Addendum: Assessment of Potential Groundwater Level Changes from Dewatering at the Proposed Roca Honda Mine

McKinley County, New Mexico

Prepared for:

Roca Honda Resources, LLC
4001 Office Court Drive
Suite 102
Santa Fe, NM 87507

Prepared by:

INTERA Incorporated
6000 Uptown Boulevard NE
Suite 220
Albuquerque, New Mexico 87110

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ABBREVIATIONS AND ACRONYMS

AF	acre-feet
AFY	acre-feet per year
BDR	Baseline Data Report
BLM	United States Bureau of Land Management
FWP	Fracture Well Package
GHB	General Head Boundary
INTERA	INTERA Incorporated
NMMMD	New Mexico Mining and Minerals Department
NMOSE	New Mexico Office of the State Engineer
RHR	Roca Honda Resources, LLC
USFS	United States Forest Service, Cibola National Forest Office
USGS	United States Geological Survey
USNAWFL database	United States National Atlas Water Feature Lines - SDC Feature Database
Westwater	Westwater Canyon Member of the Morrison Formation

DEFINITIONS

Anisotropy: Condition or situation for which physical properties vary with direction.

Aquifer: A geologic unit that conducts water at rates that yield economically significant quantities of water to wells and springs.

Aquitard: A geologic unit or confining bed that retards but does not prevent flow of water to an adjacent aquifer. It does not readily yield water to wells or springs.

Basalt[1]: A fine-grained, dark-colored, extrusive igneous rock that forms by the crystallization of lava flows.

Confined aquifer[2]: An aquifer bounded above and below by confining units of distinctly lower permeability than that of the aquifer itself.

Ephemeral[3]: A stream or reach of a stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times higher than the water table.

Groundwater: Subsurface water found in a zone of saturation, wherein all or nearly all pores are water-filled.

Groundwater flow model[5]: A numerical tool for describing and predicting water flow in the sub-surface by solving the equation for flow through porous or fractured media.

Hydraulic conductivity: The rate of water flow through a unit cross-section (e.g., 1 foot or 1 meter) under a unit gradient for groundwater head. It is defined by the permeability (the capacity of a material to transmit fluid) and the fluid properties of water.

Hydrostratigraphic unit[4]: A formation, part of a formation, or a group of formations of significant lateral extent that compose a unit of reasonably distinct (similar) hydrogeologic parameters and responses.

Intermittent[3]: A stream that ceases to flow occasionally or seasonally because evaporation and leakage to groundwater exceed the available water supply.

Isopleth[4]: A line or surface of constant composition.

MODFLOW[5]: The three-dimensional, finite-difference code for solving the governing equation for groundwater flow through porous media developed by the United States Geological Survey.

Perennial[3]: A stream that flows continuously.

Permeability[2]: The property of a porous medium to transmit fluids under a hydraulic gradient.

Porosity[5]: The volume of empty pore space (voids) within a material divided by the total volume of the material.

Shale[4]: A common clastic rock composed primarily of silt and clay-sized particles.

Specific storage[5]: The volume of water released from a unit volume of confined aquifer solely due to the expansion of water and aquifer compression when the pressure head decreases by a unit amount.

Specific yield[5]: The proportion of porosity from which water freely drains after the water table drops in an unconfined aquifer.

Spring[2]: A discrete place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

Storage coefficient[2]: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Transmissivity[5]: The product of the thickness of an aquifer and a representative hydraulic conductivity.

Unconfined aquifer[2]: An aquifer that has a water table.

* Unless otherwise indicated, definitions adapted from Bates and Jackson, 1984, Dictionary of Geological Terms, 3rd ed., Bantam Doubleday Dell Publishing Group, Inc., NYC, NY. 571 p.

1 Definitions adapted from: http://vulcan.wr.usgs.gov/Glossary/volcano_terminology.html

2 Definitions adapted from: http://or.water.usgs.gov/projs_dir/willgw/glossary.html

3 Definitions adapted from: http://nm.water.usgs.gov/glossary.html

4 Definitions adapted from: http://www.geo.utexas.edu/faculty/jmsharp/sharp-glossary.pdf

5 Definitions adapted from Domenico and Schwartz, 1998, Physical and Chemical Hydrogeology, 2nd ed., John Wiley and Sons, Inc., NYC, NY. 506 p.

1.0 THE RHR GROUNDWATER MODEL

In November 2011, Roca Honda Resources, LLC (RHR), submitted the report *Assessment of Potential Groundwater Level Changes from Dewatering at the Proposed Roca Honda Mine, McKinley County, New Mexico* (INTERA, 2011) to the New Mexico Office of the State Engineer (NMOSE) in support of RHR's application to dewater the RHR mine. The report was also provided to the Cibola National Forest Office (USFS), the New Mexico Mining and Minerals Department (NMMMD), the New Mexico Environment Department, and the New Mexico State Land Office.

The primary purpose of the report is to support RHR's mine dewatering application by providing the NMOSE with analyses of potential impacts on water resources that may result from the proposed mine dewatering. The report also provides the information required by the NMMMD and the USFS to support RHR's application for its mine permit, its Plan of Operations, and the third-party Environmental Impact Statement currently being prepared by Mangi Environmental Group.

An interagency technical group has undertaken review of RHR's document and has requested certain additional information and clarification. RHR has prepared this Addendum to respond to these requests. This Addendum discusses the overall philosophy and approach to the development of the RHR groundwater model constructed by RHR's consultant INTERA Incorporated (INTERA). It provides clarification regarding the model's intended uses and how it is an appropriate tool for those uses. It also provides a discussion of the success of the model and its application as a tool for assessing the potential impacts of mine dewatering.

This Addendum also addresses the inter-agency group's requests for information and clarification on the following technical areas:

- The rationale for selection of the boundary conditions used in the model, particularly the use of a General Head Boundary (GHB) condition to represent mountain front recharge in the Gallup Sandstone along the western flank of Mt. Taylor.
- The rationale for the hydraulic parameter values used in the model.
- The potential impact on springs of mine dewatering.
- The rationale for the representation in the model of the Mt. Taylor volcanic core as a low transmissivity zone.
- The availability and use in the RHR model of historical data from the Gulf Mt. Taylor mine.

- The physical sources of groundwater to the mine area during and after mine dewatering with reference to the aquifers that supply existing domestic wells.
- A more detailed discussion of numerical issues such as variations in mass balance error, river flow budget components, and water budgets.

Because some of the language and concepts used in the model report may be unfamiliar to persons not themselves involved in groundwater modeling, an attempt has been made to make this Addendum intelligible to the layperson. Those who want more technical detail regarding the model should refer to the modeling report, *Assessment of Potential Groundwater Level Changes from Dewatering at the Proposed Roca Honda Mine, McKinley County, New Mexico*, prepared for RHR by INTERA (2011), which describes the construction, calibration, and application of a groundwater flow model to answer the question "What potential impact will the construction and dewatering of RHR's new mine have on local groundwater levels and springs?"

1.1 The RHR Project

The RHR mine will be a new underground mine located 23 miles northeast of Grants, New Mexico, to the east of the Ambrosia Lake uranium mining district (Figure 1.1 in INTERA, 2011). The mine will be constructed to remove ore from rock located between 2,100 and 2,600 feet below land surface within the geologic formation called the Westwater Canyon Member (Westwater) of the Morrison Formation. Mine construction will take place in stages: first, a vertical mine shaft will be constructed in Section 16 of the permit area from land surface to 2,100 feet below land surface. The shaft will provide access to the rocks to be mined. Next, mine workings and tunnels will be developed horizontally from the bottom of the shaft within the rock of the Westwater and uranium ore will be removed. This will occur over a period of years, with the mine workings advancing out from the shaft location as mining continues. A second shaft is planned for construction several years later in Section 10 of the permit area to provide additional access to the ore. Finally, when mining is complete, the mine will be closed and the surface will be reclaimed.

The shaft will pass through three aquifers: the Gallup Sandstone, the Dakota Sandstone, and the Westwater. Mining will take place within the Westwater aquifer. In order to mine the ore and ensure the safety of the miners, it will be necessary for RHR to remove groundwater from aquifers penetrated by the mine workings and by the shaft. Pumping groundwater from the mine area is called "dewatering" the mine, although the term "depressurizing" the mine is more accurate for the purpose of the pumping. The pumping of water from the aquifers will be conducted to sufficiently reduce water pressure in the formations so as to reduce groundwater inflow to the mine and allow mining to be done safely and efficiently. The entire mine area will not be dewatered or depressurized at once: for approximately the initial two years, the area where groundwater will be removed will be limited to the area immediately around the mine shaft. The depressurized area will then expand slowly over time as the mine develops.

The groundwater pumping rate from the mine area will increase from 810 acre-feet per year (AFY) in the first year to 7,315 AFY in year five. The rate will continue at 7,315 AFY for ten more years through the anticipated life of the mine, and then the pumps will be shut off and water levels will be allowed to recover after mining has ceased. In total, 79,106 acre-feet (AF) of groundwater will be pumped from the Westwater, 1,410 AF of groundwater will be pumped from the Gallup Sandstone, and 232 AF of groundwater will be pumped from the Dakota Sandstone. The Dakota will be pumped only during the first few years of mine construction. The pumped groundwater will be treated in a water treatment plant to meet state or federal water quality standards, and a local rancher will use the water to irrigate pasture. An Application to Dewater an Underground Mine has been filed with the NMOSE by RHR. The application describes the proposed dewatering process in detail. Additional details regarding the construction, development, and operation of the mine are contained in RHR's *Mine Operation Plan, Revision 1, January 2012*, submitted to the NMMMD and the USFS.

Information available from the NMOSE and data collected by RHR as part of its baseline data collection efforts (RHR BDR, Rev. 1, January 2011ab) indicate that within 10 miles of the mine, few individuals rely on groundwater from the Westwater, the Dakota Sandstone, or the Gallup Sandstone. Some mining companies have established water rights to groundwater they pumped from the Westwater from the 1960s through the 1980s during mine dewatering that was used for milling and irrigation purposes. Some communities at a distance from the mine have established water rights to groundwater pumped from the Gallup Sandstone. The Dakota Sandstone is not typically relied on as an aquifer, although some individuals may be producing small amounts of water from it.

1.2 What is a Groundwater Model and Why Use One?

A "model" is constructed to represent a real thing or system with the purpose of answering specific questions about the real thing or system. Some models are physical models. A model airplane is a "model" of a real airplane, although it will not be expected to fly in the same way a real plane flies. Engineers test physical models of airplane wings in wind tunnels to better understand how wing design can improve airplane performance. Likewise, a physical model of a simple groundwater flow system might be constructed in a tank filled with sand and water. In this case, the flow of water through the tank could be directly observed and measured, allowing simple questions about a groundwater flow system to be asked and answered. However, representing a real, large-scale groundwater flow system with a physical model is difficult because of the size and the complexity of the real system. A physical model of a 1,000-square-mile aquifer may not be sufficiently accurate to answer the questions driving the construction of the model. Time passes at the same rate in the physical model and the real groundwater system, making it difficult or impossible to predict long-term future changes using the physical model. Physical models are also limited in the physical conditions and situations they can represent. The engineer's wind tunnel may not be able to provide hurricane-force winds with which to test the physical model of the airplane wing. To answer questions about the future or about situations beyond the limits of physical models, mathematical models must be used.

The physical flow of groundwater through porous materials can be expressed with differential equations. Using these equations, it is possible to construct mathematical models of simple and complex groundwater flow systems. A mathematical model for a simple groundwater flow problem can sometimes be solved easily using a calculator or paper and pencil. The solution for the simple system can then be compared against a physical model, like the water and sand in the tank. However, most natural aquifer systems are too large in size and too complex to be defensibly modeled using a simple mathematical model. Aquifer materials (sand, rock, etc.) typically exhibit heterogeneity and anisotropy – terms that simply mean that the ability of aquifer materials to transmit and store water may vary in different locations or in different directions within the aquifer. Geohydrologic boundary conditions are often complex. Boundary conditions are discussed in more detail in Section 2, but in brief, they are mathematical representations of the physical features or driving processes that control groundwater flow. Rivers, mountains, pumping wells, and geologic faults are examples of physical features or forces that influence groundwater movement and are represented in a mathematical model as boundary conditions. The number of mathematical equations needed to capture these important physical features and processes in order to answer the questions behind the model is almost always too large to be solved with analytical methods.

Solving complex flow problems is possible using numerical approximations of the groundwater flow equation by methods such as the finite difference method. That is to say, the groundwater flow equations can be re-written so they can be solved with the finite difference method using a computer. The set of commands used to solve a mathematical model on a computer is the computer program or code (Anderson and Woessner, 1992). A commonly used groundwater flow code is MODFLOW (McDonald and Harbaugh, 1988), developed by the United States Geological Survey (USGS) in the late 1980s and improved on many times in the last 30 years. The code is not a groundwater model, but a computer program that can solve groundwater flow problems once the appropriate information or input has been entered into the program. The model is created by dividing the area to be modeled into a grid and defining the initial conditions, boundary conditions, and hydraulic parameter values. Numerical groundwater flow models can reproduce observations made in a simple groundwater flow system or physical model. They can also closely reproduce observations made in a complex groundwater flow system, depending on how the mathematical model is divided up in space and time and the data used to characterize boundary conditions and parameters.

Each model, physical or mathematical, should be thought of as a tool to improve understanding of the system by answering specific questions. A successful model represents the physical processes and features important to the questions asked with sufficient accuracy in space and time. The level of accuracy required depends on the questions asked. This principle applies to all models, including those of groundwater flow. A successful numerical model of groundwater flow can:

- Assist in improving our understanding of the groundwater aquifer system.
- Provide useful estimates about cause and effect relationships in such systems.
- Be used to answer questions about the future.

For example, a groundwater flow model may be used to calculate what will happen to water levels 20 years after a new well field is constructed.

Groundwater models can incorporate complicated physical conditions and flow conditions and analyze complicated groundwater flow problems much better than humans can using intuition, and they can predict future changes in water levels. Most hydrologists share the opinion that "…use of a groundwater model is the best way to make an informed analysis or prediction about the consequences of a proposed action" (Anderson and Woessner, 1992).

1.3 Purpose and Use of the RHR Model

The ultimate purpose of the RHR groundwater flow model is to provide scientifically defensible answers to the question, "What potential impact will the construction and dewatering of RHR's new mine have on local groundwater levels and springs?" The RHR model is a tool specifically designed to answer this question. It was not designed to provide answers to every question about groundwater in the San Juan Basin.

The drawdowns that the model predicts will result from RHR pumping are shown on maps (Figures 5.5 to 5.10 in INTERA, 2011). The smallest contour shown on the maps is the 10-foot drawdown contour. The model can calculate contours for any specified drawdown, but the choice of 10 feet is consistent with the United States Bureau of Land Management's (BLM) current numeric groundwater modeling standard, which is based on an assessment of the accuracy of models. The BLM recently responded to a comment from the United States

Environmental Protection Agency about water resources that would be impacted by the proposed Crescent Dunes Solar Energy Project by stating:

> BLM's current numeric water-modeling standard is to predict impacts at the 10-foot drawdown contour or isopleths. The BLM believes that due to uncertainty in water model parameters, the models cannot accurately predict drawdown contours beyond the 10-foot isopleth. (BLM, 2010, FEIS, *Tonopah Solar Energy, LLC's Proposed Crescent Dunes Solar Energy Project*).

Although the RHR permit area is only 3 square miles in size, the area modeled includes the entire San Juan Basin. The entire basin was included in the modeled area for several reasons. Much of the groundwater flowing though the Westwater aquifer originates as mountain-front recharge far to the north along the San Juan uplift (see sections 2 and 3 of INTERA, 2011 and Sections 2 and 7 below). Some of the water leaving the Westwater aquifer discharges to the San Juan River at the western edge of the San Juan Basin (Sections 2 and 3 of INTERA, 2011 and Sections 2 and 7 below). Also, it is good modeling practice to place sufficient distance between these boundary conditions that drive flow in the Westwater and the Roca Honda permit area where dewatering will occur to ensure that any uncertainty in the boundary conditions does not affect the estimated water level declines. The basin is a large, complex hydrogeologic system, and it was not intended that the model would represent all areas and features of the basin with equal accuracy. The objective was to first create a reasonable model of the groundwater flow systems through the basin by correctly defining the geologic structure of the basin and the inflow to and outflow from the modeled area. After model construction was completed, the objective was to calibrate the model in the vicinity of the RHR permit area where more data specific to the area are available and impacts from the proposed pumping will be greatest.

The general structure of the San Juan Basin is well documented and the general pattern of groundwater flow is known (see Section 2 of INTERA, 2011). Even so, there are limited hydrogeologic data such as water levels, aquifer parameters, and recharge and discharge rates in the northern and western parts of the basin. The RHR model results are therefore not highly constrained by data in these areas, that is, there is a larger uncertainty about the simulated groundwater levels in these areas. However, because the basin is very large and the impacts of RHR pumping do not extend out very far, the limited amount of data at a distance from the mine is not important to the calibration of the model in the area of the mine. Most of the model calibration effort was focused within the southeastern part of the basin where the mine will be located. This is also the area for which the most hydrogeologic data, water levels, and previous pumping records are available. Model calibration focused on obtaining a reasonable mass balance for the inflow and outflow of groundwater through the basin, and then on matching historical water levels and pumping rates in the general vicinity of the RHR mine and Ambrosia

Lake. Site-specific aquifer test results were used where available to provide site-specific values for aquifer parameters. The tops and bottoms of geologic layers in the RHR permit area were generated from drilling at the RHR mine site.

