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# Water Resources Impacts of Uranium Mining in the San Juan Basin, New Mexico

by

**Kent Steinhaus**

B.S., Civil Engineering, University of New Mexico, 2011

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

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# Dedication

*I dedicate this thesis to my parents Kurt and Jo Beth Steinhaus who have supported and encouraged my education for my entire life. For that I am eternally grateful.*

*My girlfriend Katy Belvin who has put up with my endless rants and random thoughts and supported me through all of it, thank you so much.*

*Wes Greenwood who has also encouraged me and supported me with my studies, my research would not be what it is without his technical support and overall input, thank you.*

*Lets not forget and all my fellow researchers, students and others who helped me along my process of writing this document, thank you.*

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I would also like to acknowledge my colleague Wes Greenwood who has also encouraged me and supported me with my studies. My research would not be what it is without his technical support and overall input.

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## Abstract

The objective of this research was to improve understanding of the groundwater impacts of uranium mining in the San Juan Basin by estimating the volumetric amount of water removed from the underlying Westwater Canyon member aquifer. This was achieved by modeling a conceptual mine that is based on the physical characteristics present near the proposed Roca Honda Mine near Grants, New Mexico. An analysis of the uncertainty of the physical, situational, and model parameters and their associated sensitivities was conducted so that an understanding of potential groundwater withdrawals for uranium mining could be gathered. Uranium mining in the San Juan Basin, New Mexico, has ranged from being active between the years of 1950 and 1980, to currently non-existent due to volatility in the price of uranium. Previous mining in the area has caused detrimental effects to water resources in the area and future mining activity in the area could have a similar effect. Although it is well known that mining has and will affect water resources in the San Juan Basin, there is little knowledge on this subject available. The key findings through

the analysis and understanding of the uncertainty and sensitivity of these aquifer properties were the probability and the range of the volumes and flow rates that would be extracted for the conceptual mine. This analysis allows for better decisions and research to be made about future mining activity.

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# Chapter 1

# Introduction

- General description of the problem

The goal of this research was to improve the understanding of the potential groundwater resource impacts of uranium mining in the Grants Mineral Belt by accomplishing the following objectives. First, model a conceptual mine based on the physical characteristics present at the proposed Roca Honda Mine in the Grants Mineral Belt, Ambrosia Lake District, by applying the Theis equation. The proposed mine is located within portions of Sections 9, 10, and 16, Township 13 North, Range 8 West, New Mexico Principal Meridian (figure 1.4). These sections are located in McKinley County, New Mexico, approximately 3 miles northwest of San Mateo and 22 miles northeast of Grants, New Mexico [2]. The Theis equation allows for an aquifer to be simulated so that calculations about the aquifer and well drawdown can be conducted. Second, quantify the sensitivity of the model parameters within the area so that future work can be focused towards the most sensitive parameters and that more accurate quantification of future water resource impacts can be calculated. Third, explore the uncertainty that is involved in modeling the proposed Roca Honda Mine site and provide quantified results of groundwater extraction within the ten to

ninety percent probabilities of a cumulative distribution so that better decisions can be made concerning the existing water resource.

There have been previous attempts at quantifying impacts of uranium mining in the San Juan Basin [1], but there is a noted high degree of uncertainty that is involved with these calculations. The general uncertainty involved with this research is both epistemic and aleatory as there is both random variability as well as a lack of knowledge and understanding [3]. Uncertainty will be discussed in detail later on in this document. Calculations about potential water resource impacts have been made at the Roca Honda Mine to fulfill National Pollutant Discharge Elimination System (NPDES) requirements by Roca Honda Resources Inc. in conjunction with the United States Forest Service [2]. To study the groundwater impacts of uranium mining, a model was constructed that simulates how much water a conceptual uranium mine will withdraw from the underlying geologic layer that contains uranium. The model will be used to estimate the amount of water that must be removed from underlying aquifers to support mining.

The calculations of groundwater impacts in this study were done using the Theis equation [4]. The Theis equation relates a discharge, aquifer drawdown, and the physical properties of the aquifer that affect flow in a transient groundwater system. It is used in this research to calculate the flow out of a dewatering well for a conventional mine to operate in the San Juan Basin. This equation was used because it is a simple approximation and can be rapidly applied to the situation where as a more complex approach would be much more difficult to manipulate. It can also be noted that the Theis equation is applied very often to approximate ground water flows in real situations and is a proven method of approximation [5–7].

The San Juan Basin of New Mexico has yielded the largest amount of uranium ore mined in the United States and accounts for over 51 percent of the total uranium mined in the United States since the 1940s [8]. Currently, Wyoming is the largest

producer of uranium in the United States [9], but historically the San Juan Basin generated more than 154 million kilograms (kg) of uranium from the Grants deposits in New Mexico between 1950 and 2002, and more than 136 million kg of uranium remains as unmined resources [10]. Although it is speculated that uranium mining has affected the water quality and the health of the general population in the area [11], there has been little research focused on the current and future impacts of uranium mining on water resources in the region. Employment of mining in the state began in as early as 1950 with a mine operated by the Kerr McGee Oil Company [12], reaching its peak in 1978, then rapidly declining to almost zero in the 1980s due to the rapid decline in price for uranium. Currently, coal, copper and potash make up the majority (80%) of the mining activity in the state [13].

The Grants district, also referred as the Grants Mineral Belt (Figure 1.1) is located within the San Juan Basin and is divided up into seven sub-mining districts. These districts are Ambrosia Lake, Church Rock, Crownpoint, Laguna, Marquez, Nose Rock, and Smith Lake. There are approximately 115 identified bodies of uranium resource in the San Juan Basin [10]. The mine site studied in this research is located in the Ambrosia Lake District of the San Juan Basin in the Grants Mineral Belt. The Ambrosia Lake district is historically the most active district and currently has the most momentum for renewed uranium-mining activity.

The Roca Honda Mine site was used to quantify the effects of uranium mining on underground resources in the San Juan Basin because it has a record of aquifer properties, historical pumping rates, and it is a proposed site for future uranium mining in New Mexico. Calculations were conducted using the Theis equation (e.g. [4]) and was compared to a MODFLOW 2005 model developed by Intera [2]. Results were validated from historical pumping records via the New Mexico Bureau of Mines and Minerals Resources [1]. These calculations were then conducted via a MATLAB program to allow evaluation of uncertainty and sensitivity to input parameters.
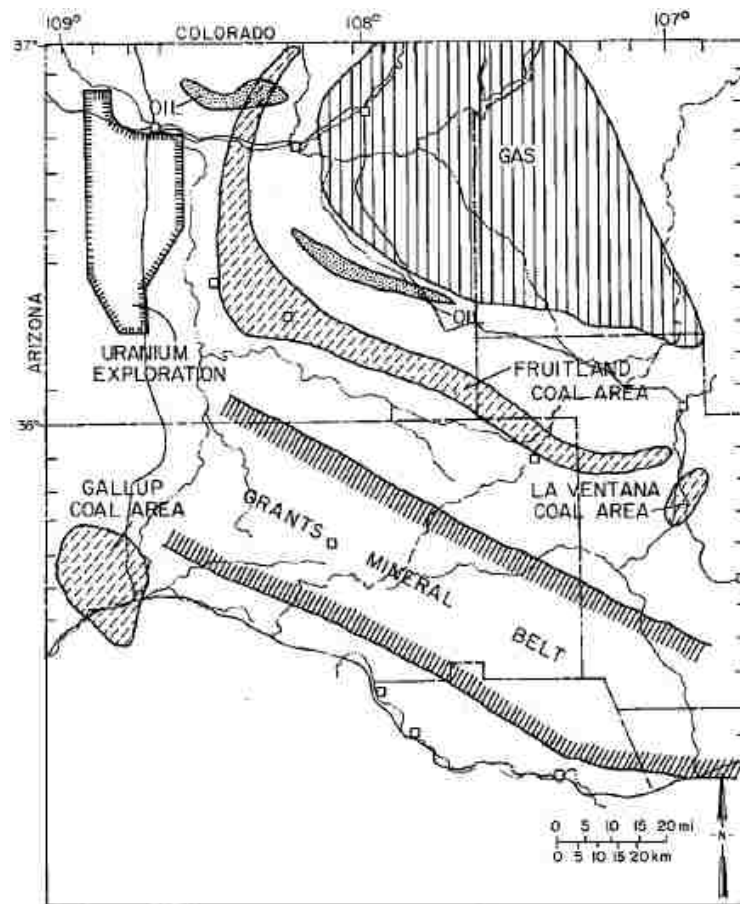
Figure 1.1: Energy Resource Regions in the San Juan Basin [1]

## 1.1 Current State of Knowledge

Water resources impacts from uranium mining in the San Juan Basin are poorly understood. The information that is generally relied on regarding the hydrogeologic properties of the San Juan Basin originate from a groundwater model developed by Kernodle [14] and aquifer properties defined by [1] in a study by the New Mexico Mines and Minerals Bureau. Interested mining companies hold information about aquifers in the San Juan Basin, but this information is not readily available to the public. Recent attempts at defining the aquifer properties have been focused on

the Westwater Canyon Member of the Morrison Formation (described below). Data has been collected by Roca Honda Mineral Resources Inc. [2] by constructing a test well and conducting drawdown/recovery tests [15]. This data along with information from [1, 14] was used by Intera to create a three-dimensional (3D) groundwater model using MODFLOW 2005. This model was created to study the potential groundwater impacts of the proposed Roca Honda mine in accordance of meeting environmental impact study (EIS) requirements.

## 1.2   Geology, Hydrology and Resources of The San Juan Basin (Site Description)

The San Juan Basin is located predominately in New Mexico, but the extent of the basin extends into Colorado, Arizona, and a small part of Utah (Figure 1.3). The area of land that it makes up is 54,390 square kilometers. Formed during the Laramide Orogeny, the San Juan basin consists of layers of sedimentary rock that date from the Cambrian to Tertiary age [14]. The geology of the San Juan Basin has been studied mainly from outcroppings and well drilling logs [1]. The general geologic stratigraphy can be seen in Figures 1.3 & 1.2. There are approximately 17 hydrostratigraphic units that range in elevation from approximately 3,048 m above sea level to 3,048 m below sea level Figure 1.2.

