazard scenarios are chosen. The development of scenarios to define specific hazards is a common technique in quantitative risk analysis in order to ensure a rigorous, consistent analysis (Sutton, 2010).

3.2.3 Likelihood analysis

A rigorous assessment of the likelihood of the above scenarios is challenging. Statistical techniques using historical data is infeasible because of a lack of data. Industry data on spills is proprietary. The PA DEP has records of inspections and violations from shale gas wells in the Marcellus; however, the quality of this data is poor. It is not readily discernible from the violation records whether or not a spill has occurred from each violation; the volume of spills is very infrequently reported. I provide an assessment of what is available, but the results are at best an order of magnitude evaluation of the number of spills that have happened in the past. Even if an accurate count could be obtained for the previous few years, the rapid pace of growth and change in the industry could make the future frequency significantly different from the past.

Engineering techniques using a fault or event tree analysis for each scenario are a better approach. However, this approach is still limited by a lack of data. (Rozell & Reaven, 2011) perform fault tree analysis of water contamination on a similar set of scenarios using a min-max approach; the authors set conservative upper and lower bounds for each required probability to assess the range of possible outcomes.

As an alternative, expert elicitation is a commonly used technique for characterizing quantitative uncertainty distributions using expert judgment when data is limited. This is the approach I use in this thesis. A thorough description of the expert elicitation methodology and its applicability to this problem is provided in chapter 5.

3.2.4 Consequence-exposure analysis

In order to assess the consequence of a fluid spill, the exposure paradigm from environmental risk assessment is used. The biological pathway depicted in Figure 11 above is directly applicable to the assessment of groundwater contamination from fracturing fluid spills in Pennsylvania. Shale gas extraction, the industrial activity, loses physical control of fracturing fluid, which is discharged into the environment. Some of the fluid seeps into the ground and undergoes a series of complex physical, chemical and biological fate and transport processes. Some of the remaining contaminants enter water wells, where they can be ingested by people.

In order to assess this process, and therefore the risk of water contamination, I develop a groundwater contaminant transport model in Part III. There is a wide range of variation in the hydrogeology in Pennsylvania and also uncertainty from a lack of data to fully characterize the hydrogeology. I use Monte Carlo analysis to capture the range of possible transport options. I also take a worst-case scenario approach to the model; this sets upper bound for the risk of contamination.

3.2.5 Stakeholder analysis and management

Finally, I perform stakeholder analysis aimed at identifying the relevant stakeholders and their respective interests in shale gas extraction and the risk of fluid spills. These stakeholder preferences, as well as the outcome of the technical risk assessment in Part II and Part III, lead to an identification of the relevant factors to include in an effective and credible risk management strategy.

Part II: Frequency and Volume of Spills

Chapter 4: Approach and data

The previous part of this thesis described the problem of water contamination risk from fracturing fluid spills in the Marcellus shale in Pennsylvania and developed a framework for addressing it. Part II now addresses the first central research question: what is the expected frequency and volume of hydraulic fracturing fluid spills in Pennsylvania? The objective of this chapter is as much methodological as it is results-driven; I develop an approach for eliciting quantitative probability distributions to describe the likelihood and volume of spills and present some initial results.

First, I define a set of four scenarios that comprise some of the major potential spill points across the extraction process. I then describe the limitations of the PA DEP violation record in characterizing risk from those scenarios and present a motivation for the use of expert judgment. Finally, I develop an expert elicitation protocol for characterizing the likelihood and spill size from the scenarios and present some results from a preliminary elicitation.

In order to clearly define the risk in questions, I have made some important assumptions. First, I define a spill as being at least 5 gallons in volume; this is the minimum reportable quantity in Pennsylvania (PA Code §25.78.). Second, I aim to assess the risk of spills over the course of the next year, given normal developments in industry practice without any major regulatory change.

4.2 PA DEP violations

The Office of Oil and Gas Management of the PA DEP keeps a record of all the inspections and violations made at gas wells.[8] Each inspection record contains: the date and reason for inspection, the identification ID and permit number of the well, and a note of any violation or enforcement action taken. Violations range widely, from administrative errors to significant technical failures.

According to the PA DEP records, 17,815 inspections were made at 4,866 wells from the beginning of 2009 to the end of 2011. Of these inspections, 1,652 included violations; some inspections included multiple violations for a total of 3151 violations. A total of 777 enforcement actions were taken. Of these enforcement actions, 275 were for environmental, health and safety (EH&S) violations, as opposed to administrative violations.

The quality of the reports on violations varies widely. Some records explain in detail what law or regulation has been violated and what the on-site failure is. Some records, however, are missing any kind of comment explaining the specific nature of the failure. Of those records that indicate that some kind of fluid may have been spilled, the vast majority do not indicate the amount of fluid spilled. This is in stark contrast to the records kept by the Railroad Commission of Texas, which keeps detailed records of all fluid spills that include

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[8] These records are publicly available for download at: http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_compliance_report/20299.

the amount of fluid spilled, the amount of fluid recovered, and the technical point of failure.[9] It is likely that the 275 EH&S enforcement actions reported are not comprehensive. However, of these 275 enforcements, not all indicate a spill; it is unclear what portion of the enforcement actions were the result of a spill.

4.1 Fracturing fluid spill scenarios

Surface spills of fracturing fluid and flowback water can happen at a variety of points in the extraction process. A complete assessment of the risk of surface spills would require a systematic analysis of the likelihood and volume potential at all spill points; the large variation in operations across Pennsylvania and scarcity of data makes a rigorous analysis of this kind infeasible. Instead, I identify four scenarios that are intended to comprise the majority of spills that occur and also to span a range of different spills sizes, causes of failure and processes during extraction. For example, small spills often happen as the result of poor pipe connections or leaks; large spills sometimes occur as the result of a major well blowout, but such blowouts rarely happen. Additionally, spills from some parts of the extraction process may be the result of human error, while others stem from equipment failure or acts of nature. The cause of the spill, as well as is its size, plays a critical role in developing an effective risk management strategy.

The analysis in Part II of this thesis is targeted at characterizing the likelihood and volume distribution of surface spills from the following scenarios:

1. Fracturing fluid is spilled during transportation by pipe to the wellhead.
2. Fracturing fluid is spilled due to a well blow out.
3. Flowback water is spilled due to a retaining pit overflow or leak.
4. Flowback water is spilled during transportation by truck to a wastewater treatment facility.

4.1.1 Pipes

This scenario encompasses all spills that occur while fracturing fluid is between the blender and the wellhead; this is the part of the process in which fracturing fluid has been mixed together but is not yet down the borehole. While this is usually a relatively short distance (see Figure 7), pipes are under high pressure from the pumping to the borehole. Spills can be caused by small leaks in pipe connections, pipe burst, or pump failures. Common secondary containment includes liners on the ground under pipes and the blender; such liners are recommended but not required by PA regulation (NY SGEIS, 2009).

4.1.2 Blowouts

A well blowout is a catastrophic failure of the wellhead that leads to an inability to control the pressure in the borehole, which can lead to the uncontrolled release of large volumes of fracturing fluid. Blowouts can occur as the result of poor casing or cementing of the wellbore. The wellhead is equipped with a series of valves and a blowout preventer to

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[9] See "Crude Oil, Gas Well Liquids or Associated Products (H-8) Loss Reports" on the Texas RRC website: http://www.rrc.state.tx.us/environmental/spills/h8s/index.php

control pressure in the well and prevent blowouts. Figure 15 provides a photograph of a well head, with labels of the valves and blowout preventer. PA DEP regulation requires well casing and cementing to meet technical specifications; operators must submit a cementing and casing plan in order to obtain a well permit (PA Code §25.78.).

Well blowouts do occur, however. Two high profile blowouts have occurred in Pennsylvania since the beginning of 2010. A major blowout occurred on June 3, 2010 in Clearfield County, PA at an EOG Resources well operated by C.C. Forbes LLC. Investigators report that between 35,000 and 1 million gallons of fracturing fluid were released over the ground and into local waterways (Michaels, Simpson, & Wegner, 2010; Vaughan & Pursell, 2010). Another major blowout occurred on April 19, 2011 in Bradford County, PA at a Chesapeake well; fluid flowed from the well for almost two days and forced the evacuation of seven local families (Helman, 2011; McAllister, 2011).

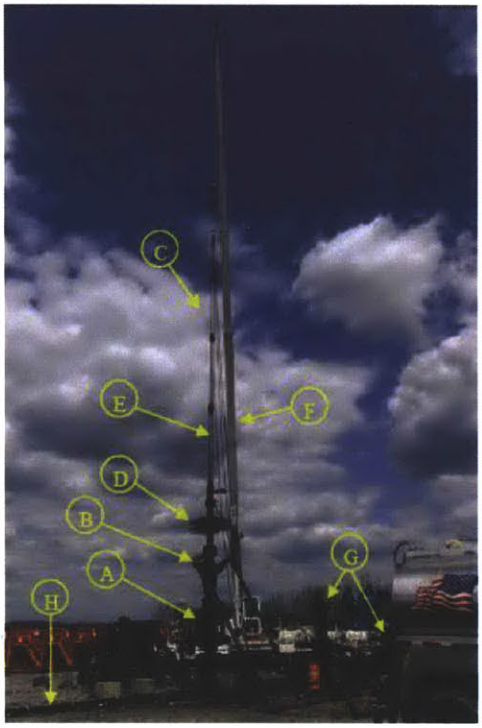

Figure 15: Photograph of wellhead. Photograph, labels and caption from (NY SGEIS, 2009).

A. Well head and frac tree (valves)
B. Goat Head (for frac flow connections)
C. Wireline (used to convey equipment into wellbore)
D. Wireline Blow Out Preventer
E. Wireline lubricator
F. Crane to support wireline equipment
G. Additional wells
H. Flow line (for flowback & testing)

4.1.3 Retaining pits

This scenario encompasses all spills or leaks from retaining pits that hold produced water after it is flowed up the well. Retaining pits are dug holes on the well site that are covered with a liner. Retaining pits are smaller than the centralized impoundments for freshwater in Figure 5; small pits do not need a permit (Marcellus Shale Advisory Commission, 2011). The shape and size of the pit varies from site to site, but regulation requires that all pits have at least two feet of freeboard at all times, be structurally sound, and have an impermeable liner (PA Code §25.78.). An alternative to retaining pits is tanks; some recommend that the industry move to tanks instead of pits to prevent spills (Marcellus Shale Advisory Commission, 2011).

There are two main ways in which fluid can spill from a retaining pit. The pit can overflow, either because the pit capacity is too small to hold the volume of produced water or because of heavy rainfall or stormwater runoff. Additionally, tears or holes in the pit liner can allow fluid to leak through the bottom of the pit. Because multiple wells are now frequently drilled on the same well site, pits are being reused over a longer period of time; regulation of pits liners was not designed for prolonged use of pits.

Of the 43 widely reported incidents in the MIT *Future of Natural Gas* study (2011), four are overflows or leaks from retaining pits, suggesting the pits are a significant concern to communities.

4.1.4 Truck transportation

Just as all the freshwater and chemical additives must be transported to the well site by truck, the produced water must be transported off site by truck. This scenario includes all trucking that takes wastewater to an offsite wastewater treatment facility; it does not include trucking to on-site treatment facilities or any pipe or hose transportation of wastewater on site. Between 200 and 300 truck loads are required to transport flowback water off-site for a single well on a well pad (MIT, 2011). Each truck typically transports 5,500 gallons of fluid (*Marcellus Shale Freight Transportation Study: Final Report*, 2011).

The most significant cause of flowback water spill from a truck is a collision or accident of some kind while driving. Because this scenario takes place off site, secondary containment options are limited and spills can be more difficult to clean up.

Chapter 5: Expert elicitation

5.1 Motivation

While the data above provide an order of magnitude estimate about the number of fracturing fluid spills over the past several years in Pennsylvania, it is not sufficient to fully assess the risk of spills or make recommendations for policy-makers and industry. First, it is likely incomplete and inaccurate. The PA DEP violation record log was inconsistent in amount and format of information provided for each violation, making it likely that some reported spills were omitted and some were possibly double counted. Moreover, it is likely that some spills were not reported at all. Second, in order to characterize risk as a product of both likelihood and consequence, data on both the number of spills and the size of the spills is needed. Spill size was infrequently documented in the PA DEP violation record log, making it impossible to characterize a distribution of spill sizes. Finally, the pace of shale development, the advance of industry practice, and the state of regulation in Pennsylvania are all rapidly changing, limiting the usefulness of past data in predicting future outcomes.

5.2 Expert elicitation methodology

5.2.1 History and recent examples

Expert elicitation is a methodology for using experts to characterize quantitative estimates about uncertain information. Although data-derived values from traditional statistical techniques are often more credible in policy or decision-making processes, it is often necessary to make decisions before the necessary science and data are available. In this case, relying on expert judgment is the only remaining option (Morgan & Henrion, 1990). Expert elicitation allows an analyst to develop a probability distribution for an uncertain value rather than a single best estimate; this distribution can be used to evaluate the array of potential future outcomes and make decisions accordingly.

The use of expert judgment in policy and decision making has a long history. The elicitation technique was pioneered in the 1950s with the inception of the RAND Corporation as a way to use expert judgment in decision-making processes in a coherent, structured format (Cooke, 1991). Use of the methodology expanded rapidly through the 1970s, with the most widely used elicitation protocol developed in the 1960s and 1970s by a team of decision analysts at the Department of Engineering-Economic Systems at Stanford University and Stanford Research Institute (Morgan & Henrion, 1990).

Expert elicitation continues to be frequently used in energy and environmental policy. The prediction of future cost and performance of energy technologies is a popular recent application. (G. Chan, Anadon, M. Chan, & Lee, 2010) elicit the cost and efficiency of coal-fired power plants with carbon capture and sequestration under various funding scenarios. Similarly, (Baker, Chon, & Keisler, 2009) ask experts to estimate the effect of R&D investment on technical change in advanced solar photovoltaic. Expert elicitation has also been frequently used in determining the relationship between fine particulate matter and mortality (Cooke et al., 2007; Knol et al., 2009; Roman et al., 2008). These applications suggest the appropriateness of our current problem: assessing the future of shale gas technology in order to inform environmental policy.

5.2.2 Subjective probability, cognitive bias, and overconfidence

The use of expert elicitation requires a subjective, as opposed to objective or frequentist, approach to probability. Under the subjective view, a probability distribution represents an observer's belief about the range of possible outcomes that a value might take. It is not an intrinsic property of the event itself; there is no single "correct" value being estimated. Rather, subjective probabilities vary from person to person depending on the information available to each one. Under a subjective view, probability allows a person to make an optimal decision based on their beliefs about what will happen in the future.

The subjectivist construction of probability is powerful in the context of expert elicitation because it allows policy-makers to use experts' belief of what will happen in the future in order to make decisions. However, it also presents challenges. Different people, experts included, may have different subjective probability distributions about the same event. This may be because they have different information available to them, or instead because they evaluate probability differently. While no subjective probability distribution is considered "wrong" unless it violates the fundamental axioms of probability theory, some may be better than others. Subject matter experts may not also be normative experts—that is, they may not be well-versed in describing probability distributions.

A large body of literature suggests that humans are not inherently skilled at making judgments about uncertain information. When faced with uncertain information, people routinely use a set of heuristics—quick, rule-of-thumb learning aids—in order to make decisions (Kahneman, Slovic, & Tversky, 1982). These heuristics allow us to make quick decisions that are often effective in everyday life, but suffer from inherent biases. Such biases limit a person's normative ability to accurately characterize their own subjective probability distribution.

(Tversky & Kahneman, 1974) present a series of psychological experiments that reveal three commonly employed heuristics that lead to systematic error:

- Availability
- Representativeness
- Adjustment and anchoring

Availability. The availability heuristic causes people to discern probabilities through the ease with which they can imagine the event occurring. This is a problem when the person's direct experience with the event is disproportional to the actual frequency of the event. For example, (Lichtenstein, Slovic, Fischhoff, Layman, & Combs, 1978) performed an experiment in which groups of well-educated people were told that 50,000 people die in car accidents each year and asked to estimate the frequency of death from several other causes. The results in Figure 16 demonstrate that people tend to overestimate the frequency of events that are rare but widely reported in the media such as tornados; similarly, they underestimate routine causes of death such as heart disease that do not cause headlines. This is a compelling demonstration of the effect of availability on perception of probabilities.

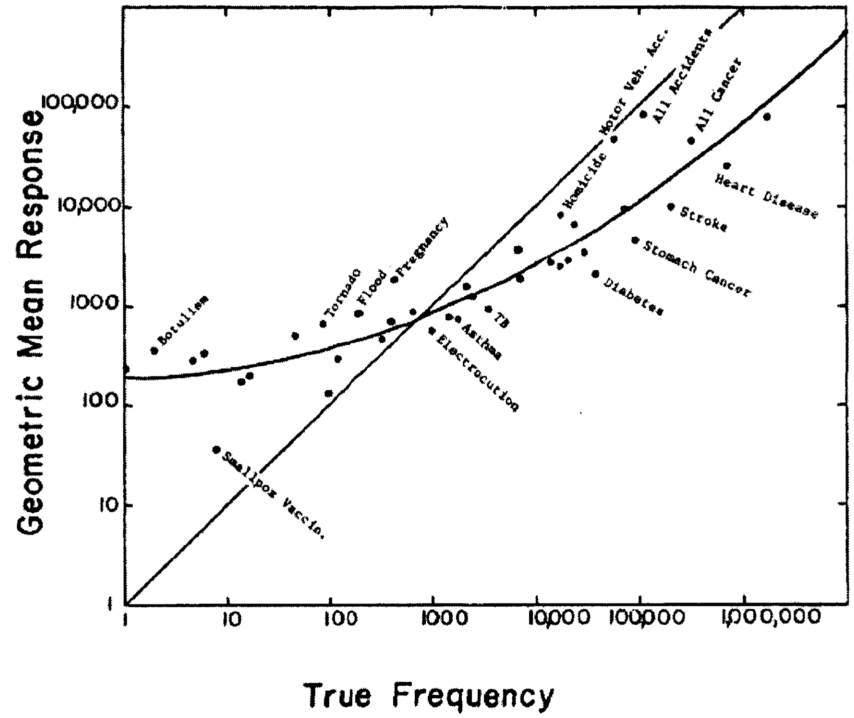

Figure 16: Plot showing estimated deaths per year vs. the actual frequency of death from a variety of sources. Subjects overestimated widely-reported events like botulism but underestimated routine events like heart disease. (Lichtenstein et al., 1978).

Representativeness. Representativeness is the process by which people associate an object in a group with the properties of the group. This leads people to assume, often incorrectly, that the details of the object will reflect the properties of the larger group. For example, (Tversky & Kahneman, 1974) report on people's misconceptions about probability in heads-tails coin tosses. People thought that the sequence H-T-H-T-T-H had a higher probability of occurring than the sequence H-H-H-T-T-T because the former looks more random; in fact the probability of any single sequence is the same. This suggests that, because people know that the process of coin tossing is inherently random, they expect the outcome of any particular outcome to reflect that randomness. In this case, the first sequence looks more random than the second. In addition to this problem of "misconception of chance," the representativeness heuristic can also lead to systematic biases resulting from insensitivity to sample size, insensitivity to prior probabilities, and the illusion of validity, among several others (Tversky & Kahneman, 1974).

Anchoring and adjustment. Finally, adjustment and anchoring is the heuristic process in which people attach to an initial estimate, the anchor, and make small adjustments even when the initial estimate is no longer relevant. This is particularly important in characterizing subjective probability distributions; people tend to make their best guest for the median or average value first, and then base their estimates for the tails of the distribution on their best guess value. The result is usually insufficient adjustment, which leads to overconfidence—the probability distribution becomes too narrow (Tversky & Kahneman, 1974).

While the experiments above describe layperson estimates of probabilities, experts can also suffer from similar cognitive biases. Studies on expert overconfidence are mixed. (Lichtenstein, Fischhoff, & Phillips, 1982) report that the greater the amount of knowledge an expert has in an area, the less likely he is to be overconfident. However, this seems to be true only in some cases. (Morgan & Henrion, 1990) discuss examples in which expert calibration is measured. Experts in some subject areas perform well—that is, they are neither overconfident nor under confident—while experts in other fields do not. This suggests that the state of development of the field and the amount of credible science available to it may have an impact on whether experts in that field are well calibrated when estimating probability distributions (Morgan & Henrion, 1990). A compelling illustration of expert overconfidence is presented by (Henrion & Fischhoff, 1986) in which prominent historical estimates of the speed of light were compiled. As seen in Figure 17, the current (1986) accepted value for the speed of light is outside the error bars for over half the estimates; perfectly calibrated experts would have included the correct value within the error bars 67% of the time.

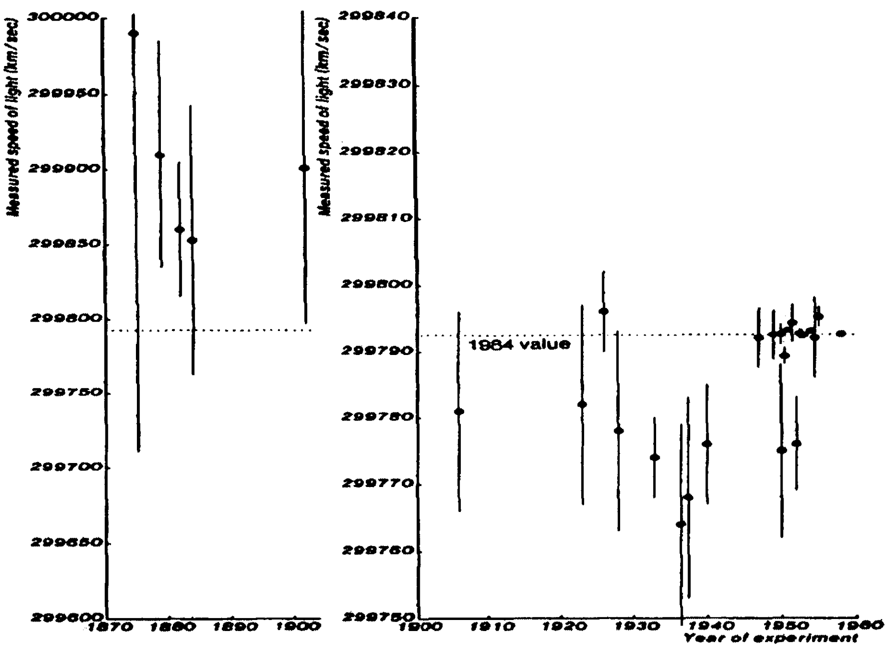

Figure 17: Historical estimates of the speed of light with error bars, compared to the current accepted value. (Henrion & Fischhoff, 1986)

The use of expert judgment in policy-making has several limitations. Experts are not perfect at characterizing subjective probability distributions to describe future events, and the set of information available to and assumptions made by different experts often leads to different results. However, the reality of policy-making often requires decisions to be made before hard data and credible science are available. In the case of hydraulic fracturing fluid spills, it is clear that spills have been occurring; due to incomplete reporting, there is not enough data to accurately assess the extent of the problem across the industry. The use of expert elicitation for this problem can be useful in assessing the uncertainty around the number of spills that are occurring, the volume of fluid that might be spilled, and how trends will change in the future. This added information can be helpful in developing better risk management policy today.

5.2.3 Elicitation protocol and design

Note that practically speaking, a credible and well-performed expert elicitation can take many months or even years to complete from start to finish, and require substantial budgets in order to compensate experts.[10] Given the time constraints of a master's thesis and the absence of budget to compensate experts, the goal of the elicitation performed in this thesis is not to provide finalized results. Rather, I hope to demonstrate that expert elicitation is a useful methodology for this problem, design an appropriate elicitation tool, and present some initial results.

The structure and design of an expert elicitation protocol can vary widely from study to study. Sometimes experts are elicited in groups and asked to come to consensus; other times, consensus-building is avoided as a potential source of bias. Elicitation instruments can take the form of in person or phone interview, or also written surveys or questionnaires. There is no one-size-fits-all protocol; the design should be adapted to the problem at hand instead of using an overly rigid, inflexible protocol (Morgan & Henrion, 1990).

The first complete and influential protocol, as mentioned above, is the Stanford/SRI protocol (Spetzler & Stael von Holstein, 1975). (Morgan & Henrion, 1990) build on this protocol, and (Meyer & Booker, 2001) provide a practical guide aimed at practitioners. A combination of these three protocols adapted to the problem at hand, along with advice from a symposium on expert judgment at Resources for the Future (Cooke & Probst, 2006), form the core of the elicitation design process used in this thesis.

Both the Stanford/SRI protocol and (Morgan & Henrion, 1990) follow five basic steps: motivating, structuring, conditioning, encoding and verifying. Other important design considerations include expert selection and data aggregation.

Motivating. Start by providing the justification and purpose for the elicitation; this must be communicated to the experts in order to engage them in the process. It is also important to analyze any potential for motivational bias during this step (Spetzler & Stael von Holstein, 1975). In the context of hydraulic fracturing fluid spills in Pennsylvania, an often controversial and polarized policy topic, there is significant potential for participants to attempt to game the elicitation. This must be mitigated by including a diverse group of experts with varying incentives and by targeting the questions at less sensitive data (Meyer & Booker, 2001).

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[10] Expert compensation can vary greatly, but it is not uncommon to pay external experts on the order of $15,000 for their time and participation (Cooke & Probst, 2006).

Structuring. After the initial motivation, it is necessary to clearly define the information to be elicited. Questions must be specific enough that all experts interpret them the same. When eliciting information about the number of spills of fracturing fluid in Pennsylvania, many details must be considered: Which parts of the extraction process should be included, what industry players are included and over what time frame, and what assumptions are made about technology improvements, industry best practice, and regulation going forward? Another important piece of structuring is making sure that the questions are of the appropriate level of granularity such that they are well-understood by the experts while still providing enough information to answer the question of interest. It is also important to frame questions in a manner that is aligned with the experts' natural way of thinking about the problem (Meyer & Booker, 2001). Finally, it is important to decide whether the expert judgment should serve as input or output of a model; one method may be more appropriate depending on the question. In the case of assessing groundwater contamination from fracturing fluid spills, experts could provide either a spill volume distribution to input into a groundwater transport model, or a direct assessment of the likelihood of groundwater contamination. The structuring process is often the most time-consuming piece of the elicitation process and requires great care. Piloting the elicitation instrument with both internal and external experts can play a critical role (Meyer & Booker, 2001).

Conditioning. Before experts make estimates about the uncertain quantities of interest, it is important to instruct them in how to go about making subjective probability judgments and alert them to the type of cognitive biases to which they may be susceptible. Fortunately, experts in the oil and gas industry are well versed in probability, as it is a tool essential to the industry. This makes it more likely that our substantive experts will also be normative experts. However, they should still be educated about the tendency towards overconfidence and problems of availability and representativeness that may result from working in one part of the industry and hearing media reports about the industry at large.

Encoding. This is the step in which the elicitor works with the expert to obtain probability distributions to describe the uncertain quantities. This can be done in several ways: by eliciting percentile estimates (e.g. P5, P50, and P95), asking experts to draw a pdf or CDF, or using a probability wheel (Spetzler & Stael von Holstein, 1975). Whatever method is chosen, it is important that experts are asked to consider extreme events and not anchor to a single best estimate first in order to avoid overconfidence. It is then up to the analyst to numerically define a probability distribution, and combine distributions from different experts if appropriate.

Verifying. After the analyst encodes the probability distribution, (Spetzler & Stael von Holstein, 1975) recommend following up with the experts to ensure that the distribution accurately reflects the information the expert intended to convey.

Expert selection. In addition to the protocol for the elicitation itself, another important overarching design consideration is the selection of experts. There are several established methods for selecting experts. The two main criteria for choosing a set of experts are: 1) do the experts all have expertise in the question elicited at the appropriate level of granularity, and 2) is a diverse range of viewpoints reflected (Meyer & Booker, 2001). The diversity criteria should play a relatively larger role in questions such as ours where controversy has the potential to lead to motivational bias. The ideal number of experts is generally thought to be between 6 and 12 (Cooke & Probst, 2006).

If the elicitation is limited to experts from academia, a literature review can be used and experts can be evaluated based on number of relevant publications or citations. This can also be used as a first step, after which identified experts would nominate other experts, and the final set to be used in elicitation would be chosen from the list of peer-nominated experts (Morgan & Henrion, 1990). This is more difficult when industry experts are needed. Some common required technical experience or skill should be identified, and a diverse group chosen in order to preserve multiple perspectives. Choosing experts with normative expertise in addition to substantive expertise is ideal if possible; however, at a bare minimum all experts should have substantive expertise in the relevant topic at the relevant level of granularity (Meyer & Booker, 2001).