1.4 Success of the Model

The RHR groundwater model is a tool for estimating changes in groundwater levels caused by the proposed mine dewatering. The modeling tool was designed and constructed to make scientifically defensible estimates of groundwater flow through the San Juan Basin in a regional (or large scale) sense, and to estimate groundwater flow in a more site-specific (or small scale) sense around the proposed Roca Honda mine. This means that the tool had to be constructed to represent the hydrogeologic processes and features that control groundwater flow through the basin in a regional way, while also making sure that the tool represented groundwater flow near the proposed mine in a more detailed or site-specific way.

The RHR model was created by combining the most recent hydrogeologic data for the area near the proposed mine, either generated by RHR through study of the permit area or collected from public and private sources, with data from past efforts to develop an understanding of the geology and hydrology of the San Juan Basin. The geologic framework and general understanding of hydrogeologic processes and features developed in the USGS groundwater flow model of the San Juan Basin (Kernodle, 1996) provided a foundation for the Roca Honda mine model. The USGS groundwater flow model was a tool constructed to determine the water balance (see Section 8 below) for the entire San Juan Basin under predevelopment conditions. It was built to answer a more limited set of questions than the Roca Honda mine model, which was built to not only simulate predevelopment conditions, but also to simulate the large-scale changes in groundwater levels from the start of mining to the present, especially the changes in groundwater levels that occurred in the Ambrosia Lake mining district. However, both the USGS and Roca Honda models share the same geologic framework, scientific basis, and modeling approach for capturing the most important processes and features that govern groundwater flow.

In general, the success of the Roca Honda mine model as a tool depends on how well it estimates observed groundwater levels over time. However, some locations in the modeled area are not as important as others. The model's success primarily depends on estimating groundwater levels in the mine vicinity: most important is the Westwater aquifer (the aquifer to be dewatered during mining), followed by the Dakota and Gallup aquifers, followed by the uppermost geologic units and the shales that separate the aquifers. To a lesser degree, the model's success depends on how well it estimates groundwater levels in the Westwater, Dakota, and Gallup aquifers elsewhere in the San Juan Basin. Lowest in priority is the model's ability to estimate groundwater levels in the remaining geologic units, particularly those that are separated by many hundreds or thousands of feet of shale and other low-permeability rocks from the three aquifers to be pumped by RHR.

Model success is measured by evaluating how well the model's estimated groundwater levels match observed groundwater levels. Estimated and observed groundwater levels were compared both quantitatively and qualitatively for the pre-development and transient 1930 through 2012 calibration simulations (Section 4, INTERA, 2011). The difference between an observed groundwater level (i.e., a groundwater level measured in a well) and an estimated groundwater level (i.e., a groundwater level predicted by a model at the model location that represents the well screen location for the observed groundwater level) is called a "residual." Residuals can be either positive (i.e., the model value is less than the observed value) or negative (i.e., the model value is larger than the observed value). A general measure of modeling success is achieving small absolute values of the residuals; that is, the values of the residuals are small without regard to positive or negative sign.

How small should residuals be? As described above, the answer depends on where and when the groundwater level observation was made. Observations made far from the area of interest – in this case the RHR mine – are not as important as nearer observations, so small residuals are desirable but not necessary for a successful model. The answer also depends on when the observation was made. It is more important for residuals to be smaller for observations made closer in time to the event being simulated in the model than for observations that were made decades earlier or later. The answer also depends on how the location of the observation is treated in the model. Most groundwater level observations are made in wells that were built with a screen that spans a single aquifer. A smaller residual is expected if the well is represented by a small-sized model grid block, whereas a larger residual can still be a successful measure of the groundwater level in a large-size grid block or in a grid block that simplifies two or more aquifers into a "hydrostratigraphic unit" or two or more hydrostratigraphic units into one combined unit. For example, in the USGS model and the Roca Honda model, the Crevasse Canyon Formation, Menefee Formation, and Point Lookout Sandstone are all treated as a single hydrostratigraphic unit and are represented as a single model layer, model layer 5, in the Roca Honda model.

The predevelopment and transient 1930-2012 period simulations for the Roca Honda model are very successful. The residuals for the RHR model are typically fairly small, on the order of tens of feet, within 20 miles of the permit area. Far from the mine area, they are typically larger, tens of feet up to between 100 and 200 feet. This is shown in the residual maps for the predevelopment simulation (Figures 4.4 to 4.6 in INTERA, 2011). Groundwater levels estimated by the model also show good agreement to groundwater level plots of observed and estimated groundwater levels over time (Appendix C in INTERA, 2011). This is particularly true in the area near the Roca Honda permit area. Plots of historical and model-estimated groundwater levels for the Westwater aquifer at three different times also match well (Figures 4.10 to 4.12 in INTERA, 2011).

Statistical analysis of the residuals for the RHR predevelopment model further supports the success of the RHR model. It is common, desirable, and part of good modeling practice to statistically analyze residuals for flow models that represent long-term conditions like the RHR predevelopment model. The results from the statistical analysis for the predevelopment model, described in Section 4.1.2 in INTERA (2011), revealed:

- An average residual of approximately 2 feet (Table 4.2 in INTERA, 2011).
- A normalized root mean square error for the residuals of 4.4% (Table 4.2 in INTERA, 2011), far below the 10% recommended maximum given by Spitz and Moreno (1996).
- A lack of any bias in the residuals (Figures 4.4 to 4.6 and 4.8 in INTERA, 2011).

There are two other measures of the success of the Roca Honda model. One is the low mass balance error in the predevelopment and transient 1930-2012 period models. Mass balance error for a flow model is based on the water balance and refers to the difference between inflows and outflows (see Sections 8 and 9 for additional discussion). The total mass balance error for the predevelopment model was -0.21% (Table 4.3 in INTERA, 2011). Mass balance errors should be less than 1%, and ideally less than 0.1% for groundwater flow models like the Roca Honda predevelopment model (Anderson and Woessner, 1992). Mass balance errors for the transient 1930-2012 simulation change over time, but are typically less than 1%. The few exceptions are discussed in Section 9 below. The other measure of success for the Roca Honda mine model is the agreement in water balance between the Roca Honda mine model and previous models. Previous studies of the San Juan Basin estimated a range of values for total inflow or outflow from the basin (see Section 4.1.2 in INTERA, 2011). The water balance for the Roca Honda mine model falls within the range of these previous estimates.

In conclusion, the RHR model is the best available tool for predicting groundwater level changes over time in the aquifers of interest. The RHR model is a very successful tool for this application based on several measures of success, including the primary measure: good agreement between estimated and observed groundwater levels near the area of interest.

2.0 BOUNDARY CONDITIONS

"Boundary conditions" represent the real world processes or features that control the inflow and outflow of groundwater in a real world flow system. Physical features that can be represented as boundary conditions can include the presence of impermeable rocks at the edges of an aquifer that block or redirect the flow of groundwater. Physical processes typically important to a groundwater flow model and which are included in the RHR model as boundary conditions are hydraulic processes, like rivers that can put water into the aquifer or receive water from the aquifer, pumping wells, or recharge from precipitation to the subsurface. Some boundary conditions are applied at the edges of the system, like the edges of aquifers. Many boundary conditions are set within the model, such as wells or rivers. Boundary conditions are required for any mathematical model of groundwater flow. The mathematical equations that make up the numerical flow model must be constructed so that they include these boundary conditions.

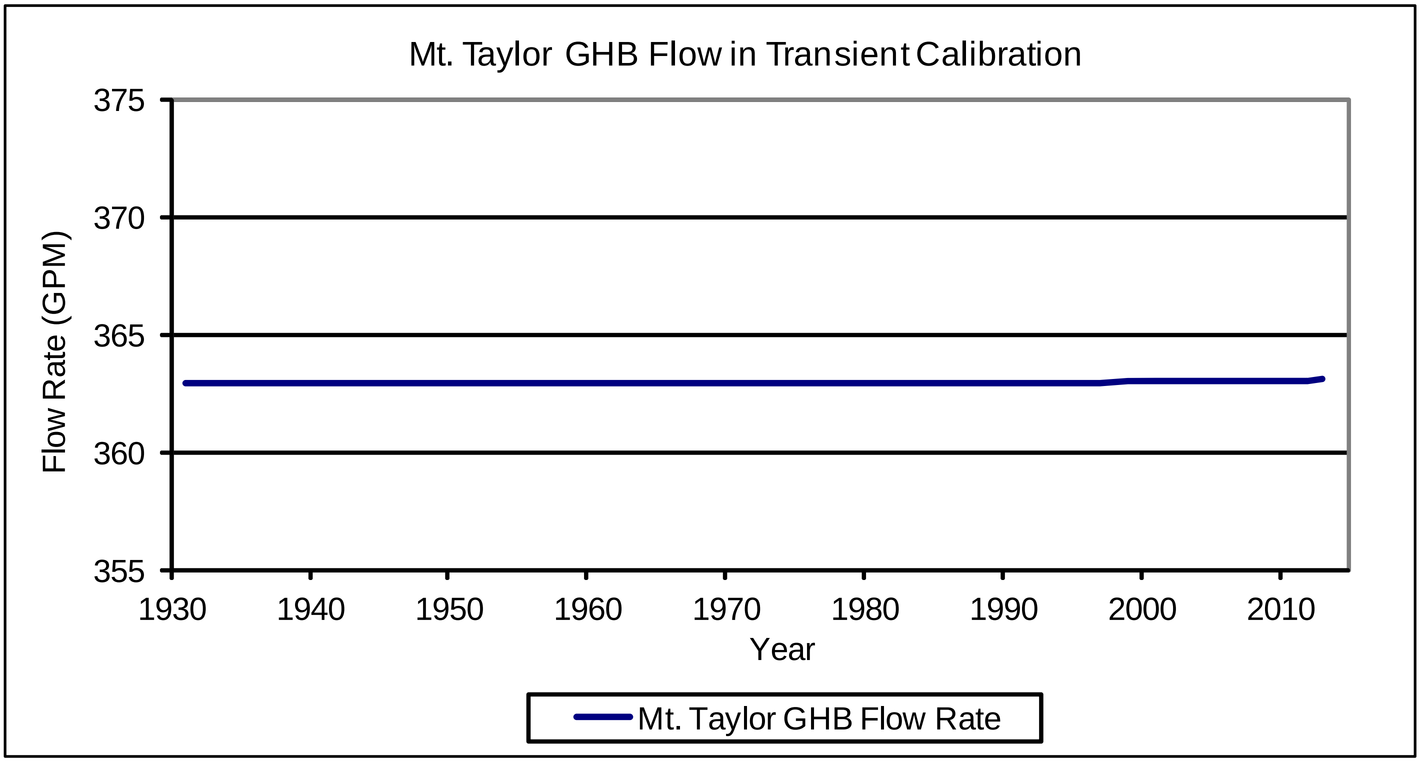
It is important that the boundary conditions used in a model provide a reasonable representation of the physical features and hydrologic processes on which they are based. Otherwise, there is a risk that the model will cause unrealistic amounts of water to enter or leave the groundwater flow system, resulting in unrealistic patterns of groundwater flow. The RHR model used the most recent USGS groundwater flow model of the San Juan Basin (Kernodle, 1996) as a foundation for selecting and applying boundary conditions governing groundwater flow in the San Juan Basin. Both the RHR and USGS models include boundary conditions that represent recharge, mountain-front recharge, rivers, ephemeral drainages, and steady pumping in the basin. The only difference in boundary conditions is that the Roca Honda mine model includes pumping that varies over time to represent historical mine dewatering, whereas the USGS model focused only on steady flow (unchanging with time). Use of incorrect boundary conditions, that is, boundary conditions that do not represent the real physical system, may create a model that incorrectly calculates potential future impacts, such as changes in water levels. For example, if a mountain range is present within the area modeled and that mountain range receives significant snow and rainfall, then a portion of that water probably enters the groundwater system along the base of the mountain. If this recharge is not put into the model as a boundary condition, then groundwater levels in the model could be too low in the vicinity of the mountain. This could cause the modeler to calibrate model hydraulic conductivities to values that are too low in the vicinity of the mountains.

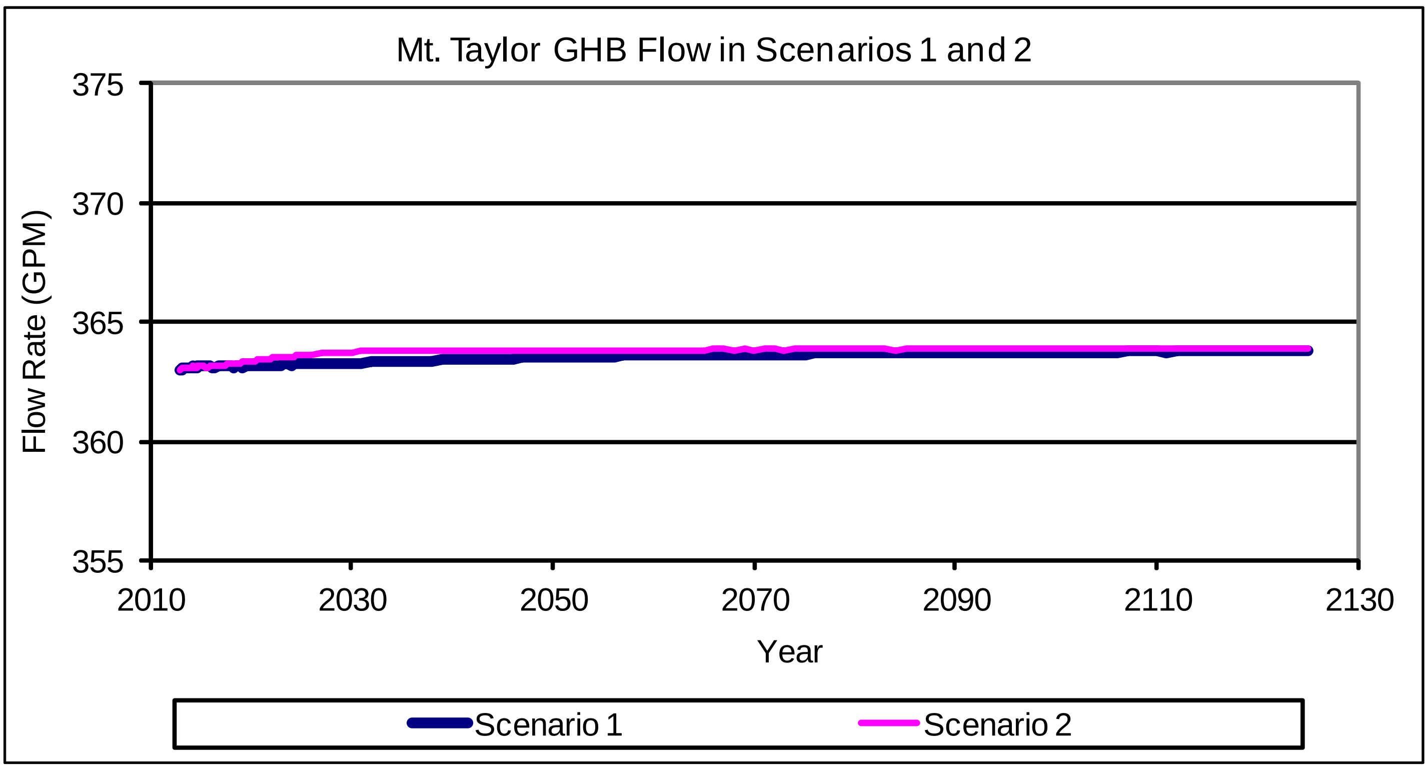
2.1 Mountain Front Recharge Boundary Conditions

Groundwater moves through porous rocks and sediments. In order for groundwater to flow, it is necessary for water to enter the system in areas of "high potential;" i.e., high elevation areas, and to discharge from the system in areas of "low potential;" i.e., low elevation areas. Water enters the San Juan Basin at high elevation areas where there is more precipitation; i.e., mountains, and leaves the basin at low elevation areas; i.e., rivers. Just as water enters a real groundwater system, water must be put into a groundwater flow model through boundary conditions. The water that enters the groundwater systems by infiltrating into aquifers that are exposed at the surface at the mountain front is called "mountain-front recharge." Mountain-front recharge can be put into the groundwater model by two types of boundary conditions. A GHB condition (McDonald and Harbaugh, 1988) was used to represent mountain front recharge along the western flank of Mt. Taylor and the Chuska Mountains at the south edge of the model (Figure 3.7 of INTERA, 2011). Specified flux boundaries were used to represent mountain front recharge at the northern edge of the model. Along a specified flux boundary, the amount of water entering or leaving the aquifer is specified in the model. At a GHB, either a groundwater level or a flux is specified. As described further below, both of these ways of representing recharge are appropriate and work well in the RHR model.

