Modeling the Interdependencies of Energy and Water in New Mexico: Historic Drivers, Hydrologic Impacts, and Energy Requirements

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Modeling the Interdependencies of Energy and Water in New Mexico: Historic Drivers, Hydrologic Impacts, and Energy Requirements

by

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DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Doctor of Philosophy

Engineering

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Albuquerque, New Mexico

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Dedication

To my family, and to the smallest members especially.

Ruby, Leo, Frankie, Lane, and June:

The future is a brighter place with you in it.
Acknowledgements

I would like to thank my advisor, Dr. Bruce Thomson for his guidance and mentorship over the last four years. Without you, I would have never found my way to civil engineering. Thank you for your consistent encouragement, your willingness to review anything and everything I’ve ever sent you, countless enchiladas at the Frontier, and the terrifying and unforgettable flying lesson. This process wouldn’t have been as enjoyable as it was without you.

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Abstract

There is increasing need to understand the interdependencies between energy resource development and water resources, particularly in arid regions with vast energy reserves like New Mexico. The state has a long history of energy resource development, including both uranium and fossil fuels. These activities have and continue to impact scarce water resources. There exist gaps in knowledge regarding the drivers of historic uranium mining and the uncertainties inherent in past estimates of groundwater impacts because of mining activity and in current understanding of the energy required to manage water in the oil and gas industry. Although uranium has not been mined in the state for decades there is increasing interest in sourcing uranium domestically, for which the state ranks second in national reserves. While historic mining had extensive impacts on water resources, past estimates have not considered uncertainty when evaluating the range of
potential impacts in the future. Addressing these gaps will improve our understanding of the connections between energy resource development and water resources and add to existing knowledge by developing modeling methods and tools. This research addresses these gaps by developing modeling approaches to improve understanding of the interrelationships between energy development and water resources and to aid in future decision-making. The three objectives of this research are to 1) improve understanding of the roles that economics and policy played in the operation of U mines in New Mexico using a system dynamics modeling (SD) framework; 2) to develop a decision support tool to evaluate the impacts on and uncertainties associated with renewed uranium mining on groundwater in the San Juan Basin, NM; and to 3) to evaluate the energy required to manage fresh and produced water associated with oil and gas production in NM. This work was developed using SD modeling and incorporated optimization techniques to understand how changes in economics and federal energy policy influenced uranium mining operations, and geospatial modeling uncertainty analyses to identify a range of prospective hydrologic impacts of renewed uranium mining. Geospatial modeling was also utilized to evaluate the energy footprint of alternative water management strategies in the oil and gas industry. The results of this work further existing knowledge regarding the connections between water and energy resource development. First, historic uranium mining operations were increasingly influenced by policy as compared to economics, indicating that future uranium mining decisions will be driven by federal energy policy. Second, the potential impacts of renewed uranium on groundwater including dewatered volume and drawdown of the potentiometric surface in the San Juan Basin vary by location. By addressing uncertainty associated with these impacts, this work indicated the
importance of uncertainty evaluation in future site-specific analyses. Third, alternative water management strategies in the oil and gas field can be less energy intensive than conventional management methods. These strategies have the potential to reduce demands on limited fresh water resources and risks associated with deep well disposal. Last, the methods developed as a result of this research address the diverse needs of decision makers and are applicable to other industries, locations, and water resources investigations.
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1 Introduction

1.1 Motivation and Objectives

Understanding the connections between energy and water, two critical and intertwined resources, is becoming increasingly important to human society. Water is used for energy production and energy is required for water management. Awareness of the linkages between energy and water has grown, particularly in arid regions where limited water resources are constrained by numerous and often competing demands. Population growth, increasing energy demands, and a changing climate may further intensify the interdependencies of these resources in the future (US DOE, 2014). As a result, the development of modeling methods to address the dynamics between energy and water and to aid in decision support are important tools for future planning (US DOE, 2014; US EPA, 2009; Brookshire et al., 2013).

The linkages between water and energy resources are numerous, complex, and inherently dynamic. Additional factors such as economics and policy influence the way both resources are managed. Therefore, the impacts of the development of one resource on the other, and within the larger system over time can be difficult to anticipate. Comprehensive numerical modeling approaches have become increasingly prominent in the suite of management methods employed by water managers, states, and researchers (US EPA, 2009; Ahmad & Simonovic, 2004; Winz et al., 2009). These approaches have the potential to improve decision making by quantifying dynamic interactions and potential future impacts (McIntosh et al, 2011; Brookshire et al., 2013). Although uranium mining was integral to New Mexico’s history as an energy producer, the roles
that economics and policy played in their operations has never been evaluated quantitatively. Furthermore, the impacts of future mining activity on water resources have not explicitly considered uncertainty. Lastly, although the water both produced by and required for oil and gas production have received increasing research focus (Clark and Veil, 2009; Murray, 2013; Veil et al., Veil, 2015; Gallegos et al., 2015; Scanlon et al., 2015; Scanlon et al., 2017), the energy required to manage this critical resource have not been investigated. An integrated understanding of these interconnected resources will aid in future decision making.

The overarching goal of this research was to develop flexible and transparent modeling tools to address the connections between energy resource development on water resources and to aid in long-term planning. Three energy resources are considered: uranium, oil, and natural gas. Although these models were developed to address issues in NM, the methodologies are applicable to other regions and resources. New Mexico was once the largest producer of uranium and its current reserves are the second largest in the nation (McLemore et al, 2013). Although uranium mining in NM ceased nearly thirty years ago, increasing interest in sourcing nuclear fuels from domestic supplies may lead to renewed mining in the state (Tabuchi, 2018; Donnan, 2018). Historic mining was influenced by regional and national economic and policy dynamics and these activities had impacts on regional water sources (SJBRUS, 1980). Oil and natural gas resources have been developed in NM for more than a century and recent advances in production technologies (horizontal drilling and hydraulic fracturing (HF)) have amplified the role of the industry not only in the state, but in the nation’s energy portfolio (US EIA, 2017).
However, these new technologies increasingly require water for production and generate large volumes of water that must be managed. To accomplish this goal, models were developed to address the following three questions:

1) How did changes in economics and energy policy impact historic mine operations in the Grants Mining District, NM and how did mine size and additional commodities produced influence these responses?

2) What are the potential impacts of renewed underground uranium mining on ground water in the San Juan Basin region and how are these impacts influenced by uncertainty?

3) What are the energy requirements for alternative water management strategies associated with O&G production, including fresh water pumping, water conveyance, produced water treatment and reuse, and water disposal and how do they vary regionally?

These objectives are investigated in the following three chapters which were developed as individual papers for publication. Chapter 2 describes the development of a system dynamics model (SD) to improve understanding of the impacts of economics and policy on historic uranium mining operations in New Mexico using optimization techniques (Zemlick et al., 2017). Chapter 3 builds upon knowledge of historic mining generated by Chapter 2 to evaluate the impacts of future U mining on water resources in the San Juan Basin. A SD model is developed that evaluates the combined uncertainty and spatial heterogeneity of potential future hydrologic impacts (Zemlick et al., in preparation). In Chapter 4, the focus of this research shifts from uranium to oil and
natural gas, two resources that have gained prominence in NM both because of the availability of unconventional resources and the water associated with production. This chapter uses geospatial modeling tools to evaluate the energy required for alternative management strategies for water in the oil and gas industry (Zemlick et al., 2018).

1.2 Scientific Contribution of this Research

There is great potential for NM to increase its status as one of the nation’s leading energy producing states but that role is contingent upon the efficient management of water required for energy resource development. While the interests and goals of industry, regulators, and communities are often disparate, improved understanding of the tradeoffs that exist between energy and water resources is of benefit to all. This research develops tools to quantitatively assess these potential impacts and illustrates critical connections between the drivers of historic development, and the energy and water required for energy resource production in the future.

This research addresses three research gaps that have not been addressed by previous studies. First, contemporary assessments of resumption of uranium mining are primarily based on commodity prices (McLemore, 2013) and have not considered the dynamics between economics and policy on mine operations. Chapter 2 considers both components within the context of state and federal energy policy as well as the economics of both uranium and vanadium production. The results of this research illustrate the importance of economies of scale as compared to decision-making agility in historical operational responses of uranium mines to changes in commodity prices and energy policies.
Second, previous estimates of the impacts of uranium mining on groundwater availability have not considered uncertainty associated with both mine dewatering and regional groundwater hydrology (Lyford et al, 1980; USDA, 2013). In addition, these studies have relied on time and computationally intensive numerical models that do not allow for sensitivity or uncertainty analysis, nor are they easily coupled with existing models designed to address interdisciplinary water management issues. These gaps are addressed in Chapter 3 where a compartmental SD model of the San Juan Basin is developed and uncertainty quantified using Monte Carlo analysis. This approach enables rapid evaluation of future scenarios while considering the potential for uncertainty in projected impacts. Because the results of this work indicate that renewed uranium mining could result in a wide range of hydrologic impacts, it highlights the importance of considering uncertainty in future site-specific analyses. Variation in the amount of water produced from future mines will influence management opportunities as well as the potential impacts on existing water users.

Third, the energy required to manage water has been considered in nearly every sector except for energy resource production. As water becomes increasingly critical in the oil and gas industry, understanding the spatial variation in the energy required to manage it will influence how future decisions are made. Chapter 4 addresses this gap through the development of metrics which quantify the energy required to pump and transport fresh water for hydraulic fracturing, as well as the energy to transport, treat, reuse, and dispose of produced water. The results illustrate that reuse of produced water is in many cases less than the energy required for conventional management strategies.
Increasing production and demand for water may provide regional incentives for alternative water management techniques that reduce disposal volumes and stress on fresh water resources.

1.3 Energy and Water in New Mexico

Energy resource development has been an integral part of New Mexico’s history and is critical to the current and future energy needs of both the state and the nation. However, development of energy resources including uranium, oil, and natural gas have impacts on an essential resource: water. Water is a critical resource in New Mexico, a state that is characterized by water scarcity. Limited water resources and periodic drought can constrain both the state’s economy and the livelihoods and quality of life of its residents. In addition, groundwater resources supply nearly half of the water used annually in the state and three-quarters of water used for public supply (Longworth et al., 2013) but recharge to these aquifers is minimal.

Mines and mills in NM produced more uranium than any other region in the US historically (McLemore et al). Although production has not occurred in more than three decades, there exists the potential for future development based upon the existing resources in the state, as well as in sourcing U from domestic suppliers in the future. However, little is known regarding the interactions between economics and policy that influenced historic mining. A better understanding of these dynamics may serve to inform the conditions under which renewed U mining may occur in the future.
In addition to their unique operational dynamics, historic U mines were primarily located in water-bearing formations and dewatering was required to recover ore. At the height of production, dewatering of uranium mines produced nearly 8 billion gallons per year (BGY), more than one and a half times the volume of groundwater withdrawn in McKinley County at present. This activity led to drawdown in groundwater head in excess of 500 ft. where mining was most intense (Lyford et al., 1980) and extensive cones of depression (SJBRUS, 1980).

At present, O&G production defines NM’s role as an energy-producing state. Advances in drilling and production technologies combined with the amount of unconventional reserves in the state have contributed to NM rising to the third top energy producer in the country (Montoya Bryan, 2018). Production from these reserves with new technologies requires increasing amounts of water and produces even greater volumes that must be managed. Because both these trends and the O&G industry are projected to persist into the future, understanding how much energy is required to manage both sources of water may inform management alternatives and reduce fresh water impacts. Identifying the locations where and the circumstances under which alternative management may be beneficial may improve the sustainability of these activities while preserving scarce water resources.

1.4 Modeling Approaches

Model-driven decision support systems (DSS) were developed beginning in the 1960s to aid in decision making and long-term planning. Initially, DSS tools were developed to improve business decisions through the evaluation of large and diverse sets
of information. As computing systems evolved, so did the complexity and utility of DSS both within and outside of the business world. By the 1990s, DSS tools were increasingly developed to address complex and intertwined social, environmental, and resource allocation issues (McIntosh et al., 2011). These tools incorporate diverse modeling approaches and software environments and aim to identify management choices that improve resource use efficiency and minimize environmental impacts (McIntosh et al., 2011). Numerous studies have employed this approach to water management issues. The DSS tools developed as a result of this research employ system dynamics (SD) and geospatial modeling techniques.

1.4.1 System Dynamics Modeling

Powersim (Powersim, 2015) is an SD modeling software that tracks the relationships and feedbacks within components in a system and allows for uncertainty analysis of model parameters. This software has been used in previous water resources and interdisciplinary resource allocation studies. However, there is no evidence in the literature that it has been applied to evaluate uranium mining. This research used Powersim in two studies with different objectives and modeling approaches. First it was used to evaluate the impacts of economics and policy on historic uranium mining operations in New Mexico using historic mine data and optimization techniques. Next, Powersim was used to evaluate the range of potential impacts of uranium development on ground water resources in the San Juan Basin, NM. This work specifically considers uncertainty in its analysis because understanding the range of potential outcomes is of
import when considering how water is managed and the impacts of dewatering can be mitigated.

1.4.2 Geospatial Modeling

Understanding the impacts of resource allocation in a holistic way requires consideration of geospatial relationships in the larger environment (Laniac et al., 2013). Arc GIS (ESRI, 2014) is the most widely used software for spatial analysis. It allows for the incorporation and analysis of large and diverse sets of spatially-based information. Furthermore, built-in tools enable evaluation of statistical relationships. Understanding existing and future spatial dynamics is particularly important for DSS tools, where a diversity of users may have minimal knowledge about the specifics of the system but are familiar with and find spatially based results useful. Geospatial modeling was utilized to evaluate the heterogeneity of hydrologic impacts of uranium mine dewatering in the San Juan Basin (Chapter 3). These methods are also used to evaluate the spatial relationships between O&G wells, groundwater wells, and disposal wells in the state to quantify the variation in energy demand in four major O&G producing basins (Chapter 4).
2 Modeled Impacts of Economics and Policy on Historic Uranium Mining Operations in New Mexico


2.1 Abstract

New Mexico was at the forefront of the nuclear age, producing more uranium (U) than any other state in the U.S. for more than three decades until the early 1980s. The state is also unique because these historic activities have been studied and quantified over during this time, providing a unique opportunity to identify how historic uranium mining operations were influenced by economics and policy. To quantify these relationships, this study used a system dynamics approach to determine how these factors affected mining industry decisions and how those impacts varied based on mine size. The results of this work found that as the industry evolved over time, the influence of these factors changed and that they did not impact all mining operations equally. Results indicate that price guarantees for U concentrate and subsidies for mining and milling in the early years (1948-1964) of U mining encouraged mines of all size, although smaller mines opened and closed more quickly in response to changes in price. The economic environment created by these policies encouraged exploration and production. However, the latter led to an excess in supplies and declining prices when these incentives lapsed in the mid-1960s, which negatively impacted small- and medium-sized mines, neither of which opened after 1964. The presence of larger mines had more impact on the closing of small mines than closing of medium mines, possibly because of economies of scale for the
medium mines or their ability to access milling resources after 1964. Lastly, medium and large mines that produced both uranium and vanadium may have had a slight historic advantage over mines that produced only uranium, as evidenced by longer delays in closing response to a unit change in average price. Quantification of these relationships assists in an improved understanding of the factors that influenced historic mining operational decisions and illustrates the complexity of the roles played by economics and policies in the boom and bust cycle manifested in the uranium industry.

2.2 Introduction

The uranium industry in New Mexico experienced rapid growth following the advent of the nuclear age. Mines and mills in the state produced more uranium (U) than any other region in the United States and were, in the mid-60s, responsible for up to 30% of U concentrate (U₃O₈) produced globally (Roskill, 1991). Between 1947 and 2002, more than 200 recorded mines and 8 mills throughout the state produced more than 340 million pounds of U₃O₈ and generated $4.7B in revenue (McLemore, 1983; McLemore et al., 2013; McLemore, in press). An integral part of uranium mining in New Mexico is the Grants uranium district. The region became known as the “Uranium Capital of the World” (Fitch, 2012) because the Grants mining district produced more than 99% of state-wide production between 1948 and 1982 (McLemore, 1983).

While the growth of the industry was rapid, it was also marked by a degree of randomness because of varying demand for U (used primarily for weapons by the Federal government and nuclear power generation by both the Federal government and commercial utility companies), discovery of new reserves and concerns of U scarcity, and
evolving regulatory frameworks -- all of which impacted both negotiated prices for long term contracts and U spot prices (Roskill, 1991). Spot price refers to an estimated value regarding transactions involving "significant quantities of natural uranium concentrates" (Roskill, 1991) that could be completed at a specific date; it is often considered to be the average price of negotiated large, long-term contracts and does not typically include smaller sales that would be included in an average price estimate (Roskill, 1991).

Roskill (1991) and Walker and Wellock (2010) describe the historic complexity of the U market. Of interest is how successive discoveries of new uranium reserves and uranium's practical uses increased public perception of the utilitarian value of this commodity. They also note how the rapid development of the nuclear power industry was encouraged by government subsidies and information-sharing (Walker and Wellock, 2010). “Probably the single most important difference is that the uranium industry [as compared to other mineral industries], born under a nuclear cloud, was the brainchild of the government” (Roskill, 1991).

Although the regional and national U industry thrived for nearly 30 years, it rapidly diminished in the early 1980s due to declines in prices, delays and cancellations of orders for new nuclear power plants (Roskill, 1991), and disasters, such as Three Mile Island, that altered the trajectory and credibility of the nuclear industry (Walker and Wellock, 2010). Uranium production in New Mexico ended in 2002 with the closure of the Quivira Mining Co. (formerly Kerr-McGee Corp.) mill, which at the end of its operation solely recovered U from mine water (McLemore and Chenoweth, 2003)
Nuclear energy currently supplies 19% of U.S. electric power, but nearly all the U fuel supply is imported (US EIA, 2016). Increasing U prices and improvements in mining technologies, recognition that nuclear power is carbon free, as well as the desire for energy security and energy supply stability have resulted in renewed interest in U production in NM and elsewhere. While many factors influence mining operations, historic U.S. mining of U was driven by government-related markets, regulations, and subsidies enacted to encourage the development of the nuclear industry by ensuring a stable and reliable supply of uranium.

The objective of this study was to improve understanding of the roles that economics and policy played in the operation of U mines in New Mexico using a system dynamics modeling (SD) framework. Because New Mexico was at the forefront of the U boom, was a leading domestic producer for nearly three decades, and because a historic record of mine production exists, this area provides a unique opportunity for evaluating how these two factors influenced past mining operations. While numerous additional factors influence the development and operation of a U mine (e.g., geologic or geographic setting), understanding the dynamics of mine opening and closure through use of historical data may provide insight into historic U mining operational decisions and a useful tool in understanding and planning for future activities associated with extractive industries.

2.2.1 Historical Background

Uranium is a radioactive element that had been used to color glass and ceramic products in the 19th and early 20th Centuries (Roskill, 1991. The 1910 discovery of the
medical application of radium, a daughter product of uranium, increased the value of what had been previously considered a relatively useless element (Roskill, 1991). The following year, one gram of radium sold for between $120,000 to $160,000 (Roskill, 1991), approximately 11-15 million dollars per gram in current dollars. However, it was the discovery of nuclear fission in 1939 that would propel U from “an element of little value to one of the most sought-after commodities in the world” (Ballard and Conkling, 1955; SJBRUS, 1980). This discovery and the development of the nuclear industry, including both weapons and power generation applications, would leave an indelible mark on both New Mexico and the world.

Uranium-vanadium deposits were discovered in the eastern Carrizo Mountains in the San Juan Basin in 1918 (Chenoweth, 1997). Initially, these deposits were primarily mined for vanadium, an economically important metal used both to strengthen steel and as a catalyst for sulfuric acid production (Hilliard, 1994). The Vanadium Company of America (VCA) produced more than ten thousand pounds of ore between 1942 and 1946 (McLemore, 1983) and more than half of the vanadium produced domestically came from this and other regions within the Colorado Plateau until the mid-1980s (Hilliard, 1994). Uranium became increasingly important during the second World War, when an estimated 44,000 lbs. of U$_3$O$_8$ were recovered from the VCA’s mill tailings for the Manhattan Project (McLemore, 1983; McLemore and Chenoweth, 2003).