Data aggregation. The final major design question is how to aggregate data from multiple experts. First, decide whether it is appropriate to aggregate. It may not be necessary to aggregate data if no single probability distribution is needed as the input to a model. Even if a single distribution is desired, if experts have widely varying viewpoints, it may or not may sense to attempt to combine drastically different distributions (Morgan & Henrion, 1990). In this case, modeling analysis could use scenario analysis or sensitivity analysis across multiple input distributions. If data aggregation is desired, several methods are available. Typically, the component probabilities are combined using either traditional statistical techniques or standard Monte Carlo simulation. However, there is no consensus in the literature as to how to choose the best weighting scheme across experts. Some studies suggest that equal weighting performs just as well (or nearly as well) as other methods (Seaver, 1978). A more recent symposium of several leading researchers in expert elicitation concludes that better weighting schemes exist (Cooke & Probst, 2006). Options include evaluating how well each expert performs on seed questions—these questions are given before the elicitation to determine how well-calibrated each expert is in characterizing probability distributions (Cooke, 1991). Alternatively, experts can be asked to rate the expertise of other experts in the group (Morgan & Henrion, 1990).

5.3 Applied methodology: hydraulic fracturing fluid spill elicitation design

Now that the motivation and methodology of expert elicitation have been outlined and the major design criteria presented, the following section will describe the protocol used in the elicitation performed for this thesis. The final elicitation instrument distributed to experts can be found in Appendix A.

5.3.1 Question scope and focus

As described earlier in this thesis, the main purpose of this elicitation is to aid in assessing the risk of groundwater contamination from hydraulic fracturing fluid spills in the state of Pennsylvania. I approach this problem in two steps. First, I characterize the likelihood of a spill and the distribution of volumes expected; this varies for different pieces of the extraction process. This is the information that is elicited. Second, a groundwater contaminant transport is presented in chapter 7; the model is designed to output the likelihood of well contamination given an input spill of a specified size. The results from the expert elicitation can serve as input to this groundwater contamination model.

An alternative that was considered is to assess the risk of contamination all in one step, using expert judgment as the model of groundwater transport itself instead of as input to a freestanding analytical model. The advantage of this is that it eliminates many of the challenges of developing such a groundwater model, as we will see later. However, it presents two significant problems. The first is that it presents increased motivational bias for experts; asking the volume expected from a spill is much more benign than asking whether that spill is going to contaminate a water well. Given that the issue of water contamination from shale gas extraction is so controversial, all efforts should be taken to minimize motivational bias. Second, asking an expert to perform this assessment requires a much more complicated mental process. Either the expert must go through the two-step process of spill size then likelihood of contamination, or he must use some more poorly defined data-based method that could lead to wide variations in expert opinion. It would also require the use of experts who have expertise in both shale gas extraction operations and groundwater hydrology; very few such people exist. As a result, this alternative was not considered to be viable.

5.3.2 Elicitation format

A written questionnaire was developed as the elicitation instrument. There are two motivations for using a written format instead of in person or phone interviews. From a practical perspective, it allows unpaid, busy experts to complete the elicitation on their own time. Second, it allows the expert to look up proprietary data and consult with colleagues to inform his answers. The primary drawback of the written format is that it does not allow the elicitor to coach the expert through the process of encoding distributions. To mitigate this problem, experts were required to complete an example problem that teaches them about cognitive bias and takes them through the process of encoding a distribution. Percentile estimates (P5, P50 and P95) are used in the example question and throughout the survey, and experts are asked to assess the tails before the median. All experts were required to discuss the example problem, the survey questions and common misunderstandings by phone before completing the questionnaire.

5.3.3 Questions

A series of four identical questions were posed for each of the four scenarios developed in chapter 4. The first question is aimed at encoding a distribution to characterize the number of spills that would be expected to occur in the next year as a result of each scenario.[11] The second elicits the distribution of likely spill volumes, should a spill occur. This question also asks, for each of the percentile estimates, what percentage of the spill is expected to be recovered or captured through secondary containment. This allows us to characterize a distribution for the actual amount of fluid that enters the environment, which is the

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[11] Note that most experts were given the survey in the last few months of 2011, so "the next year" corresponds roughly to the year 2012.

quantity most relevant for the groundwater model. The third question is aimed at discerning the cause of the spill, so the scenarios can be categorized as discussed above to develop effective risk management plans for each. Finally, the last question is targeted at understanding what assumptions are made about regulation, best practice, etc. in order to explain differences across experts. The questions are below:[12]

1. Assuming that current drilling rates continue (approximately 1500 new wells in 2010), how many times do you expect this type of spill to occur in PA in the next year? Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   P5: ____________________ (spills)
   P50: ____________________ (spills)
   P95: ____________________ (spills)

2. Assuming that a spill occurs as a result of this scenario, please answer the questions below to estimate its size. Your answers will characterize the distribution of possible spill sizes.

   Part a): In the left hand column below estimate the total amount of fluid this scenario would release. Include both fluid that will be recovered and fluid that will enter the environment. Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   Part b): For each of the spill sizes indicated in the left column, estimate in the right column the amount of fluid that would be recovered. For example, if you indicated for your P5 estimate in part a) a volume of x gallons, now estimate what percentage of those x gallons would be recovered (i.e. fluid that does not enter the environment).

   P5: _____________ (gallons) Percent of P5 estimate recovered: ______ (%)
   P50: _____________ (gallons) Percent of P50 estimate recovered: _____ (%)
   P95: _____________ (gallons) Percent of P95 estimate recovered: _____ (%)

3. What percentage of spills of this type would you expect to be primarily caused by:
   Human error on the well-site: ___
   Equipment failure ___
   Acts of nature: ___
   Other ___

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[12] In addition, experts were asked to identify other major sources of spill and draw a histogram characterizing the total number of spills by expected volume from all sources. The experts' responses were incomplete and therefore not presented. The elicitation tool in Appendix A includes the histogram question for reference.

4. Comments: Use the space below to include any assumptions, explanations, questions, or ideas. Were there particular assumptions or events underlying part or all of your answers?

5.3.4 Expert selection

Because of the nature of the questions asked, the primary criterion for expert selection is operational experience in fluid management on the well site. Such experts are more likely to have knowledge and data on spills than observers from academia or policy. However, asking experts in the field presents a large potential for bias: each expert may have an incentive to skew his results. For example, an expert from a gas production company may be incentivized to report fewer, smaller spills than he really believes to be true in order to help the public perception of the industry. This bias is mitigated by choosing a variety of experts with different incentives. Experts from five types of institutions were included in the elicitation:

- Natural gas production companies
- Service providers
- Regulatory officials with experience in well inspection
- Insurance providers to natural gas production companies
- Environmental organizations with technical experts

In approaching experts from each category, initial contact was obtained from: six production companies, three service providers, three regulatory officials, six insurance providers, and one environmental organization. Of those, two production companies, two service providers, two regulatory officials, two insurance providers, and one environmental organization agreed to participate and participated in the elicitation training and phone call. In the end, results were obtained from one production company and one regulatory official.

5.3.5 Pilot

Two in-house experts on shale gas extraction at MIT and two experts from natural gas companies piloted the survey. Two of the pilots (one internal and one external) were limited pilots: participants read through each question and then discussed any points of confusion or suggestions for improvement. The other two pilots were full pilots: participants were given the full instruction and pre-survey training, and them completed the entire survey and discussed it for improvements. The pilots took place at different stages through the development of the survey, and were critical to ensuring that questions were within the range of experts' expertise and that each question was clear and interpreted in the same way by each expert.

In addition to the four pilots, each of the nine experts who consented to participate was given the opportunity to ask for clarification and make suggestions before taking the survey. Small changes were made based on these suggestions and included in the final survey that was distributed to all participants.

One important outcome of the piloting process was a confirmation that the four scenarios chosen accounted for the majority of sources of fluid spills. All four pilot experts confirmed this. One additional major source of spill identified was bringing chemicals and water to location, before they enter the blender.[13]

5.4 Results and analysis

The survey results from the two experts who returned surveys are presented and analyzed below. Appendix B contains a data table with full results from both experts. Expert elicitation results should never be treated as hard data; in this case in particular, the intention is to provide some preliminary insight into expert perceptions of the industry. Some order of magnitude conclusions can be drawn, but much work remains to be done in order to thoroughly assess the likelihood and size of fluid spills from this industry.

General results across all four scenarios are presented first; each scenario is analyzed in greater detail thereafter.

5.4.1 Number of spills

For each of the four scenarios in the survey, experts were asked to provide P5, P50 and P95 estimates of the number of spills that would occur in the next year, given a well drilling rate of 1500 per year (the approximate rate of wells drilled in PA in 2010).[14] Figure 18 below displays experts' responses for spill size for each of the scenarios. The ends of each error bars represent the P5 and P95 estimates; the center point is the P50 estimate. Note that the vertical axis is represented in log scale.

The results across the two experts do not show signs of systematic bias either in the number of spills estimated or the level of confidence; in fact, the two experts make similar estimates. In all four of the scenarios, the range of estimates provided by each expert overlap; this is not necessarily expected in expert elicitation results. Likewise, the sizes of the confidence intervals are generally similar. This suggests that although the two experts have different motivations and perspectives on the industry, they view the expected number of spills fairly similarly.

Several broad trends are shown. First, the estimates across scenarios are similar in order of magnitude. With the exception of expert 2's estimation for scenario 1, all of the P50 estimates are between 1 and 10 spills per year. Likewise, the upper bound is expected to be no greater than 20 spills per year, for all but scenario 1. The maximum P95 estimate is 100 spills per year from expert 2 regarding scenario 1, or 1 in 15 new wells. This suggests that even small spills from pipe connections are not systemic to the process; the vast majority of new wells drilled do not yield spills of five gallons or more from any of these scenarios.

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[13] Scenario 1 includes spills only after they are blended. This point was clearly articulated in all of the pre-survey phone calls with experts.

[14] Experts were also asked to draw a histogram describing the total number and size of all spills, including both the four scenarios and other sources of spill. The quality of the drawn histograms was poor; they are not included in this analysis.

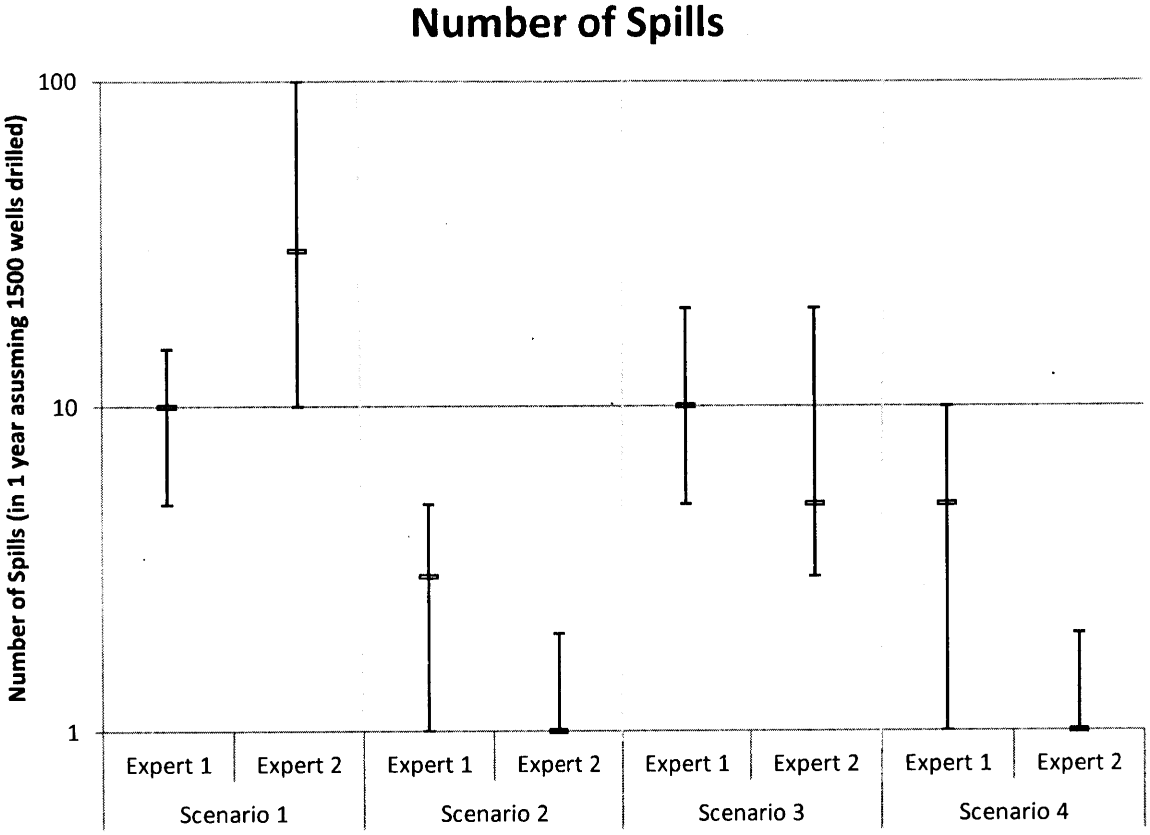

Figure 18: Expert estimates of annual number of spills at current drilling rates, by scenario.

The definition of a spill as greater than or equal to 5 gallons or more plays large role in characterizing the number of spills. It is possible that spills of less than 5 gallons do occur routinely during operations. These spills would not be captured in any reporting data from the PA DEP, as spills less than 5 gallons do not have to be reported. The part of the operation in which small spills are most likely to occur is during piping of liquids across the well-pad; tarps are typically used as secondary containment to control these small but frequent leaks.

5.4.2 Volume of spills

The experts were asked to make two estimates related to spill volume for each of the scenarios. First, they were asked to assume that a spill of five gallons or more occurred from the given scenario; they then made P5, P50 and P95 estimates for the amount of fluid that would be spilled. This assumption is important, because it means that the distribution of spill sizes do not reflect the large number of spills of less than five gallons that might occur. Note that experts accurately understood this distinction, as none of the lower bound estimates were below the five gallon minimum.

This first estimate includes fluid that is recovered either through secondary containment mechanisms or through clean up. However, since we are interested in assessing the risk of groundwater contamination, the most relevant quantity is fluid that actually enters the environment. Fluid that enters the environment has the potential to infiltrate the groundwater system and be transported to a water well. In order to assess how much fluid enters the environment, experts were asked to estimate what percentage of fluid they expect to be recovered for each of their spill volume estimates. I use this to then calculate the volume after recovery, or the volume that enters the environment.

Figure 19 below shows the spill volume before recovery; this is the total amount spilled including fluid captured by secondary containment or recovery. This means that some portion of the volume reported in this figure may not ever enter the environment.

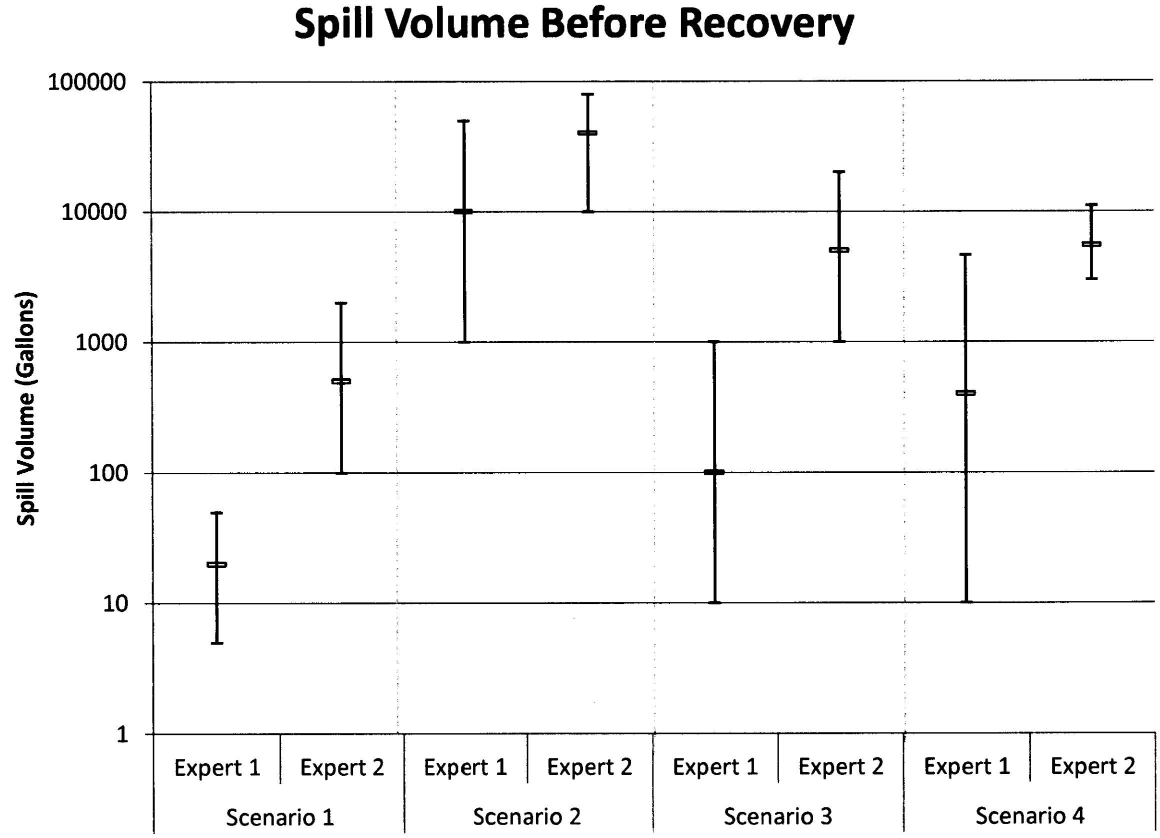

Figure 19: Expert estimates of spill volume before recovery, by scenario.

The expert estimates of spill volume have significant overlap; the ranges provided by each expert overlap for scenarios 2 and 4. In scenario 3 the upper bound of 20 gallons provided by expert 1 is just below the lower bound of 25 gallons provided by expert 2. In scenario 1, however, expert 2 indicates a significant higher volume that expert 1. Additionally, the median and upper bound estimates provided by expert 2 are consistently higher than those provided by expert 1 across all scenarios.

It is possible that these systematic differences are the result of motivational bias on the part of one or both experts. However, because the differences are small, it is more likely that they are explained by differences in assumptions or knowledge available to each expert. This assertion is sustained by the relative comments, both written and verbal, made by each expert. These will be explained in detail in the specific scenario analyses below.

Given that the disparity from whatever source is small, some generalizations can still be drawn. The well blowout described in scenario 2 is the only scenario with the potential to spill several tens of thousands of gallons of fluid. This is consistent with the widely reported incidents discussed in chapter 2; well blowouts were the only incidents in which tens of thousands of gallons of fluid were released. At the opposite end of the spectrum is scenario 1; the upper bounds for both experts are below 100 gallons. This is consistent with the intuition that spills from pipes are more frequent but small in size. The volume possible from scenarios 3 and 4 seem to be somewhere in the middle; the results indicate that spills on the order of thousands of gallons are possible.

The results for spill volume after recovery are presented below.

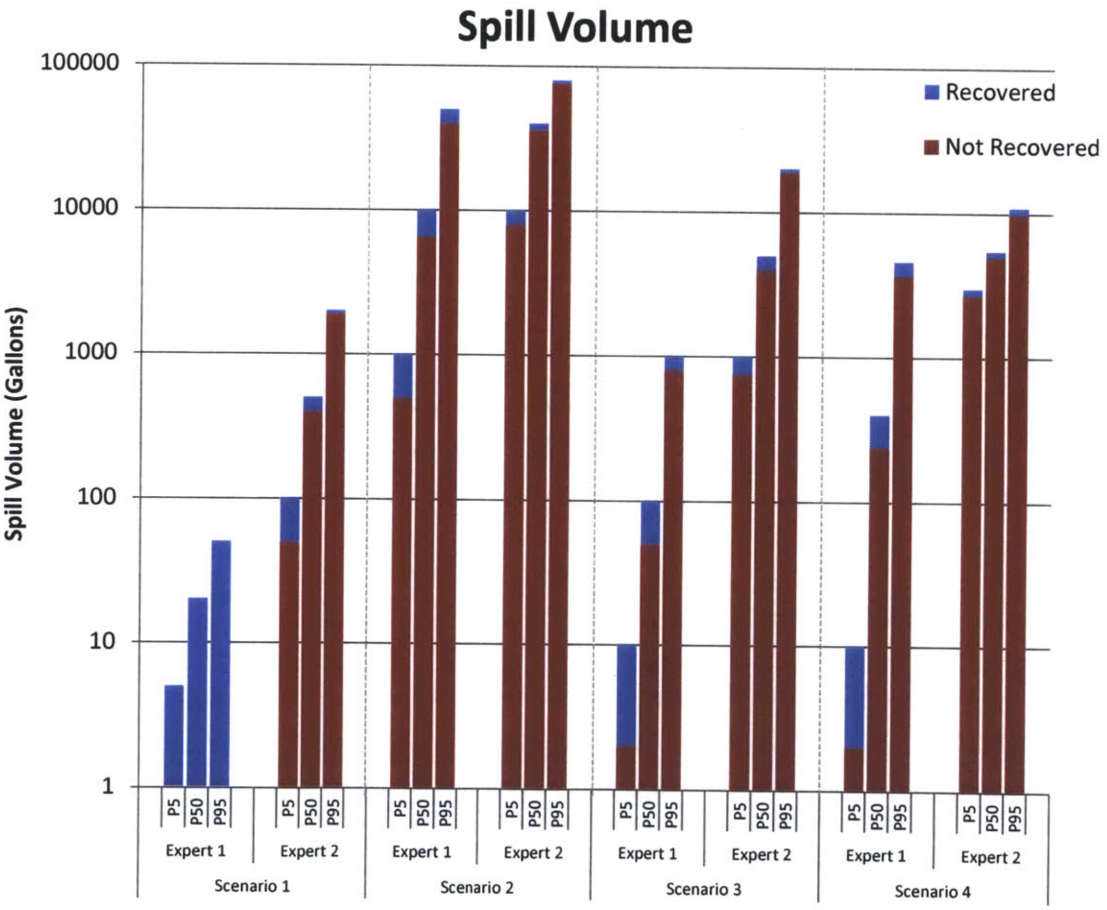

Figure 20: Expert estimates of recovered and unrecovered spill volume, by scenario

The stacked bar graph in Figure 20 illustrates the recovered and unrecovered portion from each volume estimate. In this graph, the upper and lower bounds are represented as separate bars to the left and right respectively of the median estimate, instead of as error bars.

The chart in Figure 21 shows experts' estimates for the volume of spill that enters the environment. This was generated using the data from Figure 19 but taking out the percent recovered estimated for each data point by each expert.

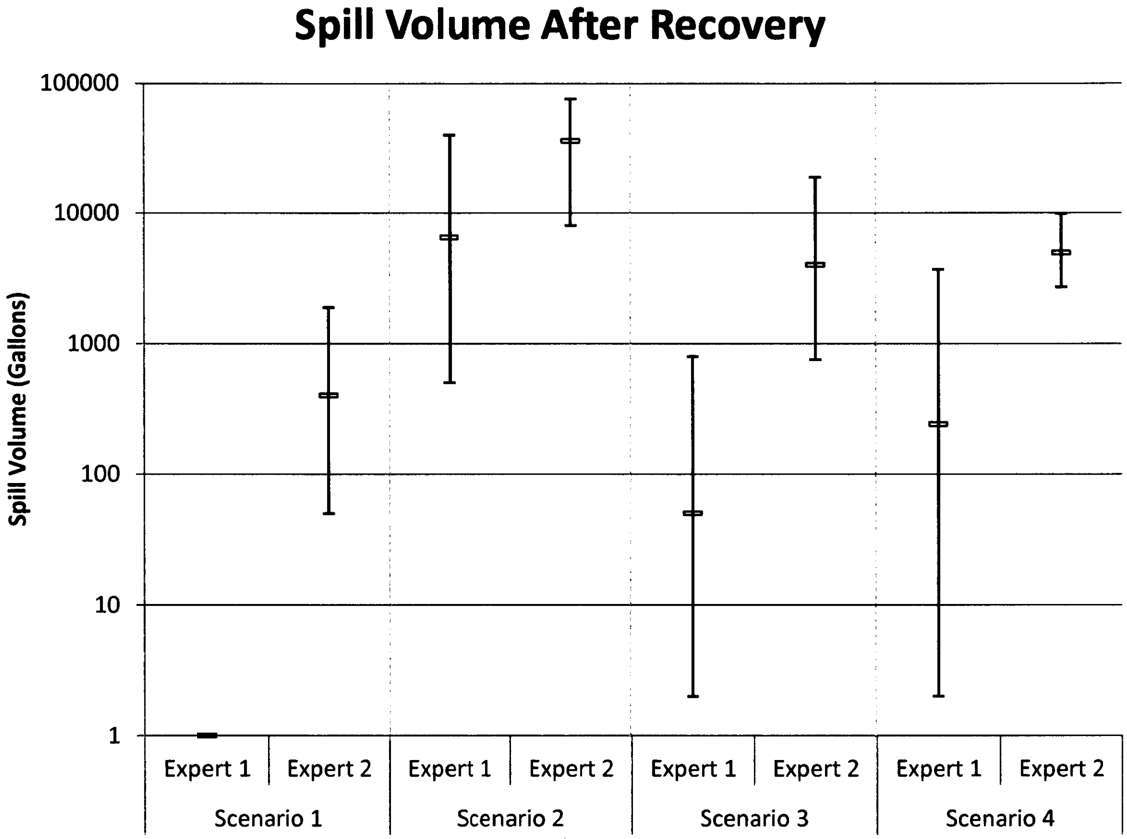

Figure 21: Expert estimates of spill volume after recovery, by scenario.

One trend is clear across both experts and confirmed by both the plots above and the expert-drawn histograms: a larger percentage of fluid is recovered from smaller spills. In fact, less than half is expected to be recovered for large spills; neither expert reported a recovery rate of 50% or greater for spills greater than 100 gallons. This suggests that secondary containment and recovery practices do not sufficiently mitigate the most severe spills, such as those from blowouts.

5.4.3 Cause of spills

In addition to characterizing the number and volume of spills expected from each scenario, experts were also asked to identify the primary cause of spills from each scenario. Four possible causes were identified for experts: human error, equipment failure, acts of nature, or other. Human error was restricted to only human error on the well site; human error in manufacturing of equipment is included under the equipment failure category.[15] For each category, each expert identified the percentage of spills each category caused. Figure 22 below illustrates these responses.

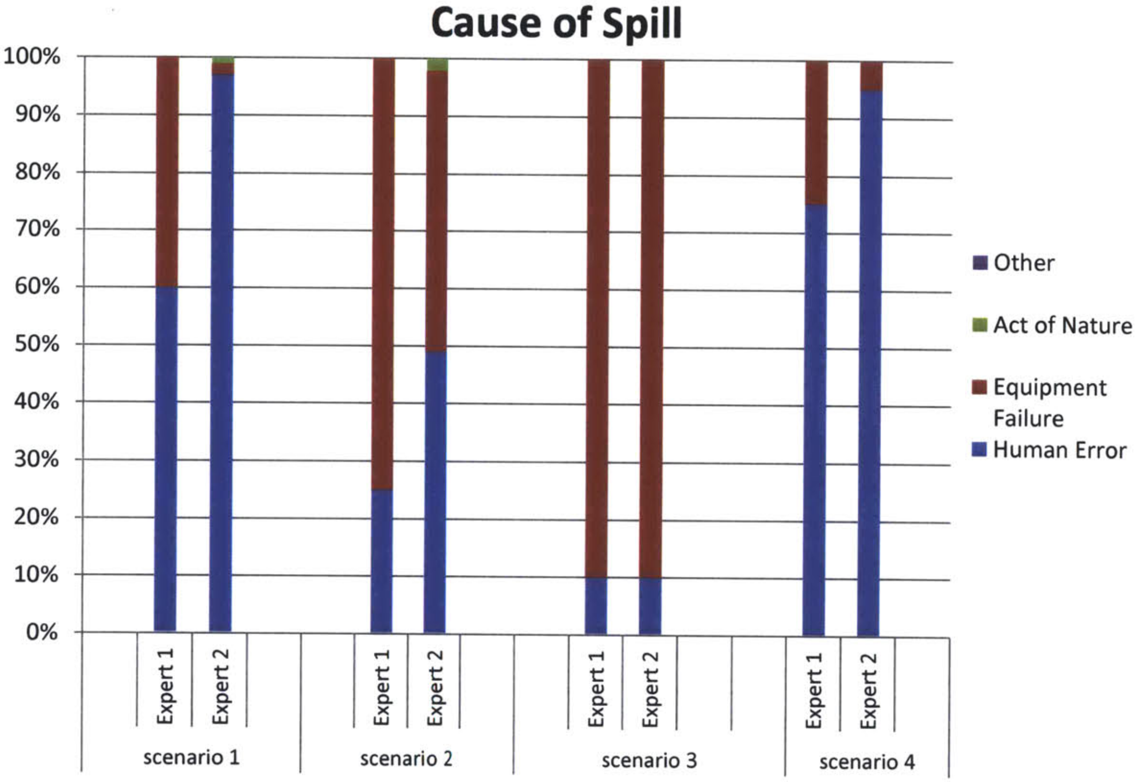

Figure 22: Expert estimates of the primary cause of spills, by scenario

Both experts agree that human error and equipment failure are the two major sources of fluid spill. Only expert 2 listed acts of nature at all, as a potential cause of pipe leaks or well blow outs, but only in a very small fraction of incidents. Neither expert identified any other sources of spill.

