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

McKinley County, New Mexico

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November 4, 2011

Revised March 8 and August 7, 2012

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EXECUTIVE SUMMARY

Roca Honda Resources, LLC (RHR) is planning to develop a new underground mine at a location approximately 23 miles northeast of the City of Grants and 2.5 miles northwest of the community of San Mateo in McKinley County, New Mexico. The Roca Honda permit area encompasses Sections 9, 10, and 16 of Township 13 North, Range 8 West. Mine workings will be developed at depths between 2,100 and 2,800 feet below ground surface within the Westwater Canyon Member of the Morrison Formation (Westwater). The mine will include vertical production shafts, ventilation shafts, underground workings, and related surface facilities.

The proposed Roca Honda mine is located within the San Juan Basin. The proposed Roca Honda mine will pump water from the Gallup Sandstone (Gallup) and the Westwater during a 13-year period of mine construction and operation, and from the Dakota Sandstone (Dakota) during construction only for one year. All pumping will cease with the end of mining. Almost all the water will be pumped from the Westwater aquifer. RHR has filed an Application for Dewatering an Underground Mine with the New Mexico Office of the State Engineer (NM OSE) that proposes maximum dewatering rates for various time periods during construction and operation of the mine.

RHR commissioned INTERA Incorporated (INTERA) to construct a groundwater flow model to evaluate potential changes in groundwater levels from the mine dewatering in order to support the mine dewatering application submitted to the NM OSE and the Mine Permit Application submitted to state and federal agencies. The specific objective of the model is to estimate the groundwater level changes that mine dewatering might have on aquifers, wells, springs, rivers, and local and regional water supply systems, including those for the nearby population centers of Grants, Gallup, Milan, Crownpoint, San Mateo, and the Acoma and Laguna Pueblos.

INTERA constructed a three-dimensional numerical model of groundwater flow in the San Juan Basin to represent current and historical groundwater conditions within the Gallup, Dakota, and Westwater aquifers, and to estimate possible future changes from dewatering at the Roca Honda mine (RHR Model). A United States Geological Survey (USGS) model of steady groundwater flow in the San Juan Basin constructed by Kernodle (1996) was used as a basis for the RHR model. The RHR model significantly improves on previously constructed numerical models of the San Juan Basin by incorporating new data on aquifer parameters and stratigraphy in the vicinity of the RHR permit area, modifying boundary conditions to represent important processes, increasing the number of calibration data for the steady-state calibration, carrying out a transient calibration for the period from 1930 to 2012, and performing evaluations to test model

sensitivity to changes in hydraulic parameter ranges. The model has been successfully calibrated to both pre-development and transient conditions. The RHR model represents potential impacts on hydrologic conditions in the area, including on the Rio San Jose and Horace Spring, better than any other available numerical model because it is the only model to accurately represent the hydrogeology of this area, including the McCartys Syncline. Thus, the calibrated RHR model is the most reliable and accurate tool available for estimating the effects of proposed RHR dewatering.

The model predicts that the 10-foot groundwater level drawdown contour in the Westwater aquifer will extend a maximum of 17 miles from the RHR permit area boundary. The model predicts that the maximum extent of the 10-foot drawdown contour in the Gallup aquifer will remain within the permit area boundary, and within or near to the RHR permit boundary in the Dakota aquifer. Drawdown is predicted to be 10 feet or more at nine wells screened in the Westwater. Three of these wells are used for mining, three for domestic supply, one for livestock, and two for unknown uses. Drawdown is predicted to be 10 feet or more at one domestic well screened in the Dakota and three wells in the Gallup. One of the Gallup wells is permitted for exploration, one for livestock, and one with an unknown use. Drawdown is predicted to be less than 10 feet at wells in the Mancos Shale and aquifers overlying the Gallup.

Dewatering the Roca Honda mine will not adversely affect the water resources of the Village of Milan, Acoma Pueblo, Laguna Pueblo, the City of Grants, the community of San Mateo, the Crownpoint area, or the City of Gallup. Mine dewatering will not have adverse impacts on area springs or decrease groundwater discharge to rivers. Drawdown at the two wells for the San Mateo community water supply wells, which are nearest to the mine, is predicted to be 0.5 to 1.7 feet at or near the end of mining.

Drawdown at springs, including Horace Spring, is predicted to be negligible. Dewatering at the Roca Honda mine is predicted to have no impacts on groundwater discharges to the perennial reach of the Rio San Jose, the Rio Puerco, and the San Juan and Puerco Rivers. The proposed RHR dewatering activities will therefore not adversely impact surface water resources of the San Juan Basin.

The public water supplies for the Village of Milan and the City of Grants will not be affected by Roca Honda mine dewatering because they pump groundwater from aquifers that are stratigraphically lower than the Westwater and separated from it by thick shale intervals with low hydraulic conductivity.

The pumping rates and time periods used in the model to represent RHR dewatering in the mine dewatering simulation over-estimate water level declines because the model assumes maximal pumping rates occur over the entire period of mine operations. Actual Roca Honda dewatering rates will not begin at the maximum rates as simulated in the groundwater models, but will instead increase gradually over the 13-year mining period.

The RHR groundwater flow model constructed by INTERA demonstrates that dewatering of the Roca Honda mine as proposed in the RHR dewatering application will not adversely impact groundwater and surface water resources of the San Juan Basin.

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ABBREVIATIONS AND ACRONYMS

ac-ft	acre-feet
ac-ft/yr	acre-feet per year (10 ac-ft/yr = 6.2 gpm)
ASTM	American Society for Testing Materials
BDR	Baseline Data Report
bgs	below ground surface
Brushy Basin	Brushy Basin Member of the Morrison Formation
cfs	cubic feet per second
Dakota	Dakota Sandstone
DBSAI	Daniel B. Stephens and Associates, Inc.
ft amsl	feet above mean sea level
ft/day	feet per day
ft^2/day	square feet per day
ft^3/day	cubic feet per day
ft^3/s	cubic feet per second
Gallup	Gallup Sandstone
GIS	geographic information system
gpm	gallons per minute
in/yr	inches per year
INTERA	INTERA Incorporated
JSAI	John Shomaker and Associates, Inc.
Mancos	Mancos Shale
NM OSE	New Mexico Office of the State Engineer
NRMSE	normalized root mean square error
PCG	Pre-Conditioned Conjugate Gradient
PWS	public water supplies
Recapture	Recapture Shale Member of the Morrison Formation
RHR	Roca Honda Resources, LLC
US BLM	United States Bureau of Land Management
USGS	United States Geological Survey
Westwater	Westwater Canyon Member of the Morrison Formation

DEFINITIONS

Acre-foot[1]: Volume equal to a depth of one foot over an area of one acre.

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.

Aquifer test[2]: A procedure for measuring the characteristics of an aquifer by pumping a well and monitoring changes in groundwater levels (heads) and the pumping rate. Also called hydraulic testing or pumping test.

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.

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

Groundwater flow model[2]: A numerical tool for describing and predicting water flow in the sub-surface by solving the equation for flow through porous or fractured media.

Groundwater Vistas[3]: Software for building, testing, and applying groundwater flow and transport models from Environmental Simulations, Inc.

Head: Elevation to which water rises at a point; a measure of the energy in water controlling flow; usually refers to the energy from pressure, elevation, or the sum of the two. Also referred to as "groundwater level."

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.

MODFLOW[2]: The three-dimensional finite-difference code for solving the governing equation for groundwater flow through porous media developed by the United States Geological Survey.

MODFLOW-SURFACT[4]: A version of the MODFLOW modeling code with proprietary improvements to more efficiently solve groundwater flow problems. Developed by HydroGeoLogic, Inc.

Porosity[2]: Volume of empty pore space (voids) within a material divided by the total volume of the material.

DEFINITIONS (CONTINUED)

Specific storage[2]: 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[2]: Proportion of porosity from which water freely drains after the water table drops in an unconfined aquifer.

Transmissivity[2]: The product of the thickness of an aquifer and a representative hydraulic conductivity.

[1] 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.

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

[3] Adapted from Rumbaugh and Rumbaugh (2007).

[4] Adapted from HydroGeoLogic Inc. (1996).

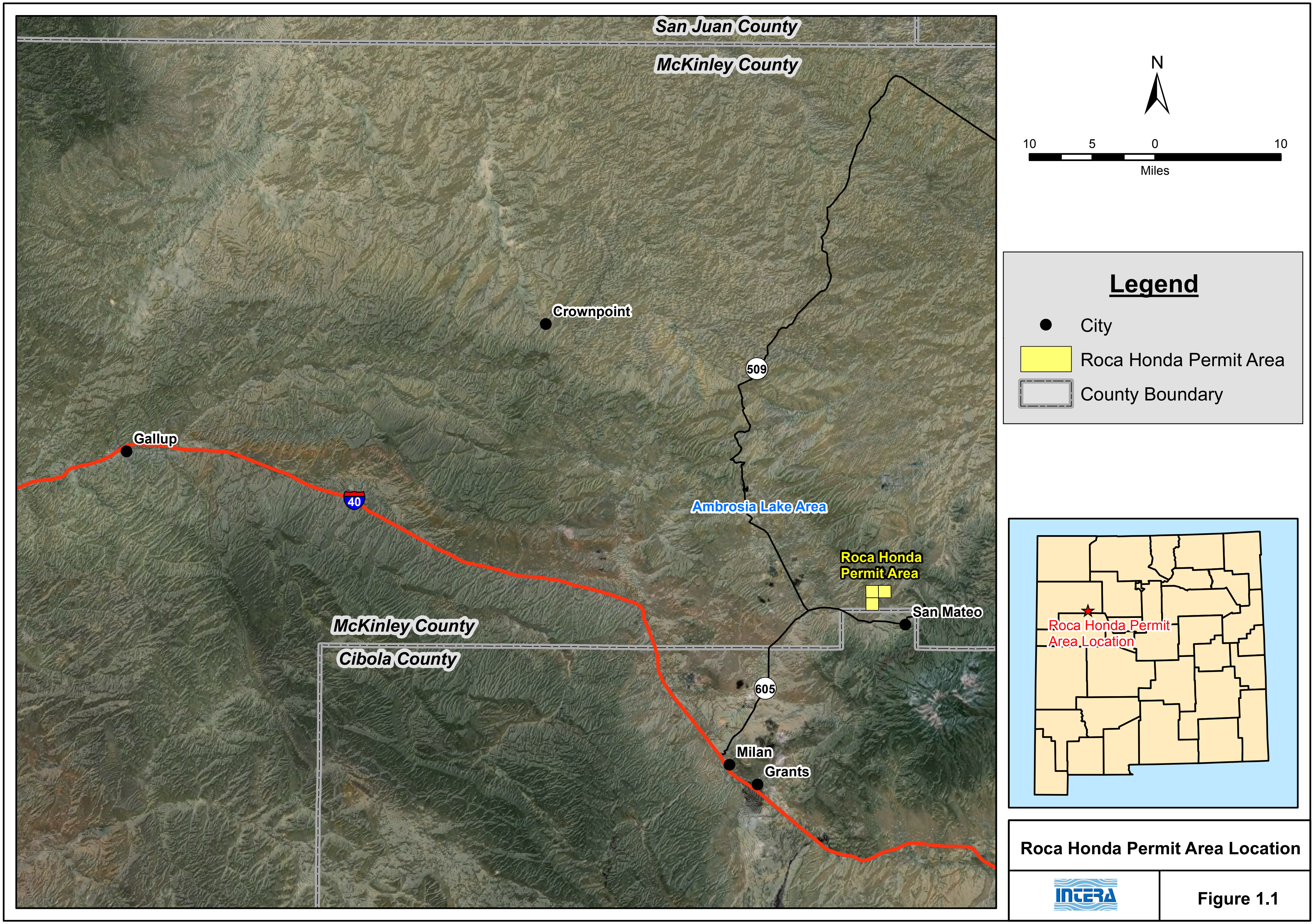
1.0 INTRODUCTION

Roca Honda Resources, LLC (RHR) is planning to develop a new underground mine at a location approximately 23 miles northeast of the City of Grants and 2.5 miles northwest of the community of San Mateo in McKinley County, New Mexico (Figure 1.1). The Roca Honda permit area encompasses Sections 9, 10, and 16 of Township 13 North, Range 8 West (yellow squares in Figure 1.1). Mine workings will be developed at depths between 2,100 and 2,800 feet below ground surface (bgs) within the Westwater Canyon Member of the Jurassic Morrison Formation (Westwater). The mine will include vertical production shafts, declines, ventilation shafts, and underground workings.

Construction of the production shaft and surface facilities is projected to take three years; mining will last another ten years. The shaft will pass through three geologic units that contain groundwater in the area of the mine: the Gallup Sandstone (Gallup), the Dakota Sandstone (Dakota), and the Westwater. The mine will be developed in the Westwater. Shaft construction will require temporary depressurization of groundwater in the Gallup, Dakota, and Westwater geologic units in the area of the shaft as it is constructed in each geologic unit. After shaft construction is complete, wells will initially be used to dewater the Westwater, the declines, and drifts constructed to develop the mine. The mine workings will be the primary means of dewatering the mine so that mining can occur safely and efficiently.

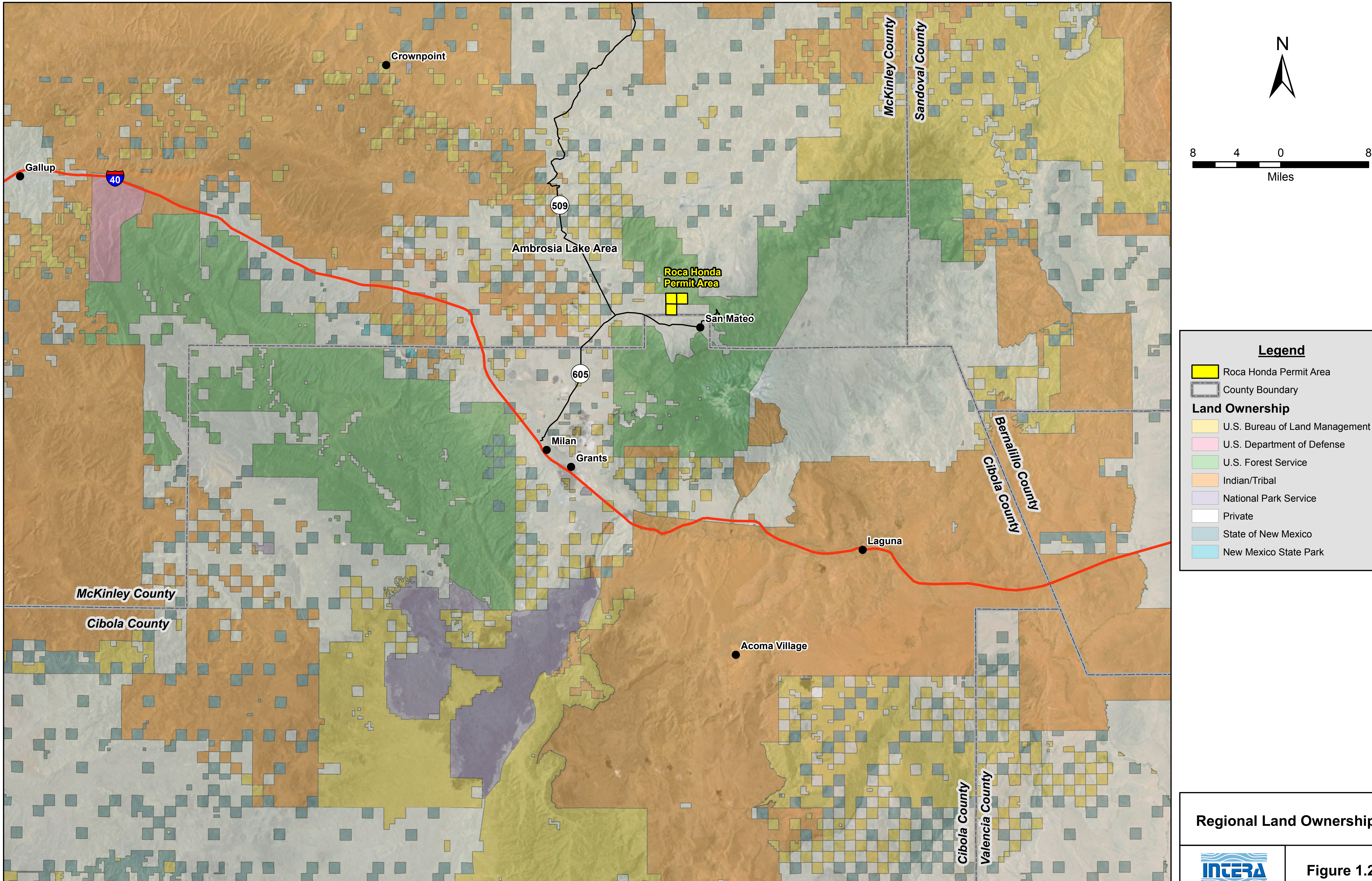
The Westwater, Dakota, and Gallup are geologic units within the San Juan Basin, the large depositional basin that encompasses most of northwestern New Mexico and adjacent portions of Colorado, Utah, and Arizona (see Section 2). The proposed mine is situated along the San Juan Basin's southern margin, towards the eastern edge of the Grants uranium district and the Ambrosia Lake sub-district (McLemore and Chenoweth, 1989). Uranium has been mined in the San Juan Basin's late Jurassic sandstones within the Grants uranium district for decades, with most of the mining occurring from the 1950s to the 1980s (McLemore et al., 2005).

The region within thirty miles of the proposed Roca Honda mine is sparsely populated with most people living in the Cities of Grants and Gallup, the Town of Crownpoint, the Village of Milan, the community of San Mateo, and the pueblos of Acoma and Laguna (RHR, 2011a). Landowners include the federal government, the state of New Mexico, pueblos, land grants, and private owners (Figure 1.2). Historical land use was dominated by ranching, forestry, mining, and farming (RHR, 2011a). Ranching, forestry, outdoor recreation, and coal mining are the primary present-day land uses (RHR, 2011a).



Roca Honda Permit Area Location

Figure 1.1



Regional Land Ownership

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Figure 1.2

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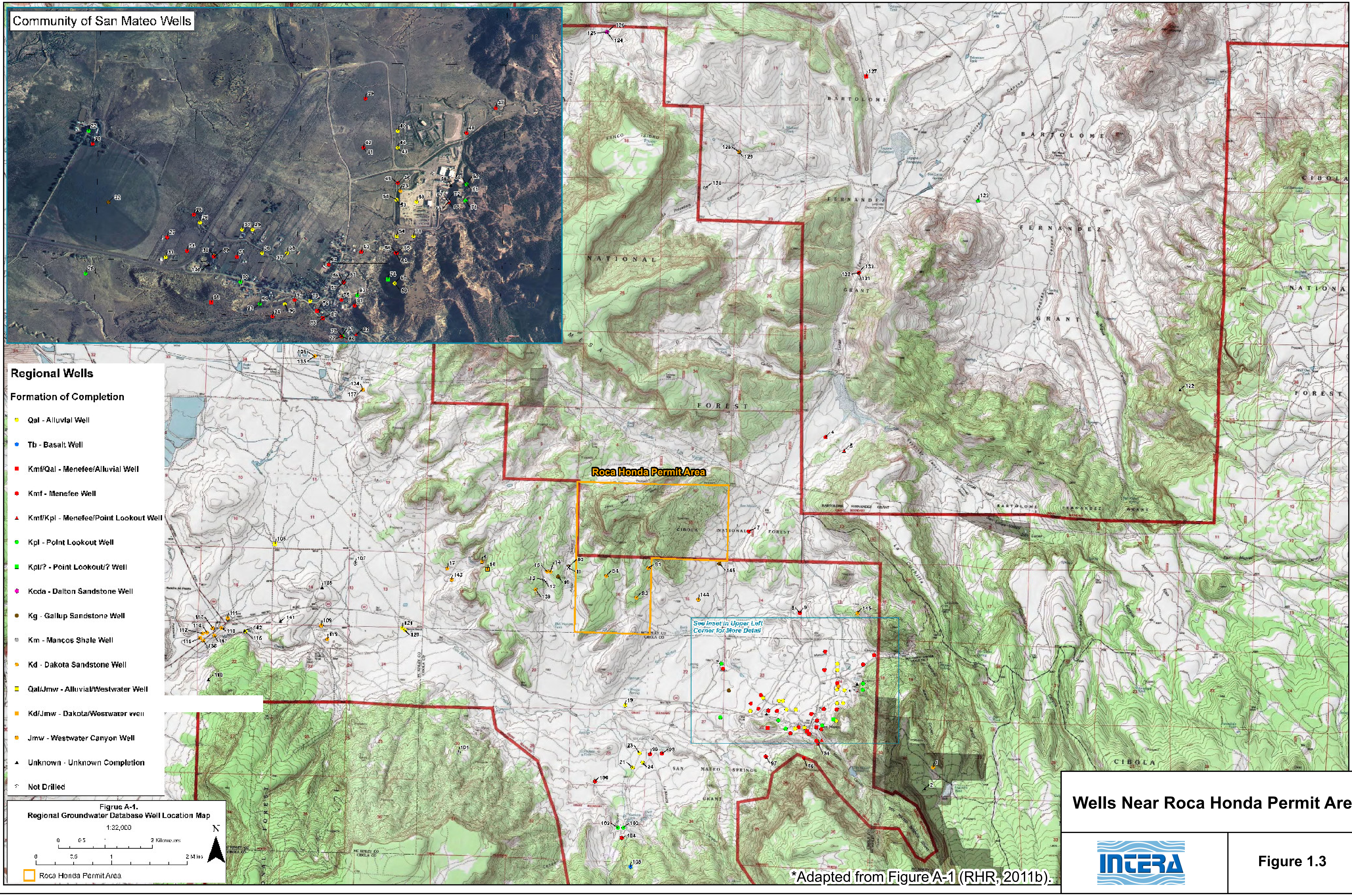
Wells are used to extract water from various geologic units for domestic and agricultural purposes in the San Juan Basin. Geologic units that yield economically significant quantities of water to wells or springs are termed "aquifers," whereas units that yield little water to pumping are termed "aquitards" (see Definitions on page ix). The Gallup, Dakota, and Westwater geologic units are aquifers along the southern, eastern, and western margins of the San Juan Basin, including the Roca Honda permit area. Wells located near the RHR permit area are shown in Figure 1.3. This figure is taken from Plate 1 of the RHR Baseline Data Report (RHR, 2011b); information about the numbered wells shown in the figure can be found in Table A-1 of the Baseline Data Report (RHR, 2011b). Mine dewatering in the vicinity of the Roca Honda mine is limited to the Lee Ranch coal mine at present, but historical mining caused significant drops in groundwater levels, which are still recovering.

RHR has filed an Application for Dewatering an Underground Mine with the New Mexico Office of the State Engineer (NM OSE) that proposes maximum dewatering rates for various time periods during construction of the production shaft and during the operating life of the mine (Table 1.1). The rates define the volume of water removed from the Gallup, Dakota, and Westwater aquifers in a given period of time. During the sinking of the production shaft, groundwater will be pumped at a rate of up to 502 gallons per minute (gpm) for a period of up to 12 months (a maximum of 810 acre-feet) from wells finished in the Gallup, the top of which is located 530 feet bgs in the area of the production shaft. After the production shaft is completed through the Gallup, construction of the shaft will continue to the Dakota, where groundwater will be pumped at a rate of up to 144 gpm for a period of up to 12 months (a maximum of 232 acre-feet) from wells finished in the Dakota, the top of which is located at 1,660 feet bgs in the area of the production shaft. Pumping from the Gallup and the Dakota will cease after the shaft has been completed through these formations, except for a continued withdrawal of approximately 30 gpm (50 ac-ft/yr) from the Gallup over the life of the mine.

Table 1.1. Proposed Roca Honda Production Shaft and Mine Dewatering Schedule

Aquifer	Dewatering Depth (feet)	Maximum Pumping Rate (ac-ft/yr)	(gpm)	Pumping Period (days)
Gallup	640	810	502	365
Dakota	1,710	232	144	365
Westwater (shaft construction)	2,100	3,228	2,000	730
Westwater (mining)	2,100 – 2,800	7,265	4,500	3,653



Wells Near Roca Honda Permit Area

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Figure 1.3

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After the production shaft is completed in the Dakota, shaft construction will continue into the Westwater. Groundwater will be pumped from the Westwater for a period of up to 12 years during shaft construction, mine development, and over the life of the mine. Groundwater will be pumped from the Westwater at a rate of up to 2,000 gpm during shaft construction over a period of up to two years (a total of 3,228 ac-ft/yr), and no more than 7,265 ac-ft/yr (an average pumping rate of 4,500 gpm) for the ten-year life of the mine. Groundwater will be withdrawn from the Westwater by means of wells and sumps around the production shaft and along the main mine tunnel (called a decline) in advance of its construction, and from within the mine. When mining is complete, pumping from the Westwater and Gallup will end.

1.1 Objectives

RHR requested that INTERA Incorporated (INTERA) construct groundwater flow models to evaluate potential changes in groundwater levels from the mine dewatering in order to support the mine dewatering application submitted to the NM OSE and the Mine Permit Application submitted to state and federal agencies. The specific objective is to estimate the groundwater level changes that mine dewatering might have on aquifers, wells, springs, rivers, and local and regional water supply systems, including those for the nearby population centers of Grants, Gallup, Milan, Crownpoint, San Mateo, and the Acoma and Laguna Pueblos (Figure 1.2).

1.2 Approach

INTERA constructed numerical models of groundwater flow in the San Juan Basin to represent historical groundwater changes within the Gallup, Dakota, and Westwater geologic units, as well as future changes from dewatering at Roca Honda mine. A United States Geological Survey (USGS) model of steady groundwater flow in the San Juan Basin constructed by Kernodle (1996) was used as a basis for the INTERA models (see Section 3 below). INTERA's specific modeling tasks are described as follows:

1. Construct and calibrate a numerical model of groundwater flow to estimate predevelopment groundwater levels, i.e., groundwater levels prior to the year 1930, for conditions prior to the onset of large-scale mining in the Grants uranium district.
2. Construct and calibrate a transient historical numerical model of groundwater flow to simulate changes in groundwater levels from 1930 to 2012 caused by pumping at public water supply wells, historical mine dewatering, and partial recovery from the historical mine dewatering.
3. Construct and apply predictive, transient, numerical groundwater flow models that simulate changes in groundwater levels from the beginning of Roca Honda mine construction through the projected end of mining 13 years later.

The models were also used to simulate changes in groundwater levels during the hundred years following cessation of mining activities. The predictive transient models represent scenarios with and without pumping at Roca Honda mine and scenarios with and without pumping by water rights from the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. The differences in groundwater levels between scenarios with and without Roca Honda dewatering define the "drawdown" due to Roca Honda mine dewatering.

1.3 Report Structure

The geologic and hydrologic characteristics of the Roca Honda mine area and the San Juan Basin important to the impact assessment are described in Section 2. Construction of the numerical models is detailed in Section 3. Calibration of the predevelopment model and transient historical model is described in Section 4. Section 5 provides the results of the transient predictive models. Section 6 presents INTERA's conclusions, and Section 7 lists the references cited in the report. Appendices A and B depict model boundary conditions and parameter assignments by layer. Appendix C presents calibration plots for the transient calibration. Appendix D lists the wells and the estimated drawdown for the predictive simulations. Appendix E, a new appendix that has been added to this report, describes the geology and hydrogeology of Horace Spring and the perennial reach of the Rio San Jose.

2.0 HYDROGEOLOGY

INTERA reviewed available published and unpublished information and data about the geology and hydrology of the San Juan Basin and the Roca Honda mine area to develop an updated conceptual hydrogeologic foundation for this assessment. These studies included Mercer and Cooper (1970), Brod and Stone (1981), Stone et al. (1983), Craigg et al. (1990ab), Dam et al. (1990ab), Kernodle et al. (1989 and 1990), Levings et al. (1990ab), Thorn et al. (1990ab), Levings et al. (1996), and Craigg (2001). Two previously developed groundwater flow models for the basin (Frenzel and Lyford, 1982; Kernodle, 1996) contributed important information to developing the new conceptual foundation and numerical models.

This information and data were used to develop an overall understanding or mental picture of groundwater flow in the San Juan Basin, that is, an understanding of the basin's geologic structure and composition, and how water enters it, moves through it as groundwater and surface water, and leaves it as stream flow, evaporation, or diversions. For this impact assessment, the overall understanding includes the San Juan Basin's geologic structure and stratigraphy, major surface water bodies, aquifer and aquitard characteristics, groundwater flow patterns, recharge, surface water-groundwater interactions, and groundwater pumping stresses. This overall understanding in turn is the basis for designing the numerical groundwater flow models described in later sections of this report.

INTERA further refined its understanding of the hydrogeology around the Roca Honda mine area using data from recent investigations, pump tests, and several sections from the RHR Baseline Data Report (BDR). The RHR BDR, which was submitted to state and federal agencies as part of RHR's Mine Permit Application, describes the geologic, hydrologic, cultural, and biological baseline conditions at the Roca Honda mine area. The specific sections reviewed by INTERA included land use (RHR, 2011a), groundwater (RHR, 2011b), geology (RHR, 2011c), and surface water (RHR, 2011d).

This section of the report provides a general overview of the San Juan Basin as well as key features in the vicinity of the Roca Honda mine. Detailed descriptions of the basin's geology and hydrology can be found in the sources listed above.

2.1 Geologic Setting

Groundwater flow in the Westwater, Dakota, and Gallup aquifers is partly controlled by the geology, extent, and characteristics of the aquifer units, and partly by the overall geologic structure of the San Juan Basin. The overall geologic setting of the San Juan Basin and the RHR permit area are briefly described below.

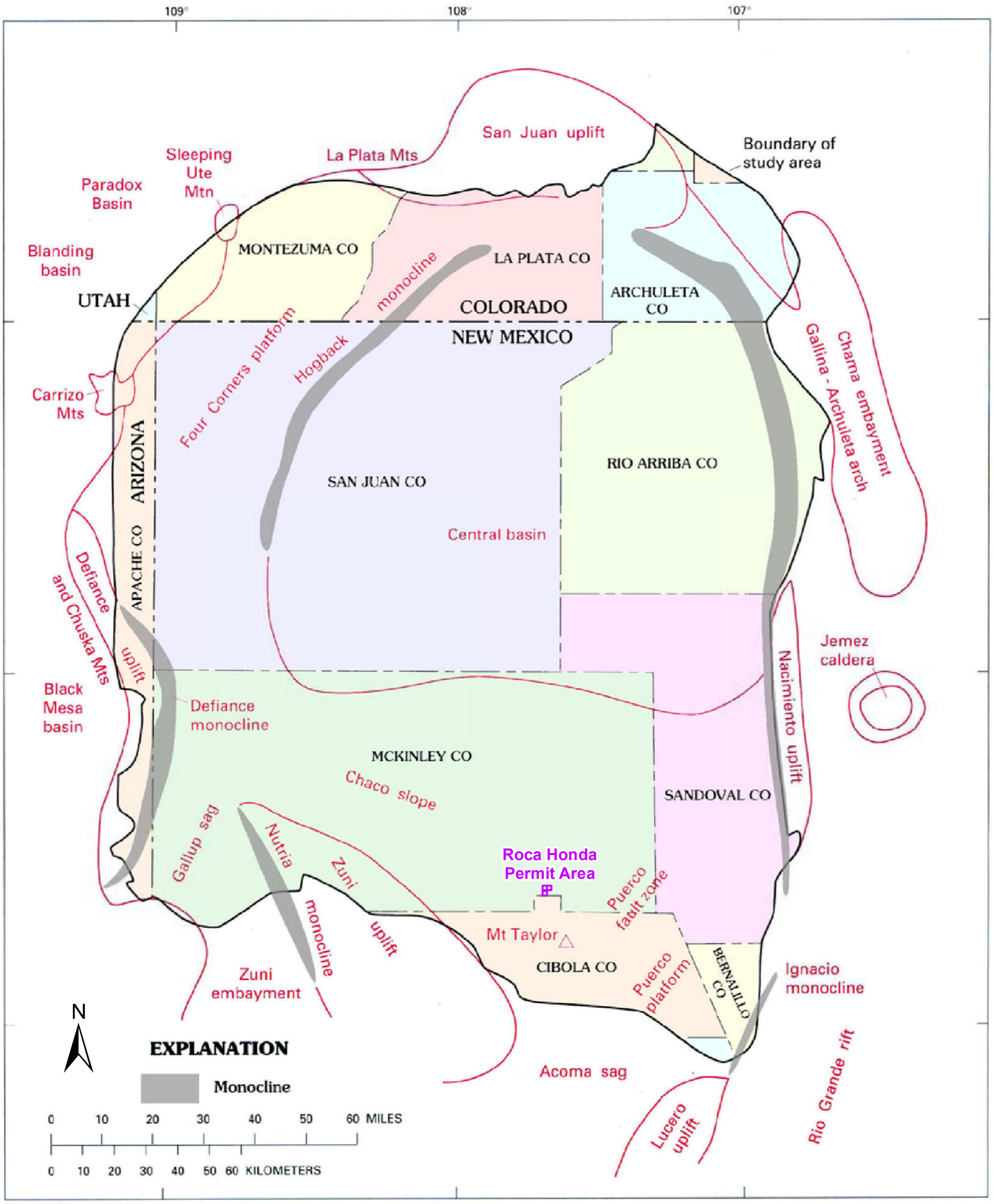
2.1.1 San Juan Basin

The San Juan structural basin covers approximately 21,600 square miles, primarily in northwestern New Mexico, with smaller portions in adjacent parts of southwestern Colorado and northeastern Arizona (Figure 2.1). It is about 140 miles wide and 200 miles long. The proposed Roca Honda mine is situated along the basin's southern margin.

The basin is bounded by structural uplifts on all sides (Kelley, 1963), whereas the central part of the basin consists of relatively flat-lying sedimentary rocks. Topographic relief spans more than 7,000 feet between the high-elevation mountains and uplifts and the low-elevation sags and basin center. The structural center of the basin is located beneath the northeastern part of the basin. Up to 14,400 feet of sedimentary rocks ranging in age from Devonian to Tertiary fill the basin (Craigg, 2001). These rocks dip into the basin relatively steeply on the northern, western, and eastern margins of the basin, and less steeply along the southern margin, as illustrated in Figure 2.2, a regional cross section adapted from Stone et al. (1983) and Kernodle (1996). The older rocks crop out along the basin perimeter and are overlain by successively younger rocks toward the center of the basin (Figures 2.2 and 2.3).