The creation and evolution of policy and regulatory frameworks for U influenced the development of the nuclear industry and affected U mining. In 1943, the Atomic Energy Act established the Atomic Energy Commission, which placed nuclear energy
under the sole control of the US government and restricted its use to military applications (Walker and Wellock, 2010). In 1954, the Atomic Energy Act was revised to allow for commercial nuclear applications, encourage collaborative research and development between national laboratories and industry, and provide subsidies for energy and defense research as well as the U supply this research required (Walker and Wellock, 2010). Both Acts included specific provisions to ensure a stable supply of U: the Federal government guaranteed a minimum price ($8/lb. U₃O₈) and offered additional subsidies towards exploration, mine engineering, ore transportation, and milling costs (Roskill, 1991). In 1955, large U deposits were discovered in what is now referred to as the Ambrosia Lake subdistrict of the Grants uranium district (Figure 2-1). These events sparked the uranium boom that lasted for more than three decades (McLemore and Chenoweth, 2003).

2.2.2 Mining Techniques and Production

Uranium production in NM historically relied on both underground and surface mining techniques (McLemore et al., 2002). The grade (concentration of uranium in the ore) and geologic position of the U deposit are the most significant factors in selection and application of mining techniques. Of the more than 1,000 uranium occurrences in the New Mexico Mines database, production activities are reported for 216 mines from 1942 until 2002 (McLemore and Chenoweth, 2003; McLemore et al., 2002). Of these, 102 were underground mines, 75 were surface or open pit mines, and 39 were characterized as both surface/open pit and underground mines. During this period of production, the grade of recovered ore ranged from 0.02-0.63% in the state (or 1 lb. of U₃O₈ from approximately 5,000 to 160 lbs. of ore respectively) (McLemore et al., 2002). Ore grade
also varied by mine and date of production. For example, the Church Rock Mine recovered U ore of 0.21% grade in 1960 and 0.16% grade in 1962 (McLemore et al, 2002). The geographic distribution of uranium mines in New Mexico and their associated average annual production are shown in Figure 2-1.

**Figure 2-1:** New Mexico uranium mines and their average annual production (1948-1985). Average production calculated as total U production divided by total operating years. Modified from McLemore et al. (2002)
2.3 System Dynamics Modeling

2.3.1 Model Approach and Development

Based on previous application to other mining operations (O'Regan and Moles, 2001, 2006), we propose that a system dynamics (SD) approach is well suited to understand and quantify the impacts of economics and changing regulatory environments on the opening and closure of historic U mines. This procedure quantifies the variability of mine openings or closings as a function of mine size, mining method, and the historic production of metals such as vanadium. In the context of this model, opening and closing represent the historic operational lifecycle of a mine (start and end of U production) rather than the legal and physical closing incorporated into a contemporary mine’s lifecycle. This modeling technique allows for both the separation and interaction of these variables to understand how mine characteristics such as size and mining methods are affected by policy and economics over time. Our objective was to quantify the effect of each variable on historic mining operations. Note that the impact of these variables on one mine may have implications on other mines. The results of the model help to explain how and why mining companies decide to open a new mine or close an existing one.

This model assumes historic mining decisions were influenced by both market forces, particularly U price and competition, and government-related changes in nuclear policy. Although a poor proxy for the actual prices negotiated between producers and purchasers, we used the average price of U because no quantitative data exists for these individual transactions. In addition to market price, government policies towards the industry provided additional incentives to encourage development. For example, in 1954
the Atomic Energy Commission provided subsidies for transportation, processing facility construction, and mine engineering costs in addition to minimum price guarantees ($8/lb. U₃O₈) for U in order to ensure a steady supply for both weapons and the developing nuclear power industry (Roskill, 1991).

One might postulate that profitability was greatly enhanced, regardless of mine size, during early U mining due to a guaranteed market for U and subsidies for production costs (resulting in profits as high as a 40% return on investment (Roskill, 1991)). Conversely, in later years a lapse in subsidies may have reversed this trend in favor of larger mines in later ones. For example, the upfront capital costs and expertise required to recover ore from deeper deposits may not have been possible for smaller mines in the absence of government incentives. Economies of scale, the principal that an increase in the scale of production decreases the unit cost of production, suggests that the size of a mine may have been an important factor in its response to changing market forces and policy environments. Therefore, government stimulation and market price of U may have affected the response (i.e. opening or closing) of historic mines in the region differently as a function of their size.

The influence of government policies, which are often the most challenging aspect of a system to model quantitatively, were treated by delineating four time periods initiated by passage of specific legislation that are described in brackets: 1) 1948-1954 [the Atomic Energy Act of 1946, which stated that all U produced must be used in government applications, guaranteed a market for ore if it was above 0.2% U₃O₈, and provided subsidies for exploration, mine engineering, ore transportation, and milling
costs; note we begin with the year 1948 because that is the beginning of the average domestic U sale price record, 2) 1954-1964 [the Atomic Energy Act of 1954, which reaffirmed the government’s U markets and subsidies but allowed for collaborative research on nuclear technologies between the government and private industry -- resulting in increased demand for U], 3) 1964-1974 [President Johnson’s mandated 25% cutback in enriched U production in 1963 and the 1964 Private Ownership of Special Nuclear Materials Act, which decreased government demand for U, allowed guaranteed prices and subsidies for U to lapse, and wholly opened the nuclear industry to the public domain (both nationally and internationally)], and 4) 1974-1985 [passage of the Energy Reorganization Act 1974, which ended government stewardship over the domestic nuclear power program (Buck, 1983)]. We chose 1985 as our ending date because by then all but one mine in the state had closed (McLemore et al., 2002). Rather than including these periods of regulatory changes as variables, the four time periods were represented as four distinct simulations within model optimization. The differences in economics and policies as a function of modeled time periods is shown in Table 2-1. The uranium market in the early years was a monopsony wherein the US government was the only buyer of uranium and guaranteed minimum prices and provided subsidies for mine engineering, development, and uranium processing. In later years these economic incentives lapsed but the sales market of U concentrate broadened to include both national and international buyers.
Table 2-1: Comparison of economics and policy on U markets for the four modeled time periods.

<table>
<thead>
<tr>
<th>Policy Time Periods</th>
<th>Government Price</th>
<th>Subsidies</th>
<th>Government Usage</th>
<th>Public Usage</th>
<th>International Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948-1954</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>1954-1964</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1964-1974</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1974-1985</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

As in any model, a number of real-life complexities hinder this model's accuracy. One, average historic prices do not reflect the entire spectrum of U commerce dynamics. These dynamics were often dominated by long-term contracts between mines, mills, and energy companies (Roskill, 1991), the terms of which are not often reported. Given data limitations, it is difficult to assess the impact on the accuracy of the model due to exclusion of long-term contracts. Two, the production of other metals such as vanadium (V), the price of which has been lower but more stable compared to U historically, may have influenced the ability of a mine to weather low U price environments. Because V mining in the region was as a by-product of U mining (Hilliard, 1994), we assume that trends in U prices were representative of both U and V commerce. Therefore, we ran our model first using mines that produced U only and then using mines that produced both U and V.

Our model is designed to evaluate three hypotheses that depend on several assumptions. The hypotheses are: 1) subsidies from the US government for U mining both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than did large mines, and 3) mines that produced both
uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium. As mentioned earlier, we assume high U prices were a significant factor in a company’s decision to open a new mine, whereas closing may have occurred as a result of low prices. We also assume mine openings and closings are a function of mine size -- categorized as small, medium, or large and estimated based on total production averaged over the total duration of operation in years (see below). Economies of scale generally dictate that larger mines can produce a commodity at a lower per-unit cost than smaller ones, which make them more competitive in a dynamic economic environment than smaller mines. Therefore, we assume that an increase in the number of large mine operations may influence operational decisions (especially closing) for smaller mines. We describe this influence using a variable called the impact of larger mines coefficient. We believe this coefficient accounts for perceived scarcity and market flooding on competition between mines of varying sizes.

The ability of a mine to remain in operation despite low U prices may also have been a function of its ability to economically produce other commodities like vanadium. Of the 216 mines that produced U between 1948 and 1985, 68% also produced V. While the number of V producing mines was dominated by small and medium-sized mines (41 and 44%, respectively), large mines produced nearly three-quarters of total V produced during this period. Although historic V prices have consistently been a fraction of that for U, its price has been more stable. Between 1948 and 1980, average V price was 18% of U price with a standard deviation of 1 compared to U (SD = 8.9) (McLemore et al., 2003;
Therefore, the number of openings and closings for U+V mines were compared to U-only mines to discern whether commodity diversity influenced operational decisions. Like U-only mines, real annual production data for either U or V are not available in U+V mines (instead, for both we divide total production over years of operation). Therefore, it was not possible to determine whether U+V mines were able to increase production of V in low U-price environments to maintain profitability or lengthen closing response time in down markets.

2.3.2 Model Description

In order to understand historic mine operations (i.e. opening vs. closing), mines were grouped by size and evaluated in terms of response time to changes in uranium price, policy changes, and other mining activity in the region. These were included in a Powersim Studio 9 (Powersim, 2015) optimization tool to determine the optimal value for each of these variables. This system dynamics software platform allows for rapid evaluation of dynamic interaction between multiple variables over time. The model is designed to run on an annual time step from the initial date of U price availability (1948) (McLemore and Chenoweth, 1989) until the year 1985, when all but one mine in the state had closed (McLemore et al, 2002). In order to evaluate the effects of changing policies, four time periods are included in the analysis (1948-1954, 1954-1964, 1964-1974, and 1974-1985) that reflect significant changes in policy regarding U commerce, as described in the previous section.

Optimization is a method commonly used in economic modeling to quantify the value of a series of variables that, when combined, most closely represents the real
behavior of a system. The Powersim Optimization Tool uses an evolutionary search algorithm in which values of model decision variables change over time. During the optimization process, the model simulation is run many times where the best results from one simulation are used as inputs into the next simulation until a minimum difference between the number of actual and modeled mine openings and closings are achieved for each of the four policy-defined time periods. The four decision variables that potentially impact the decision to open or close a mine in the model are: 1) a coefficient response to price, 2) moving average price, 3) price time delay, and 4) impact of larger mines on smaller mine closings.

Figure 2-2 illustrates the conceptual process of the model and flow paths by which the decision variables (boxed) are determined from the input of real price data. Simulations are conducted separately for small, medium, and large mines. The various decision variables are defined as follows. The **price coefficient** indicates the number of mines that opened or closed due to a unit change in average real price of uranium, and the **moving average price** is the window of time over which the price is averaged. A large 'moving average price' implies that decisions on whether to open or close a mine depend on prices averaged over a longer term and not simply in response to short term market fluctuations. The **price time delay** is the length of time that passes before opening or closing occurs in response to a unit change in average price. Factors that delay construction or closing of a mine, such as the time needed to arrange for financing or evaluating trends in the market, are incorporated in the 'price time delay' variable. A large value for 'price time delay' indicates that decisions regarding mine operation are not an
immediate response to changes in price. Optimal values for the moving average price and price time delay are computed directly from the real price input data using the Optimization Tool. Lastly, the **impact of larger mines** is a coefficient that describes the effect of larger mines on small mine closing, where a large coefficient indicates that a greater number of smaller mines closed in response to an increase in the number of larger mines operating in the region. This coefficient is also determined by iterative optimization. This coefficient was applied to the number of large mines operating during a designated time period when evaluating their impact on medium mines, and to both large and medium mines when evaluating their impact on small mines.

![Conceptual model and system dynamics flow path used in this study](image)

**Figure 2-2:** Conceptual model and system dynamics flow path used in this study
The first tier of optimization produces a value for the price coefficient from the moving average price and the price time delay. Using the price coefficient and the impact of larger mines coefficient, the model then predicts in a second tier of optimization how many mines open and close in each policy-related time period (caps and bold) -- from which the number of operating mines can be determined. In each iteration, the predicted number of operating mines of a given size are then compared to the actual number, and variable values are then adjusted until the difference between predicted and actual are minimized.

This process is summarized by the objective function, which shows: (1) how optimized decision variables are used to predict the number of opening (a) and closing (b) of mines, and (2) how the minimum difference between the predicted values and the actual values are calculated for each time period and then summed over the four time periods. For opening and closing, the objective of each optimization is to achieve the minimum difference between actual historic mines and modeled mines of each size \((j)\) for each time period \((i)\).

**Equation 2-1**: Objective function describing the modeled opening (a) and closing (b) of historic U mines of a given size class (small, medium, large)

\[
\begin{align*}
\text{Opening:} & \quad V = \min_{d, \Delta, \beta} H_{ij} - (\beta_1 P(d, \Delta)) \quad \text{(2-1a)} \\
\text{Closing:} & \quad V = \min_{d, \Delta, \beta} H_{ij} - (\beta_1 P(d, \Delta) + \beta_2 L_{ij}) \quad \text{(2-1b)} \\
\text{Where} & \quad P(d, \Delta) = \sum_{d=t+\Delta-d}^{d=t-d} P, \quad \text{and} \ \beta \in \{\beta_1, \beta_2\} \quad \text{(2-1c)}
\end{align*}
\]

Where:
\[ V = \text{the minimum difference between the number of historic and modeled mines} \]
\[ i = \text{one of four policy-related time periods} \]
\[ j = \text{one of three mine sizes: small, medium large} \]
\[ H = \text{the number of operating historic mines of size } j \text{ during policy time period } i \]
\[ P = \text{annual uranium price} \]
\[ L = \text{the number of mines larger than mine size } j \]
\[ \bar{P} = \text{the time delayed, moving average price} \]
\[ L = \text{the number of mines larger than mine size } j \]
\[ d = \text{price time delay in years} \]
\[ \Delta = \text{moving average price in years} \]
\[ \beta_1 = \text{price coefficient} \]
\[ \beta_2 = \text{impact of larger mines coefficient} \]

It is assumed that changes in coefficients (\(\beta\)) and time delays (\(d, \Delta\)) over the four policy-related time periods (\(i\)) will quantitatively describe the effects of changing policy and economic environments and support evaluation of the three proposed hypotheses. Therefore, \(\beta_1 P(d, \Delta)\) for each policy time period represents the delay and average times over which the price coefficient and average annual price minimizes the difference between the number of historic operating mines and modeled mines. To represent the effects of economies of scale, the third term in Equation 2-1b will increase the number of smaller mines closing based on coefficient (\(\beta_2\)) and the number of larger mines operating...
in the region \((L_i)\) during time period \(i\). Lastly the time it takes for a mine to respond \((d)\) to change in both price and trends in price \((\Delta)\), is represented by Equation 2-1c.

### 2.3.3 Model Input

Historic mine operations data were obtained from the New Mexico Mines Database (McLemore et al., 2002), which lists the operation and total U recovered for each mine from 1942 to 1989. More than half (128) of these mines showed a date range of production only, nearly 40\% reported either a single year of production (64) or production amounts for every year in the production period (19), and five mines reported a combination of a range and annual production values (McLemore et al., 2002). Because of the disparate time scales for which production data was available, total production was divided by the time period of operation to determine estimated annual production. This value was used to classify mines as small (<200 lb./yr.), medium (200-12,000 lb./yr.), or large (>12,000 lb./yr.). Mines were also characterized by type (surface, underground, combined) from McLemore et al. (2002) and as either U or U+V producing mines.

The real price of U (per year) is the primary economic input into the model. It is obtained by adjusting the nominal price for inflation into 1989 dollars. This adjustment allows comparison over time of real changes in value per pound of U (Figure 2-3). Although, there are several sources of nominal price data for uranium and vanadium (Figure 2-3), Roskill (1991) was used because U prices were represented in both nominal and real (1989) dollars adjusted for inflation, whereas other sources listed only nominal values.
Roskill (1991) reported U prices from two data sources: US Atomic Energy Commission (USAEC) prices (1948-1971) and the Nuclear Exchange Commission (NUEXCO) prices (1968-1990). Figure 2-3 also shows that vanadium prices (USGS, 2013) have historically been both lower and more stable than U prices. Comparison of nominal and real prices shows how the guaranteed minimum price for U during 1948-1964 did not result in a steady market value of U, which steadily declined between 1953 and the early 1970s. This price decrease could be due to increasing supplies of U resulting from government subsidization of the early U market or to government surpluses of U due to bans on weapons testing that decreased government demand for U.

**Figure 2-3:** Comparison of reported nominal and real prices for vanadium (V) and uranium (U) for 1948 to 1985. Real prices are adjusted for inflation, nominal prices are not.
Once historic and economic inputs were incorporated into the model and prior to optimization, a range of potential values was assigned to each variable. Price (‘price coefficient’) and ‘impact of larger mines’ each have a starting coefficient ranging from -1 to 1, with a starting value of 0.1. This allows for modeling of potentially counterintuitive results, such as increasing prices resulting in a negative response from mines. Both time variables, ‘moving average price’ and ‘price time delay’ were given a range of values from 0 to 5 with a starting value of 2.5. Using these starting values and allowed ranges, the Optimization Tool obtains temporary values for each variable during a given iteration, and then reintroduces these values as inputs until the optimal value is achieved for opening and closing mines in each size category over the four specified time periods.

2.4 Results

2.4.1 Historic Mining Operations Model

Data gathered from the New Mexico Mines database (McLemore et al., 2002) indicate that uranium mining in New Mexico was dominated by small and medium-sized mines from the late 1940s to the late 1950s, when the number of these types of mines peaked (Figure 2-4). Large mines began operations in the early 1950s. The number of
large mines subsequently overtook the number of smaller mines and peaked in the mid-1960s concomitant with closing of smaller mines (Figure 2-4).

![Graph showing number of historic mine operations compared to predicted by the model. X axis is in years.](image)

**Figure 2-4**: Number of historic mine operations (top) compared to those predicted by the model (bottom). X axis is in years.

The optimal values chosen for the decision variables minimized the differences in the number of operating mines between historical data and modeled predictions (Figure 2-4). When compared to historic data, the variables included in the model accounted for 81.6% of the variability in large mine operations, 93.8% for medium mines, and 89.0% for small mines based on R-squared values (Table 2-2). Furthermore, the F-test reveals that these results are significant (Table 2-2). Generally, an F-test greater than 0.01 indicates that results are not significant and the smaller the F-statistic in a regression
output, the greater the probability modeled results are not due to chance. Model results
are summarized in Table 2-3a-c. For the opening and closing of mines in each size class,
optimized values for the decision variables are listed for the policy-relevant time frames.
Below, we discuss the economic and policy implications that can be inferred by the
modeled optimal values.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Mine Size</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Medium</td>
<td>Large</td>
<td></td>
</tr>
<tr>
<td>R-square</td>
<td>0.863</td>
<td>0.940</td>
<td>0.874</td>
<td></td>
</tr>
<tr>
<td>F-statistic</td>
<td>3.94E-17</td>
<td>1.40E-23</td>
<td>8.77E-18</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-2: Statistical comparison of actual versus modeled mining operations

2.4.2 Economic Variables

The economic variables included in the model are intended to reflect how changes
in price over time affected the opening and closing of mines of a given size. The decision
to open or close a mine is influenced by numerous factors that include both price and
competition; therefore, both the ‘price time delay’ and 'moving average price' are
intended to capture how company decision making responded to short-term fluctuations
in price stability over time.