Experts agree that equipment failure is likely to account for the vast majority of spills from scenario 3, pit leaks or overflows; they also agree that human error is likely to account for the majority of spills from during truck transportation in scenario 4. Although scenarios 3

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[15] The definitions of human error and equipment failure were not included in the written elicitation tool but discussed with all experts by phone.

and 4 are similar in order of magnitude for both number of spills and spill volume, their major causes are different. This may suggest different risk management strategies for each. The results for scenarios 1 and 2 are less straightforward; it is possible that both human error and equipment failure play a significant role in these scenarios.

5.4.4 Scenario summaries

Scenario 1: Pipe leaks between blender and wellhead

	Number of spills per year		**Volume of fluid spilled (gallons)**		**Percent of volume recovered**		**Unrecovered fluid (gallons)**	
	Expert 1	**Expert 2**	**Expert 1**	**Expert 2**	**Expert 1**	**Expert 2**	**Expert 1**	**Expert 2**
P5	5	10	5	100	80%	50%	1	50
P50	10	30	20	500	95%	20%	1	400
P95	15	100	50	2000	98%	5%	1	1900

Table 1: Scenario 1 expert estimates

The first scenario, in which fluid is spilled from pipes between the blender and wellhead, is the most likely spill to occur. Experts' best guesses for the number of spills from this scenario in the next year are 10 and 30, respectively, out of 1500 wells drilled. While this is not an insignificant number, it suggests that any systemic problem with small leaks likely yields spills below the 5 gallon definition used in this elicitation.

There is more uncertainty around the volume of spills from this scenario, as well as the percentage of fluid that would be recovered. Expert 1 indicates that it would be unlikely for more than 50 gallons to be spilled; no matter what the volume spilled, he expects all but about 1 gallon to be recovered. Expert 2, however, estimates 500 gallons to be the average spill size, with an upper bound of 2000 gallons. He also expects that, while half of the fluid would be recovered for a spill for 100 gallons, only 5% of the fluid would be recovered for a 2000 gallon spill. This is one of the largest discrepancies between experts in the results; expert 1 thinks no more than a few gallons could enter the environment from this scenario, while expert 2 thinks almost 2000 gallons could enter the environment in a worst case scenario.

This may be explained by different assumptions about the kind of pipe failure that occurs. Small spills from bad connections in pipes occur fairly routinely; sometimes liners are placed underneath as secondary containment to capture these leaks. Expert 1 also notes in the survey comments that operators closely monitor these pipes and respond quickly to problems, minimizing impact. Alternatively, larger spills from pipes may be caused by pumping failures that lead to high pressure pipe failures; these would be less likely to be stopped quickly and the larger volumes would be less likely to be captured by tarps or other secondary containment measures.

Both experts agree that human error is primarily to blame in the majority of spills that occur. However, expert 1 indicates that 40% of spills are primarily caused by equipment failure instead. This may indicate that small leaks are caused often caused by faulty pipes and connections, in addition to poor fluid management.

Scenario 2: Well blowouts

	Number of spills per year		Volume of fluid spilled (gallons)		Percent of volume recovered		Unrecovered fluid (gallons)	
	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
P5	1	0	1000	10000	50%	20%	500	8000
P50	3	1	10000	40000	35%	10%	6500	36000
P95	5	2	50000	80000	20%	5%	40000	76000

Table 2: Scenario 2 expert estimates

Opposite to scenario 1, spills from well blowouts in scenario 2 are the least likely to occur but have the greatest potential to release large volumes of fluid into the environment. Expert 1 estimates a somewhat higher frequency; he expects 3 blowout spills to occur each year with an upper bound of 9. Expert 2 expects only 1 spill per year, with an upper bound of 2.

This difference may be explained by analogous differences in their volume estimates. Expert 1 expects smaller volumes of fluid to be spilled than expert 2; it makes sense that smaller spills would occur more frequently than larger spills. Before recovery, expert 1 expects a well blowout to lead to a median spill volume of 10,000 gallons, with an upper bound of 50,000 gallons before recovery. Expert 2 expects 40,000 gallons as the median, with an upper bound of 80,000 gallons. Interestingly, expert 2's lower bound of 10,000 gallons is the same as expert 1's median spill.

The volume estimates between experts diverge further when recovery rates are considered; expert 2 expects significantly less of the fluid to be recovered for all spill sizes. After recovery, expert 1 estimates a median of 6500 gallons and upper bound of 40,000 gallons; expert 2 estimates a median spill size of 36,000 gallons and upper bound of 76,000 gallons. A likely explanation for this discrepancy is noted in expert 1's survey comments. He explains that on-site cleanup is much easier than off site cleanup; if a spill is contained within the well site's erosion and sediment controls, most of the fluid can be recovered. Fluid that travels off-site is more difficult to clean up.

The cause of well blowout is the most uncertain across scenarios. Expert 1 indicates that 75% of spills are caused by equipment failure, while 25% are caused by human error. His comments indicate that Pennsylvania regulations governing the type of blowout preventer used should prevent equipment failures occurring. Expert 2, however, indicates equal likelihood between equipment failure and human error as the cause, with a 2% chance that acts of nature cause the spill.

Scenario 3: Retaining pit leaks and overflows

	Number of spills per year		Volume of fluid spilled (gallons)		Percent of volume recovered		Unrecovered fluid (gallons)	
	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
P5	5	3	10	1000	80%	25%	2	750
P50	10	5	100	5000	50%	20%	50	4000
P95	20	20	1000	20000	20%	5%	800	19000

Table 3: Scenario 3 expert estimates

Expert responses suggest that, second to pipe leaks, spills from pit leaks and overflows are the next most likely source of spill. Expert 1 expects scenario 3 to cause roughly the same number of spills as scenario 1; the median and lower bound for both scenarios is 10 spills and 5 spills, respectively. The estimated upper bound is 20 spills for scenario 3, compared to 15 spills for scenario 1. Expert 2's distribution is similar: his median estimate is 5 spills with lower and upper bounds of 3 spills and 20 spills, respectively. This is similar to the estimates from expert 1 for this scenario, and significantly lower than expert 2's estimates for scenario 1.

However, the spill volumes estimated by each expert diverge significantly. The upper bound from expert 1 of 1000 gallons before recovery is equal to the lower bound from expert 2. The divergence in fluid entering the environment is wider; as in scenarios 1 and 2, expert 1 expects a significantly greater portion of the volume to be recovered. As a result, expert 1 expects a median and upper bound of 50 gallons and 800 gallons, respectively, to enter the environment. Expert 2 has much higher estimates for the median and upper bound at 4,000 gallons and 19,000 gallons respectively.

Two comments from expert 1's survey may or may not be helpful in explaining this disparity. He indicates that he finds it far more likely that spills will occur from tears in the liner as opposed to overflows; tears are likely to produce smaller spills than overflows. Also, he notes that operators are using tanks instead of pits more frequently in order to prevent spills. This would likely change his estimate of number of spills instead of volume of spills however.

The discrepancy in volumes in this scenario could also be an indicator of the wide range of uncertainty in spill volumes likely. Spill volumes from tears in pit liners are difficult to observe because the fluid goes directly into the ground underneath the pit instead of visibly traveling over the surface. The PA DEP inspection and violation data was particularly ambiguous when assessing retaining pits; violations cited stains near the pits but did not clearly indicate whether spills occurred.

Both experts agreed that 90% of the spills caused by pit leaks or overflows are caused by pit overflows and 10% are caused by human error. This suggests that both experts think overflows, which are caused by human error, are substantially less likely to occur than liner tears, which are caused by equipment failure.

Scenario 4: Wastewater spills during truck transportation

	Number of spills per year		Volume of fluid spilled (gallons)		Percent of volume recovered		Unrecovered fluid (gallons)	
	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
P5	1	0	10	3000	80%	10%	2	2700
P50	5	1	400	5500	40%	10%	240	4950
P95	10	2	4620	11000	20%	10%	3696	9900

Table 4: Scenario 4 expert estimates

Both experts indicate that it would be unlikely for more than 10 spills per year to occur as the result of truck transportation to wastewater treatment facilities; expert 1 indicates a somewhat higher frequency than expert 2. Expert 1's median and upper bound estimates are 5 spills and 10 spills respectively, while expert 2's median and upper bound estimates are 1 spill and 2 spills respectively.

As in scenario 2, the discrepancy may be explained by the analogous volume estimates. Expert 1 expects more frequent smaller spills, while expert 2 expects less frequent but somewhat larger spills. As in the previous scenarios, expert 1 also expects a significantly greater percent of the spilled fluid to be recovered, creating a greater disparity in the amount of fluid that enters the environment than in the amount of fluid spilled before recovery. However, there is still overlap in the ranges presented. Expert 1 estimates a median spill size of 240 gallons, with lower and upper bounds of 2 gallons and 3696 gallons, respectively. Expert 2 estimates a median spill size of 4950 gallons, with lower and upper bounds of 2700 gallons and 9900 gallons, respectively.

Expert 1's calculation of the upper bound is clearly articulated in his survey comments; his upper bound of 4650 before recovery is equal to the volume of a 100 barrel truck tank nearly full. Expert 2 may have been considering a larger truck or more than one truck involved in the spill.

Both experts agree that human error is the primary cause of spills for the majority of truck spills. Expert 1 indicates that 75% of these spills are caused by human error vs. 25% by equipment failure, while expert 2 indicates that 95% of these spills are caused by human error vs. 5% by equipment failure. This makes sense as some kind of collision or other driving accident is likely the primary cause for spillage.

Part III: Groundwater contamination analysis

Chapter 6: Groundwater contamination

6.1 Introduction

The first half of this thesis focused on characterizing the likelihood and size of fracturing fluid spills in the Marcellus Shale in Pennsylvania. It analyzed the data available from regulatory agencies, developed a methodology for eliciting information on spill likelihood and volume from experts, and presented results from a preliminary elicitation study. This information is important in characterizing the extent to which spills are happening in the industry as well as the potential threat these spills might carry to their environment.

The second central question to this thesis is: what is the potential for groundwater contamination from fracturing fluid spills in Pennsylvania? Given the characterization of spill number and volume from the previous part, the next step is to assess the potential for contaminants from such spills to be transported through the groundwater system to water wells nearby.

This is not an easy question to answer. Groundwater transport of contaminants is a complex process that is highly dependent on the hydrogeological characteristics of the specific site and specific contaminant. These characteristics—physical properties that govern the flow of groundwater as well as chemical and biological process that control the behavior of contaminants within groundwater flow—are highly variable. Not only are there a wide range of different aquifer formations within the state of Pennsylvania; the behavior of a single aquifer can vary by several orders of magnitude. High granularity data to characterize the behavior of these aquifers are limited.

Moreover, hydraulic fracturing fluid and wastewater contain a wide range of contaminants. The exact composition of any fluid varies from operation to operation, and voluntary reporting of these compositions has started only recently ("Frac Focus: Chemical Disclosure Registry," 2012). Some work has been done to assess which fluid components are most threatening based on their toxicity, travel speed, and rate of decay (U.S. EPA, 2011); such analysis is outside the scope of this thesis. Additionally, the science assessing dose-response relationships between toxic chemicals in drinking water and human health is complicated. While the model output in this section provides an assessment of the maximum contaminant concentration possible in a nearby water well, it is unclear whether these concentrations are "safe" for drinking. Much more work remains to be done in order to evaluate the potential health effects of small levels of fracturing fluid contaminants in drinking water.

This chapter develops a stochastic, analytical model of groundwater contaminant transport in order to characterize the maximum possible concentration of contaminants in a water well close to a fracturing fluid spill. Similar analytical models are used by U.S. EPA as screening tools in assessing the risk of water contamination at specific waste site (Aziz et al., 2000; Newell, McLeod, & Gonzales, 1996). The model presented here only considers the physical processes of advection and dispersion and ignores chemical, biological and nuclear processes that might affect the speed of transport or rate of decay. As such, it provides a first-order approximation of the fundamental transport processes, but is not a rigorous method for assessing the risk of contamination at a specific spill site.

This model is applied to a series of hydrogeological scenarios intended to be representative of the diverse range of actual geologies present in the state of Pennsylvania. "Worst-case scenario" spill volume and well location are assessed in order to determine the potential for groundwater contamination from the spills characterized in the first part of the risk assessment. Sensitivity analysis is performed on a range of parameters in order to assess the impact of hydrogeological differences on overall contamination potential.

The goal of this analysis is three-fold. First, I explain the fundamental processes that govern groundwater contamination as it relates to the problem of fracturing fluid spills. Second, I provide a first-order characterization of the worst-case contaminant transport outcomes possible across Pennsylvania and identify the key drivers of variation across scenarios. Third, I describe the methodology used to assess human health risk and apply it to one additive as an example. This analysis provides a basis for assessing the adequacy of the current regulatory framework governing groundwater protection from fracturing fluid spills in Pennsylvania.

6.2 Aquifers and groundwater flow

When a fracturing fluid spill occurs at a shale gas extraction site, the fluid that is not recovered enters the environment in some way. There are two pathways through which this fluid could enter the water system. First, it can run over the surface of the ground into a body of surface water, such as a local stream or river. Second, it can infiltrate the ground and enter the groundwater system. I analyze only the groundwater pathway in this thesis. The justification for this is two-fold. First, groundwater is the immediate source of drinking water for the majority of residents in rural and suburban Pennsylvania (Makuch, 1986). While surface water contamination may cause ecosystem damage and other environmental concerns, groundwater contamination is more likely to affect human health. Second, runoff into surface water is easily observable and understood; many incidents of fracturing fluid runoff into local streams are well documented. Because groundwater contamination is not readily observable, it is more difficult to link specific spills to incidents of groundwater contamination. This analysis aims to assess the likelihood of this occurrence.

This section describes the nature of groundwater aquifers and the flow of groundwater as it relates to contaminant fate and transport. The information described is easily accessed in variety of textbooks on groundwater hydrogeology. The primary references used in this description are (Domenico & Schwartz, 1998) and (Kresic, 2007).

6.2.1 Groundwater aquifers

Water or other fluids spilled on the surface of the ground infiltrate the groundwater system. Fluids first enter the unsaturated zone, the area of soil and rock immediately under the surface. The pores in the rock or soil in the unsaturated zone contain both water and air. Some of the water in the unsaturated zone is transpired by plants; the rest seeps further underground as the result of gravity and enters the saturated zone, in which rock or soil pores are completely filled with water. The saturated zone is comprised of groundwater aquifers, which store and transmit groundwater. Note that while some groundwater flow occurs in the unsaturated zone, it is at a much slower rate than groundwater flow in the saturated zone; most groundwater models ignore the unsaturated zone (Kresic, 2007).

Groundwater aquifers can be either confined or unconfined. Unconfined aquifers rest immediately below the unsaturated zone; the water table is the upper boundary of an unconfined aquifer. Confined aquifers rest below a layer of relatively impermeable rock. Contaminant spills on the surface are therefore more likely to affect unconfined aquifers, which are the primary source for water wells. Therefore, the analysis here is restricted to unconfined aquifers. See Figure 23 below for an illustration of the unsaturated zone, an unconfined aquifer and a confined aquifer, as well as the effect of a surface spill on the groundwater system.

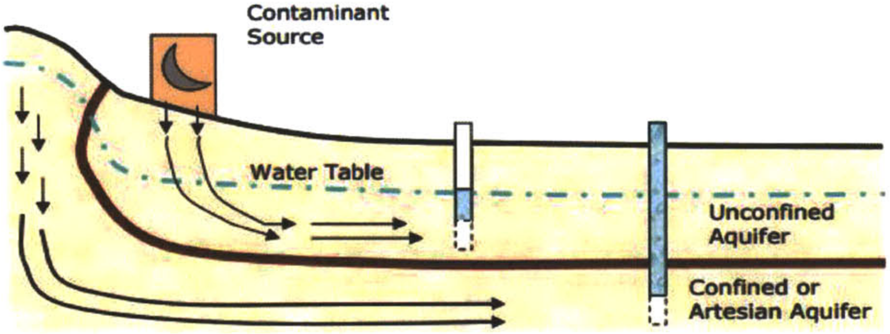

Figure 23: Unconfined aquifer and confined aquifer. Surface contamination is more likely to affect unconfined aquifers. Source: MIT Open Courseware, 1.72 Groundwater Hydrology lecture notes.

6.2.2 Groundwater flow

Groundwater flow in aquifers is slow and variable. Faster moving aquifers transmit groundwater at a rate on the order of feet per day, and slower moving aquifers transmit groundwater at speeds on the order of inches per year (Makuch, 1986). The driving forces behind groundwater flow are gravity—groundwater tends to flow from high elevation areas to low elevation areas—and pore or matric pressure. The combination of these forces determines the hydraulic head at any point in the groundwater system; the gradient in hydraulic head between any two points governs the flow of groundwater between those points.

Because of the high variability of any geologic formation in nature, it is difficult to make hard generalizations about the flow of groundwater. However, some robust empirical observations provide a solid analytical framework for analyzing flow. French civil engineer Henry Darcy observed that the velocity of flow is directly proportional to the hydraulic gradient. Darcy's law describes the relationship between hydraulic gradient and velocity of flow in porous media. This relationship can be expressed as:

$$\frac{Q}{A} = -K\frac{\partial h}{\partial x}$$

Equation 1: Darcy's Law

In the equation above, Q is a volumetric flow rate per unit surface area A. The ratio Q/A is known as the Darcy velocity. On the right hand side, $\partial h/\partial x$ is the hydraulic gradient as discussed above, and K is hydraulic conductivity, which is a measure of the ease with which fluid flows through the pores of the soil or rock in the aquifer.

Darcy's velocity, however, is not a realistic measure of actual groundwater flow because groundwater only flows through the connected pore space in the aquifer medium and not the entire surface area A. Dividing by the effective porosity, n_e, the percentage of interconnected pore space, yields a more accurate measure of groundwater velocity responsible for admixture transport. Therefore, the volumetric groundwater flow rate, v, can be expressed as follows:

$$v = \frac{Q}{n_e A} = -\frac{K}{n_e}\frac{\partial h}{\partial x}$$

Equation 2: Groundwater velocity from Darcy's Law

This characterization of groundwater flow will be useful in describing the transport of contaminants through groundwater aquifers.

6.2.3 Hydrogeological variation

While Darcy's law provides a simple analytical method for characterizing groundwater flow, the heterogeneity of groundwater aquifers makes such a characterization much more difficult in practice. Values for hydraulic conductivity in different soils and rock range across many orders of magnitude; likewise, porosity values vary widely across aquifer media. Table 5 below illustrates the range of representative porosity[16] and hydraulic conductivity values across typical soils and rocks found in groundwater aquifers.

This magnitude of variation is present not just across geologic formations at large, but also within Pennsylvania's aquifers. The major aquifer formations in Pennsylvania include soil and rock media from all three major categories in Table 5 (Makuch, 1986).

In addition to differences across geologic formations, each single aquifer varies considerably. The hydraulic conductivity of soil in a single aquifer may range across two or three orders of magnitude (Domenico & Schwartz, 1998). Likewise, the hydraulic gradient at any point is a function of the elevation and wells nearby; this varies considerably from point to point in a given formation. This makes it difficult to use deterministic analytic tools to characterize the flow at a specific location using only generalized data on soil properties.

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[16] Note that total porosity is distinct from effective porosity, the value used to characterize groundwater flow rate in Darcy's law. Total porosity is the ratio of void volume to total volume, while effective porosity is the ratio of connected pore space to total volume. The values in Table 5 indicate total porosity.

Material	Porosity (%)	Hydraulic Conductivity (m/s)
Sedimentary		
Gravel	24-38	$3 \times 10^{-4} - 3 \times 10^{-2}$
Sand, coarse	31-46	$9 \times 10^{-7} - 6 \times 10^{-3}$
Sand, fine	26-53	$2 \times 10^{-7} - 2 \times 10^{-4}$
Silt	34-61	$1 \times 10^{-9} - 2 \times 10^{-5}$
Clay	34-60	$1 \times 10^{-11} - 4.7 \times 10^{-9}$
Sedimentary rocks		
Sandstone	5-30	$3 \times 10^{-10} - 6 \times 10^{-6}$
Siltstone	21-41	$1 \times 10^{-11} - 1.4 \times 10^{-8}$
Limestone, dolomite	0-40	$1 \times 10^{-9} - 6 \times 10^{-6}$
Karst limestone	0-40	$1 \times 10^{-6} - 2 \times 10^{-2}$
Shale	0-10	$1 \times 10^{-13} - 2 \times 10^{-9}$
Crystalline rocks		
Basalt	3-35	$2 \times 10^{-11} - 4.2 \times 10^{-7}$
Weathered granite	34-57	$3.3 \times 10^{-6} - 5.2 \times 10^{-5}$
Weathered gabbro	42-45	$5.5 \times 10^{-7} - 3.8 \times 10^{-6}$

Table 5: Representative values of porosity and hydraulic conductivity for various media reproduced from (Domenico & Schwartz, 1998).

6.3 Fate and transport of contaminants

The above section describes the flow of groundwater in aquifers. In order to characterize the potential for groundwater contamination, it is also necessary to understand how the contaminants in fracturing fluid interact and travel within groundwater. A surface spill that enters groundwater is usually described and modeled as a "plume" of contaminants that move and spread over time. The physical processes of advection and dispersion govern the first-order transport of the contaminant plume, but chemical, nuclear and biological processes can also play a substantial role. These processes can be categorized into three categories: mass transport, sorption and retardation, and decay.

6.3.1 Mass transport

Contaminants in groundwater undergo the mass transport processes of advection and dispersion. Advection is simply the movement of the center of mass of the contaminant with the flow of groundwater. Dispersion acts to spread out the mass of the contaminant beyond where it would flow by advection alone. These processes are described by the mass transport equation in Equation 3.[17] C, the concentration of contaminants at location x and time t, is determined by a second-order differential on dispersion, D_x, and v_x, the velocity of groundwater flow.

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[17] A one-dimensional version of the mass transport equation is presented here for simplicity. It is easily generalizable to three dimensions; the three-dimensional version underlies the transport model developed in the following chapter.

$$D_x \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}$$

Equation 3: Mass transport equation with advection and dispersion

The rate of advection is equal to the velocity of groundwater flow as described in Equation 2. Dispersion, however, is defined in two components. The first is mechanical dispersion, the physical mixing of the contaminant with groundwater because of small variations in velocity. Mechanical dispersion is dependent on the velocity of groundwater flow as well as the porous medium in the aquifer. The second component is molecular diffusion, the random mixing of molecules due to thermal kinetic energy, which varies depending on the contaminant. Thus, dispersion can be expressed as below in Equation 4, assuming that x is the main direction of groundwater flow:

$$D_x = \alpha_x v + D_e$$

Equation 4: Mechanical dispersion and molecular diffusion

D_x is the total dispersion in the direction of groundwater flow. The first term on the right hand side is mechanical dispersion, defined as the product of α_x, the longitudinal dispersivity with units of length and v_x, the velocity of groundwater flow. Values for longitudinal dispersivity vary across different aquifer media and across different scales of observation. Longitudinal dispersivity is frequently described by the exponential relationship in Equation 5 where C is a property of the aquifer medium, L is the distance from the source at which the plume is observed, and m is a scaling factor consistent across aquifer media (Neuman, 1990).

$$\alpha_x = C * L^m$$

Equation 5: Empirical relationship for longitudinal dispersivity

Equation 5 describes the dispersion in the longitudinal direction, or the main direction of groundwater flow. Dispersion also occurs in the transverse and vertical directions, although at a significantly smaller scale. Typically, transverse dispersivity is assumed to be one order of magnitude smaller than longitudinal dispersivity, and vertical dispersivity is assumed to be one or two orders of magnitude smaller than transverse dispersivity(Kresic, 2007). Using these values, the mass transport equation in Equation 3 can be generalized to three dimensions.

D_e in Equation 4 is molecular diffusion. Note that molecular diffusion is typically small in comparison to mechanical dispersion and is often ignored in modeling approaches (Kresic, 2007). It is ignored in the analysis in this thesis.

6.3.2 Sorption and retardation

Sorption is the group of physical and chemical processes that slow the velocity of contaminants in groundwater. This effect is called retardation, causing the average speed of the contaminant plume to be slower than the average rate of groundwater flow. The retardation factor caused by sorption is defined as:

$$R = \frac{v_w}{v_c}$$

Equation 6: Retardation factor

v_w is the velocity of groundwater and v_c is the velocity of the contaminant. The addition of retardation changes the mass-transport balance described in Equation 3. With retardation, mass transport is described as follows, using the retardation factor R in Equation 6.

$$\frac{D_x}{R}\frac{\partial^2 C}{\partial x^2} - \frac{v_x}{R}\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}$$

Equation 7: Mass transport equation with advection, dispersion, and retardation

There are multiple different sorption processes that can occur and cause retardation. Particles in the contaminant fluid can be absorbed into a solid structure in the aquifer medium; they can also be adsorbed onto the surface of a solid. I do not model any of these processes in this thesis, so I do not describe their governing equations here. However, the net effect of all these processes is to slow the velocity of the contaminant plume in comparison to the groundwater velocity, making the retardation factor greater than 1. The retardation factor varies across specific contaminants; some contaminants are largely unaffected by sorption processes and therefore well-described by Equation 3.

6.3.3 Degradation

In addition to being slowed by sorption processes, contaminants can also decay as the result of biological or nuclear processes. For example, some of the naturally occurring radioactive material (NORM) present in fracturing fluid decays with its natural half-life into more stable compounds over time (U.S. EPA, 2011). Likewise, a variety of biological processes caused by interactions with soil in the aquifer can cause some contaminants to decompose over time. The overall effect of degradation, either nuclear or biological, is to decrease the overall amount of the original contaminant in the plume. The addition of degradation changes the mass-transport balance in Equation 3 as follows.

$$D_x\frac{\partial^2 C}{\partial x^2} - v_x\frac{\partial C}{\partial x} - \lambda C = \frac{\partial C}{\partial t}$$

Equation 8: Mass transport equation with advection, dispersion, and degradation

In Equation 8, λ is the decay constant of the contaminant. For radioactive materials, this is the same as half-life. The value of the decay constant varies widely across contaminants. Some contaminants do not decay and are well described by Equation 3.

Figure 24 below illustrates the effect of advection, dispersion, sorption and degradation on an initial "slug" of contaminants with initial concentration C_0. Advection simply causes the slug to move forward with time; the addition of dispersion creates the typical observed plume shape by spreading the edges of the slug. Sorption and degradation act to slow the advection of the plume and decrease its overall size.

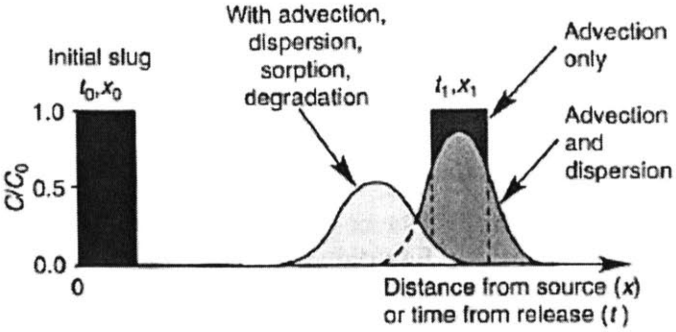


Figure 24: Fate and transport of groundwater contaminants, described by advection, dispersion, sorption and degradation processes. Source: (Kresic, 2007).

6.4 Groundwater contamination modeling

Groundwater contamination modeling is widely used in both academia and government. Groundwater transport models are frequently used as screening models, to assess the risk of groundwater contamination at the site of a new project (Aziz et al., 2000; Newell et al., 1996). They are also frequently used at the site of a contaminant spill or leak in order to assist clean up and remediation efforts. Groundwater models come in a variety of forms. They can be either analytical or numerical and either deterministic or stochastic. The choice of model depends on its use.

Most analytical models are developed by deriving solutions to the mathematical mass transport equations described in the previous section. These models provide a generalizable, first-order description of the possible transport of contaminants. However, they do not accurately describe actual transport of contaminants at any one specific site. While Darcy's law and the mass transport equations described in Equation 2 and Equation 3 above have been closely reproduced in controlled laboratory experiments, the reality of contaminant transport in nature is much more complicated. Variations in the hydrogeological setting of the contaminant transport lead to plumes of irregular shape and size that are not well described by analytical solutions to the differential mass transport equations.