The conceptual mine that is studied in this report is located near the proposed Roca Honda Mine. It is located near the town of Grants (NM), and North West of the Mt. Taylor Mountains Figure 2.1. The permit area encompasses 7.8 km$^2$ within the San Juan Basin. It is under the ownership and maintenance of the Cibola National Forest.
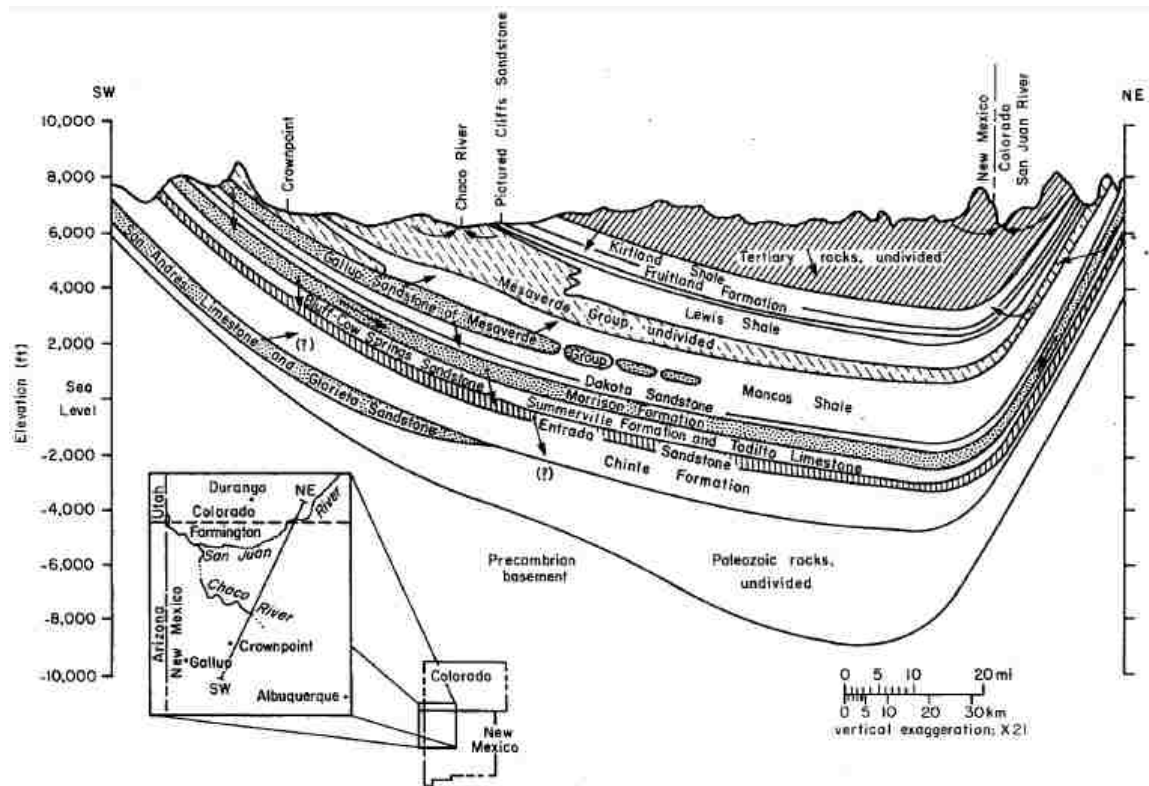
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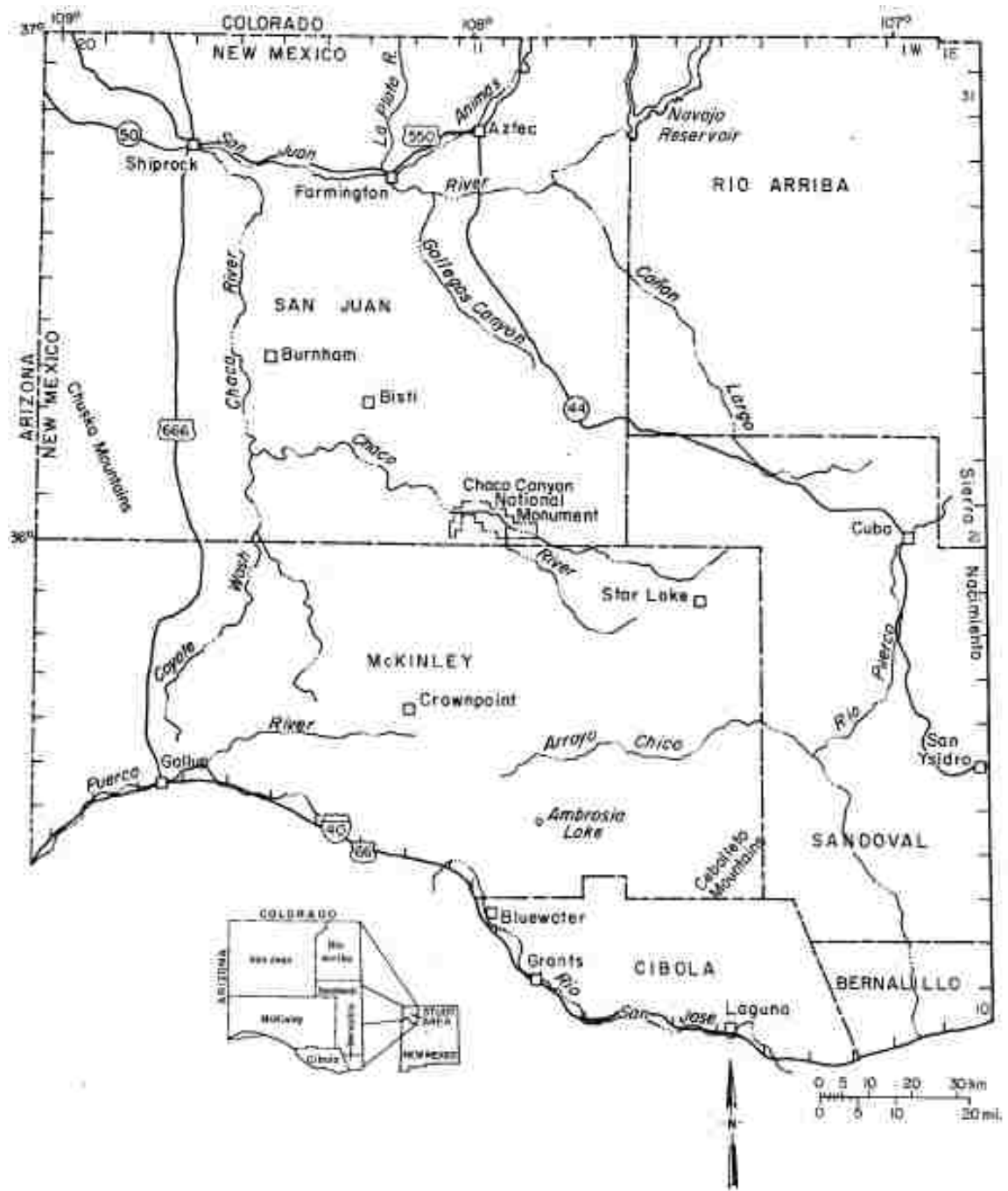
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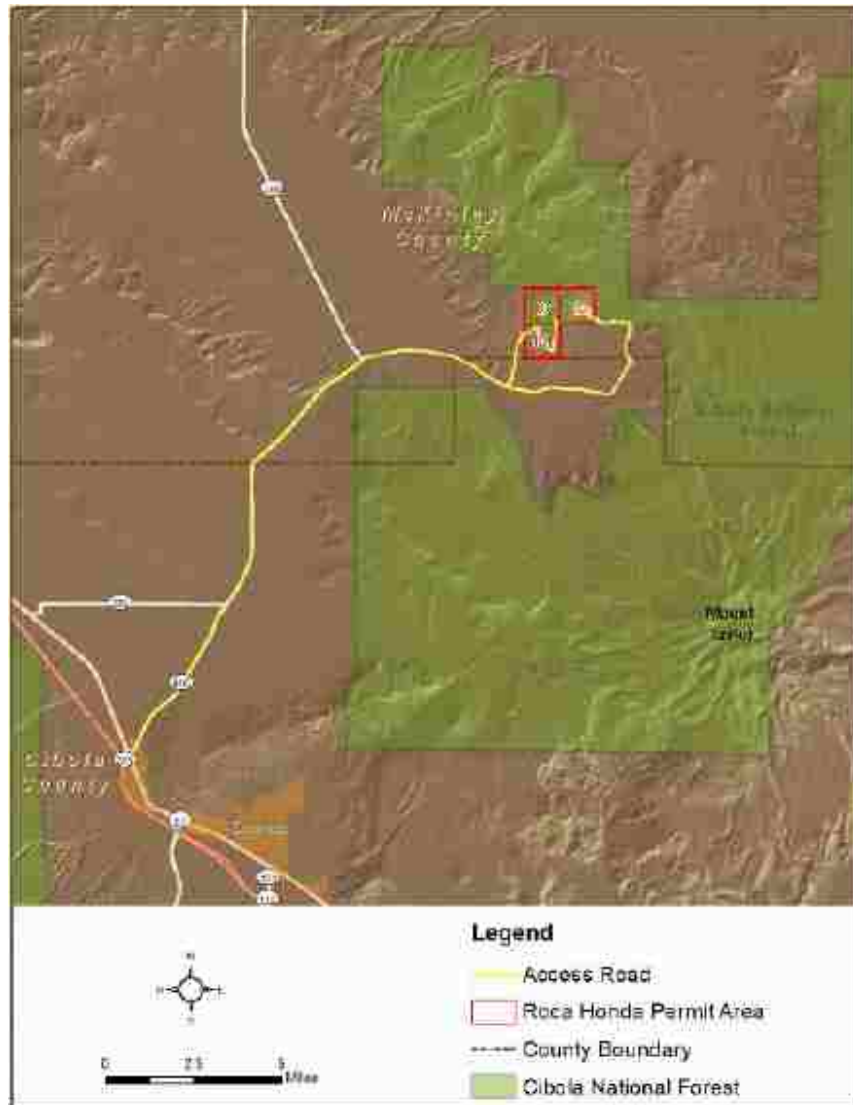
Figure 1.4: Roca Honda Mine Permit Area (U.S. Forest Service, 2013)

The layer of most interest to this research is the Morrison formation. The Morrison formation is a series of 5 layers, generally consisting of alternating sandstone aquifers and silt and shale aquitards [1]. The layers of the Morrison in the order highest elevation to lowest elevation are the Jackpile formation (sandstone, aquifer), Brushy Basin member (shale, aquitard), Westwater Canyon member (sandstone, aquifer), Recapture member (shale, aquifer), and Salt Wash member (sandstone,

aquifer). The Westwater Canyon member of the Morrison Formation is the most important geologic layer due to its mineral composition that contains the highest concentrations of uranium. See Figure 2.1 for a simple schematic of where this member is located within the Morrison formation. It mainly consists of Sandstone that is intermingled with some shale and clay stone, mainly in the northeastern portion of the San Juan Basin. However, near the Grants Mineral belt the Westwater Canyon member is known to consist entirely of sandstone.

The hydrology and hydraulic properties of the San Juan Basin's groundwater reservoirs are poorly understood although there have been a few studies done on this regional area hydraulic properties [1, 14]. The systems groundwater resources can be assumed to be in steady state equilibrium [14] since the inflows of the San Juan Basin's groundwater system have been calculated to approximately equal the outflows [14]. The main source of recharge to the aquifers is through surface water infiltration through faults and outcroppings of precipitation that is not consumed through evaporation, sublimation and transpiration [14]. The main sources of outflows are the aquifers discharging to streams and arroyos, most of which have dry beds year-round [2]. Due to these reasons it is estimated that the water budget for the groundwater resources in the San Juan Basin is $Q_{in} - Q_{out} = 0$ [2].

The hydraulic properties of the Westwater Canyon member are of much interest because it contains the highest concentration of uranium and it will need to be dewatered to extract the uranium resource via under ground mining. These hydraulic properties are known to be highly variable throughout the extent of the San Juan Basin [1]. The Westwater Canyon member has been most widely utilized for uranium mining. A majority of the wells that have been constructed down to the Morrison formation are used for the sole purpose of dewatering uranium-mine sites, though some wells in the area are used for domestic and agricultural use. The current knowledge of the hydraulic properties of this member within the San Juan Basin

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were determined through a series of drawdown and recovery tests performed on 31 wells in the study area [1]. These hydraulic properties can be found in Table 1 and are explained later in the methods section. Another study available was done in 2011 and described some limited aquifer properties of the Westwater Canyon member at the proposed Roca Honda Mine site through a similar drawdown and recovery test previously done by [1, 15]. These parameters are described in the methods section, Table 2.1.

## 1.3   History of Mining in the Grants district of the San Juan Basin

It was not until the mid 1940s in the United States that uranium was a highly valuable commodity. This was mainly due to the development of the atomic bomb in Los Alamos, New Mexico. It was originally believed that uranium ore would have had to be imported from far away locations such as Africa or Canada [16] but uranium ore was discovered near Grants and the Haystack Mountain in 1950 [16]. The Ambrosia Lake region was soon to follow in 1955 being only 25 miles northwest of Grants. This region, as we know it today, has been the largest producing region of uranium in U.S. history, containing much of the highest-grade uranium ever mined in the United States.