As shown in Figure 2.2, the San Juan Basin contains numerous geologic units. Organized by age from oldest to youngest, the major geologic units in the San Juan Basin are:

- Undivided Paleozoic-era rocks and the Permian-age San Andres Limestone and Glorieta Sandstone.
- The upper Triassic Chinle Formation and the upper Jurassic Entrada Sandstone, the Bluff-Cow Springs Sandstone, the Summerville Formation, and the Todilto Limestone.
- The upper Jurassic Morrison Formation, the members of which are, from older to younger: the Recapture Shale Member (Recapture), the Westwater Canyon Member, and the Brushy Basin Member (Brushy Basin).
- The Cretaceous Dakota Sandstone, the late Cretaceous Mancos Shale (Mancos), and the upper Cretaceous Mesaverde Group, which contains the Gallup Sandstone, the Crevasse Canyon Formation, the Point Lookout Sandstone, the Menefee Formation, and the Cliff House Sandstone.
- The upper Cretaceous Lewis Shale, the Pictured Cliffs Sandstone, the Kirtland Formation, and the Fruitland Shale.
- The Tertiary Ojo Alamo Sandstone and the Animas, Nacimiento, and San Jose Formations, shown on Figure 2.2 as undivided Tertiary rocks.



*Adapted from Kelley (1963), Levings et al. (1996), and Craigg (2001).

Structural Features of the San Juan Basin

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Figure 2.1

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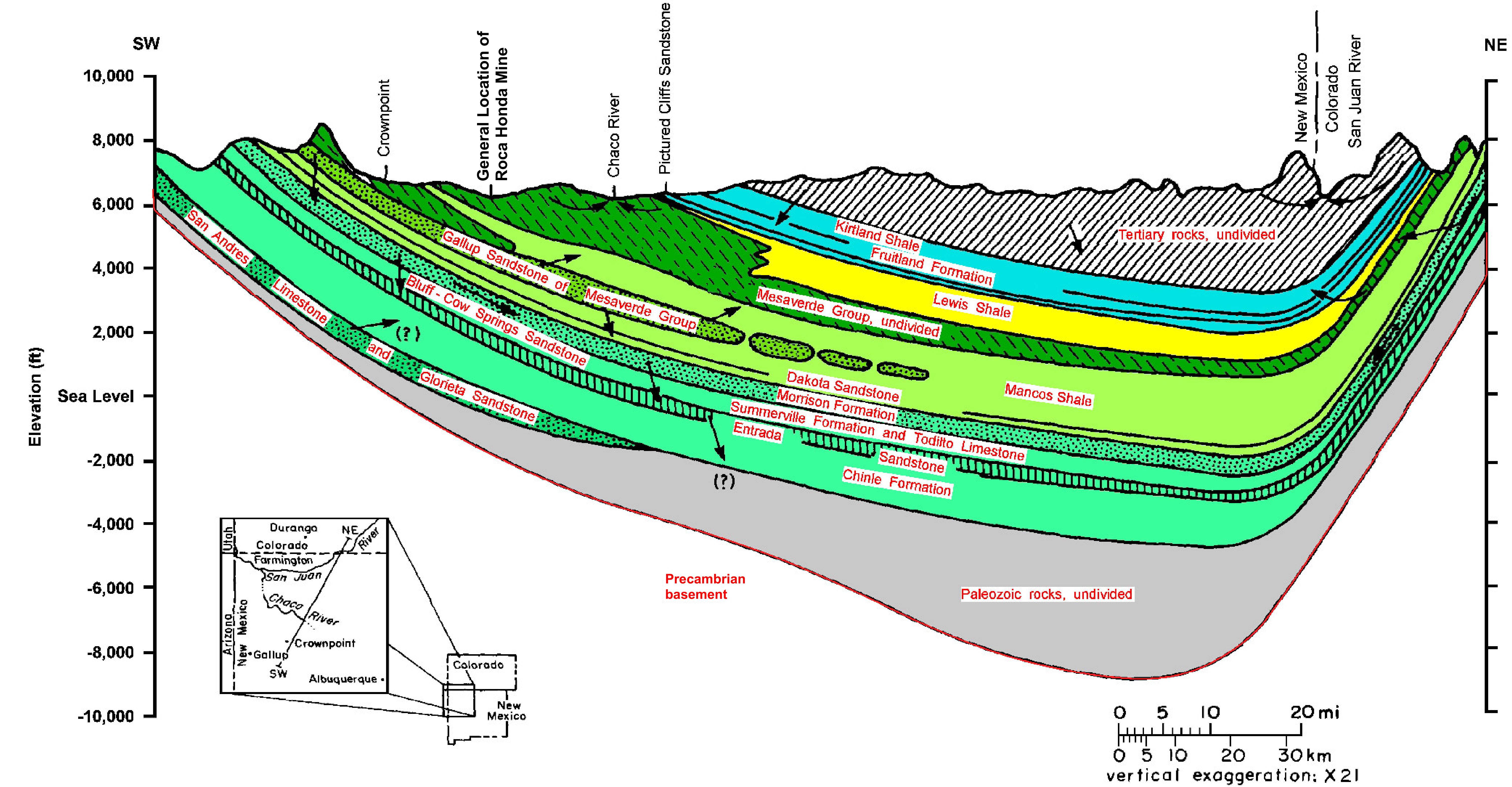

*Adapted from Stone et al. 1983 and Kernodle, 1996.

Generalized Southwest to Northeast Cross Section of the San Juan Basin

Figure 2.2

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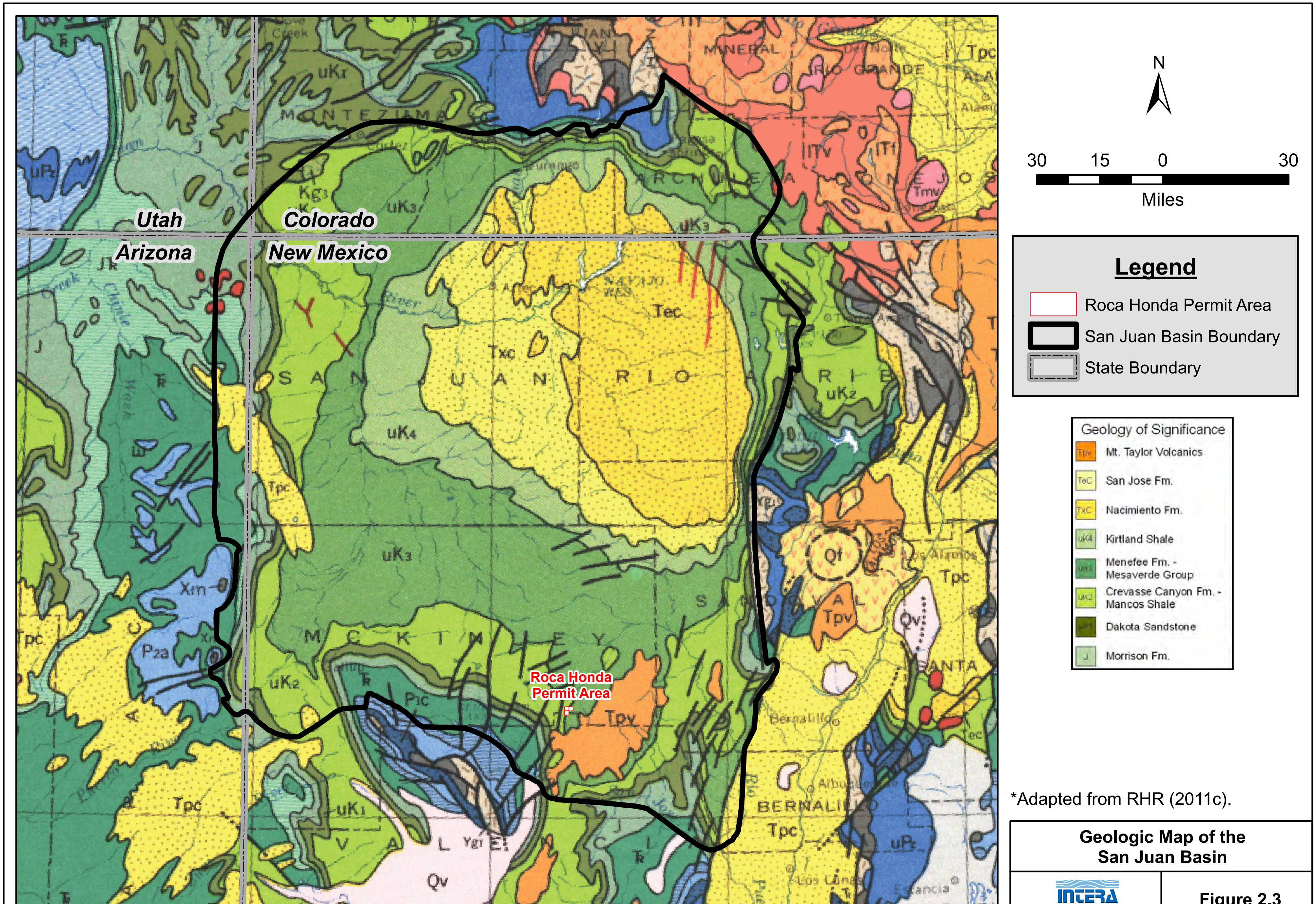

*Adapted from RHR (2011c).

Geologic Map of the San Juan Basin

INTERA

Figure 2.3

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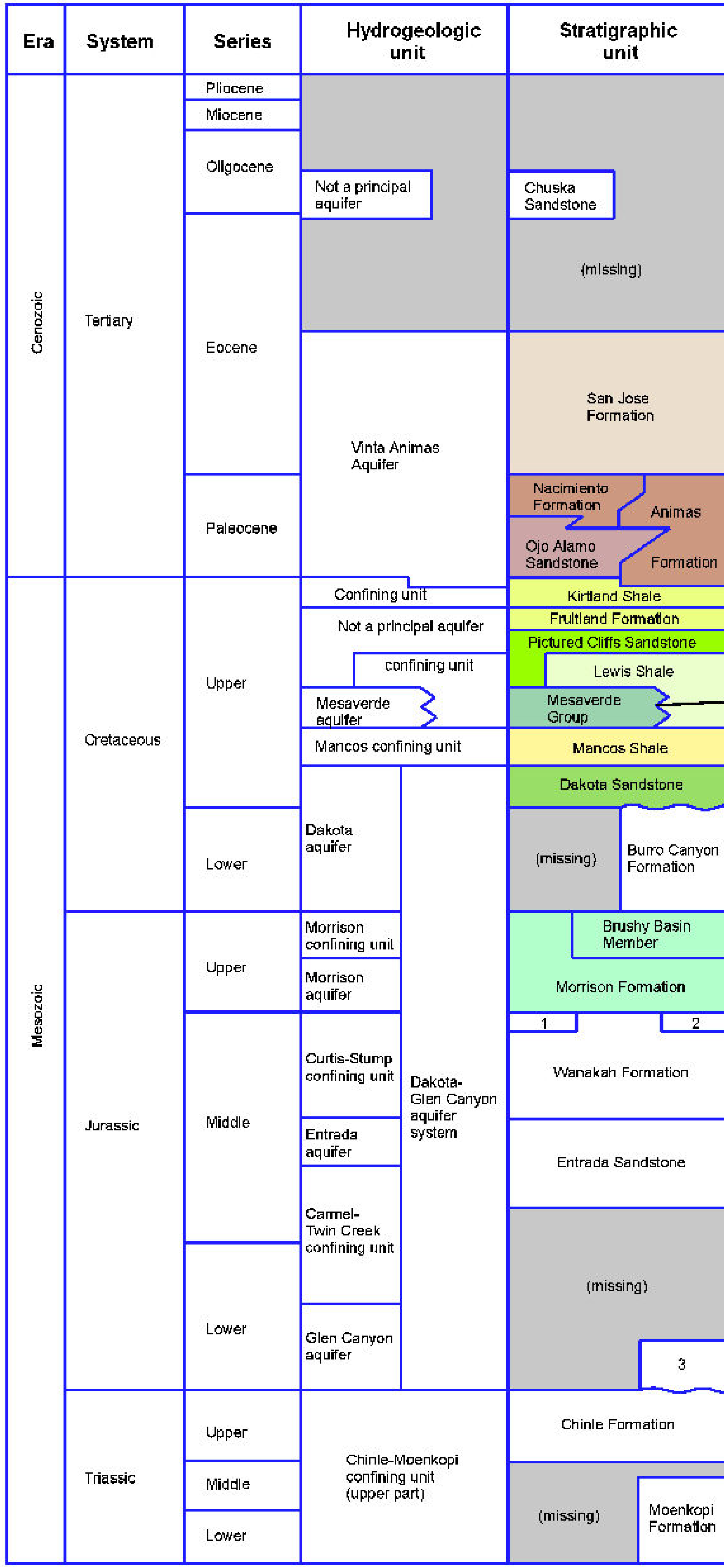
Many of these geologic units, such as the Gallup Sandstone, the Point Lookout Sandstone, and the San Jose Formation, are only found in parts of the San Juan Basin. Other units, including the Mancos Shale and the Morrison Formation, extend across all or nearly all of the San Juan Basin.

The focus of this study is on the sedimentary rocks of upper Jurassic to Cretaceous age in the San Juan Basin, that is, the Morrison Formation, the Dakota Sandstone, the Mancos Shale, and the Mesaverde Group, which are the geologic units that could be affected by the proposed Roca Honda dewatering (Figure 2.4). The vertical and horizontal extents of the geologic units considered in this study were set in accordance with the focus of the study.

The vertical extent of the study area includes the geologic units from the ground surface down to the Westwater Member of the Morrison Formation. The Westwater is considered to form the base of the study area because the geologic unit immediately below the Westwater, the Recapture Shale, is composed of low-permeability shale that greatly restricts the movement of groundwater flow between deeper aquifers and the Westwater. The thick Chinle Formation, which separates the deep aquifers of the San Andres Limestone and Glorieta Sandstone from overlying rocks, has a very low hydraulic conductivity and also restricts groundwater flow in and out of the San Andres Limestone. Even though the geologic units that are younger than the Mesaverde Group are not physically present at the Roca Honda permit area, these younger units are included in this study because of the importance of the groundwater-surface water interactions and the presence of springs and wells within these units. The vertical extent limits the horizontal extent of the study area along the basin’s southern margin to the Morrison Formation outcrops where the Westwater likely contains groundwater (Figure 2.3).

The geologic units found in the study area are grouped into hydrostratigraphic units according to the overall behavior of each group, that is, whether the group behaves as an aquifer or an aquitard for the purposes of the study. Figure 2.4 depicts the relationship between the geologic units in the study area and their corresponding hydrostratigraphic unit, which also corresponds to the model layer number (see Section 3.4). Both geologic units and hydrostratigraphic units are discussed in the following subsections; however, only hydrostratigraphic units are discussed in Sections 3 to 6.

The following descriptions of the geologic units are primarily based on the more detailed descriptions in Craigg (2001) for the San Juan Basin. Information about the vicinity of the Roca Honda permit area is taken from RHR (2011c).



Model Layer	Hydrostratigraphic Unit	Thickness (ft)
1	San Jose Formation	200 – 2,700
2	Animas and Nacimiento Fms	500 – 2,700
3	Ojo Alamo Sandstone	20 – 400
	Kirtland and Fruitland Fms	0 – 2,000
	Pictured Cliffs Sandstone	0 – 400
4	Lewis Shale	0 – 2,400
5	Cliff House Sandstone	20 – 500
	Menefee Formation	0 – 2,000
	Point Lookout Sandstone	100 – 350
6	Mancos Shale (NE only)	1,000 – 2,300
	Gallup Sandstone (SW only)	0 – 300
7	Mancos Shale	1,000 – 2,300
8	Dakota Sandstone	200 – 350
9	Brushy Basin Member of Morrison Formation	80 – 250
10	Westwater Canyon Member of Morrison Formation	100 – 300

*Stratigraphic column adapted from Maxim Technologies (2005).

Correlation of Stratigraphic Column to Conceptual Hydrostratigraphy

INTERA

Figure 2.4

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2.1.1.1 Morrison Formation

The Westwater Canyon Member and the Brushy Basin Member are the uppermost two members of the Morrison Formation. The Westwater Canyon Member is present throughout the San Juan Basin at thicknesses that range from about 50 feet in the southeast corner of the basin to about 300 feet in the southwest-central part of the basin; near the Roca Honda permit area, the Westwater thickness is roughly 200 feet. It consists of locally conglomeratic sandstone interbedded with sandstone, shale, and claystone; the proportion of sandstone and the grain size of the sandstones decrease toward the northeast. The Westwater Canyon Member is the uranium-ore-bearing unit in the area around the proposed Roca Honda mine. The Brushy Basin Member consists mainly of calcareous and bentonitic claystone and mudstone and functions as an aquitard throughout the basin. Its thickness ranges from about 80 to 300 feet and is commonly about 185 feet in the San Juan Basin. It is 200 feet thick in the vicinity of the Roca Honda permit area. The Brushy Basin member was removed from the southwestern corner of the basin by erosion that occurred before the deposition of the overlying Dakota Sandstone.

2.1.1.2 Dakota Sandstone

The Dakota Sandstone overlies the Morrison Formation throughout the San Juan Basin. It consists of a basal section of sandstone and conglomeratic sandstone overlain by a middle section of siltstone, shale, and lenticular sandstone beds, and an upper section of fine-grained sandstone interbedded with shale. The Dakota Sandstone ranges from 10 to about 500 feet thick and is commonly 200 to 300 feet thick. Its thickness near the Roca Honda permit area is only 60 feet. The thickness of the Dakota generally increases from the northern and western margins of the basin toward the eastern and southern margins, where it thins to approximately 50 feet in the southeast corner of the basin.

2.1.1.3 Mancos Shale

The main body of the Mancos Shale is present above the Dakota Sandstone throughout the basin and intertongues with sandstone units of the Mesaverde Group at some locations. In the northern part of the basin, the main body of the Mancos Shale is up to 2,300 feet in thickness. The aggregate thickness of the Mancos tongues in the southern part of the basin is about 1,000 feet. The main body of the Mancos is 900 feet thick in the area near the Roca Honda permit area.

2.1.1.4 Mesaverde Group

The Mesaverde Group includes the Gallup Sandstone, the Point Lookout Sandstone, the Menefee Formation, and the Crevasse Canyon Formation. The Gallup Sandstone is present only in the southwestern half of the basin, partly because of stratigraphic pinchout and partly because of post-depositional removal by erosion that occurred before the deposition of the upper part of the

Mancos Shale (Molenaar, 1973, as cited by Craigg, 2001). It overlies the lower part of the Mancos Shale and is truncated against the upper part of the Mancos Shale. The Gallup Sandstone is not present northeast of a truncation line that extends from the southeast corner of the basin to slightly northwest of Shiprock. The thickness of the Gallup Sandstone ranges from zero at the truncation line to approximately 300 feet in the southwest part of the basin, near Gallup. Exposures of the Gallup Sandstone crop out along the southern and western parts of the basin perimeter. In the vicinity of the Roca Honda permit area, the Gallup has a thickness of roughly 100 feet.

The Crevasse Canyon Formation is a sequence of shale, sandstone, and coal that overlies the Gallup or the Mancos where the Gallup is absent. It crops out only along the southern part of the basin and pinches out about 30 miles north of its outcrops (Kernodle, 1996). The Crevasse Canyon Formation contains the Gibson Coal Member, the Dalton Sandstone Member, the Borrego Pass Lentil, and the Dilco Coal Member in order from youngest to oldest. Its two sandstone units are separated by the Mulatto tongue of the Mancos Shale. The thicknesses of its members vary with location, but total thickness near the Roca Honda permit area is 870 feet.

The Point Lookout Sandstone typically forms either cliffs and cap buttes or erosion-resistant dip slopes and hogbacks around the margins of the central basin. The thickness of the Point Lookout Sandstone varies irregularly from about 100 feet in the southern part of the basin to about 350 to 400 feet near the Colorado-New Mexico state line. The Point Lookout has an average thickness of 150 feet in the Roca Honda permit area. The Menefee Formation is a repeating sequence of sandstone, shale, claystone, carbonaceous shale, and coal bed. It ranges in thickness from a feather edge at its outcrops in Colorado to about 2,000 feet in the south-central part of the basin. The Menefee is not present within the Roca Honda permit area.

Cliff House Sandstone outcrops form the margins of the central basin, displaying landforms similar to those formed by Point Lookout outcrops. It consists of several sandstone tongues of varying thicknesses and areal extents. The aggregate thickness is reported to range from zero to 300 feet with thicknesses between 20 and 250 feet being common throughout most of its extent (Stone et al., 1983). The Cliff House Sandstone is not present in the Roca Honda permit area.

2.1.1.5 Lewis Shale

The Lewis Shale conformably overlies and intertongues with the Cliff House Sandstone. It is made up primarily of shale and silty shale with thin interbeds of limestone, siltstone, and fine-grained sandstone. The thickness of the Lewis Shale increases from zero, where it pinches out between the Cliff House and the overlying Pictured Cliffs Sandstones in the west-central basin, to about 2,400 feet in the northern part of the basin. It is not present in the Roca Honda permit area.

2.1.1.6 Pictured Cliffs Sandstone

The Pictured Cliffs Sandstone is present in the central basin area, ranging in thickness from zero on the east side of the basin to about 400 feet in the north-central part. It consists of a sequence of sandstone with thin interbeds of shale, particularly in the lower part of the formation. It intertongues with the overlying Fruitland Formation, which contains the principal coal resources of the San Juan Basin and is generally mapped with the overlying and similar Kirtland Shale. The Fruitland Formation and Kirtland Shale both consist of variable thicknesses of interbedded and repetitive sequences of channel sandstone, siltstone, shale, and claystone. Carbonaceous shale and coal are common in the Fruitland. The thickness of the combined formations ranges from zero on the eastern side of the basin to about 2,000 feet in the northwestern part of the basin. It is not present in the Roca Honda permit area.

2.1.1.7 Ojo Alamo Sandstone

The Ojo Alamo Sandstone is the oldest formation of Tertiary age in the San Juan Basin. It crops out inside the central basin and typically forms cliffs and dip slopes, or it caps low mesas and forms rounded hills. The formation pinches out in the northwest between Farmington and the Colorado state line and ranges from 20 to 400 feet thick in the remainder of its extent, with thicknesses between 50 and 150 feet being most common. It is not present in the Roca Honda permit area.

2.1.1.8 Animas and Nacimiento Formations

The Animas and Nacimiento Formations overlie and intertongue with the Ojo Alamo Sandstone in the central basin. The Animas Formation consists of fluvial and volcaniclastic sandstone, conglomerate, and shale. The Nacimiento grades laterally into the upper part of the Animas in the northern part of the basin. It consists of interbedded shale and discontinuous lenses of sandstone, and includes carbonaceous shale and lignite in some areas. The combined thickness of the Animas and Nacimiento Formations ranges from about 500 to 2,700 feet. It is not present in the Roca Honda permit area.

2.1.1.9 San Jose Formation

The San Jose Formation is a sequence of interbedded sandstone, siltstone, and shale that overlies the Animas Formation in Colorado and the Nacimiento Formation in New Mexico. The thickness is variable, but generally increases from about 200 feet on the west to about 2,400 feet on the east and 2,700 feet in the center of the basin. It is not present in the Roca Honda permit area.

2.1.1.10 Other Geologic Units

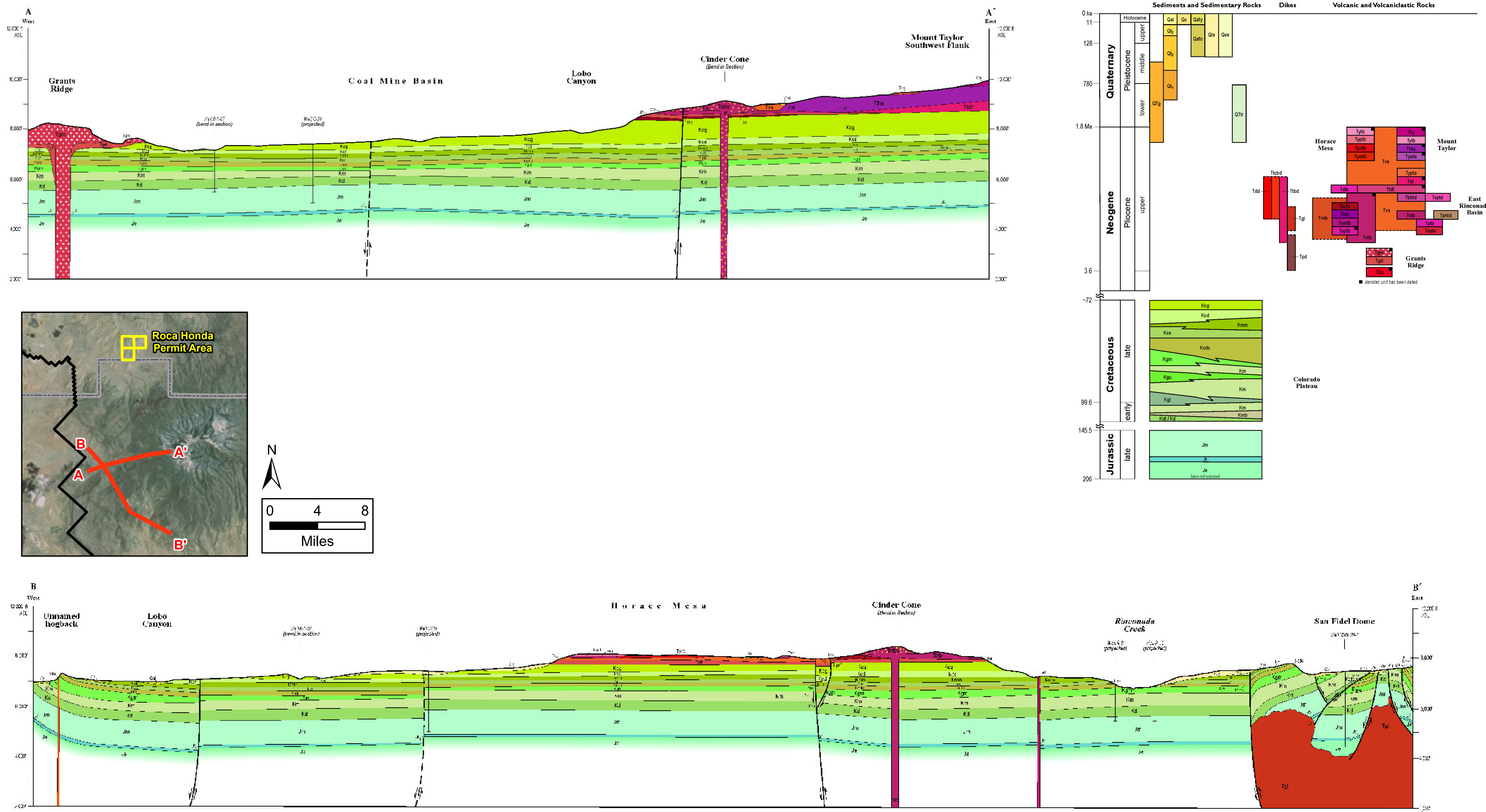
Mt. Taylor's volcanic rocks and associated basalt and andesite flows are important to understanding recharge and groundwater flow near the RHM site. The numerous volcanic necks within Mt. Taylor and Chivato Mesa and in their vicinity crosscut all of the sedimentary units in the area (Figure 2.5ab). The much more laterally extensive basalts and andesite flows created a varying-thickness cover on those same sediments (Figures 2.2 and 2.5ab). By reason of its 11,000-ft elevation, Mt. Taylor collects much more precipitation than the lower lying units.

The Chuska Mountains in the western part of the basin along the New Mexico-Arizona border are another important source of recharge to the San Juan Basin (Kernodle, 1996). The mountains comprise the eolian Chuska Sandstone, a series of volcanic necks, and associated basalt or andesite flow caps, and are depicted by the NW-SE trending yellow body labeled Tpc in Figure 2.3. The average thickness of the Chuska Sandstone is reported to be 1,000 feet and appears to be the source for the numerous springs as well as recharge to deeper sedimentary units (Kernodle, 1996).

2.1.2 Roca Honda Mine Geologic Setting

The Roca Honda permit area lies within the San Juan structural basin, and the rocks present within the permit area are the same as those described above for the basin. Approximately 2,100 to 2,800 feet of sedimentary rocks lie between ground surface and the proposed mine workings within the Roca Honda permit area. Shale dominates the strata that lie between the Westwater and the land surface. The Dakota and Gallup sandstone aquifers have average thicknesses of roughly 50 and 100 feet, respectively, and the Point Lookout Sandstone and Dalton Sandstone Member of the Crevasse Canyon Formation account for roughly another 200 feet of sandstone. The younger sandstone intervals are separated from the Gallup by approximately 450 feet of shale and shaley sandstones, and there are approximately 900 feet of Mancos Shale between the Gallup and the Dakota aquifers. Quaternary alluvium and Mesaverde Group units are exposed at the ground surface.

The geologic structure varies around the Roca Honda permit area. To the south and southwest, the Gallup, Dakota, and Morrison units are exposed at the surface where they are not covered by volcanic flows associated with Mt. Taylor. To the east and southeast the sedimentary rocks are covered by the volcanic materials from Mt. Taylor and other volcanic necks. The aquifer units dip steadily downward to the north and less steeply to the west. Greater detail about the site area geology is provided in RHR (2011c).



*Adapted from OF-GM 181, May 2008, New Mexico Bureau of Geology and Mineral Resources.

Surficial Flows and Cores of Mt. Taylor Volcanics

INTERA

Figure 2.5a

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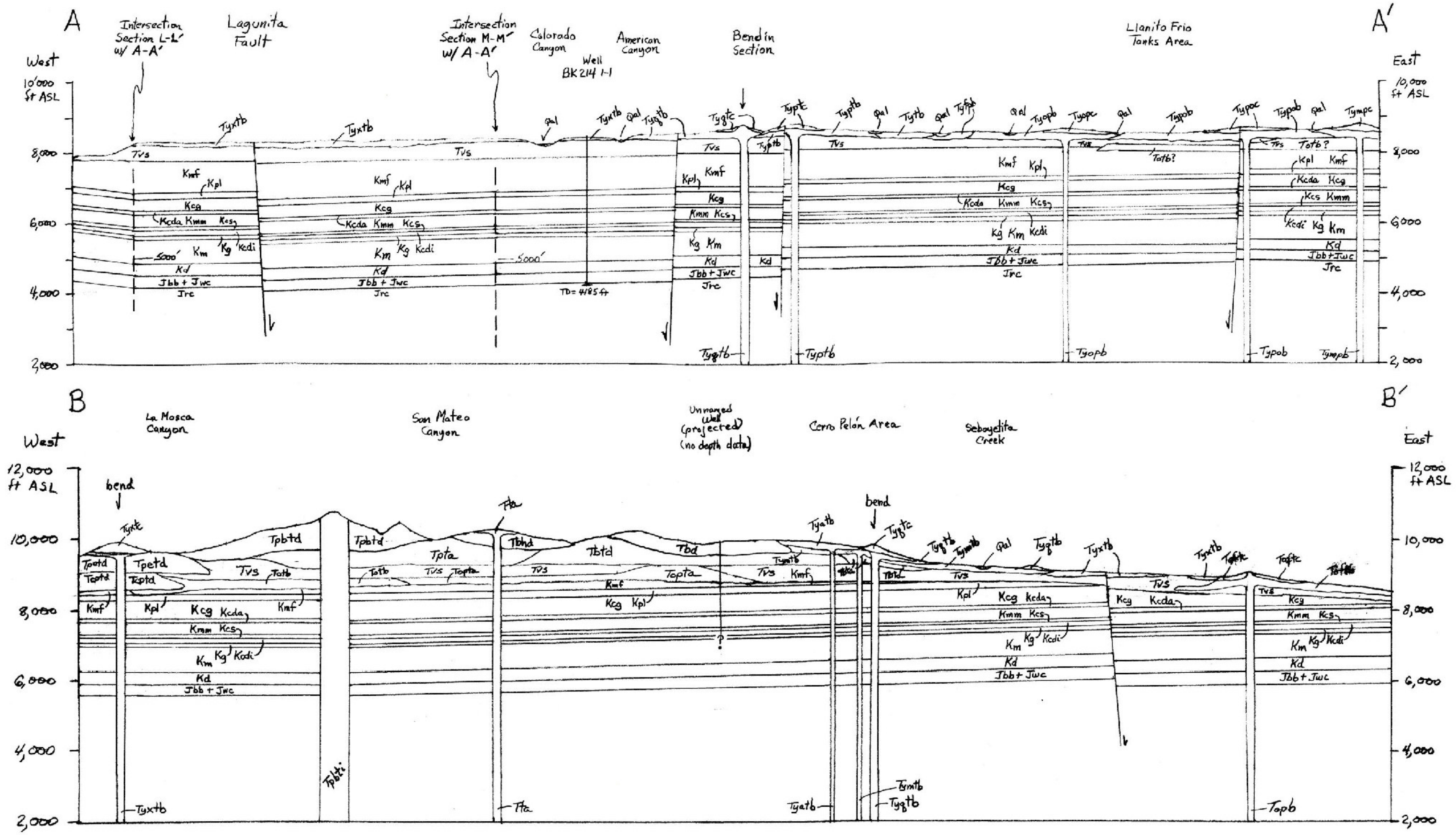
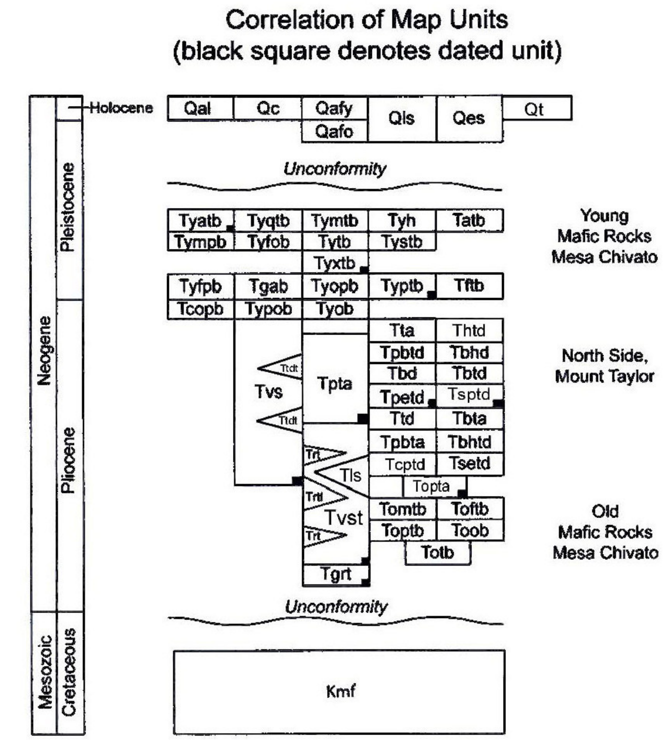
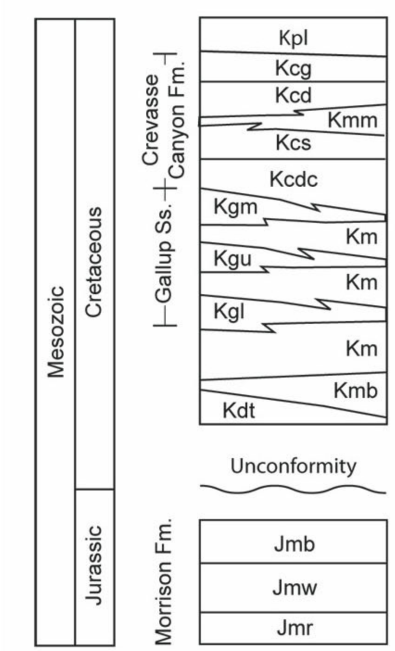
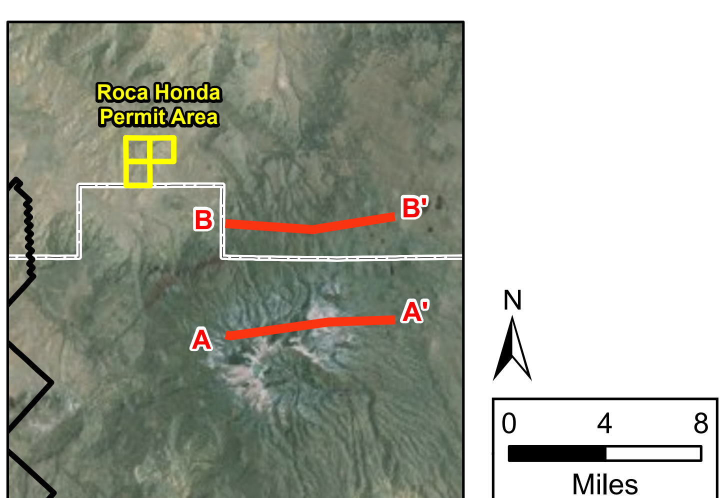




Subsurface stratigraphy
Cerro Pelon quadrangle





*Adapted from OF-GM 202, June 2010, New Mexico Bureau of Geology and Mineral Resources.