Numerical modeling approaches take these variations into account by discretizing the hydrogeological region of interest into a grid, and solving an approximate mass-transport balance for every cell of the grid. This approach requires a specific characterization of the hydrogeological parameters—such as hydraulic conductivity, porosity, hydraulic gradient, and dispersivity—for each cell in the grid. This is difficult to produce and requires a variety of physical measurements in the area surrounding the site of contamination. Moreover, while this approach more accurately describes the real shape and movement of the contaminant plume, it is still an approximation of reality. It also does not provide results that are generalizable to other sites.

Figure 25 below illustrates the difference in output from typical analytical and numerical modeling approaches. The analytical model on the left shows a generalized, regularly-shaped plume governed by advection and dispersion processes. The numerical model on the right uses a cell-by-cell description of the hydrogeological setting to produce an irregular-shaped plume that more accurately describes the transport of the contaminant at that particular site.

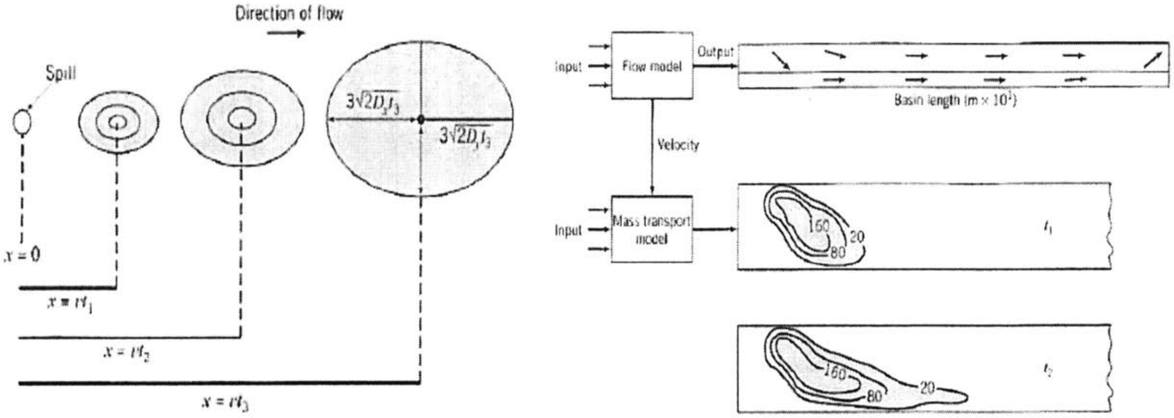


Figure 25: A comparison of an analytical model solution (left) with a numerical model solution (right). Source: (Domenico & Schwartz, 1998).

Both types of models, analytical and numerical, can be either deterministic or stochastic. Deterministic models take a single set of inputs and yield a single set of outputs based on fixed governing equations. Variability and uncertainty can only be modeled with the use of multiple scenarios describing different sets of possible inputs. Because of the high variability present within any hydrogeological setting, as well as uncertainty in the description of that variability, more robust uncertainty analysis is often needed. As a result, stochastic approaches to groundwater modeling have come into widespread use in recent years (Renard, 2007). Stochastic models use probabilistic, not fixed, governing equations. Given a range of possible hydrogeological parameters, the output of a stochastic groundwater model describes the probabilistic distribution of the possible transport results.

Chapter 7: Stochastic spill contaminant transport model

7.1 Approach

7.1.1 Stochastic, analytical model

The nature of the central question of this thesis—characterizing the risk of groundwater contamination from fracturing fluid spills across Pennsylvania—is both very broad and highly uncertain in nature. There is no single site to characterize with a numerical model. Results should be generalizable to a wide variety of settings in order to illustrate to regulators and policy-makers the range of outcomes that are possible. This requires that the inherent variability and uncertainty be well-described by the model. Therefore, I use a stochastic, analytical modeling approach in this thesis. This allows for a probabilistic description of the possible risk of groundwater contamination across the types of hydrogeological settings expected in Pennsylvania.

The analytical model used in this analysis is a closed-form solution to the mass transport balance equation in Equation 3 using the groundwater flow velocity given by Darcy's law in Equation 2. Full parameterization of the model requires a description of the hydrogeological properties of the groundwater system and a characterization of the size, shape and concentration of the initial spill. These inputs yield a function that describes the mass concentration as a function of displacement from the spill site and time since the initial spill.

The most useful output of this model is the expected level of contaminant in a water well near the spill site at any time after the initial spill. Because groundwater flow is slow, it takes a long time for a contaminant plume to travel from a spill site to a water well. The plume will eventually travel a substantial distance, but the further it travels, the more disperse the contaminant will be. At a water-well far away from the spill site, only a negligible amount of contaminant will ever reach the well, even in an infinite amount of time.

7.1.2 Worst-case scenario approach

This analysis following provides a "worst-case scenario" description of the possible level of contaminants in a water well. I assume that groundwater flows directly towards the water well (that is: the hydraulic gradient is in the direction of the water well). In reality, a well very close to the spill site but up-gradient from the spill may be unaffected. I solve for the maximum level of contaminant concentration expected in the well at any time after the spill. This occurs at the time at which the contaminant plume is centered around the water well; this time may be very long after the spill takes place.

I also perform the majority of the analysis for a water-well 200 feet from the spill site; this is the minimum setback distance allowed by current Pennsylvania regulation (PA Code §25.78.). I use 50,000 gallons as worst-case spill size, based on the results of the preliminary elicitation presented in Part II of this thesis. Figure 26 describes the necessary inputs of the model, the intermediate calculations, and the available outputs.

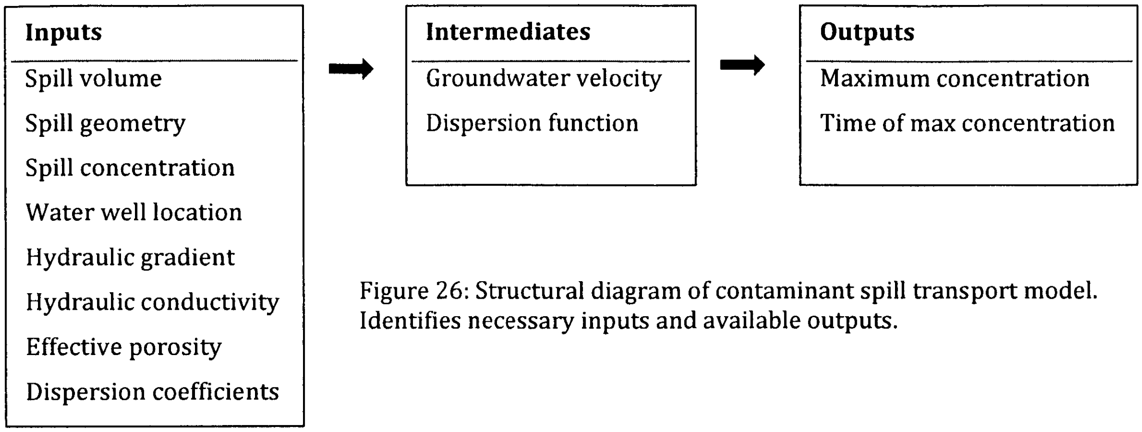


Figure 26: Structural diagram of contaminant spill transport model. Identifies necessary inputs and available outputs.

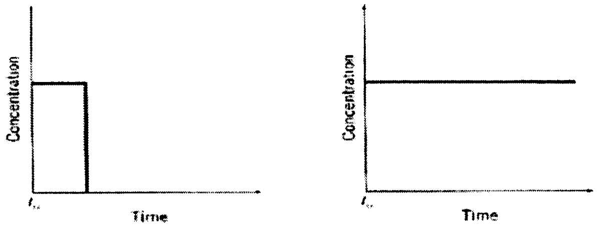
I develop a series of stochastic scenarios to input. The primary scenario analysis is a variation in the four hydrogeological parameters in order to describe the range of different aquifers that exist in the state of Pennsylvania. Because these parameters are still highly variable within each aquifer category, each hydrogeological parameter is described probabilistically, and Monte Carlo simulation is used to assess the range of outcomes in each aquifer scenario. I also use deterministic scenario analysis to vary the spill volume and the water well location.

7.2 Model Choice

7.2.1 Source loading

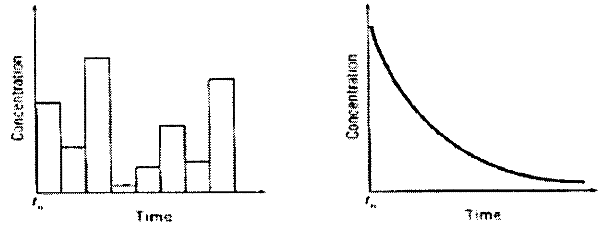
Several common analytical models for contaminant transport in groundwater exist. The mass-transport equations described in the previous sections have a variety of analytical solutions that vary by choice of boundary conditions. The geometry of the contaminant source should govern the model that is chosen. Contamination from slow leaks over a long period of time should be modeled as a continuous source; the rate of leak may be constant or decreasing over time. Spills, however, are not continuous and should be modeled by a pulse or instantaneous point source. Several common source-loading functions are depicted in Figure 27 below.

In the case of fracturing fluid contamination, most spills happen in a very short period of time in comparison to the time it takes for groundwater to travel a substantial distance underground. Pipe bursts, truck collisions, retaining pit overflows, and well blowouts all cause spills that happen over the course of minutes or hours. The possible exception to this from the four scenarios analyzed in the Part II of this thesis is the possibility of a slow leak from a retaining pit that goes unnoticed by the operator.



(a) Spill or Pulse Loading

(b) Continuous Source Loading
Constant Concentration



(c) Continuous Source Loading
Variable Concentration

(d) Continuous Source Loading
Decaying Concentration

Figure 27: Common source-loading functions used in contaminant transport models. The spill or pulse loading source (top left) best describes the geometry of a fracturing fluid spill. Source: (Domenico & Schwartz, 1998).

Because a short pulse best describes the fracturing fluid spill problem, the most appropriate analytical model to use is one that describes a solution to the mass-transport balance in Equation 3 with a pulse source as the initial boundary condition. Two such solutions in the literature are widely used in a variety of modeling applications. (Domenico & Robbins, 1985) develop a finite-pulse source model in which the initial spill is represented by a parallelepiped. (Baetsle, 1969) presents a pulse source model in which the initial spill is represented by an instantaneous point source. These two models form the basis of many of the screening models used by U.S. EPA (Aziz et al., 2000; Newell et al., 1996). I use the (Baetsle, 1969) model in the analysis presented in this thesis. The instantaneous point source is the best representation for a single, confined spill.

7.2.2 Baetsle model

The Baetsle model is a three-dimensional solution to the advection-dispersion equation with radioactive decay. It has a simple, closed-form expression as follows:

$$\frac{C(x,y,z,t)}{C_o} = \left[\frac{V_o}{8(\pi t)^{3/2}(D_x D_y D_z)^{1/2}}\right] exp\left[-\frac{(x-vt)^2}{4D_x t} - \frac{y^2}{4D_y t} - \frac{z^2}{4D_z t} - \lambda t\right]$$

Equation 9: Baetsle model for groundwater contaminant transport. (Baetsle, 1969).

x = distance from initial point source in the direction of groundwater flow
y = distance from initial point source in the transverse direction
z = distance from initial point source in the vertical direction
t = time since point source
v = groundwater velocity (described by Equation 2 above)

C = concentration of contaminants at point (x,y,z,t) given a point source at (0,0,0,0)
C_0 = concentration of contaminants in the point source
V_0 = volume of point source
D_x = longitudinal dispersion
D_y = transverse dispersion
D_z = vertical dispersion
λ = decay constant

7.3 Parameterization

7.3.1 Characterizing Pennsylvania aquifers

In order to appropriately parameterize the Baetsle model to address contamination from fracturing fluid spills in Pennsylvania, it is necessary to characterize the groundwater aquifers in Pennsylvania. While a wide range of geologic formations exist within the state, there are four main classes of aquifers (Makuch, 1986). These aquifers are illustrated in Figure 28 below, and I model four hydrogeological corresponding scenarios:

Scenario I. Unconsolidated sand and gravel aquifers
Scenario II. Fractured sandstone and shale aquifers
Scenario III. Fractured limestone and dolomite aquifers
Scenario IV. Fractured crystalline rock aquifers

The first type, unconsolidated sand and gravel aquifers, is a sedimentary aquifer; groundwater travels through pores in sediment. There is relatively high pore space and therefore slower groundwater velocities. The other three are fractured rock aquifers, in which groundwater travels through cracks in subsurface rock. There is small effective porosity, especially in fractured crystalline rock, producing relatively faster groundwater flows. While there is considerable physical variability within each type of aquifer, a significant body of literature exists describing aquifer properties at a similar level of granularity.[18] It is possible to characterize a finite range of values for each hydrogeological property needed to fully parameterize the model.

Descriptions of four variable hydrogeological properties—hydraulic conductivity (K), hydraulic gradient $(\partial h/\partial x)$, effective porosity (n_e), and longitudinal dispersivity (α_x) — are needed to parameterize each of the four stochastic hydrogeological scenarios.

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[18] See, for example, (Newell et al., 1990) and (Schulze-Makuch, 2005).

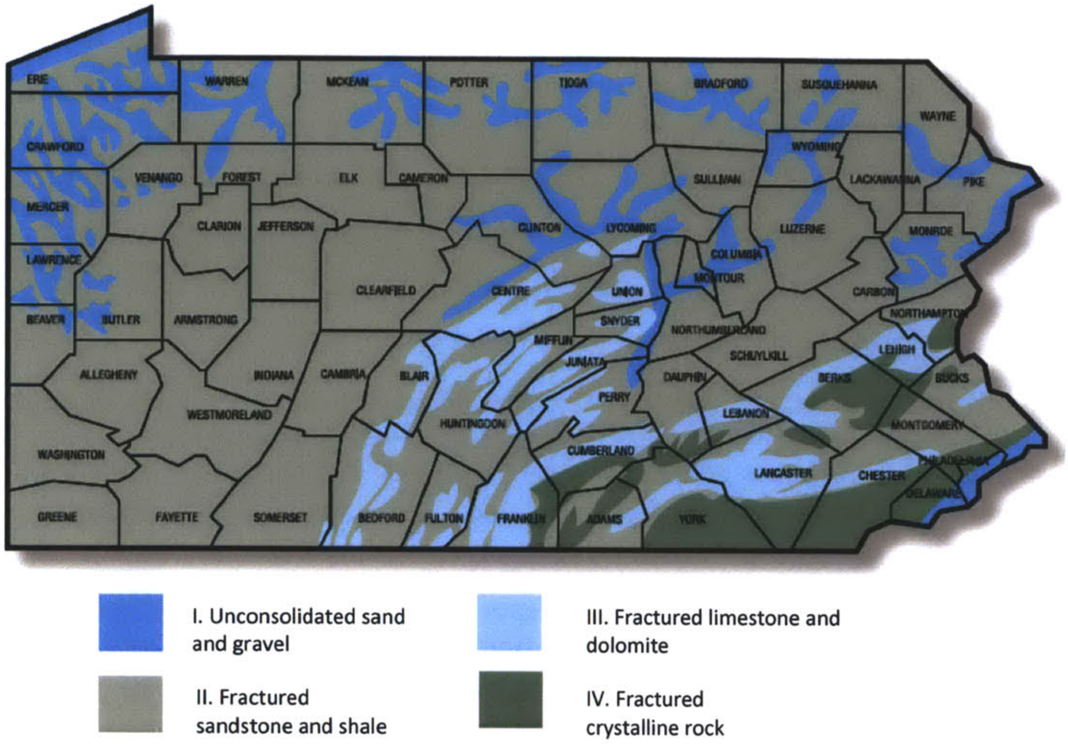

Figure 28: Generalized map of aquifer and well characteristics in Pennsylvania. Reproduced from (Makuch, 1986).

Hydraulic conductivity and hydraulic gradient data is taken from the Hydrogeologic Database for Ground-Water Modeling (HDGB) developed by (Newell, Hopkins, & Bedient, 1990). The authors compiled information from over 400 field site investigations in order to provide an independent source of data for Monte Carlo modeling. It is intended to be used for general site characterization and is therefore appropriate for the four aquifer scenarios described above. It also provides a source of data for similar U.S. EPA screening models (Newell et al., 1990). While HDBG compiles data from across the country, the data is separated into broad categories, which I map to the four Pennsylvania aquifer categories. Both hydraulic gradient and hydraulic conductivity are widely reported to follow lognormal distributions (Kresic, 2007). The data in the in HDBG also closely fits a lognormal distribution (Newell et al., 1990). Therefore, I sample from a lognormal distribution for both parameters in my model.

Effective porosity data I take from the ranges provided for various aquifer types in (Domenico & Schwartz, 1998). Because porosity values exist only on a finite range, I assume a symmetric triangular distribution to set hard tails on the distribution.

Longitudinal dispersivity data is taken from (Schulze-Makuch, 2005). Longitudinal dispersivity is widely thought to increase with the scale of observation; the farther away from the initial point of contamination, the larger the value of longitudinal dispersivity (Neuman, 1990). This relationship is presented earlier in Equation 5. Similar to HGDB, (Schulze-Makuch, 2005) characterizes the coefficient C and slope of the exponent m for several general aquifer categories. I map these categories to the four aquifer scenarios. The characterizations of C and m for each category yield a point estimate of longitudinal dispersivity, α_x. To develop a distribution, I take the estimates in (Schulze-Makuch, 2005) as the mean of a uniform distribution with variation of $\alpha_x/2$ in each direction. Transverse dispersivity and vertical dispersivity are assumed to be 1/10 and 1/100 of longitudinal dispersivity, respectively, as is common practice in groundwater modeling (Kresic, 2007).

The distributions used in the model, described above, are presented in Table 6 below. Figure 29 and Figure 30 below display PDFs for the lognormal distributions for reference.

	I	*II*	*III*	*IV*
$K[cm/s]$~ *lognormal*	μ_n[19] = -6.61 σ_n = 3.22	μ_n = -7.82 σ_n = 3.68	μ_n = -6.47 σ_n = 2.76	μ_n = -7.87 σ_n = 2.99
$\frac{\partial h}{\partial x}$ ~ *lognormal*	μ_n = -5.57 σ_n = 2.30	μ_n = -4.51 σ_n = 1.38	μ_n = -5.41 σ_n = 1.84	μ_n = -4.08 σ_n = 1.61
n_e ~ *triangular*	min = 24% max = 53%	min = 0.5% max = 10%	min = 0.1% max = 5%	min = 0.00005% max = 0.01%
$\alpha_x[m]$ ~ *uniform*[20]	min = 2.49 max = 9.97	min = 0.51 max = 2.04	min = 2.99 max = 11.95	min = 1.36 max = 5.45

Table 6: Hydrogeological model parameters by aquifer type

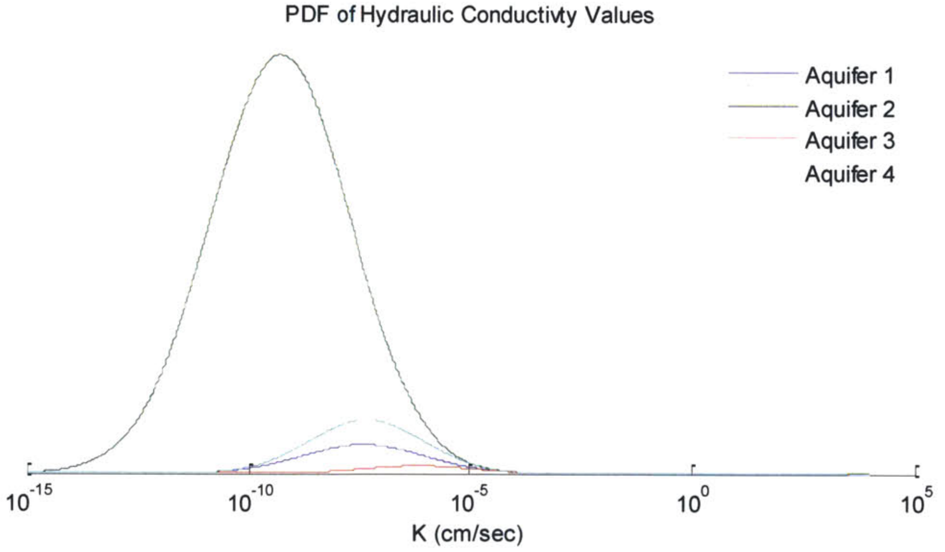

Figure 29: PDF of hydraulic conductivity values

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[19] The values μ_n and σ_n for the lognormal distributions for hydraulic conductivity and hydraulic gradient are the mean and standard deviation of the underlying normal distribution, respectively.

[20] Note: The longitudinal dispersivity coefficients displayed in Table 6 are calculated based on a flow distance of 500 ft. The flow distance is changed accordingly in sensitivity analyses that vary the location of the water well.

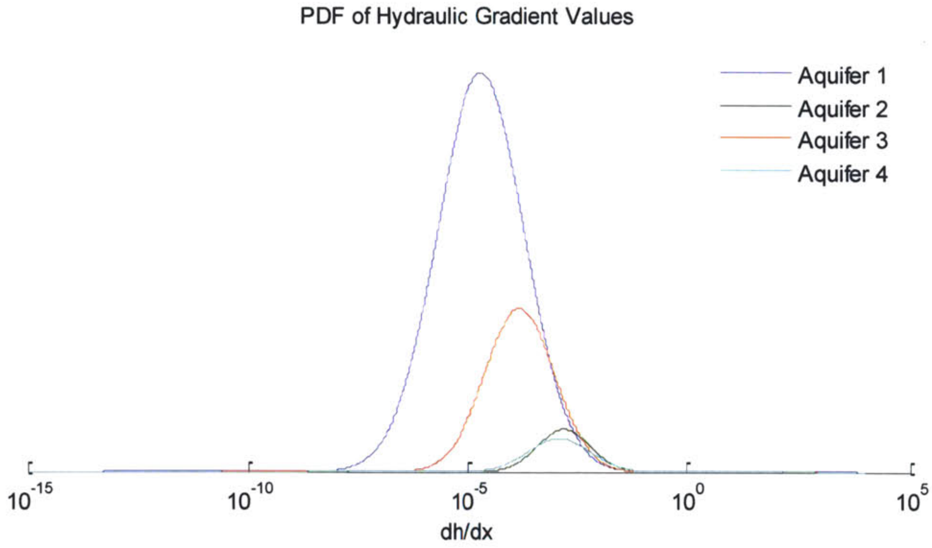

Figure 30: PDF of hydraulic gradient values

As mentioned in the description of the worst-case scenario, I assume the well is in the direction of groundwater flow, the x direction. I also measure the contaminant concentration at z = -5 meters, to account for the depth of a typical water well.

7.3.2 Uncertainty analysis

I use standard Monte Carlo techniques in order to simulate the variability in the four aquifer scenarios described above. Brute force sampling is used to sample from the effective porosity and longitudinal dispersivity. Because the hydraulic conductivity and hydraulic gradient distributions have long tails, I sample from a quasi-random Sobol sequence in order to reduce variance in output. This standard technique is described in (Rubinstein & Kroese, 2008).

In addition to the full Monte Carlo simulation, I also use sensitivity analysis to determine the relative impact of the four hydrogeological parameters on the model output.

Finally, I use scenario analysis to vary the distance to the water well, the spill volume, and the water well depth. While current regulation requires the minimum setback distance to a water well to be 200 feet, the Governor's Marcellus Shale Advisory Commission approved a recommendation to increase this distance to 500 feet (*Governor's Marcellus Shale Advisory Commission Report*, 2011; PA Code §25.78.). I model the 500 feet distance also in order to assess the effect of this regulation on contamination concentration. Additionally, while I use 50,000 gallons as the worst-cast spill size in the majority of the analysis, I also present a smaller more moderate spill scenario of 5,000 gallons for comparison. Finally, I assume that the depth of the water well is 5 meters below the center of the plume. However, I also run the model for a depth of zero meters below the center of the plume in order to assess the effect of well depth.

7.4 Model limitations

The stochastic spill contaminant transport model developed in this chapter is a screening model intended to provide a first order assessment of the risk of groundwater contamination from fracturing fluid spills. While the stochastic approach provides a good estimation of the range of possible outcomes in stylized aquifer categories, the screening model does not provide a precise assessment of the risk at any particular site. Instead, screening model is intended to assess whether more detailed numerical models should be implemented if the risk is significant.

The primary limitations of the risk model include the exclusion of retardation or decay processes, the simplification of the topography, the exclusion of the unsaturated zone, and the sampling of hydrogeological parameters without correlation. Many of the contaminants in fracturing fluid will be significantly altered by the retardation or decay processes described in the previous chapter; this model ignores these processes. This has the potential to overestimate the risk of contamination, and is therefore appropriate for a worst-case approach to risk assessment.

In nature, the specific topography of the area near the spill site has large impact on the shape and velocity of the contaminant plume. Because the screening model is not applied to a specific site, these effects are ignored. The model assumes that the plume travels directly towards the water well in question; this is also a worst-case scenario assumption.

The model ignores the unsaturated zone. As described in the previous chapter, some of the fluid will be transpired by plants or retarded by sorption processes in the unsaturated zone and never make it to a groundwater aquifer below the water table. The magnitude of this effect depends on the amount of recharge in the area and the distance to the water table. This effect is smaller in Pennsylvania than in Texas, for example, because recharge rates in Pennsylvania are relatively high and therefore fluid travels through the unsaturated zone relatively quickly. The spill volume of 50,000 gallons and 5,000 gallons input into the model are representative of the amount that actually makes to the groundwater aquifer; in reality, these inputs may correspond to substantially larger spills on the surface. Also note that because the model ignores the infiltration through the unsaturated zone, the plume is modeled just below the water table, not the surface of the ground. This means that the well depth of 5 meters in the model may corresponds to a slightly deeper well in reality. In Pennsylvania, the unsaturated zone is very shallow and moist, so the effect is relatively small.

Finally, the Monte Carlo simulation was implemented without accounting for correlation between hydrogeological parameters. In reality, the parameters are likely to be correlated, especially hydraulic conductivity and porosity. In nature, this correlation can vary widely in both magnitude and sign. However, sufficient data does not exist to describe the correlation across aquifers in Pennsylvania; therefore, parameters are sampled independently. While all the other limitations of the model are conservative in the sense that they over-estimate risk, it is unknown whether the effect of ignoring correlation would over or under-estimate risk in comparison to reality.

Chapter 8: Contaminant spill transport model results

8.1 Model output overview

The main goal of the modeling is to assess the range of maximum possible levels of contamination as a function of both distance away from the spill and type of aquifer. The maximum concentration in a water well occurs when the plume is centered around the well; this can occur at a variety of different times, depending on the speed of the plume.

In order to characterize the range of maximum concentrations, I run the model for $N=10^6$ samples across different scenarios to produce a series of boxplots of maximum concentration levels.[21] The first set of boxplots show how the maximum concentration varies at different distances for aquifer type II, the most prevalent in Pennsylvania. The next set of boxplots shows the variation across the four different aquifer types; these boxplots are reproduced at three different distances. Both sets of boxplots are duplicated for an initial volume of 50,000 gallons ("large spill") and an initial volume of 5,000 gallons ("moderate spill").

I also analyze the time it takes for the contamination to reach the water well by producing a series of CDFs of the maximum concentration time from each sample; this assesses whether signficant contamination occurs on a time scale of concern to current homeowners. Finally, I use sensitivity analysis on each of the four variable parameters in order to assess which variables are important in describing the variation in the samples.

Note that because this is a screening model, it is the range of results that is most salient. I do not calculate average or percentile values for any of the data presented.

8.2 Maximum concentration by distance

Figure 32 and Figure 33 below show the range of maximum concentration levels from 10^6 Monte Carlo samples at a variety of distances. Note that the distances represented on the x-axis are not to scale. Also note that the vertical axis is plotted on a log scale.

The value "C_{max}" is a dimensionless number; it represents the maximum concentration of the fluid at some distance away from the spill compared to the original concentration of the fluid. For example, a value of 10^{-2} means that the fluid has a maximum concentration of one hundredth of the original concentration of the fracturing fluid. For a particular component of fracturing fluid that was originally 0.001% of the fluid, the 10^{-2} values means that now that particular component is expected to have a maximum concentration of 0.00001%. It is appropriate to think of C_{max} as a dilution factor for fracturing fluid as a whole. The dilution of any partiuclar component may be greater if it is affected by sorption or decay processes, and a concetration limit or safe dose depends on the toxicity of the particular component.

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[21] Note that $N=10^6$ was sufficient for convergence when sampling from a Sobol sequence was used for two parameters. The boxplots are nearly identically reproduced for every $N = 10^6$ run.

The reults are presented as boxplots. Figure 31 below illustrates the notation used in the boxplots throughout this thesis. 50 perecent of the samples are contained within the blue box; the lower blue line marks P5 and the upper blue line marks P75. 90 percent of the samples are contained bewteen the black whiskers at P5 and P95. Outliers are denoted in red above and below the black whiskers.