Uranium production in the San Juan Basin was previously the largest producer of uranium in the United States. New Mexico alone in 1978 produced 18.3 million kg of uranium, making up 47 percent of the total uranium mined in the United States during that time. Production began to decline in 1979 due to a decline in uranium prices by up to 25% [16]. The lowered uranium prices caused a major decline in mining activity and by 1987, after the tragedy in Chernobyl, most uranium mining

had ceased in the San Juan Basin.

In the San Juan Basin there have been over 200 documented mines in the 7 sub-districts (McLemore, 2013). Over the 52 years of production of uranium, there have been over 154 million kg of uranium documented originating from the Grants District and over 136 million kg remain unmined [10]. These uranium deposits have a range of concentration ranging from the highest grade (calculated in $\frac{kg\,U_3O^8}{kg\,Soil}$) 0.5% near Mt. Taylor to lower than 0.1% in many other parts of the district. The majority of uranium resources have been mined from the Morrison formation, specifically $1.5*10^8$ kg of uranium has been mined from it [10]. Only 212,281 kg of uranium has been mined from all other sandstone formations in the Grants District [10].

Presently, uranium prices are still impacted by the disaster at Fukushima, Japan in 2011 [17]. Uranium prices were on the rise, projected to reach \$63.50/kg, but shortly after the nuclear plant failure prices of uranium dropped to around \$18.14/kg. The volatility of uranium prices has been the most probable reason for no renewed uranium mining activity in the San Juan Basin. There has been some interest in renewing mining activity in New Mexico. There are currently seven different companies in the process of assessing and acquiring permits to begin mining. The companies interested in beginning mining include Strathmore Resources US Ltd. (http://www.strathmoreminerals.com ), Uranium Resources, Inc. (URI; http://www.uraniumresources.com/), Rio Grande Resources (http://www.ga.com/nuclear-fuel/rio-grande-resources), Laramide Resources Ltd. (http://www.laramide.com/), Uranium Energy Corp. (http://www.uraniumenergy.com/), Trans America Industries Ltd., and Aus American Mining.

Strathmore Resources, although having been recently purchased by Energy Fuels Inc., is the closest to beginning mining activity and has almost completed the permitting process for a mine in the Ambrosia Lake District near Mt. Taylor. Since the recent acquisition of the company from Strathmore, Energy Fuels is awaiting

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approval from the state of New Mexico and is hoping to commence mining activity in 2016. This area has been identified to contain a large reserve of uranium (7.62 million kg of uranium) at a relatively high grade (0.404%).

# Chapter 2

# Research Methods

## 2.1  Conceptual Model Framework

An analytical model was constructed that applies the Theis equation's Cooper Jacob straight-line approximation [4] to quantify the flow rate and volume of water extracted from a single mine. The conceptual mine was constructed to allow the extraction of ore from the Westwater Canyon formation near the proposed Roca Honda Mine site by dewatering the aquifer. The Westwater Canyon formation aquifer is a known confined aquifer that exists between two aquitards, i.e., the Brushy Basin Member and the Recapture Member. These aquitards are defined to not contribute any water to the Westwater Canyon formation. To extract the ore, a shaft must be drilled and the aquifer must be initially dewatered to the radius of the shaft to commence mining. This initial time to sink the shaft and dewater the aquifer is dictated by numerous factors, and for this model it was assumed to be 2 years so that it can be compared to the conditions of the proposed Roca Honda Mine. To extract the ore, horizontal shafts (known as stopes) are blasted, scraped out, and supported by pillars along the horizontal axis that contains the ore body. The radius of the mine

is expected to expand at a constant rate for a time period of ten years, and the mine must be dewatered to the effective radius as it is expanding over time. Although the time period for the conceptual mine can contribute to the scenario uncertainty, it was selected to remain constant to simulate a comparable situation to the proposed Roca Honda mine.

These physical and situational parameters were then incorporated into the Theis equation so that the flow rates from the conceptual mine could be quantified. The output of the conceptual mine calculations is the discharge required to maintain the level of drawdown required by the effective radius as it expands. A simple schematic diagram of the simulated mine site and the variables defined can be see in Figure 2.1.
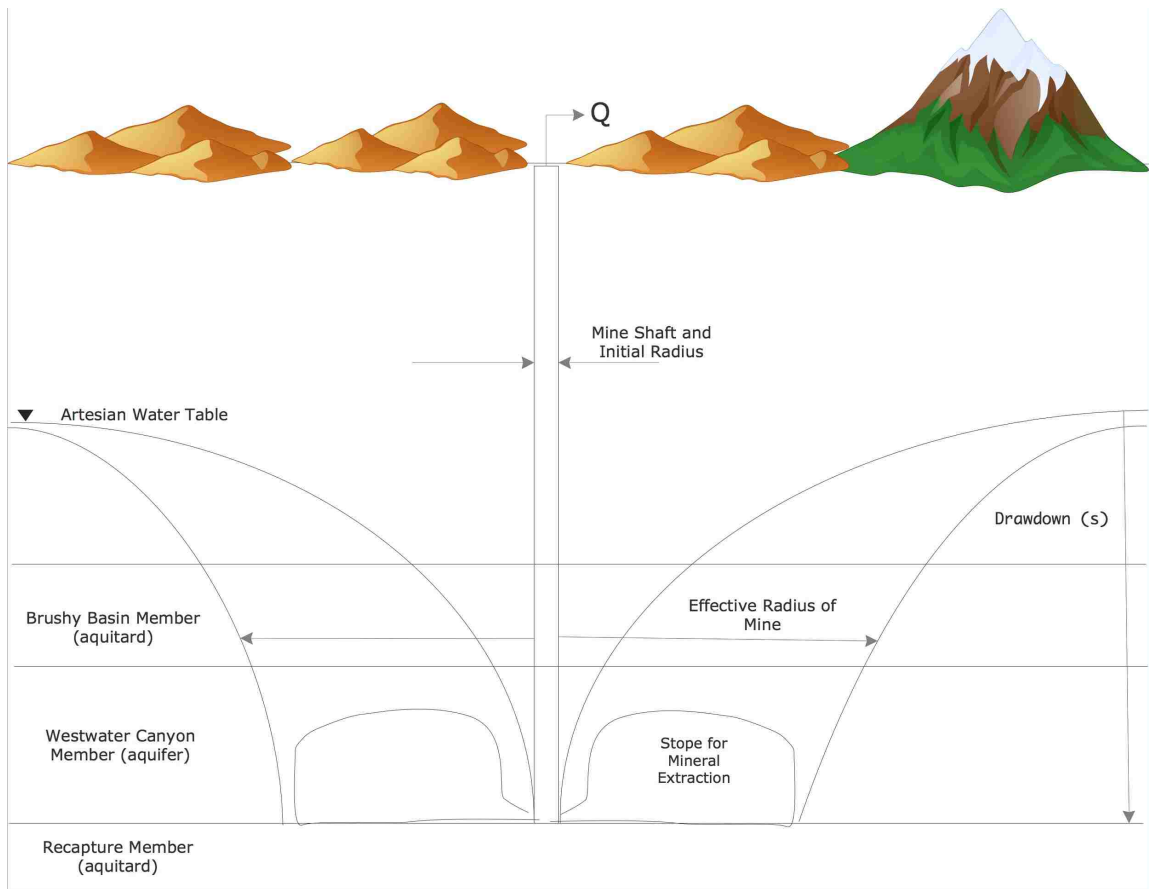


Figure 2.1: Diagram of Conceptual Uranium Mine Dewatering Well

The application of the Theis equation to quantify the discharge (Q) and volumetric water withdrawals were employed through MATLAB. The code associated with these MATLAB calculations can be reviewed in Appendix A and B.

## 2.2    Groundwater Calculations

To approximate the effects of a conceptual mine near the proposed Roca Honda Mine, the flow rate required to dewater the Westwater Canyon Member for mining activity was estimated using the Theis Equation. This method estimates the pumping rates and ultimately volume of water required for mining activity in the Morrison formation. For the application of the Theis equation, the following assumptions were made about the conceptual mine and aquifer modeled in this research  [4].

- The aquifer is homogeneous, isotropic, of uniform thickness, and of infinite area extent.

- Before pumping the piezometric surface is horizontal.

- The well is pumped at a constant discharge rate.

- The pumped well penetrates the entire aquifer, and flow is everywhere horizontal within the aquifer to the well.

- The well diameter is infinitesimal so that storage within the well can be neglected.

- Water removed from storage is discharged instantaneously with decline of head.

In reality these assumptions are rarely met although it is accepted by the scientific community that while all assumptions are not met, the Theis equation can give a

good approximation of ground water calculations [5–7]. The Theis equation has been adapted by other methods of analysis such as the Cooper-Jacob approximation and Chow Method so that simpler approximations can be readily made in the field [4].

The Theis equation(equation 2.1) relates a discharge, aquifer drawdown, and the physical properties of the aquifer that affect flow in a transient groundwater system.

$$s = \frac{Q}{4\pi T} W(u) \tag{2.1}$$

Where, $Q$ is the discharge ($L^3/t$), $T$ is the transmissivity ($L^2/t$), $pi$ (unitless) is equal to 3.14, and $W(u)$ is the well function of $u$ (L), $s$ is equal to the drawdown (L). $u$ (Eq. 2.2) is referred to as the exponential integral and is determined as follows:

$$u = \frac{r^2 S}{4Tt} \tag{2.2}$$

Where $r$ is the radius of the well (L), $S$ is the Storage Coefficient (unitless), and $t$ is the time since the beginning of pumping. The well function is an exponential integral as defined in equation 2.3 [4].

$$W(u) = \int_u^\infty \frac{e^{-u}}{u} du = -.5772 - ln(u) + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!}... \tag{2.3}$$

The equation used for calculating pumping rates is the Cooper-Jacob straight-line solution of the Theis equation (Eq. 2.4). Where r is the radius of the mine (L) and s is the drawdown (L).

$$Q = \frac{4\pi T s}{ln\left(\frac{2.25Tt}{r^2 S}\right)} \tag{2.4}$$

$$W(u) = ln\left(\frac{2.25Tt}{r^2S}\right) \tag{2.5}$$

For the Cooper-Jacob approximation, the well function W(u) from Equation 2.1 is replaced in Equation 2.4 (see Equation 2.5) and is allowed so long as u is less than or equal to 0.01 [4]. For small values of r and large values of t, u is small therefore making the values after the 2nd term in Equation 2.3 negligible. This is why the Cooper-Jacob approximation is allowed. The Cooper-Jacob approximation results in a straight-line relationship between t and s.

For all calculations of flow-rate using equation 2.4 the initial radius of the mine (r) is 3.1 m and will increase with time as defined in Equation 2.6. To simulate the conditions of a conceptual uranium mine, the radius of the mine will expand at a constant rate associated with the time vector t. The expansion rate is defined to have units of (L/t). The drawdown depth (s) for the conceptual mine is defined as the depth of water that must be removed measured as the top of the piezometeric head above the aquifer to the bottom of the aquifer at the edge of the mine radius, see Equation 2.7. This is to simulate the condition that a dry mine well must be maintained so that uranium ore can be extracted from the mine.

$$r = 3.1 + (expansion\,rate) * t \tag{2.6}$$

$$s = (depth\,of\,piezometetric\,head\,above\,aquifer) + (aquifer\,thickness) \tag{2.7}$$

The Theis Cooper-Jacob approximation (Eq. 2.4) was used for all of the calculations of discharge from the conceptual mine in this research. To ensure that these calculations did not have large errors, the exponential integral u was calculated at each step to ensure it was less than 0.01.

## 2.2.1   Model Parameters

The parameters used for the analysis of the conceptual mine studied in this research consist of both physical and situational parameters (T, S, t, s, and r) of Equation 2.4. How these parameters where used are explained below and are used in both the uncertainty analysis and the sensitivity analysis. The constant values and ranges in which the parameters have been analyzed are summarized in Table 2.1.