Surficial Flows and Cores of Mt. Taylor Volcanics

Figure 2.5b

2.2 Hydrologic Setting

Water enters the groundwater flow system of the San Juan Basin by seepage from flowing rivers or drainages and infiltration within recharge areas, especially along the mountain fronts and basin margins. Groundwater leaves the San Juan Basin aquifer units by flowing into rivers, springs, or drainages, by evaporation and transpiration, and by human extraction. In the area of the Ambrosia Lake sub-district, groundwater levels in the Westwater are presently recovering after having been drawn down by dewatering for historical uranium mining.

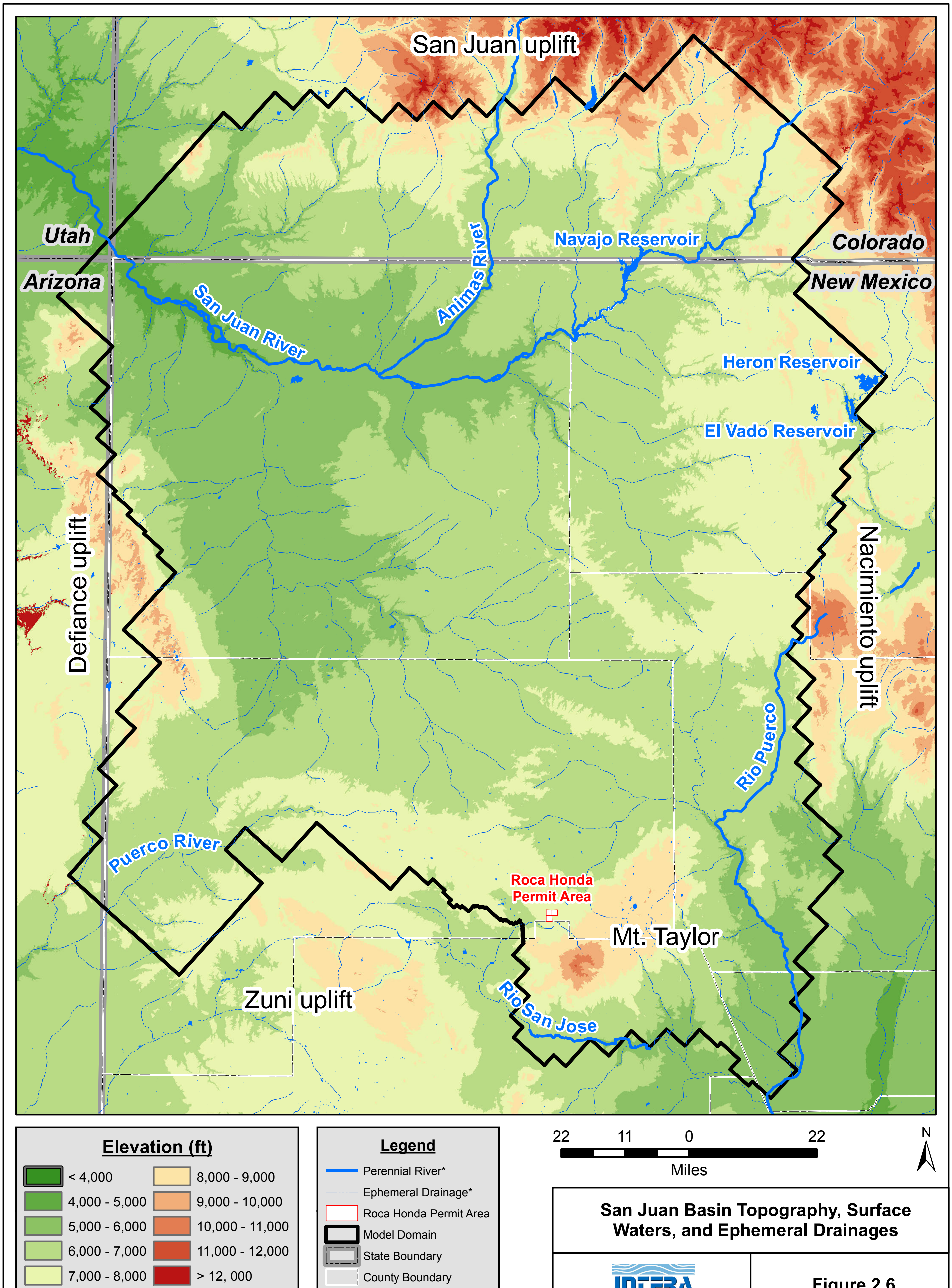
2.2.1 Surface Water

The basin's surface water bodies include a single perennial river system, the San Juan River, and many intermittent and ephemeral rivers and drainages, reservoirs, springs, and irrigation diversions (Stone et al., 1983; Kernodle, 1996). Depending on location and season, surface water bodies can act as recharge areas, where surface water seeps into the subsurface, or as discharge areas, where groundwater seeps out of the subsurface and is carried away by surface flow.

Only the San Juan River and its northern tributaries, e.g., the Animas River, in the northern part of the basin carry water into the San Juan Basin, exchange flows with the near-surface stratigraphic units, and collect groundwater discharging from the Gallup, Dakota, and Westwater aquifers (Stone et al., 1983; Kernodle, 1996). Figure 2.6 depicts the perennial and ephemeral surface water bodies and ground surface elevation across the San Juan Basin, as well as the boundary of the study area, represented in the figure as the model domain (see Section 3.4 for further details). The San Juan River system also supplies many of the irrigation diversions.

The Rio Puerco has perennial, intermittent, and ephemeral reaches in the southeastern part of the basin. This drainage drains the aquifer units it crosses, as do the ephemeral Puerco River in the southwestern corner and the numerous ephemeral drainages throughout the basin (Figure 2.6; Stone et al., 1983; Gold and Rankin, 1994; Kernodle, 1996). All ephemeral drainages, including the Puerco River and the Rio Puerco, can also discharge limited amounts of water to the subsurface during the infrequent occasions that they have flowing water. Perennial flows along short distances have been observed in a number of the ephemeral drainages, presumably where they are supplied by springs or other groundwater discharges (Stone et al., 1983; Kernodle, 1996).

The largest river near the Roca Honda permit area is the Rio San Jose (Figure 2.6), which flows along the southern margin of the San Juan Basin, and has ephemeral flow along most of its length, with perennial flow between Horace Spring and Laguna Pueblo (Risser, 1982). Most of the Rio San Jose is located on surficial geologic units that are older and stratigraphically lower than the Westwater aquifer, but a roughly 12-mile-long reach from Horace Springs to Acomita is in contact with younger geologic units and roughly 150 to 300 feet of Westwater (Risser, 1982; Baldwin and Anderholm, 1992; Frenzel, 1992; Appendix E). There are many small, ephemeral drainages in the vicinity of the mine site, with San Mateo Creek being the nearest (Figure 2.7; RHR, 2011d). Flows in these drainages are, like the Puerco River, restricted to periods following one or more rainstorms, or occur within spring-fed localized perennial reaches (RHR, 2011d).



*Perennial streams and ephermeral drainage are based on US National Atlas Water Feature Lines Database

San Juan Basin Topography, Surface Waters, and Ephemeral Drainages

INTERA

Figure 2.6

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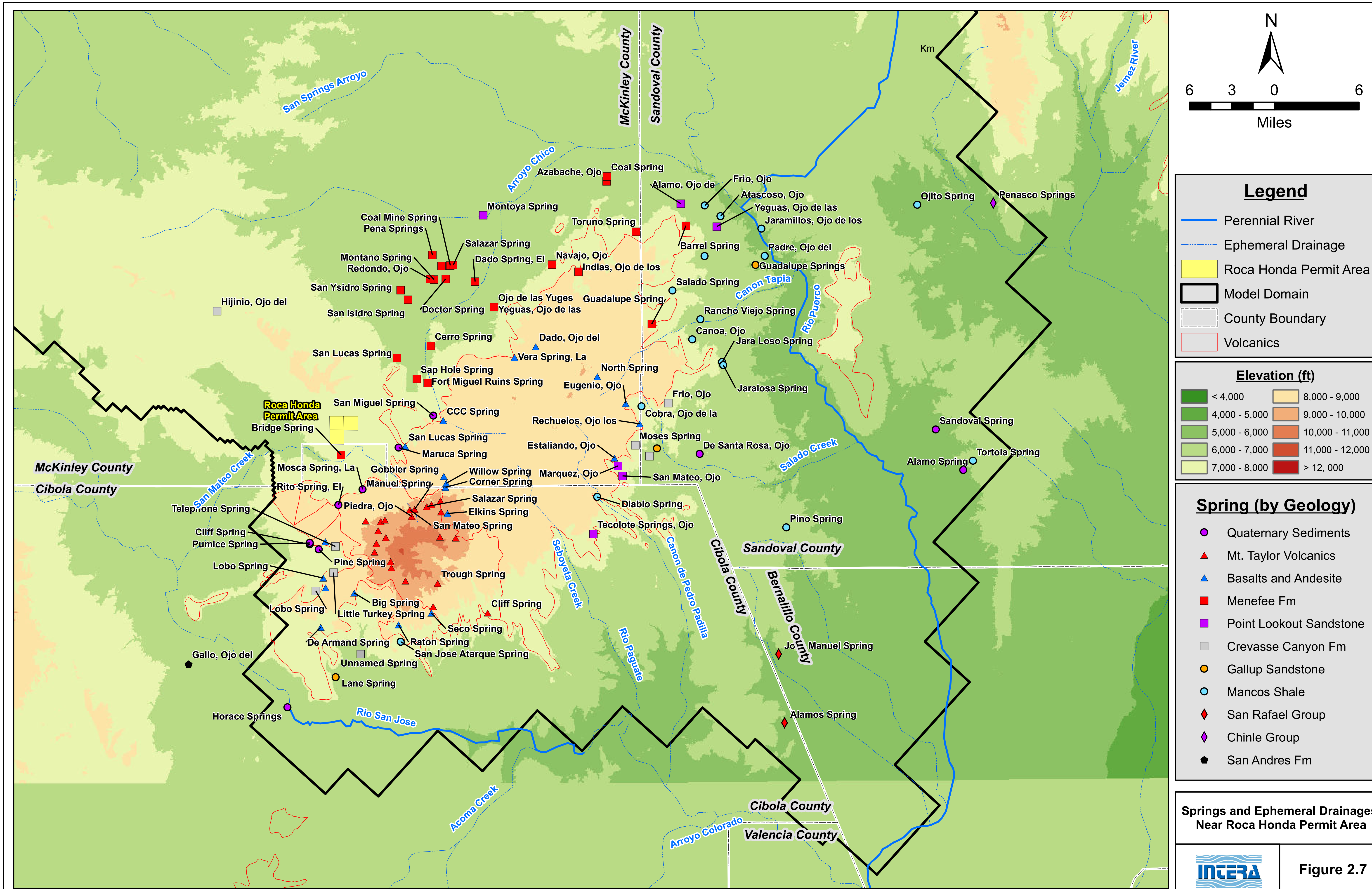


Springs and Ephemeral Drainages Near Roca Honda Permit Area

Figure 2.7

Revised August 7, 2012

The high elevation and volcanic rocks of Mt. Taylor and Mesa Chivato support the largest proportion of springs in the site vicinity (Figure 2.7). The next largest group of springs is found in the Menefee Formation, Crevasse Canyon Formation, and Point Lookout Sandstone, as is shown in Figure 2.7.

The majority of the springs located in the volcanic rocks, basalt or andesite flows, or Quaternary sediments on the west flank of Mt. Taylor are found at much higher elevations than in the Roca Honda permit area (Figure 2.7; RHR, 2011d). The remaining springs on the west side of Mt. Taylor are found in the Menefee Formation and other geologic units within the upper Mesaverde Group (Figure 2.7) that are not saturated in the permit area (RHR, 2011d). Horace Spring and unnamed springs that supply groundwater to the perennial reach of the Rio San Jose are located at the contact between the surficial basalt of the McCartys flow and underlying Jurassic and Cretaceous sediments (Risser, 1982; Baldwin and Anderholm, 1992; Frenzel, 1992; Appendix E).

The Navajo, Heron, and El Vado Reservoirs, and the irrigation diversions associated with the San Juan River, are all located in the northern part of the basin (Figure 2.6). Based on their relatively small areas and great distance from the Roca Honda mine, interactions between groundwater and the reservoirs or irrigation diversions are assumed to be negligible with respect to groundwater levels in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda mine.

2.2.2 Groundwater

Water enters the groundwater flow system as recharge in high elevation areas, as mountain-front recharge, and as infiltration from flowing rivers or drainages. Groundwater leaves the San Juan Basin aquifer units by discharging into rivers or drainages, by evaporation and transpiration, and by pumping of groundwater. All but the shallowest aquifers are unconfined along the outcrops and recharge areas, and become confined a short distance towards the basin center. Groundwater flow out of the San Juan Basin through leakage to other basins typically has been assumed to be negligible because of the basin's geometry (Stone et al., 1983; Kernodle, 1996).

Thick, low-permeability shale intervals divide the San Juan Basin's groundwater flow system into two or three relatively isolated flow systems. The Westwater, Dakota, and Gallup aquifers are separated from one another and the aquifers above and below them by units that are dominated by shale. Shale has a low hydraulic conductivity (analogous to permeability) and so offers great resistance to fluid flow. The Recapture Shale, the Brushy Basin, and the Mancos act as aquitards because their hydraulic conductivity is much lower than that of the three aquifers, and so the rate of groundwater flow into or out of the aquifers is much lower than the rate of flow within the aquifers. Similarly, the thick Mancos greatly restricts groundwater movement between the deeper Westwater, Dakota, and Gallup aquifers and those in the younger geologic units, such as the Point Lookout Sandstone or Menefee Formation in the vicinity of the Roca Honda permit area. In the northeastern part of the basin, the Lewis Shale restricts movement of groundwater between the Mesaverde Group and the Ojo Alamo Sandstone (Figure 2.4).

Historical differences in groundwater levels of 100 t o 200 feet between the Dakota and Westwater aquifers and between the Gallup and Dakota aquifer prior to the start of historical mining (Stone et al., 1983) are further evidence that the Brushy Basin and Mancos units act as aquitards. The Mancos Shale has enough thickness and sufficiently small hydraulic conductivity values to limit groundwater flow rates between the lower aquifer units (Gallup, Dakota, and Westwater) and the upper water-bearing units (e.g., Point Lookout Sandstone, sandstone lenses in the Menefee Formation) to very small values.

2.2.2.1 Inflows

Recharge from precipitation occurs only after near-surface processes including runoff, evaporation, transpiration, and sublimation have depleted any precipitation, leaving the remaining water to infiltrate. Areal recharge is limited to the northern and southern margins of the basin where elevations are high and precipitation rates are greater than potential evaporation rates. Outside of the high-elevation areas, most of the basin has an arid to semiarid climate, with transpiration by plants and potential evaporation exceeding precipitation and making recharge negligible in low-elevation areas of the basin. Bedrock units receive recharge where they crop out and in higher-elevation areas where they subcrop beneath saturated alluvium (Stone et al., 1983).

Seepage into the subsurface occurs beneath surface water bodies. Infiltration from streamflow losses to the subsurface occurs mainly along the northern margin of the basin where the larger streams draining the San Juan Mountains in Colorado flow across outcrops of the more permeable bedrock units. Infiltration from streamflow losses also occurs along the upper reaches of the Rio Puerco, Rio Salado, and Puerco River. Locally important recharge to the older bedrock aquifers occurs in the Chuska Mountains and along the flanks of Mt. Taylor (Kernodle, 1996). The number of springs around Mt. Taylor is evidence of the higher precipitation rates, resulting in greater infiltration, relative to the lower elevations.

2.2.2.2 Outflows

The San Juan River captures nearly all of the groundwater discharge from the Gallup, Dakota, and Westwater aquifers, with the remainder discharging to the ephemeral Rio Puerco and Puerco Rivers (Stone et al., 1983; Levings et al., 1996; Kernodle, 1996) and possibly the Rio San Jose (Frenzel, 1992). Groundwater flowing through the stratigraphically higher aquifer units can discharge to ephemeral drainages and rivers (Kernodle, 1996). Evaporation and transpiration remove water from the saturated intervals near ground surface, including ephemeral drainages, intermittent streams, springs, and rivers.

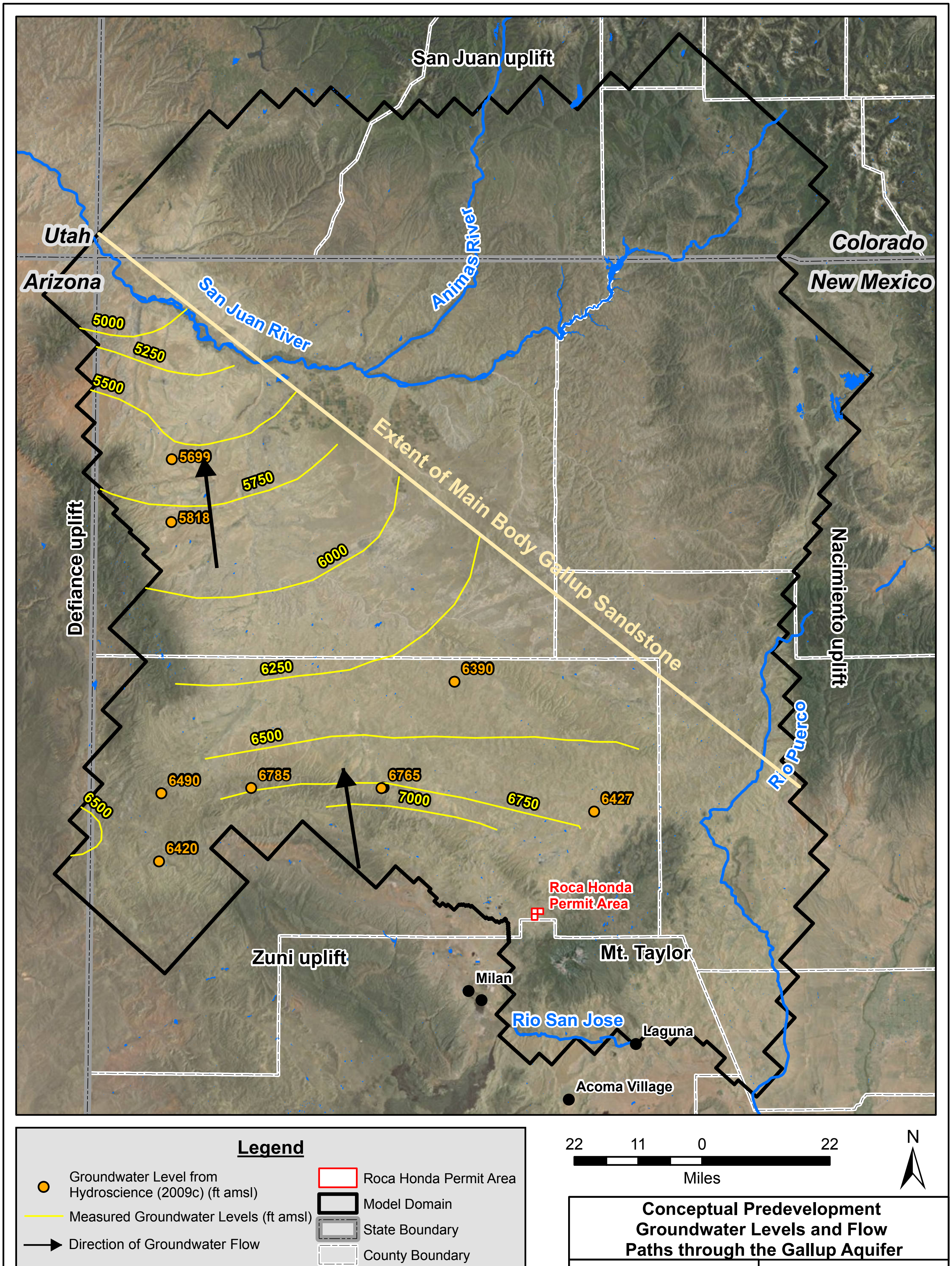
Wells in the San Juan Basin pump groundwater from a number of water-bearing units, including the Gallup, Dakota, and Westwater aquifers. Public water supply wells for Crownpoint and the two well fields for the city of Gallup pump only from these three aquifers, whereas wells for domestic consumption, irrigation, and stock watering pump mainly from shallower aquifers such as the Point Lookout Sandstone, sandstone intervals in the Mancos Shale and Mesaverde Group, and younger (overlying) geologic units. Mine dewatering of the Menefee Formation occurs at the Lee Ranch coal mine, northeast from the Roca Honda mine area.

2.2.2.3 Regional Flow Patterns

At the regional scale, groundwater enters the Gallup, Dakota, and Westwater aquifers as recharge along the southwestern and northeastern basin margins and then moves through the basin center towards the northwest and southeast (Stone et al., 1983; Kernodle, 1996). Prior to large-scale groundwater pumping, during the time period referred to as "predevelopment" time (defined for the purpose of this report as the period prior to 1930), the groundwater levels in the aquifers were high at the primary recharge areas along the southwestern and northeastern margins (Figures 2.8, 2.9, and 2.10). Groundwater flows into the basin center, and depending on i ts flow path, eventually discharges either to the lower San Juan River in the northwest corner of the San Juan Basin or to the Rio Puerco (Stone et al., 1983) and Rio San Jose (Frenzel, 1992) in the basin's southeast (Figures 2.8, 2.9, a nd 2.10). A minor amount of groundwater is discharged into the Puerco River in the southwestern area of the basin. Regional groundwater flow patterns in the shallower aquifers (those above the Mancos Shale) in the interior of the basin follow a similar pattern, but are more strongly controlled by discharge to alluvium in the ephemeral drainages of the Chaco River and its tributaries.

2.2.2.4 Impacts from Historical Uranium Mining

Uranium was mined from the Westwater in the Ambrosia Lake area. Figure 2.11 illustrates known or estimated locations of the mine workings. Dewatering of the mines formed a regional cone of depression within the upper Morrison Formation and lower Cretaceous units during the historical mining period (Bostick, 1985). The Westwater, the Dakota, and local sandstone beds in the lower Mancos Shale were essentially dewatered in the vicinity of the mines after mining started in the late 1950s. Groundwater removed from the mines was discharged to the Arroyo del Puerto drainage system and temporarily saturated portions of the formerly dry alluvium. Water also re-entered the bedrock through downward infiltration into underlying sandstones. Since 1986, when mining and dewatering ceased, groundwater levels in these units have been recovering.



*Gallup sandstone extent adapted from Stone et al. (1983).

Conceptual Predevelopment Groundwater Levels and Flow Paths through the Gallup Aquifer

INTERA

Figure 2.8

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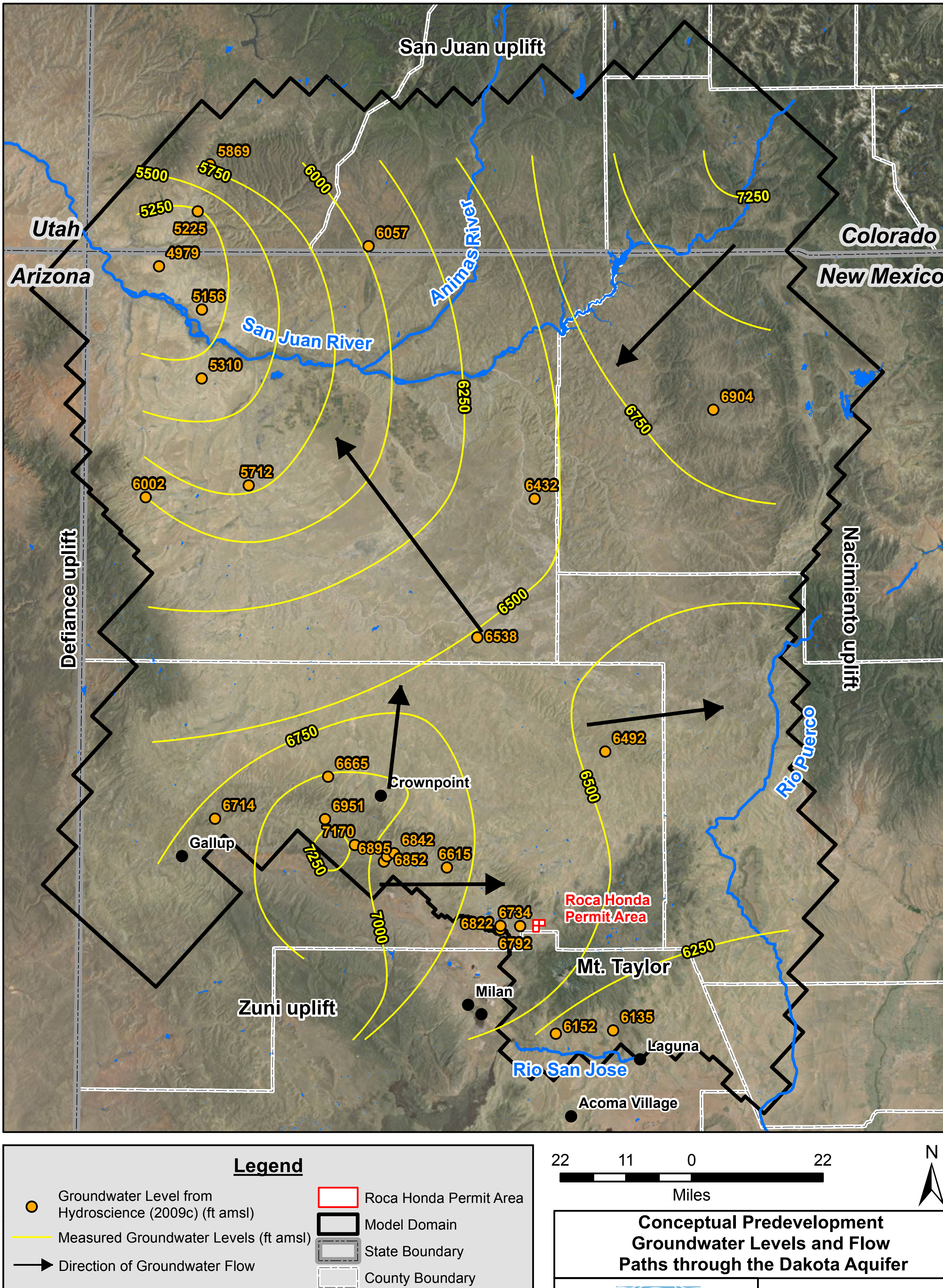
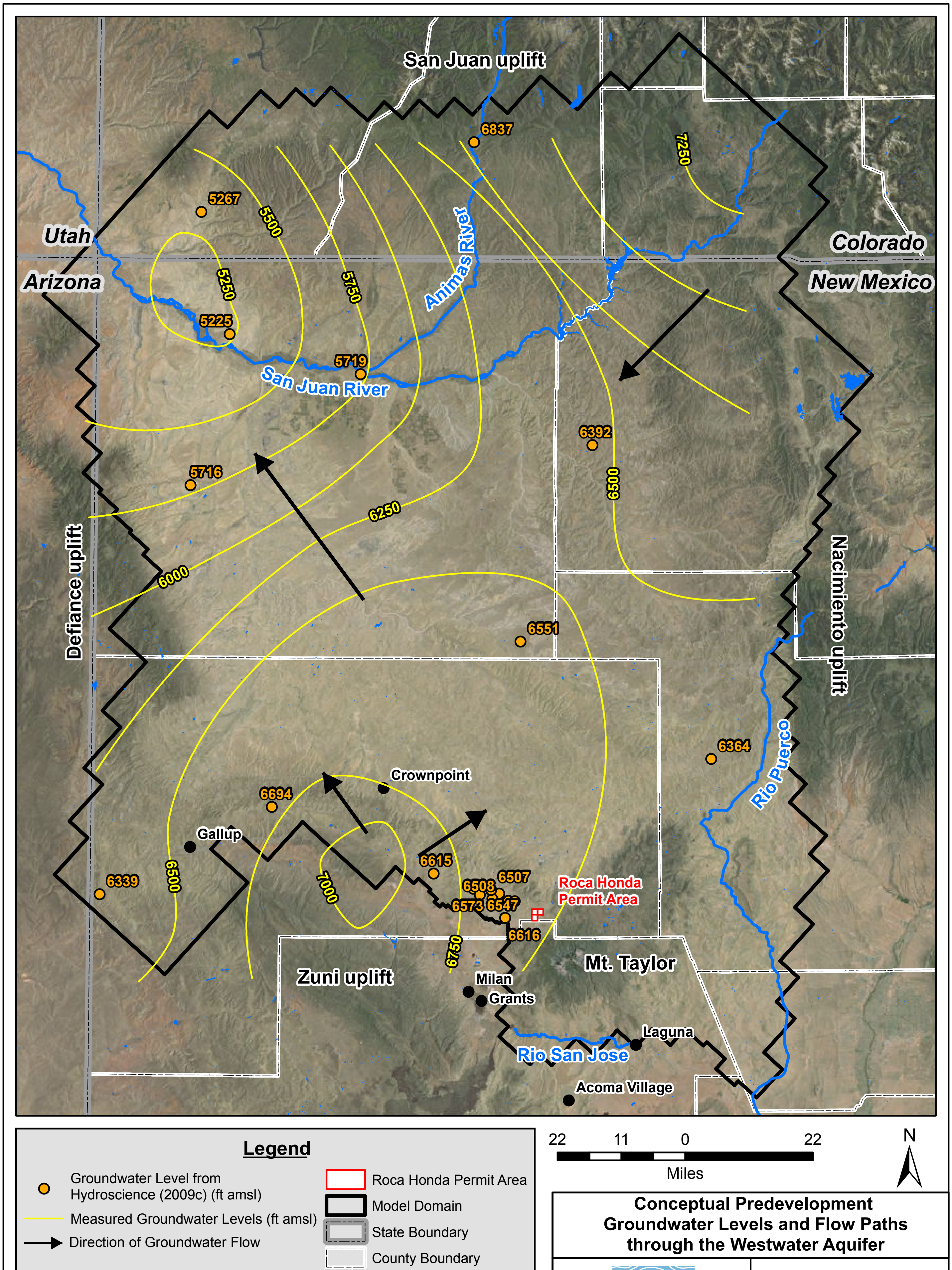


Conceptual Predevelopment Groundwater Levels and Flow Paths through the Dakota Aquifer

INTERA

Figure 2.9



Conceptual Predevelopment Groundwater Levels and Flow Paths through the Westwater Aquifer

INTERA

Figure 2.10

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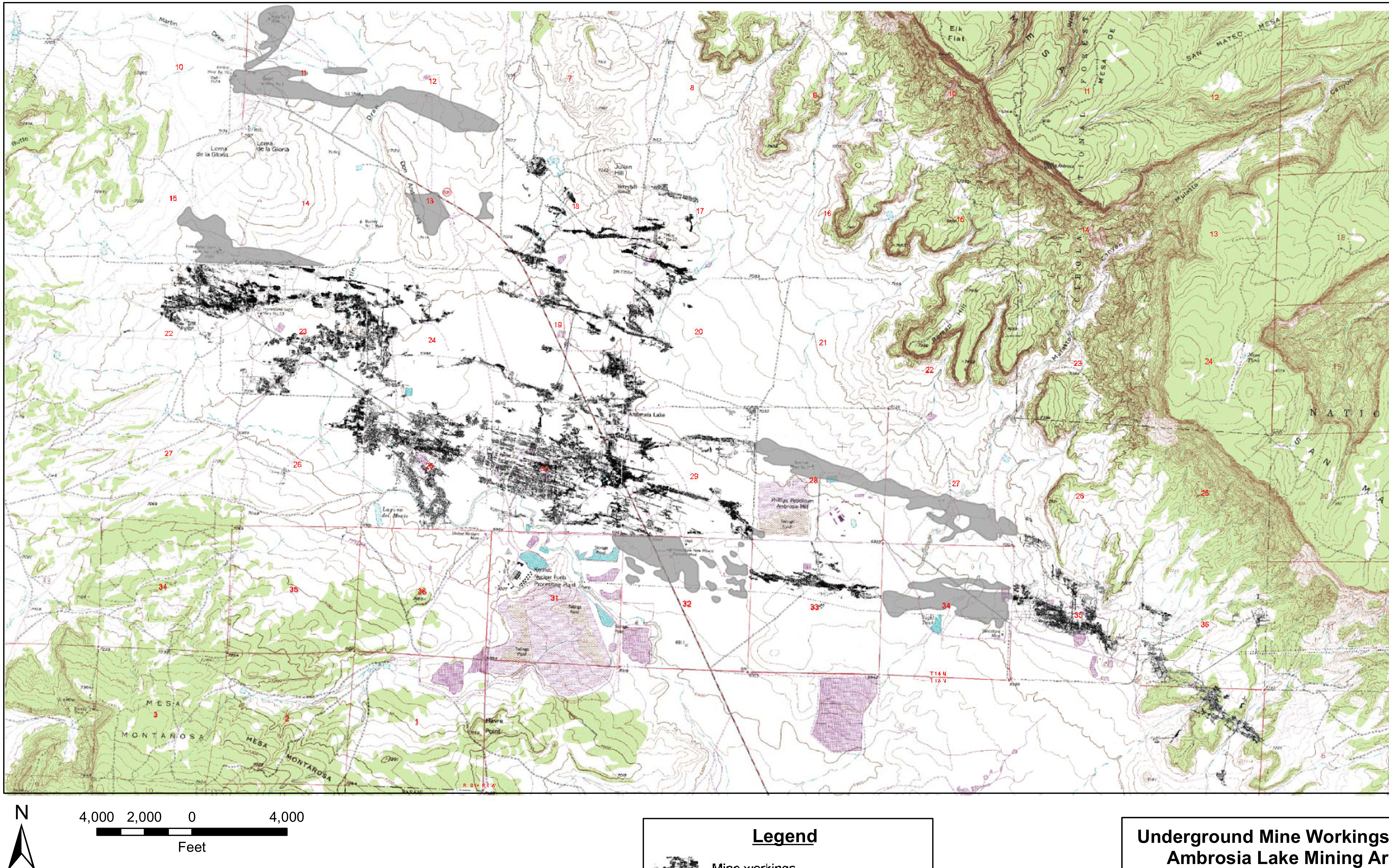

Legend

Mine workings

Estimated location of mine workings

Underground Mine Workings in the Ambrosia Lake Mining Area, New Mexico

INTERA

Figure 2.11

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2.3 Water Balance

Calculation of an annual basin-wide water budget provides information about the overall groundwater flow system and also serves as a benchmark to check numerical simulation results. An annual water budget describes the amount of water added to (inflows) or removed from (outflows) the basin over a 12-month period. Few such calculations for the San Juan Basin are available in the literature, and most were accomplished by carrying out steady-state numerical simulations. Lyford and Stone (1978) estimated that the total inflow (= total outflow) for the Jurassic and Cretaceous sandstones in the San Juan Basin was 60 cubic feet per second (ft^3/s), which equals 5,184,000 cubic feet per day (ft^3/day). Using a simple three-dimensional steady-state flow model, Frenzel and Lyford (1982) estimated that the total inflow (outflow) was 30 ft^3/s (2,592,000 ft^3/day). In comparison, Kernodle's (1996) steady-state groundwater flow model of the entire basin provided a total inflow (outflow) of 195 ft^3/s (16,850,000 ft^3/day), which is equivalent to a basin-wide recharge rate of 0.14 inches per year (in/yr). Roughly 28% of the total inflow in Kernodle's 1996 model was attributable to areal or regional recharge, 2% to localized recharge in the Chuska Mountains, and the remainder attributed to streambed infiltration. The water balance developed using the Roca Honda mine model is discussed in Section 4.1.2 of this report.