The aquifer that is recharged along Mt. Taylor and the Chuskas is the Gallup Sandstone. A GHB was defined along the areas where the Gallup was at or near land surface. The model calculates the amount of water that recharges the Gallup along the GHB by using the difference between the groundwater level at the boundary specified by the GHB and the groundwater level in the aquifer calculated by the model, multiplied by a term that represents resistance to flow between the boundary and the aquifer. As the groundwater level changes, the amount of water entering the groundwater system along the GHB changes. The previous USGS modeler, Kernodle (1996), also used the MODFLOW GHB Package to represent deep recharge along the Chuska Mountains.

GHBs are an appropriate way to represent groundwater recharge so long as they are located sufficiently far from groundwater stresses, such as wells, in the model. If a GHB is not located far enough away from wells, it may function as an artificial source of water to the wells. This does not occur in the RHR model. As shown in Figure 2.1, the flow into the Gallup supplied by the GHB cells that represent Mt. Taylor did not vary from a value of approximately 363 gpm in the transient calibration simulation, even with dewatering rates of up to 12,000 gpm from historical uranium mining. Similarly, Figure 2.1 also shows that the flow into the Gallup supplied by the Mt. Taylor GHB cells did not vary from a value of approximately 363 gpm in Scenario 1, which represents baseline conditions, and Scenario 2, which represents baseline conditions plus Roca Honda dewatering. The largest difference between the GHB flow rates for Scenarios 1 and 2 is approximately 0.4 gpm, which is a negligible difference. Mountain front recharge near Mt. Taylor remains constant in the transient simulations even with large amounts of historical or proposed dewatering. The GHBs used to represent the Chuska Mountains also show constant flow rates throughout each simulation.





Mt. Taylor GHB Flux Rate for Transient, Scenario 1, and Scenario 2 Simulations	
INTERA	Figure 2.1

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Mountain-front recharge from the mountains along the northern margin of the San Juan basin was simulated with "specified-flux" boundary conditions. Along specified flux boundaries, the amount of water that is put into aquifers in the model is defined and does not change even though water levels in the area may change. Specified amounts of water were put into the aquifers at and near land surface along the northern model boundary (the Cliff House Sandstone, the Menefee Formation, the Point Lookout Sandstone, and the Dakota Sandstone) in order to simulate recharge (Figure 3.7 of INTERA, 2011). Specified fluxes were also added to the Westwater rocks in the area where San Mateo Creek crosses the southern edge of the model in order to make the model match the high groundwater levels actually measured in wells there (Figure 3.7 inset of INTERA, 2011).

2.2 River and Ephemeral Drainage Boundary Conditions

The flow of streams can be "perennial," "intermittent," or "ephemeral." Perennial streams flow all the time; intermittent streams flow in some places along the stream course but not others, and ephemeral streams flow only after precipitation. If flowing streams are in connection with an aquifer, they can contribute water to the aquifer, or receive groundwater from the aquifer. Perennial streams or river boundary conditions are, therefore, often represented in a model as "head-dependent flux" along which the movement of water into the stream or out of the stream depends on the difference between the level of the water in the stream and the water level in the aquifer. The San Juan River, Animas River, Rio Puerco, Puerco River, and a short part of the Chaco River were represented in the RHR model with head-dependent flux boundary conditions for perennial rivers (Section 3.5 and Figure 3.5 in INTERA, 2011). All other drainages, including most of the Chaco River, the numerous washes, and the lowest reach of the Rio Puerco, were treated as ephemeral drainages, through which groundwater was lost to evaporation or plant transpiration. A boundary condition called a "drain" was used in the model to represent ephemeral drainages. A drain removes water from the aquifer. Using drains as a boundary condition in the RHR model for all ephemeral drainages is a conservative assumption because ephemeral drainages sometimes act to recharge groundwater whereas the drain boundary condition does not recharge the aquifer. The previous USGS flow model for the San Juan Basin (Kernodle, 1996) also used head-dependent flux boundary conditions for rivers and drains for ephemeral drainages.

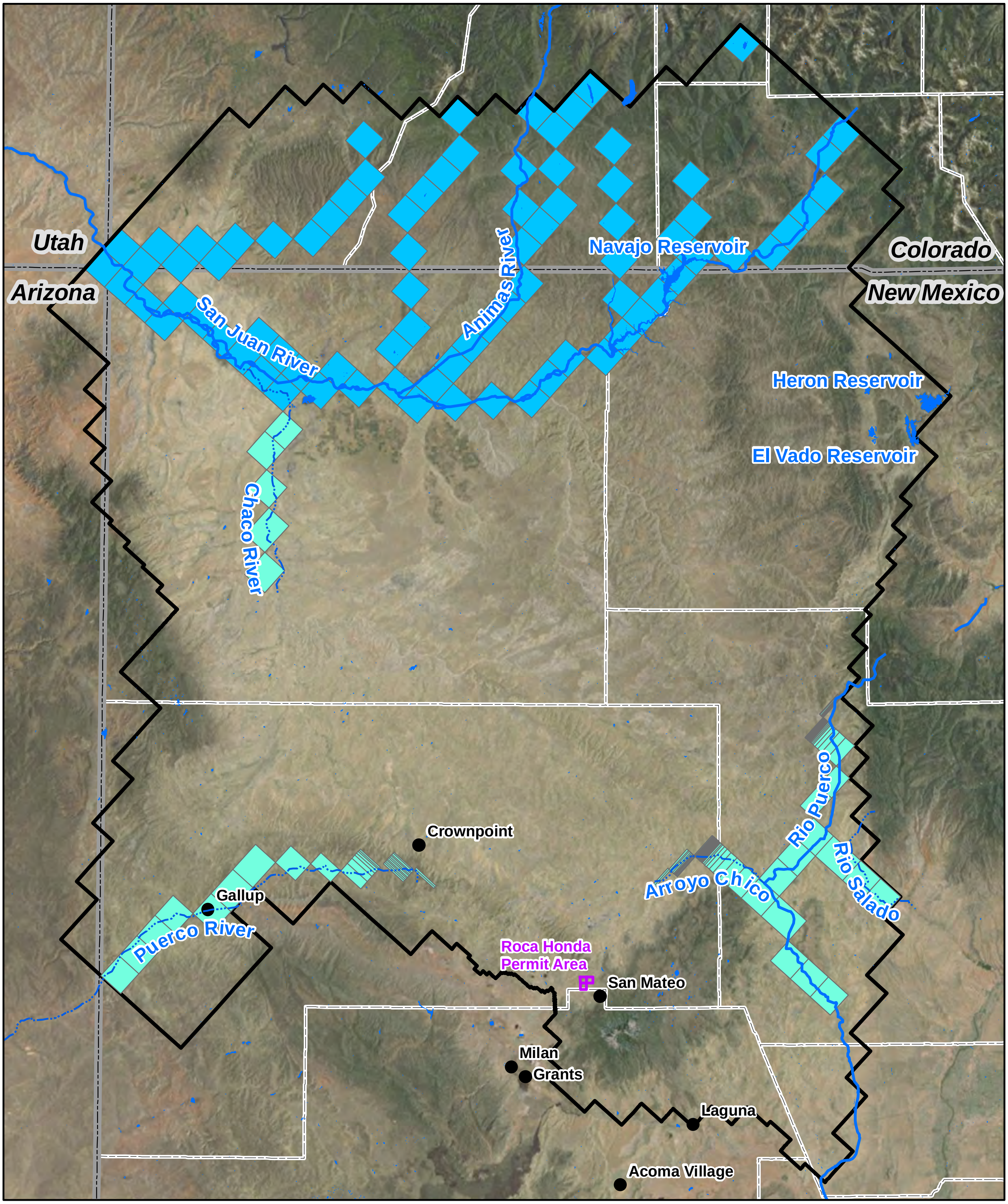
Model grid block cells were assigned river and drain boundary conditions by intersecting the model grid with a geographic information system product, the United States National Atlas Water Feature Lines – SDC Feature Database (USNAWFL database). This geographic database classifies each line as either a "stream" or an "intermittent stream." With some exceptions (as described below), model grid blocks intersected by "streams" were assigned a river boundary condition and grid blocks intersected by “intermittent streams” were assigned a drain boundary condition to simulate an ephemeral drainage. Figure 2.2 shows the “streams” and the model grid blocks that were assigned as river boundary conditions. Figure 2.3 shows the ephemeral drainages and the model grid blocks that were assigned drain boundary conditions.

River stages in the perennial streams were estimated by intersecting the USNAWFL database with the USGS digital elevation model, which provides ground surface elevation, and adding an assumed river depth of 10 feet (Section 3.5 in INTERA, 2011). River conductance, a parameter needed for the boundary condition, was calculated using the river dimensions in the grid block and a hydraulic conductivity value of 100 feet/day, which was the same value used by Kernodle (1996) in his USGS groundwater flow model for the San Juan Basin. As is discussed in Section 8.0, reducing this value to 1.0 foot/day eliminated some numerical fluctuations in flow between the stream and the aquifer. The Puerco River and the Chaco River are classified as “intermittent streams” whereas all of the Rio Puerco is classified as a “stream” in the geographic database. Based on the model response during calibration and review of the available data, the Puerco River, the lowest reach of the Chaco River, and the upper reaches of the Rio Puerco were designated as perennial streams. However, the river stage for these river boundary conditions was set to the estimated river bed elevation (Section 3.5 of INTERA, 2011).

As is shown in Figure 2.3, drain boundary conditions were assigned to model grid blocks that intersected the long “intermittent streams” from the (USNAWFL database and the lower reach of the Rio Puerco. In a few cases, drain boundary conditions were assigned to shorter “intermittent streams” where groundwater levels in the San Jose Formation extended above ground surface in the predevelopment calibration model. Drains were configured as described in Section 3.5 of INTERA (2011). The drain conductance parameter in the model was calculated assuming a bed hydraulic conductivity of 1 foot/day, as was done by Kernodle, (1996) in his earlier model of the San Juan Basin. Drain stage (the highest elevation that groundwater is allowed to reach) was set to the average surface elevation of the “intermittent stream” reach within each model grid block using data from the digital elevation model.

2.3 Dewatering and Pumping Wells Boundary Conditions

Wells remove groundwater from an aquifer, and by doing so, change water levels in the groundwater flow system. Well pumping is represented in a groundwater model as a certain kind of specified flux boundary. Whereas specified flux boundaries can be used to put a specific amount of water **into** a model along a recharge boundary, they can also be used to take a specific amount of water **out** of a model to represent well pumping. Future groundwater pumping from the RHR mine was simulated in the model by using the specified flux boundary condition with the rates and schedule shown in Table 1.1 of INTERA (2011).



Legend

- Roca Honda Permit Area
- River Cell for Perennial Streams
- River Cell for Ephemeral Streams
- USNAWFL Stream
- Model Domain
- State Boundary
- County Boundary
- USNAWFL Intermittent Stream

USNAWFL = U.S. National Atlas Water Feature Line database

0 10 20 40
Miles

N

Boundary Conditions for Rivers in Roca Honda Mine Model

INTERA

Figure 2.2

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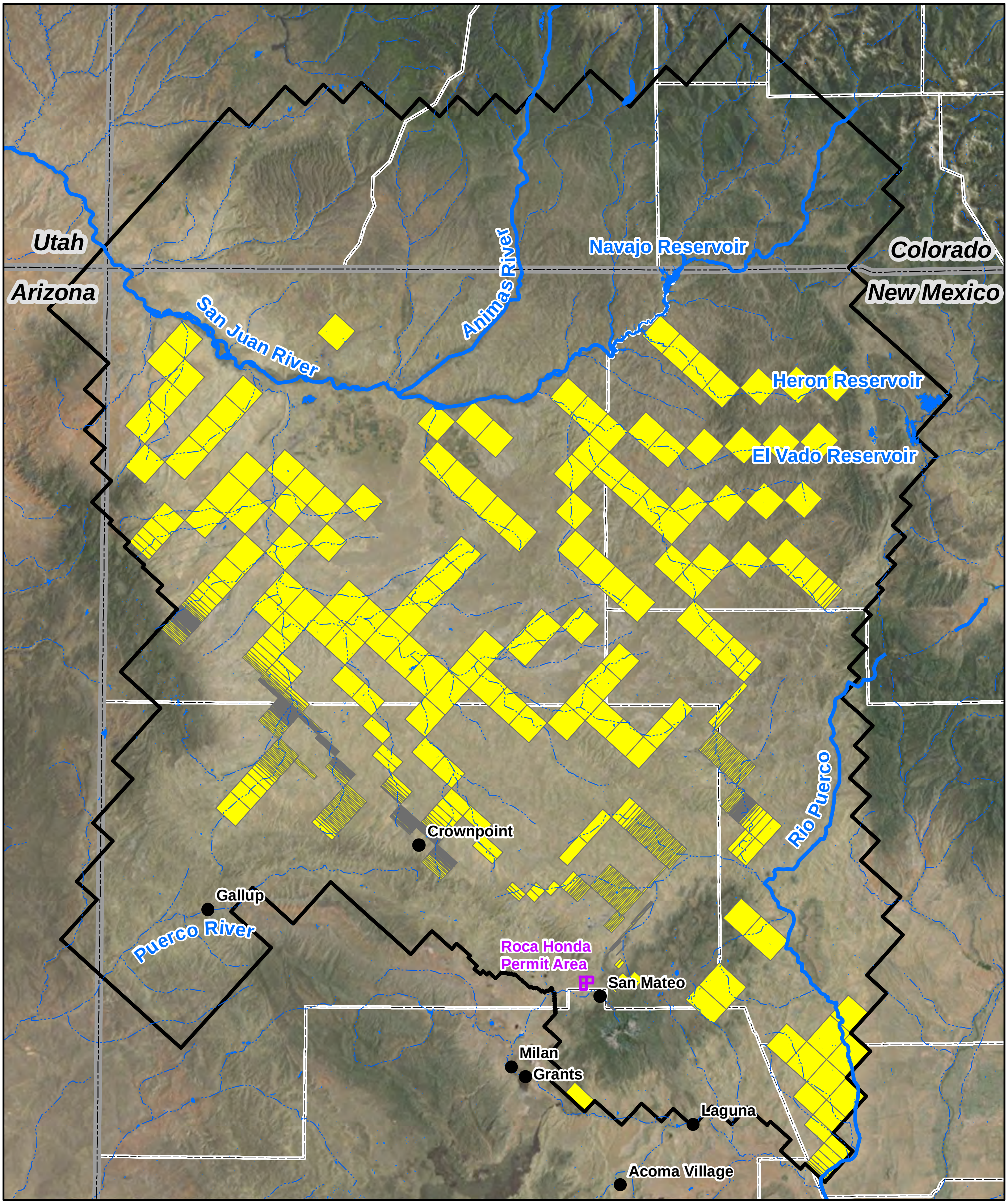

Legend

- Roca Honda Permit Area
- Drainage Cell
- USNAWFL Stream
- USNAWFL Intermittent Stream
- Model Domain
- State Boundary
- County Boundary

USNAWFL = U.S. National Atlas Water Feature Line database

Boundary Conditions for Ephemeral Drainages in Roca Honda Mine Model

INTERA

Figure 2.3

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Specified flux boundary conditions were placed in and around the model cells corresponding to the proposed RHR production shaft and mine workings to depressurize the Gallup, Dakota, and Westwater aquifers during shaft construction and to dewater the Westwater during mining. At full development, the mine area is represented as 70 model cells. Groundwater will be drained from these cells underground, and then pumped to the surface from thirteen points of diversion, including the mine shaft, as described in the Application to Dewater an Underground Mine that has been filed with the NMOSE by RHR.

The number of specified flux boundary cells were varied by trial and error so that the maximum rates stipulated in the dewatering permit application (Table 1.1 in INTERA, 2011) were achieved during the entire time for each period as described in the application. Using the maximum dewatering rates for the entire period results in a very conservative estimate of drawdown because the actual mine dewatering rates will increase gradually over time as the mine workings are extended during the 14-year mining period.

Specified flux boundaries were also used to represent historical pumping from water supply wells and Lee Ranch Coal Mine. Information about locations, aquifers pumped, and pumping rates (diversions) for the Crownpoint and City of Gallup public water supply wells and Lee Ranch Coal Mine wells was collected from the NM OSE's WATERS database and unpublished reports (Table 3.5 in INTERA, 2011).

Mine dewatering from historical uranium mining was represented using a particular type of specified flux boundary, one that allowed the model to adjust the flow rate in the wells as the groundwater level neared the bottom of the defined well. A MODFLOW SURFACT package called the "Fracture Well Package" (FWP) was used in the model to simulate pumping from the mine. The advantage to using the FWP over the very similar MODFLOW Well Package is that a model using the FWP will automatically decrease the flow rate in the wells as the groundwater level reaches the bottom of the model grid block. This is highly desirable, because otherwise unrealistically low groundwater levels will be calculated as the model not using a FWP package will continue to try to extract water at unsustainable rates.