2.4.2.1 Price coefficient

A key gauge of sensitivity to price (of a given mine type or size) is the price
coefficient, which indicates the number of mines that opened or closed due to a unit
change in average real price of U. This coefficient could not be calculated for time
periods when mines of a given size were not in operation (e.g., small mines in 1974-
1985). Note the steady decrease in the opening price coefficient for large mines through
1948-1985, where the price coefficient decreased by more than two-thirds between 1954-1964 and 1964-1974. Such a decrease was not obvious during 1948-1964 for smaller to medium mines, except for a slight decrease in the closing price coefficient. Upon comparing small- and medium-sized U vs. U+V mines (Table 2-3b and c), price coefficients are commonly an order of magnitude higher for U+V mines. This difference in price coefficient indicate that small to medium mines producing both U and V were more responsive (larger coefficient) to change in U price (Table 2-3c) than were small to medium mines that produced only U (Table 2-3b).
Table 2-3: Modeled regression results. Table 2-3(a) includes regression results from all mines regardless of the type of commodity produced; (b) includes results for U-producing mines only; and (c) includes results from mines producing both U and V. Data are categorized according to policy-relevant time periods (in years).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Mines</td>
<td>Open</td>
<td>Price Coefficient</td>
<td>3.00E-02</td>
<td>3.00E-02</td>
<td>0.00E+00</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>2.60 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
<td>0.00 yr</td>
<td>0.00 yr</td>
<td>0.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td>Close</td>
<td></td>
<td>Price Coefficient</td>
<td>3.00E-02</td>
<td>2.00E-02</td>
<td>1.90E-03</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>2.00 yr</td>
<td>2.00 yr</td>
<td>1.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
<td>3.00 yr</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact of Larger Mines</td>
<td>1.00E-02</td>
<td>1.00E-02</td>
<td>3.00E-03</td>
<td>N/A</td>
</tr>
<tr>
<td>Medium Mines</td>
<td>Open</td>
<td>Price Coefficient</td>
<td>1.50E-01</td>
<td>2.00E-02</td>
<td>0.00E+00</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>3.00 yr</td>
<td>3.00 yr</td>
<td>1.60 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>1.60 yr</td>
<td>N/A</td>
</tr>
<tr>
<td>Close</td>
<td></td>
<td>Price Coefficient</td>
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<td>3.00E-02</td>
<td>1.00E-02</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>2.00 yr</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
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<td>4.00 yr</td>
<td>2.50 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact of Larger Mines</td>
<td>5.00E-03</td>
<td>6.00E-03</td>
<td>8.50E-03</td>
<td>N/A</td>
</tr>
<tr>
<td>Large Mines</td>
<td>Open</td>
<td>Price Coefficient</td>
<td>5.00E-02</td>
<td>3.00E-02</td>
<td>1.00E-02</td>
<td>9.50E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>2.00 yr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
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<td>2.00 yr</td>
<td>2.00 yr</td>
<td>2.00 yr</td>
</tr>
<tr>
<td>Close</td>
<td></td>
<td>Price Coefficient</td>
<td>0.00E+00</td>
<td>1.00E-02</td>
<td>6.00E-02</td>
<td>9.00E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
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<td>1.17 yr</td>
<td>1.00 yr</td>
<td>3.00 yr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
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<td>4.81 yr</td>
<td>3.70 yr</td>
<td>3.05 yr</td>
</tr>
<tr>
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<td></td>
<td>Impact of Larger Mines</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
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<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Small Mines</td>
<td>Open</td>
<td>Price Coefficient</td>
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<td>9.80E-03</td>
<td>0.00E+00</td>
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<td></td>
<td></td>
<td>Moving Average Price</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
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<td>0.00 yr</td>
<td>0.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Close</td>
<td>Price Coefficient</td>
<td>7.50E-04</td>
<td>4.80E-03</td>
<td>1.00E-03</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moving Average Price</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Price Time Delay</td>
<td>1.00 yr</td>
<td>1.00 yr</td>
<td>0.00 yr</td>
<td>N/A</td>
</tr>
<tr>
<td>Medium Mines</td>
<td>Close</td>
<td>Price Coefficient</td>
<td>9.00E-04</td>
<td>1.00E-03</td>
<td>3.90E-03</td>
<td>N/A</td>
</tr>
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2.4.2.2 *Price time delay*

Figure 2-5 depicts the price time delay for mine opening and closing as a function of mine size. Except for mine closing during 1948-1954, small mines opened and closed rapidly (≤1 year). Openings for medium sized mines took ~1 year and large mines ~2 years throughout the four modeled time frames. Closing of medium to large mines took slightly longer in earlier years (4-5 years) compared to later years (3-4 years for large mines; 1.5-2.5 years for medium mines, per the model).

![Figure 2-5: Comparison of modeled time delays for mine opening and closing (from Table 2-3a).](image)

When mines producing U+V were compared to U-producing mines, the most noticeable difference in model results was in their price time delays. When compared to mines producing only U, medium and large U+V producing mines closed more slowly between 1954-1974 based on their higher price time delay values. Small mines producing U+V had similar price time delays for opening and closing as those producing only U.
2.4.3 Trends in Mine Openings and Closings

In general, there were more openings and closings of all U mines (U and U+V) in the first two periods than the last two periods (Figure 2-6) and large mines dominate openings and closings after 1964, reflective of the total number of historic operating mines as a function of size (Figure 2-6). Mines producing both U and V opened in greater numbers in the first two policy-related time periods as compared to U-only, but closed in much greater numbers between 1954-1964 (Figure 2-7). However, U+V mines were predominantly small- and medium-sized mines, so these results could be more indicative of the role mine size played in operational (opening and closing) decisions. Between 1964 and 1985, fewer U+V mines closed as compared to U-only mines and these mines were medium or large; no U+V mines opened during this time (Figure 2-7).

Figure 2-6: Total number of opening mines (left) and closing mines (right) across 4 modeled time periods
Discussion

Model results indicate that responses to changes in price and competition from larger mines influenced opening and closing and varied in response to national policies.

We expound on these topics below, but perhaps more significant than the results of the model were the development of a modeling framework for understanding the
relationships between price and policy on U mining operations that has been discussed previously (Buck, 1983; Roskill, 1991; Peach and Popp, 2008) but never quantified. This approach has utility for other commodities (such as oil and gas) in understanding the dynamic relationships between natural resource development and economics subjected to changing policy and regulatory environments.

There are several important limitations of this model. Although a production record exists of New Mexican U mines, annual production data is available for less than half of these. Furthermore, our annual production data is really an estimate using an average of total production of each mine divided by the mine's total years of operation (for both U and V) because most mines do not have year-by-year data. This introduces error and limits the number of data points available for the model. The second limitation is that the average price of U does not reflect long-term contract prices negotiated between U producers and consumers. Lastly, the role of profitability as a function of profit and fixed and variable costs are not included in this model. Although it likely influenced operational decisions, annual cost and profit data was not available for every mine or year of production. An exploration of the dynamics between actual annual production volumes of U-only mines vs. U+V mines over time as a function of changing prices warrants further study.

2.5.1 Trends in historic mining operations

Small and medium sized mines thrived in the state until the late 1950s (in terms of their overall number), but then declined coincidently with an increase in the number of large mines (Figures 2-4 and 2-6). The peak in small- to medium-sized historic mining
operations during 1952-1958 coincided with high real uranium prices (Figures 2-3 and 2-4). Small- to medium-sized operations declined in conjunction with falling prices between 1958 and ~1970. Note that the number of large operations peaked in 1960-1962, after the 1952-1958 peak in price, consistent with their higher price time delay values for opening.

A possible explanation for these trends is that in early years (1948-1964) guaranteed purchase by the Federal government, regardless of quantity, encouraged production by mines of all size. In later years, (1964-1985) after the lapse of Federal purchase guarantees and subsidies which largely benefited smaller operations (Roskill, 1991), larger mines were able to produce U at lower cost due to economies of scale, where increasing production capacity generally decreases the per-unit cost of production. Below, we use our model results to explore this possibility.

Another explanation for the increase in the proportion of large mines vs. medium-small mines after 1964 may relate to mill capacity and mill contracts. Although one-quarter of total U.S. domestic mills and more than half of domestic milling capacity operated in New Mexico during this time, many of these mills were either already nearing capacity (Peach and Popp, 2008) or ore-processing suitability to mill the ore produced in the region. In the absence of government subsidies for transportation, the added cost of moving ore from mines to mills at increasing distances would have directly impacted the profitability of existing mines. The Marquez mill was constructed in 1980 to provide additional milling capacity, but the mill owner (Bokum Resources) declared bankruptcy in 1981 and the mill was never operational (McLemore and Chenoweth,
2003). As such, larger mines may have been able to wield more market power than smaller operations, negotiating longer-term contracts at lower prices with both mills and U purchasers.

2.5.2 Influence of price versus governmental policies

Four policy situations were included in the model: the Atomic Energy Acts of 1946 and 1954, the Private Ownership of Special Nuclear Materials Act (1964), and the Energy Reorganization Act (1974) (Buck, 1983; Walker and Wellock, 2010). Mine openings and closings were modeled for each time period bracketed by these policy situations to understand how operational responses to changes in price varied as a result of regulatory changes. From 1948-1954, mines of all sizes opened rapidly while few mines closed (Figure 2-6). The passage of the Atomic Energy Act of 1954 might have caused rapid growth of uranium mining in the second time period (reflected by mine openings), but closing rates also increased for both small and medium sized mines (Figure 2-6). Declining real prices after 1954 were likely an important factor for the increase in these closing rates, perhaps influenced by the sluggish development of nuclear energy technologies (Peach and Popp, 2008). In addition, the moratorium on weapons testing signed by President Eisenhower in 1958 (Buck, 1983), combined with ample existing military stockpiles, dampened demand by the federal government for nuclear weapons.

The peak for small and medium mine closings occurred between 1954-1964 compared to the larger proportion of large mine closings which occurred in the following time period (1964-1974). The latter period coincided with a decline in domestic mining
activity in general. This decline was likely due to withdrawal of the US Government’s role as steward for the uranium and nuclear industries in 1974 (Buck, 1983) as well as increasing foreign U production (from South Africa, France, and Canada, which collectively surpassed US production by the early 1980s) (Roskill, 1991).

Coupled with other data, trends in price coefficients help to elucidate how government policies impact mine sensitivity. As a hypothetical example, assume that U prices were stable over two time periods of comparison, the first containing notable government subsidies and the second having no government subsidies. However, during these two time periods there was a decreasing trend in the opening price coefficient. One could interpret this scenario as indicating earlier government policies positively impacted mining operations, since fewer mines opened in the second time period. An increase in the closing price coefficients across the two hypothetical time periods would imply greater sensitivity to changes in price in the second time period, which might be due to the lack of stability provided by government subsidies provided in the earlier time period.

We argue that government subsidies affected mines of all sizes, but price change trends complicate whether smaller mines were disproportionally influenced. The high number of historic mining operations for all mine sizes during the early years (1948-1964) suggests that government subsidies for transportation, exploration, engineering, and milling costs impacted all mines. However, this comparison may also be due to relatively high U prices. Mine size was the most significant indicator of whether a mine would open or close in response to price in the years following these subsidies (1964-1985). In contrast to large mines, no small or medium mines opened after 1964. Also,
opening-related price coefficients for all mine sizes were greatest in earlier periods (1948-1954 and 1954-1964) and declined in later periods (Table 3a), which implies that the combination of high prices and subsidies for development encouraged mine openings prior to 1964. Although the same decreasing trend is seen for closing-related price coefficients for small and medium mines through the 1964-1974 policy time period (suggesting less sensitivity to price changes with time, even after subsidies ended), the values of closing price coefficients are greater than coeval opening price coefficients. This indicates that a decision to close rather than a decision to open had greater sensitivity to price changes following the lapse in government subsidies. Also, no small to medium mines opened after 1964, based on historical data (Figure 2-3-Figure 2-6).

Both the price coefficients and the historical data suggest that government policies prior to 1964 stimulated and sustained small and medium sized mines. Furthermore, the greatly reduced number of small- and medium-sized mines after 1964 supports our hypothesis that the loss of government subsidies, combined with the decreasing price of U, had a disproportionate impact on these size classes compared to larger mines. No clear trend is evident in the opening and closing price coefficients for large mines. Lastly, it is noteworthy that relatively few mines opened in 1974-1985 despite a large increase in real price in the early half of 1974-1985, which was actually higher than in 1952-1956 (Figure 2-3). This paucity of openings could be attributed to the lack of government subsidies or the lack of a guaranteed market and purchaser by the government (these being more amenable to small mine operators than larger mine operators, the latter being able to better negotiate complex contracts with non-government purchasers). In summary,
analysis of our data indicates that government subsidies likely impacted mines of all sizes; but due to complications posed by declining prices between 1958 and ~1970, we cannot conclusively determine that these subsidies preferentially promoted and sustained smaller mines prior to 1964.

2.5.3 Response times

For all four time periods, the smaller values of the price time delay coefficient for smaller and medium mines compared to larger mines supports our second hypothesis: that smaller mines respond more quickly to changes in price than large mines. The discrepancy in values suggest that the greater initial investment and fixed costs associated with larger mines may have tempered their response to changes in price (which was likely due to economies of scale for larger mines as well as higher operating costs and higher costs associated with opening and closing). On the other hand, the smaller initial investment and fixed costs associated with medium and smaller sized mines allowed them to open and close more rapidly in response to fluctuations in U prices. Grouping the time periods into 1948-1964 and 1964-1985, there is a general trend of a decrease in price time delay for a given mine size. This could be interpreted that decisions to open or close a mine occurred more quickly in the absence of subsidies.

2.5.4 Production of vanadium

We hypothesized that mines producing both U and V may have had a slight advantage, both in the speed and magnitude at which they responded to changes in price, over mines that produced U only. Because V is a co- or by-product of U production and because its price was consistently less than that of U, its production was subsidized by U
production (Hilliard, 1994). Across all time periods, our modeling results showed generally higher closing and opening price coefficients for small and medium U+V mines compared to U-only mines, indicating that the U+V mines were more sensitive to changes in price -- which argues against our hypothesis. However, the closing price coefficients were slightly larger for U-only large mines, consistent with our hypothesis. No difference was seen in the price time delays for small mines between U-only and U+V mines, but for medium to large mines the closing price time delay was longer for U+V mines. This suggests that the production of vanadium stabilized mine operations for medium and large mines, even in the declining price environment prior to 1974, which supports our hypothesis.

2.5.5 Impact of larger mines

Small mines were more negatively impacted by larger sized mines than were medium sized ones. This conclusion is based on the higher values of the Impact of Larger Mines coefficient for smaller mines than medium sized mines (Table 2-3a). In addition to competition from larger mines, exhaustion of mineable resources by smaller mines, which was not included in the model, may have affected the responsiveness of smaller mines to price.

2.5.6 Scarcity and Market Flooding

The U market and industry has been historically plagued by large fluctuations in price and demand. From its early discovery through the development of nuclear power, factors such as the identification of new resources, dumping of reserves, stockpiling, and fear of scarcity have affected the industry. For example, the Westinghouse Electric
Company offered a guaranteed U\textsubscript{2}O\textsubscript{8} price of $6/lb. for its customers who purchased their pressurized light water reactors in the early 1970s (Roskill, 1991). However, many companies were developing small modular reactors that increased demand for U, and the prices began to rise in the mid-1970s and peaked at over $40/lb. in 1978 (Roskill, 1991). Unable to buy U from existing producers or identify new resources, Westinghouse confirmed it could not meet its obligation to provide U at $6/lb. to its customers, and the market was again plagued by both real and imagined scarcity. After 1978, the supply of U outpaced its demand for nuclear power (Roskill, 1991), which constrained the market and caused spot prices to decline by more than a quarter between 1978 and 1980 and by nearly a third a year later.

2.5.7 Non-modeled factors influencing future mining operations

The results of this study reveal previously unquantified relationships between mining and external drivers and serves to illuminate the economic and policy considerations affecting possible renewed uranium mining in the region. It is also important to recognize that factors such as permitting and environmental regulations, tribal issues and public acceptance, and access to U mills -- which received little concern in the past -- will likely affect decisions regarding future U production.

During the historic U boom years in New Mexico, very few state and federal regulations existed which governed the environmental impacts of mining operations and waste disposal. Lack of environmental protection early on led the DOE to comment that “State and Federal controls [were] non-existent or totally inadequate,” (written commun. with DOE, documented in SJBRUS, 1980). Subsequent legislation has addressed many of
these shortcomings. Although passed towards the end of U production in NM, four federal laws address uranium mining and milling activities: Uranium Mill Tailings and Radiation Control Act (UMTRCA, 1978), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980, 1986), US Forest Service Mining Regulations and Minerals Management (1974), and BLM Mineral Land Management (1981) (Dixon, 2015). In addition, the state of New Mexico has passed important laws to address the safety of mine workers, air and water quality, and waste disposal (Dixon, 2015).

While the environmental impacts of U mining and milling operations were not often a factor historically, human impacts were even less of a consideration. In particular, the effect of these operations on Native American tribes, who own land and comprise a significant proportion of the population in the region, is an important consideration should operations resume in the future. Legacy impacts of radiation exposure to mine workers, environmental impacts of abandoned mines, and accidents like the Church Rock mill tailings pond failure (the largest radioactive spill in U.S. history) have disproportionately affected tribes in the region.

The number of U mills likely had an impact on mine operations. Between 1948 and 1982 eight mills operated in New Mexico (McLemore, 1983) whereas currently there is only one operating U mill in the U.S., the White Mesa mill in Utah (US EIA, 2016). Location of nearby mills would affect transportation costs and the marketability of U ores, an especially important fact for small U mines.
2.6 Conclusions

The objective of this study was to use systems dynamics modeling to quantify how historic uranium operations in New Mexico during 1948-1985 may have been influenced by economic and government policy factors. The number of mines operating in New Mexico during the uranium boom from 1948 to 1985 were grouped by size and classified as either U-only or U+V producing mines. To assess the impact of government policy on mining operations, four time periods were delineated that related to specific enactments of uranium-related federal legislation and policies.

We used the model to test three hypotheses: 1) subsidies from the US government both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than do large mines, 3) mines that produced both uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium. Declining opening-related price coefficients with time is consistent with government subsidies encouraging mines of all sizes. Although closing-related price coefficients decline over time as well, their values exceed those of opening-related price coefficients after 1964 -- indicating that closing rather than opening had greater sensitivity to price changes following the lapse in government subsidies. Examination of historical data indicates that no small mines and only a few medium-sized mines opened after the elimination of these subsidies. Therefore, government subsidies and/or higher U prices in 1948-1963 vs. 1963-1974 may have helped promote these mine sizes prior to 1964. Economies of scale and lower milling costs for larger mines may also have contributed to the closing of all
small and medium sized mines by 1974. Furthermore, the lapse of government subsidies, which were designed to encourage the development of the U industry, were likely an important factor in the relatively low amount of openings and total mines in operation during 1974-1985. This is particularly significant given that real prices were relatively high during most of this time period.

Our modeling generally supports our second and third hypotheses. Small mines opened and closed rapidly (≤1 year). Medium and large sized mines took 0.65-1.2 years to open and 2-5 years to close throughout the 37-year period model, with closing time delays of both medium and large mines being less after 1964 than prior to 1964 (Table 2-3a). The economic advantage of producing both vanadium and uranium was evident in longer closing times for medium and large mines, but small-medium U+V mines were more sensitive to changes in U price.

Economics, policy, and the regulatory frameworks governing the uranium industry have changed markedly since the U boom of the 1950’s and 1960’s, which encouraged mines of all sizes to produce U. Public perception, including awareness of legacy impacts of past mining activities and the risk of potential negative impacts on the environment and human health now plays a role in current and future U development decisions. Renewed mining activities will require consideration of all of these factors and will likely result in extensive planning, lengthy permitting times, and investment in public outreach efforts. In addition to planning and regulatory costs, future mines must have approved plans for mine closing and post-operative remediation, as well financial guarantees for the protection of cultural sites, the environment, and human health which
will likely increase the unit cost of production as compared to historic costs. As a result, the high ratio of large vs mid- to small-size mines, which began ca. 1960 is likely to persist into the future should activities resume. Consideration of these factors as well as their potential for change will undoubtedly play a role in future development decisions.
3 Modeling Impacts of Renewed Uranium Mining on Ground Water Resources in the San Juan Basin, New Mexico

3.1 Abstract

Until the market collapsed in the early 1980s, more than half of the total uranium produced in the US came from mines in New Mexico. It is estimated that northwestern NM contains nearly 600 million pounds of uranium ore, hence renewed interest in nuclear power as a carbon free energy source has led to proposals to resume mining here. Underground mining requires dewatering of the ore body and surrounding formation which has a very large impact on ground water resources, the only source of supply in most of the region. The objective of this study was to develop a system dynamics model of ground water for use as a decision support tool to facilitate rapid determination of the impacts of different development scenarios and to identify a range of uncertainties in model results. An analytical mine dewatering model was incorporated in a system dynamics framework. The system dynamics model was calibrated using historic data and optimization techniques. The model was used to determine the hydrologic impacts at the township and range (TR) scale for the Grants Mining District in the San Juan Basin. Because many of the deposits are located in deep confined formations with little recharge, dewatering is predicted to result in very large regional drawdowns of the piezometric surface, ranging from hundreds to more than 3,000 feet. This model also illustrates that at a basin-scale, widespread U development could result in annual dewatering volumes 2 times the current groundwater withdrawn in McKinley county, where the majority of U deposits are present. The spatial heterogeneity and uncertainty
associated with potential U mining in the region highlights the critical need for location-specific analyses to address uncertainty in their evaluation of the impacts of future mining activity. This range indicates that estimates of water handling could be underestimated by 25%. This method represents a new approach to evaluating the impacts and uncertainties associated with mine dewatering, and is advantageous in its ability to connect with both cross-platform models and interdisciplinary modeling efforts. This approach is useful to a diversity of stakeholders and is extensible to other industries which have large impacts on water resources such as hard rock mining and irrigated agriculture.