3.0 CONSTRUCTION OF THE NUMERICAL MODELS

Potential changes to groundwater levels in the Gallup, Dakota, and Westwater aquifers were estimated by applying calibrated numerical models of groundwater flow. Each numerical model is built from the set of mathematical equations that describe groundwater flow and is based on the hydrogeologic understanding of the San Juan Basin described in Section 2. The mine dewatering schedule shown in Table 1.1 is assumed to describe dewatering at the Roca Honda mine. Section 3 describes the construction of the Roca Honda mine groundwater flow models.

3.1 Modeling Objectives and Approach

The first modeling objective was to construct numerical models that are able to reasonably simulate historical groundwater levels and to compare how well these simulated groundwater levels match historical observations of groundwater levels. The process of comparing simulated groundwater levels (or flow rates if applicable) to historical observations of groundwater levels (or flow rates) and modifying model inputs until the simulated and observed values are sufficiently close is called "model calibration." Model calibration (see Section 4) demonstrates whether the flow models represent the historical changes in groundwater levels within the Gallup, Dakota, and Westwater aquifers accurately enough so that the predictive models can be relied upon to simulate future groundwater levels during dewatering at the Roca Honda mine. The second modeling objective is to construct and apply groundwater flow models to predict the future groundwater levels in the three aquifers with and without proposed mine dewatering at the Roca Honda mine.

To achieve these objectives, INTERA completed the following tasks:

- Construction and calibration of a numerical model of groundwater flow to estimate predevelopment groundwater levels, i.e., groundwater levels prior to the year 1930, for conditions prior to the onset of large-scale mining in the Grants uranium district.
- Construction and calibration of a transient historical numerical model of groundwater flow to simulate changes in groundwater levels from 1930 to 2012 caused by a combination of pumping at public water supply wells, historical mine dewatering, and partial recovery from the historical mine dewatering.
- Construction and application of predictive transient flow models that simulate groundwater levels from the beginning of mine construction to 100 years after the end of the proposed 13-year mining period with and without dewatering at the Roca Honda mine.

The pre-development model represents the time period prior to 1930, the transient model covers the period 1930 through 2012, and the predictive model extends from 2013 through 2125. The USGS steady-state groundwater flow model developed for the same area by Kernodle (1996) was used a basis for constructing INTERA's Roca Honda mine models, but INTERA significantly improved on the USGS model by modifying boundary conditions, incorporating new data on aquifer parameters and stratigraphy in the vicinity of the Roca Honda permit area, increasing the amount of calibration data for the steady-state calibration, and carrying out a transient calibration.

The calibrated Roca Honda mine models provided the basis for predictive simulations that were used to estimate changes in future groundwater levels in the Gallup, Dakota, and Westwater aquifers, including locations near wells and springs, for four pumping scenarios. Dewatering at the Roca Honda mine is conservatively assumed to follow the maximum time periods and maximum pumping rates shown in Table 1.1. The predictive simulations span the period from 2012, when mine construction is assumed to begin, to the year 2125, 100 years after the assumed end of mining. The four pumping scenarios are:

- Scenario 1 – Pumping occurs at the Crownpoint and City of Gallup public water supplies and dewatering occurs at the Lee Ranch coal mine. This scenario estimates the effects on future groundwater levels from current pumping stresses and represents current and future "baseline" conditions.
- Scenario 2 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine and dewatering at the Roca Honda mine. This scenario estimates the effects on future groundwater levels from current pumping stresses plus the Roca Honda mine dewatering.
- Scenario 3 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine, and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. This scenario estimates the effects on future groundwater levels from large water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (see Section 3.8).
- Scenario 4 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine, dewatering at the Roca Honda mine, and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area. This scenario estimates the effects on future groundwater levels from dewatering at Roca Honda and pumping of water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (see Section 3.8).

3.2 Other Models of San Juan Basin Groundwater Flow

Numerical models of groundwater flow through the entire San Juan Basin are limited in number. Numerical models were constructed to aid in planning and designing uranium mines in the Ambrosia Lake sub-district (e.g., Williams et al., 1986), but those models did not encompass the entire basin nor were they applied to estimate potential changes in groundwater levels.

Building on the hydrogeologic information provided in Stone et al. (1983), Frenzel and Lyford (1982) constructed a three-dimensional, steady-state flow model to assess potential changes to groundwater resources from new groundwater pumping and development of the basin's energy resources. The specific objective of this groundwater modeling study was to estimate groundwater flow rates between the different aquifer and aquitard units from the Entrada Sandstone up to the Lewis Shale and to estimate a steady-state water balance (see Section 2.3). The area evaluated in this study was similar to the basin area adopted for the Roca Honda mine groundwater flow models; however, recharge and discharge areas were represented by specified head boundary conditions instead of the more commonly used specified flux boundary conditions. The model was built using the Trescott (1975) finite difference code. According to Kernodle (1996), Frenzel constructed an uncalibrated transient flow model to assess potential changes to groundwater systems from mining on federal coal leases (Frenzel, 1983). Neither the steady-state nor the transient models were used to develop the Roca Honda groundwater model because of differences in numerical code, the number of hydrostratigraphic units, and the manner in which they were represented.

Frenzel (1992) also constructed a model of the San Andres-Glorieta aquifer along the southern margin of the San Juan Basin. This model was modified in 2001 b y Daniel B. Stephens and Associates, Inc. (DBSAI) to assess the impacts of pumping wells owned by the Atlantic Richfield Company on groundwater levels, stream flows and springs in the San Andres-Glorieta aquifer, and overlying shallow alluvium within part of the southern San Juan Basin (DBSAI, 2001). The original and modified Frenzel models were not used for constructing the Roca Honda mine model because they did not include the Westwater aquifer or the units between the Westwater and the San Andres-Glorieta aquifer. However, information about groundwater flow to Horace Springs and the perennial reach of the Rio San Jose from Frenzel (1992) was used as a basis for understanding and modeling these features in the Roca Honda model (see Appendix E).

Kernodle (1996) constructed a steady-state groundwater flow model of the entire San Juan Basin using the MODFLOW code (McDonald and Harbaugh, 1988). The objective of his model was to describe and simulate the basin-wide flow system in the San Juan Basin. The model encompassed the same horizontal basin extent as the Roca Honda mine groundwater flow models, but also included the Entrada Sandstone in its vertical extent. The flow model simulated areal recharge as a boundary condition, surface water-groundwater interactions using the river boundary condition, mountain front recharge in the Chuska Mountains as a general head boundary condition, and groundwater discharges to ephemeral drainages as drain boundary conditions. The input files for the Kernodle model are not available. Daniel B. Stephens & Associates, Inc. (DBSAI) reported that John Shomaker and Associates, Inc. (JSAI) partially reconstructed the Kernodle (1996) groundwater flow model (Carpenter and Shomaker, 1998; DBSAI, 2001). This partial reconstruction reportedly included the hydrostratigraphic units between the San Rafael Group and the late Cretaceous Mesaverde Group, with the entire Morrison Formation represented in a single model layer. JSAI conducted a transient calibration to 11 wells for the period 1978 to 1990. JSAI revised their model two more times. Neither the model report nor files were available during construction of the RHR model. Section 5.1.6 compares the most recent version of the JSAI model to the RHR model.

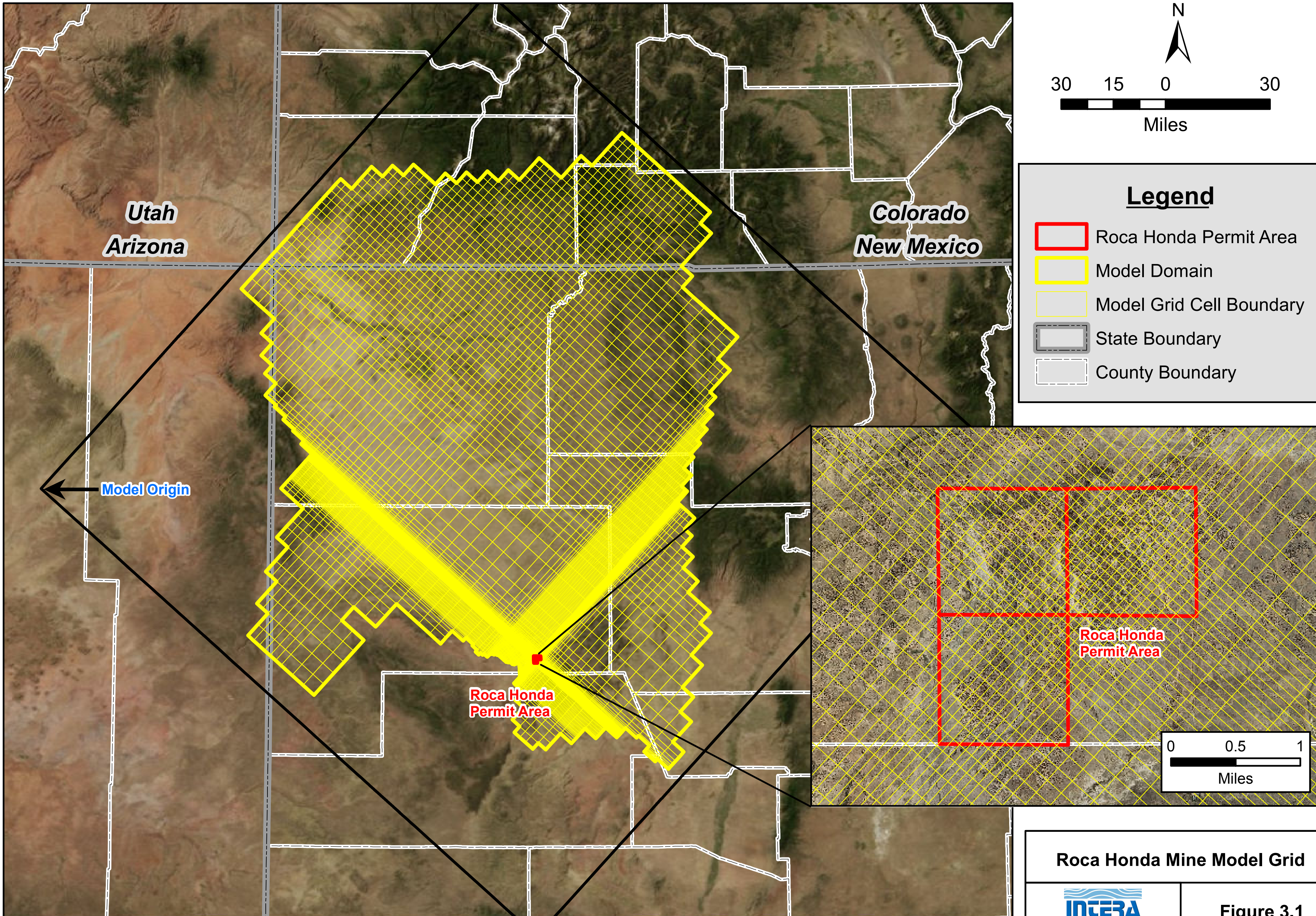
3.3 Computer Code

INTERA selected the MODFLOW-SURFACT (HydroGeoLogic, 1996) version 3 code to conduct the groundwater flow modeling because this model code is superior to MODFLOW in simulating mine dewatering and groundwater level recovery. MODFLOW-SURFACT offers significantly increased capability to quickly simulate rapidly changing groundwater levels and desaturation-saturation, compared to the MODFLOW-2005 code, by simply replacing MODFLOW's BCF package with its BCF5 package. MODFLOW-SURFACT uses nearly all of the many MODFLOW packages, including those to simulate recharge, drains, rivers, and wells, and its solver is much faster than any now available with MODFLOW. Like MODFLOW, MODFLOW-SURFACT is a three-dimensional, finite-difference, block-centered, saturated groundwater flow code, and it has been widely applied and accepted by the United States Bureau of Land Management (US BLM) and other agencies for mine permitting and other uses. All Roca Honda mine numerical models were developed, tested, and applied using the Groundwater Vistas version 5 (Rumbaugh and Rumbaugh, 2007) graphical user interface.

3.4 Model Domain and Discretization

The modeled area, called the "model domain," for the Roca Honda mine groundwater flow models includes roughly the entire San Juan Basin from the center of the basin outwards to the outcrop of the Morrison Formation around the perimeter (Figure 3.1). It is very similar in extent to the domains adopted by both Kernodle (1996) and Frenzel and Lyford (1982). The top of the domain was set to ground surface. The bottom of the domain was set to the contact between the Westwater and its underlying regional aquitard, the Recapture Member of the Morrison Formation.

The model domain was discretized horizontally into 144 rows and 140 columns and vertically into ten layers, yielding 113,382 active cells (Figure 3.1). Grid "north," which is parallel to column orientation, is rotated 43.75 degrees counterclockwise from true north, as was done for the Kernodle (1996) model. Grid block dimensions ranged from a maximum of roughly 30,000 feet on a side in locations far from the Roca Honda permit area to 330 feet on a side within the area of interest (Figure 3.1). The model domain and discretization were the same for all Roca Honda mine numerical models.



Roca Honda Mine Model Grid

INTERA

Figure 3.1

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The model's vertical structure was determined by the impact assessment's focus on the Gallup, Dakota, and Westwater aquifers, and by the San Juan Basin's asymmetric geometry. Table 3.1 and Figure 2.4 show how the geologic units were grouped into hydrostratigraphic units (see Section 2.1) represented as model layers. The three aquifers and adjacent aquitards were represented as single model layers wherever possible. The tops and bottoms of the model layers were constructed to follow the top and bottom elevations of the hydrostratigraphic units (see Section 2.1) across the model domain. Exceptions to this rule were limited to those areas in a particular model layer where a hydrostratigraphic unit thickened or pinched out. For example, in order to represent these changing thicknesses in model layers 2 through 4, individual hydrostratigraphic units were distinguished within a model layer by assigning different hydraulic properties. The top of model layer 1 represents ground surface. The top of each layer 1 grid block was assigned an elevation corresponding to the location of the grid block's centroid as derived from a 30-meter digital elevation model data set.

Tops and bottoms of model layers for the Gallup down to the Westwater (layers 6 through 10) were assigned elevations using hydrostratigraphic data obtained from a variety of sources. The bottom of the Dakota Sandstone is used as the reference point for the groundwater model construction. This contact, which represents the top of the Morrison Formation (top of model layer 9), was constructed by combining geologic contour data from Dam et al. (1990a), geologic contour data provided by RHR, an elevation raster of the contact in the mine area provided by RHR, and well logs from published and unpublished reports. Figure 3.2 depicts the Dam et al. (1990a) elevation contours in yellow, updated elevation contours from RHR in red, and RHR's detailed interpretation of the elevation in the Roca Honda permit area as a blue polygon. The top elevations for the Gallup Sandstone, Dakota Sandstone, and other hydrostratigraphic units were constructed in similar fashion. Formation elevation tops were calculated from information about geologic unit thicknesses for geographic areas in which contours had not previously been developed. Cross sections of the model layering through the Roca Honda mine site are depicted in Figures 3.3 and 3.4.

Even though faults and associated displacements are common throughout the San Juan Basin, the discretization scale in much of the basin averaged out such detailed structural differences. Faults present near the Roca Honda permit area were not specifically represented in the Roca Honda model for three reasons. First, groundwater levels do not indicate that faults have any impact on groundwater flow in the Westwater. Second, geologic cross-sections of the area west of the Roca Honda mine corroborate the groundwater level maps. Geologic mapping by Thaden et al. (1967) and Santos and Thaden (1966) shows that the San Mateo fault, which is the largest displacement fault to the west of the RHR permit area, has varying vertical offsets that decrease along its length from south to north. Vertical offsets are effectively negligible along the fault north of the permit area (Ambrosia Lake map). Offsets gradually increase southward until the fault displaces the Westwater aquifer against other permeable geologic units near the junction of State Routes 605 and 509, which is southwest of the RHR permit area. Even though the vertical offset along the San Mateo fault continues to increase further southward, the part of the fault nearest the RHR permit area is unlikely to impede groundwater flow through the Westwater because that part has small to negligible offsets. Third, a fault located east of the RHR permit area, which was mapped by McCraw et al. (2009) and is the northern extension of the San Raphael fault, is assumed to not impede groundwater flow in the aquifers of interest, despite its large vertical offsets. The larger offsets along the San Raphael fault that occur to the south of the RHR permit area appear to juxtapose the Westwater against low-permeability aquitards, including the Mancos shale. The offsets would therefore tend to disrupt the movement of groundwater between the Westwater on either side of the fault, and would block the propagation of drawdown from RHR dewatering towards Horace Spring, the Rio San Jose, and other water resources in that area. Any impacts on Horace Spring and the Rio San Jose are therefore probably over-estimated by the model because the San Raphael fault was not included in the model.

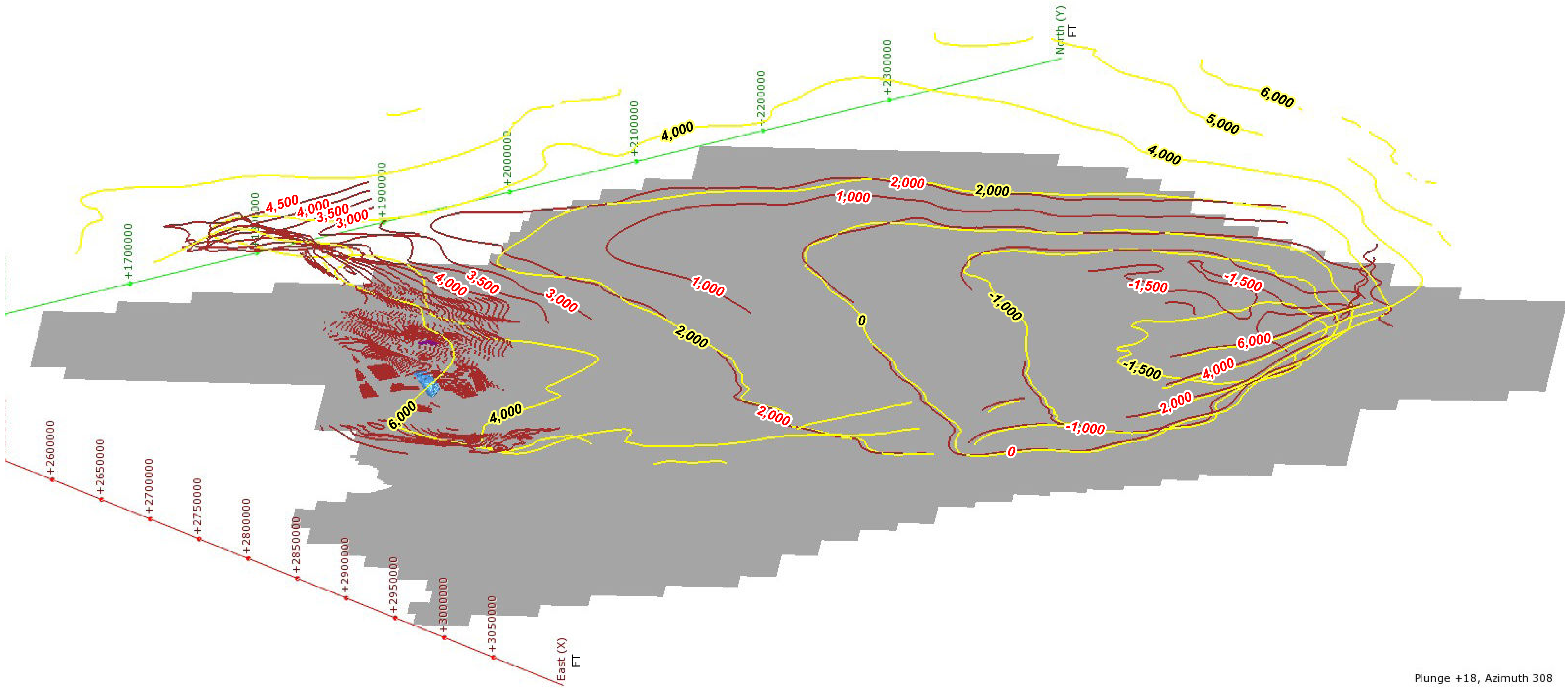
Table 3.1

Hydraulic Properties of Hydrostratigraphic Units in the San Juan Basin

Model Layer	Hydrostratigraphic Unit	Thickness Range (feet)	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day) Reported (Modeled)[c]	
				Horizontal	Vertical
1	San Jose Formation	200 – 2,700[a]	40 – 117[b]	0.4 – 1.2 (0.2)	-- (0.002)
2	Animas Fm and Nacimiento Fm	230[d] – 2700[e] 500 – 1,300[f]		-- (0.01)	-- (0.0001)
3	Ojo Alamo Sandstone	20 – 400[e]	Deep: 0.05 – 0.39[b] Shallow: 57 – 245[b]	0.14 – 1.2 (0.4 – 0.8)	-- (0.0001)
3	Kirtland Shale and Fruitland Fm	0 – 1,500[eg] 0 – 500[eg]	Kirtland: 2.4[b] Fruitland: 0.6 – 130[b]	0.05 – 0.065 (0.4 – 0.8)	-- (0.0001 – 0.003)
3	Pictured Cliffs Sandstone	0 – 400[e]	0.001 – 3[b]	0.007 (0.007)	-- (0.00007)
4	Lewis Shale	0 – 2,400		-- ($5x10^{-5}$)	-- ($5x10^{-5}$)
5	Cliff House Sandstone	20 – 500	2.1[b]	-- (0.05 - 0.1)	-- (0.00007)
5	Menefee Formation	0 – 2,000[g]	Confining unit: 2.7 – 112[b]	0.001 (0.05 – 0.1)	-- ($5x10^{-6}$ – 0.001)
5	Point Lookout Sandstone	40 – 415[a]	0.4 – 236[b]	0.002 – 0.02[ia] (0.13)	-- (.00001 – 0.01)
6	Mancos Shale (NE only)	1,000 – 2,300		-- (0.0001 – 0.0009)	-- ($9x10^{-8}$ – 0.0001)
6	Gallup Sandstone (SW only)	0 – 600[c] 0 - 700[a]	15 – 390[b]	0.1 – 1[j] (1)	-- (0.002)
7	Mancos Shale	1,000 – 2,300		-- (0.0001 – 0.0009)	-- ($9x10^{-8}$ – 0.0001)
8	Dakota Sandstone	50 – 350[a]	44 – 134[ah]	0.25 – 1.5[a] (0.25)	-- ($1.4x10^{-5}$ – 0.002)
9	Brushy Basin Member of Morrison Formation	80 – 250		0.0004 - 0.003 (0.0008 – 0.1)	-- ($9x10^{-8}$ - 0.002)
10	Westwater Canyon Member of Morrison Formation	100 – 300	2 – 490[b]	0.02 – 1.6 (0.08 – 0.1)	-- ($8x10^{-6}$ – 0.002)

Data Sources:

[a] Stone et al. (1983).
[b] Table 2 of Levings et al. (1996).
[c] Modeled values taken from Kernodle (1996) unless indicated otherwise.
[d] Barnes et al. (1954)
[e] Fassett and Hinds (1971)
[f] Molenaar (1977a)
[g] Molenaar (1977b)
[h] Brod and Stone (1981)
[i] Craigg et al. (1989)
[j] GMRC (1979)



Red contours: RHR updated contours in feet for bottom of Dakota Sandstone at various intervals

Yellow contours: Contours in feet for top elevation of Morrison Formation from Dam et al. 1990 (USGS HA-720-J)

Blue raster: RHR top of Morrison Formation in mine area

Gray polygon at bottom: Model domain

GIS Data for Bottom of Dakota Sandstone Elevation

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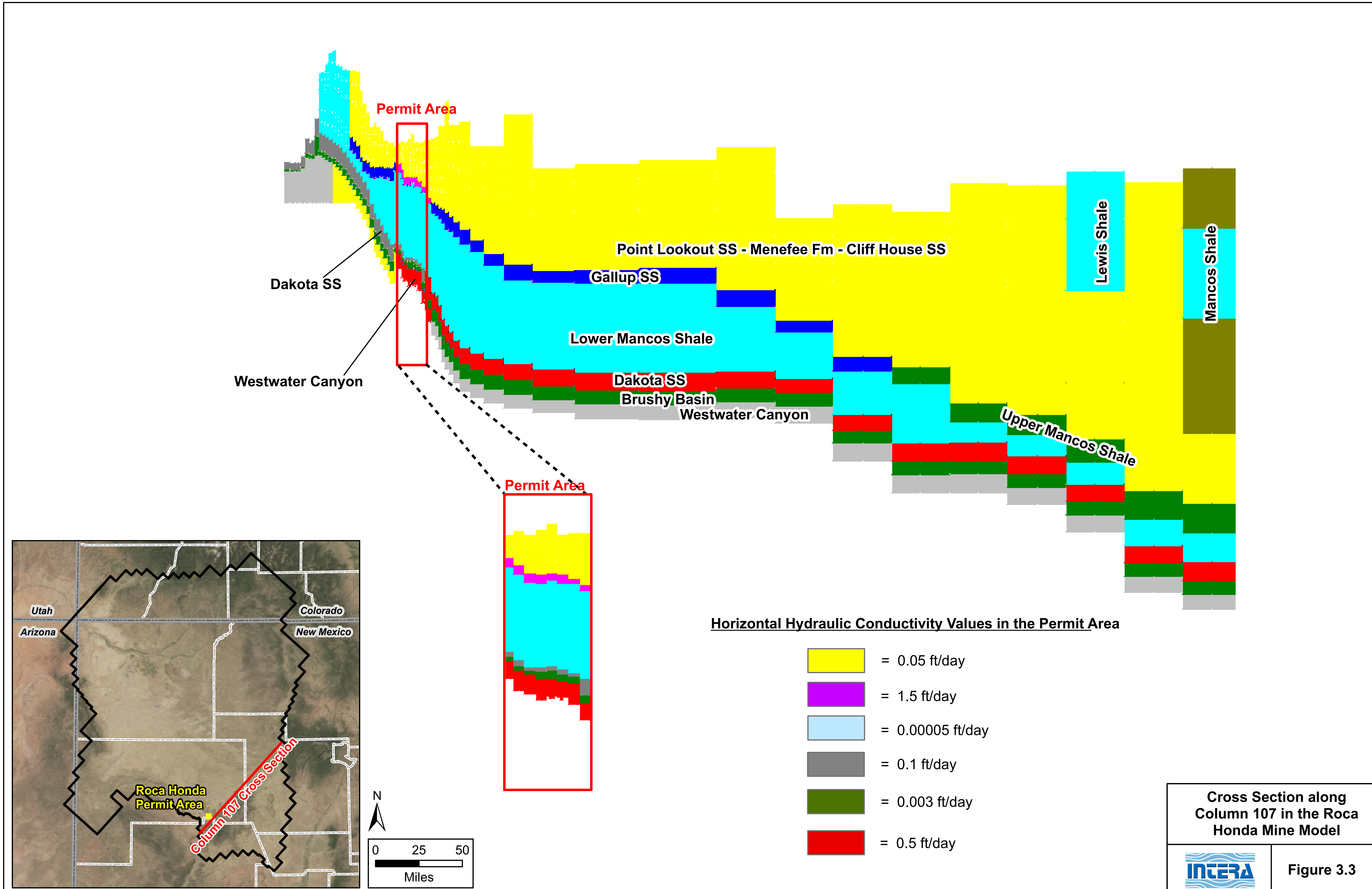
Figure 3.2



Cross Section along Column 107 in the Roca Honda Mine Model

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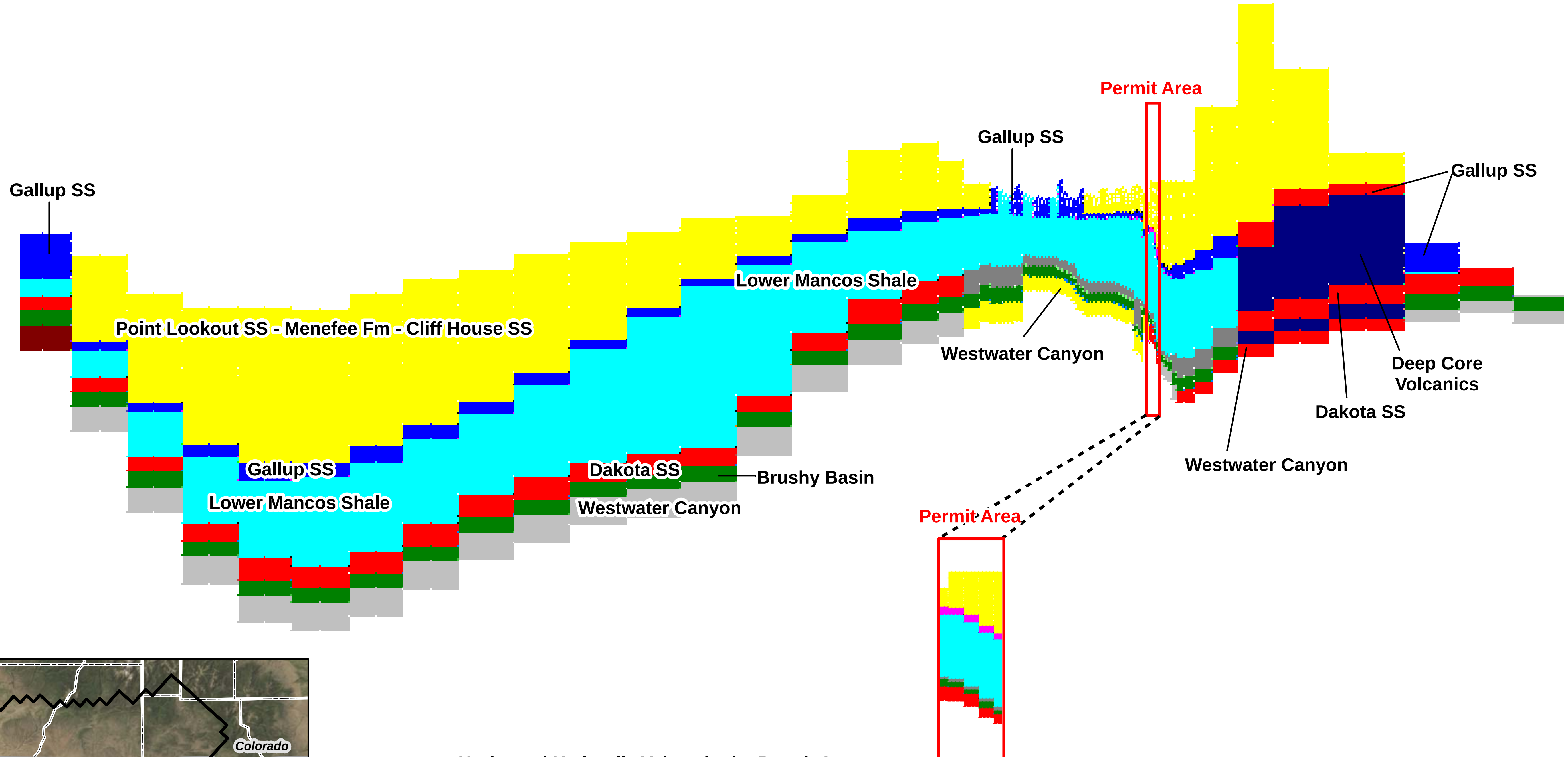
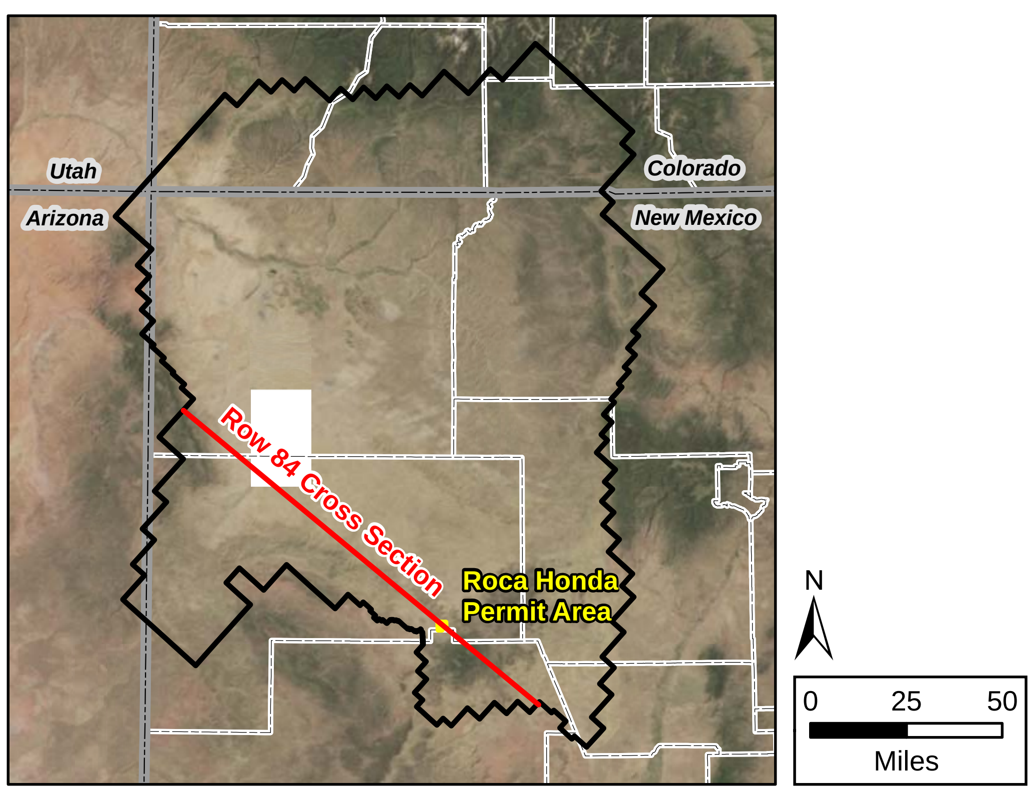
Figure 3.3