The FWP is particularly useful when the amounts of historical pumping are not precisely known, or when the total volume of pumping may be known but when the pumping occurred is only approximately known. This is the situation for historical groundwater pumping from mines during the 1960s through 1980s: the total volume is fairly well known, but only estimates are available regarding which mines produced how much water and when. Historical mine dewatering rates were compiled from the 1980 New Mexico Environmental Improvement Division report entitled *Water Quality for Discharges from Uranium Mines in New Mexico,* from

NMBMMR Hydrogeologic Sheet 2 (1981) by Brod and Stone, information available in OSE files for individual mining companies, and records from mining company files. FWP was used to simulate the historical withdraw of groundwater from mines within Ambrosia Lake, the Church Rock Mine, the Gulf Mt. Taylor Mine, and the Johnny M Mine during 1930-2012 (Section 3.5 in INTERA, 2011). "Fracture" wells were placed in model grid blocks in the Dakota and Westwater aquifers in areas indicated as mine workings (see Figures 2.11 and 3.9 in INTERA, 2011) and assigned initial flow rates that were based on dewatering rates and volumes from reports about the historical mine dewatering (for example, Stone, et al., 1983). In order to ascertain whether the simulated pumping was reasonable, the simulated dewatering flows were calculated from the cell-by-cell mass balance files reported by the model. Cell-by-cell mass balance files are simply the rates or amounts of water that the model reports as inflow and outflow from each model cell. As is described in Section 4.2.2 in INTERA (2011), the simulated dewatering rates closely matched the historical data for the mining areas.

RHR model Scenario 3 estimates the effects on future groundwater levels of groundwater pumping associated with full utilization of existing large water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (Table 3.5 in INTERA, 2011). The wells included in this scenario (and in Scenario 4) were selected based on the aquifer pumped, the amount of water pumped, and proximity to the Roca Honda permit area. In general, only wells located in the southeastern part of the San Juan Basin that pumped 100 AFY or more from the Gallup Sandstone, Dakota Sandstone, and Westwater were included, but some wells with smaller rates near to the permit area were also included. If pumping records were not available, the maximum quantity of water specified in the water right associated with each of these wells was assumed. Many of the water rights are assigned to one or more Sections within a Township and Range, so the permitted diversion rates for these water rights were combined and assigned to one or more model grid blocks corresponding to those Sections within the Township and Range. The sum of pumping rates for all cells was assigned to a water right equaling the permitted diversion rate.

2.4 Areal Recharge Boundary Condition

Infiltration of precipitation to the aquifers over the model area was represented as areal recharge. As is discussed in Section 3.5 of INTERA (2011), areal recharge is applied to essentially all the same areas that had recharge in the earlier USGS flow model (Kernodle, 1996). The areas over which the areal recharge was applied are areas of relatively high elevations where relatively permeable materials such as the Point Lookout Sandstone, the Gallup, Dakota, and Westwater aquifers outcrop at the surface. Recharge areas and rates used in the RHR model are typically smaller and therefore more conservative than those used by Kernodle (1996); that is, the RHR model will calculate more drawdown for the same amount of pumping. The Roca Honda predevelopment mine model has a total flow rate of 1,628,926 cubic feet/day for areal recharge. Figure 3.6 (INTERA, 2011) shows the areas in the RHR model over which recharge is applied.

3.0 HYDRAULIC PARAMETERS

Hydraulic properties are the characteristics of the geologic materials that control the rate of movement of groundwater through an aquifer. Hydraulic properties that are required as input to the Roca Honda mine model include hydraulic conductivity, specific storage, and specific yield. These properties are defined in the "Definitions" section of this document and in the "Definitions" section of INTERA (2011) and are discussed here to provide clarification.

3.1 Hydraulic Conductivity

Hydraulic conductivity is a measure of the relative ease with which a porous medium; for example, a sandstone, allows groundwater to move through it. The higher a material's hydraulic conductivity, the easier it is to move a given amount of water through the material. Values of hydraulic conductivity for the aquifers used in the Roca Honda model were collected from the scientific literature and from the RHR Baseline Data Report (BDR), particularly Section 9, "Groundwater" (RHR, 2011a). Table 9-13 from the BDR report (RHR, 2011a) is presented as Table 3.1 below. Table 3.1 in INTERA (2011) presents the ranges of hydraulic conductivity values either reported or used in previous groundwater models for the various aquifers in the San Juan Basin. The values used in the RHR model fell within the ranges reported in these tables. For example, hydraulic conductivity values for the Gallup were reported to range between 0.1 and 1 foot/day (Kernodle, 1996 and Table 3.1 in INTERA, 2011), whereas the BDR reports a range of 0 to 70 feet/day. The calibrated hydraulic conductivity value used in the Roca Honda mine model for the Gallup was 1.5 feet/day (Table 4.1 in INTERA, 2011), a value that is slightly larger than the range reported by Kernodle (1996) but within the range reported by RHR (2011a).

Hydraulic conductivity values were selected for the RHR model by using site-specific data when available, then reported values for the San Juan Basin, and finally modeled values for the San Juan basin. Modeled values were preferred for those model layers that combined two or more geologic units into a single unit, such as layer 5 in the RHR model that represents a combination of the Point Lookout Sandstone, Menefee Formation, and Crevasse Canyon Formation. Site-specific data based on Roca Honda pump tests (see RHR, 2011a) were used for the Westwater and Gallup units in the vicinity of the Roca Honda mine.

Table 3.1. Summary of Aquifer Characteristics in the Vicinity of the Roca Honda Permit Area

Aquifer	Thickness Range in the San Juan Basin (feet)	Probable Thickness at the Roca Honda Permit Area (feet)	Transmissivity Range (median) ($feet^2$/day)	Hydraulic Conductivity (horizontal) (feet/day)	Hydraulic Conductivity (vertical) (feet/day)	Yield Range (gpm) (median)	TDS (mg/L)	Storativity	
								Specific Yield (Sy)	Storativity
Alluvium	10-80	0	700-1,450[h]	27[h]		<20[a]	590-14,000[a]	0.1 to 0.25[f]	NA
Menefee	400-1,000[b]	<100[g]	10-100[b]	0.05-0.01[b]	0.00001[f]	<20[a]	200-1,400[a]	0.1	0.0001
Point Lookout Sandstone	40-415[b]	<120[g]	<1-240[b]	0.002-0.02[cb]	0.01-0.002[c] 0.0002-0.0001[f]	To>50[a]	200-700[a]		0.000041[f]
Dalton Sandstone	80-180[bdg]	>100[g]	10-<50		0.0001[f]		4,500[a]	0.1	0.0001
Gallup Sandstone	90-700[b]	85[g]	15-390 (123)[bhf]	0.1-1.0[h]	0.002[f]	1-645(30)[ef]	1,200-2,200[h]	0.09[h]	0.000002 to 0.000033[f]
Lower Mancos Shale Sandstones	125[g]	125[g]	134[a]	0.05	0.002[f]	0-2,000[ag]	2,500-9,000[a]	0.1	0.0001
Dakota Sandstone	50-350[b]	50-60[g]	44-134[abf]	0.25-1.5[b]	0.002[f]	1-200 (13)[e]	600-1,400[a]	0.1	0.0001
Westwater	100-250[bg]	100-250[g]	50-500[ab]	0.1	0.001[f]	1-401 (32)[e]	360-2,200[a]	0.1[f]	0.0002 to 0.00002[bf]

[a]Brod and Stone, 1981
[b]Stone et al., 1983
[c]Craigg et al., 1989
[d]RGRC, 1994
[e]Dam, 1995
[f]Kernodle, 1996 (note hydraulic conductivity [vertical] values are model-simulated)
[g]Roca Honda Resources drilling
[h]GMRC, 1979a
[i]Pike, 1947

Hydraulic conductivity values can vary significantly over physical distance, so maps of transmissivity variations were used if available and appropriate. For example, the transmissivity map for the Morrison Formation presented by Stone et al. (1983) was used to divide the Westwater into a northern zone with low hydraulic conductivity and a southern zone with higher hydraulic conductivity. Kernodle (1996) used the same approach for his steady-state San Juan Basin groundwater flow simulations. These Westwater zones were further revised to include the Roca Honda site-specific values, a value specific to the Ambrosia Lake area, and a value specific to the Gulf Mt. Taylor mine. Records of pumping from the Ambrosia Lake area during historical mining were used to calibrate the Westwater hydraulic conductivity in the Ambrosia Lake area to 1.6 feet/day. The hydraulic conductivity value for the Gulf Mt. Taylor mine was adjusted in the model from 1.25 feet/day to 3 feet/day in order to produce the high dewatering flow rates reported by Gulf. These values are all within the range of up to 3.2 feet/day reported in the BDR for the Westwater near San Mateo (RHR, 2011a).

3.2 Storage

Storage properties of an aquifer define the amount of water that can be released from or taken into an aquifer. The storage coefficient is the volume of water that a confined aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. Specific storage defines that volume per unit volume of the porous medium. In other words, storage coefficient is specific storage multiplied times aquifer thickness. Site-specific storage coefficient values calculated from aquifer pump tests of the Gallup and Westwater were used in the model for the Roca Honda mine area. Where test values were not available, specific storage values were used from recognized hydrogeology references and multiplied times the thickness of the aquifer. Specific storage values typically range between 10^{-8} and 10^{-6} ft^{-1} for compacted sediments and from 10^{-4} to 10^{-6} ft^{-1} for sands (Smith and Wheatcraft, 1993).

Specific yield is the storage property for unconfined aquifer conditions. Specific yield is the "drainable porosity" of an aquifer; the volume of water that will be released by gravity from a saturated volume of rock or soil. It is only applicable in geologic units near the ground surface that have water table conditions. Specific yield typically ranges between 0.1 and 0.3 for sands and can be as low as 0.005 to 0.05 for shales (Smith and Wheatcraft, 1993).

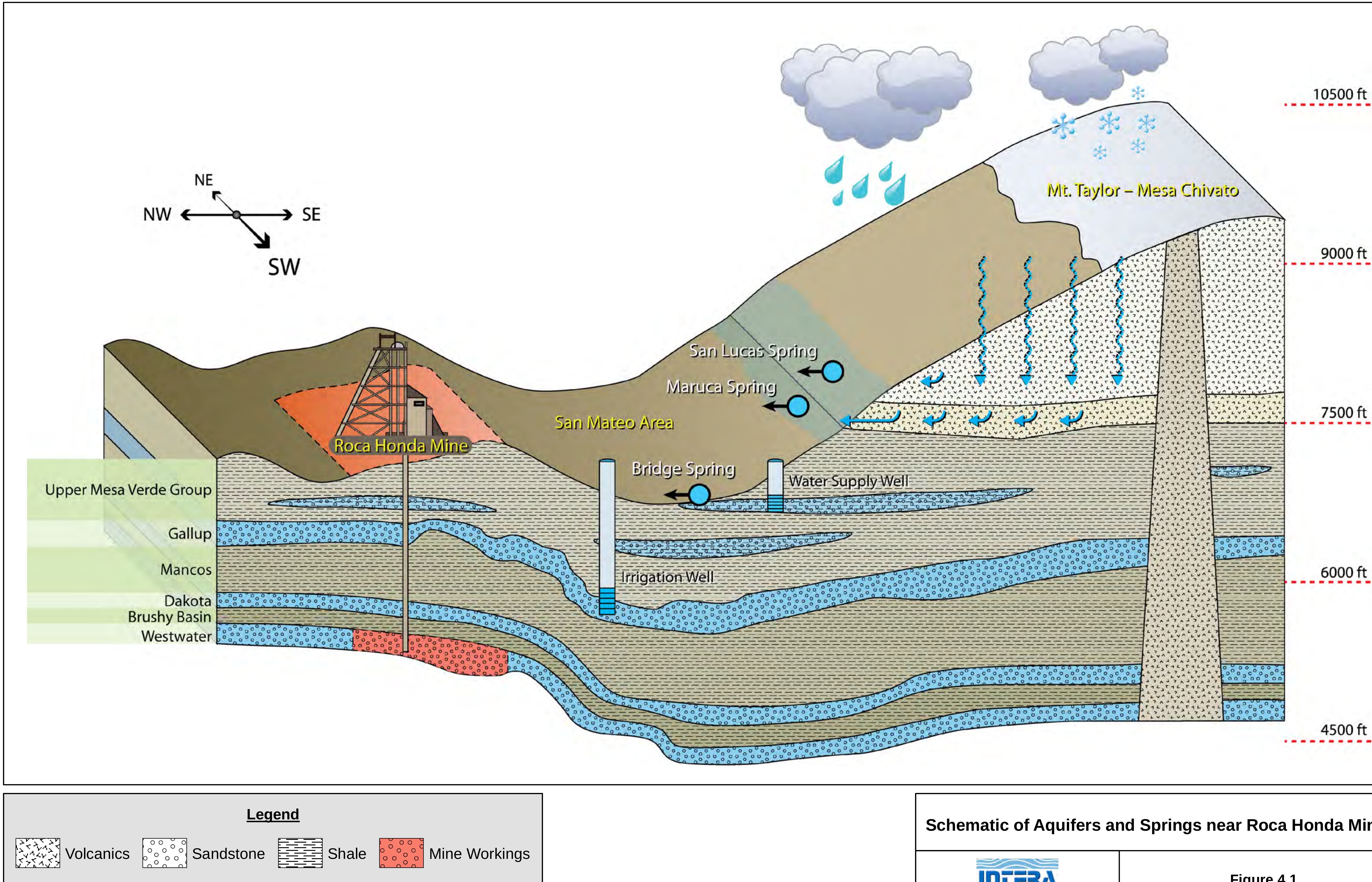
4.0 POTENTIAL IMPACTS ON SPRINGS

A spring is a place where an aquifer discharges groundwater to the land surface at a fast enough rate to create a flow of surface water. If the flow of a spring continues throughout the year, then the spring is called a perennial spring; if a spring does not flow continuously throughout the year, but rather after rainfall or snowmelt, it is called an ephemeral spring (Meinzer, 1942). Springs that are not related to rainfall or drought, and that turn themselves on and off at regular intervals through siphoning action, are called intermittent springs (Meinzer, 1942). Intermittent springs are not found in the RHR area.

Springs may also be classified according to the geologic formations from which they get their water. For example, they may be called lava-rock springs or limestone springs. They may also be classified by temperature or by the forces creating the spring; for example, whether they are created from gravity-driven flow or pressure-driven flow.

Because springs depend on groundwater flow, their flow can be affected by changes in the groundwater system to which they are connected. Figure 4.1 is a schematic diagram that shows springs, wells, aquifers, and aquitards near the Roca Honda permit area. Roca Honda mine workings are located over 2,100 feet below ground surface in the Westwater aquifer. Above it, from bottom to top, are the Brushy Basin aquitard, the Dakota aquifer, the Mancos Shale aquitard, the Gallup aquifer, Upper Mesa Verde Group shales with some sandstone (Crevasse Canyon Formation, Point Lookout Sandstone, and Menefee Formation), and the volcanic rocks from Mt. Taylor and Mesa Chivato. Wells in the vicinity of San Mateo typically draw water from the sandstone intervals in the upper Mesa Verde Group, but a few irrigation wells draw from the Gallup aquifer.

Figure 4.1 shows that snow melt and rain falling high on Mt. Taylor and Mesa Chivato supplies water to San Lucas and Maruca springs. Water that seeped into the ground flows through the fractured volcanic rocks, which are much more permeable than the underlying shales. The difference in permeability forces groundwater to discharge to land surface from the volcanic rocks at San Lucas Spring, and also at Maruca Spring, which flows from the underlying sediments (Figure 4.1). These two springs receive gravity-driven flow. The third spring, Bridge Spring, is shown receiving groundwater from a sandstone interval in the upper Mesa Verde Group sediments, and could be gravity-driven or pressure-driven flow (Figure 4.1).