### 3.2 Introduction

Until the mid-1980’s uranium (U) mines and mills in the Grants Mining District in northwestern New Mexico’s San Juan Basin produced more than half of the U mined domestically (McLemore et al., 2013). Between the late 1940s and 1980, nearly 350 million pounds of U yellow cake (U\(_3\)O\(_8\)) were produced, generating more than $4.7 billion in revenue (McLemore, 2007). By 1989 all conventional U production in the state had ceased due to a combination of factors, including declining ore grades, large stockpiles of refined U, concern regarding the safety of nuclear power, increasing mine reclamation costs, and the development of higher grade ore deposits in other countries (McLemore, 2007).

Currently, nearly all (96%) of the fuel supply for nuclear generated electricity, which supplies one fifth of US electricity demand, is imported (US EIA, 2017). There is increasing interest in nuclear energy for electric power production because it produces no greenhouse gases as well as domestic U sources, improving both energy independence
and energy security (Tabuchi, 2018; Donnan, 2018). Renewed interest in nuclear energy as well as domestic mining operations may result in resumption of U mining in NM which ranks second in the nation in total reserves with an estimated 600 million pounds of U$_3$O$_8$ (McLemore, 2007; EIA 2016).

The San Juan basin extends over more than 25,000 square miles mostly in New Mexico, but also extends into Arizona, Utah, and Colorado (Figure 3-1). The basin is arid with annual evaporation rates (40 to 60 in/yr.) exceeding precipitation (8 to 40 in/yr.) (Kernodle, 1996; Longworth et al., 2013). The highest rates of precipitation occur on the high-altitude mountain ranges surrounding the basin (Kernodle, 1996). There are no perennial surface streams in the basin except the San Juan River near the northern boundary which receives runoff from the San Juan Mountains of Colorado. As such, areas in the central and southern portions of the basin are dependent on groundwater (Longworth et al., 2013) for water supply, with minimal rates of direct recharge (<0.2 in/yr.) (Kernodle, 1996).

The geology of the San Juan structural basin is complex and dominated by layers of sandstones and shales which contain numerous resources including oil, gas, uranium, and water (Kelley et al., 2014). Thirteen major aquifers are present in the basin and the Morrison formation contains the greatest volume of water (Kelley et al., 2014) (Figure 3-1). The Morrison formation underlies the entire structural basin and is comprised primarily of sandstone with outcrops occurring at the basin’s margins (Kernodle, 1996). Of the four members of the Morrison Formation, three are present in the study area in the ascending order: Recapture Member, Westwater Canyon Member, and Brushy Basin.
Member and all are sources to local wells (Lyford et al., 1980). In addition, the majority of U deposits in the Grants Mining District are present in the Morrison Formation (Kelley et al., 2014; McLemore et al., 2007).

It is estimated that more than 180 million tons of uranium ore remain in six mining subdistricts shown in Figure 3-1: Ambrosia Lake, Church Rock-Crownpoint, Laguna, Nose Rock, Marquez, and Smith Lake (McLemore and Chenoweth, 2003; McLemore et al., 2013). The Ambrosia Lake and Church Rock-Crownpoint subdistricts contain the majority of uranium in the district (>90%) and the ore in Ambrosia Lake is the highest grade (McLemore and Chenoweth, 2003; McLemore et al., 2013). However, during the historic U mining boom, underground uranium mines were the leading cause of dewatering in the region (SJBRUS, 1980; Kernodle, 1996). While mines were estimated to produce more than 170,000 acre-feet (AF) of water between 1953 and 1980, dewatering as a result of underground mining was anticipated to produce three to twelve times that volume by the year 2000 for low to high range projection estimates (Lyford et al., 1980; SJBRUS, 1980). However, nearly all mines closed within a few years of these estimates and those in development never opened at all (McLemore et al., 2007).
Figure 3-1: Uranium deposits and subdistricts in the Grants Mining District, San Juan Basin, NM (left); Geologic cross-section of the San Juan Basin and the Morrison Formation in dark brown (right) (Kelley et al., 2014).

Historic mine dewatering resulted in numerous environmental impacts, many of which persist to this day. The removal of large volumes of water from storage resulted in the propagation of “regionally extensive” cones of depression (US EPA, 2016), which permanently reduce an aquifer’s available pore space. In general, this water was released to surface drainages with little or no treatment (McLemore et al., 2013). This resulted in impacts on both surface and groundwater quality and general environmental health.

Resumption of U mining in the San Juan Basin would have broad regional impacts on groundwater resources, but these impacts have not been evaluated since the late 1970s (Lyford et al., 1980; SJBRUS, 1980). One such study, commissioned by the
Department of the Interior estimated that 30 mines were either under development or proposed to open by 2000 (SJBRUS, 1980) with total predicted dewatering volume of 570 thousand acre-feet (kAF). Lyford et al. (1980) further estimated that the total volume water produced during the course of future mining activities (1980-2000) could exceed 2.03 million acre-feet (MAF). However, a recent hydrologic assessment of groundwater in the San Juan Basin estimated the total volumetric water content (pre-development) in thirteen major aquifers was 3.25 MAF (Kelley et al., 2014). This suggests that previous studies may have overestimated dewatering rates for proposed mines or underestimated potential impacts on groundwater in the form of regional drawdown.

The objective of this work was to develop a decision support model to quantify the potential impact of renewed conventional underground uranium mining on groundwater resources in Grants Mining District. Since the last major investigation by Lyford et al. (1980), two major studies have investigated the hydrology of the region (Kernodle, 1996; Kelley et al., 2014) but neither evaluated the hydrologic impacts due to mine dewatering. USDA (2013) investigated the impacts of renewed underground mining more recently, but this study focused specifically on the Roca Honda Mine. The system dynamics modeling methods used in this study offer unprecedented flexibility to explore the consequences of different ground water development scenarios. It is particularly well suited for evaluating impacts of renewed U mining because the location of future mines is not known. Coupling an analytical mine dewatering model within a system dynamics framework allows for rapid evaluation of alternative mining scenarios on dewatering, drawdown, and impacted spatial extent. This approach is increasingly finding use in
evaluating complex interdisciplinary issues and as a decision-support tool for policy alternatives (Roach and Tidwell, 2009; EPA, 2009; Asher et al., 2012; Guillaume et al., 2012).

3.3 Methods

Three hydrologic modeling studies of the San Juan Basin have been done previously (Lyford et al., 1980; Kernodle, 1996; USDA, 2013). These studies used the finite difference method to approximate the equations of groundwater flow. Lyford et al. (1979) evaluated the impact of uranium mining on groundwater in the Morrison Formation using decreasing sized grid cells (2 mi$^2$) where mining occurs and larger grid sizes in areas where head declines were not as intense. This work considered vertical leakage in three general layers of uniform thickness (50, 50 and 100 ft.) and hydraulic conductivity ($1 \times 10^{-12}$ ft/s) (Lyford et al., 1980). USDA (2013) considered the hydrologic impacts of a single mine (Roca Honda) on groundwater in the basin and incorporated hydrologic interactions between multiple layers. Kernodle (1996) modeled the entirety of the basin using steady-state assumptions through a gridded network of cells of uniform dimension to each layer. These included horizontal and vertical flows of aquifers and confining units and used very low vertical hydraulic conductivity in the Morrison Formation ($1.2 \times 10^{-9}$ ft./s). However, because Kernodle (1996) considered only steady-state conditions it had limited utility in evaluating future activities which might impact groundwater resources. A fourth study by Kelley et al (2014) estimated fresh groundwater volumes in the San Juan basin to evaluate the impacts of unconventional oil
and gas development on water resources in the basin using geospatial analysis of well log data.

The three previous models (Lyford et al., 1980; USDA, 2013) required extensive effort to develop and calibrate their respective models. The numerical method and associated software used is both computationally and time intensive (Roach and Tidwell, 2009; Asher et al., 2012; Guillaume et al., 2012) and the resulting models offer limited flexibility which make them difficult to use as a decision support tool. The approach used in this study combines an analytical mine dewatering model and compartmental-spatial system dynamics (CSSD) methodology (Roach and Tidwell, 2009) within a coupled modeling framework. The model was constructed in Powersim (2015) software, using spatially based hydrologic and U resource data, historic mine production information, and results from previous modeling efforts. In addition to its flexibility and utility for decision support, Powersim (2015) contains features which enable rapid sensitivity and uncertainty analysis, important analytical tools which are not often integrated in complex numerical modeling software platforms (Asher et al, 2012). This modeling approach is also well-suited to integrated modeling efforts (Asher et al., 2012). For example, a model designed to investigate the impacts of energy production on economics or human health may not consider water directly. However, the availability of water and the impacts of its use will influence how human health and local economies are affected. This work makes coupling models of different systems but which rely upon a common resource easier.
3.3.1 Spatial Model

A spatially disaggregated model of the basin was constructed using ~36 mi\(^2\) township range (SLO, 2017) compartments and no flow boundaries at the basin margins where the Morrison Formation outcrops resulting in 430 distinct compartments. Hydrogeologic data from several sources (Table 3-1) were used to estimate hydrologic characteristics including initial potentiometric head, aquifer thickness, outcrop and direct recharge area, transmissivity and storage coefficient. These values were estimated for each compartment using ArcGIS 10.1 software using a combination of spatial analysis techniques including zonal statistics, intersection, and area-weighting (ESRI, 2014). As a result, each compartment had unique hydrogeologic parameters.

The location, quality, and volume of existing U deposits also vary spatially as do the location of mines used in previous modeling efforts. Uranium subdistricts in the Grants area, volume and quality of ore present, and location of mines and nodes used in the model by Lyford et al. (1980) and the model of the Roca Honda (USDA, 2013) were added and associated with compartment Township and Range (TR) boundaries. The locations of the spatial features are shown in Figure 3-2.
<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Type</th>
<th>Value or Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Township range boundaries</td>
<td>NM State Land Office</td>
<td>shapefile</td>
<td>430 TRs ~36 mi²</td>
</tr>
<tr>
<td>No flow boundary</td>
<td>Lyford et al., 1980</td>
<td>digitized shapefile</td>
<td>N/A</td>
</tr>
<tr>
<td>Outcrop area</td>
<td>Lyford et al., 1980</td>
<td>digitized shapefile</td>
<td>0.22.9 mi²</td>
</tr>
<tr>
<td>Recharge</td>
<td>Kernodle, 1996</td>
<td>digitized shapefile</td>
<td>0.1-0.5 in/yr</td>
</tr>
<tr>
<td>Potentiometric surface</td>
<td>Lyford et al., 1980</td>
<td>digitized shapefile</td>
<td>500-6000 ft</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>Lyford et al., 1980</td>
<td>digitized shapefile</td>
<td>25-300 ft²/da</td>
</tr>
<tr>
<td>Storage coefficient</td>
<td>Lyford et al., 1980; Kernodle, 1996</td>
<td>calculated</td>
<td>confined: 0.00011 - unconfined: 0.1</td>
</tr>
<tr>
<td>Specific Yield</td>
<td>Kernodle, 1996</td>
<td>value</td>
<td>0.00103</td>
</tr>
<tr>
<td>Aquifer thickness</td>
<td>Kelley et al., 2014</td>
<td>raster</td>
<td>119-1067 ft.</td>
</tr>
<tr>
<td>Mine nodes</td>
<td>Lyford et al., 1980</td>
<td>point</td>
<td>N/A</td>
</tr>
<tr>
<td>Mine Characteristics</td>
<td>McLemore et al., 2015</td>
<td>tables</td>
<td>depth of workings, operating years</td>
</tr>
<tr>
<td>U Reserves</td>
<td>McLemore et al., 2015</td>
<td>table</td>
<td>pounds and U grade</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Ore</td>
<td>751,000-167,500,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grade</td>
<td>0.07-0.25</td>
</tr>
<tr>
<td></td>
<td>McLemore et al., 2015</td>
<td>Total U₃O₈</td>
<td>6,750-35,170,000</td>
</tr>
</tbody>
</table>

Table 3-1: Model data sources and ranges.
Historically, nearly two-thirds of the uranium producing mines in the Grants region employed underground mining techniques (McLemore et al., 2002). Where deposits occurred below the water table, mine dewatering was required to enable mining (Ulmer-Scholle, 2016). First, a vertical shaft was drilled to a depth below the ore body and water was pumped to the surface to begin dewatering. Next horizontal stopes or drifts

Figure 3-2: Description of Township Range (TR) compartment delineation, existing U deposits and historically modeled mines (and nodes), Morrison outcrop areas receiving direct recharge, and uranium subdistricts.

3.3.2 Analytical Mine Dewatering Model

Historically, nearly two-thirds of the uranium producing mines in the Grants region employed underground mining techniques (McLemore et al., 2002). Where deposits occurred below the water table, mine dewatering was required to enable mining (Ulmer-Scholle, 2016). First, a vertical shaft was drilled to a depth below the ore body and water was pumped to the surface to begin dewatering. Next horizontal stopes or drifts
were extended and ore was excavated. In the case of retreat mining, a main shaft was excavated to a maximum radial extent, then rooms were excavated off to the sides with rock pillars remaining in between for geologic stability. This is referred to as ‘room-and-pillar’ mining and was common practice in historic coal and hard rock mining as well. Figure 3-3 presents a conceptual diagram of a hypothetical uranium mine as well as dewatering parameters which are discussed next.

![Conceptual diagram of analytical mine dewatering model. Uranium ore bodies are represented in yellow and drawdown by dashed lines.](image)

**Figure 3-3:** Conceptual diagram of analytical mine dewatering model. Uranium ore bodies are represented in yellow and drawdown by dashed lines.

The amount of water produced by dewatering is dependent upon both mine and hydrogeological characteristics. The Cooper-Jacob approximation of the Theis solution calculates the transient impacts from a well in an infinite confined aquifer as a function of both well and hydrogeologic characteristics. The underlying equation and its solution are based on several assumptions including: the well fully penetrates the aquifer and does not
induce leakage or recharge; the well pumps at a steady state and water is instantaneously released from storage, and flow is axially symmetric about the well (Fitts, 2009). In this case, mine dewatering is analogous to discharge from a very large diameter well.

Assuming water is removed through a single main shaft of a given mine, dewatering rate (Q) is dependent upon mine depth and expansion rate, as well as aquifer transmissivity and storage coefficient. Because the aquifer is assumed to be of infinite extent and is considered confined, drawdown (s) never reaches steady state (Fitts, 2002). These relationships are described in Equation 3-1 and in the conceptual model in Figure 3-3.

**Equation 3-1: Cooper-Jacob Approximation of the Theis Solution**

\[ s = \frac{Q}{4 \pi T} \ln \left( \frac{2.25 T t}{r^2 S} \right) \]  

\( s \) = drawdown at radius \( r \) [L];

\( T \) = transmissivity \([L^2/T]\);

\( t \) = time [T];

\( r \) = mine radius [L]

\( S \) = Storage Coefficient

For this analysis, the drawdown is assumed to be the depth of the maximum horizontal extent (r) of the mine as shown in Figure 3-3. By applying this equation to a set of hydrogeologic and mine parameters, Figure 3-4 illustrates the effects of variation of any parameter (independent variable) on the total dewatering rate (dependent variable). This helps to understand which hydrogeologic parameters have the most effect on dewatering rate. The reference case evaluates a mine with a depth of 2,000 ft.,
transmissivity of 185 ft$^2$/day, and storage coefficient of $1 \times 10^{-4}$. Each reference case parameter is held constant while one parameter is halved (solid lines), to explore the sensitivity of dewatering to changes in individual parameters. In this analysis, the effective radius of the well increases as the mine extends to follow the ore body. This results in an increase in flow rate ($Q$). Next, the radial extent of the mine is limited to a maximum (2,100 feet) for each scenario based on the average historic mine radius reported by Lyford et al. (1980). Results (dashed lines) show that dewatering begins to decrease when the maximum radius of the mine is reached (Figure 3-4). At the maximum radius, pumping occurs to maintain the drawdown equal to the depth of the mine at its maximum extent and therefore dewatering flows decrease as the hydraulic gradient flattens out.
This analytical approach reveals that mine dewatering rate (Q) is least sensitive to the value of the storage coefficient parameter. A sensitivity analysis done in which each of the input variables used in the analysis of initial conditions was sequentially reduced by half, shown by colored lines in Figure 3-4. The results show that dewatering volume is most sensitive to change in mine depth and transmissivity (yellow and blue). When a maximum radius is reached (dashed lines) dewatering rate (Q) decreases with time. This is due to a decreasing hydraulic gradient from the dewatered ore body for which the cone of depression extends outward.

**Figure 3-4:** Dewatering rate (Q) is affected by changes in initial parameters: mine depth (s=2,000 ft.), transmissivity (T=185 ft²/da), storage coefficient (S=0.0001) and maximum mine radius (r). This figure describes how halving initial model parameters (depth, T, S) effects dewatering rate Q. In addition, when a maximum value limits mine radius (r=2,100 ft.), dewatering rate (dashed lines) begins decreasing when that limit is reached.
3.3.3 **System Dynamics Model**

System Dynamics (SD) modeling represents the dynamic interactions of a physical system through a series of stocks and flows, as well as internal feedbacks. The 430 compartments representing the Grants Mining District were added to a Powersim (2015) SD model as stocks. Initial water volume of each compartment was calculated by multiplying compartment volume (area times thickness) by the storage coefficient. Although most of the Morrison is confined, the storage coefficient was adjusted in outcrop cells. Initial water volume was further adjusted to be consistent with pre-development water volumes estimated by Kelley et al. (2014).

Three types of flows were considered for each compartment: inflow from recharge, outflow due to pumping, and inter-compartmental flows. Lyford et al. (1980). Recharge was assumed to occur only in compartments at the boundary of the system where the Morrison Formation outcrops. These were digitized in ArcGIS and areas were summed within each TR. Monthly recharge was calculated for each TR by multiplying the area of outcrop by the direct recharge rates estimated by Kernodle (1996). Aside from the City of Crownpoint, there are few major users of ground water from the Morrison Formation because of its depth (Lyford et al., 1980). Therefore mine dewatering was considered the only significant outflow in the historic period (Lyford et al, 1980).

Ground water flows occur due to head differences between compartments which create hydraulic gradients. Horizontal flow due to a hydraulic gradient was incorporated using the methods described in Roach and Tidwell (2009). At minimum, each compartment shares a boundary with at least one other; on average, a single compartment
is directly connected to four other compartments. Where these connections are present (e.g., between compartment \(a\) and compartment \(b\), the volumetric flow rate \(Q\) is calculated using Darcy’s law with the hydraulic gradient based on the head differences between compartments, the distance between the centers of the compartments, and the area of their shared boundary \((L)\). Simplified compartmental relationships are shown in Figure 3-5 and flow driven by hydraulic gradient is described by Equation 3-2.

![Conceptual model of connected flow compartments (plan view)](image)

**Figure 3-5:** Conceptual model of connected flow compartments (plan view) as described by Roach and Tidwell (2009)

**Equation 3-2:** Flow between compartments as a function of hydraulic properties and compartmental head as described in Roach and Tidwell (2009)

\[
Q = \frac{-TC}{L}(h_a - h_b) \quad (3-2)
\]

Therefore, if the head in compartment \(a\) is greater than that in compartment \(b\), water will flow out of \(a\) and into \(b\) (\(Q\) is negative) at a rate determined by the wetted area between compartments \((C*\Delta h)\) the effective transmissivity \((T)\) over distance \((L)\), described as the alpha \((\alpha)\) parameter in Roach and Tidwell (2009).
Flows between compartments are further constrained by the minimum and maximum capacity of each compartment. The minimum stability criteria described in Roach and Tidwell (2009) was applied to this model to ensure that flow out of any given compartment could not exceed its volume in a single timestep. In addition, because initial conditions are representative of pre-development water content, it is assumed when flow into any compartment exceeds its maximum storage, no infiltration occurs and recharge is redirected as runoff. This is described by Equation 3-3 where the maximum allowable inflow ($Q_{\text{max}}$) into compartment $a$ with a maximum water volume ($V_{\text{max}}$), water volume at time $i$ ($V_i$), and inflows from connected compartments $\Sigma Q$.