Horizontal Hydraulic Values in the Permit Area

= 0.05 ft/day

= 1.5 ft/day

= 0.00005 ft/day

= 0.1 ft/day

= 0.003 ft/day

= 0.5 ft/day

Cross Section along Row 84 in the Roca Honda Mine Model

INTERA

Figure 3.4

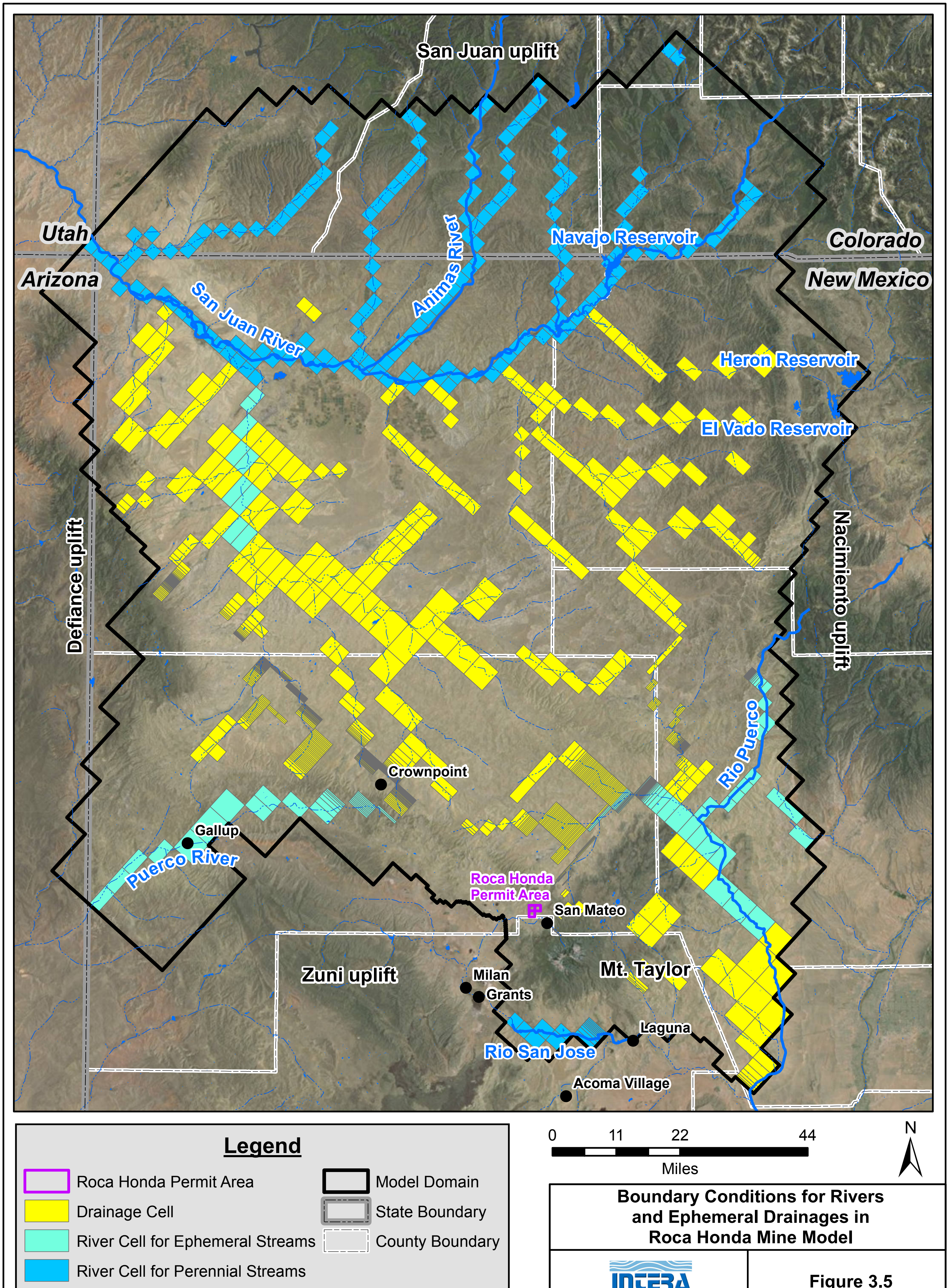
3.5 Boundary Conditions

According to Kernodle (1996, p. 57), "A ground-water-flow boundary is any physical feature or mechanism that alters movement of water in the ground-water-flow system, or is a sink or source of water to the system." A boundary condition can correspond to physical features of the area modeled, such as the limits of aquifers, or to stresses or driving forces for groundwater flow. The Roca Honda mine numerical models used boundary conditions to represent the stresses described in Section 2: areal recharge, mountain-front recharge, groundwater-surface water interactions, groundwater discharge to ephemeral drainages, and pumping for mine dewatering and water supplies. Most boundary conditions remained constant for all Roca Honda mine models. Variable boundary conditions were the time-varying pumping and dewatering stresses, and the variable flows of mine water that were historically discharged into the San Mateo Creek and Arroyo del Puerto ephemeral drainages that were included in the 1930-2012 transient calibration model. Maps of the boundary conditions assigned in each layer are presented in Appendix A.

The perennial sections of the San Juan River system were represented as river boundaries using the MODFLOW River Package (Figure 3.5). River boundaries allow for water to move from the river to the aquifer or vice versa depending on the head in the aquifer relative to the river stage. Geographic information system (GIS) tools were used to determine the river stage in each grid block by calculating the average elevation of water in a river segment in each grid block and adding a factor for river depth. The Rio Puerco, the perennial reach of the Rio San Jose, and the upper reaches of the Puerco River were also represented using river boundary conditions (Figure 3.5), but the river stages were set at ground surface in order to represent the presence of saturation in the streambeds. Kernodle (1996) employed a similar approach for the perennial rivers and the larger ephemeral drainages.

Groundwater discharge to ephemeral drainages was simulated using MODFLOW's Drain Package (Figure 3.5). These ephemeral drainages control groundwater levels in the interior of the basin (Kernodle, 1996). Drain elevations were set to the ground surface elevation at grid block centers to allow for groundwater flow out of the system if groundwater levels were higher than the drain elevation. In this way, drain cells simulated the removal of groundwater discharged to ephemeral drainages by runoff, evaporation, or transpiration (Stone et al., 1983; Kernodle, 1996).

Areally distributed recharge from precipitation on the land surface was applied to the areas indicated by Kernodle (1996) as likely recharge areas. These included the large Dakota Sandstone and Gallup Sandstone outcrops along the basin margin, the Point Lookout Sandstone outcrops, and the Mt. Taylor volcanics (Figure 3.6). Recharge rates were estimated using the approach described by Kernodle (1996) that showed rates increasing with elevation. Recharge rates spanned a range from 0.004 to 0.35 in/yr. Average annual precipitation ranges from 8 to 40 in/yr across the San Juan Basin (Kernodle, 1996). MODFLOW's Recharge Package was used to represent recharge to the aquifers that was widely distributed, spatially variable, but constant from year to year.



*Perennial streams and ephermeral drainage are based on US National Atlas Water Feature Lines Database

Boundary Conditions for Rivers and Ephemeral Drainages in Roca Honda Mine Model

INTERA

Figure 3.5

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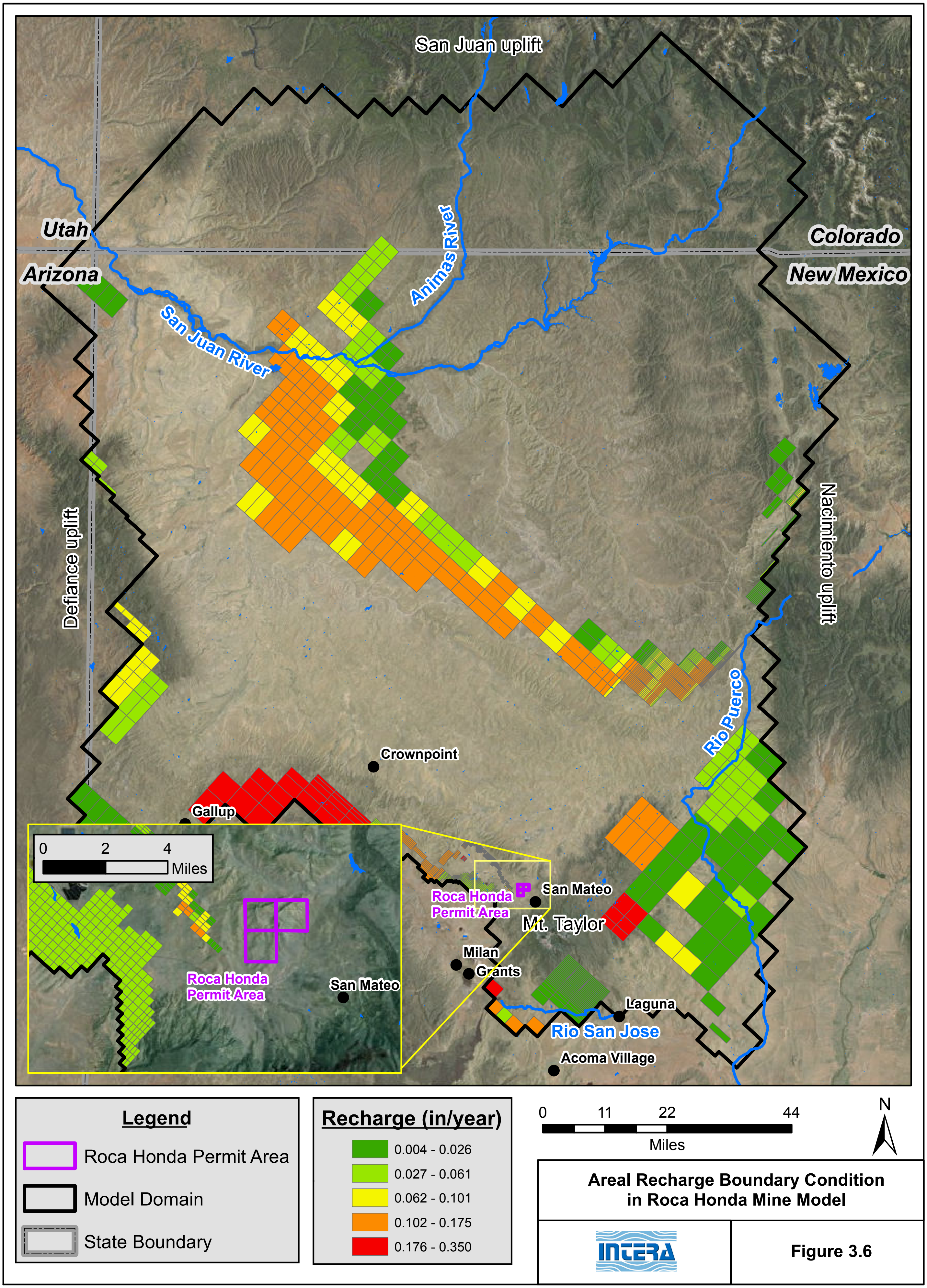


Areal Recharge Boundary Condition in Roca Honda Mine Model

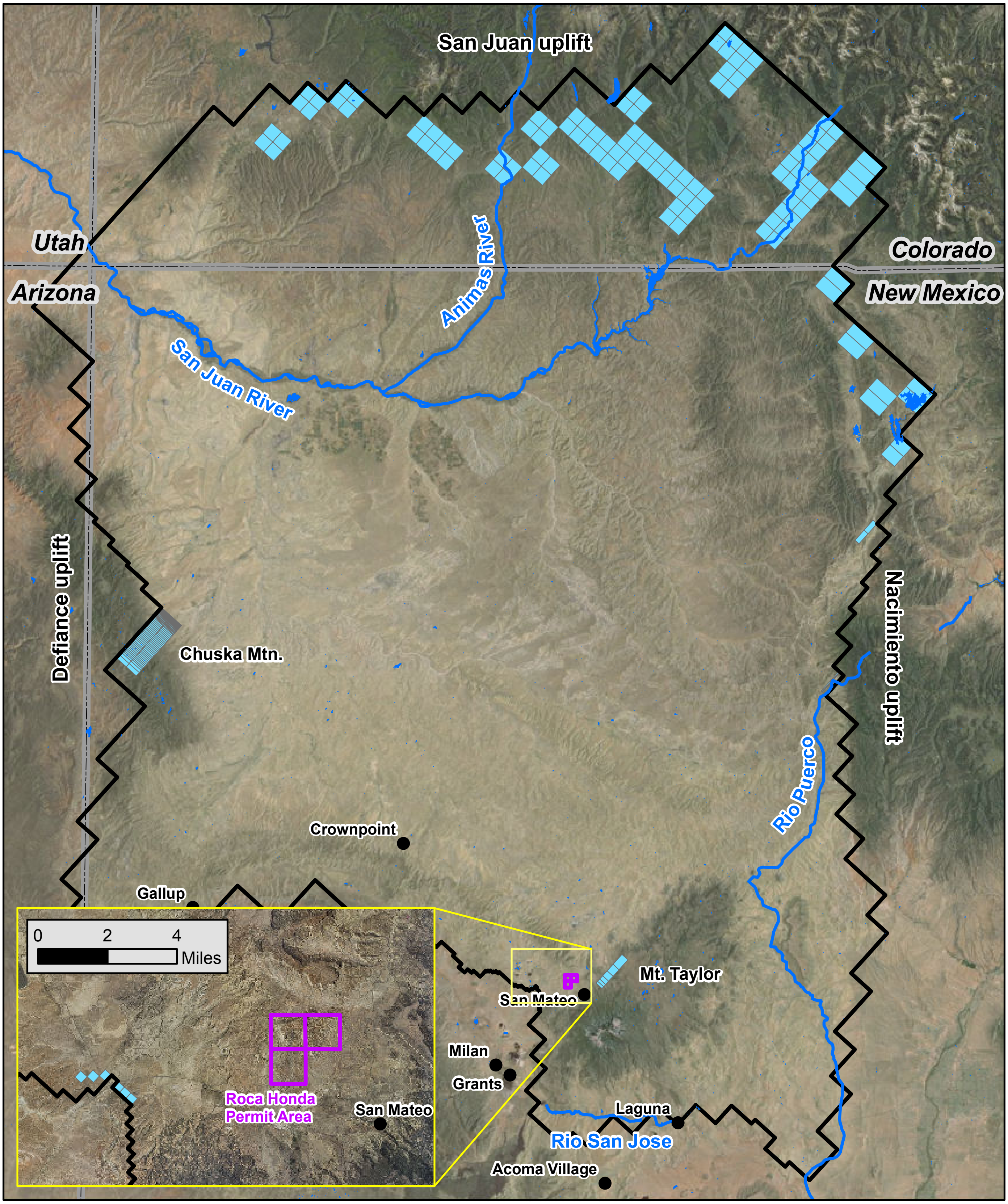
Figure 3.6

Mountain-front recharge from the mountains along the northern basin margin was simulated with specified-flux boundaries using the MODFLOW Well Package in layers 5 and 8 (Figure 3.7). Specified fluxes were added at six locations to layer 10 in the area where San Mateo Creek crosses the model domain boundary to simulate the presence of high groundwater levels there (Figure 3.7 inset). Mountain-front recharge from the Chuska Sandstone and Mt. Taylor was also simulated using specified-flux boundaries along the subcrop perimeters in layer 6 only for the Chuska Sandstone and in layers 6 and 8 for Mt. Taylor (Figure 3.7).

Well Package cells were used to simulate pumping for public water supplies (Figure 3.8 and Section 3.7). The two Gallup well fields and the Crownpoint supply well operate in the 1930-2012 transient calibration model and the predictive simulations. Rates were based on documents from the City of Gallup and the NM OSE.

MODFLOW-SURFACT's Fracture Well Package was used to represent mine dewatering at the Ambrosia Lake sub-district mines, the Church Rock Mine, the Gulf Mt. Taylor Mine, and the Johnny M Mine in the 1930-2012 transient calibration model (Figure 3.9). The Fracture Well Package is very similar to MODFLOW's Well Package, but has the additional capability of decreasing the flow rate if the model cell containing the fracture well begins to dry out. Mine dewatering rates and volumes were based on information from historical mine dewatering reported by Stone et al. (1983) as well as more recent compilations by Hydroscience (2009c). Section 3.7 describes the time periods for the historical dewatering.

For the predictive simulations with dewatering at the Roca Honda mine, dewatering was simulated using the specified flux boundary condition with the rates and schedule shown in Table 1.1. These hydraulic sink boundary conditions were placed within and around the Roca Honda production shaft and mine workings to depressurize the Gallup, Dakota, and Westwater aquifers during shaft construction and to dewater the Westwater during mining at the maximum rates stipulated in the dewatering permit application (Table 1.1).



Boundary Conditions for Mountain Front Recharge in Roca Honda Mine Model

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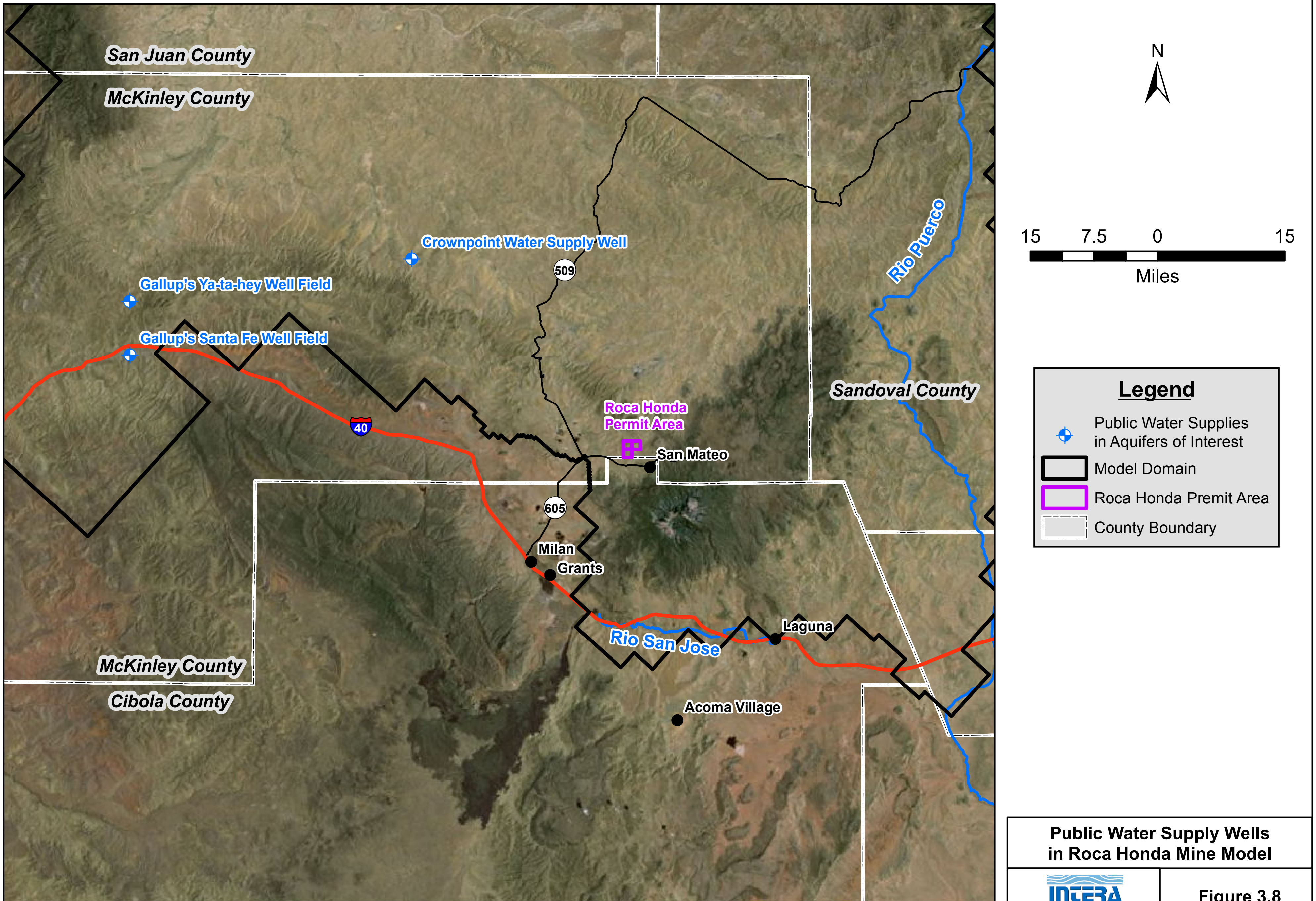
Figure 3.7



Public Water Supply Wells
in Roca Honda Mine Model

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Figure 3.8

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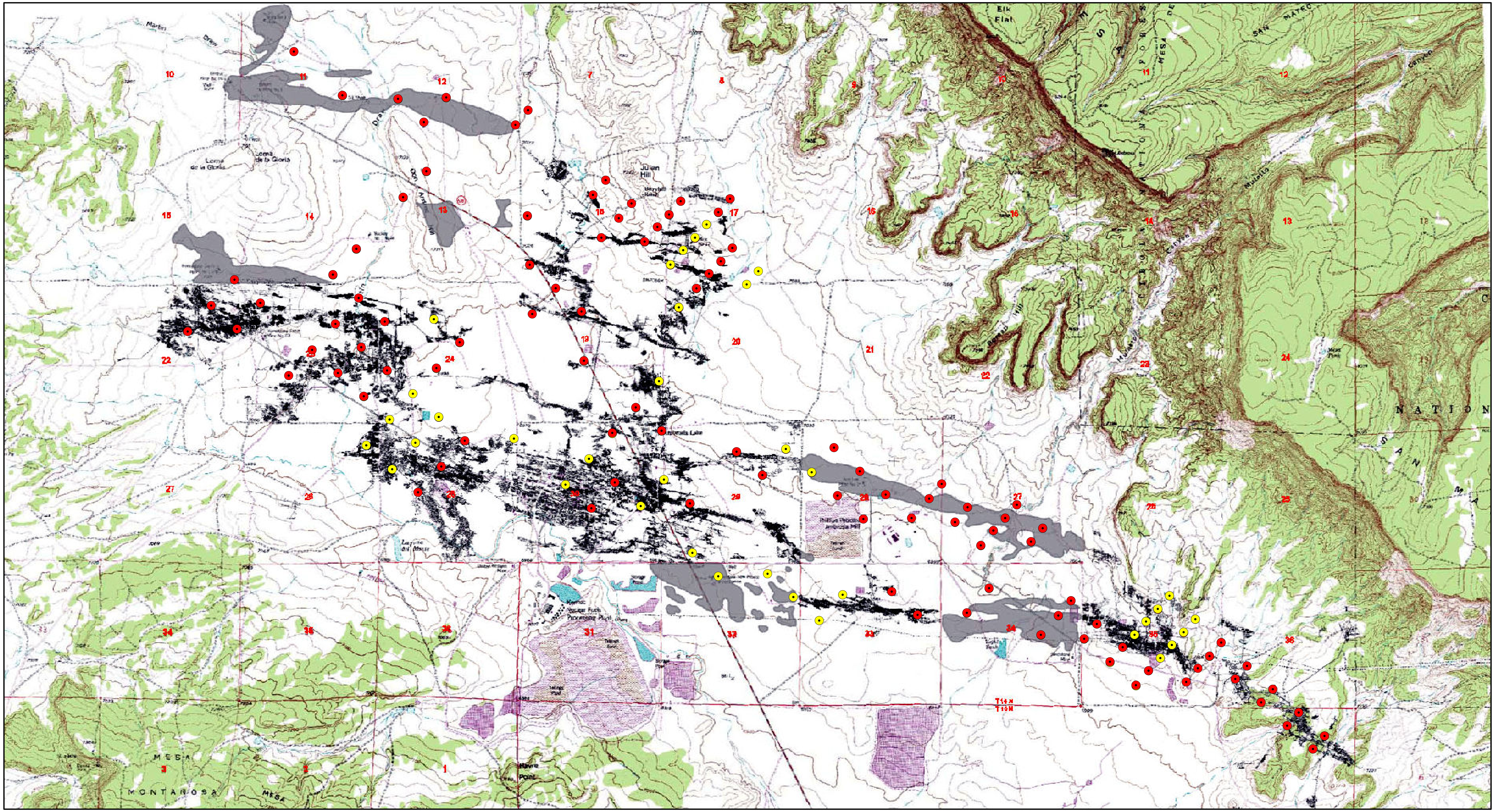


N

3,600 1,800 0 3,600

Feet

Legend

- Dakota Sandstone Specified Flux
- Westwater Canyon Member Specified Flux

Specified Flux Locations for Historical Mine Dewatering

INTERA

Figure 3.9

3.6 Hydraulic Properties

The hydraulic properties of an aquifer are measures of the aquifer's ability to transmit and store water. Hydraulic properties or parameters include transmissivity, horizontal and vertical hydraulic conductivity, specific storage, specific yield, and porosity. Determining the rates and directions of groundwater flow requires information about the hydraulic characteristics for the San Juan Basin's aquifers and aquitards. In the San Juan Basin, measurements of hydraulic properties are more numerous along the basin margins where the units of interest are closer to the surface. Very few data are available for units near the depositional center of the basin. Reported transmissivity and hydraulic conductivity values typically span a wide range, even for a single aquifer or aquitard (Table 3.1). For example, Stone et al. (1983) reported that the transmissivity of the Morrison ranges from less than 50 to 500 square feet per day (ft^2/day) across the San Juan Basin, with a general trend of values decreasing from locations in the southern margin to the northern margin. Dam et al. (1989) report Morrison transmissivity values ranging between 2 and 480 ft^2/day. Levings et al. (1996) noted that where measurements were available for the Ojo Alamo Sandstone at shallow and deep locations within the basin, the deep hydraulic conductivity values could be smaller by several orders of magnitude (Table 3.1).

Hydraulic conductivity values representative of the hydrostratigraphic units shown in Table 3.1 were assigned to the active cells in the groundwater flow models. The hydraulic conductivity values were selected based on the range and geometric means of values reported for the various hydrostratigraphic units. Selection of hydraulic conductivity values used for the regional aquitards (Lewis Shale and Mancos Shale) was based on the values used in models by Kernodle (1996) and Frenzel and Lyford (1982). The hydraulic conductivity zones are plotted for each model layer in Appendix B.

Site-specific estimates of hydraulic conductivity and storage properties for the Westwater at the Roca Honda mine were obtained from a 2009 aquifer test performed by RHR and applied to the area around the proposed mine workings in layer 10 (Hydroscience, 2009b; Figure B.10 in Appendix B). The site-specific horizontal hydraulic conductivity was set at 0.5 ft/day and the specific storage was set to 1.26×10^{-6} ft^{-1}. Single-well pump test results from a well screened in both the Point Lookout Sandstone and the Gallup Sandstone were used to estimate a site-specific hydraulic conductivity for the Gallup Sandstone of 2 ft/day that was applied to the same grid blocks in the mine area in layer 6 (Hydroscience, 2009b; Figure B-6, Appendix B). Table 9-13 of the RHR BDR (2011c) tabulates the reported ranges of values for hydraulic properties for geologic units in the RHR permit area.

The hydrologic effects of the Jemez Lineament, including the Mt. Taylor intrusive and volcanic rocks, were not explicitly represented in previous San Juan Basin groundwater flow models. Recent mapping by the New Mexico Bureau of Geology and Mineral Resources in the vicinity of Mt. Taylor reveals the presence of numerous volcanic cores that crosscut the sedimentary units represented in the Roca Honda mine groundwater flow models (Figure 2.5). It is likely that the intrusion of lower permeability igneous rocks and the resulting deformation of sedimentary rocks around the intrusions have created a zone of reduced permeability under Mt. Taylor. The low-permeability intrusions beneath Mt. Taylor have been represented by an area of reduced hydraulic conductivity (Appendix B) in model layers 6, 8 and 10, which contain the Gallup, Dakota, and Westwater aquifers. A conservatively high value of 0.1 ft/day, which equals or nearly equals the lowest hydraulic conductivity reported for the three aquifers (Table 3.1), was adopted for the impact assessment. Tests of the sensitivity of changes in groundwater levels to the hydraulic conductivity value of the Mt. Taylor volcanic cores are described in Section 5.1.3. No changes were made to the hydraulic conductivity values in model layers 1 through 5 for hydrostratigraphic units that underlie Mt. Taylor.

Values for the conductance term for the River Package cells and the Drain Package cells used to represent ephemeral streams were calculated using estimates of hydraulic conductivity for alluvial sediments. A hydraulic conductivity value of 20 ft/day was assigned to river beds, based on typical values for coarse, well-sorted sediments, and a 1.0 ft/day value was assigned to the ephemeral stream beds, based on typical values for typically medium- to fine-grained, moderately-sorted sediments.

For transient simulations, porosity, specific yield, and specific storage were estimated using data for typical sandstones and shales and data from historical aquifer tests provided to INTERA (Hydroscience, 2009b). Table 3.2 presents a summary of porosity, specific yield, and specific storage for each hydrostratigraphic unit. The specific storage coefficient in the Dakota Sandstone (layer 8) was based on a series of pumping tests conducted in 1977 and provided to INTERA by Hydroscience (Hydroscience, 2009b). For the Westwater Canyon Member (layer 10) values represent an estimate of specific storage based on reported values ranging between $1x10^{-4}$ and $1x10^{-7}$ (Hydroscience, 2009b).

Table 3.2
Transient Model Storage Parameters

Model Layer	Hydrostratigraphic Unit	Porosity	Specific Yield	Specific Storage
1	San Jose Formation	0.3	0.1	$1x10^{-5}$
2	Animas and Nacimiento Fms	0.3	0.1	$1x10^{-5}$
3	Ojo Alamo Sandstone	0.3	0.1	$1x10^{-5}$
	Kirtland and Fruitland Fms			
	Pictured Cliffs Sandstone			
4	Lewis Shale	0.1	0.05	$2x10^{-6}$
5	Cliff House Sandstone	0.3	0.1	$1x10^{-5}$
	Menefee Formation			
	Point Lookout Sandstone			
6	Mancos Shale (NW only)	0.1	0.05	$1x10^{-5}$
	Gallup Sandstone (SW only)	0.3	0.1	$2x10^{-5}$
7	Mancos Shale	0.1	0.05	$1x10^{-6}$
8	Dakota Sandstone	0.3	0.1	$5x10^{-5}$
9	Brushy Basin Member of Morrison Formation	0.1	0.05	$1x10^{-6}$
10	Westwater Canyon Member of Morrison Formation	0.3	0.1	$1.2x10^{-6}$ - $2x10^{-5}$

3.7 Time-Varying Stresses for 1930-2012 Transient Calibration Model

The 1930-2012 transient model was constructed to calibrate the flow system model to the time-varying stresses that operated from early groundwater development in 1930 to the year 2012. This model includes pumping stresses from the City of Gallup and Crownpoint public water supplies, dewatering from the Lee Ranch coal mine, dewatering for uranium mining from the 1950s to the 1980s, followed by the recovery in groundwater levels after uranium mining activities ceased. Initial groundwater levels for the 1930-2012 transient model were the simulated groundwater levels from the calibrated predevelopment model.

The simulation period was divided into 11 stress periods to represent the time-varying stresses (Table 3.3). With MODFLOW and MODFLOW-SURFACT models, stresses are constant within each stress period.

Table 3.3
Stress Periods for 1930-2012 Transient Model

Stress Period	Actual Years	Stress Period Length		Stresses
		Days	Years	
1		Steady-State		None
2	1930 to end of 1956	9,496	26	Gallup and Crownpoint public water supplies (PWS)
3	1957 to end of 1966	3,652	10	Above plus Ambrosia Lake Valley mine shafts and vent holes
4	1967 to end of 1974	2,920	8	Above plus Church Rock mines and Lee Ranch coal mine wells
5	1975 to end of 1982	3,140	8	Same as stress period 4
6	1983 to end of 1985	1,245	3	Same as stress period 4
7	1986 to end of 1992	2,555	7	Gallup and Crownpoint PWS plus Lee Ranch coal mine wells
8	1993 to end of 2009	6,210	17	Same as stress period 7
9	2010	365	1	Same as stress period 7
10	2011	365	1	Same as stress period 7
11	2012	365	1	Same as stress period 7

Public water supplies were included in 1930-2012 transient calibration model and all predictive simulations (see Section 5.0). In 2003, drawdown at the City of Gallup's Yah-ta-hey well field is reported to be 700 feet and "unsustainable in the near term" (City of Gallup, 2010). Table 3.4 shows how the changes in pumping rates for dewatering and water supplies were specified over the 1930-2012 simulation period.