Schematic of Aquifers and Springs near Roca Honda Mine

Figure 4.1

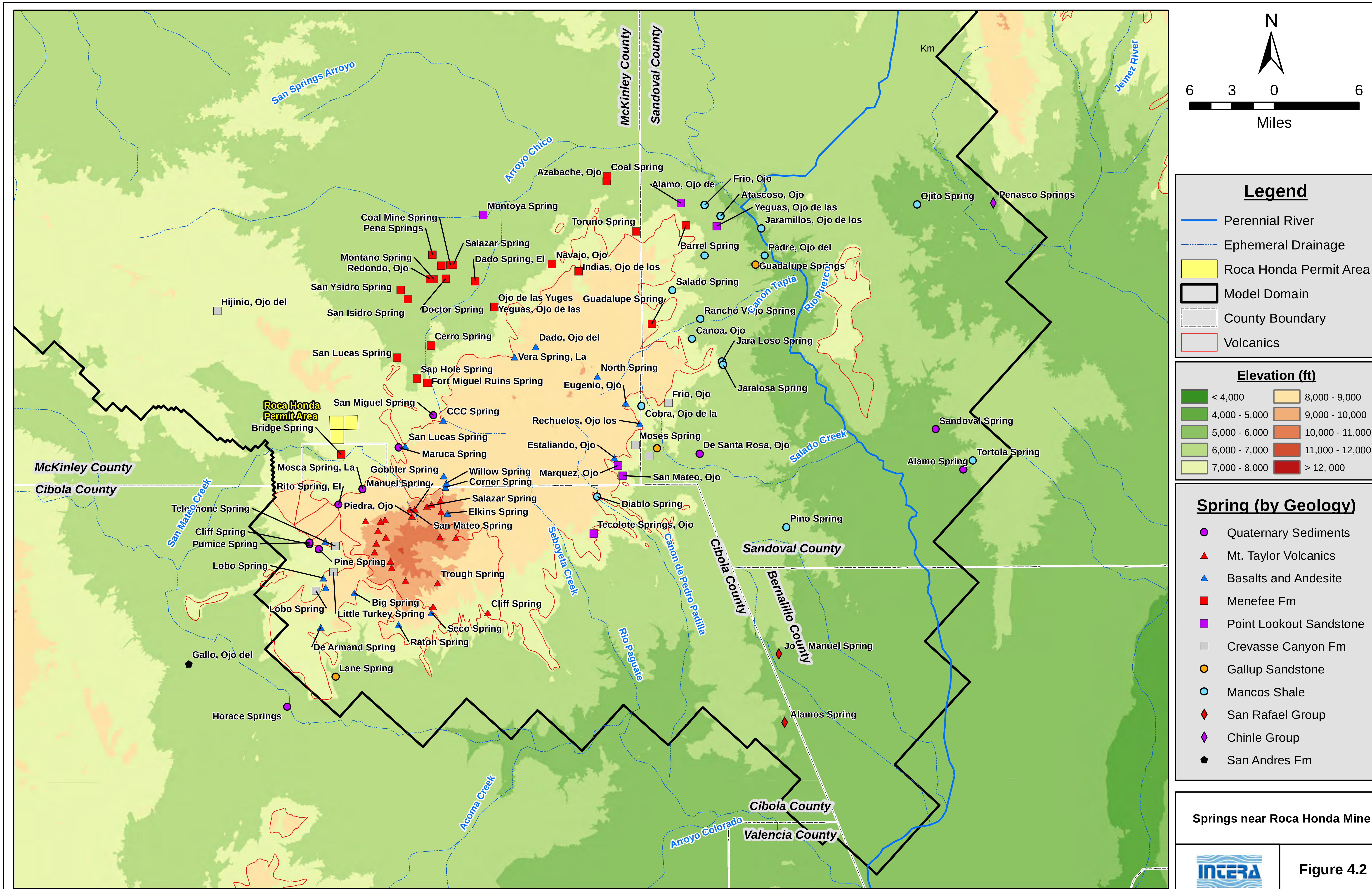
If the source of a spring is from a particular aquifer, and wells withdraw enough water from that aquifer so as to lower the groundwater level in the area of the spring, the flow of the spring may be reduced. If the groundwater level is lowered below the elevation at which the spring occurs, flow to the spring will cease. For example, if the non-RHR water supply well shown in Figure 4.1 draws enough water from the sandstone interval, it could reduce the groundwater level and flow rate at Bridge Spring. The reverse is also true: if the groundwater level rises because of increased recharge from precipitation or a reduction in pumping, a spring may flow at a higher rate, or flow out from the earth at a higher elevation.

Figure 4.1 demonstrates that a spring cannot be affected by changes in a groundwater system to which it is not hydraulically connected. For example, mine dewatering in the Westwater will not affect the flows at San Lucas and Maruca springs because these springs receive their water via gravity-driven flow from the Mt. Taylor-Mesa Chivato volcanic rocks, and the two aquifers are hydraulically disconnected by many thousands of feet of low-permeability shale (Figure 4.1). In general, if a spring flows out of an aquifer system that is physically located above the top of the groundwater surface of a deeper aquifer, and the two aquifers are hydraulically disconnected from each other, and pumping from that deeper aquifer cannot reduce the flow of the spring.

4.1 Springs within 50 Miles of the RHR Permit Area

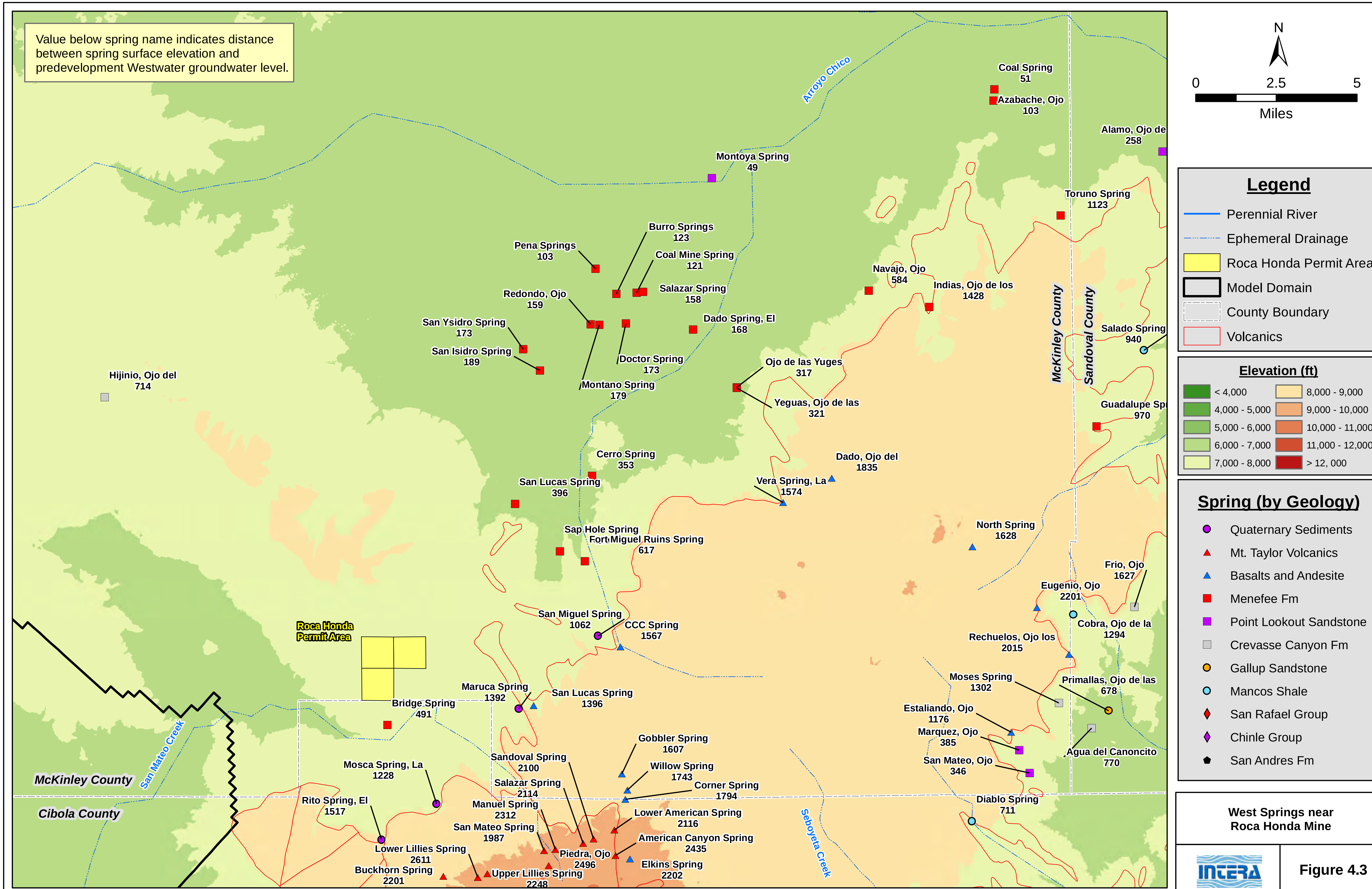
RHR and INTERA have reviewed the available information about springs within 50 miles of the RHR permit area, including geologic maps, *Geologic Framework, Regional Aquifer Properties, and Spring, Creek, and Seep Properties of the Upper San Mateo Creek Basin near Mount Taylor, New Mexico,* by Langman et al. (2011), and the New Mexico Environmental Institute 's baseline study for the Mt. Taylor Mine, *An Environmental Baseline Study of the Mount Taylor Project Area of New Mexico* (1974), which identified springs in the Mt. Taylor/RHR area. RHR also conducted field surveys to locate springs nearest the permit area, determine their sources, and sample them.

Over 100 springs were identified within 50 miles of the Roca Honda permit area (Figure 2.7 in INTERA, 2011 and Figure 4.2 of this Addendum). The springs flow from a number of rocks, including alluvium, volcanic rocks, sandstones, shale, and limestone. Forty-one of the 110 springs discharge directly from the volcanic rocks of Mt. Taylor and Mesa Chivato. Approximately 20 springs discharge at or near the contact between sedimentary and volcanic rocks along the edge of the Mt. Taylor-Mesa Chivato volcanic platform. The springs associated with the volcanics are all located between about 6,800 and 11,000 feet above sea level. Some of the springs near to the Roca Honda mine site; i.e., La Mosca, El Rito, Cliff, Pine, Pumice, San Miguel, and Maruca springs (Figures 4.3 and 4.4), are associated with the contact between the volcanics and landslide material (see geologic maps by McCraw et al. 2009 and Goff et al., 2008).



Springs near Roca Honda Mine

Figure 4.2



West Springs near Roca Honda Mine

Figure 4.3

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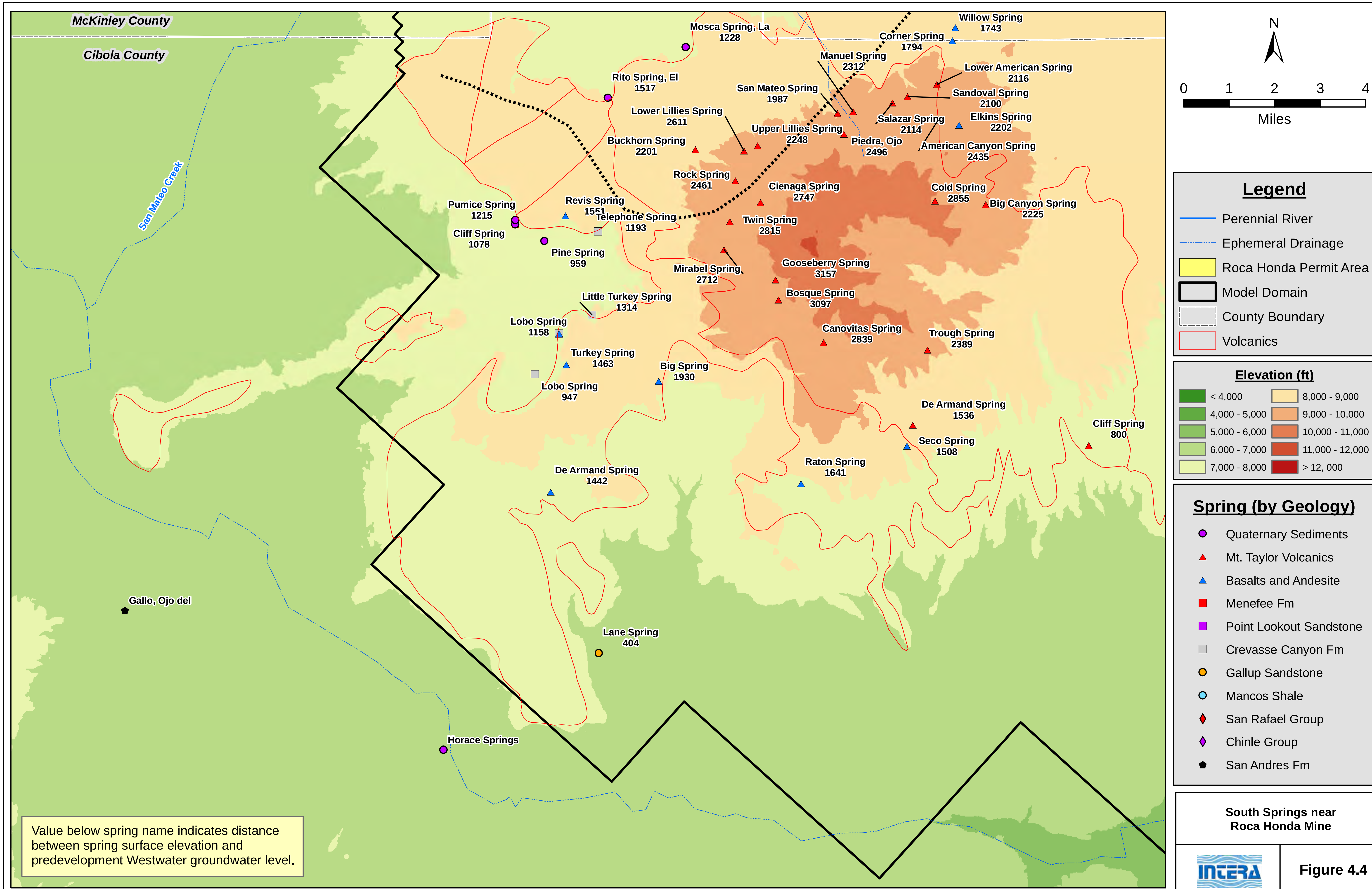

South Springs near Roca Honda Mine

Figure 4.4

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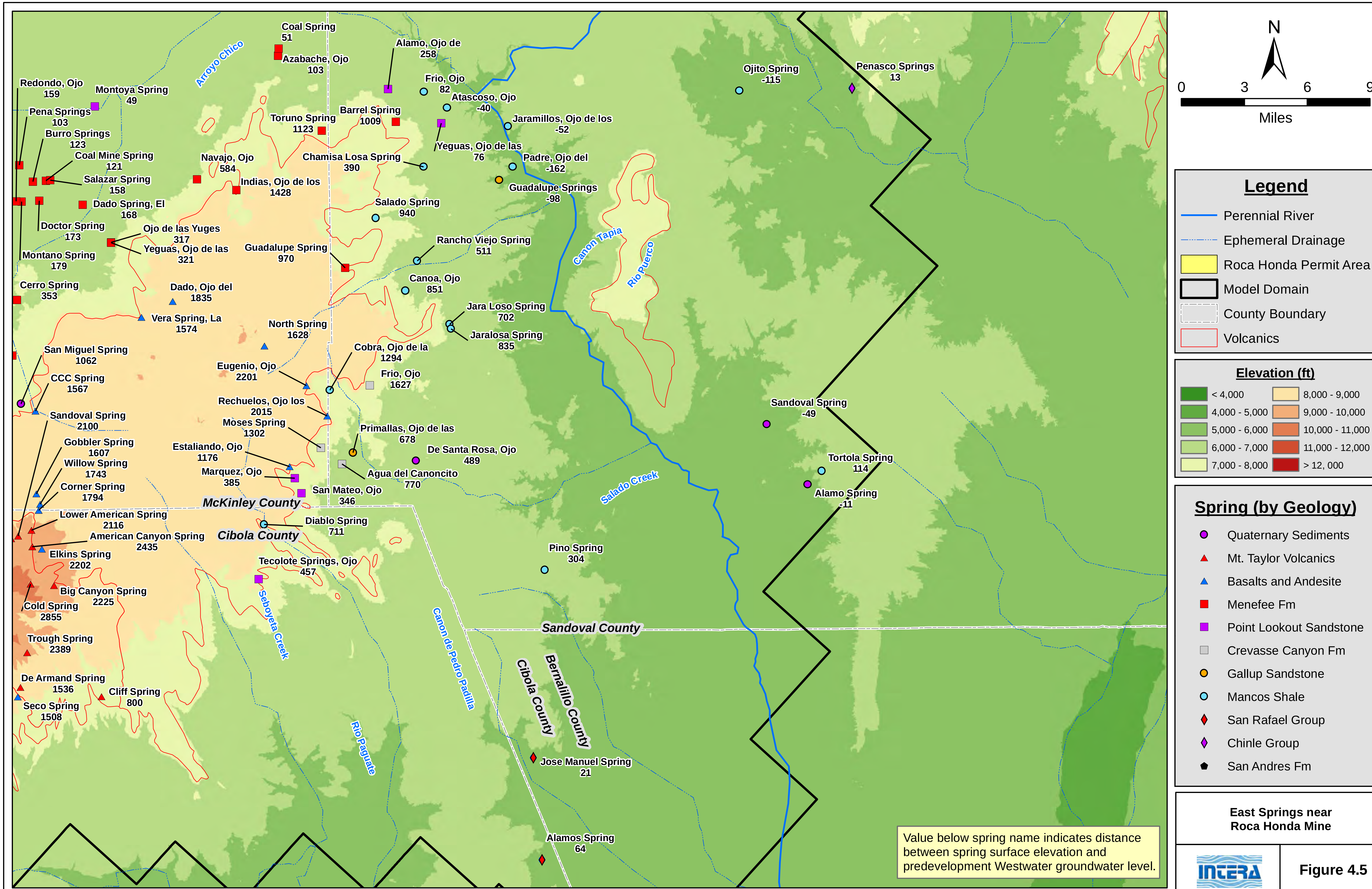

East Springs near Roca Honda Mine

Figure 4.5

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Springs that discharge from volcanics along the eastern and northern margins of the volcanic rocks at or near contacts with sedimentary rocks include Tecolote, Diablo, San Mateo, Marquez, Guadalupe, Salado, Moses, Jaralosa, and Canoa springs (Figure 4.5). Telephone and Little Turkey springs are found at the contact between the low-permeability Crevasse Canyon Formation and the volcanic rocks (Figure 4.4).

Some of the springs shown on Figure 2.7 of INTERA (2011) and Figure 4.2 get their water from other aquifers. Approximately 10 miles north of the Roca Honda permit area, El Dado, Salazar, Montoya, Coal Mine, Doctor, and Pena springs are located in the Menefee Formation (Figure 4.3), but near a local fault-controlled exposure of the Point Lookout Sandstone. Bridge Spring, the only spring located within a mile of the RHR permit area, is also located near the contact of the Point Look Sandstone and the Menefee Formation (RHR BDR, RHR, 2011b). Lane Spring is located near the contact between the Gallup Sandstone and the low-permeability mud rocks of the Mancos Shale and Crevasse Canyon Formation (Figure 4.5). Horace Springs flows from alluvium of the Rio San Jose (Figure 4.5) (Risser, 1982). Ojo del Gallo flows from rocks of the San Andres Limestone (Figure 4.5) (Frenzel, 1992). No springs flow from the Westwater or the Dakota Sandstone, i.e., the aquifers that will be pumped in the area of the mine.