**Equation 3-3:** Model estimated maximum compartmental inflow (a) and runoff (b) when maximum storage is exceeded.

$$
Q_{\text{max}} = \frac{V_{\text{max}} - V_i}{\Sigma Q} \cdot \Sigma Q
$$

(3-3a)

$$
\text{Runoff} = Q_i - Q_{\text{max}}
$$

(3-3b)

Historic and possible future mines and their associated TR were added to the SD model using four sources. First, the node locations described by Lyford et al. (1980) were representative of a combination of historic mines, and were digitized from printed documentation. The second source of historic mine location was the NM Mines Database (McLemore et al., 2012) which includes latitude, longitude, and mine characteristics (depth of workings, start and end date, total ore produced). SJBRUS (1980) also included
information on the mines that were producing at the time the initial ground water impacts were evaluated by Lyford et al., (1980). Third, the location of a potential future mine was based on the location of uranium ore bodies identified by McLemore and Chenoweth (2003) and McLemore et al. (2013). Last, the location of the Roca Honda mine (USDA, 2013) was added. This is a mine in the final stages of permitting that may open in the next few years depending on the price of U. A list of these mines is shown in Table 3-2 and their locations are shown in Figure 3-2.

As described previously, mine depth, size, and time in operation determine its dewatering rate. This information is available for historic mines (McLemore et al., 2003) and for the Roca Honda mine (USDA, 2013). However, this information was not provided for the nodes modeled by Lyford et al. (1980). Using the locations of historic mines and their characteristics, inverse distance weighting (IDW) in ArcGIS was (ESRI, 2014) employed to estimate these characteristics to the historic nodes described by Lyford et al. (1980) based on their proximity to actual historic mines. Although operational duration for future mines was determined by model scenarios, estimated mine depth at these locations was estimated using the same (IDW) methods. Mines with more than one start year represent the combination of mines within a given location with multiple start years.
Table 3-2: Location of nodes, historic mines, and the Roca Honda mine. Future locations for U mines are based upon the presence of ore as determined by McLemore et al., 2015.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Nodes (Lyford et al.)</th>
<th>Historic Underground Mines</th>
<th>Roca Honda Mines based on U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start Year</td>
<td>Depth (ft)</td>
<td>Number of Mines</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1974</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>1976-1978</td>
<td>0-672</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
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<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>5</td>
<td>1952-1979</td>
<td>0-440</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1964-1968</td>
<td>794-967</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>8</td>
<td>1957-1979</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>58</td>
<td>1</td>
<td>1960</td>
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<td>98</td>
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<td></td>
</tr>
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<td>100</td>
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<td></td>
</tr>
<tr>
<td>101</td>
<td>1974</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>2</td>
<td>1972-1976</td>
<td>1793-1851</td>
</tr>
<tr>
<td>126</td>
<td>1978</td>
<td>1309</td>
<td></td>
</tr>
<tr>
<td>139</td>
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<td></td>
</tr>
<tr>
<td>140</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>272</td>
<td>1</td>
<td>1952</td>
<td></td>
</tr>
</tbody>
</table>

A simplified SD model schematic is shown in Figure 3-6. Within the SD model framework, the analytical mine dewatering module components are in the orange box and the ground water module in blue. Each model variable contains multiple dimensions either associated with the number of modeled mines (or nodes) or 430 TR compartments. Constant values are represented by diamond shapes with names in all caps. Variables which change over time, are referred to in SD terminology as rates and are represented by circles. Stocks, the state variables which aggregate flow rates (double arrows with rates...
attached), are represented by squares. All results are aggregated to the TR compartment scale to show inflow due to recharge, intercompartmental flows, withdrawals due to mine dewatering, and change in storage and head.

Figure 3-6: Simplified coupled SD model diagram. Orange area represents analytical mine dewatering module with total dewatering rate by TR compartment (orange circle). Blue area represents the groundwater module with intercompartmental flows (white circles), recharge (large light blue circle), total ground water storage (blue hatch square), and head loss (large dark blue circle). Inputs from the spatial model are represented by green diamonds and historic mine or literature data is represented by yellow diamonds. Multiple TR dimensions are indicated by double bold lines around parameters.

3.3.3.1 Model Calibration

Calibration refers to the process by which model parameters are adjusted in order to produce results that best fit observed data (US EPA, 2009). This model was calibrated using results from two previous models by Lyford et al., (1980) and USDA (2013) because they specifically evaluated the impacts of uranium mining on ground water resources. Each model provides different data for the calibration process. Lyford et al. (1980) modeled dewatering impacts of historic mining operations over a large area using
production nodes based on historic mines and general hydrologic data. Their results were evaluated using historic production and drawdown observations and these observations were used to calibrate aspects of this model. The Roca Honda mine model (USDA 2013) simulated the impacts of a single mine (Roca Honda) but incorporated more recent hydrologic data and model parameters in their approximations and model verification.

First, the 12 production nodes described by Lyford et al. (1980) were evaluated for the historic period (1953-1980). Mine operations were based upon pre-determined characteristics including depth, start date and hydrologic parameters (Lyford et al., 1980; Kernodle, 1996). Next, the Roca Honda mine was added, including its projected 13-year operating period. Using optimization techniques, individual mine and hydrologic parameters were allowed to vary so that results from the model fit the results described previously (Lyford et al., 1980; USDA, 2013). Powersim (2015) uses a solver algorithm to find the optimal values of multiple combined parameters which satisfy the goal of the optimization. In this case, a range of values for each of the aforementioned characteristics were specified as ‘decisions’ and the optimal decisions as ‘objectives’. Optimization occurred by finding the minimum difference between modeled values for dewatering and those reported in the literature by Lyford et al. (1980) and USDA (2013).

The results of model calibration are shown in Table 3-3 where the percent difference between the historic values (both modeled and reported) are compared to the SD modeled values. Model calibration during the historic period was done using reported values when they were available (i.e. dewatering from Church Rock mines, discharges in Ambrosia Lake, and drawdown near Crownpoint and Church Rock) and modeled data.
(i.e. total dewatering of all mines) when no observed data was reported. Further calibration of the model using data from USDA (2013) included no reported data. With the exception of drawdown near Crownpoint, the calibrated model is within 10% (±/) of historically reported data. However, our calibrated model overestimates drawdown near Crownpoint and surface discharges in Ambrosia Lake compared to the historic model (Lyford et al., 1980). USDA (2013) mentions that modeled dewatering from the Roca Honda Mine may be overestimated in their model, which may explain why our results underestimate total dewatering during construction and operation by as much as eight percent as shown in Table 3-3.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Parameters</th>
<th>Unit</th>
<th>Time Period</th>
<th>Historic Value</th>
<th>SD Model Calibration Value</th>
<th>Percent Difference (Historic vs. Calibrated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyford et al. (1980)</td>
<td>Dewatering from Church Rock Mines</td>
<td>AF</td>
<td>1968-1980</td>
<td>57,000</td>
<td>60,000</td>
<td>-4.41% / 0.72%</td>
</tr>
<tr>
<td></td>
<td>Dewatering from All Mining Nodes</td>
<td>AF</td>
<td>1953-1980</td>
<td>170,000</td>
<td>175,681</td>
<td>-3.29% / -83.79%</td>
</tr>
<tr>
<td></td>
<td>Surface discharges in Ambrosia Lake</td>
<td>AF/yr</td>
<td>1978</td>
<td>12</td>
<td>5</td>
<td>-1.73% / -83.79%</td>
</tr>
<tr>
<td></td>
<td>Drawdown near Crownpoint</td>
<td>feet</td>
<td>1980</td>
<td>200</td>
<td>100</td>
<td>39.52% / -29.06%</td>
</tr>
<tr>
<td></td>
<td>Drawdown near Church Rock</td>
<td>feet</td>
<td>1980</td>
<td>240</td>
<td>260</td>
<td>-2.87% / 5.13%</td>
</tr>
<tr>
<td></td>
<td>Range of variability of drawdown</td>
<td>feet</td>
<td>1953-1980</td>
<td>-</td>
<td>-</td>
<td>-4.90% / -83.79%</td>
</tr>
<tr>
<td>USDA (2013)</td>
<td>Dewatering volume (Construction)</td>
<td>AF</td>
<td>2 years</td>
<td>6,452</td>
<td>6,109</td>
<td>-5.46% / 5.46%</td>
</tr>
<tr>
<td></td>
<td>Dewatering volume (Production)</td>
<td>AF</td>
<td>10 years</td>
<td>72,585</td>
<td>67,049</td>
<td>-7.93% / 5.46%</td>
</tr>
<tr>
<td></td>
<td>Total volume discharged</td>
<td>AF</td>
<td>13 years</td>
<td>79,037</td>
<td>73,158</td>
<td>-7.73% / 5.46%</td>
</tr>
<tr>
<td></td>
<td>Range of drawdown</td>
<td>feet</td>
<td>13 years</td>
<td>-</td>
<td>-</td>
<td>-5.50% / 5.46%</td>
</tr>
</tbody>
</table>

**Table 3-3**: Comparison of historic modeled drawdowns with system dynamics results for the calibration periods 1953-1980 and 2015-2027
Drawdown from Lyford et al. (1980) was digitized in ArcGIS from original maps. Lines of equal drawdown were intersected with TR compartment boundaries and maximum modeled drawdown was mapped in Figure 3-7a. Drawdown from the calibrated SD model was mapped by TR compartment Figure 3-7b. When compared to historic drawdown maps, the calibrated SD model underestimates the magnitude drawdown (Table 3-3) as well as its spatial extent (Figure 3-7) but offers reasonable visualization of the area affected by mining.

![Figure 3-7: Comparison of Lyford et al. (1980) model results (a) with calibrated SD model (b).](image_url)

### 3.3.3.2 Quantifying Uncertainty

Lack of information regarding hydrologic characteristics is a major source of uncertainty in models. How the model framework is developed and structured, as well as data errors and scarcity can be sources of error; identifying the specific sources of uncertainty is essential to the model’s utility (US EPA, 2009). This work the percent difference method and Monte Carlo analysis to evaluate model parameter uncertainty. Monte Carlo analysis uses repeated random sampling over a range of values for each parameter to assess the distribution of potential values. The uncertainty associated with
mine dewatering was quantified by evaluating three model parameters: transmissivity, storage coefficient, and mine depth.

A normal distribution was used to conduct this analysis using the ‘Risk Analysis’ tool in Powersim (2015). Because the parameters vary spatially, each compartment has a unique combination of values so the distribution characteristics associated with each parameter were determined as follows. First, coefficients were applied to each parameter such that the range of potential values could be evaluated for all compartments simultaneously in Monte Carlo analysis. Therefore, the average or ‘expected’ values for each parameter and compartment determined during calibration were assigned a value of 1. Next, the distributions of potential values for each parameter were determined based on the range rule of thumb where the standard deviation (σ) is the range (maximum minus minimum) divided by four. In this case, the percentage difference between average values and reported minimum and maximum values were used to estimate the maximum and minimum coefficient values as shown in Table 3-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>1</td>
<td>52%</td>
<td>148%</td>
<td>+24%</td>
</tr>
<tr>
<td>Storage Coefficient</td>
<td>1</td>
<td>18%</td>
<td>182%</td>
<td>+41%</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>1</td>
<td>38%</td>
<td>162%</td>
<td>+31%</td>
</tr>
</tbody>
</table>

Table 3-4: Normal distribution values for each parameter based on the percent difference between the percent difference range between reported minimum and maximum values used in the Monte Carlo Analysis.

A random sampling within the normal distribution of each parameter values was conducted using the Risk Analysis tool (Powersim, 2015) over 1,000 sampling runs.
Although the number of initial runs (5,000) determined to be sufficient to result in convergence (Driels & Shin, 2004; Guillaume et al., 2012) report that 5,000 model runs are sufficient to result in convergence, the distribution of results in this model was found to be independent of the number of runs over this range when comparing 1,000 and 5,000 runs. Neither opening year nor maximum radius was evaluated because future mining would specify the anticipated duration of mining (USDA, 2013) and previous results have shown that dewatering rates are not very sensitive to expansion rate (Steinhaus, 2011).

Each parameter was evaluated in separate Monte Carlo simulations. For example, when transmissivity was evaluated, total dewatered volume at the end of the simulation as well as the simulation-selected random value for transmissivity were exported to an auxiliary using the ‘SAMPLERUNS’ function. This function stored the values from each simulation run, which were then exported to Excel. As such, total dewatering volumes were attributable to a specific parameter value for each simulation (i.e. 1,000 transmissivity values associated with an equal number of dewatering volumes). For ease of visualization (Edwards et al., 2012), the results of the Monte Carlo analysis are displayed as a box and whisker plot in Figure 3-8. As with the results of the sensitivity analysis, these results indicate that the parameter with greatest contribution to uncertainty in the model is transmissivity.
Figure 3-8: Distribution of Monte Carlo results of the effect of three parameters (storage coefficient, depth, and transmissivity) on total volume of dewatering based upon the calibrated historic model (1953-1980). Greatest uncertainty in transmissivity parameter yields widest distribution of modeled volumes.

Based on estimates of U reserves in the region (McLemore et al., 2013; McLemore and Chenoweth, 2003), 24 TR compartments were identified as potential future mine sites. To quantify the potential ground water impacts of a hypothetical mine in each of these locations, each compartment was modeled for 20 years mine life. To account for uncertainty, three model simulations were evaluated using the initial calibrated average value, and standard deviation for each parameter as described in Table 3-4. Because the range rule of thumb was used to estimate standard deviation, the coefficients described in Table 3-4 represent two standard deviations or a 95% confidence interval.
To quantify uncertainty for future model runs, only the compartments where mining occurred were assumed to be significant contributors to dewatering (i.e. no dewatering occurs in compartments without mines). The model runs for these compartments yielding dewatering volume results within the confidence range were identified as were the values for transmissivity, storage coefficient, and depth that resulted in these dewatering volumes. The percent difference between the minimum and maximum parameter values (T, S, and depth) associated with dewatering volumes within the confidence range was calculated for each TR compartment. As suggested by Hamby (1994) only the minimum and maximum bounds were selected to account for a broad range of uncertainty in future scenarios (Table 3-4).

3.4 Results

The objective of this study was to construct a system dynamics model of the effects of underground mining activity in the Grants Mining District on ground water. As mentioned previously, historic estimates of water production from mines and drawdown have not considered the total volume of water present in the Morrison or in overlying formations. Kelley et al. (2014) estimate that the total pre-development water volume of the basin was 3.25 MAF and that contained in the Morrison formation was more than 700,000 AF. Dewatering of historic mines was calculated by the model but dewatering rates were limited by the total volume of water present within each compartment plus the volume of water flowing in from adjacent compartments. These results, shown in Table 3-5, represent the average values for dewatering, drawdown, and TRs affected by modeled uranium mining in subdistricts with U present. These values were determined
using the range of parameter values described in Table 3-4. Ratios of dewatering and drawdown were calculated based upon the mass of U ore present.

<table>
<thead>
<tr>
<th>Uranium Sub-District</th>
<th>Total U₃O₈ (Million lbs)</th>
<th>TRs with U Reserves</th>
<th>Total Dewatering (AF)</th>
<th>Total Drawdown (ft.)</th>
<th>Number of TRs Affected</th>
<th>Dewatering: U Extracted (AF/Mlbs U₃O₈)</th>
<th>Drawdown: U Extracted (ft/Mlbs U₃O₈)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambrosia Lake</td>
<td>409.08</td>
<td>8</td>
<td>44,500</td>
<td>1,020</td>
<td>20</td>
<td>109</td>
<td>3</td>
</tr>
<tr>
<td>Church Rock-Crownpoint</td>
<td>123.09</td>
<td>5</td>
<td>51,700</td>
<td>1,010</td>
<td>28</td>
<td>420</td>
<td>8</td>
</tr>
<tr>
<td>Laguna</td>
<td>21.90</td>
<td>2</td>
<td>22,400</td>
<td>146</td>
<td>4</td>
<td>1,020</td>
<td>7</td>
</tr>
<tr>
<td>Marquez</td>
<td>21.75</td>
<td>3</td>
<td>70,000</td>
<td>1,320</td>
<td>20</td>
<td>3,220</td>
<td>61</td>
</tr>
<tr>
<td>Nose Rock</td>
<td>83.30</td>
<td>3</td>
<td>66,300</td>
<td>2,230</td>
<td>40</td>
<td>796</td>
<td>27</td>
</tr>
<tr>
<td>Smith Lake</td>
<td>38.43</td>
<td>3</td>
<td>45,400</td>
<td>748</td>
<td>17</td>
<td>1,180</td>
<td>20</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>

**Table 3-5**: Comparison of dewatering and drawdown in six uranium subdistricts in the Grants region. Total U₃O₈ is a function of ore volume and grade (McLemore, 2015).

Ambrosia Lake has the third highest average drawdown and number of TRs affected by mine dewatering, but it has the smallest ratio of uranium extracted compared to these parameters because of the large amount of uranium reserves present in the region (Table 3-5). The range of effects of dewatering on drawdown are evident when comparing Marquez and Nose Rock subdistricts: they rank first and second in terms of the volume of water extracted but ore recovery in Marquez is more than four times more water intensive and affects twice as many TR compartments. Low values for drawdown in the Laguna district are likely due to deposits that are shallower and closer to recharge zones. Although values for storage coefficients in these areas are higher than towards the central portion of the basin, dewatering is much more sensitive to depth and transmissivity values (Figure 3-4 and Figure 3-8) which are lower as compared to other subdistricts. Figure 3-9 compares the range of annual dewatering volume for the 6
subdistricts. Church Rock-Crownpoint and Nose Rock present the greatest uncertainty (range between minimum and maximum values) relating to the annual production of water from future mines. These results indicate that while hydrologic tradeoffs exist when comparing hypothetical mines in all uranium subdistricts, the impacts of mining in a region like Ambrosia Lake are less when comparing the total uranium recovered. In addition, although Church-Rock Crownpoint and Smith Lake may have comparatively low ratios of drawdown compared to uranium extracted, model predicted dewatering volumes are relatively uncertain as compared to other subdistricts (Table 3-1;Figure 3-9).

Figure 3-9: Range (maximum - minimum) of annual dewatering volumes by uranium subdistrict for modeled time period, 2020-2040.

Because of the broad scale of the SD model and incorporation of hypothetical mining activity, the model was used to screen the impacts of mining and associated uncertainty in individual compartments. We identify three main impacts of mining: volume of water removed from storage (V), total drawdown in feet (D), and number of compartments affected by drawdown (N) which yield different results for each modeled
compartment. To compare the hydrologic impacts of mining on ground water resources we define a term referred to as the hydrologic intensity (HI). The HI in each compartment is calculated by ranking the modeled values of the three impacts (V, D, and N) ascending order against the results from all other modeled scenarios. This approach normalizes the impacts between compartments and value units. The maximum value for each parameter is 24, with a maximum potential HI of 72 indicating greatest intensity (Equation 3-4).

**Equation 3-4**: Hydrologic Intensity (HI) calculated for compartment (i) based on the ranked value of total water removed from storage (V), drawdown (D) and number of compartments affected (N).

\[
HI_i = \text{RANK}(V_i) + \text{RANK}(D_i) + \text{RANK}(N_i)
\]  

Uncertainty is an important consideration in our estimates of hydrologic intensity. Therefore, the percent difference between minimum and maximum modeled values (Sensitivity Index (SI) described by Hamby (1994)) was calculated for each compartment and for each intensity parameter and used as a proxy for uncertainty. The uncertainty of hydrologic intensity (U(HI)) estimates for a given compartment is calculated as the sum of U(HI) parameter rank described in Equation 3-5.

**Equation 3-5**: The uncertainty of Hydrologic Intensity (U(HI)) estimates calculated for compartment (i) based on the ranked value of total uncertainty associated with volume of water removed from storage (U(V)), drawdown (U(D)) and number of compartments affected (U(N)).

\[
U(HI)_i = \text{RANK}(U(HI_V)_i) + \text{RANK}(U(HI_D)_i) + \text{RANK}(U(HI_N)_i)
\]
The results are shown in Figure 3-10, where warm colors indicate high hydrologic intensity (HI) of impact in each compartment and the relative uncertainty (U(HI)) of these estimates. Hypothetical mining activity occurring in the Nose Rock subdistrict have the highest overall intensity and uncertainty, followed by the Church Rock-Crownpoint subdistrict. TRs in the Laguna and Smith Lake subdistricts rank lowest in terms of impact and uncertainty. A location that has both high intensity and high uncertainty indicates that both dewatering and spatial extent of drawdown could be much greater than that predicted under average conditions.
Figure 3-10: Intensity and uncertainty associated with TR compartments in the six mining districts with U present. Warm colors indicate greater intensity and shading (outline, hatch, cross-hatch) represent uncertainty associated with the combined parameters of dewatering, drawdown, and number of compartments affected by mine dewatering.
The extent to which dewatering impacts in U subdistricts are extensible to its TR compartments is also of interest. Each the six subdistricts have multiple ore bodies, some of which may be present in multiple compartments. However, some subdistricts present a range of intensity and uncertainty values (Figure 3-10). The range of rank values for uncertainty (U(HI)) are shown in Figure 3-11. This indicates that the TR location in which a mine is placed is more significant consideration in Ambrosia Lake where there exist a broad range of intensity and uncertainty values as compared to Nose Rock, where there is little variability among TR compartments. In addition, uncertainty in the Marquez subdistrict is primarily attributable to dewatering and drawdown, whereas the spatial extent or number of nodes affected are the greatest contributor to uncertainty in Nose Rock.