Table 3.4
1930-2012 Transient Model Groundwater Withdrawals

	Groundwater Withdrawal (ft^3/day)						
Stress Period	Ambrosia Lake Mining Area	Church Rock Mining Area	Johnny M Mine	Gulf Mt. Taylor Mine	Coal Mines	Crownpoint Water Supply	City of Gallup Water Supply
1	0	0	0	0	0	0	0
2	0	0	0	0	0	33,000	192,500
3	2,108,501	0	0	0	0	33,000	192,500
4	1,288,3712	660,000	0	80,000	24,000	33,000	192,500
5	1,072,872	660,000	152,000	589,520	24,000	33,000	500,500
6	964,127	0	0	866,240	24,000	33,000	500,500
7	0	0	0	288,800	24,000	33,000	500,500
8	0	0	0	0	41,026	39,000	500,500
9	0	0	0	0	13,475	39,000	500,500
10	0	0	0	0	13,475	39,000	500,500
11	0	0	0	0	13,475	39,000	500,500

3.8 Pumping Stresses for All Water Rights Predictive Simulations

All water rights for the Gallup, Dakota, and Westwater aquifers in the vicinity of the Roca Honda permit area were compiled for the predictive simulations for Scenarios 3 and 4 (see Section 3.1). Information regarding locations, aquifers pumped, and pumping rates (diversions) was collected from the NM OSE's WATERS database and unpublished reports (Table 3.5). 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 assigned to one or more grid blocks. The sum of pumping rates for all grid blocks assigned to a water right equaled the permitted diversion rate. The simulated wells were assumed to begin pumping at the start of Scenario 3 and Scenario 4 predictive simulations in 2012 and continue to the end of the simulation period, 100 years after the end of Roca Honda mining.

Table 3.5
Groundwater Withdrawals for Scenarios 3 and 4

Water Right	Location	Permitted Diversion (ac-ft/yr)
SJ-109-A et al.	18N 12W Section 1 19N 12W Sections 32 & 36	2,300
SJ-118	21N 9W Section 16	625
SJ-949, SJ-949-S	21N 9W Sections 3 & 4	1,000
SJ-120	16N 10W Section 2	650
G-87, G-88, G-89	16N 20W Sections 5 & 17 17N 20W Section 29	2,425
G-11 (UNC right)	17N 16W Section 35	794
G-11-A (HRI)	16N 16W Sections 8 & 17	650
G-14	15N 9W Sections 3, 4, 9, 10	200
B-993	14N 9W Sections 35, 36, 22, 24 14N 10W Sections 17, 19, 30, 33, 35, 36	4,735
B-994	14N 9W Sections 30, 33, 17, 19, 22, 24 14N 10W Sections 17, 19, 30, 33, 35, 36, 24	5,227
B-375	14N 9W Section 28	93.55
B-376	14N 9W Section 28	371
B-516 (Gulf Mt. Taylor)	13N 8W Section 24	640
B-1442	13N 8W Section 23	305.6
B-1085	13N 8W Section 22	16
B-0428S	13N 8W Section 26	26

3.9 Initial Conditions and Solver Parameters

As with boundary conditions and parameters, each numerical model requires a set of initial conditions, which is the set of groundwater heads for each model grid block that represents the system at the start of the simulation. Initial conditions for steady-state models need only be reasonably representative of the solution, but the system of equations is solved more efficiently the closer the starting heads are to the final solution; consequently, previous solutions were used as the starting heads for the predevelopment model. Results from the predevelopment simulation provided the initial conditions for the 1930-2012 transient calibration simulation. Results from the end of the 1930-2012 transient calibration model provided the initial conditions for the predictive simulations.

The Pre-Conditioned Conjugate Gradient (PCG) 4 solver, which is part of the MODFLOW-SURFACT software package, was used for all numerical models. Head tolerances for the solver were 0.001 feet for steady-state predevelopment models and 0.05 feet for transient models.

3.10 Modeling Methodology

The modeling methodology presented herein follows the general protocol developed by ASTM International (ASTM) for model application (ASTM 1993a, 1993b, 19 94, 1995, 1996a , and 1996b) including:

- ASTM 5447-93 – Application of a Ground-Water Flow Model to a Site-Specific Problem
- ASTM 5979-96 – Conceptualization and Characterization of Ground-Water Systems
- ASTM 5609-94 – Defining Boundary Conditions in Ground-Water Flow Modeling
- ASTM 5981-96 – Calibrating a Ground-Water Flow Model Application
- ASTM 5490-93 – Comparing Ground-Water Flow Simulations to Site-Specific Information
- ASTM 5718-95 – Documenting a Ground-Water Flow Model Application

4.0 CALIBRATION OF HISTORICAL NUMERICAL MODELS

Calibration is an important step in producing a reliable predictive model of groundwater flow. Model calibration is the process of making changes to the hydraulic properties and other inputs to the historical groundwater flow models so that the simulated historical groundwater levels more closely match observed groundwater levels. The Roca Honda mine model has been well calibrated to predevelopment and transient historical conditions so that it can be used to evaluate changes in groundwater levels from mine dewatering.

The calibration process for the Roca Honda groundwater flow models was carried out in three steps. The first step was to collect observations of groundwater levels, called calibration targets, for the steady-state predevelopment flow model and the transient 1930-2012 flow model. The second step was the calibration of the predevelopment flow model to groundwater level data collected prior to the start of significant groundwater pumping in the southern San Juan Basin. This involved visual and statistical comparisons of the observed and simulated groundwater levels. The third step was the calibration of the transient 1930-2012 flow model to groundwater level data collected during this time period when pumping of public water supply wells and historical mine dewatering caused changes in groundwater levels from predevelopment conditions. This involved visual comparison of observed (historical) and simulated groundwater levels. Any changes in hydraulic properties made to the transient 1930-2012 flow model were also made in the pre-development model so that both models were consistent.

Calibration targets, i.e., groundwater levels measured in wells, were collected for the Gallup, Dakota, and Westwater aquifers in and around the vicinity of the Roca Honda mine. Data sources for the calibration targets included the BDR (RHR, 2011b), data provided by Hydroscience (2009c), and reviews of water-well permit data files.

Calibration of the pre-development groundwater flow model yielded good visual matches to observations of groundwater levels and very good calibration statistics. Calibration of the transient 1930 to 2012 groundwater flow model yielded very good visual matches over many decades, including recent years and time periods with large changes in groundwater levels from mine dewatering. The very good calibrations to two independent data sets demonstrate that the historical groundwater flow models can reproduce observed groundwater flow behavior. The predictive model is therefore a valid tool for estimating the effect of projected RHR mine dewatering on the groundwater system.

4.1 Calibration of Predevelopment Flow Model

The predevelopment groundwater flow model was calibrated to observed groundwater levels (calibration targets) for the period prior to the start of significant groundwater pumping in the southern San Juan Basin representing conditions corresponding to the year 1930, prior to the commencement of significant withdrawals from aquifers of the San Juan Basin. Groundwater levels from the period ending in 1957 were also included in the calibration target dataset for a few areas for which no earlier data were available because wells had not been drilled there.

Calibration targets for the predevelopment groundwater flow model were compiled from several sources, primarily an INTERA dataset and compilations by Hydroscience (2009c). The INTERA database provided predevelopment groundwater levels for a wide range of locations within the San Juan Basin, whereas the Hydroscience compilation provided many additional targets in the southern San Juan Basin. The data sources described well locations using Township-Range-Section, with each section subdivided into quarters, and in some cases, eighths. This method of well location provides a relatively accurate method of locating the wells, relative to the scale of the model grid cells, but does not provide an exact location for each well. INTERA converted the Township-Range-Section location descriptors to a GIS projection.

Groundwater level data for the Gallup, Dakota, and Westwater aquifers from the Hydroscience and INTERA predevelopment database were also used to create contour maps of groundwater levels in each aquifer to represent the general pattern of groundwater flow during predevelopment conditions (Figures 2.8 to 2.10). The contour maps provided a visual comparator for evaluating the predevelopment calibration in these important aquifer units. Contour maps developed by Stone et al. (1983) and Kernodle (1996) were also used.

4.1.1 Methods

Both qualitative and quantitative methods were used to evaluate the predevelopment model calibration results. The qualitative method involved visual comparison between contour maps of observed (historical) and simulated groundwater levels. Quantitative methods used to evaluate model calibration included statistical analysis of simulated groundwater levels to observed groundwater levels at target locations. The following objectives were used to guide the predevelopment model calibration:

- Contours of simulated groundwater levels should resemble contours of observed groundwater levels in the Gallup, Dakota, and Westwater aquifers (Figures 2.8 to 2.10).
- Simulated groundwater levels should provide reasonable matches to calibration targets.
- Simulated water-balance fluxes (i.e., volume per unit time of water flow) should be within the range established by previous work.

Hydraulic conductivity values, mountain-front recharge rates, and areal recharge rates were systematically adjusted to produce simulated groundwater levels that matched the calibration targets and the contour maps of predevelopment groundwater levels in the three aquifers.

Traditional calibration measures (Anderson and Woessner, 1992), such as the mean error and the mean absolute error, quantify the average error in the calibration process. The basis for these statistics is the residual, which is simply the difference between the simulated groundwater level or head (h_s) and the observed groundwater level or head (h_m):

$$residual = (h_s - h_m) \tag{4.1}$$

The mean error is the mean of the residuals:

$$mean\ error = \frac{1}{n}\sum_{i=1}^{n}(h_s - h_m)_i \tag{4.2}$$

where n is the number of calibration targets or measurements. The mean absolute error is the mean of the absolute value of the residuals:

$$mean\ absolute\ error = \frac{1}{n}\sum_{i=1}^{n}|h_s - h_m|_i \tag{4.3}$$

The normalized root mean square error (NRMSE) is the square root of the sum of the squared residuals divided by the number of observations:

$$NRMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(h_s - h_m)_i^2\right]^{1/2} \tag{4.4}$$

Both the *NRMSE* and mean absolute error are routinely used as basic calibration metrics for groundwater levels. For many groundwater flow models, the typical calibration criterion for groundwater head residuals is an *NRMSE* value that is equal to or less than 10% of the observed head range in the aquifers being simulated (Spitz and Moreno, 1996).

The mean absolute error is useful for describing model error on an average basis but, as a single measure, it does not provide insight into spatial trends in the distribution of the residuals. An examination of the spatial distribution of residuals is necessary to determine if they are randomly distributed over the model grid and thus are not spatially biased, that is, the residuals are not worse in one part of the groundwater model than another. Post plots of head residuals for the predevelopment steady-state groundwater levels can be used to judge the spatial aspects of the calibration. These plots indicate the magnitude and direction of the error between the observed and simulated groundwater levels.

During the calibration process, it is important to check the overall water balances periodically to ensure that the difference between simulated inflow and simulated outflow is small. The difference between the total simulated inflow and the total simulated outflow is called the mass balance error. These errors should be calculated for the model as a whole and for each layer. Typically, the overall percent difference should be less than 1%, and ideally less than 0.1% (Anderson and Woessner, 1992).

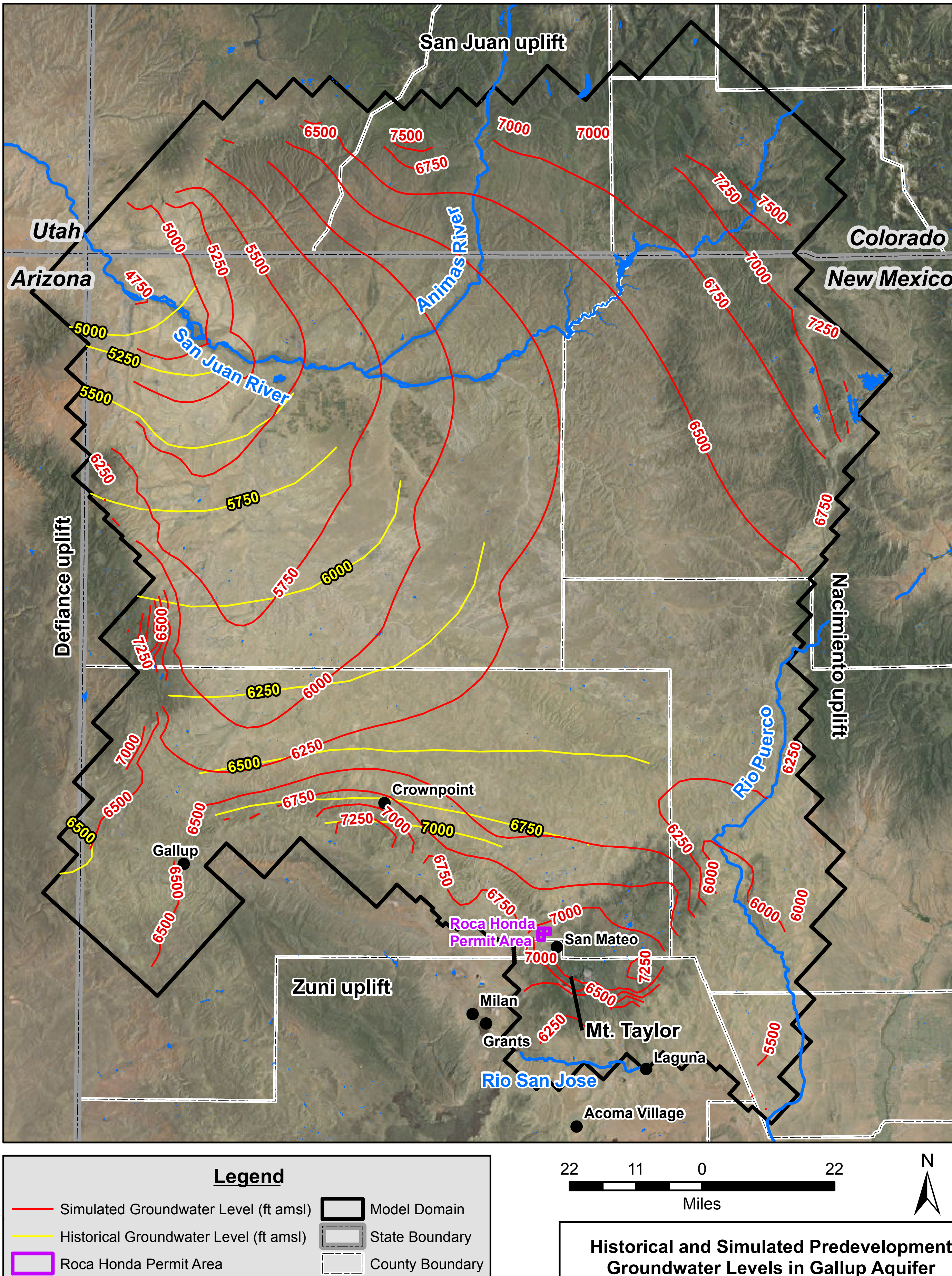
4.1.2 Results for Predevelopment Model Calibration

Calibrated hydraulic conductivity values are shown in Table 4.1. The final steady-state calibration yielded a good match to the contours of predevelopment groundwater levels for the Gallup (Figure 4.1), Dakota (Figure 4.2) and the Westwater (Figure 4.3) aquifers. Residuals are relatively small in absolute value in the Westwater aquifer, especially in and around the Roca Honda permit area (Figure 4.4). However, groundwater levels tend to be slightly over-predicted in the Ambrosia Lake sub-district and in the northwestern part of the domain (Figure 4.4 inset). Calibrated steady-state groundwater levels in the Westwater aquifer in the Ambrosia Lake Valley area range between 6,560 to 6,640 feet, which agrees well with Ganus's (1980) estimation that predevelopment heads in the Ambrosia Lake Valley area ranged between 6,550 and 6,600 feet. Residuals for the Dakota and Gallup aquifers (layers 6 and 8, respectively) also show a fairly good fit and little spatial bias (Figures 4.5 and 4.6, respectively). Residuals for calibration targets in groundwater model layers 2, 3, and 5 are relatively small with both positive and negative values, thus showing little or no spatial bias (Figure 4.7).

Plots of observed versus simulated groundwater levels for all layers (Figure 4.8a) reveal relatively little scatter from the 1:1 line that represents ideal behavior. A plot (Figure 4.8b) for targets in layers 6 (Gallup) through 10 (Westwater), also shows little scatter from the ideal 1:1 line. The observed and simulated groundwater levels are randomly distributed along either side of the 1:1 line, indicating that the distribution shows little or no bias and that the model is well-calibrated (Anderson and Woessner, 1992).

Table 4.1 Calibrated Hydraulic Conductivity Values for Hydrostratigraphic Units

Model Layer	Hydrostratigraphic Unit	Hydraulic Conductivity Zone	Description	Hydraulic Conductivity (ft/day)	
				Horizontal	Vertical
1	San Jose Formation	Tsj	Basin-wide	0.5	0.002
1 to 2	Animas and Nacimiento Fms	Tka	Basin-wide	0.01	0.0001
1 to 3	Ojo Alamo Sandstone	Toa	Basin-wide	0.3	0.001
	Kirtland and Fruitland Fms	Kkf			
	Pictured Cliffs Sandstone	Kpc			
1 to 4	Lewis Shale	Kls	Basin-wide	$5x10^{-5}$	$2.5x10^{-6}$
1 to 5	Cliff House Sandstone	Kch	Basin-wide	0.05	0.0003
	Menefee Formation	Kmf			
	Point Lookout Sandstone	Kpl			
	Crevasse Canyon Formation	Kcc			
1 to 5	Mancos Shale	Km1	Basin margin	$1x10^{-4}$	$1x10^{-4}$
6		Km2	Upper Mancos	$3x10^{-3}$	$5x10^{-6}$
1 to 7		Km3	Lower Mancos	$5x10^{-5}$	$2.5x10^{-6}$
1 to 6	Gallup Sandstone	Kg1	Southern basin	0.25	0.0025
6		Kg2	Roca Honda permit area based on RHR pump test	1.5	0.002
7 to 8	Dakota Sandstone	Kd1	Basin-wide	0.1	0.0001
1 to 8		Kd2	Ambrosia Lake sub-district	0.1	0.002
7 to 8		Kd3	Rio San Jose River	1	0.001
9	Brushy Basin Member of Morrison Formation	Jmbb	Basin-wide	$3x10^{-3}$	$5x10^{-6}$
10	Westwater Canyon Member of Morrison Formation	Jmw1	Northern basin	0.02	0.0002
		Jmw2	Southern basin	1.25	0.00125
		Jmw3	Ambrosia Lake sub-district	1.6	0.002
		Jmw4	Roca Honda permit area based on RHR pump test	0.5	0.001
		Jmw5	Gulf Mt. Taylor mine area based on historical dewatering rates	3	0.003
6 to 10	Mt. Taylor volcanic rocks	Tnv1	Volcanics in the aquifer	0.1	0.001
		Tmv1	Basalt and andesite flows in the aquifer		
		Tnv2	Volcanics in the aquifer	$1x10^{-4}$	$5x10^{-6}$
		Tnv2	Basalt and andesite flows in the aquitard		



Historical and Simulated Predevelopment Groundwater Levels in Gallup Aquifer

INTERA

Figure 4.1

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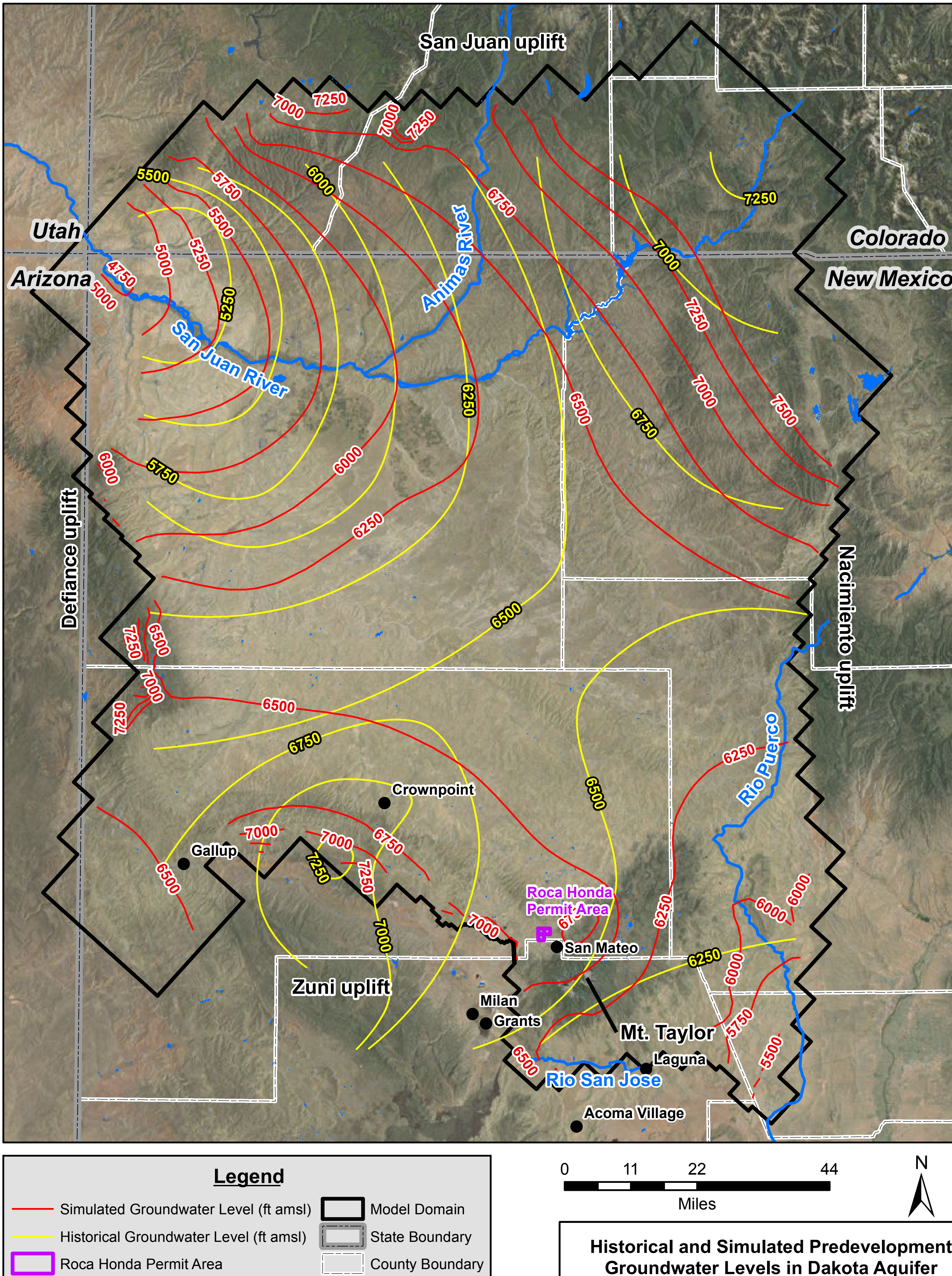

Historical and Simulated Predevelopment Groundwater Levels in Dakota Aquifer

INTERA

Figure 4.2

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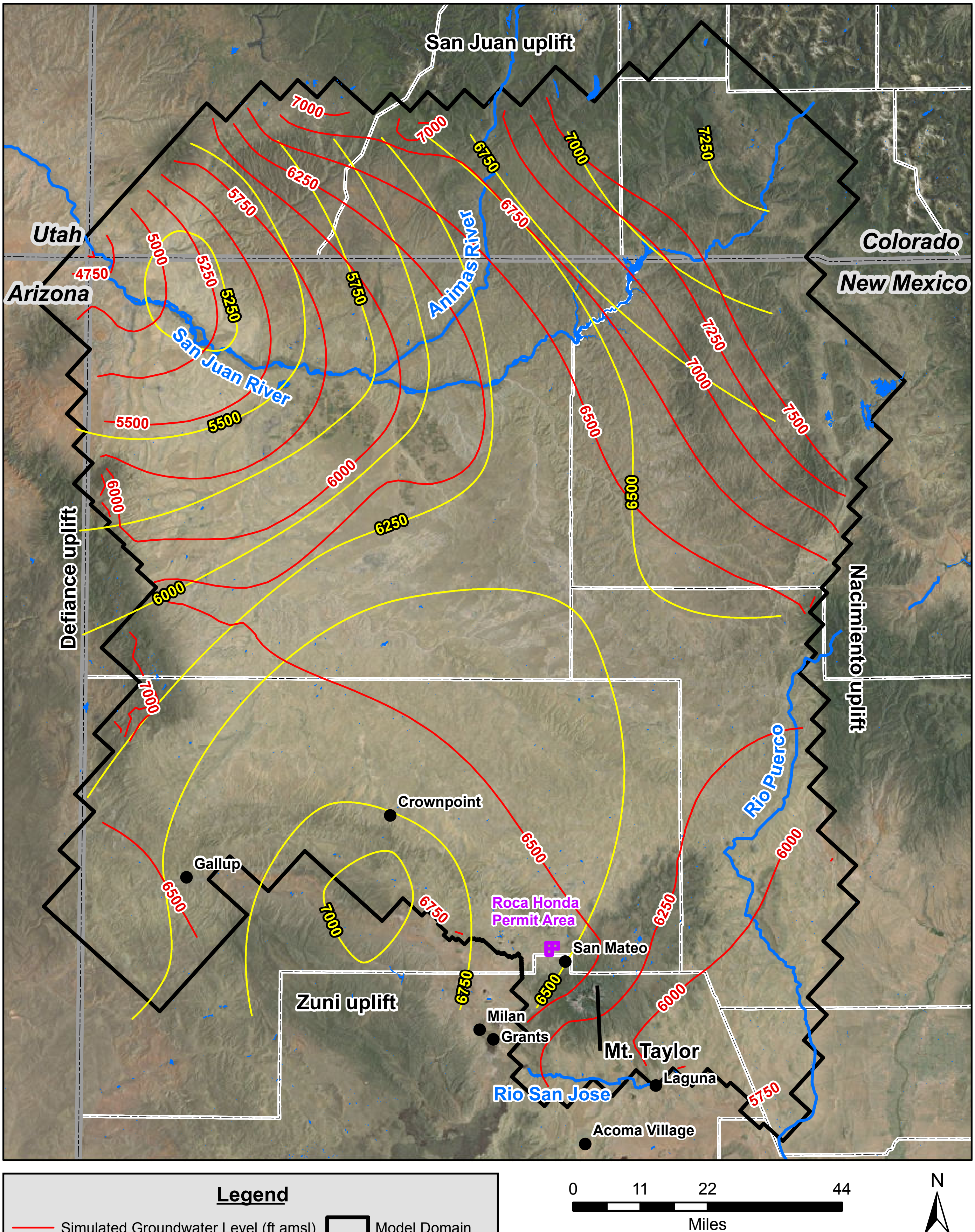
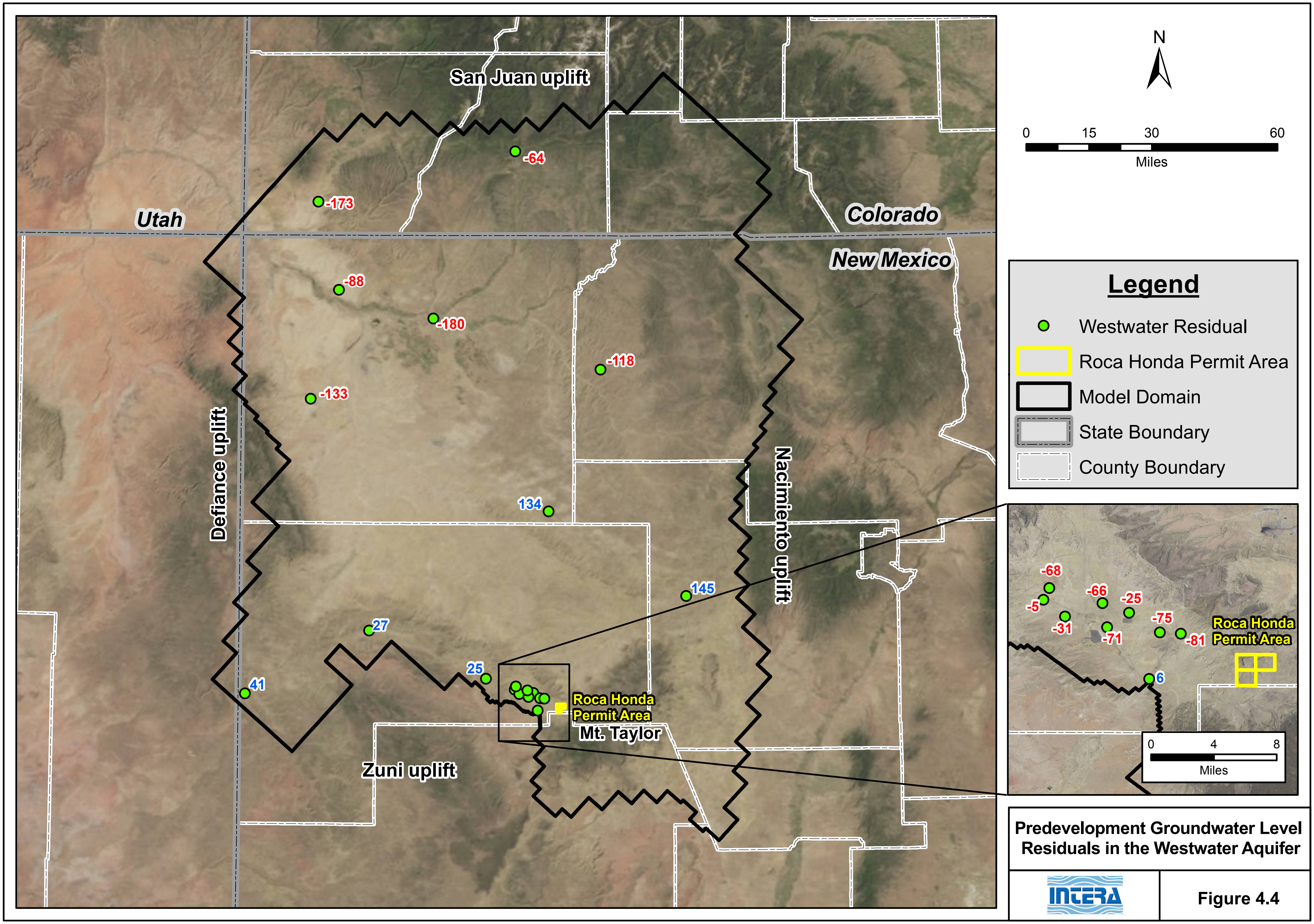
Revised August 7, 2012



Historical and Simulated Predevelopment Groundwater Levels in Westwater Aquifer

INTERA

Figure 4.3



Predevelopment Groundwater Level Residuals in the Westwater Aquifer

Figure 4.4

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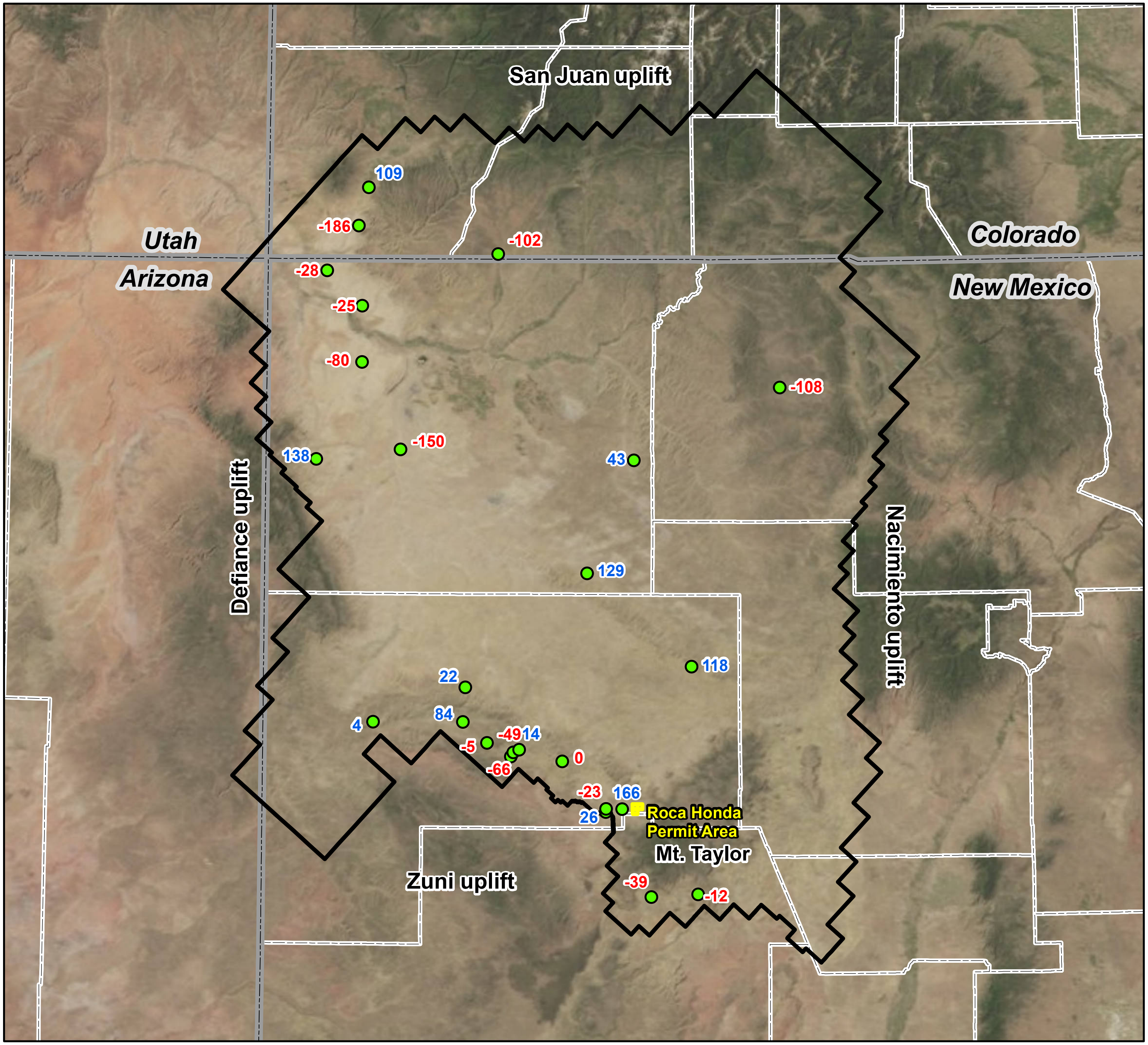