Transmissivity represents the rate at which water flows horizontally through an aquifer and is defined in this model in units of meters squared per day. Transmissivity ranges between values of 0.19 m²/d to 44.6 m²/d within the San Juan Region [1]. From the pumping test performed within the permit area of the Roca Honda Resources (RHR) Mine site, a better understanding of the transmissivity was achieved. It ranges between the values of 6 m²/d to 11.6 m²/d  [15]. The constant value for transmissivity is 10.6 m²/d this is the median value of transmissivity in the Westwater Canyon member of the San Juan Basin defined in [1]. The transmissivity parameter was evaluated between both the regional range and the RHR mine site range to better understand how the spatial variability affects the final water resource impact.

The storage coefficient represents the property of the Westwater Canyons Member to store water. The storage coefficient ranges between 0.00002 - 0.0002 [1]. Since Roca Honda Resources defined the value of the storage coefficient within the Roca Honda Mine site to be 0.00024 [15], it was used as the constant value for analysis.

Depth of drawdown, measured in meters, represents the drawdown parameter s of the Cooper-Jacobs approximation of the Theis Equation (Eq. 2.4). The piezometric head in the Westwater Canyon Member is known to be around 243.8-274.3 m above the top of the aquifer near the Roca Honda Mine site [2] and the thickness of the aquifer is known to vary between 30.5 and 121.9 m [1], making the depth of drawdown

to range between 274.3-396.2 m. The constant value for aquifer thickness was selected to be 76.2 m as this was the median value defined by [1] for the Westwater Canyon member in the San Juan Basin. The constant value of 243.8 m for the piezometric head of the Westwater Canyon member above the top of the aquifer was chosen to compare to the proposed Roca Honda mine as this was the value used in the groundwater impact calculations made by Hydroscience Associates Inc. (2011).

Expansion rate, measured in meters per day, represents the rate at which the initial mine radius of 3.1 m will expand each day due to mining activity. The expansion rate can be considered part of the scenario uncertainty that will be explained later. It is not a known parameter and thus the range of 0.3 to 1.5 m/d was considered. Other scenario parameters include the time of initial dewatering and time to sink the mineshaft. These have both been lumped into one parameter so that it can be compared to the proposed Roca Honda Mine and is set to 2 years. The constant value of 1.5 m/d was selected for the expansion rate since there were no values to compare to the situation.

The remaining two situational parameters summarized in Table 2.1, initial dewatering/time to sink shaft, and duration of mining have potential ranges of values that are not known and were estimated. The constant values were chosen to compare to the proposed Roca Honda Mine [2].

The model parameter of the time step allows the conceptual model to calculate the instantaneous volume discharged from the mine during different times during the dewatering and mining period. Since the model input of t is the time since the beginning of pumping the time step would begin with a value of 30 days increasing by 30 days for each time step until it reaches the end of the mining period at a maximum value of 4370 days (12 years). The time step of 30 days was chosen so that calculations could provide a detailed resolution of results.

Table 2.1: Modeled parameters used in the Theis Cooper-Jacob Approximation

| | Physical Parameters of Westwater Canyon Member | | |
|---|---|---|---|
| | Range | Constant Value[4] | Units |
| Transmissivity | .19-44.6 | 10.6 | $m^2/d$ |
| | [6.0-11.6][1] | 10.6 | |
| Storage Coefficient (S) | .00002-.0002 | 0.00024 | unitless |
| | [.00024][1] | 0.00024 | |
| Piezometric Head Above Aquifer | 243.8-274.3 | 243.8 | m |
| Aquifer Thickness | 30.5-121.9 | 76.2 | m |
| | Scenario Parameters | | |
| | Range | Constant Value[4] | Units |
| Expansion Rate | .3-1.5 | 1.5 | m/d |
| Initial Dewatering Period/Time to Sink Shaft[2] | 180-1000 | 720 | d |
| Duration of Mining | 3-20 | 10 | years |
| | Model Parameters | | |
| | Range | Constant Value[4] | Units |
| Time Step[3] | 1-365 | 30 | days |

[1] RHR aquifer properties after aquifer testing (Hydroscience Associates Inc., 2011)

[2] Values held constant for comparison to the properties of the proposed Roca Honda Mine

[3] Model parameters were not varied for uncertainty.

[4] Values used when not varied during analysis

## 2.2.2 Uncertainty Analysis

To understand and quantify the confidence of the estimates of the amount of water needed to be removed for uranium mining, an uncertainty analysis was performed so that better decisions can be made about potential uranium mining in the San Juan basin in the future. The uncertainty analysis involved the parameters (T, S, t, s,

and r) of Equation 2.4. This was conducted to determine which parameters have the greatest uncertainty, the range in which they vary, and which parameters have the greatest effect on the flow rate from the dewatering mines and volume of water extracted from the aquifer.

Since knowledge about the San Juan Basin and its aquifer parameters consist of empirical data such as observations many of the known ranges of values have an associated uncertainty. One source of uncertainty comes from the measurement of these parameters. It exists because there is only one set of data used to determine the aquifer parameters and this data is limited to only 31 well tests across the entire San Juan Basin [1]. Another source of uncertainty comes from applying these parameters as if they were uniform across the entire San Juan basin. In systems this large and variable, this assumption introduces uncertainty to calculations. In reality it is understood that these parameters are not uniform and that for each individual location the properties of the aquifers are different from site to site.

There are at least three types of uncertainty that are involved with any uncertainty analysis, parameter, scenario, and model uncertainty [18]. Many of the physical parameters such as T, S, and aquifer thickness used to quantify the effects of dewatering a mine for uranium extraction in the San Juan basin are uncertain because they rely on the limited knowledge about the geology and aquifer properties of the ore bodies, these are the parameters that have been modeled in this research to understand the parameter uncertainty. Furthermore, there is general uncertainty about future mining activity in the area such as expansion rate of the mine, time it will take to sink the mineshaft, and the duration that mining activity will occur. These are the parameters that contribute to the scenario uncertainty. Since the proposed Roca Honda Mine has been used to define some of these scenario parameters [2], the only scenario parameter that was studied for uncertainty in this research is the expansion rate. Finally, there is general uncertainty involved in how the model

is constructed. It must be noted that a model that simulates a conceptual uranium mine can be constructed in many different ways and that parameters such as the length of the time step or the modeling program that the conceptual model was calculated in can inevitably affect the final outcome and can contribute to uncertainty. No model uncertainty was modeled in this research, but it could be incorporated in future work.

The calculations for uncertainty were performed using the Theis Cooper-Jacob approximation through a MATLAB code that allowed for multiple simulations of various configurations of parameters. This MATLAB code simulated the mining conditions of the proposed Roca Honda Mine by using the parameters defined in Table 2.1. The MATLAB code allowed the transmissivity, storage coefficient, depth of drawdown, and expansion rate parameters to vary randomly for each iteration within its range of known values. It was assumed that all values of input parameters are equally likely (uniform distribution) unless it was defined as a constant value, since the information about the spatial variability of these values was not known. With more information about how these parameters vary throughout the San Juan Basin, different types of distributions for the physical parameters could be selected. 100,000 iterations of the model were performed for each variation of the model described below. The output of the model at each iteration was a total volume extracted for the 12 year simulation period.

To better understand how the parameters that had a variable range of values and did not have a single constant value defined in Table 2.1 (transmissivity, storage coefficient, depth of drawdown, and expansion rate) it was studied how they affected the uncertainty of the total volume extracted from the conceptual mine. Three different scenarios were used to evaluate this uncertainty. The first scenario (scenario 1) studied allowed all of the parameters to be varied randomly between their value ranges with a uniform distribution. The second scenario (scenario 2) allowed each

parameter to be held constant while the others varied randomly so that the effect each parameter on the uncertainty analysis could be studied. Finally, scenarios one and two were performed in the same fashion while using the transmissivity values defined by RHR's pump test (Table 2.1) so that the effect of the spatial variability of this parameter could be studied (scenario 3).

### 2.2.3   Sensitivity Analysis Methods

The parameters used to calculate the flow rate and final volume of water removed from the Westwater Canyon Member for uranium mining are known to exist over a range of values within the San Juan Basin, see Table 2.1  [1, 15]. By varying each parameter within its known range while holding the other parameter values constant, the sensitivity of the resultant flow rate and total volume removed can be better understood. The parameters that were varied are transmissivity, storage coefficient, depth of drawdown, and expansion rate.

The sensitivity analysis was performed by calculating the groundwater flow rate required for extracting uranium at the proposed Roca Honda Mine over a 12-year time period. The conceptual model described earlier was used for this calculation by holding all of the parameters at their constant value (Table  2.1) while allowing one parameter vary across its range of values describes in Table 2.1. The parameters that where studied for sensitivity are transmissivity, storage coefficient, depth of drawdown, and expansion rate. This allowed for a better understanding of how each parameter affected the flow rate.

# Chapter 3

# Results

## 3.1  Verification of Model

Two methods were used to verify the results of the analytical model. For both methods, the historical data from the NM Bureau of Mine & Minerals Resources (NMBMMR) [1] were used to compare observed flow rates to modeled flow rates (Table 3.2). The first way the model was verified was through a single run of the analytical model with a time vector of 12 years using the aquifer parameters that are determined by [1] as median values in the Morrison formation. Since these are accepted values for the aquifer parameters of the Morrison formation that is why they were used as the criterion of the Morrison aquifer during the first validation method. The parameters used in the first verification method can be seen in Table 3.1. The resulting flow rate from the model is 10.98 $\text{m}^3/\text{s}$ and is only about 10% different from the historical flow rates reported for mining in the Ambrosia Lake District (Table 3.2). This serves to verify that the method used in this analysis is a reasonable approximation.

The second way that the results of this model was verified is by comparing the

Table 3.1: Parameters Used for 1st Method of Model Verification, data from Kernodle (1996) and Hydrosceince Associates Inc. (2011)

| Parameters Used for Calibration | Kernodle Median Value | RHR Pump Test | Units |
|---|---|---|---|
| Transmissivity | 14.4 | 6.0-11.6 | $m^2/d$ |
| Storage Coefficient | $2.0*10^{-4}$ | $2.4*10^{-4}$ | unitless |
| Depth of Water Table Above Aquifer | 243.8 | N/A | m |
| Thickness of Westwater Canyon Formation | 76.2 | Approx 122 | m |

median of the total volume removed from the aquifer for the uncertainty analysis (100,000 iterations) to historical values. The median volume from this analysis is $6.07*10^7$ m$^3$. This volume, when averaged over 12 years, equates to a flow rate of 9.6 m$^3$/min. It can be seen in Table 3.2 that this flow rate is only 1.5% different from the historical values reported for mining the Ambrosia Lake District (Table 3.2) and serves to verify that the method used in this analysis is a reasonable approximation.

Previous attempts of validating the parameters used by [14] have been made by Roca Honda Resources (RHR). A test well was installed in the area near the proposed Roca Honda Mine that provides some limited data on the hydraulic properties of the Westwater Canyon member. The data about the hydraulic properties from the Westwater Canyon Member collected by the test well can be seen in Table 2.1, [15]. Since the aquifer parameters reported by RHR lies within the reported hydraulic parameter range reported by [1], the parameters used for the Roca Honda mine permit site can be considered validated as well.