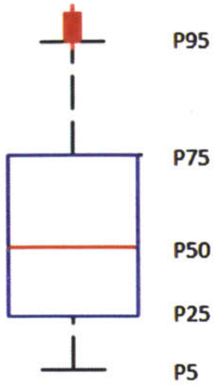

Figure 31: Sample boxplot

The results show that for both size spills, the highest concentrations are possible at a distance 1,000 feet away from the spill. Greater than 1,000 feet from the well, concentrations decrease as a result of dispersion of the plume. Close to the well, concentrations are low because the spill, modeled as a point source, has not dispersed significantly in the vertical direction to reach the bottom of the well 5 meters below the source of the spill.

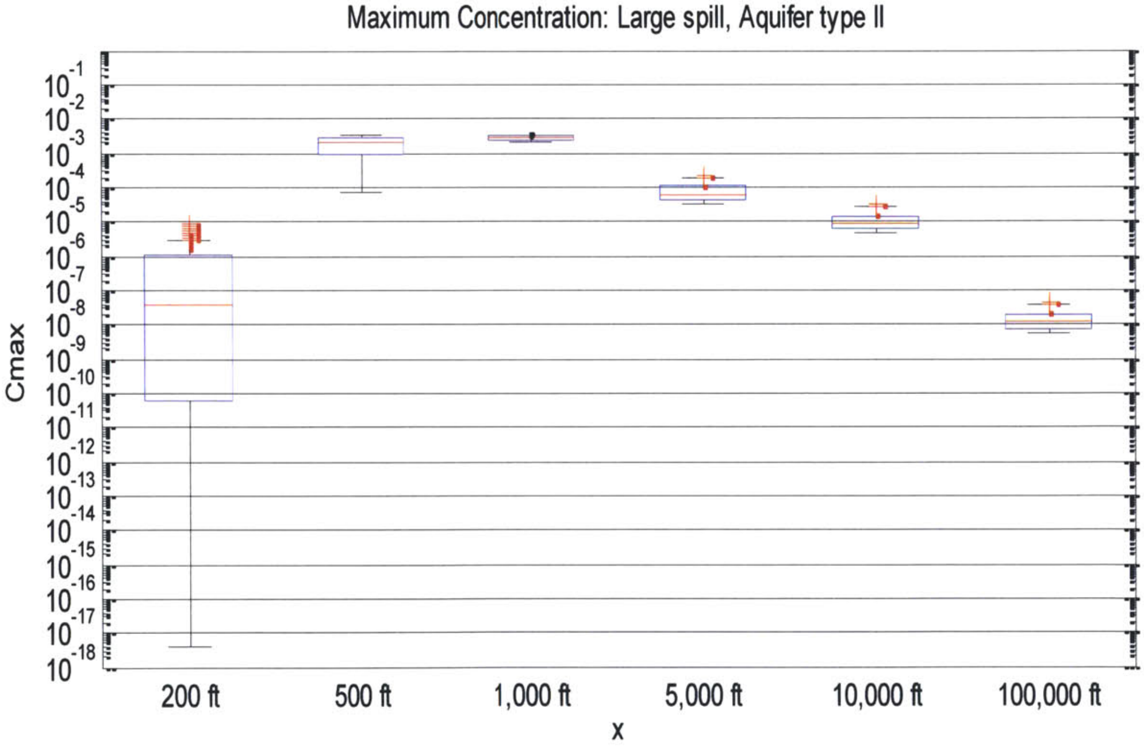

Figure 32: Boxplot of maximum concentration from a large spill in fractured sandstone and shale aquifers. X-axis not to scale.

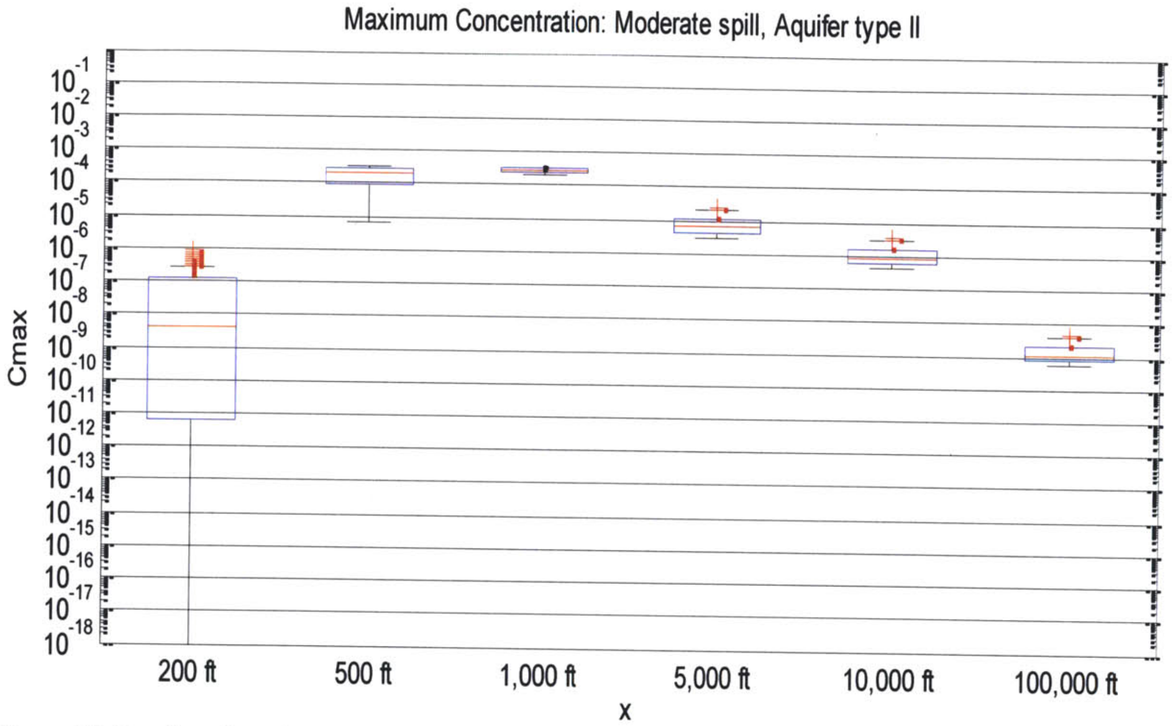

Figure 33: Boxplot of maximum concentration from a moderate spill in fractured sandstone and shale aquifers. X-axis not to scale.

Figure 34 below depicts this effect. The plume in the figure travels in the x direction, and disperses in both the longitudinal and vertical directions. However, dispersion is much smaller in the vertical direction. As a result, the plume does not reach z = -5 meters until t = 3. Note that this is a highly stylized depiction of a plume and does not take into account the vertical infiltration through the unsaturated zone. In reality, this plume looks more like the right hand side of Figure 25 in the previous chapter. However, the overall effect of limited vertical dispersion causing low concentration close to the well is still applicable.

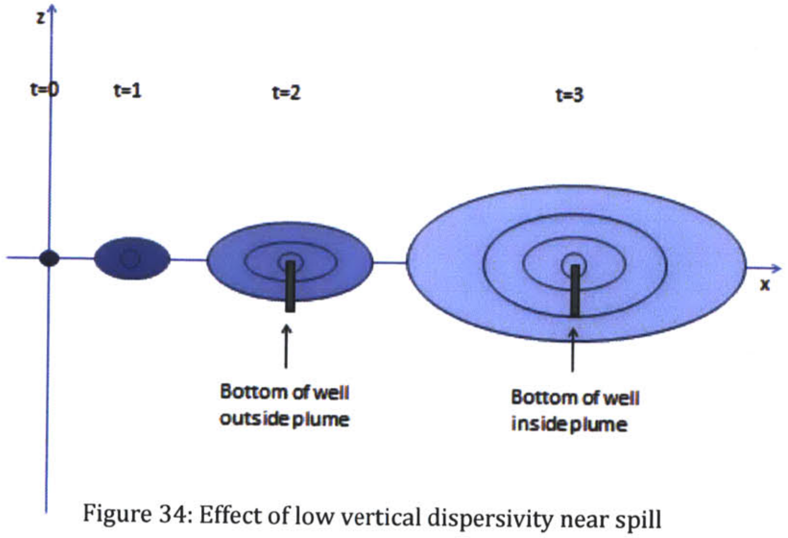

Figure 34: Effect of low vertical dispersivity near spill

Indeed, when the concentration is instead measured at the same height as the initial point source (z=0), this effect is not observed. The concentration monotonically decreases with increasing distance from the spill, as shown in Figure 35 below.

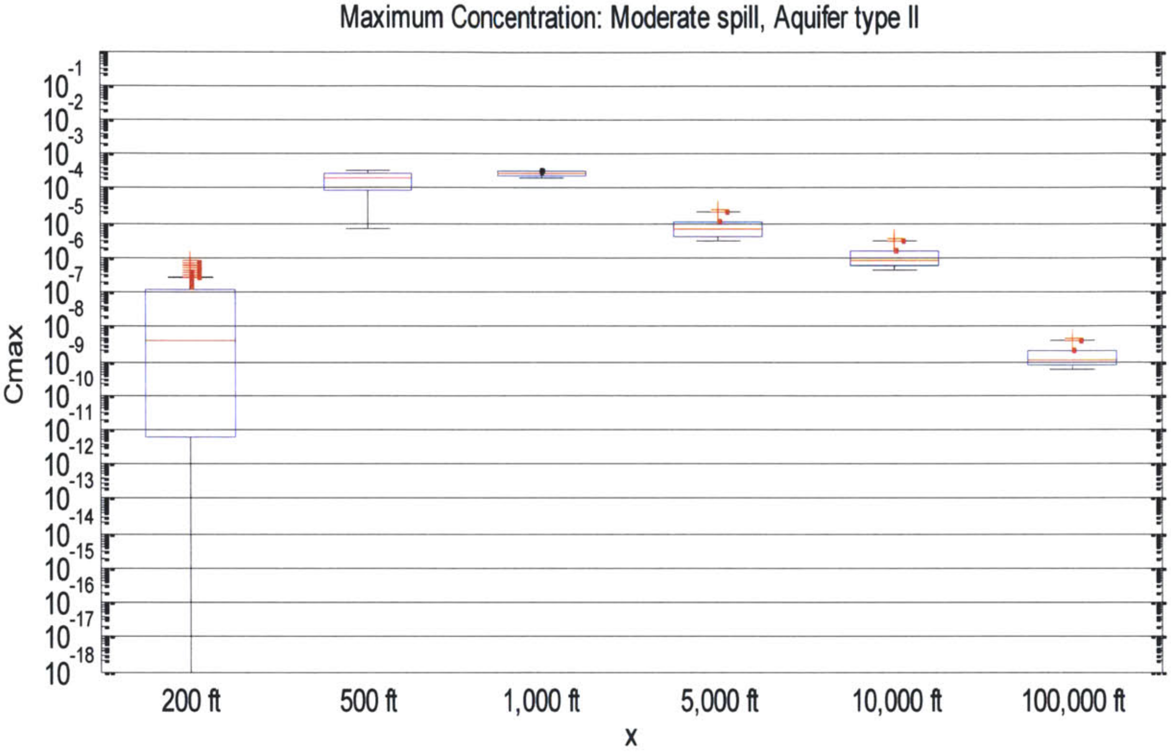

Figure 35: Boxplot of maximum concentration, assuming zero well depth. X-axis not to scale.

The comparison between Figure 33 and Figure 35 demonstrates that the depth of the well has a significant effect on the amount of contamination expected. Note that pumping from a water well has a drawdown effect: water above the bottom of the well is pulled down towards the bottom of the well to replace the pumped water. This could have the effect of pulling contaminants at a higher vertical position into the well beyond what is expected from vertical dispersion. However, a small, private water well has a small cone of depression, which means that the effect is relatively small transient in comparison to field effects from the spill. The difference between Figure 33 and Figure 35 is an important result; the depth of the water well impacts the amount of contamination possible.

8.3 Maximum concentration by aquifer

The previous boxplots demonstrated the effect of distance from the spill on contamination level. Now that this relationship is understood, the plots below show two other important results: the overall magnitude of the range of maximum contamination levels, and the variation of this result across the four aquifer types in Pennsylvania. I plot these results for large and moderate spills, at distances of 200 feet, 500 feet, and 5,000 feet from the spill.

The "Aquifer type" labeled on the horizontal axis corresponds to the four types of aquifers in Pennsylvania described in chapter 6:

Aquifer I. Unconsolidated sand and gravel aquifers
Aquifer II. Fractured sandstone and shale aquifers
Aquifer III. Fractured limestone and dolomite aquifers
Aquifer IV. Fractured crystalline rock aquifers

Figure 36 and Figure 37 below show the range of maximum concentration levels across the four aquifer types at a distance 200 feet from the well, for a large spill and a moderate spill respectively.

The overall level of C_{max} is significantly lower in aquifer type II than in the other aquifers, for both spill sizes at 200 feet. This is because the dispersivities in aquifer II are significantly lower than in the other aquifers; therefore, the near-field effect discussed in the above section is more significant. The distributions of C_{max} from a large spill in aquifer types I and IV are similar, ranging primarily between 10^{-4} and 10^{-2}. The distribution of C_{max} from a large spill in aquifer type III is somewhat higher and narrower. The results for a moderate spill are very similar for all aquifers, except one order of magnitude lower. This corresponds directly to the difference in size; the moderate spill is exactly one order of magnitude lower in volume than the large spill.

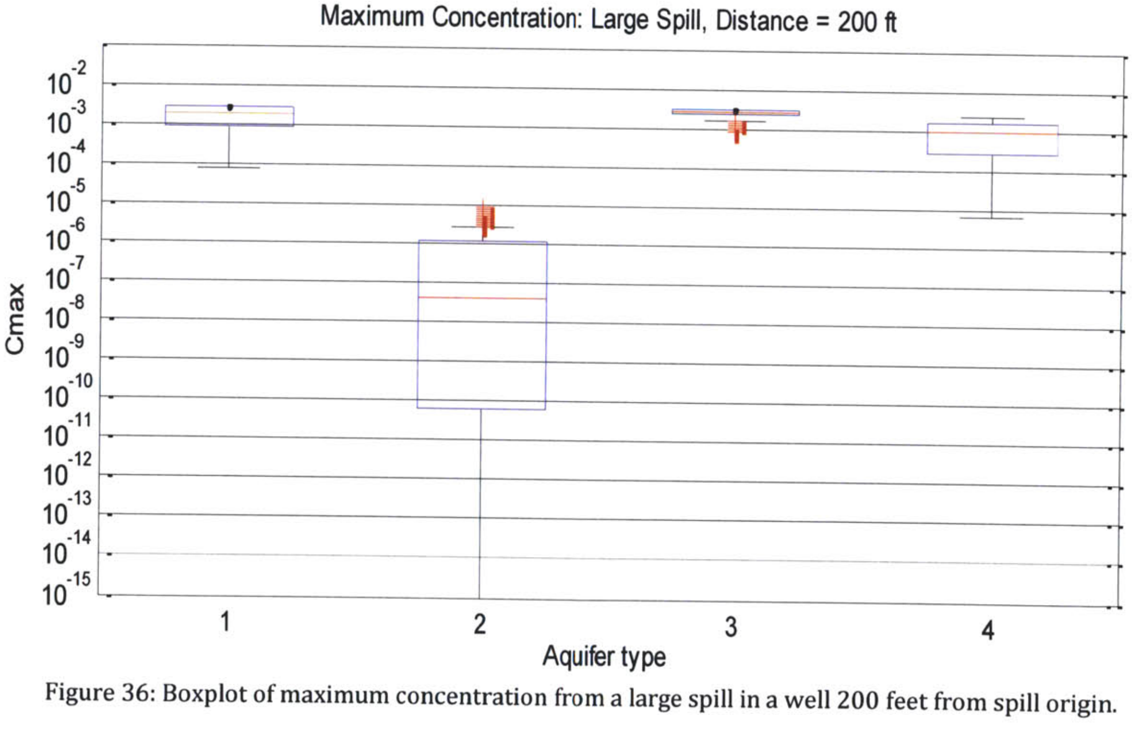

Figure 36: Boxplot of maximum concentration from a large spill in a well 200 feet from spill origin.

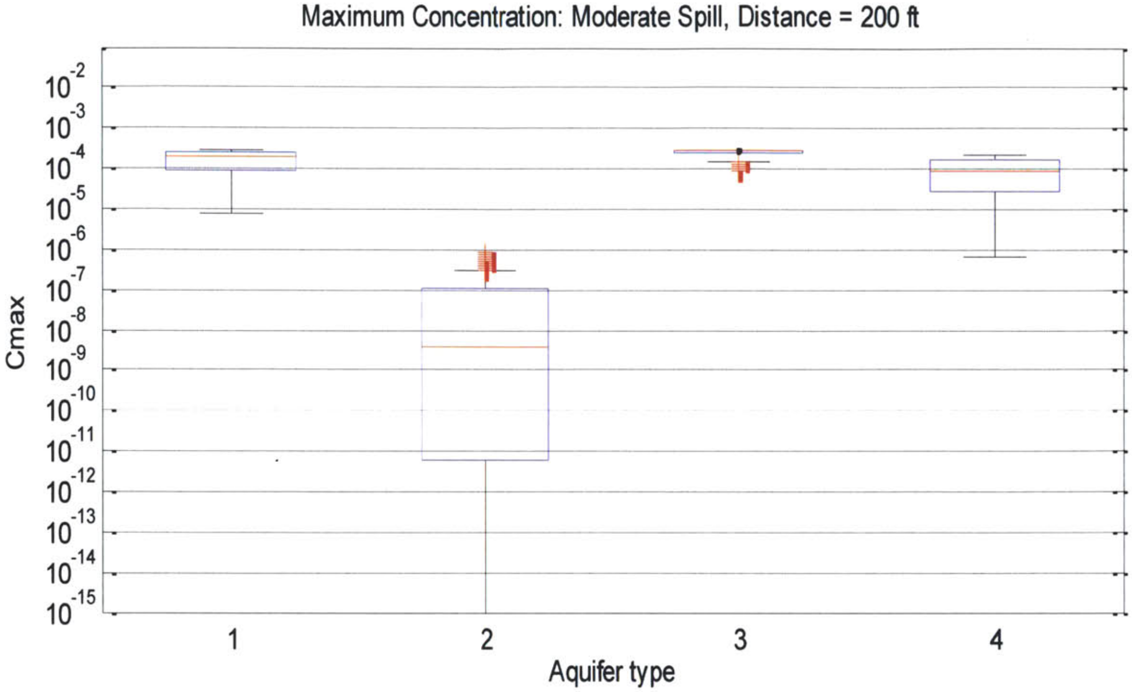

Figure 37: Boxplot of maximum concentration from a moderate spill in a well 200 feet from spill origin.

Figure 38 and Figure 39 below show the same results as Figure 36 and Figure 37, respectively, except at a distance 500 feet away from the spill instead of 200 feet. The near-field effects are not as prominent in these plots; all four aquifer types have most variation between 10^{-3} and 10^{-2}, with the bottom quartile of aquifer II extending just below 10^{-4}. As in the previous set of graphs, the moderate spill results are identical to the large spill results except for one order of magnitude lower, corresponding to the one order of magnitude difference in input volume.

Likewise, Figure 40 and Figure 41 display the same results for a well 5,000 ft away from the spill. I chose 5,000 ft to demonstrate the effect of increasing the regulated setback distance by a full order of magnitude above the 500 feet setback distance recommended by (Marcellus Shale Advisory Commission, 2011). There is a significant difference. The one order of magnitude increase in distance causes a two order of magnitude decrease in the range of C_{max}. The majority of data for the large spill is between 10^{-5} and 10^{-4}, with upper quartiles extending above 10^{-4} in aquifer types II and IV and the lower half of the data from aquifer type II extending below 10^{-5}. The moderate spill data are an order of magnitude lower across aquifers.

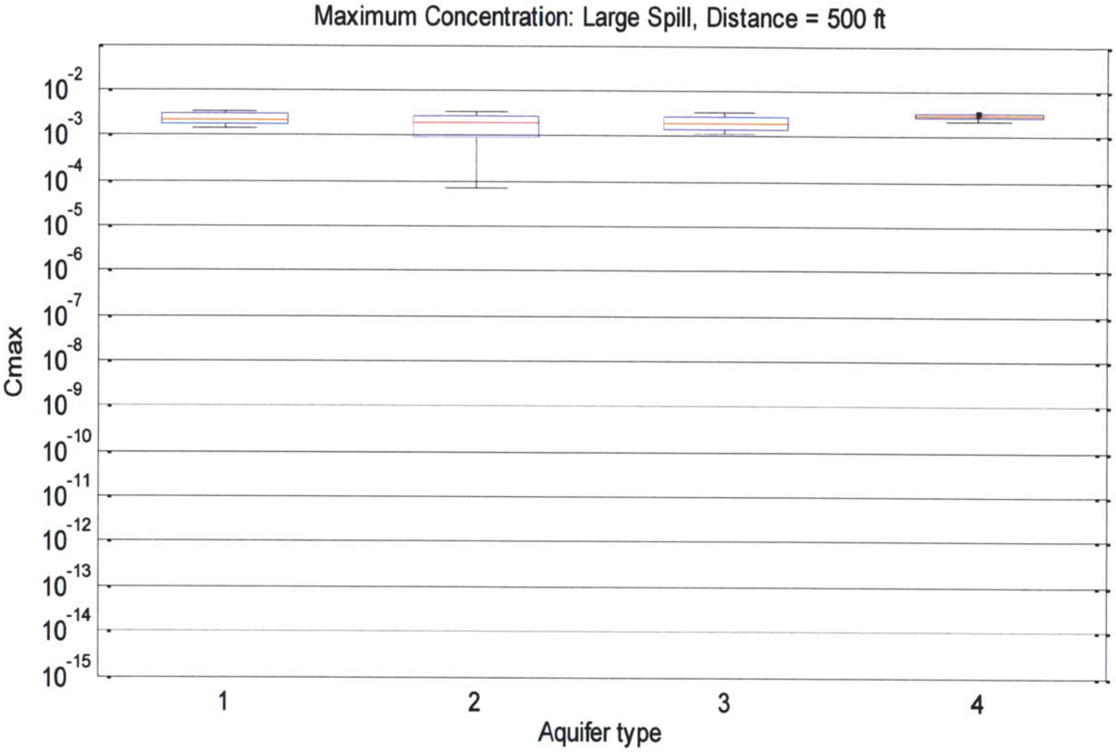

Figure 38 Boxplot of maximum concentration from a large spill in a well 500 feet from spill origin.

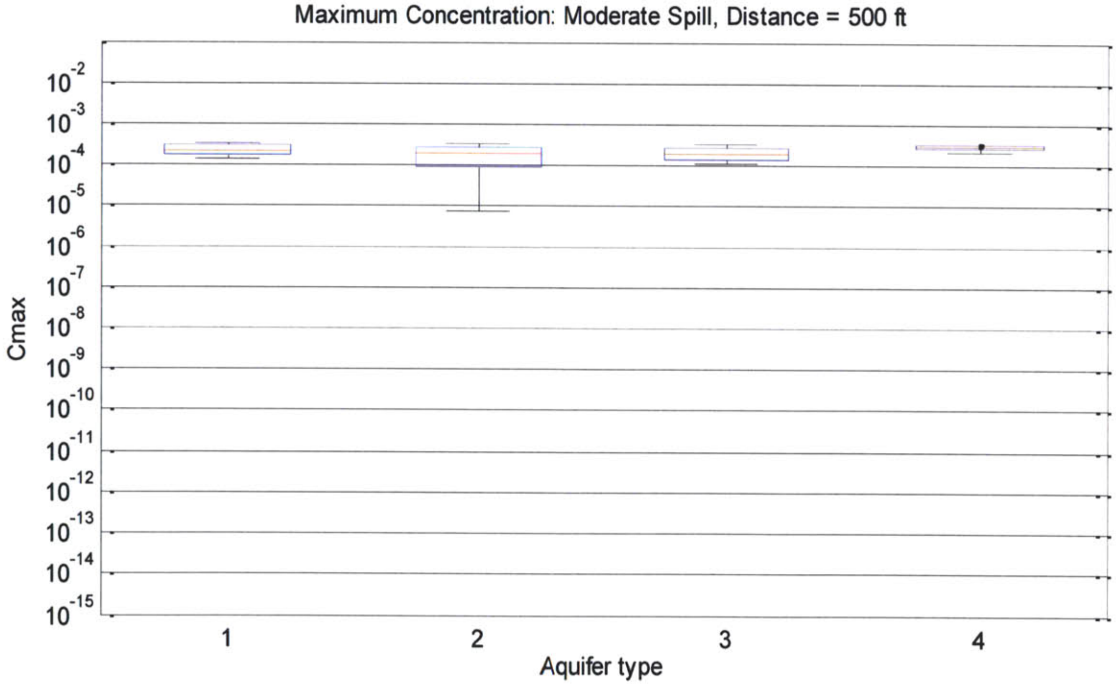

Figure 39: Boxplot of maximum concentration from a moderate spill in a well 500 feet from spill origin.

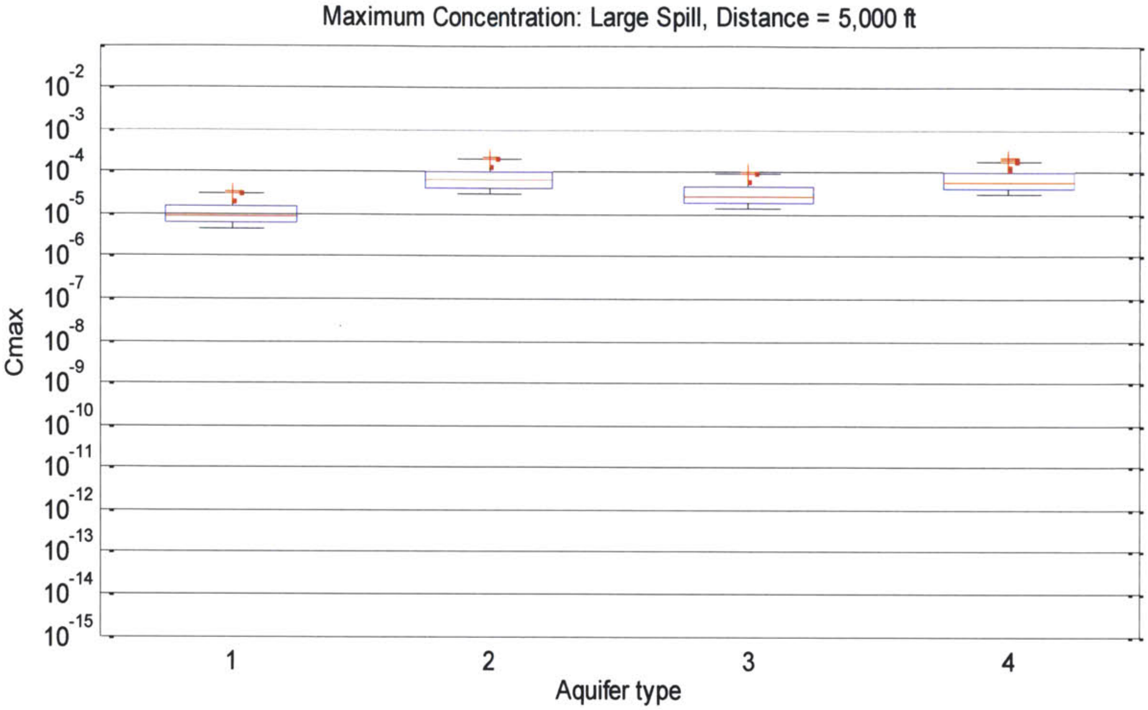

Figure 40: Boxplot of maximum concentration from a large spill in a well 5,000 feet from spill origin.