Predevelopment Groundwater Level Residuals in the Dakota Aquifer

INTERA

Figure 4.5

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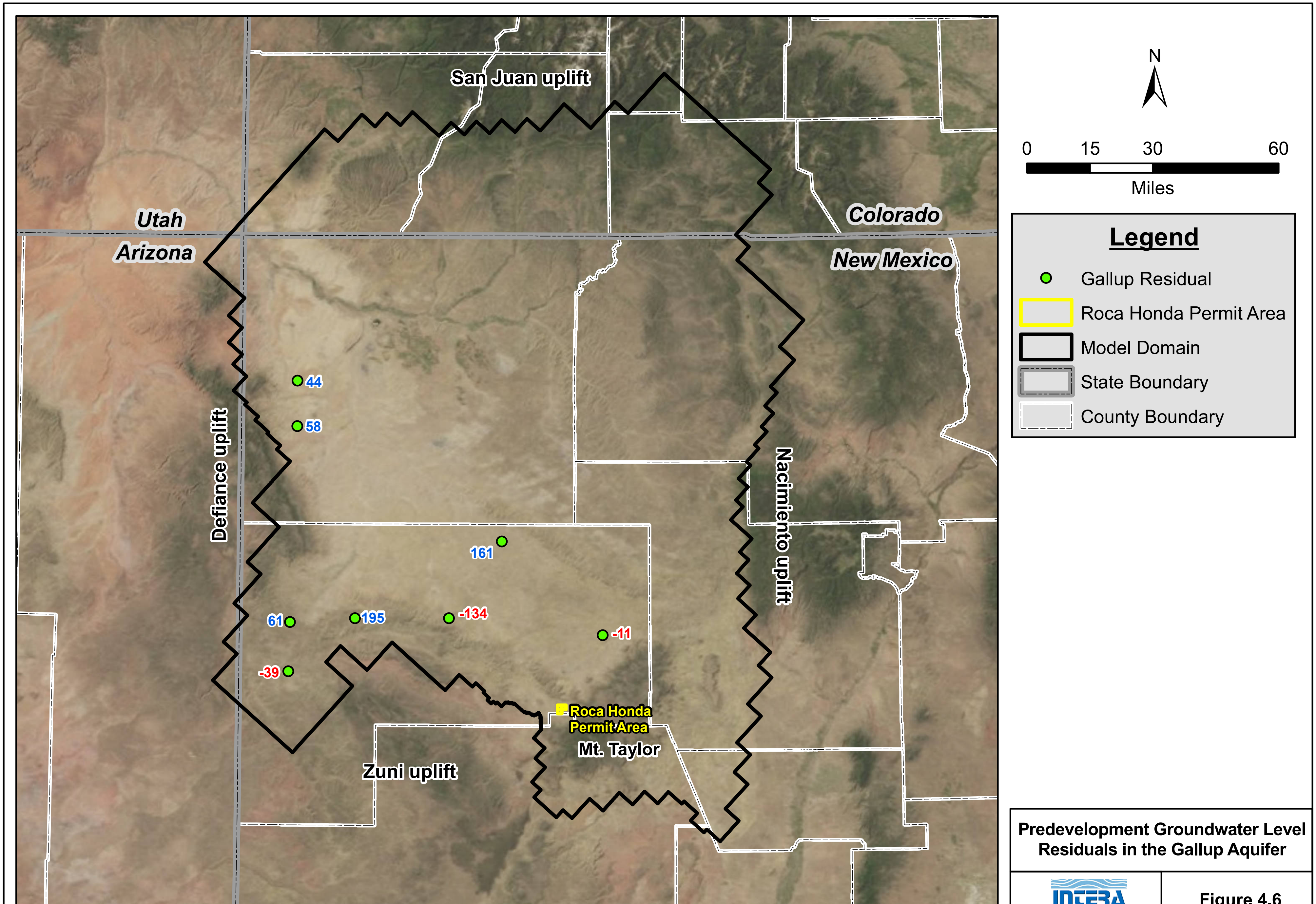

Predevelopment Groundwater Level Residuals in the Gallup Aquifer

INTERA

Figure 4.6

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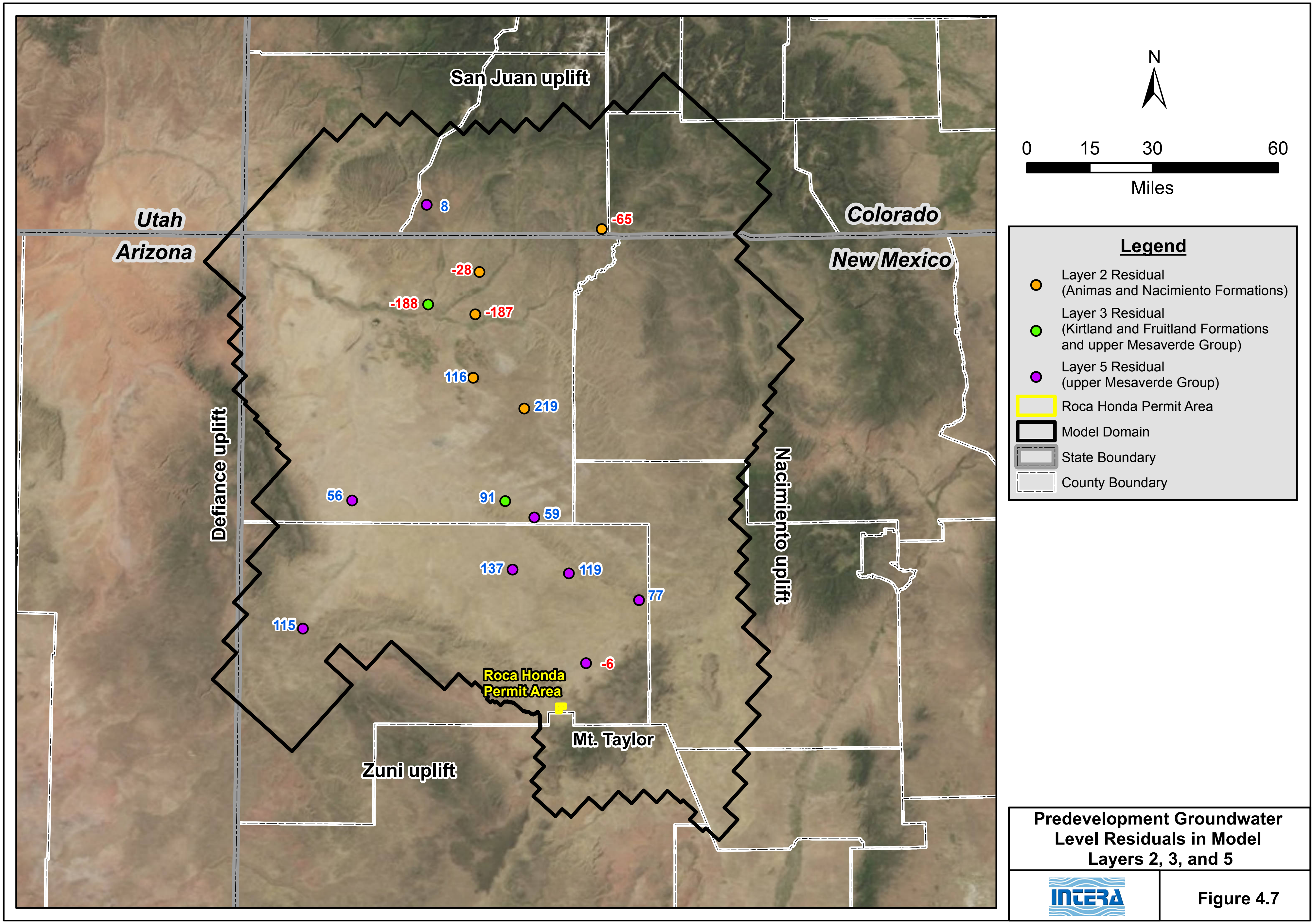

Predevelopment Groundwater Level Residuals in Model Layers 2, 3, and 5

INTERA

Figure 4.7

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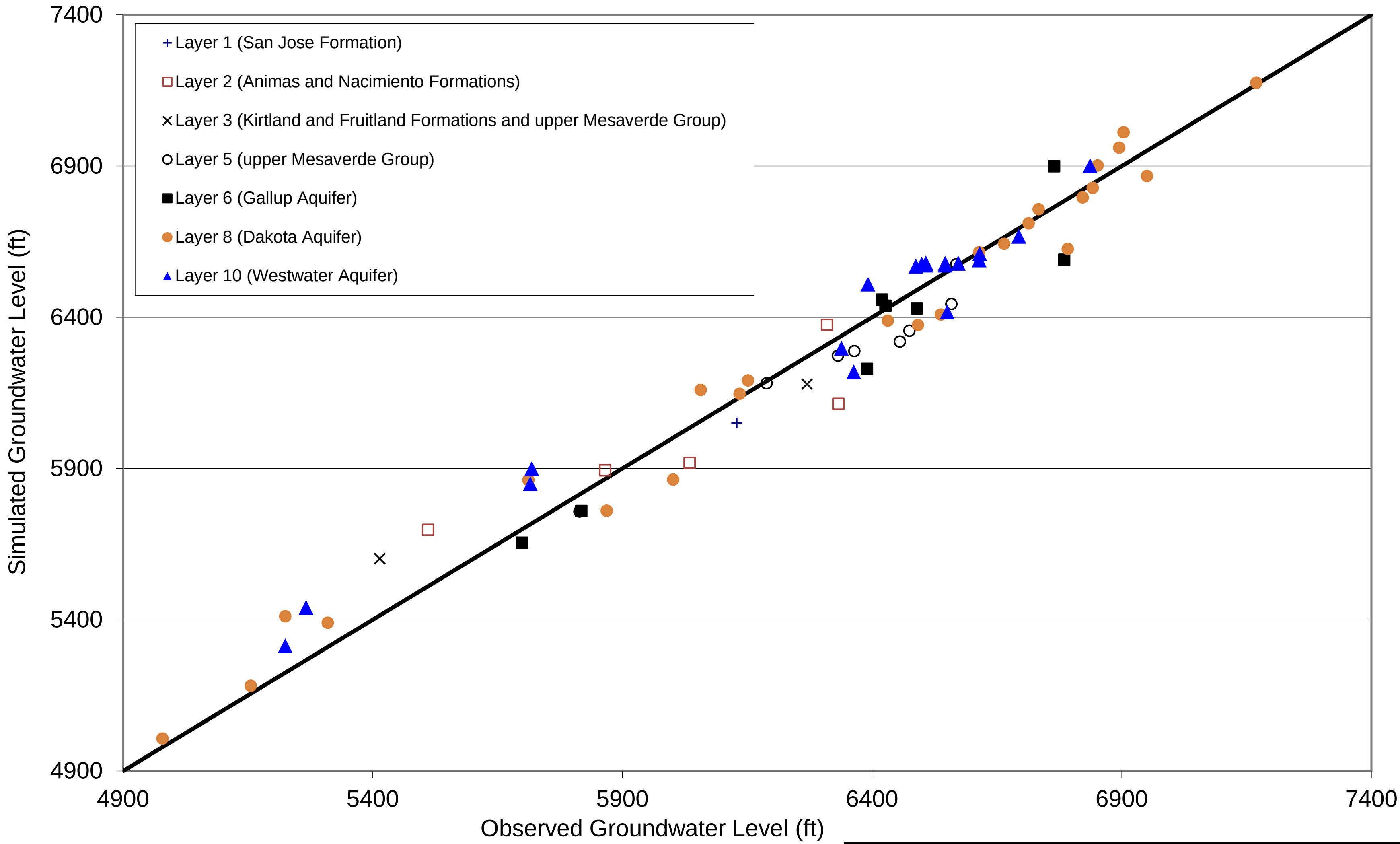

Simulated versus Observed Groundwater Levels of all Layers in the Calibrated Predevelopment Model

INTERA

Figure 4.8a

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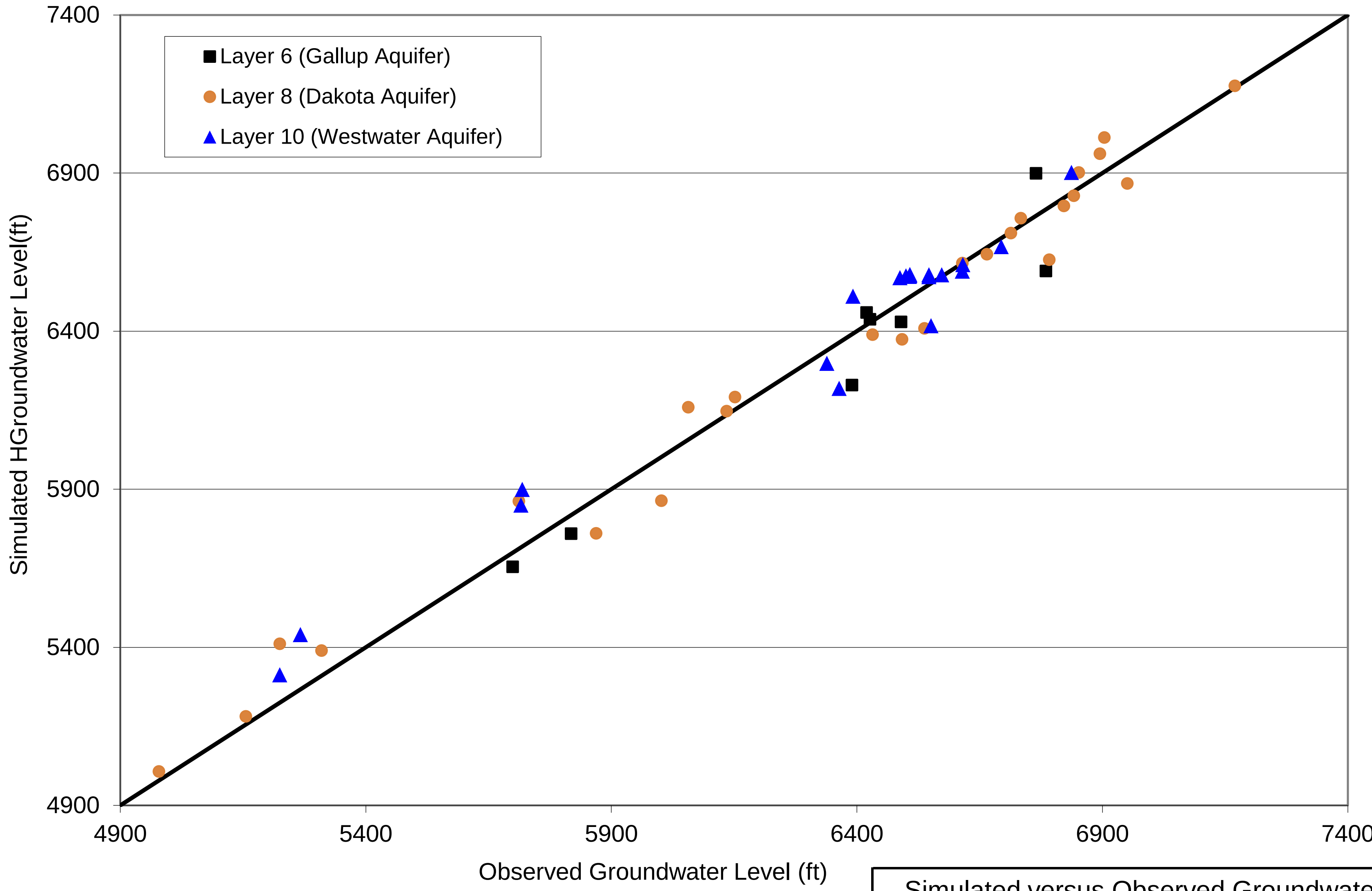
Revised August 7, 2012



Simulated versus Observed Groundwater Levels of Layers 6 through 10 in the Calibrated Predevelopment Model

INTERA

Figure 4.8b

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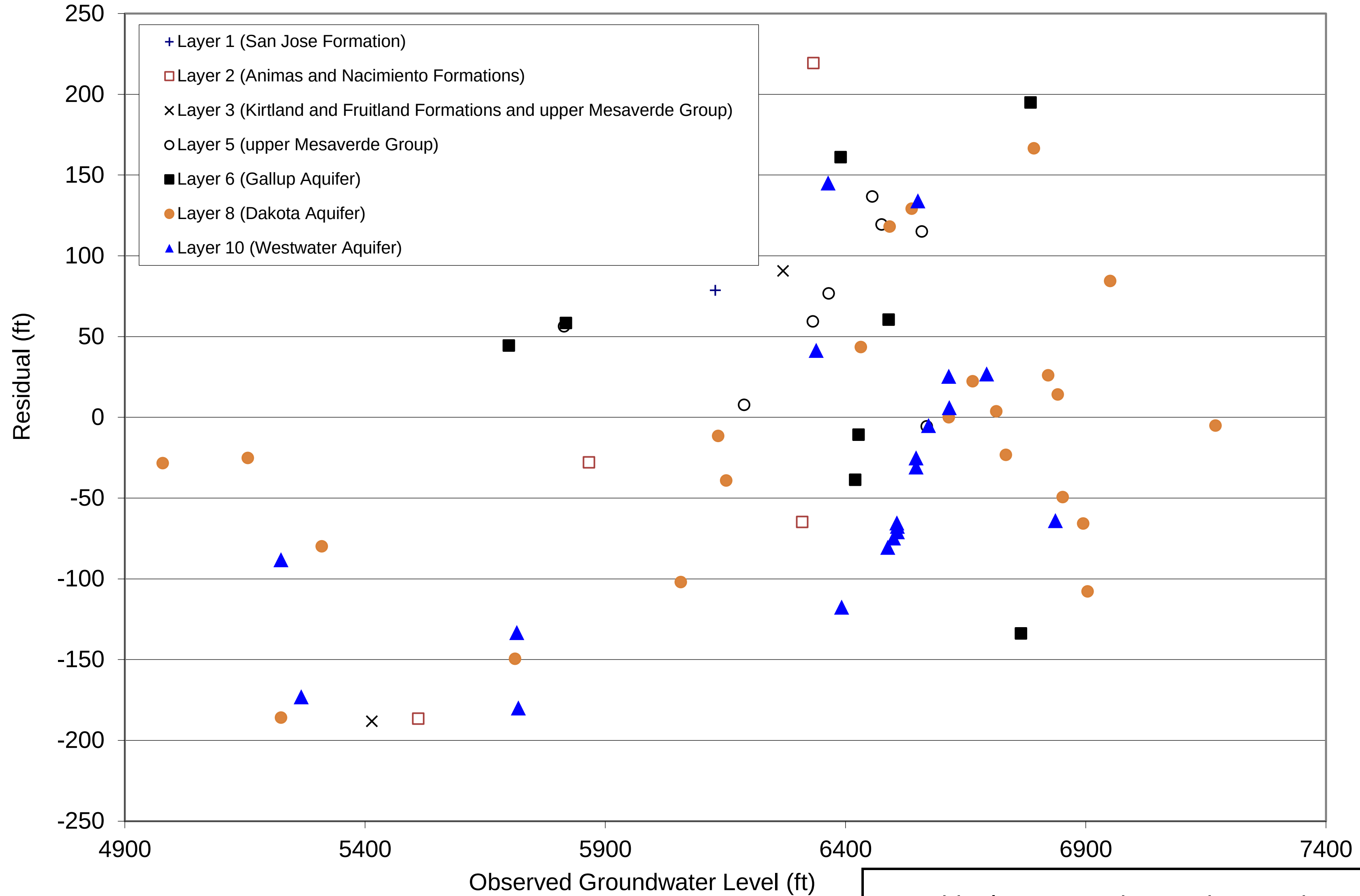
Data scatter about the 1:1 line appears smaller in layers 6 through 10 compared to all layers. Similarly, plots of residuals versus observed groundwater levels show the desired random distribution of points, whether for all layers (Figure 4.9a) or just layers 6 through 10 (Figure 4.9b), and thereby indicate little or no bias in the calibration.

Statistics for the predevelopment model calibration's 69 residuals over all layers are quite good for a large-scale flow model (Table 4.2). Mean error is slightly more than 2 feet, mean absolute error is less than 80 feet, and *NRMSE* is 4.4% (Table 4.2), much less than the 10% guidance given by Spitz and Moreno (1996). When calculated for the residuals from layers 6 to 10 (Gallup down through the Westwater) only, the statistics improve slightly, with the exception of the mean error, which is -10.25 feet (Table 4.2).

Table 4.2
Residual Statistics from the Predevelopment Model Calibration

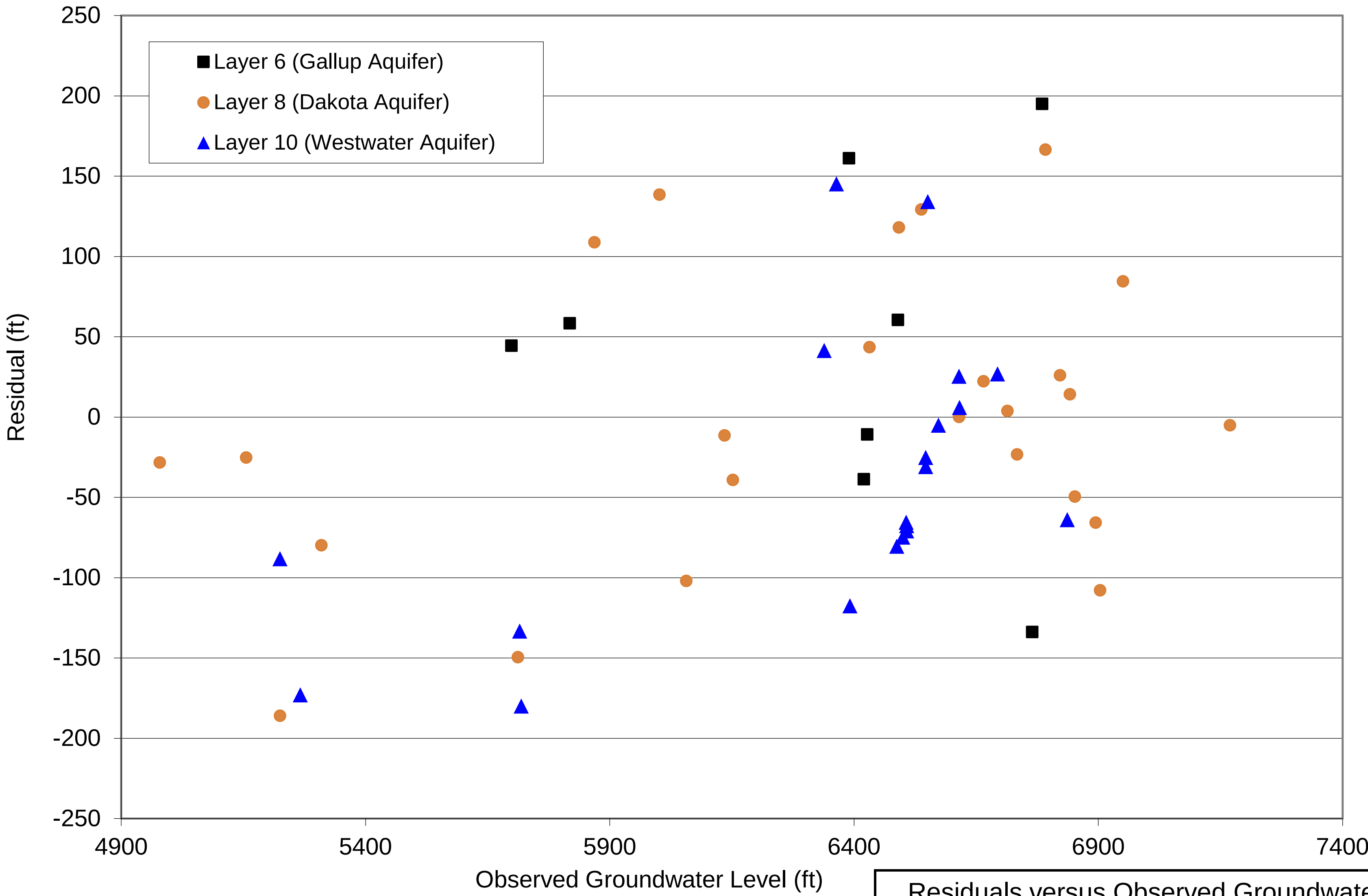
Statistic	All Layers	Layers 6 to 10
Number of residuals	69	53
Mean error (feet)	1.76	-9.08
Error standard deviation (feet)	98.79	93.09
Sum of squares (ft^2)	6.74×10^5	4.64×10^5
Mean absolute error (feet)	80.22	75.21
Minimum residual (feet)	-188.23	-185.96
Maximum residual (feet)	219.38	194.91
Range of target groundwater levels (feet)	2,191	2,191
Normalized root mean square error (dimensionless)	0.045	0.043



Residuals versus Observed Groundwater Levels of all Layers in the Calibrated Predevelopment Model

INTERA

Figure 4.9a



Residuals versus Observed Groundwater Levels of Layers 6 through 10 in the Calibrated Predevelopment Model

Figure 4.9b

The water balance fluxes for the calibrated predevelopment model reveal that infiltration from river beds is the largest single input to the San Juan Basin flow system (Table 4.3). The total mass balance error was -0.21% (Table 4.3). Mass balance errors should be less than 1%, and ideally less than 0.1% (Anderson and Woessner, 1992).

Table 4.3
Calibrated Predevelopment Model Flux Values

Water Balance Component	Flux Rate (ft^3/day)	Percent Total
Inflow		
Areal recharge	1,644,404	32.5%
River infiltration	1,922,097	38.0%
Deep Mountain-front recharge	1,299,301	25.7%
Mountain-front recharge from Chuska Sandstone and Mt. Taylor	195,688	3.8%
Total In:	*5,061,490*	
Outflow		
Discharge to perennial rivers	3,836,435	75.9%
Discharge to ephemeral drainages	1,220,459	24.1%
Total Out:	*5,056,894*	
Mass Balance Error (percent error)	**0.09%**	

The total inflow groundwater flow rate for the predevelopment model is roughly 5,000,000 ft^3/day (58 ft^3/s), which is equivalent to a basin-wide average inflow rate of 0.042 in/yr. By definition, inflow should equal outflow for a steady-state groundwater flow model such as the predevelopment model. Total inflow for the calibrated predevelopment model falls within the range of 30 and 195 ft^3/s estimated for the San Juan Basin by Frenzel and Lyford (1982) and Kernodle (1996), respectively, and is very close to the 60 ft^3/s estimated by Lyford and Stone (1978).

4.2 Calibration of Transient 1930-2012 Model

The transient 1930-2012 model simulates the changes to the predevelopment groundwater levels caused by time-varying pumping for public water supplies and historical mine dewatering. Groundwater level values for the period of 1930 to 2012 were compiled and reviewed by INTERA and Hydroscience (2009c). The review yielded 27 transient calibration targets in the Gallup, Dakota, and Westwater aquifers. Transient calibration targets have one or more observations of groundwater level over time. Most of the targets had one or two observations, but 12 targets had more than two observations, particularly those in mine shafts and vents at former uranium mines.

4.2.1 Methods

Both qualitative and quantitative methods were used to evaluate the transient 1930-2012 model calibration results. The qualitative method involved visual comparison between contour maps of observed and simulated groundwater levels for specific time periods as well as comparison of simulated to observed groundwater levels at target locations. The quantitative check on t he calibration compared simulated and reported dewatering rates and volume of water in historical uranium mining areas. The following objectives were used to guide the transient 1930-2012 model calibration:

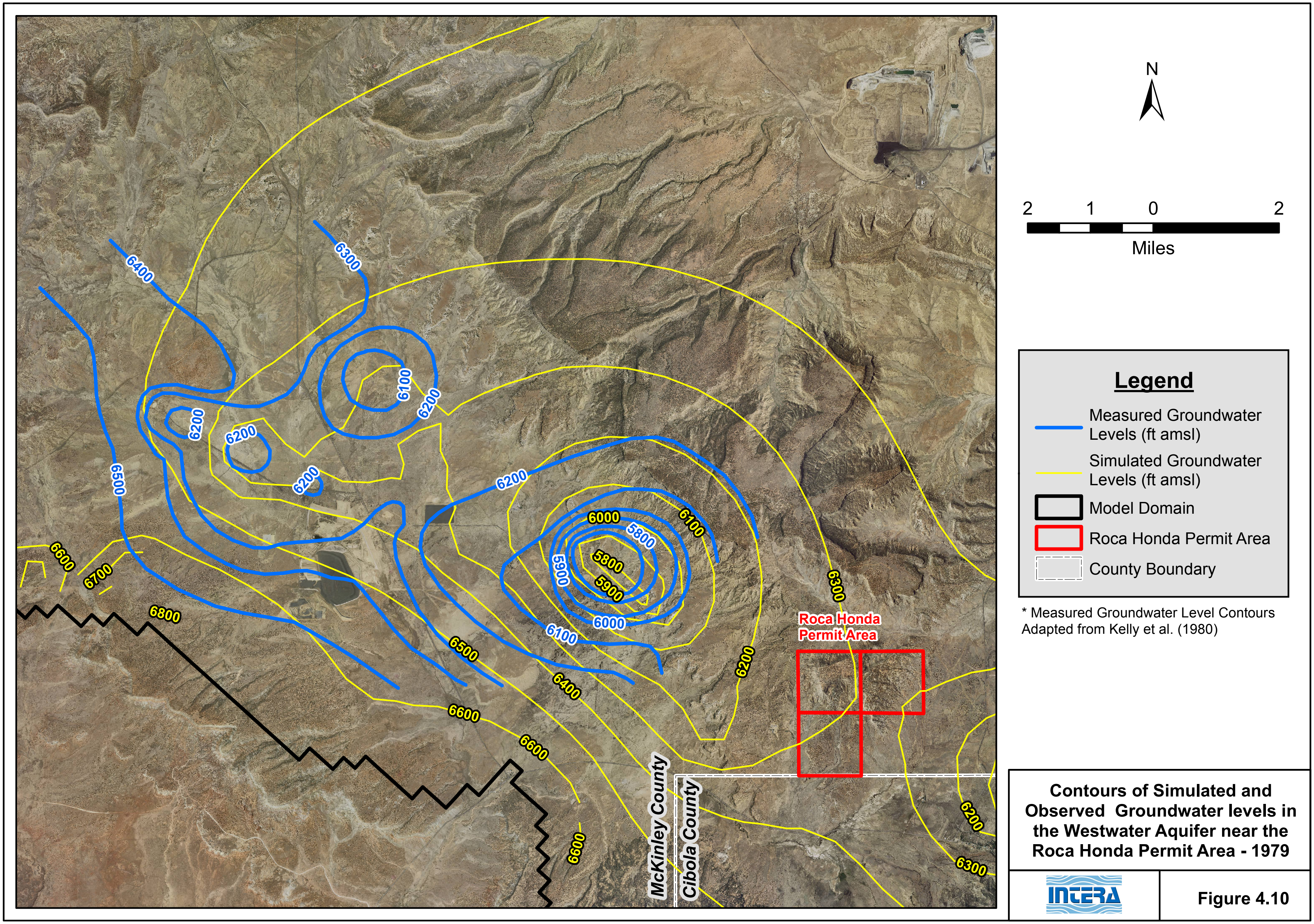
- Contours of simulated groundwater levels should resemble contours of groundwater levels observed in the Westwater aquifer at various time periods.
- Simulated groundwater levels should provide reasonable matches to the calibration targets over time.
- The dewatering rates and total volume produced from the transient 1930-2012 model should be similar to estimated pumping rates for the Ambrosia Lake and Church Rock mines from Stone el al. (1983).

Model parameters were adjusted by trial and error to achieve good matches to all three objectives listed above.

4.2.2 Results for Transient 1930-2012 Model Calibration

Comparison of contours of simulated groundwater levels to contours of groundwater levels observed in the Westwater aquifer near the Roca Honda permit area during three time periods demonstrated good agreement. There is good agreement for the 1979 contours (Figure 4.10), whereas the agreement between the 2007 s imulated contours and the contours of observed groundwater levels from 2003 to 2007 is fairly good (Figure 4.11). Westwater groundwater level data were contoured for the RHR BDR (RHR, 2011b) and a comparison of simulated to 2010 observed contours shows good agreement (Figure 4.12).

The final transient 1930-2012 calibration yielded a close match to eight Westwater well targets with single observations (Appendix C.1 to C.8) and a good match to two Westwater well targets with numerous observations (Appendix C.9 and C.10). Simulated and observed groundwater levels matched very closely in wells located in the Roca Honda vicinity (Appendix C.11 to C.14). These matches are important because the observations were made late in the simulation period, long after dewatering had ceased, and thus indicate that the transient 1930-2012 model accurately represents Westwater groundwater levels prior to the start of the predictive simulations. Good matches were also found for two wells in the Dakota aquifer (Appendix C.15 to C.16).