Table 3.2: Historical Pumping Rates from Uranium Mines in the San Juan Basin

| Location of Mine | Quantity pumped (m$^3$/min) | Quantity discharged to streams (m$^3$/min) | Other |
|---|---|---|---|
| Ambrosia Lake area | | | |
| 14.10.22 14.09.33 14.09.30 14.09.24 14.09.17 14.09.30 14.09.19 | 9.46 | 1.13-1.89 | 8.33 m$^3$/min is used in mill process. Some is recirculated for stope leaching. |
| 14.09.35 14.09.36 | 6.06 6.06 | 0 0 | Water diverted for irrigation of rangeland |
| 14.09.28 14.09.34 | 1.32-1.51 1.32 | 0 0 | Most water is recirculated for stope leaching |
| 14.10.25 14.10.23 14.10.32 | 7.57 | 2.46 | 4.54-4.92 m$^3$/min used for stope leaching |
| 13.08.07 | 3.79 | 3.79 | Entire discharge diverted for irrigation and stock watering during summer months. |
| Church Rock area | | | |
| 17.16.35 17.16.35 | 4.73-5.30 14.20-15.14 | 0.19 14.20-15.14 | Most water used in mill process |
| Smith Lake area | | | |
| 15.14.12 | .76-1.14 | Intermittent | |
| San Mateo area | | | |
| 13.08.24 | 18.81-19.00 | 18.81-19.00 | Water provided from shaft and wells. Most of water diverted for irrigation and stock water |
| Laguna-Marquez area | | | |
| 11.04.19 11.05.13 11.05.04 11.04.19 11.05.25 11.03.18 | .08-.19 0.09 0.57 0.09 4.54 1.89 | 0 0 0 0 4.54 1.89 | Water produced from shaft |
| Crownpoint area | | | |
| 19.11.31 | 4.77-5.30 | 4.77-5.30 | Water produced from shaft and wells during shaft construction |

## 3.2 Sensitivity Analysis Results

The results of this analysis can be seen in Figure 3.1 and Table 3.3. Each individual parameter was varied between the ranges specified in Table 2.1, while the other parameters were held constant, also specified in Table 2.1. By performing the conceptual model within the specified parameters ranges, a range of resultant flow rates and volumes of water removed from the Westwater Canyon member for uranium mining from a conceptual mine was determined. This will help to give a better understanding of how much each individual parameter can affect the final volume of groundwater extracted.

The results of the sensitivity analysis are presented in Figure 3.1 as well as Table 3.3 so that a comparison of how each parameter affects the flow rate and total volume extracted to its minimum, and maximum value within its specified range can be determined. One note about Figure 3.1 is that the scenario for the max storage coefficient and max expansion rate coincidentally had the same parameters. This is why they have the same values in Figure 3.1. The "Transmissivity RHR" in the legend of Figure 3.1 corresponds to holding the transmissivity parameter values between what was determined during the pump test performed on the Roca Honda Mine permit site, (6.0-11.6 m$^2$/d).

Table 3.3: Volumes of Water Extracted in m$^3$ and Flow Rates in m$^3$/s from Sensitivity Analysis

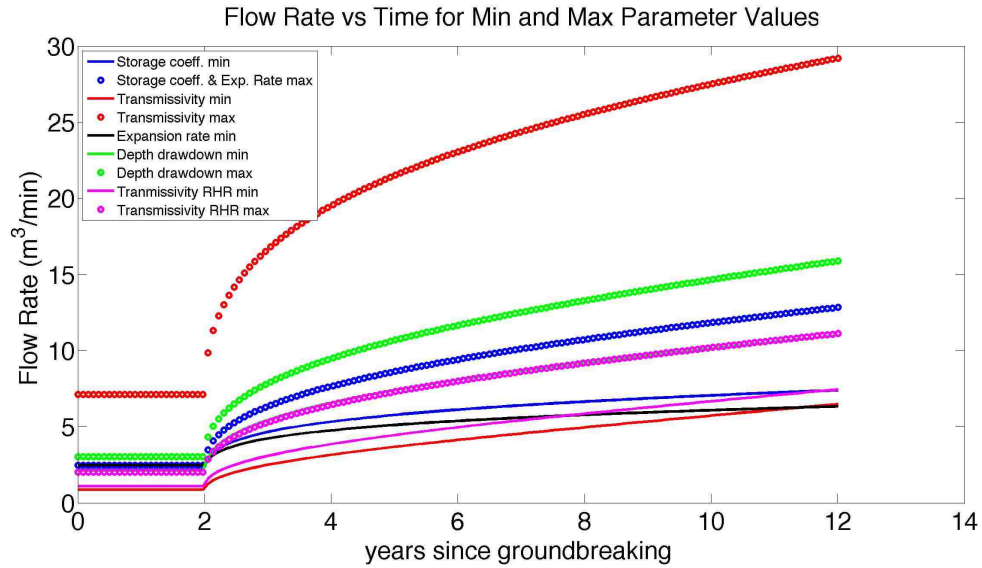| | Flow Rate (m$^3$/min) | | | Volume (m$^3$) | | |
|---|---|---|---|---|---|---|
| Parameter | Max | Min | Median | Max | Min | Median |
| Storage Coefficient | 12.84 | 7.4 | 10.78 | 5.48E+07 | 3.47E+07 | 4.70E+07 |
| Transmissivity | 29.21 | 6.48 | 18.74 | 13.1E+07 | 2.43E+07 | 8.14E+07 |
| Transmissivity RHR | 11.2 | 7.45 | 9.33 | 4.58E+07 | 2.88E+07 | 3.75E+07 |
| Expansion Rate | 12.84 | 6.33 | 9.68 | 5.38E+07 | 3.10E+07 | 4.33E+07 |
| Depth of Drawdown | 15.89 | 11 | 13.45 | 6.66E+07 | 4.61E+07 | 5.64E+07 |

Figure 3.1: Time dependence Parameter Sensitivity

It can be seen in Figure 3.1 that when the transmissivity values were allowed to range between what is accepted within the entire San Juan Basin, the values of flow rates are the largest compared to the other flow rates. Once this range is reduced to the RHR permit site where there is a better understanding of what parameter values truly exist, transmissivity no longer causes the greatest increase to flow rate in the model. Once transmissivity is less variable, the parameters of the model are approximately equally sensitive to their known or estimated ranges.

## 3.3  Uncertainty Analysis Results

The following figures 3.3, 3.4, 3.6, 3.7, 3.2, 3.5 and tables 3.4 and 3.5 summarize the output from the three uncertainty scenarios defined in the methods section. Results are presented graphically in three ways. The first method is presented through a histogram that plots the number times the resultant volume occurs for each iteration of the 100,000 iterations versus the resultant volume extracted from the conceptual

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mine over 12 years (Figures 3.3 and 3.2). This allows the reader to determine the distribution of volumes extracted for each scenario. Figures 3.3, 3.4,  3.6 and 3.7 present Cumulative Distribution Function (CDF) graphs that allow the reader to quickly gather information about each scenario's modeled volume of water extracted by displaying the probabilities during the 100,000 simulations performed for analysis. Finally, this information is summarized in Tables 3.4 and 3.5 for quick comparisons among the scenarios modeled.

It was found that for scenario 1 the total volume of water extracted during the 12-year simulation had a broader distribution (Figure 3.3) than other scenarios. The values for the final water extracted between the 10% and 90% probabilities (Figure 3.2) were $2.53*10^7$ m$^3$ and $9.91*10^7$ m$^3$ (Table 3.4). The results of what type of statistical distribution this result produces was not explored although future work could be focused on the relevance of the distribution for better understanding the results.



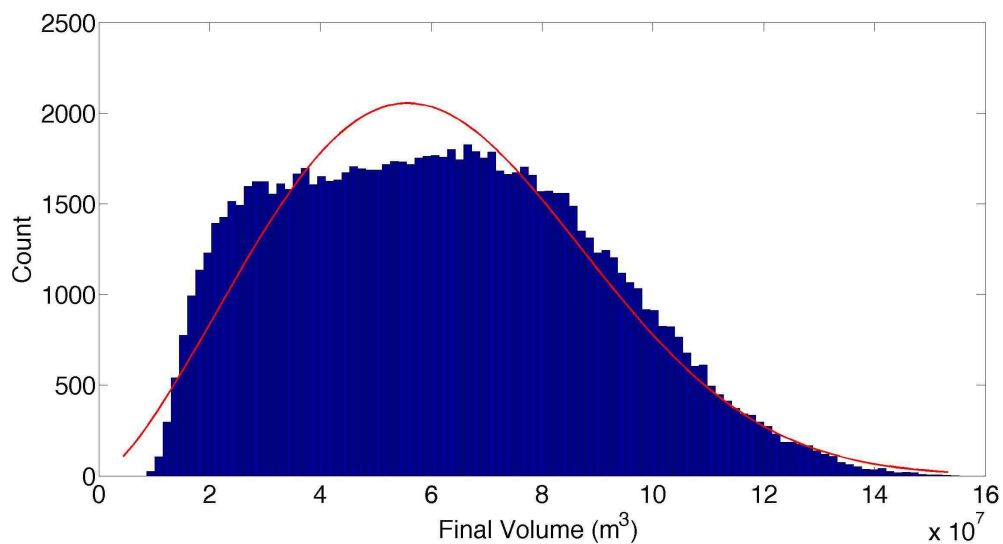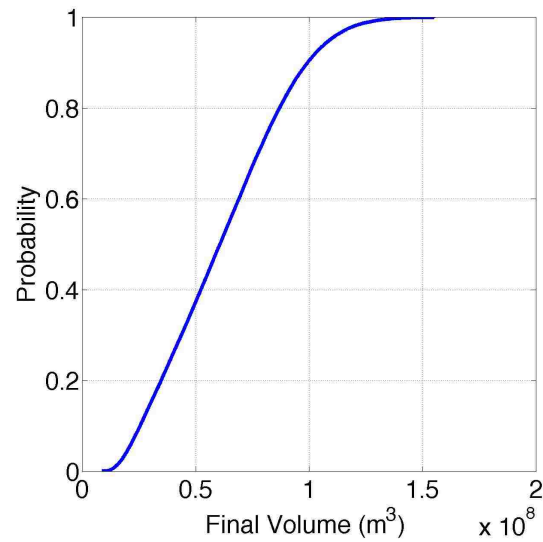Figure 3.2: Distribution of Scenario 1

Figure 3.3: Cumulative Distribution Function of Scenario 1
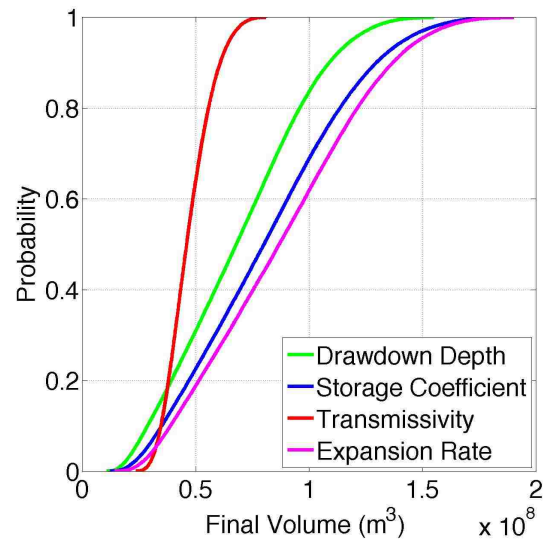


Figure 3.4: Cumulative Distribution Function Plots from Scenario 2

In scenario 2 the result of holding each parameter constant that was previously allowed to vary randomly in scenario 1 made for a better understanding of which parameter contributed the greatest amount of uncertainty. When Figures 3.3 and

*Chapter 3. Results*

3.4 are compared, it can be seen that while the parameters depth of drawdown, storage coefficient, and expansion rate are held constant, they have similar results of scenario 1, but when transmissivity is held constant it does not. The effect of the transmissivity parameter has on the uncertainty of the results is significant and will be addressed in the discussion.

Table 3.4: Volume of Water Extracted in m$^3$ for Method 1 & 2

| Analysis Type | 10% | 25% | 50% | 75% | 90% |
|---|---|---|---|---|---|
| Vary all parameters | 2.53E+07 | 3.90E+07 | 6.04E+07 | 8.17E+07 | 9.91E+07 |
| Hold T constant | 3.46E+07 | 3.94E+07 | 4.60E+07 | 5.36E+07 | 6.08E+07 |
| Hold S constant | 3.50E+07 | 5.28E+07 | 8.01E+07 | 10.7E+07 | 13.0E+07 |
| Hold s constant | 2.87E+07 | 4.42E+07 | 6.78E+07 | 9.06E+07 | 10.9E+07 |
| Hold ER constant | 3.88E+07 | 5.76E+07 | 8.68E+07 | 11.5E+07 | 13.7E+07 |

In scenario 3 the effect of having a better understanding of the transmissivity is shown. In this scenario the transmissivity was defined to range between the values of 6.0 m$^2$/s to 11.6 m$^2$/s in the situations it was not held constant. When all of the parameters (T,s,ER,S) were allowed to vary, a distribution similar to a lognormal distribution was found through visual inspection (Figure 3.5). This statistical distribution was not tested but future work could be preformed so that the significance of this type of distribution can be explored.