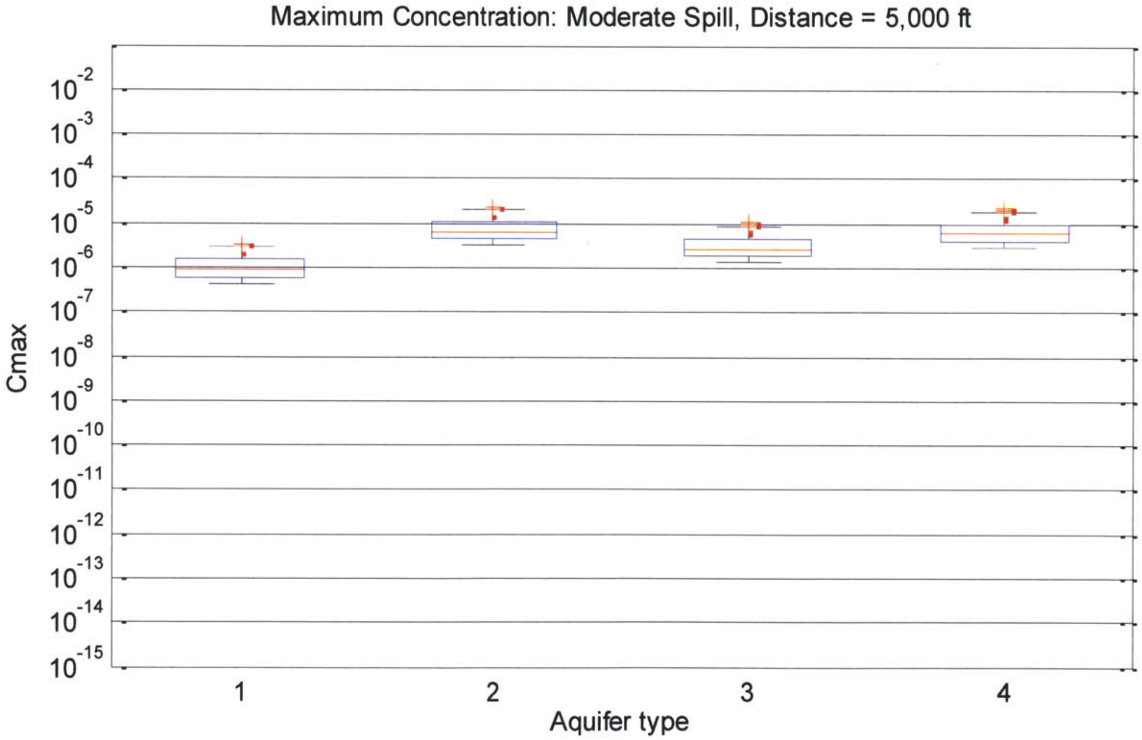

Figure 41: Boxplot of maximum concentration from a moderate spill in a well 5,000 feet from spill origin.

8.4 Time at maximum concentration

The boxplots above display samples of the maximum concentration level possible in a water well, regardless of time at which maximum concentration occurs. This time, t_{max}, is the time it takes for the plume to travel such that it is centered over the water well. t_{max} is a salient value because if it affects the extent to which the current homeowner of the well, the most direct stakeholder, will be impacted by the water contamination. If it takes hundreds of years for significant contamination to reach a water well, the homeowner of the well at the time of the spill will not be directly impacted. If it takes decades for significant contamination to reach the well, the homeowner may or may not be impacted by health effects but will likely be impacted by decreased property value. Finally, if t_{max} is on the order of days or years, the current homeowner's health could be affected by contamination.

To analyze the range of t_{max}, I plot CDFs of all the values for t_{max} calculated in $N=10^6$ Monte Carlo samples. Each plot contains CDFs for each of the four aquifer types, and I perform the analysis for distances of 200 feet, 500 feet and 5,000 feet away from the spill. I only model the large spill scenario; the speed of advection is not dependent on spill size, so the results for large spills and moderate spills are similar. Note that the irregular shape of the curves is an effect of Monte Carlo sampling; each model run produces different irregularity in shape. The overall range and typical times are the salient values.

Figure 42 shows the CDF of t_{max} values for a distance of 200 feet. Across all aquifers, 50% or more of the values are below 10^3 days, indicating that any contamination that occurs would do so on the order of days or years, and therefore of direct impact on current homeowners. Aquifer IV, the fractured crystalline rock aquifer characterized by high pore velocity, has particularly short travel times, on the order of days. Figure 43 shows the same CDFs for a distance of 500 feet. While over 50% of the t_{max} values in aquifers II, III and IV are below 10^4, most of the values for aquifer I, the sand and gravel aquifer with slower pore velocity, are over 10^4 days. This means that current homeowners may not be directly impacted by contaminated drinking water but could face indirect economic impacts. Figure 44 shows the same CDFs for a distance of 5,000 feet. The t_{max} values are significantly higher in this case; aquifer types I, II, and III may not pose a direct health risk to current homeowners but still pose economic impacts. Aquifer type IV, however, has the majority of t_{max} values under one years, suggesting that current homeowners may be impacted by drinking contaminated water if C_{max} is sufficiently high.

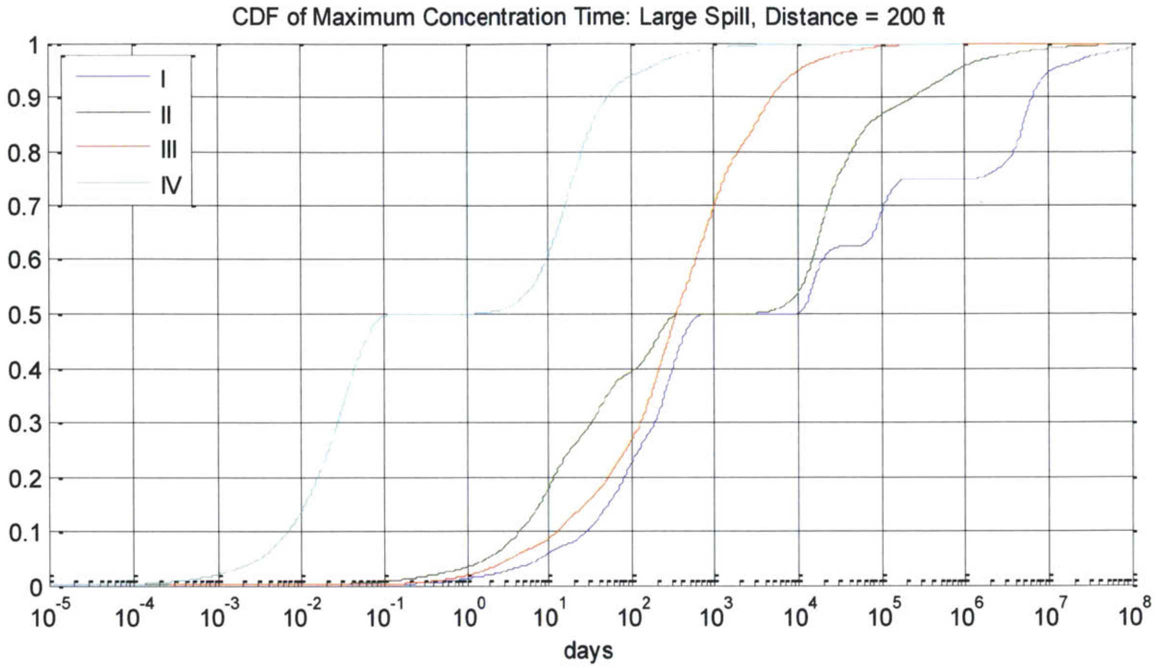

Figure 42: CDF of maximum concentration times for a large spill in a well 200 feet from spill origin.

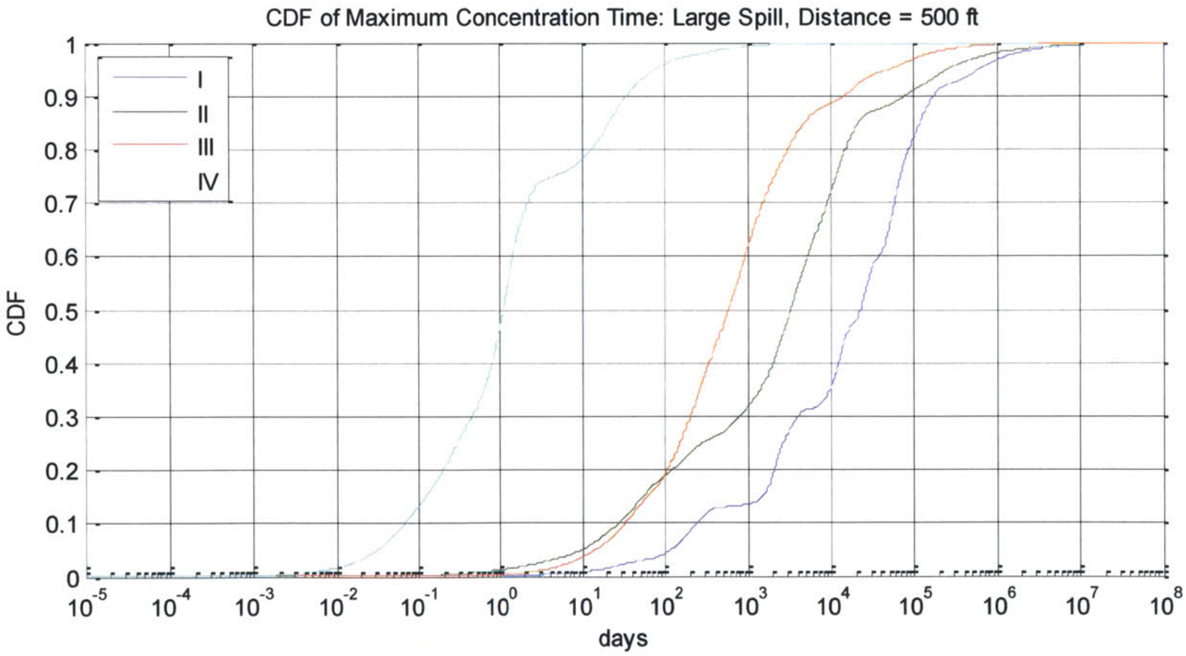

Figure 43: CDF of maximum concentration times for a large spill in a well 500 feet from spill origin.

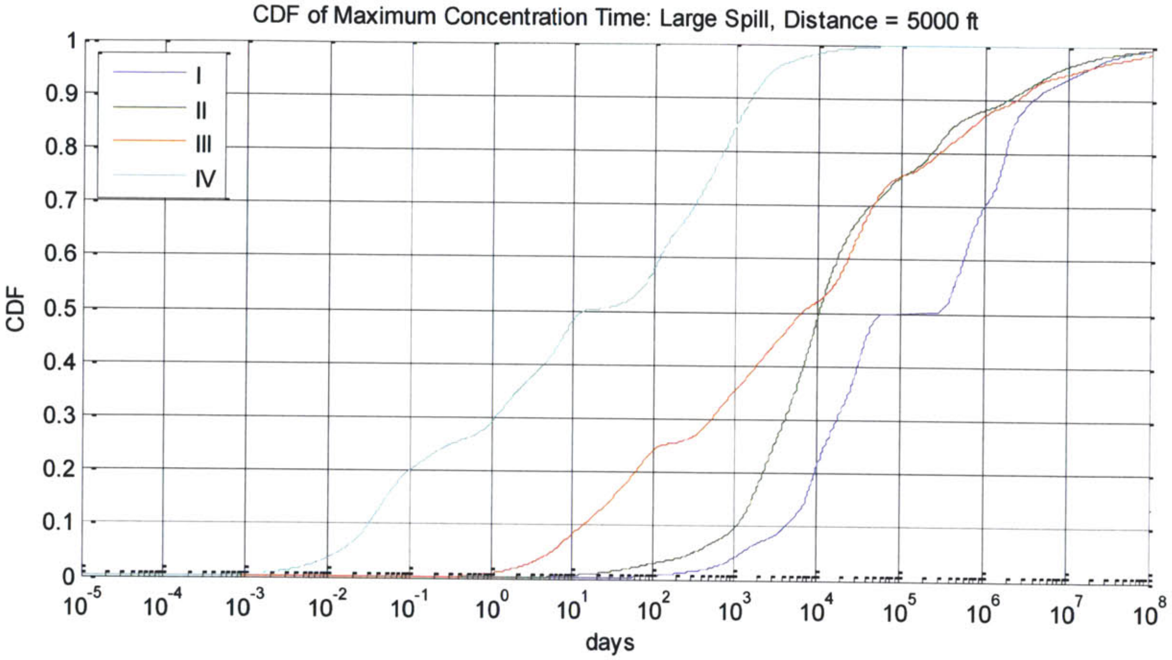

Figure 44: CDF of maximum concentration times for a large spill in a well 5,000 feet from spill origin.

8.5 Sensitivity analysis

I perform sensitivity analysis in order to see which of the four uncertain parameters—longitudinal dispersivity, hydraulic gradient, effective porosity, and hydraulic conductivity—account for the variation in the boxplots of the maximum concentration data. In order to do this, I re-run the model with the variable in question fixed to its mean value, instead of sampling from its entire distribution. I then compare the new results side by side with the normal run with variation in all four parameters. I present only the results for the large spill at 500 feet; the other scenarios are similar.

Figure 46 shows the sensitivity analysis on longitudinal dispersivity. When longitudinal dispersivity is fixed, the width of the boxplots for all aquifers shrinks to nearly nothing. This means that virtually all of the variability in the data is the result of variability in dispersivity. This is confirmed by the sensitivity analysis on the other three parameters. Figure 48, Figure 45, and Figure 47 show the sensitivity analysis on hydraulic gradient, effective porosity and hydraulic conductivity, compared to the original plot with variability in all parameters. In each case, the sensitivity plots in all aquifers appear identical to the original plots.

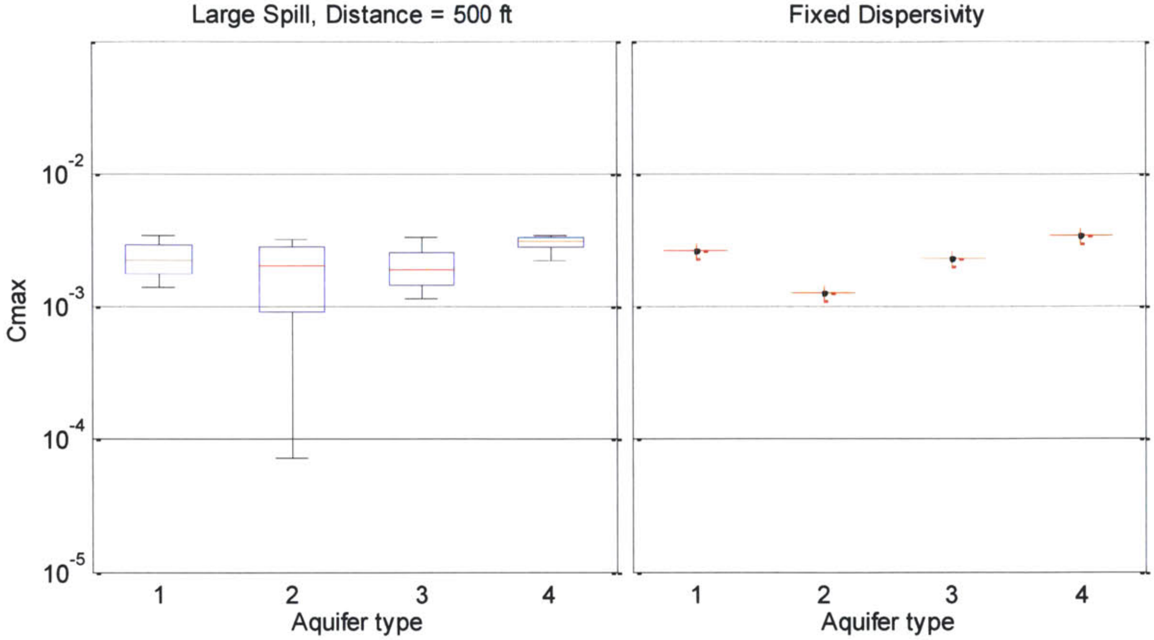

Figure 46: Sensitivity analysis on dispersivity.

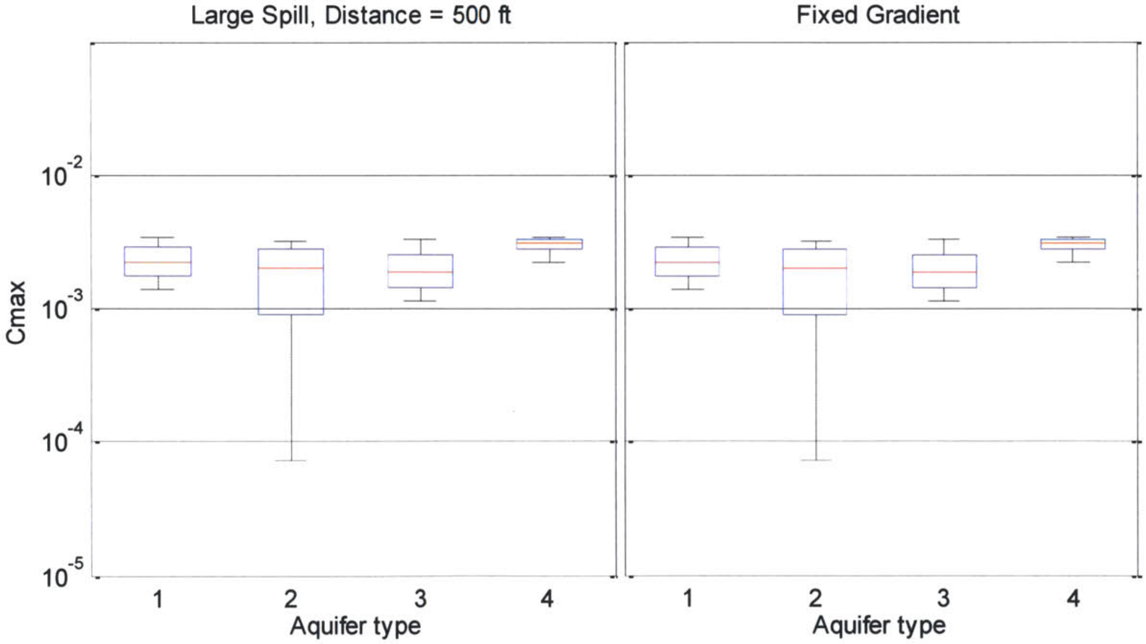

Figure 45: Sensitivity analysis on hydraulic gradient.

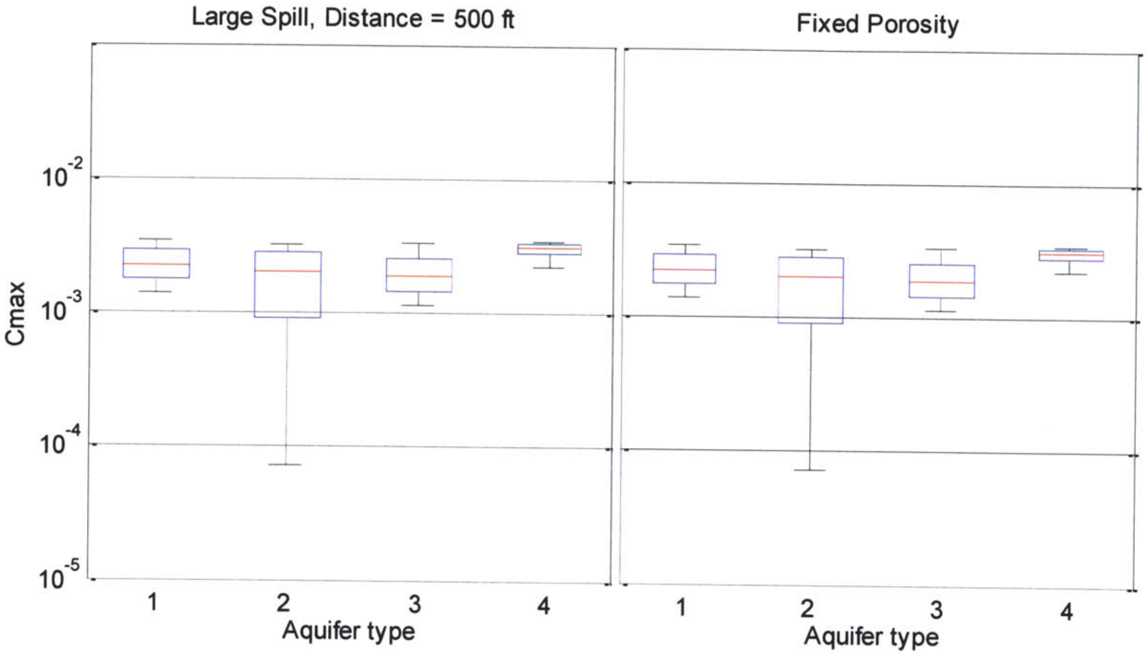

Figure 48: Sensitivity analysis on effective porosity.

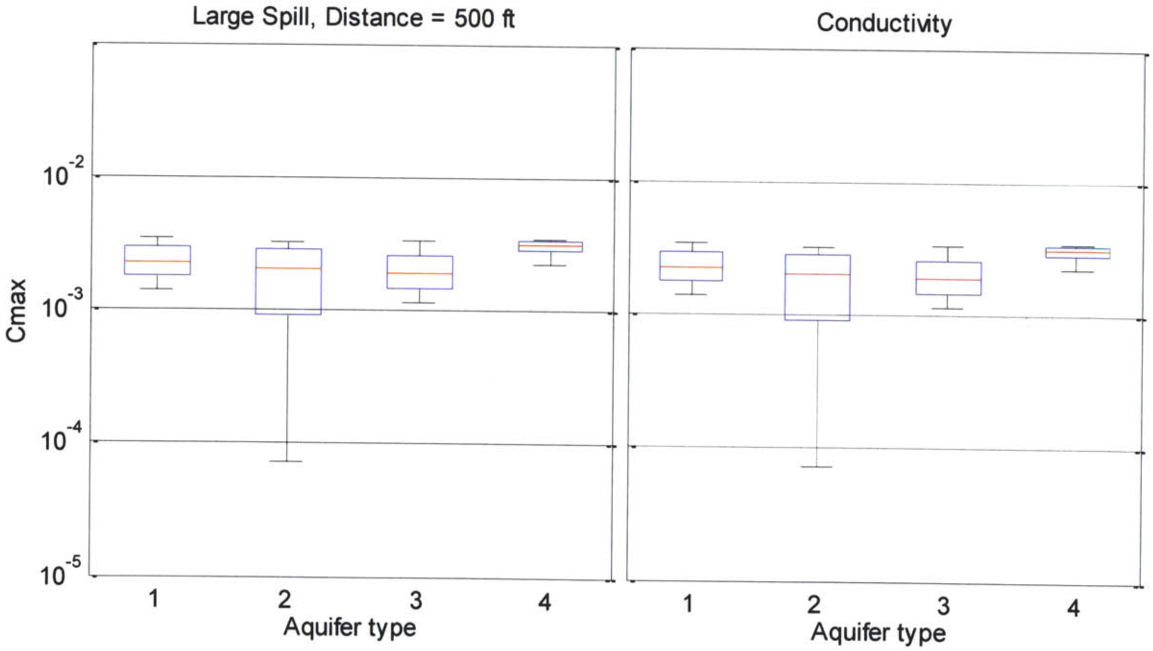

Figure 47: Sensitivity analysis on hydraulic conductivity.

8.6 Toxicity assessment: an example

As discussed in the risk assessment overview in chapter 3, a toxicity assessment is required in order to determine whether these concentrations pose a risk to human health. Because fracturing fluid has a complex mixture of many chemical additives that varies significantly across wells, a toxicity assessment is difficult. I do not attempt a toxicity assessment in this thesis; in this chapter I describe the methodology and apply it to one additive, methanol, as a demonstration.

The first step is to identify the chemical additives in fracturing fluid and their relative concentrations. Because different wells use a different cocktail of chemical additives, a worst-case scenario approach is to identify the highest possible concentration of each additive. ("Frac Focus: Chemical Disclosure Registry," 2012) provides voluntarily reported data on chemical additives and can be used for this analysis. I compile data from a sample of 20 wells chosen across the state of Pennsylvania, and find the maximum level of each chemical additive. This list is shown in appendix C. The maximum concentration of methanol found in any of the wells was 0.012% by mass of the total fracturing fluid.

The next step is to assess how much the chemical concentration is diluted as a result of the groundwater transport process; this is done using the modeling results from this chapter. The maximum concentration analysis presented earlier in this chapter show that a worst-case scenario spill can lead to C_{max} values of between 10^{-3} and 10^{-2} at a well 500 feet to 1,000 feet away the spill. This means that, in the worst case, the original fluid may only be diluted a hundred times. By the time the contaminant plume reaches the well, methanol is now 0.00012% of the water taken up by the well by mass.

The next, and most difficult step, is to assess whether drinking water with 0.00012% methanol is harmful to human health. The science underlying dose-response relationships, especially the effect of long term exposure to low levels of contaminants, is complex and often poorly understood. As described in chapter 2, toxicity reporting requirements under EPCRA require a Mineral Safety Data Sheet (MSDS) to be available for all toxic chemicals used in shale gas operations. However, the toxicity of the chemical is described by the concentration level at which it causes acute effects on animals such as mice, rats or rabbits. The translation to a level that is safe for long term exposure to humans is difficult. EPA has performed this type of analysis using a combination of extrapolation from animal studies and statistical epidemiological studies for some of the most common water pollutants, including methanol. EPA defines a reference dose (RfD) for these pollutants and aims to design regulations that ensure that people are not exposed to an amount greater than the RfD. The RfD is calculated by taking the dose at which no effects are observed in animals, and adding in a series of safety factors to account for uncertainty and the transition between humans and animals. The RfD is measured in mg/kg/day—the mass of contaminant that can be consumed per mass of body weight per day(U.S. EPA, 1993). The RfD for methanol is 0.5 mg/kg/day (U.S. EPA, 1998).

Finally, the 0.00012% concentration of methanol in the well must be compared to the 0.5 mg/kg/day limit. If a 60 kg person consumes 3 liters of water a day that contains 0.00012% methanol, this is equivalent to 0.06 mg/kg/day. This is approximately one order of magnitude lower than the reference dose. Because this thesis has taken a worst-case approach to risk, and because the RfD is designed to be conservative, this suggests that fracturing fluid spills are unlikely to pose significant health threats from methanol consumption.

However, it must be clear: this is not a generalizable result. Methanol is one of the less toxic contaminants in fracturing fluid; it is possible that much lower concentrations of other contaminants could pose a significant threat to human health.

This approach has several limitations. First, the groundwater transport model used in this chapter does not model retardation or decay processes; these processes will affect the level of each contaminant present in the water well. The most dangerous chemicals are the ones that are both highly toxic and not affected by sorption or decay processes during transport. Secondly, the RfD threshold approach used by EPA may not apply to carcinogens; it is possible that any exposure to a carcinogen can increase the risk of cancer, no matter how low the level of exposure (Ashford & Caldart, 2008). This means that there may be no non-zero "safe" level for contaminants that are carcinogens. Finally, the fact that there are many chemicals in combination in fracturing fluid may increase its overall risk. Often, the risk of consuming a combination of contaminants is greater than the sum of the risk of consuming each component individually. A body of science suggests that some subset of the population is particularly sensitive to the presence of multiple chemicals in combination (Ashford & Caldart, 2008).

8.7 Conclusions

The results from the screening model indicate that more attention to the risk of groundwater contamination from fracturing fluid spills is warranted. The worst-case scenario spill, a volume input of 50,000 gallons, yields C_{max} values ranging between 10^{-3} and 10^{-2} at water wells 500 feet to 1,000 feet away from the spill. This could result in contaminant concentrations on the level of parts per million or parts per billion in water wells, depending on the concentration of the contaminant in fracturing fluid. Depending on the toxicity of the contaminant, such a level of concentration could have significant impacts on human health.

While the worst case approach to risk here uses a large input volume (50,000 gallons), the results for C_{max} for smaller spills scale proportionately. A spill one hundredth of the size could be expected to have C_{max} values one hundredth of the values presented for the large spill.

Of the four variable hydrogeological parameters, dispersivity accounted for nearly all of the variation in results. Dispersivity is a property of both the aquifer and the contaminant fluid; it is highly variable and difficult to measure or predict. It is possible that the distribution used to describe dispersivity in this model is too narrow, or inaccurate; other data sources exist with significantly different values (Neuman, 1990). As such, the range of results presented here should not be considered a complete range of all the transport outcomes possible. Related to the issue of dispersivity, the depth of the water well has a significant impact on the contamination that may be observed. However, because dispersivity is so uncertain, it is not possible to optimize water well depth to avoid risk. Moreover, the source of contamination was modeled as a point source at the top of the water table; if the source of contamination was instead subsurface, which as discussed in chapter 2 is a significant risk from well-casing failures, a completely different set of well depths would be vulnerable to contamination.

Differences in aquifer characteristics did not have a significant impact on the maximum level of contamination; however, they did have a significant impact on the time it takes for the maximum level of contamination to reach a well. Aquifers with faster groundwater velocities could transport the plume to a nearby well in just a few days, while aquifers with slower groundwater velocities may take decades. However, both of these time frames are short enough to have significant impacts on the homeowner of the water well.

Further research is needed to fully assess the risk of groundwater resource contamination from hydraulic fracturing fluid spills. Future research should include more site-specific numerical modeling at high-risk sites in Pennsylvania; these sites are areas in which groundwater aquifers have the potential for high dispersivity and groundwater velocity is relatively high. Additionally, research on the transport potential and toxicity of each component of fracturing fluid, as well as the combined toxicity of the fluid as a whole, is needed in order to fully characterize the potential health effects on people.

Part IV: Risk management: analysis and recommendations

Chapter 9: Risk management, stakeholder and perception analysis

Part I of this thesis developed a framework for risk assessment of fracturing fluid spills in Pennsylvania; Parts II and III performed a technical analysis of the risk of groundwater contamination from fracturing fluid spills. While technical assessment is a critical to developing an effective and credible risk management strategy, other criteria must also be taken into consideration. This fourth and final part of the thesis focuses on addressing the final question stated in the introduction to this thesis:

> What factors should be considered in developing an effective risk management strategy for water contamination from fracturing fluid spills?