4.2 Potential Impacts to Springs from RHR Mine Dewatering

In order to dewater the mine area, RHR is planning to pump groundwater mostly from the Westwater aquifer for the life of the mine. Small amounts of groundwater will also be pumped for shorter time periods from the Dakota Sandstone and the Gallup Sandstone while the mine shaft is being constructed. No groundwater will be pumped from any aquifer above the Gallup Sandstone. In the area where the dewatering wells will be installed, the top of the Gallup is located 800 to 1,200 feet below land surface, the top of the Dakota is located 1,600 to 2,000 feet below land surface, and the top of the Westwater is located 1,900 to 2,300 feet below land surface (Figure 4.1).

A spring could be impacted by RHR pumping under two sets of conditions. The first set of conditions is the most obvious: the source of the water to the spring is one of the three aquifers pumped, and the water level in the source aquifer is lowered below the elevation of the spring. For example, if a spring flowed from the Dakota at an elevation of 6,700 feet above sea level, and RHR pumping lowered the water level in the Dakota at the spring to 6,600 feet above sea level, the spring would probably dry up.

The second set of conditions involves dewatering an aquifer that is in hydraulic connection with another aquifer that provides water to a spring. Determining whether there is a hydraulic connection between the aquifer to be pumped and the spring involves establishing that the pressure in the aquifer to be pumped supports the groundwater level in the aquifer that supplies the spring with groundwater. The spring could be affected if pumping in the lower aquifer sufficiently lowers the supporting pressure.

Whether springs will be impacted by RHR dewatering under the first situation conditions is easy to assess. If the source of water to a spring is the Westwater or the Dakota, and water level declines occur in the source aquifer near the point where the spring issues, the flow of the spring would probably be impacted. This situation will not occur due to RHR pumping because no springs near the mine have the Westwater or the Dakota as their sources. Springs for which the Gallup is a possible source are discussed in Section 4.2.2.

Whether springs will be impacted by RHR under the second set of conditions is slightly more complicated to assess and explain. Figure 4.3 shows the springs nearest to the Roca Honda permit area. The difference between the spring elevation and the groundwater level determined for the Westwater aquifer under predevelopment conditions is noted next to each spring. The predevelopment groundwater level represents the highest expected groundwater level in the Westwater aquifer because it was estimated for a time prior to any large-scale pumping of the Westwater. The distances are typically very large, hundreds to thousands of feet, for nearly all of the 110 springs. RHR pumping will not impact these springs because there is no hydraulic connection between the Westwater and the spring.

In the case of a small number of springs, the predevelopment Westwater groundwater level is estimated to be below the spring elevation by less than roughly 100 feet or is higher than the spring elevation (negative values on Figure 4.5). As is discussed in Section 4.2.2, RHR pumping will not impact these springs because the distance to the RHR permit area is miles away and water level declines in the pumped aquifers will be small at the spring locations. RHR pumping will cause a small water level decline at Bridge Spring, which is located near the permit area. The estimated impacts are discussed in Section 4.2.2.

4.2.1. Impacts to Springs Associated with the Volcanics

The springs that flow from the volcanics or at contacts between the volcanics and other rocks that underlie them are located high on Mt. Taylor, at elevations of 6,800 to 11,000 feet above sea level, thousands of feet above the aquifers that will be pumped. The groundwater supplying the springs associated with the Mt. Taylor volcanics primarily originates as recharge from the relatively high rate of precipitation falling on the high-elevation volcanic rocks. The surface elevation of the volcanics ranges from the top of Mt. Taylor at approximately 11,100 feet above sea level to approximately 6,800 feet above sea level across the length of Mesa Chivato. Mt. Taylor is estimated to receive 39.9 inches per year of precipitation (PRISM Climate Group, 2012). Rain and snow melt seep into fractures within the volcanic and migrates down slope through these rocks until they are discharged at springs. These springs are gravity springs; i.e., the spring water drains out of the rocks under gravity and is not forced upward from below by pressure (Figure 4.1). There is therefore no hydraulic connection between these springs and the aquifers that will be pumped, and it will not be possible for RHR pumping in the permit area to change the groundwater level in the aquifer supplying these springs.

4.2.2. Impacts to Non-Volcanic Springs in the Model Area

Table 5.1 in INTERA (2011) shows that with the exception of Bridge Spring, negligible changes in water levels are predicted at non-volcanic springs in response to changes in groundwater levels in the Westwater, Dakota, and Gallup aquifers due to RHR pumping. Discharge from these springs will therefore be unaffected by RHR pumping.

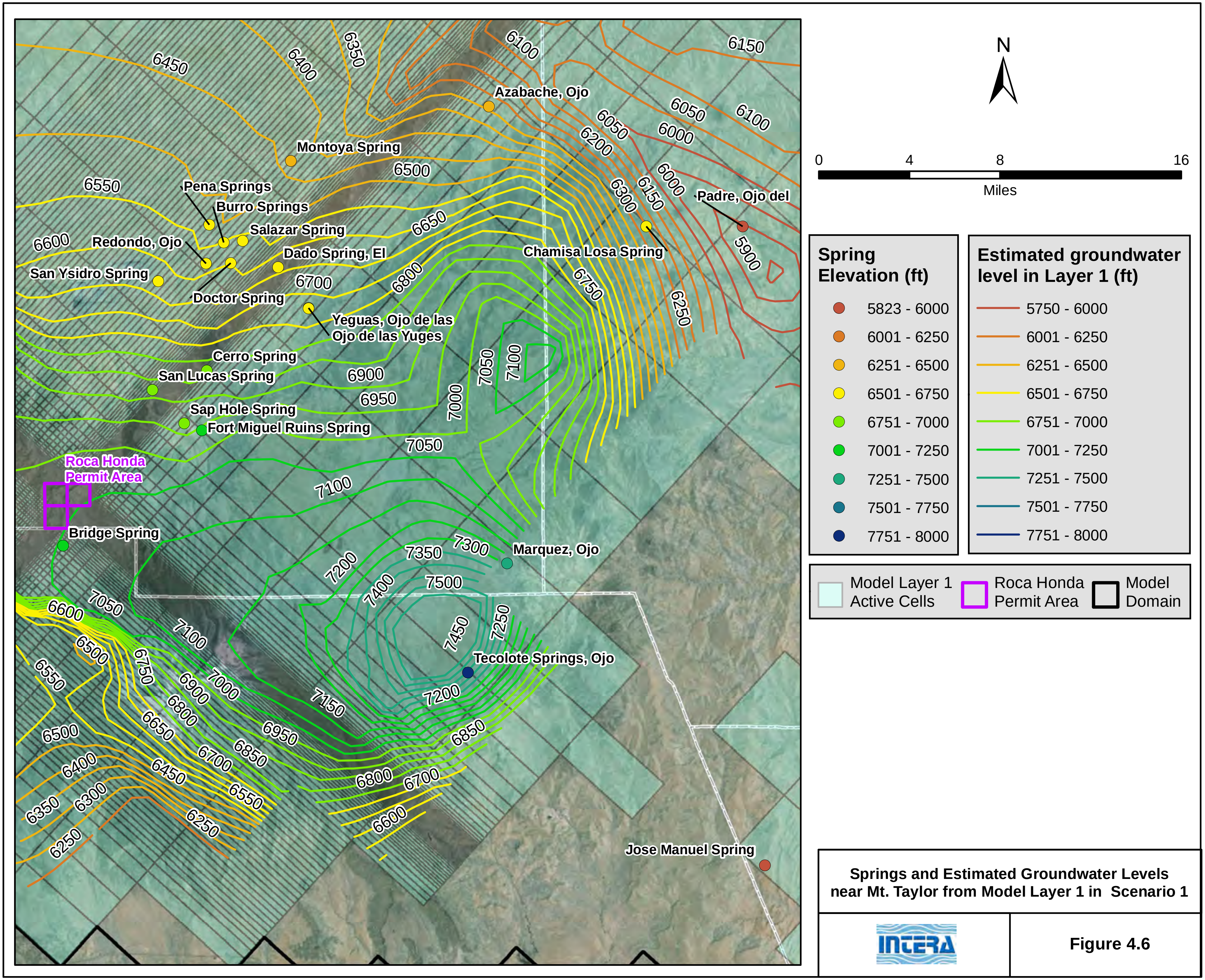
Figure 4.2 shows no springs that receive groundwater from the Westwater or the Dakota Sandstone. RHR pumping therefore cannot directly affect any springs flowing from these aquifers because there are none. Figure 4.2 shows that two springs flow from the Gallup Sandstone on the northeast side of the Mt. Taylor-Mesa Chivato area about 22 miles or more from the RHR permit area. Figure 4.4 shows one spring, Lane Spring, that is 17 miles from the mine site. The RHR groundwater model estimated changes in groundwater levels at these three Gallup Sandstone springs to be less than 0.01 foot.

Westwater predevelopment groundwater levels were predicted to be higher than ground surface at seven springs, shown in Figure 4.5 as negative numbers. These seven springs are located more than 30 miles from the permit area: Guadalupe Springs, Ojo del Padre, Ojo de los Jaramillos, Ojo Atascoso, Ojito Spring, Sandoval Spring (near Alamo Spring), and Alamo Spring (Figure 4.5). Seven other springs have estimated Westwater predevelopment groundwater levels that are less than 100 feet below the spring elevation: Montoya Spring, Coal Spring, Ojo Frio (near Ojo Atascoso), Ojo de las Yeguas (east of Mt. Taylor), Penasco Spring, Jose Manuel Spring, and Alamos Spring (Figures 4.3 and 4.5). Dewatering will not affect these springs because they are located far from the mine permit area and because there are thick low-permeability rocks between the land surface and the Westwater aquifer that will prevent pressure changes from affecting the springs (Figure 4.5).

For example, Bridge Spring is the closest spring to the RHR permit area. Figure 4.3 shows that the spring elevation is 419 feet above the predevelopment groundwater level for the Westwater aquifer. The RHR model estimates that the Westwater groundwater level is 660 feet below Bridge Spring in 2012 and that dewatering will decrease the groundwater level in the Westwater beneath Bridge Spring to a maximum of 910 feet below the spring elevation. The RHR model estimates that this 910-foot decrease in Westwater groundwater level will only decrease the groundwater level at Bridge Spring by 0.43 foot (Table 5.1 in INTERA, 2011). Figure 4.1 helps explain why the large decrease in Westwater groundwater level causes such a small change in the Bridge Spring groundwater level. The thick, low-permeability shale intervals between the Westwater aquifer and Bridge Spring reduce downward flow of groundwater to essentially negligible levels. Almost all of the water removed from the Westwater aquifer during dewatering comes from water stored in the Westwater, with the remainder coming from leakage from the Brushy Basin aquitard (see Section 7 below for a detailed explanation).

4.2.3. Predictions of Groundwater Levels at Springs in the Model Area

The RHR model was used to estimate groundwater levels at non-volcanic springs. Comparison of the spring elevations with the groundwater levels estimated by the RHR model for baseline conditions in 2012 (Scenario 1) were close (Figure 4.6). As shown on Figure 4.6, the top model layer contains groundwater at levels that are close to the elevations estimated for the springs. For the springs listed in Table 4.1, the match between spring elevation and estimated groundwater level in model layer 1 (the topmost layer where most springs would be found) is very good. A "good" match is considered to be one where the predicted water level does not differ from the spring's elevation by more than the range between the minimum and maximum land elevations found within the grid block. This is considered to be reasonable because, as shown in Table 4.1 below, each grid block represents a physical area within which land surface elevations vary with topography. For the springs listed in Table 4.1, predicted groundwater levels in the top model layer are very good. The difference between the predicted groundwater level and the estimated spring elevation is typically within several tens of feet for all springs but two. Two springs in Table 4.1 show differences between estimated spring elevation and simulated groundwater level of more than 100 feet. Even though the simulated groundwater level for Fort Miguel Ruins Spring is 133 feet below the estimate spring elevation, the match is "good" because the groundwater level still falls within the range of surface elevations for the model grid block containing this spring. The only match that is not "good" is for Ojo del Hijinio; however, surface elevation for this spring lies over 700 feet above the Westwater aquifer's predevelopment water level, so this spring will not be affected by Roca Honda dewatering.



Springs and Estimated Groundwater Levels near Mt. Taylor from Model Layer 1 in Scenario 1

INTERA

Figure 4.6

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Table 4.1. Spring Elevations and Groundwater Levels Calculated by the RHR Model

NAME	Grid Minimum Elevation (feet)	Estimated Spring Surface Elevation (feet)	Grid Maximum Elevation (feet)	Range in Grid Elevation (feet)	Simulated Model Groundwater Level (feet)	Difference Between Simulated Head and Elevations (feet)	
						Spring	Grid Minimum
Bridge Spring	**7037**	**7043**	**7053**	**16**	**7052**	**9**	**15**
Burro Springs	**6499**	**6563**	**6660**	**161**	**6528**	**-35**	**29**
Cerro Spring	**6824**	**6844**	**7165**	**341**	**6844**	**0**	**20**
Coal Mine Spring	6538	6556	6715	177	6554	-2	16
Dado Spring, El	**6535**	**6597**	**6692**	**157**	**6637**	**40**	**102**
Doctor Spring	**6574**	**6603**	**6791**	**217**	**6568**	**-35**	**-6**
Fort Miguel Ruins Spring	**6961**	**7098**	**7460**	**499**	**6965**	**-133**	**4**
Hijinio, Ojo del	7244	7277	7335	91	6986	-291	-258
Montano Spring	6515	6616	6679	164	6544	-72	29
Montoya Spring	**6368**	**6434**	**6745**	**377**	**6411**	**-23**	**43**
Ojo de las Yuges	**6702**	**6739**	**7319**	**617**	**6708**	**-31**	**6**
Pena Springs	6519	6545	6650	131	6511	-34	-8
Redondo, Ojo	**6509**	**6596**	**6672**	**163**	**6544**	**-52**	**35**
Salazar Spring	**6558**	**6595**	**6745**	**187**	**6563**	**-32**	**5**
San Isidro Spring	6601	6661	6765	164	6620	-41	19
San Lucas Spring	**6899**	**6901**	**7352**	**453**	**6901**	**0**	**2**
San Ysidro Spring	**6604**	**6646**	**6781**	**177**	**6620**	**-26**	**16**
Sap Hole Spring	**6902**	**6923**	**7086**	**184**	**6923**	**0**	**21**
Yeguas, Ojo de las (west of Mt. Taylor)	**6702**	**6745**	**7319**	**617**	**6708**	**-37**	**6**

Springs in bold are from Table 5.1 of INTERA (2011).

4.2.4. Impacts to Springs Located Outside the Modeled Area

Two springs shown in Figure 2.7 of INTERA (2011) and Figure 4.2 are not within the area of the Roca Honda model. Ojo del Gallo and Horace Spring are located south of the modeled area in geologic units that are not in hydraulic connection with the aquifers that will be affected by Roca Honda dewatering.

Ojo del Gallo discharges groundwater from the San Andres Formation (Frenzel, 1992). The San Andres is the sole source of groundwater for this spring and its flows have decreased as pumping for agriculture has decreased groundwater levels in the San Andres. The San Andres Formation lies far beneath the Westwater, Dakota, and Gallup aquifers elsewhere in the San Juan Basin. Thick shales and other low-permeability units including the Recapture Member of the Morrison Formation, the well-cemented units of the underlying San Rafael Group, and the thick, low-permeability mudstones of the Chinle Formation (see Figure 2.4 of INTERA, 2011) separate the San Andres from the overlying Westwater. Dewatering at the Roca Honda mine cannot affect groundwater levels in the San Andres Formation because the groundwater in the geologic units that will be pumped is not in connection with the groundwater that flows out of the spring. The groundwater systems of the nearest saturated part of the Westwater and the San Andres Formation are separated by hundreds of feet of low permeability materials, and the hydraulic head in the Westwater is upward, not downward.

Horace Spring is found where volcanic basalts meet the alluvium of the Rio San Jose just beyond the southern boundary of the Roca Honda mine model (Figure 1.1). The source of the spring water has been reported as either alluvium (Risser, 1982) or the San Andres Formation (Frenzel, 1992). According to Frenzel, the alluvium receives groundwater discharge from the San Andres Formation upriver from Horace Spring (Frenzel, 1992). A recent geochemical investigation demonstrated that the water chemistry of Horace Spring is indicative of the San Andres Formation (Wolf, 2010), the same aquifer that provides water to Ojo del Gallo. Roca Honda dewatering will not affect Horace Spring for the same reasons that it will not impact the Ojo del Gallo.

4.3 Summary

Only one spring, Bridge Spring, will be affected by the proposed dewatering. The RHR model estimated that the groundwater level at Bridge Spring, which is located near the contact of the Point Lookout and the Menefee within a mile of the permit area, will be reduced by 0.43 foot. No other springs will be affected by RHR dewatering.