Similar results where achieved with the model when the parameters S,T,s, and ER were individually held constant in scenario 3,. Previously in scenario 2, when transmissivity was held constant, there was a significant difference in results (Figure 3.4), yet when the range of values for the transmissivity parameter was held to a smaller range it did not have such a large impact on uncertainty in the model (Figure 3.7).
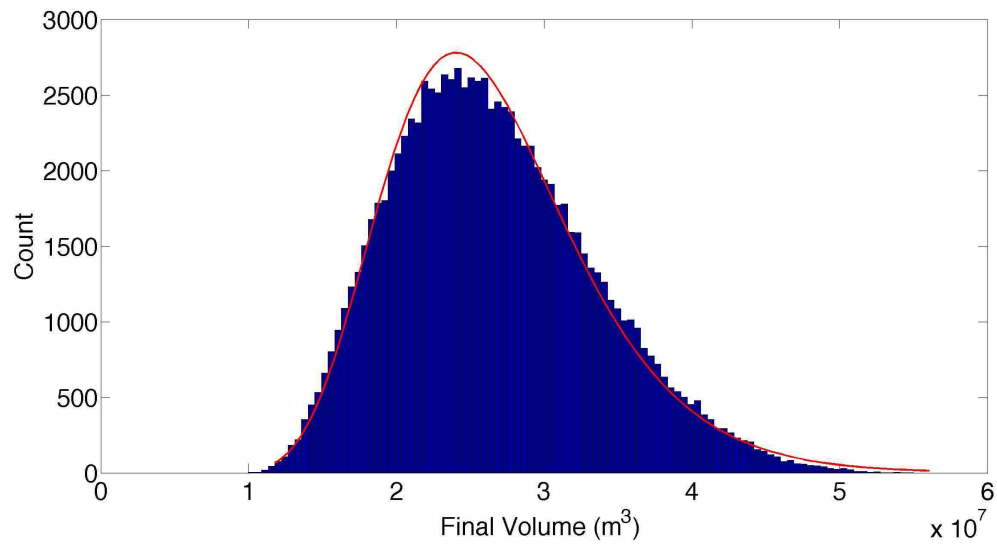
Figure 3.5: Distribution of Scenario 3, With T, S, Expansion Rate and Depth of Drawdown varied
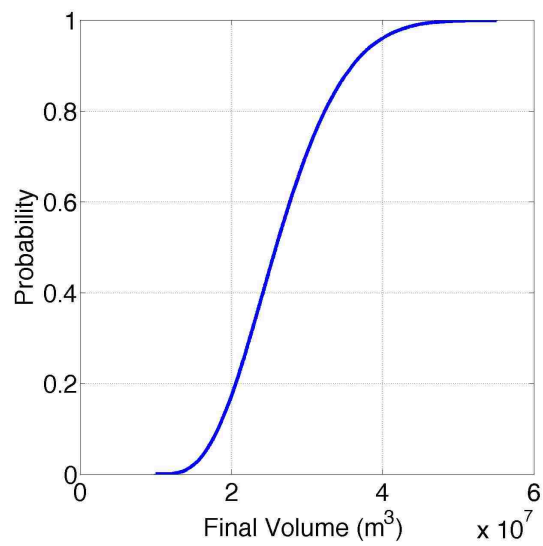


Figure 3.6: Cumulative Distribution Function of Scenario 3
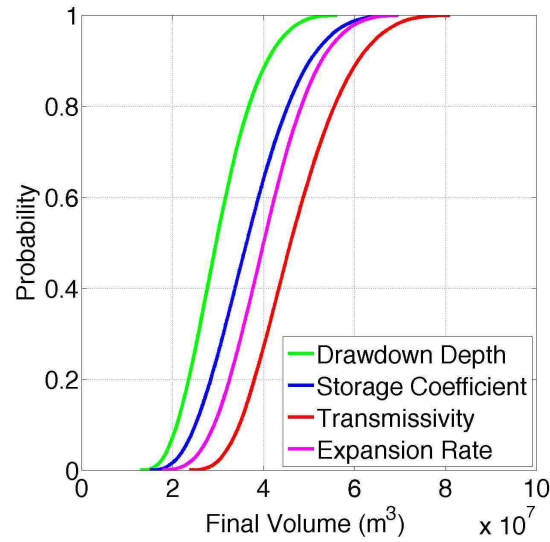
Figure 3.7: Cumulative Distribution Function while holding individual parameters constant

Table 3.5: Final Volume of Water Extracted in m$^3$ for Method 3

| Analysis Type | 10% | 25% | 50% | 75% | 90% |
|---|---|---|---|---|---|
| Vary all parameters | 1.82E+07 | 2.15E+07 | 2.59E+07 | 3.10E+07 | 3.60E+07 |
| Hold T constant | 2.09E+07 | 2.46E+07 | 2.95E+07 | 3.52E+07 | 4.08E+07 |
| Hold S constant | 3.46E+07 | 3.95E+07 | 4.60E+07 | 5.36E+07 | 6.08E+07 |
| Hold s constant | 2.49E+07 | 2.98E+07 | 3.62E+07 | 4.33E+07 | 5.00E+07 |
| Hold ER constant | 2.91E+07 | 3.39E+07 | 4.01E+07 | 4.66E+07 | 5.28E+07 |

# Chapter 4

# Discussion

The goal of this research was to improve our understanding of the future groundwater resource withdrawals of potential uranium mining in the San Juan Basin. For this, a conceptual mine was modeled using the Theis equation, whose parameters were informed from the physical characteristics present at the proposed Roca Honda Mine in the Grants Mineral Belt, Ambrosia Lake District. This research quantified the sensitivity of the model parameters within the area so that future work can be focused towards the most sensitive parameters and that more accurate quantification of future water resource impacts can be calculated. This research explored the uncertainty that is involved in modeling this situation and provided quantified results within confidence bounds so that better decisions can be made concerning the existing water resource.

The sensitivity of the parameters that was calculated in this research provided flow rates and volumes of potential water extracted for uranium mining. Transmissivity, among the other parameters evaluated for its sensitivity had the largest range of flow rates and volumes. This parameter has long been known to cause the most variance in groundwater impact. Since it is understood that this parameter is not

well defined, the estimates of groundwater flow rates tend to use conservatively high values of groundwater pumping for uranium mining [2]. Each parameter such as the situational rate at which a mine will expand, storage coefficient, and depth of the water table each individually have enough uncertainty about what flow rates and volumes a potential uranium mine could extract. When combined together, they have similar if not greater impacts on calculations than the transmissivity alone.

Since the majority of previous research about the groundwater impacts of uranium mining use parameters that are part of a spatial area that covers the entire 54,390 $km^2$ of the San Juan Basin, parameters such as transmissivity have a large range of values. The parameter that contributes the greatest amount of sensitivity and uncertainty in the analysis of this model is the transmissivity parameter. This can be seen in both the sensitivity results and the uncertainty results (Tables 3.4 and 3.5, Figures 3.2-3.5). When this value is more tightly bound to a spatial area of 7.8 $km^2$, like in the case of the Roca Honda Resources pump test of the permit site [15], the results are more constrained (Table 3.5, Figures 3.5,3.6,3.7.

Being that this is one of the first attempts at calculating flow rates from uranium mining dewatering wells the distributions of the inputs of physical, model, and scenario parameters in the model was not known. Since there was no information about the distributions of the parameters used in this research, the distribution was selected to be a uniform distribution. Gathering more information about these parameters could allow for a most customized distribution and allow for a comparison of what different distributions can do to affect the resulting ground water impacts.

The uncertainty analysis provides a range of values that serves to allow for better decisions to be made about groundwater pumping for underground uranium mining. The uncertainty analysis allows the reader to understand that there are many potential impacts that uranium mining in the San Juan Basin can cause to groundwater resources. For example, it is interesting to note that from the results of the

uncertainty analysis, the calculated flow rates were on average below the current projections that Roca Honda Resources have published in the DEIS report for the proposed Roca Honda mine. The volume of $9.18*10^7$ m$^3$ was one of the highest results that this particular model calculated, and it was the singular value that RHR's used as the groundwater impact over a modeled 12 year mining period. It is not known what range of values RHR's model calculated when modeling dewatering for the mine but it can be assumed they experienced a similar distribution of flow rates and volumes of water extracted for uranium mining, similar to what was calculated in this report. It can be seen in the results of the uncertainty analysis that a large range of calculated final volumes and flow rates imply that these calculations are uncertain.

# Chapter 5

# Conclusion

The results from the conceptual mine based on the proposed Roca Honda Mine incorporated the Theis Method Cooper Jacob Approximation and can be considered a reasonable result although the technique of modeling is simple. The advantage of using this simple technique allowed for a greater range of possibilities to be studied in a shorter period of time versus other modeling techniques such as Modflow 2005 among other groundwater modeling programs. Future work could be conducted to more thoroughly understand the model uncertainty by modeling the same situation and parameters with different modeling programs or equations.

The goal of this research was to increase the knowledge about the groundwater impacts of uranium mining in the San Juan Basin. One of the ways this research can be useful is that it provides a range of quantified results within calculated probabilities where other studies do not. This can also be useful as a comparison to an environmental impact statement (EIS) provided by a mining company. This EIS could have a different method for calculating groundwater impacts that do not take into account or recognize that the parameters they are using are uncertain for the associated calculations. Another way this research can be useful is that it provides

a better understanding of what volumes and flow rates can be expected from potential uranium mines in the San Juan Basin. With this information provided in this research better understanding of groundwater impacts of uranium mining in the San Juan basin and can be used to make better decisions about future mining activity in the area.