![Figure 3-11](image)

**Figure 3-11**: Range of ranked uncertainty values for the three evaluated parameters in six uranium subdistricts. The height of each bar indicates the variation of ranked uncertainty values (U(HI)) associated with each parameter (dewatering, drawdown, number of TRs impacted) where a longer bar height represents greater variation in uncertainty. The sum of bar heights represents the range of ranked uncertainty for each subdistrict.
Screening Analysis

This model was developed to answer screening-level questions regarding the impacts of future uranium development on ground water which are of import to a diversity of stakeholders. While the specific questions of these stakeholders vary, understanding of ground water impacts can lead to improved decision-making capabilities collectively. For example, the broad regional impacts of mine dewatering may be of interest to regulators and water planners whereas industry or local communities may want to understand the effects of a mine cited in a specific location. To demonstrate this utility, seven locations in four U subdistricts identified by McLemore et al., (2013) and shown in Table 3-6. Although the mine in Church Rock-Crownpoint will likely employ in-situ leach (ISL) recovery techniques, should mining resume, it was modeled as a conventional underground mine for comparison with the other locations.

<table>
<thead>
<tr>
<th>Model TR No</th>
<th>Sub-District Name</th>
<th>Deposit Name</th>
<th>TR Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>La Jara Mesa</td>
<td>T12N R09W</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Mount Taylor</td>
<td>T13N R08W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roca Honda</td>
<td>T13N R08W</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>Church Rock Sec 8</td>
<td>T16N R16W, Sec. 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Church Rock Sec 4</td>
<td>T16N R16W, Sec. 4</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Marquez</td>
<td>T13N R05W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marquez Canyon</td>
<td>T13N R05W</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>Nose Rock</td>
<td>T18N R12W, Sec. 1, 2, 11, 14, 16, 32, 36</td>
<td></td>
</tr>
<tr>
<td>139</td>
<td>Nose Rock</td>
<td>T19N R11W, Sec. 10, 11, 15, 17-20, 29-31</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>Nose Rock</td>
<td>T19N R12W, Sec. 36</td>
<td></td>
</tr>
</tbody>
</table>

Deposit Ownership (McLemore et al., 2013): ¹Laramide Resources, ²Rio Grande Resources, ³Strathmore Minerals Corp. (acquired by Energy Fuels, Inc.), ⁴Uranium Resources International

Table 3-6: Location and ownership of potential new mines described by McLemore et al. (2013)
First, the impacts of mining on ground water is modeled separately for each potential location, using the range of parameter values described in Table 3-4 and locations in Table 3-6. The percent difference between the maximum and average dewatering volume is similar for all potential sites, ranging from 23% (La Jara Mesa) to 28% (Mount Taylor/Roca Honda). However, the range of additional water that might require management ranges from 150 AFY in Ambrosia Lake to 3,500 AFY in Nose Rock. These are important considerations when determining treatment system design capacity as well as the end-use of the treated water.

The spatial extent and magnitude of drawdown must also be considered because it has the potential to impact other water users. If mine dewatering results in impairment (drawdown) in ground water wells, the Mine Dewatering Act (§NMSA 72-12A) requires replacement. This may involve drilling deeper or additional wells, or providing an alternate source which will come at additional cost to the mining company. The range of uncertainty in the magnitude of potential drawdown varies according to mine location. Figure 3-12 shows the difference in feet between maximum and minimum drawdown. Mines in the Nose Rock subdistrict (Figure 3-12d) have a much broader range and extent of impacts on ground water head than do mines in Church Rock-Crownpoint (Figure 3-12c), whereas the impacts of mining are very similar in magnitude and extent in Marquez (Figure 3-12a) and Ambrosia Lake (Figure 3-12b). However, impacts in the Nose Rock subdistrict near the center of the basin will likely result in minimal drawdown in area wells which occur primarily near the margins of the southern portion of the basin.
Figure 3-12: Difference in maximum and minimum drawdown (ft.) for mines in the four subdistricts: a) Marquez (25), b) Ambrosia Lake (28), c) Church Rock-Crownpoint (81), and d) Nose Rock (139).
While large-scale U development will be driven by economics and federal policy its impacts on ground water is primarily of interest to regulators and water planners in the state. In order to understand what these impacts might look like, all seven locations were modeled simultaneously assuming a single mine in each location. Under the right economic conditions, these have the most potential to be developed first (McLemore et al., 2013). Total dewatering ranges from 30 to 36kAF/year, approximately twice the volume of ground water withdrawn annually in McKinley County (Longworth et al., 2013), where the majority of U deposits are present. The difference between minimum and maximum dewatering projections is 85 kAF, with maximum dewatering volumes of more than 700 kAF. This latter volume amounts to one-quarter of the total volume of water (pre-development) contained in all major aquifers in the basin (Kelley et al., 2014). In addition, drawdown increases in magnitude and extends to the southern no-flow boundary and into the central portion of the basin when evaluating the maximum range of hydrologic parameter values (Figure 3-12b). The interaction between drawdowns created by multiple mines may pose questions regarding which mines are impacting existing wells, particularly in the high scenario and near the basin margins.
An intuitive and flexible interface is integral to the utility of this model as a decision support tool. In addition to built-in uncertainty analysis capabilities, Powersim (Powersim, 2015) contains user interface design features. An interface was constructed that allows users to alter model scenarios and quickly compare results in a single format. Users can select from pre-defined scenarios where compartments with evaluated levels of uncertainty and hydrologic intensity are displayed (e.g. Figure 3-10) or to define development scenarios of their choice. Examples of user determined scenarios were
described in the previous section. When pre-defined scenarios are selected (radio buttons) only those compartments that meet the requirements of either (or both) hydrologic intensity and uncertainty scenarios are run. Values for both transmissivity and storage coefficient can be adjusted with slider bars which allow either a percentage reduction or increase in the mean values determined during uncertainty analysis. Alternatively, users can select which compartments to run, for what length of time, and specify mine characteristics (depth, expansion rate, maximum radius) in the yellow shaded table in Figure 3-14. These locations can be selected based on user knowledge and preferences, aided by the map of U deposit location and total U ore (thousand tons) present. While mine locations cannot be specified at a scale finer than a TR location, the interface allows users to simulate the activity of multiple mines in a given TR compartment. Visualization of results are displayed as graphs of mine dewatering rates (AF/month) and total drawdown (ft.).
3.5 Discussion and Summary

There are several limitations of this modeling approach. First, numerous assumptions and generalizations were incorporated in the ground water model. While
data is often an issue when constructing large-scale hydrologic models, these estimates were made with the best available information. In addition, because this work relies on surrogate modeling (Asher et al., 2012), incomplete information from the work of previous studies will impact the accuracy of this work.

For the purposes of simplicity, only one ground water unit was considered: the Morrison Formation. In reality, vertical interactions between the numerous stacked geologic layers of the San Juan basin do occur. However, both previous studies by Lyford et al. (1980) and Kernodle (1996) estimated vertical conductivities between the Morrison Formation and overlying formations to be 3 to 6 orders of magnitude less than estimates of horizontal conductivity in the Morrison. Furthermore, the top-most member of the Morrison, the Brushy Basin member acts as a confining unit with vertical hydraulic conductivity less than members of the Mancos and Lewis shales (USDA, 2013). While the Roca Honda model (USDA, 2013) projected drawdown in the Dakota and Gallup formations that directly overlie the Morrison, the model anticipated pumping directly from these formations during both mine construction and operation. And although we limit the volume of water extracted to estimates of fresh water available (Kelley et al., 2014), it is estimated that the basin may contain more than ten times this amount, up to 50 MAF, of brackish ground water (Shomaker, 2004). Excessive dewatering may lead to the upwelling of these brackish ground water sources, which impact both hydrodynamics and ground water quality.

This model is intended to enable rapid high-level screening of the potential hydrologic impacts of future uranium mining in the region, not serve as a siting tool. As
such, it does not take the place of site-specific analysis (e.g. USDA, 2013). However, if the specifications of a proposed mine (depth, radius, years of operation) are known, the model could provide insight into the intensity and scope of its impacts and reduce uncertainty of a significant parameter.

While this work attempts to convey the trade-offs of mining in a given location in the Grants Mining District, there are numerous factors that were not considered. These include economics, geology, land ownership, access to transportation infrastructure and processing facilities, and potential environmental impacts.

3.6 Conclusion

The objective of this research was to develop a streamlined modeling tool to evaluate the potential impacts and uncertainties of renewed uranium mining on ground water in the San Juan Basin. Two models: an analytical mine dewatering model and a ground water model were coupled within a system dynamics framework. The model was calibrated using historic data and the sensitivity and uncertainty of model parameters were evaluated. Last, the calibrated model was used to evaluate the impacts of mine dewatering, drawdown, and spatial extent of these impacts within the context of model parameter uncertainty. These results provide a high-level screening analysis of the intensity and uncertainty of the hydrologic impacts of future mining in the region.

The model that was constructed and evaluated for this study provides a useful tool for decision-makers as well as an approach for other water-intensive extractive industries such as potash. Key findings of this study include the variation in impacts of mining across the Grants Mining District. While the hydrologic impacts of mining are least in the
Laguna subdistrict, Ambrosia Lake offers the most efficient water-to-resource ratio of all six subdistricts. The subdistricts in the central and western portions of the basin have more intense hydrologic impacts but also greater uncertainty. This approach resulted in a tool with identified sources of uncertainty and sensitivity, with a reasonable acceptance of error (95%). In addition, it resulted in valuable initial information regarding the uncertainty of hydrogeologic parameters and the need for improved data. It also provides the basis for future studies that may consider more complex hydrogeology or incorporate economics, land-use, and other environmental impacts as a result of mining. Lastly, this method is advantageous because of its ease of connection across platforms and disciplines. In particular, the results of this work could be incorporated into the New Mexico Dynamic Statewide Water Budget (DSWB) which takes a mass-balance approach to surface and groundwater estimation and planning at regional and state levels (Roach et al, 2017).

The uranium has a long and complex history in New Mexico and with communities in the Grants region. The 1980s ushered in a shift in perspective regarding uranium production and use in nuclear power generation. By the end of the decade, prospects for the region had gone from high anticipation of future production (SJBRUS, 1980) to the extinction of the industry. Since then, low uranium prices have reduced uranium mining operations in the US to a few in-situ mining locations (EIA, 2018). Until recently, this trend was projected to persist. However, the current push by the industry to limit uranium imports and encourage domestic uranium mining in the interest of national security (Donnan, 2018; Tabuchi, 2018) may change the outlook for the industry in the
Grants region. The ability to anticipate the potential impacts of these operations on the region’s water resources is of great value; historic operations did not and their impacts are evidenced in the region to this day.
4 Mapping the Energy Footprint of Produced Water Management in New Mexico


4.1 Abstract

Hydraulic fracturing (HF) and horizontal drilling have revolutionized the fossil fuel industry by enabling production from unconventional oil and gas (UOG) reserves. However, UOG development requires large volumes of water, and subsequent oil and gas production from both conventional and unconventional wells generate large volumes of produced water (PW). While PW is usually considered a waste product, its reuse may lessen demand for freshwater supplies, reduce costs for transportation and disposal, and reduce the risks for injection-induced seismicity. Whether this water is disposed of or treated and reused, both methods require significant amounts of energy. The objective of this study was to identify the primary energy demands of alternative water management strategies, and to characterize and quantify their geographic variability in four oil and gas producing basins in New Mexico using a single year of production. Results illustrate the importance of each component of each produced water management strategy in determining its total energy footprint. Based on 2015 production and water use data, the energy to extract fresh ground water for hydraulic fracturing (34 GWh-th/yr.) exceeds the energy that would be required if the same volume of PW were treated chemically (19 GWh-th/yr.). In addition, the energy required to transport fresh water and dispose of PW
(167 GWh-th/yr.) is far greater than that required to move treated PW (8 GWh-th/yr.) to a point of reuse. Furthermore, transportation distances, which contribute significantly to the total energy footprint of a given management strategy, are underestimated by nearly 50% state-wide. This indicates that reuse may be an even more energy efficient way to manage PW, even with energy-intensive treatment strategies like electrocoagulation. Reuse of PW for HF is not only more energy efficient than conventional management techniques, it also reduces both demand for scarce fresh water resources and use of disposal wells. By evaluating components of each management strategy individually, this work illustrates how the energy footprint of regional PW management can be reduced. The advent of UOG recovery in the last decade highlights the need to understand existing water management in the industry, identify opportunities and strategies for improvement, and recognize that these dynamics are likely to change into the future.

Key words: produced water, hydraulic fracturing, energy footprint

4.2 Introduction

Virtually all aspects of fossil fuel energy production and are tightly coupled to water resources (US DOE, 2014). The oil and gas (O&G) industry is especially influenced by water resource considerations where water is used for well drilling and completion, dust suppression, reservoir pressure management, enhanced oil recovery (EOR), and increasingly for hydraulic fracturing (HF) to allow development of unconventional oil and gas (UOG) reserves. In this paper UOG refers to oil and gas
reserves in shale and tight sand formations as well as gas resources associated with coal formations and produced as coal bed methane (CBM).

Currently, more than half of crude oil and natural gas produced domestically is from UOG reserves (US EIA, 2017). HF allows development of low permeability UOG reservoirs (shale gas and tight oil) (Ratner & Tiemann, 2015) and increased CBM gas flow in coal formations. However, HF requires substantial quantities of water, between 15,300 m$^3$ and 19,400 m$^3$ for oil and gas wells, respectively (Gallegos et al., 2015). Subsequent O&G production also generates large volumes of flow-back of hydraulic fracturing fluids (HFFs) following well completion and formation water during O&G production (Bai et al, 2013). Collectively these waters are referred to as produced water (PW) and represent the largest volume waste stream in the industry (Veil et al., 2004; Benko & Drewes, 2008; Clark & Veil, 2009; Veil, 2015). Nationally, most PW generated onshore is injected into Class II wells (EOR (46%), SWD (40%)) while a small fraction (<1%) is reused (Veil, 2015).

Produced water is usually considered a waste product because of its high salinity and complex chemistry (Veil et al., 2004; Benko & Drewes, 2008; Clark & Veil, 2009; Veil, 2015; Gregory et al., 2011). However, in arid regions like NM, escalating demand for fresh water for UOG recovery (Gregory et al., 2011; Rahm & Riha, 2012; Scanlon et al., 2014; Sullivan Graham et al., 2015; Scanlon et al., 2017) has led to increased interest in reuse opportunities (US DOE, 2014; Vengosh et al., 2014). Reuse of PW also has the potential to minimize disposal costs and the reduce potential for induced seismicity associated with disposal wells (Gregory et al., 2011; Weingarten et al., 2015). Also, the
risk of transportation accidents, spills and environmental contamination are of increased public concern (Vengosh et al., 2014; US EPA, 2015; Torres et al., 2016).

Water management decisions in the O&G industry are based primarily on freshwater availability, PW volumes, and costs (Veil et al., 2004; Clark & Veil, 2009; Veil, 2015; Gregory et al., 2011; Scanlon et al., 2017); energy requirements for these activities as a whole are seldom considered. Energy is required for extraction, treatment, and conveyance of water; however, most studies have focused on use of high quality fresh water (US DOE, 2014; Fthenakis & Kim, 2010; Sanders & Webber, 2012; Plappally & Lienhard, 2012; Tidwell et al., 2014). Increasingly the O&G industry is turning to low-quality (i.e. high-salinity) water in lieu of expensive fresh water (Scanlon et al., 2017; Shaffer et al., 2013; Lebas et al., 2013). Previous studies have considered PW treatment and energy requirements (Sullivan Graham et al., 2015; Fakhru’l-Razi et al., 2009; Igunnu & Chen, 2012; Xu et al., 2016; Hearne et al., 2015; Meng et al., 2016), water used for unconventional O&G development (Bai et al., 2013; Benko & Drewes, 2008; Nicot & Scanlon, 2012, Murray, 2013; Kondash & Vengosh, 2015), and PW management (Clark & Veil, 2009; Veil, 2015; Gregory et al., 2011).

The objective of this research was to quantify and compare energy requirements for three water supply and management strategies for four basins in New Mexico. This work adds to the growing body of PW literature by characterizing tradeoffs between energy requirements for alternative PW management strategies and considers how these requirements vary geographically based on access to fresh water and opportunities for disposal and reuse. A distributed spatial approach to quantifying and comparing energy
requirements highlights variability and allows for comparison over large geographic regions (Gallegos et al., 2015; Tidwell et al., 2014; Nicot & Scanlon, 2012; Murray, 2013). Although demonstrated in New Mexico, the general method for characterizing energy required to manage PW using GIS analysis, processing and interpretation of large databases, and incorporation of energy metrics to facilitate this comparison has broad applicability in other settings.

4.3 Methods

4.3.1 Site Description

New Mexico has large and diverse O&G reserves, located in four regions (Figure 4-1). The two largest basins, both geographically and in terms of energy reserves, are the Permian Basin in southeastern NM and the San Juan Basin in northwestern NM. The Permian predominantly produces oil whereas the San Juan is mainly gas-producing. Unconventional oil (Permian) and gas (San Juan) comprise the majority of undiscovered reserves in both basins (Ridgley et al., 2002; Schenk et al., 2008). Although predominantly the Raton Basin in northeastern NM produces coal bed methane (CBM) and the Bravo Dome produces CO₂, both also produce lesser quantities of oil and gas (Figure 4-1). Extraction of all of these resources generates produced water, but production of oil (Figure 4-2a) and gas (Figure 4-2b) statewide is increasingly from horizontal wells (NM OCD, 2016), which in turn generate an increasing fraction of the total volume of PW (Figure 4-2c).
Figure 4-1: Geographic distribution of oil, gas, coal bed methane (CBM), and CO2 wells and producing basins in New Mexico.
Figure 4.2: Production volumes of a) natural gas, b) oil, and c) PW by well type and year from wells in New Mexico from 2006 to 2016. Directional wells include those designated as multilateral. Not Assigned wells lack directional status in the state database (NM OCD, 2016).
In 2015, New Mexico produced nearly 24 million cubic meters (Mm$^3$) of crude oil and 40 billion cubic meters (Bm$^3$) of natural gas, representing 4-5% of current domestic production (US EIA, 2017). It is estimated that the state contains more than 230 Bm$^3$ of crude oil, 400 Tm$^3$ of natural gas, and 125 Mm$^3$ of natural gas liquids, representing between 4 and 5% of domestic reserves (US EIA, 2015).

In an arid region like New Mexico the use of fresh water for HF can impact scarce fresh water resources. In 2015, more than 28 Mm$^3$ of water were used for HF (NM OCD, 2016), comparable to the volume of fresh ground water water withdrawn for public supply in the major O&G producing counties in the Permian Basin (NM OCD, 2016, Longworth et al., 2013). Nearly three times this amount was generated as PW (90 Mm$^3$) (NM OCD, 2016) and nearly all was either disposed of in SWD wells or reused for EOR. Reuse of PW offers the dual benefits of reducing both demand for fresh water and disposal costs. But the energy required to transport and treat this water may exceed that required for simple disposal. These energy requirements depend on many factors including demand for reuse water, the location of PW and reuse demand, and the water quality and subsequent treatment needed for reuse.

This study quantified the energy required to manage PW in O&G basins in New Mexico by calculating the energy requirements of each component for alternative water supply/management strategies. Methods included use of spreadsheets and GIS analysis to calculate the energy requirements based on the energy intensities of unit processes described below. In order to compare the electricity required to power pumps and treatment systems with gasoline consumed during the transportation of produced water,
We converted all energy requirements to a consistent unit of measure using primary (thermal) energy in kilowatt-hours (kWh-th). Compared to end-use energy (the amount of energy consumed at a point of use), primary energy accounts for heat and energy lost during the generation and transmission of electricity (American Physical Society, 2017). We assumed a hypothetical coal-fired power plant that generated and delivered electricity at 33% efficiency (1 kWh-th_{electricity} = 10,339 Btu) (American Physical Society, 2017). Because transportation energy is dependent on the total volume of fuel consumed, which includes efficiency losses during combustion, the total energy content of diesel fuel is considered (1 kWh-th_{diesel fuel} = 3,412 Btu). These values were normalized by dividing by the volume of water used or produced (kWh-th/m³). Monthly production data from oil and gas wells producing within the last 10 years (~54,000) and HF data collected for the last five years were analyzed energy intensities were evaluated at 90 km² township-range (TR) scale, which coincides with O&G pool designations in the state.