Springs associated with the Mt. Taylor volcanic rocks, located between elevation 6,800 and 11,000 feet above sea level, are separated from the Westwater aquifer by thousands of feet of shale-rich sediments, and receive their water from the Mt. Taylor and Mesa Chivato volcanics. They therefore have no hydraulic connection with the Westwater aquifer and cannot be affected by RHR pumping in the permit area.

No springs that receive groundwater from the Westwater or the Dakota Sandstone were identified within 50 miles of the permit area. Dewatering will not affect springs that receive their groundwater from other non-volcanic rocks because the springs are located far from the mine permit area and because there are thick, low-permeability rocks between the land surface and the

Westwater aquifer that will prevent pressure changes in the Westwater due to RHR pumping in the permit area from affecting the springs.

Ojo del Gallo and Horace Spring flow from aquifers that are not in hydraulic connection with the Westwater aquifer. Therefore these springs cannot be affected by RHR pumping in the permit area.

5.0 MOUNT TAYLOR VOLCANIC CORES

Mt. Taylor is a volcano that lies roughly nine miles southeast of the permit area. Lava moved up from deep in the earth out of Mt. Taylor and flowed out, building up the mountain. The core of the mountain is lava that did not make it to the surface, but cooled in place. Mt. Taylor is part of a larger volcanic field that includes Mesa Chivato to the northeast and Grants Ridge to the southwest. Mesa Chivato is an area of hundreds of fissure vents through which lava erupted onto land. The vents are typically a few meters wide by many kilometers long (Kelley, 2008). Hundreds of basalt vents that are oriented both northeast and west-northwest, depicted as dots on Figure 5.1, are also present on the mesa (Kelley, 2008). These features were conduits or pipes that connected the deep lava source to the land surface and allowed lava to flow vertically through the intervening sedimentary rocks, including the Westwater, the Dakota, the Gallup, the Point Lookout, the Crevasse Canyon and the Menefee. When the flows and eruptions ceased, the lava in the pipes and fissures solidified. Figure 4.1 and Figures 2.5ab of INTERA (2011) depict examples of this cross-cutting for a few volcanic conduits in the geologic cross-sections.

The underground presence of the cooled lava within the sedimentary rocks influences groundwater flow through the aquifers. Wherever the volcanic rocks cross cut the aquifers, the ability of the aquifers to transmit water, i.e. their permeability, is decreased because in general, volcanic rocks have a much lower permeability than sandstone aquifers. Porosity and permeability can also be decreased by the intense heat of the volcanic intrusions, which alters the sandstones, and the movement of the intruding volcanic material, which disturbs and deforms the aquifer material. Based on these influences, it was apparent that it was appropriate to include a zone of reduced permeability beneath Mt. Taylor and Mesa Chivato to represent the presence of the volcanic lava within the sedimentary rocks.

In order to evaluate the impact of this zone of low permeability on model predictions, sensitivity analyses were performed on hydraulic conductivity (*K*) values used in the model in the area of the Mt. Taylor volcanic core. That is, the values of *K* used in the model were adjusted in order to test how using higher or lower values would change drawdowns calculated by the model. As illustrated in Figure 5.2, the lower the *K*, the larger the zone of influence from mine dewatering. Therefore, use of a lower *K* to represent the volcanic core is more conservative because use of a lower *K* causes the cone of depression to move farther out from the RHR mine. As shown by the yellow and white contours in Figure 5.2, the location of the maximum 10-foot drawdown contour is not "sensitive to" the lowest *K* values, that is, the drawdown contour does not change much when *K* in the area of Mt. Taylor varies between the two lowest values, 0.0001 foot/day and 0.001 foot/day. However, the drawdown contour changes much more if unrealistically high *K* values are used for the volcanic core. In other words, the predevelopment calibration was much worse if high *K* values were used for the volcanic core. It is concluded that the value of *K* used in the RHR model to represent the volcanic cores beneath Mt. Taylor and Mesa Chivato is reasonable.

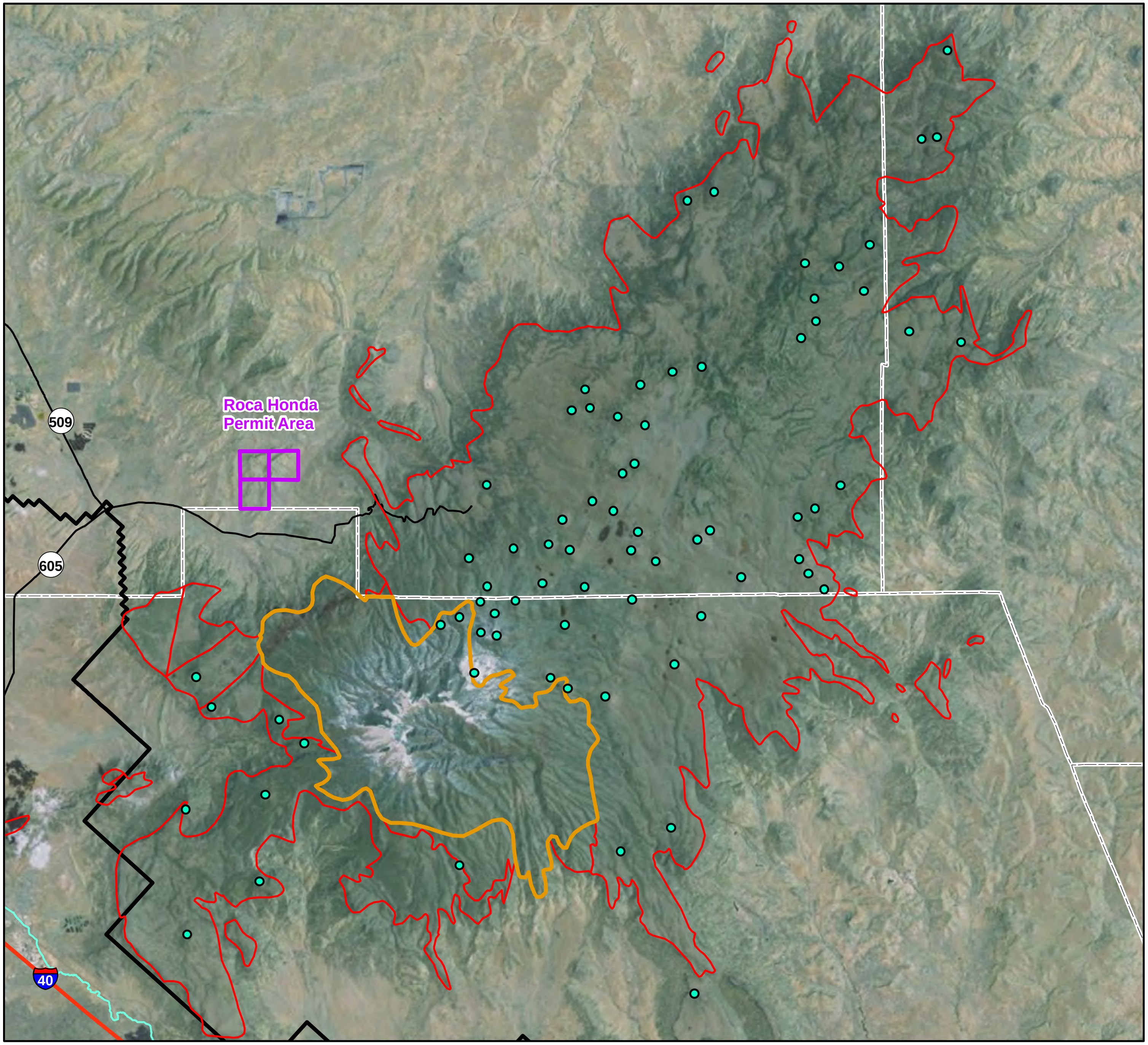

Figure adapted from Kelley, S.A. Mt. Taylor Volcanic Field. New Mexico Bureau of Geology and Mineral Resources web page, last revised 12 November 2008. Accessed 20 February 2012. http://geoinfo.nmt.edu/tour/landmarks/mt_taylor/home.html

Basaltic vents near Mt. Taylor

INTERA

Figure 5.1

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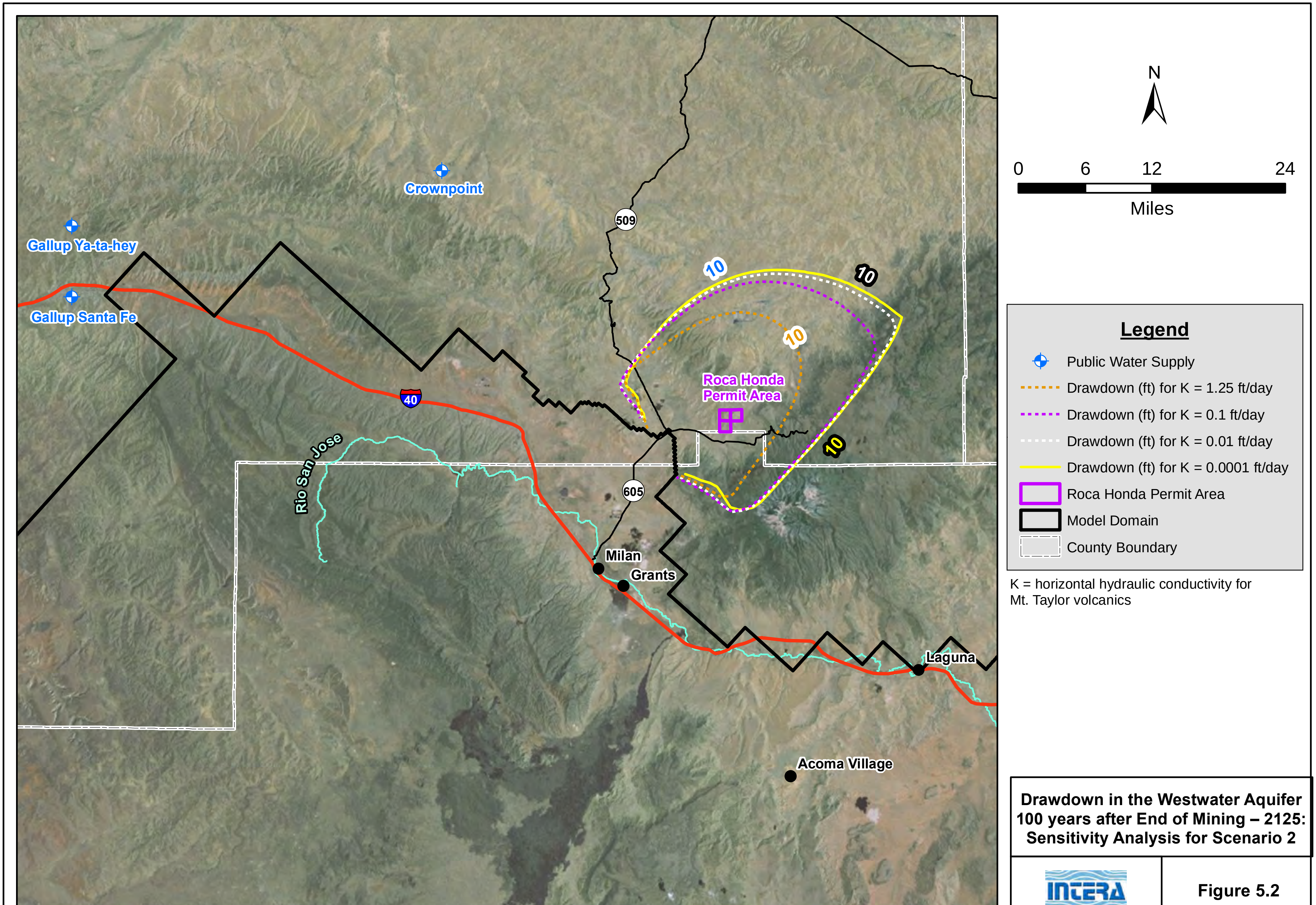

Drawdown in the Westwater Aquifer 100 years after End of Mining – 2125: Sensitivity Analysis for Scenario 2

INTERA

Figure 5.2

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6.0 AVAILABILITY AND USE OF DATA FROM GULF MT. TAYLOR MINE

RHR and INTERA collected and used all available and pertinent hydrogeologic documents, information, and data in constructing the groundwater model. Unfortunately, only a limited amount of information is publically available concerning the hydrogeology of the Gulf Mt. Taylor Mine, located three miles to the southeast of the Roca Honda mine permit area. The Gulf Mt. Taylor Mine was an operating uranium mine during the 1960s to mid 1980s (RHR, 2011a), and was developed prior to the Mining Act and the groundwater dewatering statute. To RHR's knowledge few data generated during Gulf Mt. Taylor operations are publically available.

The documents available regarding the Gulf Mt. Taylor mine are tabulated in the "References" section of Section 9 of the RHR BDR (RHR, 2011a). Of those documents, the following documents were of most importance in calibrating the model:

- The *Environmental Baseline Study of the Gulf Mount Taylor Project Area of New Mexico* (1974) developed by the New Mexico Environmental Institute.
- Gulf's *Groundwater Discharge Plan* (GMRC, 1979b).
- Gulf Oil Corporation's Declaration B-516 from the NMOSE file.
- Records kept by Gulf regarding the design and operation of the mine dewatering wells.

The pumping rates used to dewater the mine during the 1969 to 1994 period and maximum depth of the Gulf Mt. Taylor mine workings are available from a number of sources. In addition, a few groundwater level measurements at a Gulf Mt. Taylor well were obtained (Figure C.11 in Appendix C of INTERA, 2011). These data were used in combination with other Westwater groundwater level observations to calibrate the transient 1930-2011 simulation. The Declaration B-516 source document indicated that the pumping rate from 1977 to 1982 was kept consistent at a rate of approximately 4,500 gpm. The pumping rate decreased a few years after 1982 to keep the shaft dewatered after mining had ceased. These rates, shown in Figure 4.15 of INTERA (2011), were included in the transient 1930-2012 simulation so that the Roca Honda mine model contained the best available estimate of dewatering at the Gulf Mt. Taylor Mine.

The information sources provided a range of 3,250 to 3,300 feet below land surface, or 3,950 to 4,000 feet above sea level, for the lowest mine workings at the Gulf Mt. Taylor Mine. During the transient calibration, the hydraulic conductivity value for the Westwater aquifer in the vicinity of the Gulf Mt. Taylor mine was increased from the original estimate of 1.25 feet/day to 3 feet/day to bring the relatively high Gulf Mt. Taylor Mine pumping rates and known elevation of mine workings into balance. The 3 feet/day value is within the range of observed Westwater hydraulic conductivity values, (Section 2.0). In the end, the calibrated Roca Honda model predicted groundwater levels at the location of the Gulf Mt. Taylor that provided a good match to the elevation of the mine workings during the period of mining after taking into account the large size of the model grid blocks relative to the extent of the mine workings.

The information currently available for the Gulf Mt. Taylor Mine is sufficient for the Roca Honda model. The available data provides a complementary understanding for the pumping at the mine and the changes in water levels, all of which are credibly represented in the Roca Honda model. Additional Gulf Mt. Taylor Mine data are not necessary because the Roca Honda mine model already defensibly represents historical changes in groundwater levels at the Gulf Mt. Taylor mine and elsewhere in the Westwater aquifer. The Roca Honda model's predictions of future groundwater level changes from Roca Honda dewatering are unlikely to change significantly even if the calibration is further refined near the Gulf Mt. Taylor Mine because the refined calibration would only affect a relatively small part of the Westwater aquifer. However, should additional information become available RHR will evaluate it and perform additional modeling analyses as necessary.

7.0 SOURCE OF GROUNDWATER REMOVED DURING ROCA HONDA DEWATERING AND SOURCE OF WATER DURING RECOVERY OF GROUNDWATER LEVELS

In general, groundwater within the Westwater aquifer flows from topographically high areas in the north and south parts of the San Juan Basin towards the western boundary of the basin where it eventually discharges into the San Juan River. This pattern of groundwater flow is shown in Figure 4.3 of INTERA (2011), which represents conditions before large-scale pumping began in the Westwater. Westwater groundwater levels for this period reach their highest value of more than 7,000 feet above sea level along the northern part of the San Juan Basin, where the mountains and numerous high-elevation rivers provide recharge to the aquifers. Westwater groundwater levels also reach 7,000 feet along part of the southern San Juan Basin where local recharge enters the aquifers. The Westwater aquifer discharges into the San Juan River where groundwater levels are less than 5,000 feet above sea level.

Water enters the Westwater aquifer through mountain front recharge, recharge at outcrop areas, and seepage through the overlying Brushy Basin Member of the Morrison Formation. The Brushy Basin is mostly shale with minor sandstone beds, so it acts as an aquitard and only allows water to flow in or out at a very slow rate. Water leaves the Westwater aquifer by discharge to ephemeral drainages near outcrops, pumping from wells, and seepage back into the overlying Brushy Basin aquitard. Depending on location, rivers remove or add water to the Westwater, but overall the Westwater discharges much more water to rivers than it receives.

These inflows and outflows together make up a water balance for the Westwater aquifer. If either inflows or outflows change over time, groundwater levels will change with a resultant change in the amount of groundwater held in storage in the aquifer. If water levels rise, the amount of water in storage in the aquifer will increase; if water levels fall, the amount of water in storage will decrease.