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# Appendix A

# MATLAB code used for uncertainty analysis

- Setting Initial Parameters
- Depth of Draw down uncertainty analysis

```
clc; clear all; close all
tic
ploti = 1;
fig_size = get(0,'Screensize');

% Note about code: this code parametriclly varies all but one of the
% following parameters: the depth of drawdown, storage coefficient,
% the transmissivity or the expansion rate.  Meanwhile the 4th parameter
% is held constant.  The constant values and the parametric ranges are
% stated here:

% % Constant Paramters
```

*Appendix A. MATLAB code used for uncertainty analysis*

```
% inD = 1050; % Depth of drawdown (ft)
% inT = 155; % as Transmisivity (ft^2/d)
% inS = 2.00e-4; % as Storativity (unitless)
% inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
% inT = 2:2:480; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)
```

## Setting Initial Parameters

```
inSink = 185; % as initial time to Sink Shaft (d)
inr = 10; % as initial Mine Radius (ft)
daysStep = 30;
inTime = 1:daysStep:(365*12)+1; % initial time vector (d)


Tfinal = inTime(length(inTime));
```

## Depth of Drawdown uncertainty analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%% Depth of Draw down uncertainty analysis %%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Depth of drawdown uncertainty analysis %%%%')

steps = 500;
```

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*Appendix A. MATLAB code used for uncertainty analysis*

```
calcs = 100000;
% Constant Paramters
inD = 1050; % Depth of drawdown (ft)
% inT = 155; % as Transmisivity (ft^2/d)
% inS = 2.00e-4; % as Storativity (unitless)
% inExpRate = 5; % as Expansion Rate (ft/d)
% Varied Parameters
% inDrange = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
inTrange = 50:(480-50)/steps:480; % as Transmisivity in San Juan Basin (ft^2/d)
% inTrange = 65:(125-65)/steps:125; % as Transmisivity in RHR Site (ft^2/d)
inSrange = 2.00e-5:(2.00e-4 - 2.00e-5)/steps:2.00e-4; % as Storativity (unitless)
inExpRaterange = 1:(5-1)/steps:5; % as Expansion Rate (ft/d)


Vfinal = zeros(1,calcs);
for j = 1:calcs
%     locRand = round(steps*rand(1)) + 1; % random location in vector
%     inD = inDrange( locRand );
    locRand = round(steps*rand(1)) + 1; % random location in vector
    inT = inTrange( locRand );
    locRand = round(steps*rand(1)) + 1; % random location in vector
    inS = inSrange( locRand );
    locRand = round(steps*rand(1)) + 1; % random location in vector
    inExpRate = inExpRaterange( locRand );

    % Calculate Initial Q
    outQinitial = (inT*inD) ...
        ./( 0.183*log10((2.25*inT*inSink)./(inr^2*inS)) ); % Initial Q (ft^3/d)
%     outQinitialCFS = outQinitial/86400; % Converting Q to CFS
```

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*Appendix A. MATLAB code used for uncertainty analysis*

```
    % Calculate Volume of Water up to Sink Date
    outVsink = outQinitial*inSink;


    % Cacluating Q for Each Time
    outQvector = zeros(length(inTime));
%     outQvectorCFS = zeros(length(inTime));
    outVvector = zeros(length(inTime));
    outVDiffvector = zeros(length(inTime));


    for i=1:length(inTime)
        currentDay = inTime(i);


        if currentDay < inSink
            % Radius at this point
            mineRadius = inr;


            % Q at this point
            outQvector(i) = outQinitial;
%             outQvectorCFS(i) = outQinitialCFS;


            % Volume removed at this point
            currentVadd = 0;
            outVDiffvector(i) = outQinitial * ( inTime(2) - inTime(1) );
            outVvector(i) = outQinitial * inTime(i);
        else
            % Radius at this point
            dayDiff = currentDay - inSink;
            mineRadius = inr + dayDiff*inExpRate;
```

```
            % Q at this point
            outQvector(i) = (inD*inT) ...
                /( 0.183*log10((2.25*inT*currentDay)/(mineRadius^2*inS)) ); % Init
%           outQvectorCFS(i) = outQvector(i)/86400; % Converting Q to CFS

            % Volume removed at this point
%            currentVadd = outVsink;
            outVDiffvector(i) = outQvector(i) * ( inTime(i) - inTime(i-1) );
            outVvector(i) = outVvector(i-1) + outQvector(i) * ( inTime(i) - inTime
        end
%          outVvector(i) = outVvector(i) + currentVadd;
    end
    Vfinal(j) = outVvector(length(outVvector));
end
% convert units: 1ft^3 = 2.29568411e-5 acre feet
% Vfinal = Vfinal*(2.29568411e-5);


% convert to metric units: 1ft^3 = 2.29568411e-5 acre feet, 1 acre foot = 1233.451
% m^3
Vfinal = Vfinal*(2.29568411e-5)*(1233.48184);


% Saving Vfinal for joint CDF plot
Vfinals = Vfinal;


toc


%%%% Depth of drawdown uncertainty analysis %%%%
```

*Appendix A.  MATLAB code used for uncertainty analysis*

```
Elapsed time is 154.422615 seconds.
```

# Appendix B

# MATLAB code used for sensitivity analysis

## Contents

- Setting Initial Parameters
- Storage coefficient sensitivity analysis
- Transmissivity for SJB In General sensitivity analysis
- Transmissivity @ RH Mine Site sensitivity analysis
- Expansion rate sensitivity analysis
- Depth of drawdown sensitivity analysis

```
clc; clear all; close all
ploti = 1;
pagei = 1;
fig_size = get(0,'Screensize');

% Note about code: this code parametriclly varies either the storativity,
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```
% the transmissivity, depth of drawdown, or the expansion rate while
% holding all otherparametrs constant.  The constant values and the
% parametric ranges are stated here:


% % Constant Paramters
% inD = 1050; % Depth of drawdown (ft)
% inT = 155; % as Transmisivity (ft^2/d)
% inS = 2.00e-4; % as Storativity (unitless)
% inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
% inT = 2:2:480; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)
```

## Setting Initial Parameters

inD = 1050; % Depth of drawdown (ft)

```
inSink = 2*365; %185; % as initial time to Sink Shaft (d)
inr = 10; % as initial Mine Radius (ft)
daysStep = 30;  % (d)
inTime = 1:daysStep:(365*12)+1; % 1:daysStep:(365*3)+1; % initial time vector (d)

% Prealocate time dependence sensitivity
% This vector contains the flow rate versus time since ground breaking for
% each parameter's minimum and maximum values to be plotted side-by-side
% Row         scenario          parameter value
```

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```
%   1          Storage coeff     min
%   2          Storage coeff     max
%   3          Transmissivity    min
%   4          Transmissivity    max
%   5          Expansion rate    min
%   6          Expansion rate    max
%   7          Depth drawdown    min
%   8          Depth drawdown    max
TimeDepSensVec = zeros(8,length(inTime));
```

## Storage coefficient sensitivity analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%% Storage coefficient sensitivity analysis %%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Storage coefficient sensitivity analysis %%%%')

% % Constant Paramters
inD = 1050; % Depth of drawdown (ft)
inT = 155; % as Transmisivity (ft^2/d)
% inS = 2.00e-4; % as Storativity (unitless)
inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
% inT = 50:2:480; % as Transmisivity (ft^2/d)
inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)
```

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*Appendix B.  MATLAB code used for sensitivity analysis*

```matlab
% Calculate Initial Q
outQinitial = (inT*inD) ...
    ./( 0.183*log10((2.25*inT*inSink)./(inr^2*inS)) ); % Initial Q (ft^3/d)
outQinitialCFS = outQinitial/86400; % Converting Q to CFS
% Calculate Volume of Water up to Sink Date
outVsink = outQinitial*inSink;


% Cacluating Q for Each Time
outQvector = zeros(length(inS),length(inTime));
outQvectorCFS = zeros(length(inS),length(inTime));
outVvector = zeros(length(inS),length(inTime));
outVDiffvector = zeros(length(inS),length(inTime));


for j = 1:length(inS)
    for i=1:length(inTime)
        currentDay = inTime(i);

        if currentDay < inSink
            % Radius at this point
            mineRadius = inr;

            % Q at this point
            outQvector(j,i) = outQinitial(j);
            outQvectorCFS(j,i) = outQinitialCFS(j);

            % Volume removed at this point
            currentVadd = 0;
```

*Appendix B. MATLAB code used for sensitivity analysis*

```matlab
                outVDiffvector(j,i) = outQinitial(j) * ( inTime(2) - inTime(1) );
                outVvector(j,i) = outQinitial(j) * inTime(i);
            else
                % Radius at this point
                dayDiff = currentDay - inSink;
                mineRadius = inr + dayDiff*inExpRate;

                % Q at this point
                outQvector(j,i) = (inD*inT) ...
                    /( 0.183*log10((2.25*inT*currentDay)/(mineRadius^2*inS(j))) ); % 1
                outQvectorCFS(j,i) = outQvector(j,i)/86400; % Converting Q to CFS

                % Volume removed at this point
                currentVadd = outVsink(j);
                outVDiffvector(j,i) = outQvector(j,i) * ( inTime(i) - inTime(i-1) );
                outVvector(j,i) = outVvector(j,i-1) + outQvector(j,i) * ( inTime(i) -
            end
%           outVvector(j,i) = outVvector(j,i) + currentVadd;
    end
end

% METRIC convert units: 1 ft = 0.3048 m; 1 ft^2 = 0.092903 m^2
inD = inD*(0.3048); % Depth of drawdown (ft)
inT = inT*(0.092903); % as Transmisivity (ft^2/d)
inS = inS; % as Storativity (unitless)
inExpRate = inExpRate*(0.3048); % as Expansion Rate (ft/d)

% convert units: 1ft^3 = 2.29568411e-5 acre feet
```

```
outVvector = outVvector*(2.29568411e-5);

outVDiffvector = outVDiffvector*(2.29568411e-5);

% METRIC convert units: 1 acre ft = 1233.48184 m^3

outVvector = outVvector*(1233.48184);

outVDiffvector = outVDiffvector*(1233.48184);


% change to 30-Day difference

outVDiffvector = outVDiffvector*30;


% convert units: 1 gal/min = 1/448 CFS

outQvectorGPM = outQvectorCFS*(448);     % GPM

% METRIC convert units: 264.172 gal = 1 m^3

outQvectorGPM = outQvectorGPM/(264.172);    % m^3/min


TimeDepSensVec(1,:) = outQvectorGPM(1,:);

TimeDepSensVec(2,:) = outQvectorGPM(length(inS),:);
```

## Transmissivity for SJB In General sensitivity analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%% Transmissivity sensitivity analysis %%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Transmissivity sensitivity analysis %%%%')


% % Constant Paramters

inD = 1050; % Depth of drawdown (ft)
```

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*Appendix B. MATLAB code used for sensitivity analysis*

```
% inT = 155; % as Transmisivity (ft^2/d)
inS = 2.00e-4; % as Storativity (unitless)
inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
inT = 50:2:480; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)


% Calculate Initial Q
outQinitial = (inT*inD) ...
    ./( 0.183*log10((2.25*inT*inSink)./(inr^2*inS)) ); % Initial Q (ft^3/d)
outQinitialCFS = outQinitial/86400; % Converting Q to CFS
% Calculate Volume of Water up to Sink Date
outVsink = outQinitial*inSink;


% Cacluating Q for Each Time
outQvector = zeros(length(inT),length(inTime));
outQvectorCFS = zeros(length(inT),length(inTime));
outVvector = zeros(length(inT),length(inTime));
outVDiffvector = zeros(length(inT),length(inTime));


for j = 1:length(inT)
    for i=1:length(inTime)
        currentDay = inTime(i);

        if currentDay < inSink
            % Radius at this point
```

```matlab
                mineRadius = inr;

                % Q at this point
                outQvector(j,i) = outQinitial(j);
                outQvectorCFS(j,i) = outQinitialCFS(j);

                % Volume removed at this point
                currentVadd = 0;
                outVDiffvector(j,i) = outQinitial(j) * ( inTime(2) - inTime(1) );
                outVvector(j,i) = outQinitial(j) * inTime(i);
            else
                % Radius at this point
                dayDiff = currentDay - inSink;
                mineRadius = inr + dayDiff*inExpRate;

                % Q at this point
                outQvector(j,i) = (inD*inT(j)) ...
                    /( 0.183*log10((2.25*inT(j)*currentDay)/(mineRadius^2*inS)) ); % I
                outQvectorCFS(j,i) = outQvector(j,i)/86400; % Converting Q to CFS

                % Volume removed at this point
                currentVadd = outVsink(j);
                outVDiffvector(j,i) = outQvector(j,i) * ( inTime(i) - inTime(i-1) );
                outVvector(j,i) = outVvector(j,i-1) + outQvector(j,i) * ( inTime(i) -
            end
%           outVvector(j,i) = outVvector(j,i) + currentVadd;
        end
    end
```

```
% METRIC convert units: 1 ft = 0.3048 m; 1 ft^2 = 0.092903 m^2
inD = inD*(0.3048); % Depth of drawdown (ft)
inT = inT*(0.092903); % as Transmisivity (ft^2/d)
inS = inS; % as Storativity (unitless)
inExpRate = inExpRate*(0.3048); % as Expansion Rate (ft/d)


% convert units: 1ft^3 = 2.29568411e-5 acre feet
outVvector = outVvector*(2.29568411e-5);
outVDiffvector = outVDiffvector*(2.29568411e-5);
% METRIC convert units: 1 acre ft = 1233.48184 m^3
outVvector = outVvector*(1233.48184);
outVDiffvector = outVDiffvector*(1233.48184);


% change to 30-Day difference
outVDiffvector = outVDiffvector*30;


% convert units: 1 gal/min = 1/448 CFS
outQvectorGPM = outQvectorCFS*(448);     % GPM
% METRIC convert units: 264.172 gal = 1 m^3
outQvectorGPM = outQvectorGPM/(264.172);    % m^3/min


TimeDepSensVec(3,:) = outQvectorGPM(1,:);
TimeDepSensVec(4,:) = outQvectorGPM(length(inT),:);


V format.
```