Risk is a value-laden quantity; a quantitative assessment of the possible contaminant concentration in drinking water resources will be evaluated on different criteria and perceived differently by different stakeholders. A successful risk management strategy should be developed with stakeholder involvement in order to ensure its acceptance.

In this section, I briefly discuss some of the theory surrounding risk management. I then perform a stakeholder identification and mapping, followed by a risk perception analysis from the perspective of community stakeholders. These analyses then inform the risk management recommendations made in chapter 10.

9.1 Risk management theory

Risk management is the last step in the risk assessment process; after an identification and analysis of the risks in question is performed, the risk manager must decide what strategies should be implemented to prevent or mitigate the risk. The risk manager can take a variety of forms; a company implementing a project, a government entity, or a community organization. I assess risk management from the perspective of the government: what should government do to address the risk from fracturing fluid spills in Pennsylvania?

The heavy reliance of environmental risk analysis on complex science and expert judgment presents challenges for developing an effective risk management strategy that is credible to stakeholders. The federal regulatory framework, in which U.S. EPA is responsible for both risk analysis and risk management, exacerbates the problem. The process of assessing the exposure to and toxicity of chemical hazards is highly uncertain. This was demonstrated in this thesis; a wide range of tools for characterizing and assessing uncertainty—expert elicitation, Monte Carlo simulation, and scenario and sensitivity analysis—were required to assess the full range of possible risk outcomes. A scientifically credible analysis of the risk requires such a deconstruction; however, making an authoritative decision regarding how to manage the risk requires a reconstruction of the evidence (Jasanoff, 1987). That is, after U.S. EPA analyzes the uncertain science behind an environmental risk, it must then use the same science to build a credible argument to defend its choice of regulation to industry, environment, and other stakeholders.

This reconstruction of scientific evidence presents opportunities for manipulation. Scientific research purports to present objective, neutral results; however, the representation of this information is often far from objective. (Stone, 1997) argues that facts are never neutral; the act of choosing words and numbers to represent scientific ideas is inherently subjective. The fact that the same federal agency that is performing the technical analysis is also developing the management strategy compounds this problem; the line between risk assessment and risk management is blurry (Jasanoff, 1987). It is hard to identify where science and technical assessment ends and where policymaking begins.

This presents challenges for both industry and community stakeholders. Regulatory agencies are often subject to "capture" by commercial interest. This is because commercial stakeholders have a vested interest in influencing regulation; a member of the public, conversely, does not have an incentive to exert influence because the benefits of doing so are dispersed across society (Stigler, 1971). Experts, too, can be captured by commercial interests when performing technical analysis for risk assessment (Munger, 2000). This leads members of the public to distrust the risk assessment results performed by federal agencies like U.S. EPA. Industry also frequent takes issue with the risk assessment-management process used by U.S. EPA; it argues that the environmental agenda influences the way that scientific results are presented in order to develop more stringent environmental regulation (Jasanoff, 1987).

These problems are very relevant to the assessment of risk from shale gas extraction. There is much debate surrounding the exemption of both the oil and gas industry and of hydraulic fracturing specifically from many of the major federal environmental statutes as discussed in chapter 2. Some argue that these exemptions are the result of regulatory capture of the federal government by the oil and gas industry. A New York Times editorial criticized the 2004 U.S. EPA study on hydraulic fracturing as "whitewashing the industry" and demanded a peer-reviewed, transparent process ("The Halliburton Loophole," 2009). U.S. EPA is now undertaking a more thorough, 3 year assessment of the hydraulic fracturing process; the results of this assessment are likely to impact the design of regulation going forward.

These issues suggest that greater trust of the government's risk assessment process is needed; the ongoing EPA study presents an opportunity to increase stakeholder trust. Risk is multi-dimensional, value-laden quantity. While the public is often seen as reacting irrationally to risk, the problem may in reality stem from a distrust of the process by which decisions about risk are made (Slovic, 1993). Scientific assessment for decision-making should be designed to be more salient, credible and legitimate to both stakeholders and policy-makers in order to be more impactful in risk management decisions (Farrell, Jager, & VanDeveer, 2006). While early approaches to government risk assessment emphasized improved technical analysis as a means to better risk assessment, more recent criticism suggests a process-oriented approach in which stakeholders are integrated into the assessment process (Slovic, 2003).

In light of these suggestions, I use the remainder of chapter 9 to analyze the stakeholders and public perception issues relevant to this problem.

9.2 Stakeholder analysis

Stakeholder analysis can serve a variety of purposes. It can be used to identify strategies to make a predetermined policy or project more acceptable to relevant stakeholders; it can also be used to help decide the appropriate policy or course of action to take given stakeholder preferences. The former is more commonly used by businesses and the latter by governments or policy analysts (Varvasovszky, 2000). I use the latter approach in the context of current regulation and industry practice.

While stakeholder analysis can take on a variety of forms, methods typically start with brainstorming and identifying relevant stakeholders. Definitions of "stakeholder" vary; some broadly describe all groups who have an interest in the project, policy or company; others require a legitimate claim or power of influence. Likewise, some users define stakeholders as only those who currently have a relationship to the project or policy, while others include potential relationships (Mitchell, Agele, & Wood, 1997). For the purposes of this analysis, I use a narrow definition in that I consider only groups who have both interest and power, but a broad approach in that I consider people who may not be directly affected now but could be in the future. I think this is appropriate given the quickly expanding nature of shale gas extraction in Pennsylvania.

After the stakeholders are identified they can then be evaluated on a variety of different metrics to assess how important they are to the problem at hand. Common metrics include power, interest, attitude, urgency, etc. (Mitchell et al., 1997). It is also common to use a power-interest matrix to group stakeholders into four categories depending on whether they have high or low power and interest (Bryson, 2004).

The stakeholders related to shale gas extraction in Pennsylvania, and particularly the risk of water contamination, fall into five main categories:

- Industry
- Communities
- Environmentalists
- Government
- Researchers/analysts

While the primary focus of this thesis is the water contamination risk of fracturing fluid spills, I discuss below the major incentives and attitudes toward risk of shale gas extraction at large. This is important because the perception of the operation at large has significant potential to influence perception of the water contamination risk in particular.

9.2.1 Industry

Industry's main interest in the shale gas extraction process is financial. However, there are multiple types of industry players, each of which has a different business model and set of incentives. First, there are natural gas production companies; these companies sell natural gas to make a profit. Production companies include major integrated companies, such as ExxonMobil, that have upstream and downstream oil and gas business around the world. Production companies can also be independent companies, such as Chesapeake or Range

Resources, focused on domestic oil and gas exploration. Given this difference in the range of business interests between major integrated companies and independent companies, the approach they take to maximize return on their investment portfolios can vary. Major integrated companies treat shale gas as one of several important profit streams in their upstream business; they balance their investment resources across a portfolio of business sectors. Independent companies, on the other hand, have a smaller portfolio of investment options and so have a more focused interest on shale gas. It is difficult to say which type of company has more power. Independent companies currently own the majority of wells in Pennsylvania; however, as major integrated companies such as ExxonMobil enter the market, they can bring greater technical expertise and financial flexibility.

Despite these differences, both types of production companies have an incentive to minimize the environmental risk from shale gas development. Production companies want shale to be available to them as an extraction resource in the long term. Given the history of moratoriums and municipal legal battles surrounding shale gas extraction in the Appalachian region, poor environmental performance—or widespread perception of poor environmental performance—has the potential to hinder or halt shale development in the region. Even if development is not prohibited because of poor environmental performance, increased environmental regulation could make extraction more expensive. This gives production companies an incentive to build community support. However, the rapid pace of development and different public perception towards oil and gas in Pennsylvania has made successful community outreach difficult. A new approach to community relations may be needed.

In addition to the production companies that sell natural gas, service providers and contractors also play a significant role in industry operations. Service providers, such as Schlumberger and Halliburton, perform much of the technical operations on the well site, such as drilling and hydraulic fracturing and fluid management. Smaller contractors are often hired to perform some of the more routine tasks necessary, such as trucking fluids to and from the well site. Service providers and contractors do not sell the natural gas product; they profit by selling their services to the production company. Major service companies are concerned with demonstrating technical expertise and good operation; this know-how is the reason they are hired, and environmental impacts could prevent them from getting business in the future. However, smaller, routine contractors may have less incentive to minimize risk of spills. This is a significant problem, as actors across the entire value chain need to cooperate in order to prevent problems.

9.2.2 Community

Communities are affected by a more diverse set of interests in shale gas extraction. People living near drilling activity are often worried about the impacts on their water resources and environment. Heavy trucking also has the potential to cause significant damage to roads, and drilling can cause noise pollution. There are often economic benefits such as increased jobs. A recent Wells Fargo report estimates that 60% of the new jobs in Pennsylvania over the next eight years will be in the shale gas industry (Bryson, Quinian, & Seydl, 2012). Additionally, those who own mineral or land rights have the potential to earn a significant return in leases to production companies. Some of the indirect effects are harder to predict, however. For example, a recent article in a local Pennsylvania newspaper reports that rents for housing are increasing substantially, making it difficult for residents to find affordable housing (Bevins, 2012). Likewise, a recent study by the Penn State Extension assessed the potential for shale gas activity to increase revenue for local schools and concluded that no significant impact is likely (Penn State Extension, 2012).

A survey project conducted by Penn State, Cornell, and the Institute for Public Policy and Economic Development in 2009 compiled survey data from 1917 residents in Pennsylvania and New York about their satisfaction with shale gas development. (Brasier, 2010) finds three main groups with different perspectives on shale gas development. One group is uncertain or ambivalent; the two other groups are polarized, with different views of risk and benefits from development. One of the most interesting results is that the level of support was higher among people who lived in areas in which more wells had been drilled. People who support shale gas development are: aware of the development activity, more likely to seek information, more likely to expect increased job opportunities, and perceive lower drilling risks (Brasier, 2010).

The perception of lower drilling risks among supporters is an interesting result. Given that supporters are also more exposed to drilling activity, it may be explained as the result of greater familiarity with the operations, which could have a large impact on risk perception (Morgan, 1993). In light of this, I apply some of the emotive attributes of risk perception described in chapter 3 to three community stakeholder groups:

> Group 1: People who have leased land or mineral rights for development
> Group 2: People without land or mineral rights who live an area with significant shale development
> Group 3: People who live an area that has not yet seen significant shale development but is likely to in the future

Note that this my own assessment of potential perception. It is not supported by any survey data from these community groups themselves; a more rigorous analysis should be data-driven. The goal here is to identify potential differences across the relative perceptions of the three groups.

- *Involuntary, uncontrollable.* The rapid pace of industry-driven shale development is likely to make all community groups feel a lack of control about the risks. However, group 1 is less likely to view this risk as involuntary or uncontrollable because they made the decision to lease their property for production. Groups 2 and 3 are more likely to perceive this risk as involuntary because they did not make any voluntary choices related to development.
- *Unfamiliar, uncertain.* Because Pennsylvania was not exposed to significant oil or gas development before shale development grew in recent years, community groups are likely to view the risks as unfamiliar and uncertain in the beginning. Once development has been ongoing in their area for some time, this perception is likely to decrease. This means that the unfamiliar and uncertain nature of the risk is less important in group 1 and group 2 than in group 3.

- *Dreadful.* Contamination of drinking water is a highly dreadful risk. Clean water is required for life, and drinking harmful water is a fearful consequence.
- *Unfair.* People view clean water as a basic human right, and drinking contaminated water violates a sense of basic fairness.
- *Catastrophic, memorable.* Although fearful, the risk of water contamination is not associated with large-scale disastrous events with dramatic outcomes.
- *Immoral.* It is possible that some people view the extraction of fossil fuels as immoral; this perception likely decreases as drilling activity becomes more prevalent and some of the local economic benefits are realized. This means that group 1 and group 2 perceive the immoral attribute as lower than group 3.
- *Untrustworthy.* As discussed in the section on risk management theory, there is a large potential for a lack of trust in risk assessment in this domain as the result of potential capture of experts and regulators.

Table 7 below summarizes this analysis. The important takeaway is the relative comparison across groups. The potential for emotive responses to this risk increases from group 1 to group 2, and from group 2 to group 3. This may help explain why (Brasier, 2010) found people in areas with more drilling activity to be more supportive of shale gas development on average.

Emotive Attribute	**Group 1**	**Group 2**	**Group 3**
Involuntary	Moderate	High	High
Uncontrollable	Moderate	High	High
Immoral	Low	Low	Moderate
Unfamiliar	Moderate	Moderate	High
Dreadful	High	High	High
Uncertain	Moderate	Moderate	High
Catastrophic	Low	Low	Low
Memorable	Low	Low	Low
Unfair	High	High	High
Untrustworthy	High	High	High

Table 7: Emotive attributes of risk assessed by community groups for water contamination risk from shale gas extraction.

9.2.3 Other stakeholders

While industry and communities are the two most visible, and arguably the most salient, stakeholders in this problem, a variety of other groups also have an interest and a potential to influence industry or communities. Three important groups include environmentalists, government and researchers.

Environmental organizations are non-profits dedicating to protecting the environment. They can take on a variety of roles including research, government advocacy, and public outreach. Some lobby for increased regulation of the industry, others work with communities to empower grassroots movements. Some focus on disseminating information to communities about the environmental risks. The idea of capture, Jasanoff's problem of blurry lines between research and advocacy, and Stone's problem of bias in facts and numbers are all relevant here too. It is possible that environmental organizations present information in a way that is designed to promote fear of the environmental risks and downplay the economic benefits.

The government is a stakeholder as well. Indeed, various government entities at both the state and the federal level have a variety of incentives, as discussed in the risk management theory section above. An additional important note is that many government agencies are constrained from effectively meeting their mandates by resource limitations. One of the recommendations from the STRONGER analysis of the PA DEP was to increase well permit fees in order to hire more staff (STRONGER, 2010).

Finally, it is important to note that researchers and analysts are stakeholders as well, subject to personal biased also to capture. Even researchers at universities must acquire funding, and this funding can come from industry, government, or environmental organizations.

Community stakeholders receive their information from a variety of sources, including all of the stakeholder groups above. As (Slovic, 1993) notes, it is important that communities trust that they are getting objective information in order to ensure their acceptable of policies and risk management strategies. As part of the Marcellus community satisfaction survey, (Brasier, 2010) asked respondents to evaluate the trustworthiness of a variety of sources of information. The most trustworthy group was scientists, followed by the Penn State Cooperative Extension, which provides outreach and education to communities about shale gas development. Environmental groups and the PA DEP were next, evaluated very similarly, followed finally by the natural gas industry and trade groups.

Chapter 10: Recommendations and conclusions

Assessment of the risk of fracturing fluid spills in Pennsylvania is a complex problem, involving technical engineering operations, a multifaceted legal and regulatory framework, complex and uncertain science, and powerful and wide-ranging stakeholder incentives. This thesis has attempted to develop a specific and comprehensive risk assessment framework to analyze this risk, and present some initial findings to characterize the extent of the risk.

Based on the results of the analysis, lessons learned from the development of the risk framework, and insights from the stakeholder perception analysis, I now present some recommendations and conclusions. Note that I separate "findings" from "recommendations" to make clear that the former are positive statements and the latter normative.

10.1 Risk Assessment framework

In order to assess the risk of water contamination from fracturing fluid spills, a full toxicity-exposure assessment is required. Much more data and research are necessary.

The likelihood-consequence paradigm from probabilistic risk assessment can be used to quantify contaminant releases, the first step in the exposure pathway. While this thesis presents a methodology for using expert elicitation to quantify the expected frequency and size of spills, an engineering approach assessing the range of probabilities across a variety of wells would be the most rigorous method. However, there is currently not enough data to undertake such an approach.

Recommendations:

- U.S. EPA should undertake an engineering analysis of the potential for fracturing fluid spills as part of its ongoing hydraulic fracturing fluid assessment. This should include both site visits and data gathering and analysis.
- PA DEP should improve the quality and consistency of its inspection and violation reporting. An easily searchable database of spill reports including the amount of fluid spilled, amount of fluid recovered, type of fluid spilled, and cause of spill should be made publicly available online. This could be modeled on the Texas RRC's spill database.[22]

The rest of the exposure pathway, after the initial release of the spill through groundwater transport to water wells, is best characterized by groundwater transport models. A screening model approach can provide a good first order assessment of the risk in a generalizable location. Such models can be parameterized for different groundwater scenarios within the state of Pennsylvania. The transport of chemicals in the environment varies widely from contaminant to contaminant as the results of various sorption and decay processes; this variation is ignored in the model presented in this thesis. Now that more detailed information about the composition of fracturing fluid is being made available

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[22] See "Crude Oil, Gas Well Liquids or Associated Products (H-8) Loss Reports" on the Texas RRC website: http://www.rrc.state.tx.us/environmental/spills/h8s/index.php

by voluntary reporting on fracfocus.org, more research can be performed to assess the specific transport characteristics of each contaminant.

Recommendations:

- In consultation with the Pennsylvania Geological Survey, PA DEP should develop a screening model for groundwater contaminant transport it can use to perform preliminary exposure assessments. This model could be based on the one presented in this thesis or those used by EPA such as BIOSCREEN or BIOCHLOR. [23]
- U.S. EPA should include an analysis of groundwater transport potential of each of the chemical additives in fracturing fluid, as well as the additional solids and NORM in flowback water, as part of its ongoing risk assessment of hydraulic fracturing.

The final essential component of the risk assessment is the toxicity assessment. An overview of the MSDS requirement for shale gas operators who use toxic chemicals and an overview of the dose-response methodology were presented in this thesis. As with the analysis of transport characteristics, a more rigorous analysis of the toxicity of hydraulic fracturing fluid is now possible using the voluntarily reported data on fracfocus.org. Because of the large number of additives and complex composition of hydraulic fracturing fluid, it is possible that the overall toxicity of the components could be higher than the combined toxicity of each component.

Recommendation:

- U.S. EPA should include an analysis of the toxicity of hydraulic fracturing fluid as part of its ongoing risk assessment of hydraulic fracturing. A comprehensive analysis would include dose-response relationships descriptions of both the individual components of the fluid as well as the fluid as whole.

10.2 Spill analysis

While the expert elicitation results presented in this thesis are only preliminary, some broad conclusions can be drawn. First, the two experts, one regulatory official with experience with oil and gas in Pennsylvania and one natural gas production company, agree on the order of magnitude of the number and volume of spills they expect in the next year from each of the four risk scenarios.

Fewer than 100 spills in 1,500 wells are expected across all scenarios. This is on the same order of magnitude as the number of EH&S enforcements reported by PA DEP; they report 275 EH&S enforcements across 4,866 wells. Furthermore, fewer than 20 spills are expected from truck spills and pit overflows, and fewer than 5 spills are expected from well blowouts; this is consistent on order of magnitude with a review of the widely reported incidents of blowouts and spills from shale gas operations over the past several years.

Finding:

- The vast majority of shale gas operations do not incur reportable spills (5 gallons or more). The fluid management process can be, and usually is, managed safely and effectively.

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[23] See (Aziz et al., 2000; Newell et al., 1996).

The volume of the spill varies significantly across spill scenarios. Pipe spills are not expected to release more than a thousand gallons into the environment; one of the experts expected significantly smaller volumes on the order of tens of gallons. Retaining pit spills and truck spills are not expected to release more than ten thousand gallons of fluid into the environment. Blowouts are expected to cause the largest spills, with the potential to release tens of thousands of gallons into the environment.

Finding:

- 50,000 gallons is a reasonable volume to represent a worst-case scenario spill; well blowouts are the only spill scenario which could lead to a release of this magnitude. 5,000 gallons is a reasonable volume to represent a moderate spill as both truck spills and retaining pit spills have the potential to release volumes on this order of magnitude.

Some broad conclusions about the containment and recovery of the spills can be made as well. Small spills occur with greater frequency than large spills, and a larger percent of the total fluid is recoverable for small spills than for large spills. For spills on the order of several thousand gallons of fluid, it is expected that less than half the fluid may be captured by secondary containment or recovered.

Recommendation:

- Given that secondary containment and recovery techniques are insufficient for large spills, a greater emphasis should be placed on spill prevention for scenarios such as well blowouts and truck spills that can lead to spills on the order of thousands of gallons.

The cause of these spills is mixed; human error on the well site and equipment failure both play an important role. Both experts expect that majority of pipe spills and truck spills are caused by human error, while the majority of retaining pit spills are caused by equipment failure. Blowouts appear to be caused by a combination of human error and equipment failure.

Recommendation:

- Risk management strategies for spills should include a combination of equipment tests and best management practices for on-site operation.

10.3 Groundwater transport analysis

The stochastic groundwater contaminant transport model developed in this thesis provides a good first-order estimate of the risk of contamination of groundwater resources. The use of a screening model instead of a site-specific numerical model allows for a characterization of the range of transport outcomes across the state of Pennsylvania.

The largest drivers of variation in contamination levels are dispersivity, well depth, and well location. Dispersivity is a function of both the aquifer and the contaminant fluid; it has the potential to vary by orders of magnitude in the aquifers that exist within Pennsylvania. The location of the water well with respect to the direction of groundwater flow and the depth of the well can determine whether or not an appreciable amount of contamination will ever reach the well.

I use a "worst-case scenario" approach in my modeling; this is implemented in the choice of spill volume, well-location, and assumption of no sorption or decay. I solve for the time at which the contaminant plume is centered over the water well in order to find the maximum possible concentration at any time after the spill. A worst case spill yields maximum concentration levels of 10^{-2} of the original concentration of the fluid. Given that the chemical additives in fracturing fluid comprise less than 1% of the total fluid, this means that we could expect to see contaminant levels on the order of parts per million in the worst-case scenario. The time at which maximum concentration occurs varies widely depending on groundwater velocity, ranging from less than a day to several decades.

The stochastic groundwater contaminant transport model in this thesis assesses the potential for exposure of contaminants to humans through groundwater resources. The full risk to human health is a function of both exposure and toxicity. The chemicals that pose the greatest threat to human health are those that are both high in toxicity and also unlikely to be affected by sorption or decay processes.

Findings:

- Worst-case scenario spills have the potential to lead to water-well contamination levels on the order of parts per million. While the risk to human health of this level of exposure depends on the toxicity of the contaminant, this level is high enough to warrant additional research.
- If significant water contamination does occur, it is expected to occur on a short enough time frame that current homeowners could experience direct health or economic impacts.
- The Governor's Marcellus Shale Advisory Commission's recommendation of increasing the setback distance from 200 feet to 500 feet may have negligible impact on decreasing the risk of water contamination from a worst-case scenario spill.

Recommendations:

- PA DEP should be given statutory authority to permit gas wells based on not only the setback distance from the water well, but also the speed and direction of groundwater flow, depth of the local groundwater aquifers and water wells, and potential dispersivity of the local groundwater aquifer. PA DEP should develop the capacity to make these measurements in conjunction with the Pennsylvania Geological Survey.
- Risk management regulation should provide incentives for pollution prevention instead of just spill mitigation. Using less overall chemical additives or less toxic chemicals is just as effective as reducing the size and frequency of spills. This is a particularly effective strategy for managing the risk of large spills such as blowouts which are not effectively managed by secondary containment or recovery.
- Regulation should place greater burden of proof on industry to demonstrate that the shale gas development process, including activities outside of hydraulic

fracturing itself, do not contaminate groundwater resources. This should include offering baseline well testing for nearby well owners. The RCRA cradle-to-grave program for hazardous waste is an excellent example of the impact that legal burden-of-proof can have on industry operations.

10.4 Stakeholder analysis

Shale gas development is a complex operation with an array of environmental, community and economic implications. There are many stakeholders with interest in the outcomes and power to affect the development going forward. Shale development in Pennsylvania has grown rapidly in areas where people are not accustomed to oil and gas development; the lack of familiarity and a sense of loss of control have large potential to impact the way in which communities perceive this risk. Different groups of people in the Marcellus region have varying levels of support for shale gas extraction; these differences may be explained by the level of drilling activity that has occurred and their economic stake in the development.

There is large potential for a lack of trust between industry, community, and regulatory stakeholders. Both industry and communities need to perceive regulation as fair and based on credible and legitimate science in order to garner support for regulation from both groups. Likewise, industry must gain trust from communities in order to gain support for increased development.

Findings:

- Local and nearby communities are important stakeholders in shale gas development in Pennsylvania. Different community members perceive the risks and benefits of development differently. This is the result of different levels of familiarity, control and trust in the development process.

Recommendations:

- Pennsylvania should increase support for stakeholder engagement programs. The Penn State Cooperative Extension is an excellent example of a program that has gained the trust of communities and provided educational outreach. Industry could gain community trust through increased engagement with these groups.
- Greater industry transparency is needed. The development of fracfocus.org is a good starting point by providing a forum for the voluntary disclosure of the chemical composition of fracturing fluid. This initiative should expand to include a section on voluntary spill reporting from shale gas operators.

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Appendix A: Elicitation instrument

Water Risks of Natural Gas Extraction in the Marcellus Shale: An Expert Elicitation Study

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Introduction

Thank you for your participation in our study. Natural gas from shale formations in the United States has the potential to play an essential role in energy supply in the coming years. Your expertise in evaluating some of the environmental risks associated with the extraction process will be valuable in promoting fact-based discussion surrounding this important natural resource.

Before you begin completing the survey please read through this entire document carefully. In addition to the survey itself, the following pages contain FAQs for participants as well as information on the goals, scope, and methodology used in this study.

Most importantly, pages 6 – 8 contain critical information on estimating uncertain parameters and common biases in expert judgment. This section will prepare you to answer the survey questions consistently and accurately. Please review this material and complete the example within this section before your pre-survey phone call.

Finally, all participants must have a pre-survey phone call with the researchers to discuss the survey questions and provide clarification as needed.

Thank you again for your participation, and please contact Sarah Fletcher or Linda Liang with any questions.

Contents

FAQ for Survey Participants

Q1: Will the information I provide be confidential?

A1: Yes. Each participant will be assigned a number which will be used to identify his/her data in all future analysis and publications. Participant's names will be removed from all written survey responses, and the identification information linking names to numbers will be stored electronically on a secure server.

Q2: Will my name and/or company be listed in publications?

A2: We would like to acknowledge your contribution by listing you as a survey participant in any publications. If you are uncomfortable releasing this information, we can identify you by your industry/area of expertise instead.

Q3: Why do I need to sign a consent form?

A3: MIT research protocol requires a consent form from anyone participating in MIT research. The consent form provides you with a record of our confidentiality procedures, and provides MIT with a record of what personal information we are allowed to publish.

Q4: How will this study be published?

A4: This study will be first published as a working paper of the MIT Energy Initiative and will be used in a master's thesis. Our goal is to publish in a peer-reviewed journal. All publications will be publicly available.

Q5: Who else is participating in this survey?

A5: Participants all have expertise in natural gas extraction in the Marcellus Shale. Participants have a wide range of backgrounds and have been recruited from gas production companies, service providers, insurance companies and agencies, regulatory and government agencies, and academia.

Q6: What is the timeline of the survey?

A6: Our goal is to send the survey to participants in October after piloting is complete, obtain responses within two weeks, and have a draft of the study completed by January.

Overview of Study

Goal

The purpose of this study is to characterize the risk of fluid spills from shale gas extraction in the Marcellus. The survey contains a set of scenarios on operational hazards that might cause a fluid spill at the well site. These scenarios were chosen be to representative of a larger set of risks, some which happen frequently with small consequence, and others that are less likely but more severe in consequence. In addition, we hope to characterize the distribution of all spills that might occur in a one year time period.

Scope

Of the widely discussed water contamination risks associated with shale gas extraction, most fall into two categories: fluid management (water, chemicals, fracturing fluid, and flowback water), and gas migration. This study focuses exclusively on fluid management issues. In addition, the study analyzes only the likelihood and size of spills. The further consequences of these spills are left for future analysis.

Methodology

To gather data we use the expert elicitation methodology, in which experts—producers, service providers, regulators, insurers—with experience in the Marcellus Shale are asked to evaluate the likelihood and consequences of the risk scenarios. This is intended to capitalize both on the dispersed data that exists as well as expert judgment about the state of the industry going forward. Expert elicitation is particularly useful in this context because of the lack of available data to date. Use of current hydraulic fracturing technology is only a few years old in the Marcellus, and this short history makes it difficult to accurately characterize low probability events.

Setting

Please consider the Marcellus Shale in the state of Pennsylvania in the near-term future. The risks will obviously vary widely in different settings. Think about the entire range of variation in operation throughout the state, and incorporate this into your uncertainty estimates. Likewise, we are interested in all operators across the Marcellus, not just a specific operator or operators with whom you may be most familiar.