The management strategies considered were (see Figure 4-3): 1) procurement and transportation of fresh water for HF and subsequent disposal of PW in SWD wells, 2) treatment, transportation, and reuse of PW for HF, and 3) transportation and reuse of PW for EOR.

![Figure 4-3: Conceptual model of water types and flow for three management strategies: 1) procurement and transportation of fresh water for HF and subsequent disposal of PW in SWD wells, 2) treatment, transportation, and reuse of PW for HF, and 3) transportation and reuse of PW for EOR.](image-url)
for EOR. Although the third strategy is a combination of the first and second strategies, it represents common practice both nationally and in NM (Veil, 2016; NM OCD, 2016).

### 4.3.2 Data Sources and Analysis

The NM OCD compiles monthly production data from O&G producers (NM OCD, 2016). Table 4-1 shows the average annual oil, gas, and water production by basin between 2006 and 2016. Most O&G production over this period was from conventional vertical wells which, on average, produce roughly 2-4 times more water per unit of hydrocarbon compared to unconventional oil wells.

<table>
<thead>
<tr>
<th>Well Location &amp; Well Type</th>
<th>Number of Gas Wells</th>
<th>Gas (Mm³)</th>
<th>Natural Gas (Mm³ MBOE*)</th>
<th>Produced Water (Mm³)</th>
<th>Produced Water: Natural Gas (Mm³/Mm³ MBOE*)</th>
<th>Number of Oil Wells</th>
<th>Oil (Mm³)</th>
<th>Produced Water (Mm³)</th>
<th>Produced Water: Oil (Mm³/Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRODUCING BASIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bravo Dome</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>3</td>
<td>0.01</td>
<td>0.01</td>
<td>1.72</td>
<td>1.72</td>
</tr>
<tr>
<td>Permian</td>
<td>7,080</td>
<td>5,583</td>
<td>32.84</td>
<td>4.52</td>
<td>0.14</td>
<td>26,870</td>
<td>12.81</td>
<td>63.86</td>
<td>4.98</td>
</tr>
<tr>
<td>Raton</td>
<td>841</td>
<td>709</td>
<td>4.17</td>
<td>1.53</td>
<td>0.37</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>San Juan</td>
<td>21,536</td>
<td>22,854</td>
<td>134.43</td>
<td>3.10</td>
<td>0.02</td>
<td>2,133</td>
<td>0.37</td>
<td>0.45</td>
<td>1.21</td>
</tr>
</tbody>
</table>

* 1 BOE = 170 m³
** Includes both directional and multilateral wells

**Table 4-1: Comparison of average oil, gas, and water production by basin, 2006-2016 (NM OCD, 2016)**

Water supply for HF comes almost exclusively from freshwater sources (Sullivan Graham et al., 2015). Counties overlying the Permian and Bravo Dome basins rely almost entirely on ground water for all sources of water including irrigated agriculture and domestic and public supply, whereas the San Juan and Raton basins mainly use surface water for irrigation (Longworth et al., 2013). Water withdrawn for HF comprises a small fraction of total water withdrawals in each basin, ranging from near zero to less than 3%.
Nearly all water withdrawn for HF (94%) occurs in the Permian which also generated more than four times the volume of PW than the other three basins combined (NM OCD, 2016).

The quality of PW is one of the most important factors when considering whether it can be reused. The state maintains a database of nearly 10,000 PW quality measurements in NM (Cather et al., 2016). Although it contains information on total dissolved solids (TDS) and electrical conductivity (EC) for half of these samples, little data is available on other physical or chemical parameters that could be used in treatment technology and process selection.

Location of supply, production and disposal wells is important to PW management because it introduces logistical considerations, principally transportation of water for HF, EOR, and disposal in SWD wells. The ‘Near’ tool in Arc GIS 10.1 (ESRI, 2014) was used to select the nearest wells by type and calculate the distance between them. Median distances between producing wells and EOR or SWD injection wells are shown in Figure 4-4. Although well ownership or injection capacity may limit injection volumes for SWD and EOR wells, distance was the only factor considered in this analysis.
4.3.3 Energy Requirement Metrics

The metrics considered in this study were the energy required for fresh water pumping and transportation, and energy for PW transportation, treatment, and disposal. The number of HF wells peaked in 2013 but the average volume of water used for HF increased by nearly an order of magnitude from 2012 to 2016 as the industry increasingly switched to horizontal wells (NM OCD, 2016). In 2015, wells used 28,000 and 37,000 m$^3$ of water per well for HF in the San Juan and Permian Basins, respectively (NM OCD, 2016). Average county-wide HF water use was used to estimate fresh water demand for HF for a single well within that county in order to quantify potential extraction and transportation energy. Statewide, more than 97% of PW is disposed of in Class II injection wells (NM OCD, 2016); more than half is disposed of in SWD wells and the rest is used for EOR. The only treatment for water that is injected is usually filtration to remove suspended solids thus no energy use is assessed for treatment prior to PW
disposal. Energy for transportation is based on distance to the nearest well (fresh ground water, O&G, or SDW well). Additional information pertaining to the components of these metrics and total scenario energy (E) are described in Table C1.

**Scenario 1: Conventional Disposal**

Energy requirements for conventional PW management (EC) includes that needed to obtain fresh water for HF and for disposal of PW.

\[
E_C = P_F + T_{ff} + I_F + T_{ef} + T_{fPW} + I_{PW} + T_{ePW}
\] (4-1)

Where the energy required for pumping fresh ground water (P_F), truck transportation of fresh water to the well (T_{ff}), the return trip of the empty truck to the well (T_{ef}), truck idling during filling and emptying (I_F), transportation of PW to the SWD well (T_{fPW}), injection of the PW (I_{PW}), and the return trip of the empty truck (T_{ePW}).

**Scenario 2: Treatment and Reuse of PW for Hydraulic Fracturing**

Energy for treatment and reuse (ET&R) in HF applications assumes no fresh water will be used, and that PW is treated and transported to new wells for reuse:

\[
E_{T&R} = R_{PW} + T_{fPW} + I_{PW} + T_{ePW}
\] (4-2)

Where energy for treatment (R_{PW}), transportation of PW to a well for HF (T_{ePW}), idling and injection of the PW into the well (I_{PW}), and the return trip of the empty truck to the producing well (T_{ePW}). Although solids disposal is a component in PW treatment, it is a very small volume compared to liquid waste (Puder & Veil, 2006) that incurs negligible energy costs and was not included in this analysis.
Scenario 3: Enhanced Oil Recovery (EOR)

Approximately half of the PW in NM is used for EOR and the energy required (E_{EOR}) is that used for transportation and the energy consumed while tanker trucks are idling. This is represented by the equation:

\[ E_{EOR} = T_{fPW} + I_{PW} + T_{ePW} \]  \hspace{1cm} (4-3)

Where the energy for truck transportation of PW (T_{fPW}) to the EOR well, idling and injection of the PW (I_{PW}), and the return trip of the empty truck (T_{ePW}). Note that EOR is not widely used outside of the Permian.

4.3.3.1 Fresh Water Acquisition

Fresh water for O&G development in NM is primarily obtained through leases from agricultural enterprises (Brown, 2006) by temporary permit through the Office of the State Engineer (OSE). Wells in the OSE database (NM OSE, 2016) were filtered to include only wells identified for either agricultural or O&G use.\(^1\) The energy required for fresh water pumping is based on dynamic head (Tidwell et al., 2014), flow rate (annual diversion specified by NM OSE (NM OSE, 2016), and pump efficiency.

\[ P_F = \frac{q \rho g h}{\eta} \]  \hspace{1cm} (4-4)

---

\(^1\) Use Types Included: AGR (Agricultural use other than irrigation), IRR (Irrigation), OFM (Oil field maintenance), OIL (Oil production), SRO (Secondary Recovery of Oil), STK (Stock) (NM OSE, 2016)
Pumping energy ($P_F$) depends on flow rate ($q$) \([L^3/T]\), density of water ($\rho$) \([M/L^3]\), gravity ($g$) \([L/T^2]\), dynamic head \([L]\), and pump efficiency ($\eta$), assumed to be 65% (Tidwell et al., 2014). Annual energy requirements (kWh-th) are calculated assuming the pump operates year-round (8,760 hours). Because not all water from a given well would be used for HF, pumping energy (kWh-th/m\(^3\)) was applied only to the fraction of the well’s permitted volume withdrawn for HF.

4.3.3.2 Transportation

Transportation of water is a major component of O&G production in NM and elsewhere. This includes transportation of fresh water to HF operations, and transportation of PW to EOR and SWD wells and total distances vary by basin in NM (Figure 4-4). In addition, empty trucks must return to respective wells to pick up more water. We assumed standard tanker trucks (30.28 m\(^3\) capacity) (Xu et al., 2016) are used to haul both fresh and PW and corresponding diesel fuel efficiencies of 2.5 and 3.4 kilometers per liter (kpL) of fuel (Davis et al, 2015) were used for full and empty trucks respectively. Total diesel consumed was used to calculate energy required (1L diesel fuel = 10.6 kWh-th = 36,167 Btu) (US EIA, 2017).

On average, a single HF operation New Mexico requires more than one thousand water-hauling trips (Xu et al., 2016; NM OCD, 2016) (Hearne et al., 2015; NM OCD, 2016). Because HF operations occur over a short time (days to weeks) and water is needed on-site at the start of the process, traffic congestion is a consideration. We assumed that idling accounted for 5% of vehicle fuel consumption at a fuel consumption of 3.8 L/hr. (Davis et al., 2015; US EIA, 2017; US EPA, 2002).
4.3.3.3 Treatment

Produced water quality, especially its salinity (TDS), varies widely across basins and will determine its potential for reuse and the degree of treatment required for reuse and disposal options. Median TDS in the San Juan is less than 15,000 mg/L in contrast to the Permian where it exceeds 100,000 mg/L (Cather et al., 2016). Numerous studies have evaluated the energy and cost associated with desalination of PW (Sullivan Graham et al., 2015; Lebas et al., 2013; Fakhru’l-Razi et al., 2009; Iggunnu & Chen, 2012; Xu et al., 2016). However, minimally treated PW is widely used for EOR because wells are typically older and nearing the end of their productive life span. Advances in HF fluid chemistry and fresh water blending allows use of lower quality water for HF (Shaffer et al., 2013; Lebas et al., 2013) although additional treatment is required to reduce fouling. PW with an average TDS of 190,000 mg/L was reported in the Marcellus (Shaffer et al., 2013) and PW with TDS greater than 200,000 mg/L has been reused for HF in the Permian Basin (Scanlon et al, 2017; Lebas et al., 2013).

Treating PW for HF reuse generally involves removal of oil and suspended solids, and as well as softening to reduce scale forming potential (Sullivan Graham et al., 2015; Xu et al., 2016) which could lead to fouling. Removal of suspended solids through coagulation and flocculation can be accomplished by addition of chemicals such as alum or ferric chloride, or through electrocoagulation, which initiates coagulation by applying an electrical current. It is particularly effective in high salinity waters with high electrical conductivity (Lebas et al., 2013; Fakhru’l-Razi et al., 2009; Xu et al., 2016).
We compared conventional chemical coagulation with electrocoagulation to treat PW prior to reuse for HF. Between 0.68 and 0.72 kWh-th/m$^3$ for conventional water treatment (Racoviceanu et al., 2007) and 39-100 kWh-th/m$^3$ are required for electrocoagulation based on the electrical conductivity (EC) of the water (Xu et al., 2016). Most existing water quality data are for the Permian and San Juan Basins, with little or no data available for Raton Basin and Bravo Dome waters (Cather et al, 2016). Because of the limited data, inverse distance weighted (IDW) interpolation was used to estimate TDS and EC of PW for each TR (Meng et al., 2016; ESRI, 2014).

Solids removed by the treatment process require disposal, however, this volume of waste is very small. These solids are disposed of in lined evaporation ponds which do not require any solids removal until the pond is taken out of service and closed. Accordingly, the energy required for solid waste management is small and was not considered in this study.

4.3.3.4 Injection Disposal

The NM OCD database of Class II injection wells includes monthly volumes and injection pressures, as well as maximum allowable pressure which depends on well depth (NM OCD, 2016). We assumed that disposal will occur at the closest well and calculated well utilization (U) (Equation 4-5) and truck idling time (t) (Equation 4-6) (Digital H2O, 2015):

\[
U = \frac{\text{average reported pressure}}{\text{maximum permitted pressure}}
\]  

(4-5)
Because of the large depths and resulting hydrostatic pressure little pumping is required for injection wells. Therefore, injection energy was not considered in this analysis. However, as more water is injected into a well, the injection pressure and well utilization (U) both increase resulting in slower injection rates and longer injection times which translates to longer idling times for the tanker trucks.

4.4 Results

The goal of this analysis was to quantify energy requirements of alternative water sources and management strategies in the O&G industry, and to compare energy requirements for fresh water HF to those for PW reuse. Toward this goal, energy requirements per unit volume (kWh-th/m$^3$) of PW, based on alternative management strategies, are mapped at the TR level for the state of New Mexico in Figure 4-5(a-d). Warm colors indicate higher energy requirements. While the values mapped in all four figures are measures of energy requirements, they are influenced by production well density and the presence of disposal wells. The Raton and Bravo Dome basins together contain only a dozen SWD wells and no EOR wells, hence transportation for disposal or reuse are high.
Figure 4-5: Treatment energy requirements in kWh-th/m³ by TR boundary and basin for a) use of fresh water for hydraulic fracturing and disposal of PW (Scenario 1), b) reuse of PW in EOR wells (Scenario 3), and c) chemical and d) electrocoagulation treatment of PW and reuse for hydraulic fracturing (Scenarios 2a & b).
The data suggest that, regardless of management method, energy requirements for PW management in the Permian Basin are lowest for all scenarios (Figure 4-5a-d; Table 4-2). Use of fresh water for HF requires 2-6 times more energy than chemical treatment and reuse of PW for the same purpose (Table 4-2). Reuse of PW for EOR (Scenario 3, Figure 4-5b; Table 4-2) is lowest in the Permian, resulting from widespread EOR activities and short distances to EOR wells (1.3 km) (Figure 4-4). Because median distances to producing wells are small in all four basins, energy estimates for reuse (Scenario 2b), are influenced more by PW quality (Figure 4-5d). The energy required for chemical treatment is less than that for electrocoagulation, which reflects a tradeoff between chemical costs and energy costs (Figure 4-5c-d). When the least energy intensive treatment method is selected, treatment and reuse of PW requires less energy than use of fresh water which provides further incentive to limit demand for fresh water resources.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy Requirements (kWh-th/m³-yr)</th>
<th>Bravo Dome</th>
<th>Permian</th>
<th>Raton</th>
<th>San Juan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fresh Water Pumping</td>
<td>0.83</td>
<td>0.78</td>
<td>1.15</td>
<td>1.96</td>
</tr>
<tr>
<td></td>
<td>Fresh Water Transportation</td>
<td>1.34</td>
<td>0.55</td>
<td>3.97</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>Fresh Water Transportation - Idling†</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Transportation of produced water to SWD</td>
<td>3.63</td>
<td>0.48</td>
<td>1.06</td>
<td>2.57</td>
</tr>
<tr>
<td></td>
<td>Injection of produced water into SWD well†</td>
<td>0.24</td>
<td>0.22</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td><strong>Scenario 1 Total</strong></td>
<td><strong>6.26</strong></td>
<td><strong>2.26</strong></td>
<td><strong>6.64</strong></td>
<td><strong>6.13</strong></td>
</tr>
<tr>
<td>2</td>
<td>Treatment of produced water - Chemical</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Treatment of produced water - EC</td>
<td>5.03</td>
<td>5.17</td>
<td>1104.67</td>
<td>30.77</td>
</tr>
<tr>
<td></td>
<td>Transportation of produced water to O/G well</td>
<td>0.33</td>
<td>0.07</td>
<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Injection of produced water into O/G well†</td>
<td>0.24</td>
<td>0.22</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td><strong>Scenario 2a Total: Chemical Treatment</strong></td>
<td><strong>1.23</strong></td>
<td>0.96</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td><strong>Scenario 2b Total: EC Treatment</strong></td>
<td><strong>5.60</strong></td>
<td>5.47</td>
<td><strong>1105.04</strong></td>
<td><strong>31.14</strong></td>
</tr>
<tr>
<td>3</td>
<td>Transportation of produced water to EOR</td>
<td>70.48</td>
<td>0.37</td>
<td>46.20</td>
<td>14.16</td>
</tr>
<tr>
<td></td>
<td>Injection of produced water into EOR well†</td>
<td>1.24</td>
<td>1.55</td>
<td>1.31</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td><strong>Scenario 3 Total</strong></td>
<td><strong>71.72</strong></td>
<td><strong>1.92</strong></td>
<td><strong>47.51</strong></td>
<td><strong>16.49</strong></td>
</tr>
</tbody>
</table>

† Reflects the amount of fuel energy consumed while trucks are idling during filling and emptying of both fresh water (IF) and produced water (IPW).

Table 4-2: Comparison of annual energy requirements (kWh-th/m³-yr) for PW by basin and scenario.
Transportation is the greatest contributor to the energy footprint of each produced water management strategy state-wide, particularly when given a choice between treatment techniques (Table 4-2). When distances between producing wells (n=25) and SWDs are compared to measured road distances using ESRI (2014) orthographic imagery, actual travel distance is underestimated by more 26-54%. (Table C2). Although this translates to a range of less than 1 km in the Permian to more than 10 km in the Bravo Dome basins, these results indicate that reuse is even more favorable state wide as compared to conventional PW management.

Although transportation to SWD wells comprises much of the energy for conventional management, it is far exceeded by the energy for electrocoagulation treatment of PW in the San Juan and Raton Basins. This is due to the lower electrical conductivity of PW as compared to that in other basins (Table 4-2). In higher salinity waters of the Bravo Dome and Permian basins, treatment and reuse of PW is more favorable. Because electrochemical coagulation requires more energy in fresh water, an economic analysis may show that conventional chemical treatment is cheaper in the Raton Basin where water quality from CBM production has low TDS (Veil et al., 2004). This finding illustrates the need to consider both costs and end-use energy requirements when considering PW management.

This study characterizes the energy requirements for each step of produced water management for three scenarios in four energy producing basins in New Mexico. This approach allows for comparison both within and between PW management strategies as well as in the context of the state’s energy-water footprint. In 2015 PW was not widely
reused, and the majority of the nearly 28 Mm$^3$ of mostly fresh water was used for HF (NM OCD, 2016) in the Permian Basin where ground water levels have been declining due to over pumping for agriculture and public supply. Fresh water pumping for HF required roughly 11 GWh/yr. (34 GWh-th/yr.) of end-use energy for ground water pumping or between 1-2% of total state-wide energy use for ground water pumping energy (Tidwell et al., 2014). Comparing the total volume of water associated with O&G production and the water required to manage it in 2015 (Table C4), the energy to extract fresh ground water for hydraulic fracturing (34 GWh-th/yr.) exceeds the energy that would be required if the same volume of PW were treated chemically (19 GWh-th/yr.). In addition, the energy required to transport fresh water and dispose of PW (167 GWh-th/yr.) is far greater than that required to move treated PW (8 GWh-th/yr.) to a point of reuse. When disposal energy is considered, reuse is nearly ten times more energy efficient than conventional management. In the Permian Basin, where both the majority of PW is generated and HF occurs, both treatment and reuse strategies (Scenario 2a-b) are more energy efficient than conventional management (Scenario 1). Because transportation distances may be underestimated by as much as 50%, reuse may be even more energy efficient.

4.4.1 Analysis Limitations

There are several limitations of this study that will be addressed in future work. Transportation, treatment energy, supply and demand rely on assumptions that would
need to be refined should these characterizations be used determine management strategies for individual wells.

The first limitation is that transportation energy estimates are based on straight line rather than actual road distances because information on routes, topography, weight limits and other factors are not known. Transportation energy increases linearly with distance but sensitivity analysis revealed that distance is underestimated in all basins. A more detailed routing analysis would likely result in more energy required for the transportation for all scenarios. While pipeline conveyance would more closely adhere to straight line distance estimates, topography, land ownership, and climate would need to be considered in order to justify the up-front costs of laying pipe.