The Roca Honda mine model provides estimates of each of these water balance inflows and outflows. The model calculated that during the future period 2012 to 2026 without RHR pumping (Scenario 1 in INTERA, 2011), the inflows to the model would be the amounts shown in column 1 of Table 7-1 and the outflows from the model would be the amounts shown in column 2. Inflows to the model are 16,000 AF of mountain front recharge, 90 AF of recharge at outcrop areas, and 45,230 AF of leakage from the Brushy Basin aquitard. Outflows from the model are 10,540 AF of pumping, 4,940 AF of discharge to ephemeral drainages near outcrops, and 31,150 AF net discharge to rivers. The volume of leakage from the Brushy Basin aquitard appears quite large as it is the largest inflow to the Westwater aquifer, but it occurs over an area of approximately 17,000 square miles. Therefore, the flow rate is very small per unit area. During this 14 year period, the amount of water in the Westwater aquifer increased by almost 14,700 AF. This increase in storage was caused by the slow, steady rebound in groundwater levels from the 1950 to 1980 period of historical uranium mining and dewatering.

The model calculated that during the future period 2012 to 2026 with RHR pumping (Scenario 2 in INTERA, 2011), the inflows to the model would be the amounts shown in column 3 and the outflows from the model would be the amounts shown in column 4 of Table 7.1. Inflows to the model are 16,000 AF of mountain front recharge, 90 AF of recharge at outcrop areas, 46,630 AF of leakage from the Brushy Basin aquitard and 60,610 AF decrease in aquifer storage represented by the decrease in water levels. Outflows from the model are 78,970 AF of RHR pumping, 10,540 AF of pumping, 4,940 AF of discharge to ephemeral drainages near outcrops, and 31,360 AF net discharge to rivers. Both mountain front recharge and recharge at outcrops are unaffected by pumping and so are constant for Scenarios 1 and 2.

Table 7.1. Westwater Aquifer Water Balances During 2012 to 2026 for Scenarios 1 and 2

	1	2	3	4
Water Balance Component	Volume (AF)			
	Scenario 1 Inflow	Scenario 1 Outflow	Scenario 2 Inflow	Scenario 2 Outflow
Mountain front recharge	16,000		16,000	
Recharge at outcrops	90		90	
Leakage from Brushy Basin aquitard	45,230		46,830	
Water supply pumping		10,540		10,540
Discharge to ephemeral drainages		4,940		4,940
Discharge to rivers		31,150		31,360
Roca Honda dewatering		0		78,970
Total	61,320	46,630	62,920	125,810
Change in Westwater aquifer storage	14,690		-60,610	
Percent error	0.2%		-1.8%	

Pumping for RHR dewatering was balanced by a change in Westwater aquifer storage and a change in the leakage from the Brushy Basin aquitard. The amount of water that leaked out of the Brushy Basin aquitard under Scenario 2 is 1,600 AF larger than that for Scenario 1. The amount of water stored in the Westwater aquifer decreased by 60,610 AF under Scenario 2, and the 14,690 AF increase in aquifer storage that would have occurred as water levels rebounded from historical pumping did not occur. The 79,000 AF of Roca Honda dewatering in the Westwater over 14 years was balanced by:

* 60,610 AF loss in groundwater stored in the Westwater aquifer.
* 14,690 AF loss in groundwater that would have been added to storage in the Westwater aquifer as water levels rebounded from historical pumping.
* 1,600 AF of increased leakage from the Brushy Basin aquitard.

Note that the total for the three bulleted items above is 76,900 AF, which differs from the 78,970 AF of proposed Roca Honda dewatering by the 1.8% error shown in the rightmost column of Table 7.1. No other water is captured by the proposed Roca Honda dewatering. The main sources are a very small amount of increased leakage from the Brushy Basin aquitard and a change in the amount of water stored in the Westwater aquifer. No water is removed from the other aquifers, including the Gallup and Dakota aquifers or other sandstone intervals, such as the wells near the mine permit area (like those shown in Figure 4.1).

Although groundwater removed for the proposed Roca Honda mine dewatering will come from the Westwater aquifer, near the mine permit area changes in Westwater groundwater levels will have some effect on groundwater levels in other aquifers without actually removing water from those other aquifers. Dewatering the Westwater near the mine workings is predicted to cause groundwater level changes of ten feet or more at nine Westwater wells, one well in the Dakota aquifer, and three wells in the Gallup aquifer (Sections 5.1 and 5.1.1 in INTERA, 2011). The predicted changes in the groundwater levels at the nine Westwater wells are caused by removing water from the Westwater for mine dewatering. However, Roca Honda dewatering only changed the pressure in the other aquifers. All three aquifers are confined, which means that the water pressure causes the water level in a borehole to rise higher than the top of the aquifer. It also means that pumping removes water by reducing the pressure within the aquifer. Dewatering the mine workings is predicted to cause drawdown at the Gallup and Dakota wells by locally reducing the water pressure in the Westwater and the overlying aquitards and aquifers. This leads to a decrease in the groundwater levels in the Brushy Basin aquitard, and that pressure reduction causes a small flow into the Westwater and a decrease in the groundwater level for the overlying Dakota aquifer. The reduction of water level in the Dakota causes a reduction in water levels in the overlying Mancos Shale, and that leads to a decrease in groundwater levels in the Gallup. No water flows from the Dakota or the Gallup down to the Westwater. The amount of water level decline in the Dakota and Gallup is much less than in the Westwater at the same location because of the presence of the low-permeability shales.

The Roca Honda mine model simulates the rebound in Westwater groundwater levels after Roca Honda dewatering ends. The rebound takes many decades because it is primarily controlled by the slow rate of water leaking through the Brushy Basin aquitard. Under Scenario 1 conditions, storage in the Westwater aquifer increased by 51,880 AF during the period 2026 to 2125 (Table 7.2), yielding a total storage increase of 66,570 AF over the entire period of simulation (Tables 7.1 and 7.2). This rebound is due to the continued recovery of water levels after historical pumping in the Ambrosia Lake area ceased in the 1980s. Under Scenario 2, Westwater aquifer storage increases by 61,430 AF after mine dewatering ends, which exceeds the storage increase under Scenario 1 for the same period (Table 7.2) However, the total increase in Westwater aquifer storage over the entire simulation period for Scenario 2 is very small compared to the total increase under Scenario 1 (Tables 7.1 and 7.2). Thus, the water for the slow rebound in Westwater groundwater levels from Roca Honda dewatering also comes from storage, in this case, the change in storage is smaller than it would have been without Roca Honda dewatering.

Table 7.2. Westwater Aquifer Water Balances During 2026 to 2125 for Scenarios 1 and 2

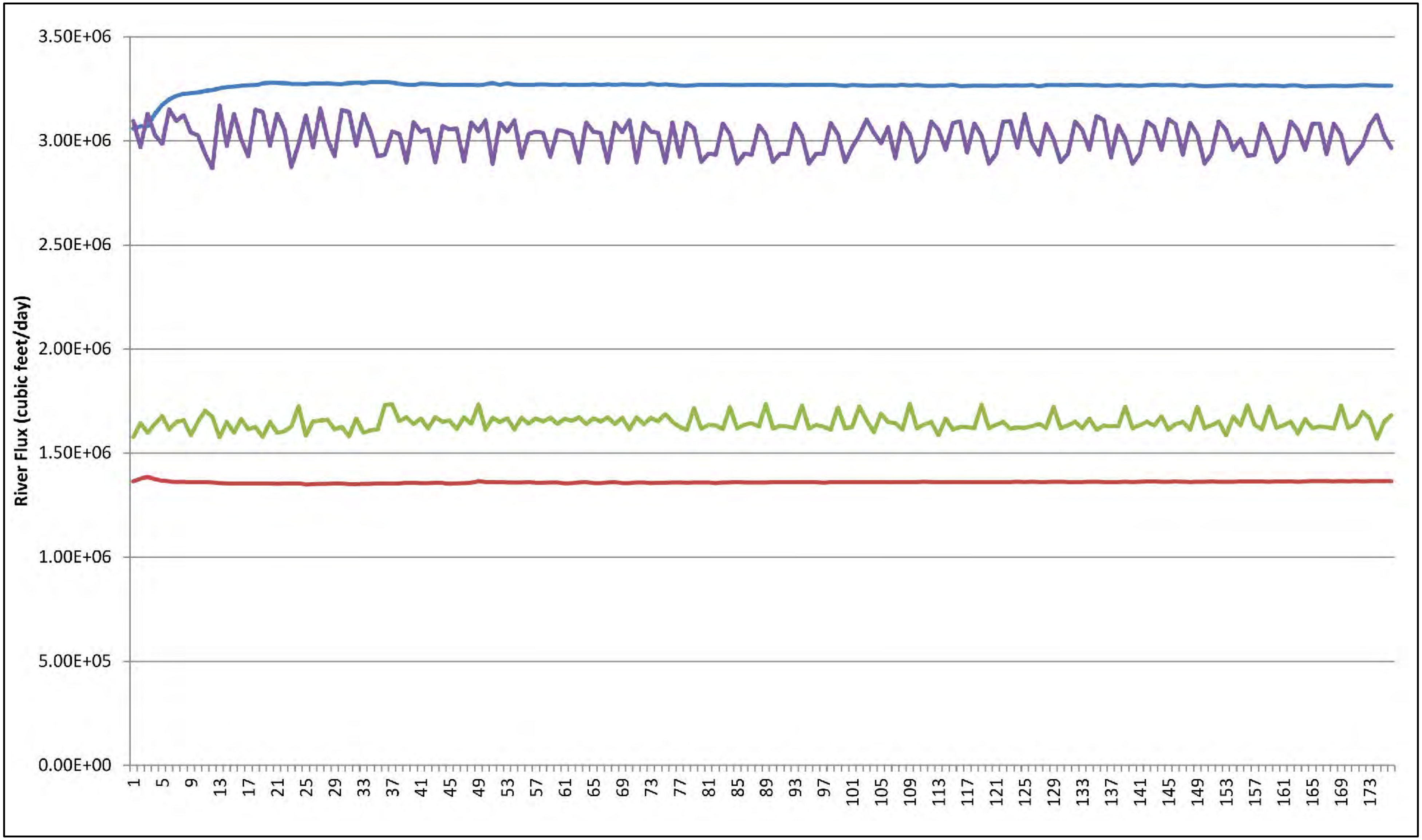
	1	2	3	4
Water Balance Component	**Volume (AF)**			
	Scenario 1 Inflow	**Scenario 1 Outflow**	**Scenario 2 Inflow**	**Scenario 2 Outflow**
Mountain front recharge	72,380		72,380	
Recharge at outcrops	670		670	
Leakage from Brushy Basin aquitard	331,270		338,840	
Water supply pumping		81,060		81,060
Discharge to ephemeral drainages		38,220		38,220
Discharge to rivers		234,020		233,790
Roca Honda dewatering		0		0
Total	404,320	353,300	411,890	353,070
Change in Westwater aquifer storage	51,880		61,430	
Percent error	-0.2%		-0.6%	

8.0 NUMERICAL ISSUES

The Roca Honda groundwater model showed some variability in modeled flow rates for the river boundary condition grid blocks. Nearly all of the river grid blocks are located in layer 1, but because of basin topography, layer 1 is not the topmost active layer everywhere, so river grid blocks are located in other layers. Almost all of the variability in the river flux was observed to occur in layer 1. Small changes in groundwater levels appeared to cause large frequent changes in flow rates, indicating that too much water was being released or added to storage. These observations suggested that the conductance for the river boundary condition was set too high, especially for the river grid blocks that were very large in size. The large size of these grid blocks means they have a very large storage capacity, so that a very small change in groundwater level can cause a large flow into or out of the aquifer represented by the grid block.

The value of conductance used in the RHR model, 100 feet/day (Section 3.5 of INTERA, 2011), was the same as the value used in the previous groundwater model of the San Juan basin (Kernodle, 1996). Although this hydraulic conductivity value is higher than those typically assumed for such river bed materials, it had been used to maintain consistency with previous modeling work. Reducing the hydraulic conductivity to 1 foot/day for the river boundary condition eliminated the frequent flow rate variations for the river boundary condition in all simulations. Figure 8.1 compares the river flow rates for Scenario 1 for a river conductance based on a hydraulic conductivity of 100 feet/day (river flow rate values fluctuate rapidly in time) and for a river conductance based on K = 1 foot/day (river flow rates produce a smooth, steady line over time).

The Roca Honda model also showed variability in mass balance errors over time in the transient simulations, including Scenario 1. Reducing the hydraulic conductivity for river boundary condition conductance and slightly changing the solver criteria and time stepping criteria significantly reduced the impact of the river fluxes on the mass balance errors (Figure 8.2). Using K = 1 foot/day to calculate the river conductance had the largest effect. Together with using the PCG5 solver instead of the PCG4 solver, reducing the initial time step size, the time step multiplier, and number of outer iterations also helped reduce the mass balance errors. The mass balance errors for most simulation time steps (except the first 'warm-up' stress period) in the transient 1930-2012 and Scenario 1 simulations (shown in Figure 8.2) were typically close to or much less than 1%.



Legend

- River Flux Out: K=1 ft/day
- River Flux In: K=1 ft/day
- River Flux In: K=100 ft/day
- River Flux Out: K=100 ft/day

Comparison of Scenario 1 River Fluxes for High and Low Conductance

INTERA

Figure 8.1

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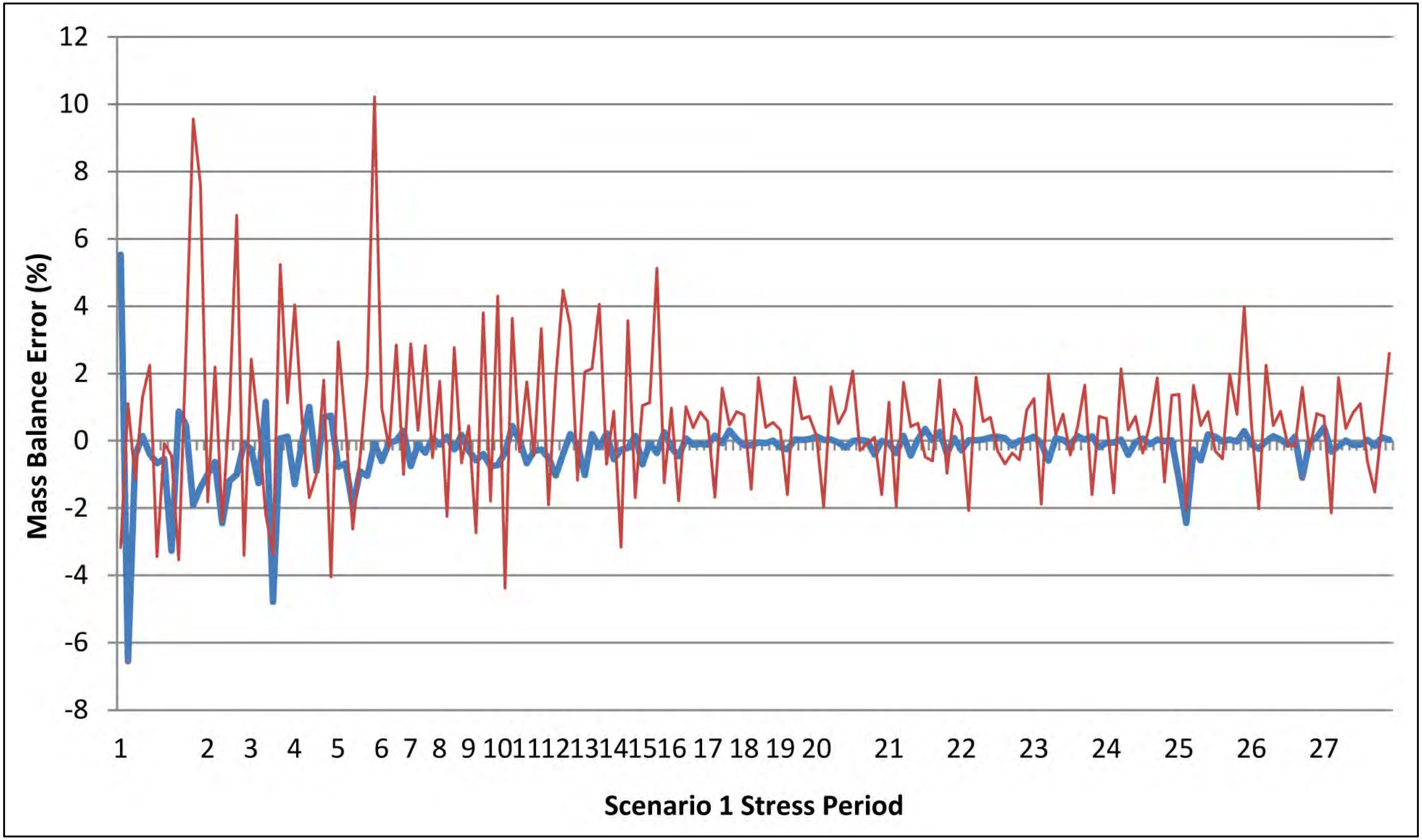

Legend

Mass balance error with lover river conductance and time step criteria

Original mass balance error

Comparison of Scenario 1 Mass Balance Errors for High and Low Conductances and Time Stepping Criteria

INTERA

Figure 8.2

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