CONSENT TO PARTICIPATE IN SURVEY

You have been asked to participate in a research study conducted by Sarah Fletcher and Linda Liang from the Massachusetts Institute of Technology (M.I.T.). The purpose of the study is to assess the water risks associated natural gas extraction in the Marcellus Shale. You were selected as a participant in this study because of your expertise in shale gas extraction in the Marcellus. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- This survey is voluntary. You have the right not to answer any question, and to stop the survey at any time or for any reason. We expect that the survey will take about one to two hours.

- You will not be monetarily compensated for your participation.

- Information you provide will be de-identified in all resulting publications.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

(Please check all that apply)

☐ I give permission for the following information to be included in publications resulting from this study:

☐ my name ☐ my title ☐ my company/institution

Name of Subject

Signature of Subject ______________________________ Date __________

Signature of Investigator ____________________ Date ________

Please contact Sarah Fletcher (sfletch@mit.edu, 410.493.0929) or Linda Liang (linda@mit.edu, 847.372.7123) with any questions or concerns.

If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

Quantitative Estimation of Uncertain Parameters

Throughout this survey, you will be asked to provide a variety of quantitative estimates for uncertain parameters. You are likely familiar with much of the information below, as the natural gas industry is grounded in probability theory. However, expert judgment presents its own unique challenges.

Please carefully read and complete through the example below—it is designed to be directly parallel to the spill questions in the survey. The comments in italics will provide insight on how to best analyze the questions.

Example:

Pretend you are a meteorologist providing expert estimates to predict precipitation patterns in your home town next year. Answer the following questions.

1) A "precipitation day" is defined here as a day in which at least 0.1 inches of precipitation are recorded. Estimate the number of precipitation days that will occur in the next year. Please characterize the distribution of possibilities by completing the percentile estimates below.

   Your estimate for P5 is a lower bound at a 5% confidence level; if you chose 47 days, that would suggest you think there is a 5% chance that there will be fewer than 47 precipitation days in the next year. Likewise, your estimate for P95 is an upper bound at a 5% confidence level. P50 is your best guess.

   Start with the upper and lower bounds and think about extreme events that might occur. For the lower bound, maybe there is both an extended summer drought and no major snowstorms during the winter. How many precipitation days would that cause? Is there about a 5% chance that both of these events would occur? If you think it is more likely to occur than 5 times in 100 years, then you should adjust your estimation downwards. For the upper bound, maybe consider the possibility of an El Nino year, bringing lots of storms and hurricanes. Is the likelihood of this happening about 5%? If so, how many precipitation days would you expect in an El Nino year? Only after you have considered the upper and lower bounds, make your best guess for P50.

   Now that you have made your best estimates for P5, P50, and P95, consider your uncertainty in these estimates. Given that you are not really a meteorologist, it is likely considerable. If you made this estimate 100 times for 100 different cities, only 5 of them should be above your P95 estimate and only 5 of them should be below your P5 estimate, even if you are very uncertain. Do you need to broaden your confidence interval to account for your uncertainty?

   Now, provide your final answer for the question:

   P5: ____________________________ (days)

   P50: ____________________________ (days)

   P95: ____________________________ (days)

2) For any given precipitation day, estimate the amount of precipitation that will occur on that day. Please characterize the distribution of possible amounts of precipitation by completing the percentile estimates below.

   Imagine that that you took the all the precipitation days considered in the distribution in the previous question, and picked one at random. What is the range of possible amounts of precipitation if you did this repeatedly?

   Start again by setting a lower bound. Remember that a precipitation day is defined as having at least 0.1 inches of precipitation, so your lower bound must be at least this high. How much higher should you set your lower bound such that 5% of your random samples would be between 0.1 inches and P5? For your upper bound think again of extreme events. How much rain do you expect to get on a very stormy day?

   Remember that your distribution describes precipitation days only. For example, when considering the upper bound don't think about the type of storm that only happens 5 in 100 days—think about the type of storm that only happens 5 in 100 rainy days.

   Analyze your uncertainty as you did before: would your confidence interval include 90 out of 100 of your random samples?

   Finalize your upper and lower bounds and make your best guess.

   P5: ______________________________ (inches)

   P50: ______________________________ (inches)

   P95: ______________________________ (inches)

The questions you will be asked in the survey about the likelihood and size of fluid spills are very similar in format to the questions above. You may find the thought process outlined above useful: think about extreme events to characterize your bounds, check that this interval is wide enough to capture your uncertainty, and then make your best estimate.

Common Biases in Human Judgment

Now that you understand the kind of quantitative estimates you will be asked to make, please review the following information about bias. Experts are often prone to several common cognitive biases when making judgments about uncertain information. As you read assess how your own judgments may be susceptible to bias.

Availability

Probability judgments are often influenced by the availability of data or memory of an event occurring. Throughout this survey we are interested in comparing a variety of scenarios that may cause fluid spills in the shale gas extraction process. If you have more personal experience with some of the scenarios and less with others, this may bias your view of their relative rates of occurrence; you may find it helpful to discuss with others who have different expertise. You may also be more closely familiar with one specific operation, while we are interested in the probability of these scenarios happening in the industry at large. Please attempt to generalize specific data or information to the industry at large.

Inconsistency

Bias often arises when people are inconsistent in their cognitive reasoning when solving a series of problems. This survey contains a series of scenarios for which you will be answering the same set of questions several times. If you discover a new method of thinking about the problem in the middle of the survey, it may be helpful to go back and apply this method to previous questions.

Overconfidence and Anchoring

When providing confidence intervals for point estimates, experts typically provide answers that are greatly overconfident. One such example of experts' overconfidence is demonstrated by historical estimates of the speed of light. Though many physicists were experts in this field, most of their estimates were highly overconfident; the current accepted value of the speed of light is outside the confidence interval for over half of their prominent estimates between 1870 and 1950[24]. In this survey, beware of the tendency to make the range between your P5 and P95 estimates too narrow.

A related bias is that of anchoring, in which people are hestitant to deviate from initial impressions even when more information is provided. As described in the example above, you should provide upper and lower bounds for your point estimates before the median. This will help prevent you from anchoring your P5 and P95 estimates to you median estimate, causing overconfidence bias.

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[24] Henrion, M. and Fischoff, B. (1896.) "Assessing Uncertainty in Physical Constants," *American Journal of Physics, 54,* No. 9 (September): 791-798.

Survey

If you have read the background information and completed your pre-survey phone call, you are ready to begin the survey. Thank you for your patience.

Scenarios

Each of the following is a scenario in which fracturing fluid or flowback water could be released above ground on the well site. You will be asked a series of questions for each to assess the likelihood of occurrence for each scenario and the size of spill it has the potential to cause.

1. Fracturing fluid is spilled during transportation by pipe to the wellhead.

2. Fracturing fluid is spilled due to a well blow out.

3. Flowback water is spilled due to a retaining pit overflow or leak.

4. Flowback water is spilled during transportation by truck to a wastewater treatment facility.

Notes and Definitions:

- For this survey, we consider a "spill" a **release of 5 gallons or more of fluid**.
- These **scenarios are not completely comprehensive**, but rather representative of the types of risks that may cause fluid spills.
- Consider only shale operations in Marcellus in **Pennsylvania.**
- Consider **all shale operators**, both major integrated and independent, in your estimates.

Scenario 1: Fracturing fluid is spilled during transportation by pipe to the wellhead.

This includes all pumped fluid between the blender and the wellhead. It does not include bringing water or chemicals to location.

1. Assuming that current drilling rates continue (approximately 1500 new wells in 2010), how many times do you expect this type of spill to occur in PA in the next year?

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   P5: ______________________ (spills)

   P50: _____________________ (spills)

   P95: _____________________ (spills)

2. Assuming that a spill occurs as a result of this scenario, please answer the questions below to estimate its size. Your answers will characterize the distribution of possible spill sizes.

   Part a): In the left hand column below estimate the total amount of fluid this scenario would release. Include both fluid that will be recovered and fluid that will enter the environment.

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   Part b): For each of the spill sizes indicated in the left column, estimate in the right column the amount of fluid that would be recovered. For example, if you indicated for your P5 estimate in part a) a volume of x gallons, now estimate what percentage of those x gallons would be recovered (i.e. fluid that does not enter the environment).

P5: ________________________ (gallons) Percent of P5 estimate recovered: _________ (%)

P50: _______________________ (gallons) Percent of P50 estimate recovered: ________ (%)

P95: _______________________ (gallons) Percent of P95 estimate recovered: ________ (%)

3. What percentage of spills of this type would you expect to be primarily caused by:

Human error on the well-site: ____

Equipment failure ____
(this may include human error in manufacturing):

Acts of nature: ____

Other ____
(Please explain "other" in comments)

4. Comments: Use the space below to include any assumptions, explanations, questions, or ideas. Were there particular assumptions or events underlying part or all of your answers?

Scenario 2: Fracturing fluid is spilled due to a well blow out.

1. Assuming that current drilling rates continue (approximately 1500 new wells in 2010), how many times do you expect this type of spill to occur in PA in the next year?

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   P5: ________________________ (spills)

   P50: _______________________ (spills)

   P95: _______________________ (spills)

2. Assuming that a spill occurs as a result of this scenario, please answer the questions below to estimate its size. Your answers will characterize the distribution of possible spill sizes.

   Part a): In the left hand column below estimate the total amount of fluid this scenario would release. Include both fluid that will be recovered and fluid that will enter the environment.

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   Part b): For each of the spill sizes indicated in the left column, estimate the amount of fluid that would be recovered in the right column. For example, if you indicated for your P5 estimate in part a) a volume of x gallons, now estimate what percentage of those x gallons would be recovered.

P5: __________________________ (gallons) Percent of P5 estimate recovered: _________ (%)

P50: _________________________ (gallons) Percent of P50 estimate recovered: _________ (%)

P95: _________________________ (gallons) Percent of P95 estimate recovered: _________ (%)

3. What percentage of spills of this type would you expect to be primarily caused by:

Human error on the well-site: ____

Equipment failure ____
(this may include human error in manufacturing):

Acts of nature: ____

Other ____
(Please explain "other" in comments)

4. Comments: Use the space below to include any assumptions, explanations, questions, or ideas. Were there particular assumptions or events underlying part or all of your answers?

Scenario 3: Flowback water is spilled due to a retaining pit overflow or leak.

This scenario includes only flowback fluid that has not yet undergone on-site or off-site wastewater treatment.

1. Assuming that current drilling rates continue (approximately 1500 new wells in 2010), how many times do you expect this type of spill to occur in PA in the next year?

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   P5: ________________________ (spills)

   P50: ________________________ (spills)

   P95: ________________________ (spills)

2. Assuming that a spill occurs as a result of this scenario, please answer the questions below to estimate its size. Your answers will characterize the distribution of possible spill sizes.

   Part a): In the left hand column below estimate the total amount of fluid this scenario would release. Include both fluid that will be recovered and fluid that will enter the environment.

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   Part b): For each of the spill sizes indicated in the left column, estimate the amount of fluid that would be recovered in the right column. For example, if you indicated for your P5 estimate in part a) a volume of x gallons, now estimate what percentage of those x gallons would be recovered.

P5: ________________________ (gallons) Percent of P5 estimate recovered: __________ (%)

P50: ________________________ (gallons) Percent of P50 estimate recovered: _________ (%)

P95: ________________________ (gallons) Percent of P95 estimate recovered: _________ (%)

3. What percentage of spills of this type would you expect to be primarily caused by:

Human error on the well-site: ____

Equipment failure ____
(this may include human error in manufacturing):

Acts of nature: ____

Other ____
(Please explain "other" in comments)

4. Comments: Use the space below to include any assumptions, explanations, questions, or ideas. Were there particular assumptions or events underlying part or all of your answers?

Scenario 4: Flowback water is spilled during transportation by truck to a wastewater treatment facility.

This scenario includes only offsite wastewater treatment facilities, after all on site water recycling has taken place.

1. Assuming that current drilling rates continue (approximately 1500 new wells in 2010), how many times do you expect this type of spill to occur in PA in the next year?

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   P5: ________________________ (spills)

   P50: ________________________ (spills)

   P95: ________________________ (spills)

2. Assuming that a spill occurs as a result of this scenario, please answer the questions below to estimate its size. Your answers will characterize the distribution of possible spill sizes.

   Part a): In the left hand column below estimate the total amount of fluid this scenario would release. Include both fluid that will be recovered and fluid that will enter the environment.

   Please set upper and lower bounds at a 95% confidence level and then make your best estimate.

   Part b): For each of the spill sizes indicated in the left column, estimate the amount of fluid that would be recovered in the right column. For example, if you indicated for your P5 estimate in part a) a volume of x gallons, now estimate what percentage of those x gallons would be recovered.

P5: __________________________ (gallons) Percent of P5 estimate recovered: __________ (%)

P50: __________________________ (gallons) Percent of P50 estimate recovered: _________ (%)

P95: __________________________ (gallons) Percent of P95 estimate recovered: _________ (%)

3. What percentage of spills of this type would you expect to be primarily caused by:

Human error on the well-site: ____

Equipment failure ____
(this may include human error in manufacturing):

Acts of nature: ____

Other ____
(Please explain "other" in comments)

4. Comments: Use the space below to include any assumptions, explanations, questions, or ideas. Were there particular assumptions or events underlying part or all of your answers?

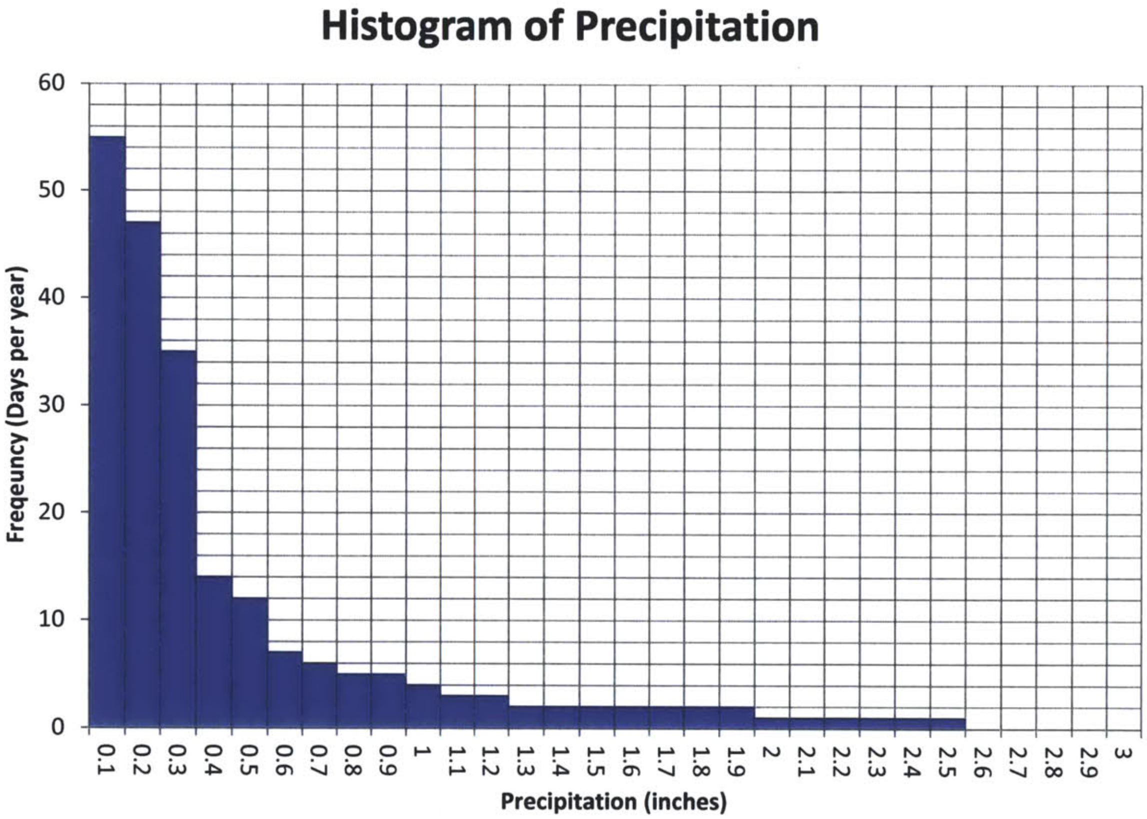
Cumulative Spill Distribution

In the previous questions, you were asked to assess the likelihood and size of spills caused by four operation risk scenarios. While these scenarios encompassed many of the common sources of surface spills at the well site, they are not comprehensive. Now, please consider *all* possible sources of surface spills of fluid that contains chemical additives and/or naturally occurring radioactive material.

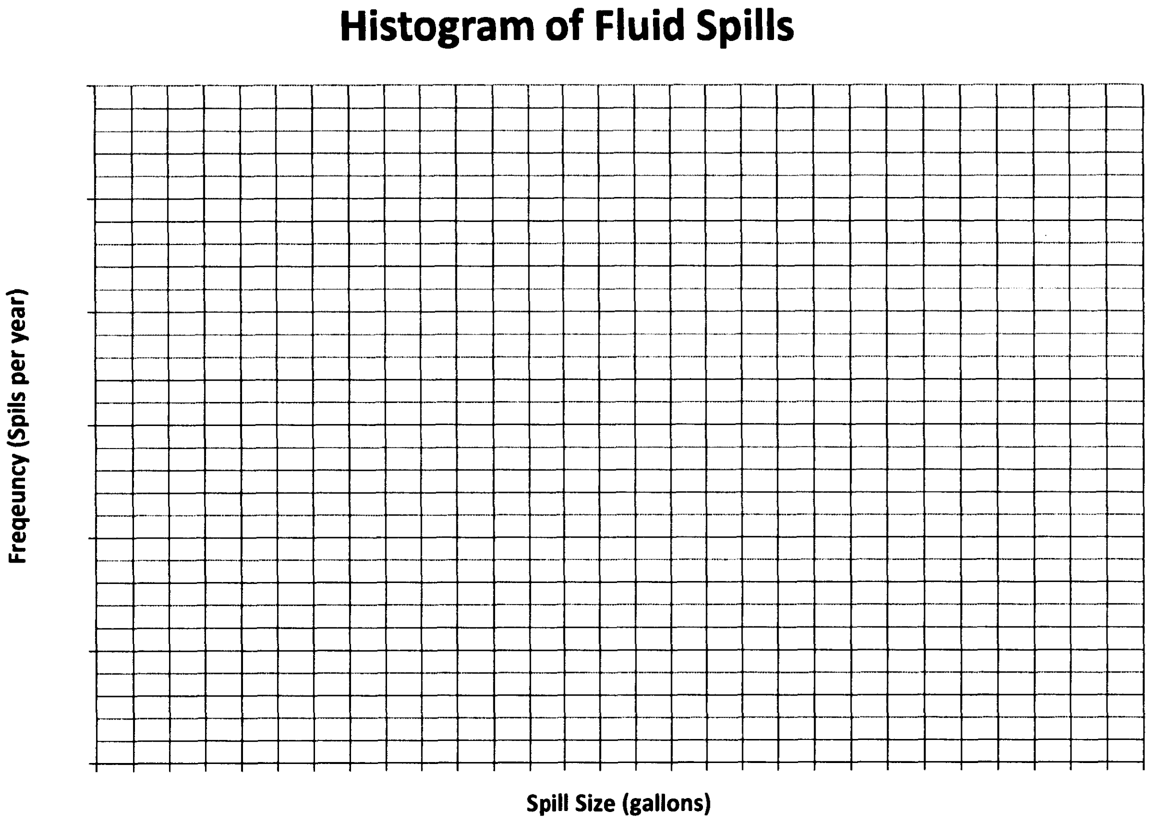
a) In the space below, please list other sources of surface spills that were not included in the scenarios. Do not include sources of underground water contamination (such as well casing failure or stray gas migration).

b) The next page contains an empty graph for you to fill in with your best guess of the histogram describing all spills that will happen in PA in a one year period. Consider both the survey scenarios and the other sources of spills listed above.

Below is an example of a histogram that you might have drawn for the example question on precipitation.



Now fill out your own histogram. The horizontal axis is the spill size and the vertical axis is the spill frequency. Please fill in the axes with a numerical scale. Then color in the rectangles to produce a histogram.



Expert 1	Number of Spills			Spill volume (gallons) and percent recovered						Cause of Spill			
	P5	P50	P95	P5	%	P50	%	P95	%	Human	Equip	Nature	Other
Scenario 1	5	10	15	5	80	20	95	50	98	60	40	0	0
Scenario 2	1	3	5	1000	50	10000	35	50000	20	25	75	0	0
Scenario 3	5	10	20	10	80	100	50	1000	20	10	90	0	0
Scenario 4	1	5	10	10	80	400	40	4620	20	75	25	0	0

Expert 2	Number of Spills			Size of Spill and Percent recovered						Cause of Spill			
	P5	P50	P95	P5	%	P50	%	P95	%	Human	Equip	Nature	Other
Scenario 1	10	30	100	100	5	500	20	2000	50	97	2	1	0
Scenario 2	0	1	2	10000	5	40000	10	80000	20	49	49	2	0
Scenario 3	3	5	20	1000	5	5000	20	20000	25	10	90	0	0
Scenario 4	0	1	2	3000	10	5500	10	11000	10	95	5	0	0

Expert 1 comments

Scenario 1
Recovered numbers: "This would be assuming that you could clean up all but maybe a gallon of the size of the spill."

"This first scenario is the most unlikely source of contact, as people are watching close and can respond quickly in this scenario minimizing impact. Also, these operations would take place on a liner with berm to contain any potential spills."

Scenario 2
"This is the least likely to occur with the greatest possibility of a large impact if it does occur. Clean up on site is much easier than off site. If the spill is contained within the sites erosion and sediment controls it can all be recovered (mostly). If the spills goes off location, clean up is more difficult."

"Current PA CH. 78.72 regulations should prevent this occurrence if operator is using a full BOP stack running on an accumulator not rig hydraulics."

Scenario 3
"It is unlikely that someone would allow a pit to overflow. It is far more likely that a liner would tear due to subsidence on the embankment. The more that leaks, the less they will recover. Clean up is difficult when it leaks into the ground instead of onto the surface. Operators are starting to use tanks instead of pits to prevent this occurrence."

Scenario 4
"4620 gallons would be the entire 100 BBL tank nearly full, but it's more likely that a small amount would leak, if any at all. Clean up would be more difficult due to drainage systems on public roads. This is why spills in a water reservoir are require a 911 call for emergency response."

Total
"Spills less than 50 gallons may happen at the same frequency as spills of 100 gallons but as the spill size increases the amount recovered will decrease. There really is not "in between" size spill. Most spills are small, but blowouts, although extremely rare, pose a slim chance of catastrophe."

Expert 2 comments

Total
"Sources of spill not included in the scenario: transporting to location in pipe (pre-blender), well head to storage (gas buster pipe)"

Appendix C: Chemical additives in fracturing fluid

I compiled data on fracturing fluid composition from 20 wells across a variety of operators and locations in Pennsylvania. For each chemical, I found the highest concentration of the chemical as a percentage of mass of fracturing fluid across all 20 samples. This is listed in the column "Maximum Concentration." "Count" is the number of wells out of the 20 sampled that used the chemical additive.

Purpose	Ingredients	CAS number	Maximum Concentration	Count
Acid	Hydrochloric Acid	007647-01-0	0.15978%	20
Corrosion inhibitor	Methanol	000067-56-1	0.00076%	13
	Aliphatic acid	NA	0.00057%	7
	Aliphatic alcohols, ethoxylated # 1	NA	0.00057%	7
	Propargyl Alcohol (2-Propynol)	000107-19-7	0.00019%	13
	Ethoxylated Alcohols^ C14-15	068951-67-7	0.00025%	4
	Modified Thiourea Polymer	068527-49-1	0.00025%	5
	Alkenes^ C>10 alpha-	064743-02-8	0.00004%	5
	Isopropanol	000067-63-0	0.00106%	7
	Organic Amineresin Salt	NA	0.00053%	4
	Aromatic Aldehyde	NA	0.00018%	4
	Dimethyl Formamide	000068-12-2	0.00049%	7
	Quaternary Ammonium Compounds	NA	0.00018%	4
	Ethylene Glycol	000107-21-1	0.00065%	4
	Decanol	000112-30-1	0.00011%	4
	Octanol	000111-87-5	0.00011%	4
	2-Butoxyethanol	000111-76-2	0.00008%	4
	Fatty Acids	NA	0.00004%	1
	Polyoxyalkylenes	NA	0.00004%	1
	Olefin	NA	0.00001%	1
Iron Control Agent	Trisodium NTA	018662-53-8	0.00175%	4
	Sodium Sulfate	007757-82-6	0.00009%	4
	Sodium Hydroxide	001310-73-2	0.00004%	4
	Sodium Erythorbate	006381-77-7	0.00289%	7
	Citric Acid	000077-92-9	0.00459%	5
Friction Reducer	POLY(ACRYLAMIDE-co-ACRYLIC acid	009003-06-9	0.01871%	4
	Aliphatic amine polymer	NA	0.02868%	4
	Ammonium Sulfate	007783-20-2	0.02868%	4
	Petroleum Distillate Hydrotreated Light	064742-47-8	0.04922%	13
	Aliphatic alcohol polyglycol ether	NA	0.00076%	5
	Polyethoxylated Alcohol Surfactants	NA	0.00318%	2
	Sodium Chloride	007647-14-5	0.01230%	4

	Alcohols ethoxylated C12-16	068551-12-2	0.00861%	4
	Quaternary Ammonium Chloride	012125-02-9	0.00861%	4
Non-Emulsifier	2-Butoxyethanol	000111-76-2	0.00019%	4
	Methanol (Methyl Alcohol)	000067-56-1	0.00019%	4
	Coconut oil, Diethanolamide	068603-42-9	0.00009%	4
	Diethanolamine	000111-42-2	0.00004%	4
Anti-Bacterial Agent	Glutaraldehyde (Pentanediol)	000111-30-8	0.02042%	16
	Didecyl Dimethyl Ammonium Chloride	007173-51-5	0.00301%	7
	Quaternary Ammonium Compound	068424-85-1	0.00361%	15
	Ethanol	000064-17-5	0.00180%	15
	Chlorine Dioxide	010049-04-4	0.00097%	3
Scale Inhibitor	Methanol	000067-56-1	0.01124%	9
	Sodium polyacrylate	NA	0.01245%	5
	Sodium Hydroxide	001310-73-2	0.01124%	1
	Sodium polycarboxylate	NA	0.01270%	4
	Ethylene Glycol	000107-21-1	0.00088%	1
	Trisodium Ortho Phosphate	007601-54-9	0.00088%	1
Gelling Agent	Carbohydrate polymer	NA	0.25802%	2
	Petroleum Distillate Hydrotreated Light	064742-47-8	0.14715%	4
Breaker	Ammonium Persulfate	007727-54-0	0.00766%	7
Surfactant	Amine derivative	NA	0.04122%	1
Flowback Control Additive	Synthetic Organic Polymer	NA	0.08059%	1
Clay Stabilizer	Tetramethyl Ammonium Chloride	000075-57-0	0.04995%	1
Cross Linker	Aliphatic polyol	NA	0.04308%	1
	Potassium Hydroxide	001310-58-3	0.02154%	1
	Ethylene Glycol	000107-21-1	0.01275%	2
	Boric Acid	010043-35-3	0.00546%	2
	Ethanolamine	000141-43-5	0.00364%	2
	Petroleum Distillate Hydrotreated Light	064742-47-8	0.01270%	1
pH Adjusting Agent	Potassium Carbonate	000584-08-7	0.03019%	2
	Potassium Hydroxide	001310-58-3	0.02012%	2

LIST OF ACRONYMS

CERCLA – Comprehensive Environmental Response, Compensation and Liability Act
CWA – Clean Water Act
EH&S – Environmental, health and safety
EPCRA – Emergency Planning and Community Right to Know Act
FACS – Foundation for American Communications
GHG – Greenhouse gas
HDGB – Hydrogeologic Database for Ground-Water Modeling
MIT – Massachusetts Institute of Technology
MSDS – Mineral Safety Data Sheets
NORM – Naturally occurring radioactive material
NPDES – National Pollutant Discharge Elimination System
NRC – National Research Council
NY DEC – New York Department of Environmental Conservation
OPA – Oil Pollution Act of 1990
PA DEP – Pennsylvania Department of Environmental Protection
PPC – Preparedness, Prevention and Contingency
PRA – Probabilistic risk assessment
RCRA – Resource Conservation and Recovery Act
RfD – Reference dose
SGEIS – Supplemental Generic Environmental Impact Statement
SPCC – Spill Prevention, Control and Countermeasure
SPR – Spill Prevention Response
SWDA – Safe Water Drinking Act
STRONGER – State Review of Oil and Natural Gas Environmental Regulations Inc.
Tcf – Trillion cubic feet
TRI – Toxics Release Inventory
UIC – Underground Injection Control
U.S. EIA – United States Energy Information Administration
U.S. EPA – United States Environmental Protection Agency
U.S. DOT – United States Department of Transportation