The second limitation is that treatment energy is estimated based on limited treatment methods and generalized energy requirements. Desalination of PW is not practiced in NM except at a very small scale because its very high salinity and complicated chemistry make it extremely difficult and costly to treat. We do not believe that desalination of PW is likely to occur on a large scale in the foreseeable future in NM. Chemical treatment energy is estimated using data from municipal wastewater treatment plants, which is likely less than mobile treatment systems due to economies of scale. In addition, delivery of treatment chemicals to remote locations will require more energy than to municipal treatment facilities.

Another limitation of this study is that it does not account for supply and demand dynamics that occur over time. The selection of the nearest well is not constrained by whether the fresh water withdrawn from multiple wells exceeds permitted availability.
Likewise, the capacity of SWD and EOR wells is not accounted for. In addition, supply and demand time scales are not easily matched: HF occurs over days or weeks and PW generation which occurs over many years. Competition for fresh water, disposal space, and PW available for reuse would likely result in longer travel distances to wells with available water or disposal space. These shifting dynamics will impact both reuse opportunities and energy requirements for produced water.

Increased production from UOG wells will affect PW management. Although the amount of water produced per unit of oil or gas is less for UOG wells than for conventional wells, much more water is needed to hydraulically fracture UOG wells. In basins like the Permian with multiple stacked shale plays, wells can be tightly spaced. As a result, demand for fresh water for HF will likely be more concentrated, but PW volumes will be less compared to that generated from the same number of conventional wells. Furthermore, declines in conventional production will impact PW volume as well as opportunities for reuse for EOR.

4.5 Discussion and Summary

The objective of this study was to quantify and compare the differences in energy requirements for three O&G water management strategies: fresh ground water withdrawn for HF with subsequent disposal of PW, and two PW treatment, reuse, and disposal scenarios. The energy components of these management scenarios included in this analysis were pumping of fresh water, transportation of fresh and PW, treatment of PW, and disposal or reuse of PW. Four O&G regions in NM were considered, each with
different production characteristics consisting of predominantly shale oil, shale gas, CO₂, and coal bed methane. The median energy requirement per unit water (kWh-th/m³) was mapped at an approximately township and range (TR) (90 km²) scale.

Key findings of this study are the identification and quantification of tradeoffs between alternate PW management strategies in New Mexico. First, transitioning from fresh water to reused PW for HF offers significant energy savings when transportation energy is included. While EOR is not a viable management technique in all basins, where conventional oil production is widespread, reused PW is a viable alternative to fresh water. Lastly, this study illustrates how each component of these management strategies contribute to their overall energy footprint, thus identifying areas where regional PW management energy can be reduced.

Produced volumes, management strategies, and energy requirements vary markedly throughout the country. This analysis provides a comparison of the energy requirements for the major water supply and PW management strategies. Additional factors such as change in production of O&G, competition for fresh water resources, equipment, and disposal well space also influence PW management strategies. This work sets the basis for future research which will allow for the incorporation of these factors.

The method for quantifying energy requirements for O&G water management strategies described here is applicable to other industries that depend on transportation, water supply, wastewater production, wastewater treatment and disposal, notably extractive industries such as mining.
The large energy requirements for water management by the O&G industry partly explains the shift away from freshwater use and SDW disposal towards reuse. In March of 2015, the NM OCD issued new regulations which allowed for increased storage of PW prior to treatment, reuse, and/or disposal. In the following five months, more than a dozen permits for new containment and recycling facilities were submitted (NM OCD, 2017) even though oil prices dropped by more than half during the same period. Currently, there are more than 50 permits (NM OCD, 2017), for both the San Juan and Permian basins NM OCD 2017. This experience shows that factors other than cost and energy requirements influence management decisions, but also demonstrate industry’s interest in reducing its impact on freshwater supplies by utilizing innovative treatment, reuse and disposal alternatives.
5 Conclusions

As both energy demands and the awareness of limited water resources grow, so does the need to understand the ways in which the two resources are interconnected. Modeling tools have the capability to evaluate these linkages and to provide mechanisms with which decision-making can be improved. The first step in improving knowledge about the connections between energy and water is to understand how economics and policy influenced historic development. In the case of uranium development, previous studies have not considered the dynamics between these important drivers. Next the magnitude and extent of energy resource recovery via mining requires retrospective analysis and uncertainty quantification in order to evaluate the potential for future impacts. Previous ground water studies have taken a deterministic approach to understanding the impacts of mine dewatering on regional ground water resources. These approaches are typically time and computationally intensive and are not well suited to evaluating uncertainties associated with multiple development scenarios. Last, O&G production will likely have a prominent role in the state of NM for years to come but so will the industry’s use and management of water. Evaluating the tradeoffs between the energy required to manage this water serves as the basis for considering alternative management strategies that may both be less energy intensive and more water conservative.
This research addresses knowledge gaps by developing modeling techniques whose results can aid in decision support. First, optimization techniques are utilized within an SD modeling framework in order to quantify how economics and policy influenced historic U mining operations in the state. Second, spatially based SD modeling was used to construct a calibrated model of the impacts of U mining on ground water which addresses the uncertainty of hydrogeologic parameters and thus the range of potential outcomes resulting from future U mining. Third, the geospatial relationships between O&G producing wells, ground water wells, disposal wells, and existing transportation infrastructure was used to evaluate the energy required to manage water associated with O&G production. These modeling efforts are unique in their approaches and provide a holistic view of the interdependencies of water and energy production.

5.1 Summary of Objectives

This research addressed the following three questions:

1) How did changes in economics and energy policy impact historic mine operations in the Grants Mining District, NM and how did mine size and additional commodities produced influence these responses?

2) What are the potential impacts of renewed underground uranium mining on ground water in the San Juan Basin region and how are these impacts influenced by uncertainty?

3) What are the energy requirements for alternative water management strategies associated with O&G production, including fresh water pumping, water conveyance,
produced water treatment and reuse, and water disposal and how do they vary regionally?

The previous three chapters of this dissertation address these questions in detail. Two have been published as stand-alone papers (Zemlick et al., 2017; Zemlick et al., 2018) and the third is in preparation for submittal to a peer-reviewed journal. A brief description of each chapter and the most significant results of the research are summarized below.

5.1.1 Chapter 2

The critical role played by NM in the nation’s development of nuclear capabilities by supplying more than half of the uranium produced domestically, has been evaluated by numerous sources over many decades. However, the ways in which national energy policies and economics influenced the operations of the mines that supplied this uranium have not been examined. In addition, vanadium (V) production, which was more important than uranium prior to the development of nuclear energy and weapons application, has often been overlooked.

This work considers the dynamics of these interconnected systems (energy policy, economics, uranium production) with optimization techniques in an SD model framework. Mines were grouped by size according to historic U production volumes and distinguished as single- (U) or multi-commodity (U+V) mines. Historic prices for U and V were adjusted for inflation and incorporated into the model on an annual timestep. The model was run at the same timestep over four distinct periods which represented shifts in
federal energy policies. The operation of a mine, specifically mine opening and closure, was evaluated in response to changes in price and policy. Optimization was used to determine how mines of different sizes responded to these changes by minimizing the difference between historic data pertaining to mine operations and modeled behavior.

The results demonstrate the utility of this method in evaluating the interrelationships between how mining operational decisions are made in response to larger economic and policy forces. As was expected, smaller mines were more responsive to changes in price (e.g. opening faster in a high-price environment and closing more rapidly in response to downturns in price) than were larger mines. Perhaps because of economies of scale, the opening of larger mines resulted in the closure of small mines. Medium and large mines that produced both U and V did not close as quickly in response to falling prices as did the same sized mines that produced only U. However, even in high-price environments, the lapse of federal incentives and subsidies encouraged the closure of all but large U mines. The results of this study illustrate the importance of federal policy in historic uranium mining operations. This provides not only historic insight but future perspective should U mining resume in the state. This is particularly significant at present when, even in a low-price U environment there is renewed discussion of domestic U mining because of the potential for federal restrictions on U imports.

5.1.2 Chapter 3

Previous studies have evaluated the impacts of U mining on ground water resources using less flexible deterministic modeling methods. While these approaches
can investigate ground water impacts at a finer spatial scale than can SD models, the latter approach has distinct advantages as a planning tool. First, SD modeling allows for evaluation of uncertainty in model parameters. Second, the incorporation of multiple scenarios and rapid results generation distinguish SD as advantageous where decision support is the goal.

This model integrated an analytical mine dewatering model within a spatially-based SD framework in order to evaluate the impacts of U mine dewatering on ground water in the San Juan Basin. The Morrison Formation, which contains the majority of U deposits in the basin was subdivided into ~36 mi² interconnected compartments based on existing township range boundaries. These compartments were incorporated into a SD model using Powersim software (Powersim, 2015) where each compartment represented water in storage in which the volume was determined by the compartment’s distinct hydrogeologic characteristics. Therefore, dewatering from a mine placed in any compartment would instigate flows between compartments. The model was calibrated using historic data and the sensitivity of hydrogeologic characteristics was evaluated to provide the basis for uncertainty analysis in future scenarios.

This effort explicitly considers uncertainty in hydrogeologic parameters and their impact on model results. Aquifer characteristics including transmissivity and storage coefficient are difficult to quantify in detail on a large scale because they require the analysis of production characteristics from wells. Therefore, spatial inference from existing wells provides the basis of knowledge for these characteristics. But because they are neither numerous nor evenly spaced, values associated with these parameters are
inherently uncertain. If the impacts of dewatering are evaluated without consideration of parameter uncertainty, the range of potential impacts cannot be fully understood. This effort used Monte Carlo simulation within Powersim to evaluate the range of uncertainty associated with each parameter on dewatering volume in all compartments where U was mined or U deposits are present.

Results indicate that the hydrologic impacts of future mining activity are both location dependent and subject to uncertainty. The volume of water removed from storage and drawdown vary not only by subdistrict but within subdistricts. This variation suggests that while some areas like the Nose Rock subdistrict have impacts that are both highly intense and uncertain, there is little variation within the compartments within the subdistrict. In contrast, the Ambrosia Lake subdistrict has the lowest average impacts as a function of ore mined, but it has the greatest range of uncertainty among compartments. These comparisons illustrate both the importance of uncertainty analysis in basin-scale evaluations such as this, but to site-specific studies as well. This tool has the capability of evaluating U development from a single-mine to multiple mine scales, which is pertinent to developers, communities, regulators, and water planners. For example, this model could be added to the Dynamic Statewide Water Budget (DSWB) which also operates using the same software (Roach et al., 2017), to understand how renewed uranium mining would impact other water users. Furthermore, these methods are transferable to other water resource investigations such as hard-rock mining and agriculture.
5.1.3 Chapter 4

The objective of Chapter 4 is to evaluate the energy requirements for alternative water management strategies in the O&G industry. Unlike U mining, O&G development is increasing in NM as is its reliance and impact upon regional water resources. This chapter is distinct from Chapters 2 and 3 in that it does not consider uranium nor does it use SD methods in its analysis. The latter is in part because of the large number of O&G wells and complexity of how one well or producer manages its water. Instead, this work evaluates the energy requirements of water management using a spatially-based approach where the proximity of producing wells, water wells, and disposal wells are used to evaluate the energy intensity of prospective management strategies.

The results of this work reveal that alternative water management techniques including reuse of produced water are less energy intensive than the use of fresh water for hydraulic fracturing and deep well disposal of produced water. While electrical treatment of produced water is much more energy intensive than chemical treatment in most basins, it is a viable option in the highly saline produced water of the Permian. Particularly since the Permian is projected to become one of the most productive unconventional oil basins in the US, if not the world, a suite of treatment options will improve the viability of alternative management strategies. Lastly, transportation is the most significant component of the energy footprint of water management in New Mexico and increased production will heighten competition for infrastructure and resources. Given the volume of water per well that must be managed, even a small increase in transportation distance will greatly improve the competitiveness of existing alternative water management
options. In turn, these strategies will enable industry and other water users to sustainably manage both critical resources: energy and water.

5.2 Future Work

The final chapter in this dissertation focused on energy requirements for produced water management strategies but how these choices are made are far more complex than this factor alone. Future research will focus on the numerous factors including economics, policy, infrastructure, and climate influence the dynamics between how operators, regulators, and water rights holders make water management decisions. The use of SD modeling in Chapters 2 and 3 provide the methodological basis for evaluation of these dynamics, in addition to the initial work conducted in Chapter 4. In an arid region like the Southwestern US where the ability to develop energy reserves economically is often at odds with traditional water users, this research will further understanding of how individual stakeholder choices interact within the water-energy nexus.
References


Meng, M., Chen, M., & Sanders, K. T. (2016). Evaluating the feasibility of using produced water from oil and natural gas production to address water scarcity in California’s Central Valley. Sustainability, 8(12), 1318. https://doi.org/10.3390/su8121318


NM SLO [New Mexico State Land Office]. (2016). Hypothetical Township Range Boundaries. (shapefile)


doi:10.1016/j.ijggc.2015.07.026


US Department of Agriculture [USDA], (2013) Draft environmental impact statement for Roca Honda Mine: Sections 9, 10 and 16, Township 13 North, Range 8 West, New Mexico Principal Meridian, Cibola National Forest, McKinley and Cibola Counties, New Mexico. MB-R3: 03-25. Albuquerque, N.M.


Appendices
Appendix A

This original publication can be found here:


Model and source files can be found at www.unm.edu/~czemlick/AppendixA
Appendix B

Model and source files can be downloaded at www.unm.edu/~czemlick/AppendixB
Appendix C

The original publication can be found here:


Model source data can be found at www.unm.edu~czemlick/AppendixC
<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable Description</th>
<th>Scenario</th>
<th>Equation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pf</td>
<td>Fresh groundwater pumping</td>
<td>1</td>
<td>$P_f = \frac{q \rho gh}{\eta}$</td>
<td>Tidwell et al., 2014; NM OSE, 2016; ESRI, 2016</td>
</tr>
<tr>
<td>Tf</td>
<td>Transportation of fresh water trucks (full) to producing well</td>
<td>1</td>
<td>$T_f = (D \times FE) \times DCF$</td>
<td>Davis et al., 2015 (reflects heavy truck fuel efficiency modified from Table 5.4); NM OCD, 2016; ESRI, 2016</td>
</tr>
<tr>
<td>Tef</td>
<td>Transportation of fresh water trucks (empty) to producing well</td>
<td>1</td>
<td>$T_{ef} = (D \div FE) \times DCF$</td>
<td>Davis et al., 2015 (reflects medium truck fuel efficiency modified from Table 5.4); NM OCD, 2016; ESRI, 2016</td>
</tr>
<tr>
<td>TfPW</td>
<td>Transportation of produced water by truck (full) to injection well</td>
<td>1, 2, 3</td>
<td>$T_{fPW} = (D \div FE) \times DCF$</td>
<td>Davis et al., 2015 (reflects heavy truck fuel efficiency modified from Table 5.4); NM OCD, 2016; ESRI, 2016</td>
</tr>
<tr>
<td>TefPW</td>
<td>Transportation energy required to return empty truck from Class II well to producing well</td>
<td>1, 2, 3</td>
<td>$T_{efPW} = (D \div FE) \times DCF$</td>
<td>Davis et al., 2015 (reflects medium truck fuel efficiency modified from Table 5.4); NM OCD, 2016; ESRI, 2016</td>
</tr>
<tr>
<td>Ipw</td>
<td>Injection of produced water into Class II well</td>
<td>1, 2</td>
<td>$I_{pw} = \text{number of trucks} \times \text{injection time (t)} \times ICF \times DCF$</td>
<td>Digital H2O, 2015; NM OCD, 2016; EPA, 2002</td>
</tr>
<tr>
<td>Rpw</td>
<td>Energy required to treat produced water with electrocoagulation</td>
<td>3</td>
<td>$R_{pw} = \frac{PW \text{ volume} \times (TE + PP)}{TE} = 5726.5 \times EC^{-1.062}$</td>
<td>Xu et al., 2016; Cather et al., 2016</td>
</tr>
</tbody>
</table>

Table C1: Energy Metrics Equations
Table C2: Results of sensitivity analysis for 25 wells (n=25) in each basin. Estimates are median values of straight line distances compared to measured distances using orthographic imagery.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Straight line distance (km)</th>
<th>Measured distance (km)</th>
<th>Percent difference by basin (%)</th>
<th>Length difference by basin (km)</th>
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<tbody>
<tr>
<td>Permian</td>
<td>1.44</td>
<td>2.35</td>
<td>-48%</td>
<td>-0.78</td>
</tr>
<tr>
<td>San Juan</td>
<td>5.87</td>
<td>9.17</td>
<td>-38%</td>
<td>-3.30</td>
</tr>
<tr>
<td>Raton</td>
<td>1.96</td>
<td>2.75</td>
<td>-26%</td>
<td>-0.36</td>
</tr>
<tr>
<td>Bravo Dome</td>
<td>22.48</td>
<td>33.72</td>
<td>-54%</td>
<td>-11.36</td>
</tr>
<tr>
<td>Basin</td>
<td>Permian</td>
<td>Raton</td>
<td>Bravo Dome</td>
<td>San Juan</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------</td>
<td>-------</td>
<td>------------</td>
<td>----------</td>
</tr>
<tr>
<td><strong>MANAGED WATER (Mm(^3))</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Produced water</td>
<td>74.6</td>
<td>5.2</td>
<td>1.0</td>
<td>10.2</td>
</tr>
<tr>
<td>Injected water - SWD</td>
<td>55.8</td>
<td>4.5</td>
<td>0.9</td>
<td>12.6</td>
</tr>
<tr>
<td>Injected water - EOR</td>
<td>57.9</td>
<td>0.9</td>
<td>0.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Injected Water - HF</td>
<td>21.8</td>
<td>0.0</td>
<td>0.5</td>
<td>5.7</td>
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<tr>
<td><strong>ENERGY METRICS (GWh-th)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh Water Pumping</td>
<td>23.1</td>
<td>0.0</td>
<td>1.1</td>
<td>9.7</td>
</tr>
<tr>
<td>Fresh Water Transportation</td>
<td>4.9</td>
<td>0.0</td>
<td>0.1</td>
<td>1.3</td>
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<tr>
<td>Fresh Water Transportation - Idling†</td>
<td>18.0</td>
<td>0.0</td>
<td>0.1</td>
<td>2.5</td>
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<tr>
<td>Transportation of produced water to SWD</td>
<td>23.6</td>
<td>3.1</td>
<td>0.6</td>
<td>7.8</td>
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<td>Injection of produced water into SWD well†</td>
<td>76.0</td>
<td>8.7</td>
<td>0.9</td>
<td>19.7</td>
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<td><strong>Scenario 1 Total</strong></td>
<td><strong>145.5</strong></td>
<td><strong>11.8</strong></td>
<td><strong>2.9</strong></td>
<td><strong>40.9</strong></td>
</tr>
<tr>
<td>Treatment of produced water - Chemical</td>
<td>14.6</td>
<td>0.0</td>
<td>0.3</td>
<td>3.8</td>
</tr>
<tr>
<td>Treatment of produced water - EC</td>
<td>113.0</td>
<td>0.1</td>
<td>2.5</td>
<td>116.7</td>
</tr>
<tr>
<td>Transportation of produced water to O/G well</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Injection of produced water into O/G well†</td>
<td>5.0</td>
<td>0.0</td>
<td>0.1</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Scenario 2a Total: Chemical Treatment</strong></td>
<td><strong>21.4</strong></td>
<td><strong>0.0</strong></td>
<td><strong>0.5</strong></td>
<td><strong>5.5</strong></td>
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<tr>
<td><strong>Scenario 2b Total: EC Treatment</strong></td>
<td><strong>119.8</strong></td>
<td><strong>0.1</strong></td>
<td><strong>2.7</strong></td>
<td><strong>118.5</strong></td>
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<tr>
<td>Transportation of produced water to EOR</td>
<td>7.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Injection of produced water into EOR well†</td>
<td>92.0</td>
<td>0.6</td>
<td>0.5</td>
<td>1.3</td>
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<td><strong>Scenario 3 Total</strong></td>
<td><strong>99.0</strong></td>
<td><strong>0.7</strong></td>
<td><strong>0.6</strong></td>
<td><strong>1.7</strong></td>
</tr>
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</table>

**Table C3:** Managed water in 2015 in NM and associated total energy requirements based on alternative strategies including conventional fresh water use and disposal (Scenario 1), treatment and reuse of PW for HF (Scenarios 2a-b), and reuse of PW for EOR (Scenario 3).