# Transmissivity @ RH Mine Site sensitivity analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%% Transmissivity sensitivity analysis %%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Transmissivity sensitivity analysis %%%%')

% % Constant Paramters
inD = 1050; % Depth of drawdown (ft)
% inT = 155; % as Transmisivity (ft^2/d)
inS = 2.00e-4; % as Storativity (unitless)
inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
inT = 65:2:125; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)

% Calculate Initial Q
outQinitial = (inT*inD) ...
    ./( 0.183*log10((2.25*inT*inSink)./(inr^2*inS)) ); % Initial Q (ft^3/d)
outQinitialCFS = outQinitial/86400; % Converting Q to CFS
% Calculate Volume of Water up to Sink Date
outVsink = outQinitial*inSink;

% Cacluating Q for Each Time
outQvector = zeros(length(inT),length(inTime));
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```
outQvectorCFS = zeros(length(inT),length(inTime));
outVvector = zeros(length(inT),length(inTime));
outVDiffvector = zeros(length(inT),length(inTime));


for j = 1:length(inT)
    for i=1:length(inTime)
        currentDay = inTime(i);


        if currentDay < inSink
            % Radius at this point
            mineRadius = inr;


            % Q at this point
            outQvector(j,i) = outQinitial(j);
            outQvectorCFS(j,i) = outQinitialCFS(j);


            % Volume removed at this point
            currentVadd = 0;
            outVDiffvector(j,i) = outQinitial(j) * ( inTime(2) - inTime(1) );
            outVvector(j,i) = outQinitial(j) * inTime(i);
        else
            % Radius at this point
            dayDiff = currentDay - inSink;
            mineRadius = inr + dayDiff*inExpRate;


            % Q at this point
            outQvector(j,i) = (inD*inT(j)) ...
                /( 0.183*log10((2.25*inT(j)*currentDay)/(mineRadius^2*inS)) ); % I
```

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```
            outQvectorCFS(j,i) = outQvector(j,i)/86400; % Converting Q to CFS


            % Volume removed at this point
            currentVadd = outVsink(j);
            outVDiffvector(j,i) = outQvector(j,i) * ( inTime(i) - inTime(i-1) );
            outVvector(j,i) = outVvector(j,i-1) + outQvector(j,i) * ( inTime(i) -
        end
%           outVvector(j,i) = outVvector(j,i) + currentVadd;
    end
end


% METRIC convert units: 1 ft = 0.3048 m; 1 ft^2 = 0.092903 m^2
inD = inD*(0.3048); % Depth of drawdown (ft)
inT = inT*(0.092903); % as Transmisivity (ft^2/d)
inS = inS; % as Storativity (unitless)
inExpRate = inExpRate*(0.3048); % as Expansion Rate (ft/d)


% convert units: 1ft^3 = 2.29568411e-5 acre feet
outVvector = outVvector*(2.29568411e-5);
outVDiffvector = outVDiffvector*(2.29568411e-5);
% METRIC convert units: 1 acre ft = 1233.48184 m^3
outVvector = outVvector*(1233.48184);
outVDiffvector = outVDiffvector*(1233.48184);


% change to 30-Day difference
outVDiffvector = outVDiffvector*30;


% convert units: 1 gal/min = 1/448 CFS
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```
outQvectorGPM = outQvectorCFS*(448);    % GPM
% METRIC convert units: 264.172 gal = 1 m^3
outQvectorGPM = outQvectorGPM/(264.172);    % m^3/min


TimeDepSensVec(9,:) = outQvectorGPM(1,:);
TimeDepSensVec(10,:) = outQvectorGPM(length(inT),:);
```

## Expansion rate sensitivity analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%% Expansion rate sensitivity analysis %%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Expansion rate sensitivity analysis %%%%')


% % Constant Paramters
inD = 1050; % Depth of drawdown (ft)
inT = 155; % as Transmisivity (ft^2/d)
inS = 2.00e-4; % as Storativity (unitless)
% inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
% inD = 900:(1300-900)/steps:1300; % Depth of drawdown (ft)
% inT = 50:2:480; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)


% Calculate Initial Q
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```matlab
outQinitial = (inT*inD) ...
    /( 0.183*log10((2.25*inT*inSink)/(inr^2*inS)) ); % Initial Q (ft^3/d)
outQinitialCFS = outQinitial/86400; % Converting Q to CFS (ft^3/s)


% Calculate Volume of Water up to Sink Date
outVsink = outQinitial*inSink;  % (ft^3)


% Cacluating Q for Each Time
outQvector = zeros(length(inExpRate),length(inTime));
outQvectorCFS = zeros(length(inExpRate),length(inTime));
outVvector = zeros(length(inExpRate),length(inTime));
outVDiffvector = zeros(length(inExpRate),length(inTime));


for j = 1:length(inExpRate)
    for i=1:length(inTime)
        currentDay = inTime(i);

        if currentDay < inSink
            % Radius at this point
            mineRadius = inr;   % (ft)

            % Q at this point
            outQvector(j,i) = outQinitial;  % (ft^3/d)
            outQvectorCFS(j,i) = outQinitialCFS;    % (ft^3/s)

            % Volume removed at this point
            currentVadd = 0;    % (ft^3)
            outVDiffvector(j,i) = outQinitial * ( inTime(2) - inTime(1) );  % (ft^
```

```matlab
                outVvector(j,i) = outQinitial * inTime(i);  % (ft^3/d)
            else
                % Radius at this point
                dayDiff = currentDay - inSink;  % d - d_sink
                mineRadius = inr + dayDiff*inExpRate(j);    % ft + d*ft/d

                % Q at this point
                outQvector(j,i) = (inD*inT) ...
                    /( 0.183*log10((2.25*inT*currentDay)/(mineRadius^2*inS)) ); % Init
                outQvectorCFS(j,i) = outQvector(j,i)/86400; % Converting Q to CFS

                % Volume removed at this point
                currentVadd = outVsink; % (ft^3)
                outVDiffvector(j,i) = outQvector(j,i) * ( inTime(i) - inTime(i-1) );
                outVvector(j,i) = outVvector(j,i-1) + outQvector(j,i) * ( inTime(i) -
            end
%           outVvector(j,i) = outVvector(j,i) + currentVadd;
    end
end

% METRIC convert units: 1 ft = 0.3048 m; 1 ft^2 = 0.092903 m^2
inD = inD*(0.3048); % Depth of drawdown (ft)
inT = inT*(0.092903); % as Transmisivity (ft^2/d)
inS = inS; % as Storativity (unitless)
inExpRate = inExpRate*(0.3048); % as Expansion Rate (ft/d)

% convert units: 1ft^3 = 2.29568411e-5 acre feet
outVvector = outVvector*(2.29568411e-5);
```

```
outVDiffvector = outVDiffvector*(2.29568411e-5);
% METRIC convert units: 1 acre ft = 1233.48184 m^3
outVvector = outVvector*(1233.48184);
outVDiffvector = outVDiffvector*(1233.48184);


% change to 30-Day difference
outVDiffvector = outVDiffvector*30;


% convert units: 1 gal/min = 1/448 CFS
outQvectorGPM = outQvectorCFS*(448);     % GPM
% METRIC convert units: 264.172 gal = 1 m^3
outQvectorGPM = outQvectorGPM/(264.172);    % m^3/min


TimeDepSensVec(5,:) = outQvectorGPM(1,:);
TimeDepSensVec(6,:) = outQvectorGPM(length(inExpRate),:);
```

## Depth of drawdown sensitivity analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%% Depth of Drawdown sensitivity analysis %%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('%%%% Depth of drawdown sensitivity analysis %%%%')


% Constant Paramters
% inD = 1050; % Depth of drawdown (ft)
inT = 155; % as Transmisivity (ft^2/d)
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```matlab
inS = 2.00e-4; % as Storativity (unitless)
inExpRate = 5; % as Expansion Rate (ft/d)
% % Varied Parameters
inD = 900:10:1300; % Depth of drawdown (ft)
% inT = 2:2:480; % as Transmisivity (ft^2/d)
% inS = 2.00e-5:2.00e-6:2.00e-4; % as Storativity (unitless)
% inExpRate = 1:0.1:5; % as Expansion Rate (ft/d)


% Calculate Initial Q
outQinitial = (inT*inD) ...
    ./( 0.183*log10((2.25*inT*inSink)./(inr^2*inS)) ); % Initial Q (ft^3/d)
outQinitialCFS = outQinitial/86400; % Converting Q to CFS
% Calculate Volume of Water up to Sink Date
outVsink = outQinitial*inSink;


% Cacluating Q for Each Time
outQvector = zeros(length(inD),length(inTime));
outQvectorCFS = zeros(length(inD),length(inTime));
outVvector = zeros(length(inD),length(inTime));
outVDiffvector = zeros(length(inD),length(inTime));


for j = 1:length(inD)
    for i=1:length(inTime)
        currentDay = inTime(i);

        if currentDay < inSink
            % Radius at this point
            mineRadius = inr;
```

```
                % Q at this point
                outQvector(j,i) = outQinitial(j);
                outQvectorCFS(j,i) = outQinitialCFS(j);


                % Volume removed at this point
                currentVadd = 0;
                outVDiffvector(j,i) = outQinitial(j) * ( inTime(2) - inTime(1) );
                outVvector(j,i) = outQinitial(j) * inTime(i);
            else
                % Radius at this point
                dayDiff = currentDay - inSink;
                mineRadius = inr + dayDiff*inExpRate;


                % Q at this point
                outQvector(j,i) = (inD(j)*inT) ...
                    /( 0.183*log10((2.25*inT*currentDay)/(mineRadius^2*inS)) ); % Init
                outQvectorCFS(j,i) = outQvector(j,i)/86400; % Converting Q to CFS


                % Volume removed at this point
                currentVadd = outVsink(j);
                outVDiffvector(j,i) = outQvector(j,i) * ( inTime(i) - inTime(i-1) );
                outVvector(j,i) = outVvector(j,i-1) + outQvector(j,i) * ( inTime(i) -
            end
%           outVvector(j,i) = outVvector(j,i) + currentVadd;
        end
    end
```

*Appendix B.  MATLAB code used for sensitivity analysis*

```
% METRIC convert units: 1 ft = 0.3048 m; 1 ft^2 = 0.092903 m^2
inD = inD*(0.3048); % Depth of drawdown (ft)
inT = inT*(0.092903); % as Transmisivity (ft^2/d)
inS = inS; % as Storativity (unitless)
inExpRate = inExpRate*(0.3048); % as Expansion Rate (ft/d)


% convert units: 1ft^3 = 2.29568411e-5 acre feet
outVvector = outVvector*(2.29568411e-5);
outVDiffvector = outVDiffvector*(2.29568411e-5);
% METRIC convert units: 1 acre ft = 1233.48184 m^3
outVvector = outVvector*(1233.48184);
outVDiffvector = outVDiffvector*(1233.48184);


% change to 30-Day difference
outVDiffvector = outVDiffvector*30;


% convert units: 1 gal/min = 1/448 CFS
outQvectorGPM = outQvectorCFS*(448);     % GPM
% METRIC convert units: 264.172 gal = 1 m^3
outQvectorGPM = outQvectorGPM/(264.172);    % m^3/min


TimeDepSensVec(7,:) = outQvectorGPM(1,:);
TimeDepSensVec(8,:) = outQvectorGPM(length(inD),:);
```