Contours of Simulated and Observed Groundwater levels in the Westwater Aquifer near the Roca Honda Permit Area - 1979

INTERA

Figure 4.10

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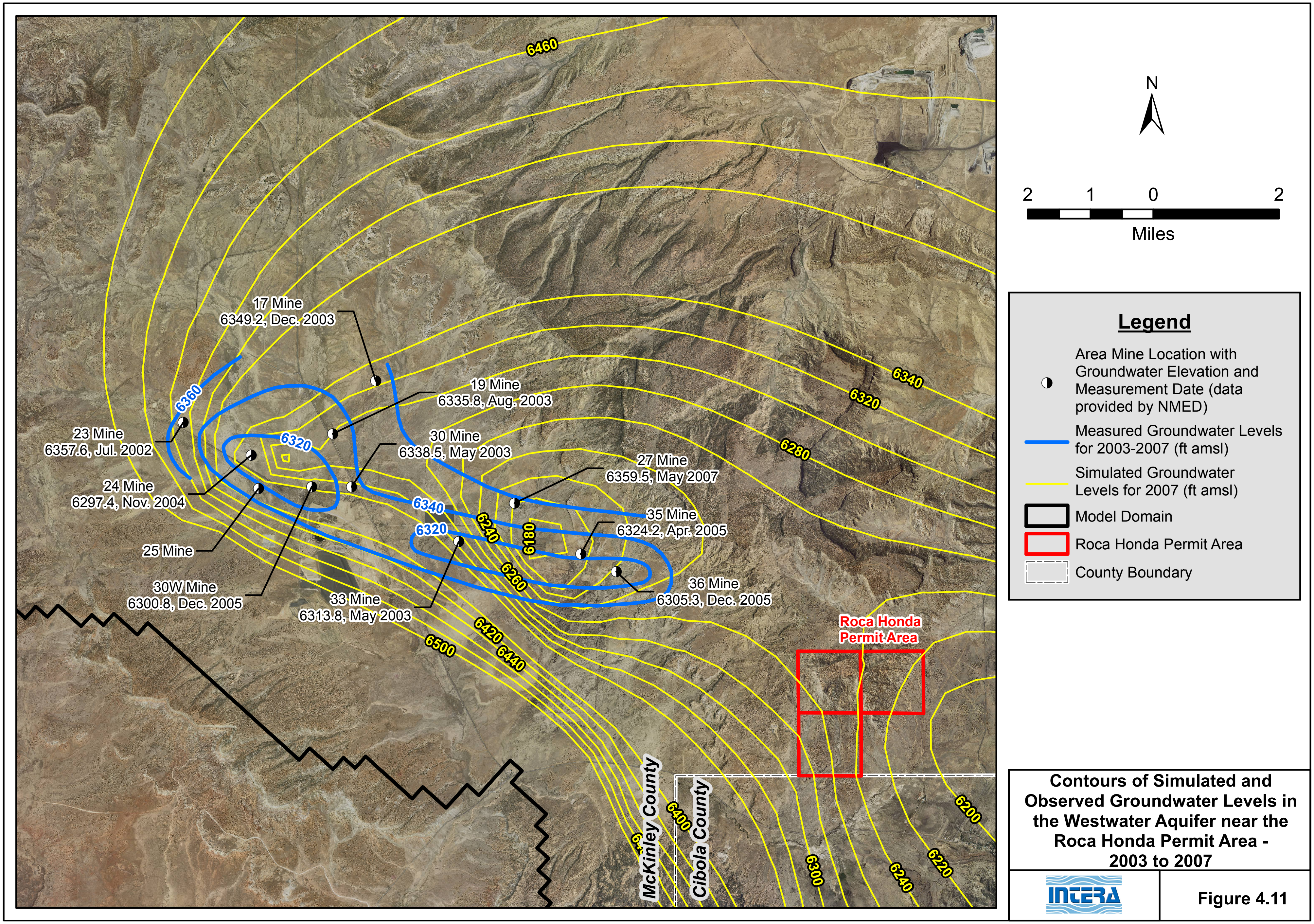

Contours of Simulated and Observed Groundwater Levels in the Westwater Aquifer near the Roca Honda Permit Area - 2003 to 2007

INTERA

Figure 4.11

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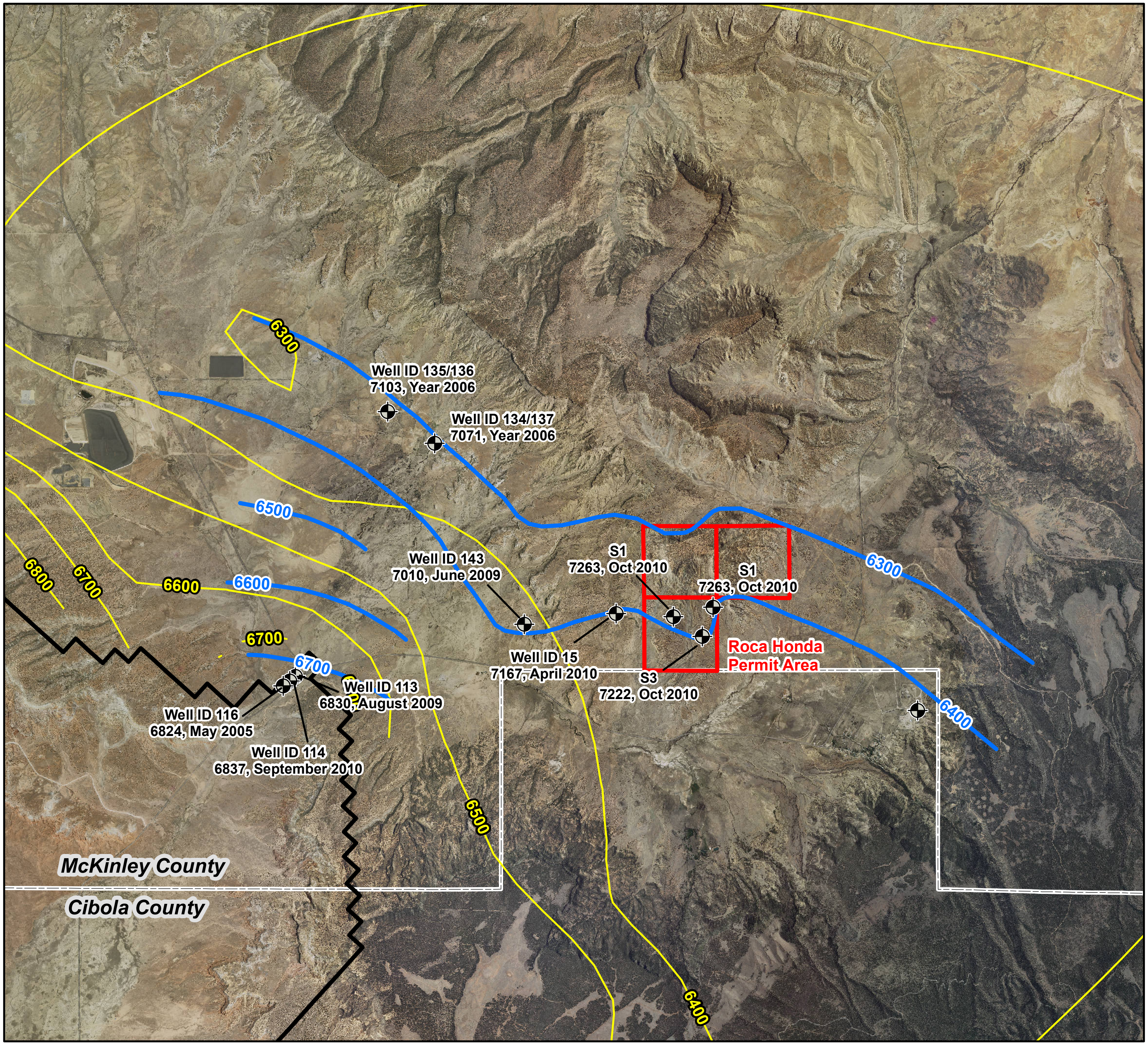

Contours of Simulated and Observed Groundwater Levels in the Westwater Aquifer near the the Roca Honda Permit Area - 2010

INTERA

Figure 4.12

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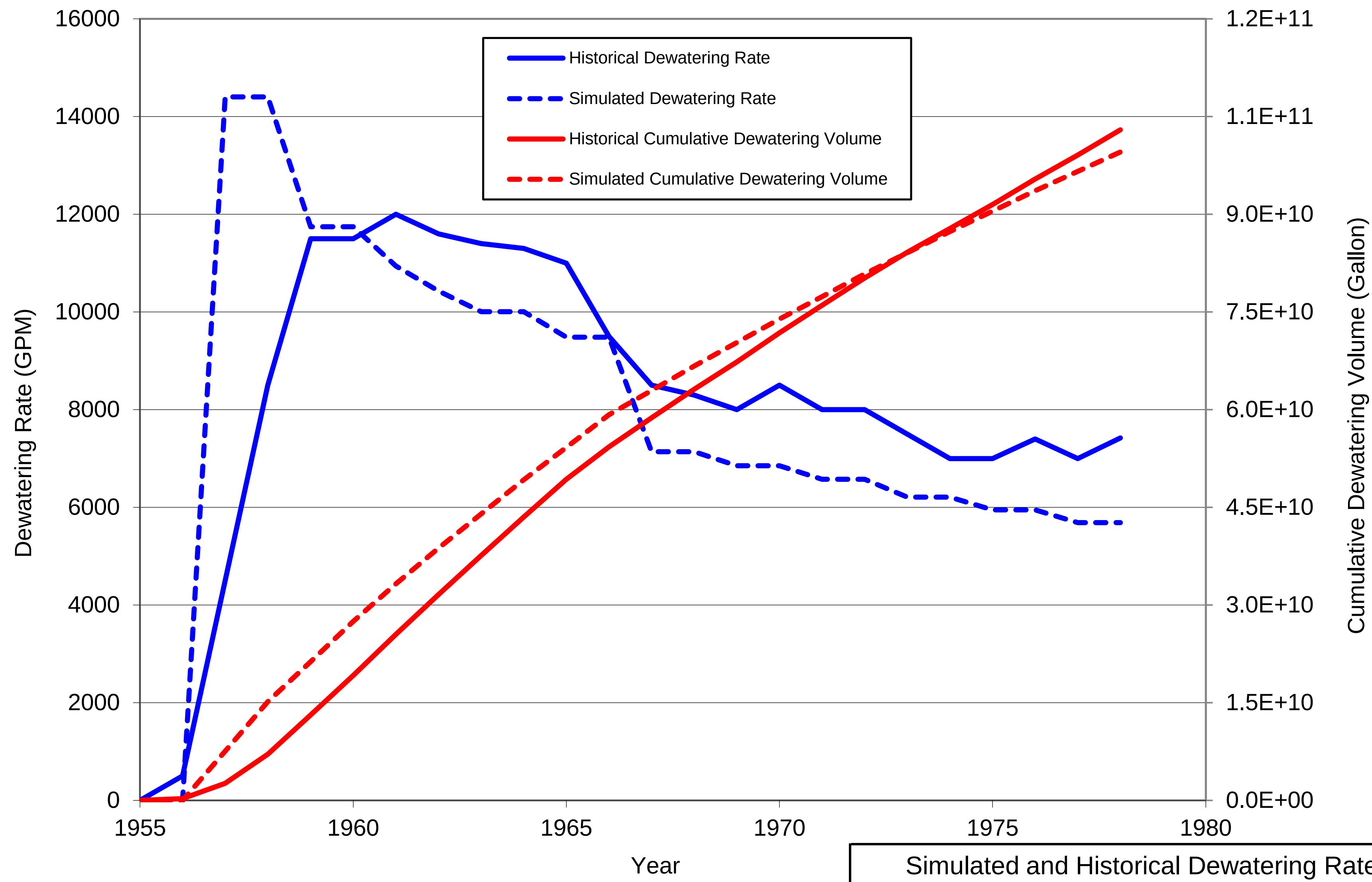
Simulated and observed groundwater levels measured in four mine shaft targets matched fairly well (historical Kerr-McGee mine shafts in Sections 17, 19, 35, and 36 shown in Appendix C.17 to C.18 and C.23 to C.24), whereas the others did not match as closely (shafts in Sections 24, 30, 30W, and 33 shown in Appendix C.19 to C.22). The hydrographs show good overall agreement, but the simulated groundwater levels do not reflect the relatively high-frequency changes observed in several shafts. Some of the observed shaft groundwater levels (Sections, 19, 24, and 30W) show the effects of additional mine dewatering after 1985 due to some pumps being turned back on a round 1995 a nd ultimately turned back off a number of years later. Due to the constraints imposed by the selected modeling stress periods, INTERA was unable to capture this brief period of renewed pumping. However, the slopes of the recovery curves are very similar during periods without pumping. Similarly, comparison of measured and simulated groundwater levels at three locations in the Gallup (Figures C.25 to C.27) show that pumping in the Gallup, demonstrated by the changes in measured groundwater levels, is not represented in the model. All three sets of measurements are located more than 20 miles from the Roca Honda permit area. Simulated groundwater levels in the Gallup are lower than measured groundwater levels at two of the three locations, indicating that overall the model yields a conservative estimate of groundwater levels at those time periods and locations in the Gallup.

Simulated and reported dewatering rates and volumes were compared as a final check on the transient 1930-2012 model calibration for several locations. Plots for Ambrosia Lake mines compare reported rates (Stone et al., 1983) with simulated dewatering rates, as well as cumulative volume produced (Figure 4.13). Differences in the rate curves are caused by the number and size of stress periods used, but the total water produced shows excellent agreement (Figure 4.13). Reported and simulated dewatering rates and total produced volume for the Church Rock Mine are also very similar (Figure 4.14). Simulated dewatering rates and produced volumes for the Gulf Mt. Taylor (Figure 4.15) and Johnny M mines (Figure 4.16) were in agreement with data compiled by Hydroscience (2009a).



Simulated and Historical Dewatering Rates and Cumulative Volume for Ambrosia Lake Area Mines in the Westwater Aquifer

INTERA

Figure 4.13

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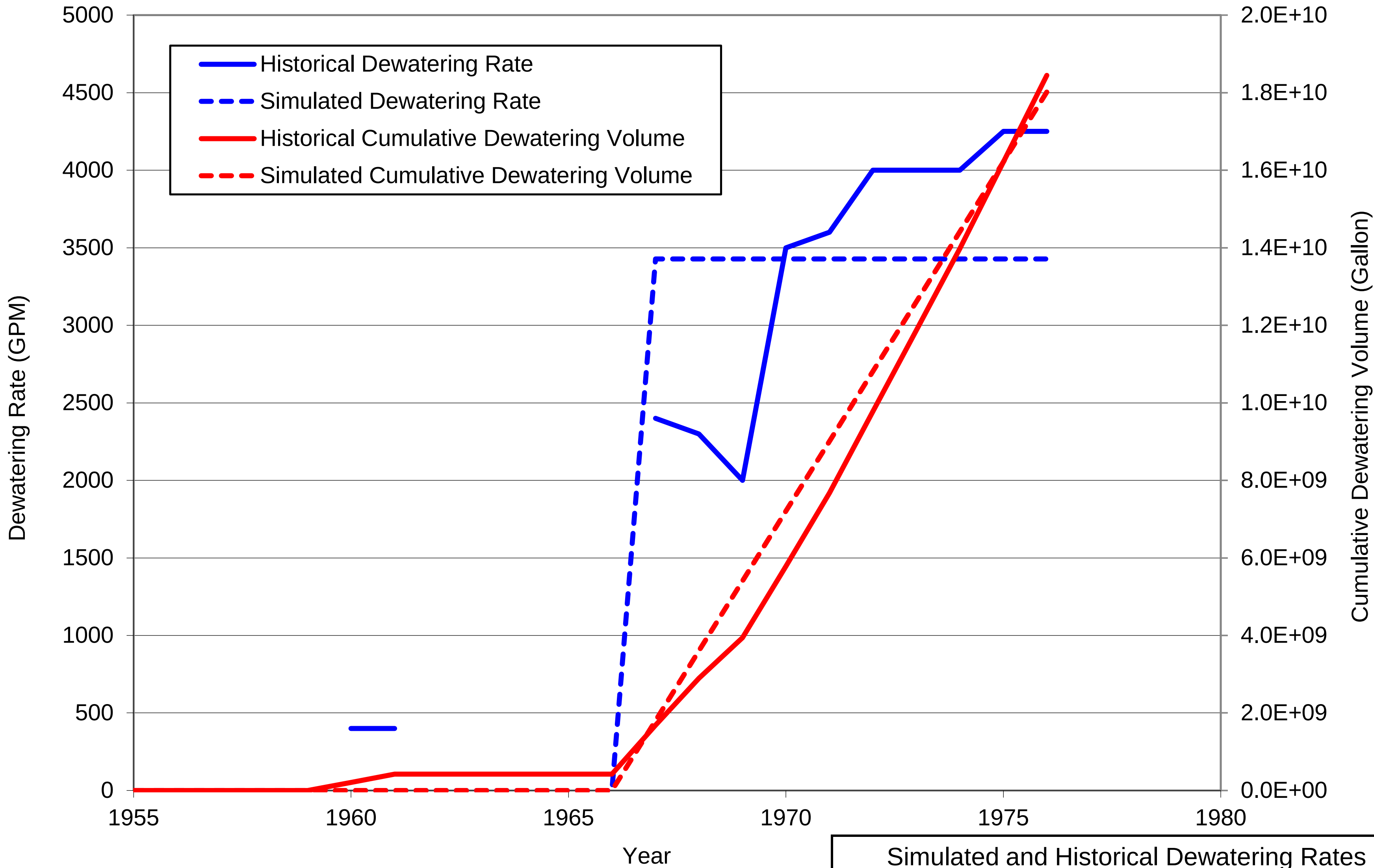

Simulated and Historical Dewatering Rates and Cumulative Volume for Church Rock Mine Area in the Westwater Aquifer

INTERA

Figure 4.14

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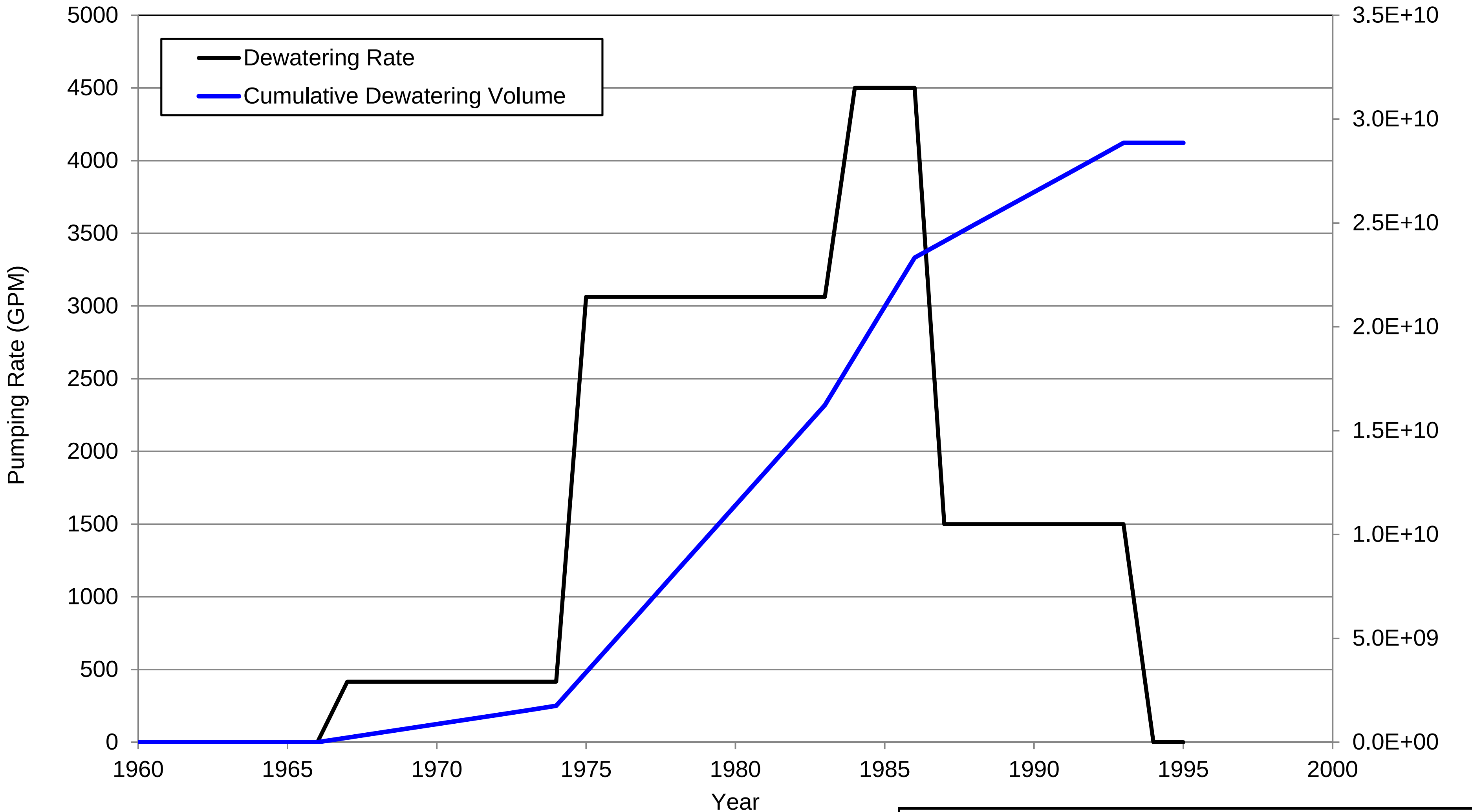

Simulated Dewatering Rates and Cumulative Volume for Gulf Mt. Taylor Mine in the Westwater Aquifer

INTERA

Figure 4.15

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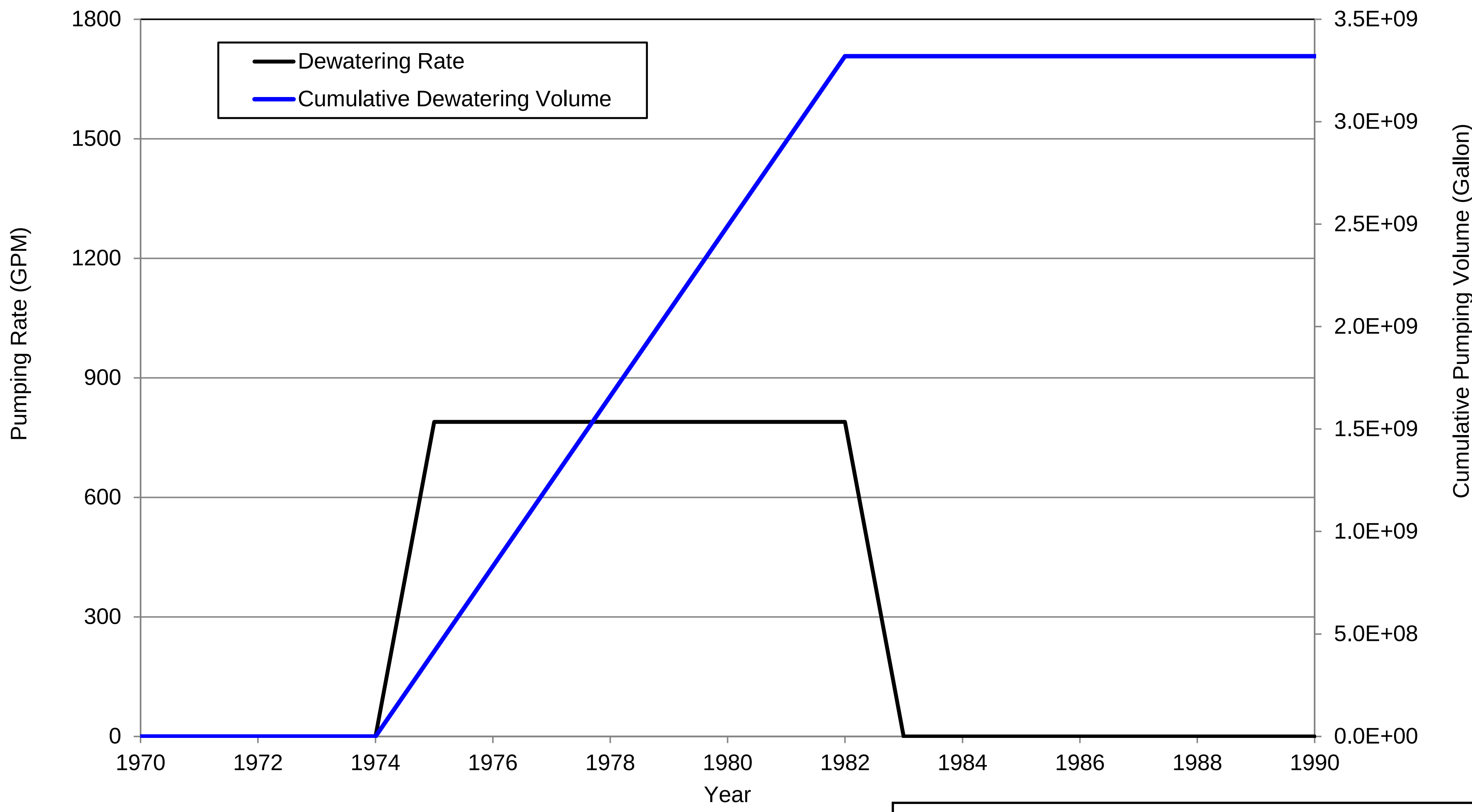


Simulated Dewatering Rates and Cumulative Volume for Johnny M Mine in the Westwater Aquifer

INTERA

Figure 4.16

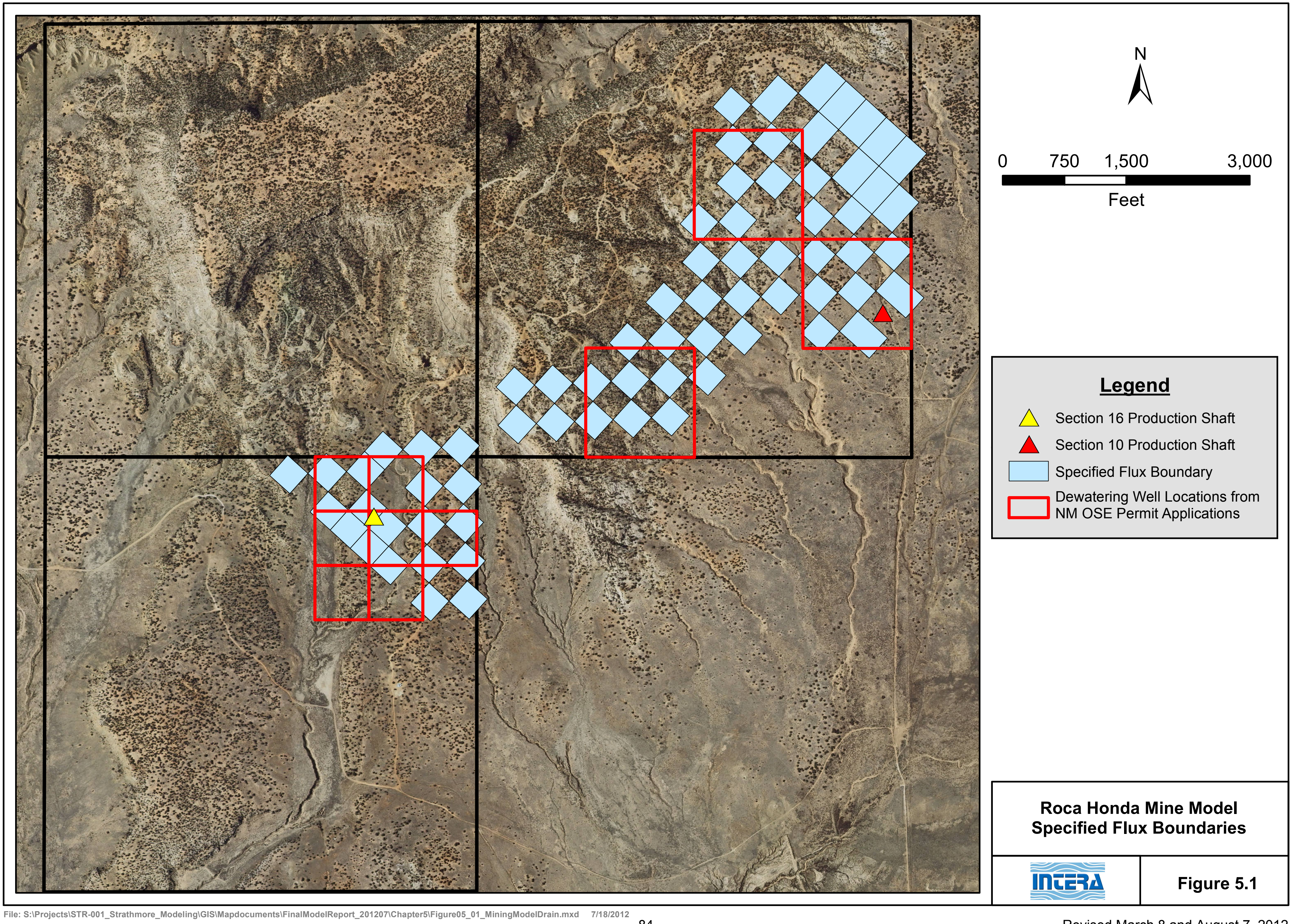
5.0 ROCA HONDA MINE DEWATERING IMPACT ASSESSMENT

Predictive simulations constructed from the calibrated transient 1930-2012 groundwater flow model were used to evaluate changes to groundwater levels in the aquifers affected by RHR's planned mine dewatering. The predictive simulations span the period from 2012, when mine construction is assumed to begin, to the year 2125, 100 years after the assumed end of mining.

This assessment determined changes in groundwater levels within the Gallup, Dakota, and Westwater aquifers, including locations near wells and springs, with respect to the four pumping scenarios (Section 3.1). The four pumping scenarios for predictive simulations are:

- Scenario 1 – Pumping occurs at the Crownpoint and City of Gallup public water supplies and dewatering occurs at the Lee Ranch coal mine. This scenario estimates the effects on future groundwater levels from current pumping stresses and represents current and future "baseline" conditions.
- Scenario 2 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine and dewatering at the Roca Honda mine. This scenario estimates the effects on future groundwater levels from current pumping stresses plus the Roca Honda mine dewatering.
- Scenario 3 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the RHR permit area. This scenario estimates the effects on future groundwater levels from large water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (Table 3.5).
- Scenario 4 – Pumping occurs at the Crownpoint and City of Gallup public water supplies with dewatering at the Lee Ranch coal mine, dewatering at the Roca Honda mine, and pumping of large water rights in the Gallup, Dakota, and Westwater aquifers in the vicinity of the RHR permit area. This scenario estimates the effects on future groundwater levels from RHR dewatering and pumping of large water rights in the Gallup, Dakota, and Westwater on file with the NM OSE (Table 3.5).

Dewatering at Roca Honda mine is conservatively assumed to follow the maximum time periods and maximum pumping rates shown in Table 1.1. Maximum dewatering rates were simulated as specified flux boundary conditions in all pumping scenarios that included RHR dewatering. Figure 5.1 illustrates the location of the specified flux boundary conditions.



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Changes to groundwater levels in pumping scenarios with RHR dewatering (Scenarios 2 and 4) are determined by calculating the differences in groundwater levels for the Gallup, Dakota, and Westwater aquifers over time between Scenarios 1 and 2 and between Scenarios 1 and 4. Changes in groundwater levels from large water rights are determined by calculating the differences in groundwater levels in each aquifer between Scenarios 1 and 3. These differences in groundwater levels are called "drawdown" in the subsections that follow below.

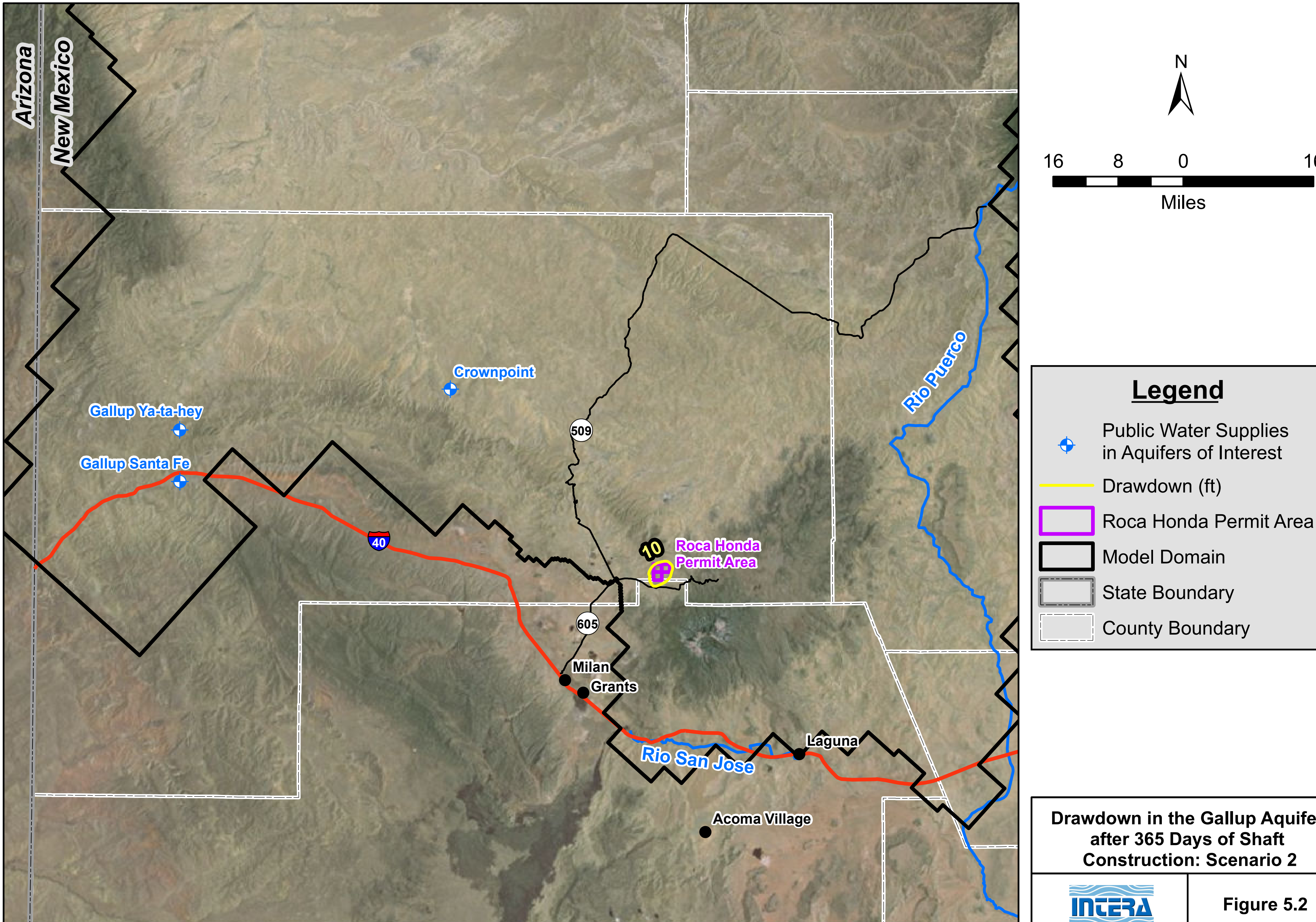
5.1 Changes in Groundwater Levels from Roca Honda Mining (Scenario 2)

Drawdown in the Westwater, Gallup, and Dakota aquifers from dewatering at the Roca Honda mine will not affect groundwater levels at the public water supplies for Crownpoint and Gallup or at the pueblos of Laguna and Acoma. Drawdown at all springs is predicted to be negligible except at the closest spring to the mine, Bridge Spring, where less than 0.7 foot of drawdown is predicted. Drawdown at wells in the vicinity of the RHR permit area is predicted to range between 27 and 258 feet at nine wells screened in the Westwater, three of which are used for mining, three for domestic supply, one for livestock, and two for which the uses are unknown. Drawdown is predicted to be 10 feet or more at one domestic well screened in the Dakota and three wells in the Gallup, of which one is used for exploration, one for livestock, and one has an unknown use. None of the six wells completed in the Mancos Shale is predicted to have drawdown greater than 3 feet. None of the 92 wells in model layer 5 (Point Lookout Sandstone, Menefee Formation, Crevasse Canyon Formation, and other upper Mesaverde Group units) is predicted to have drawdown of 10 feet or more. Drawdown values all decline once the maximum drawdown is reached. Impacts on the flow of all rivers are predicted to be negligible. The following subsections provide more detailed discussion of the impacts.

5.1.1 Aquifer Drawdown

Maximum drawdown in the Gallup aquifer occurs at the end of the first year of depressurization for construction of the RHR production shaft. Thereafter, water levels in the Gallup recover rapidly. After one year of depressurization pumping at a rate of 502 gpm (Table 1.1), drawdown in the Gallup reaches a maximum of 366 feet at the production shaft, but the 10-foot contour of drawdown does not extend beyond the RHR permit area (Figure 5.2). Drawdown in the Gallup equals 10 feet during the second year after the end of mining, and decreases to 1 foot 100 years after the end of mining (Figure 5.4).

Maximum drawdown in the Dakota aquifer occurs at the end of the second year of depressurization for the production shaft, but the 10-foot contour of drawdown is restricted within or near the RHR permit area (Figure 5.3) Drawdown in the Dakota near the production shaft reaches a maximum 1,655 feet after 730 days of pumping, and recovers more gradually than drawdown in the Gallup, recovering to approximately 14 feet at the end of the simulation period, 100 years after the end of RHR mining (Figure 5.4). As illustrated in Figures 5.2 and 5.3, the 10-foot drawdown contours in the Gallup and Dakota aquifers do not reach the public water supplies at Crownpoint or the City of Gallup, or the pueblos of Laguna or Acoma.



Drawdown in the Gallup Aquifer after 365 Days of Shaft Construction: Scenario 2

INTERA

Figure 5.2

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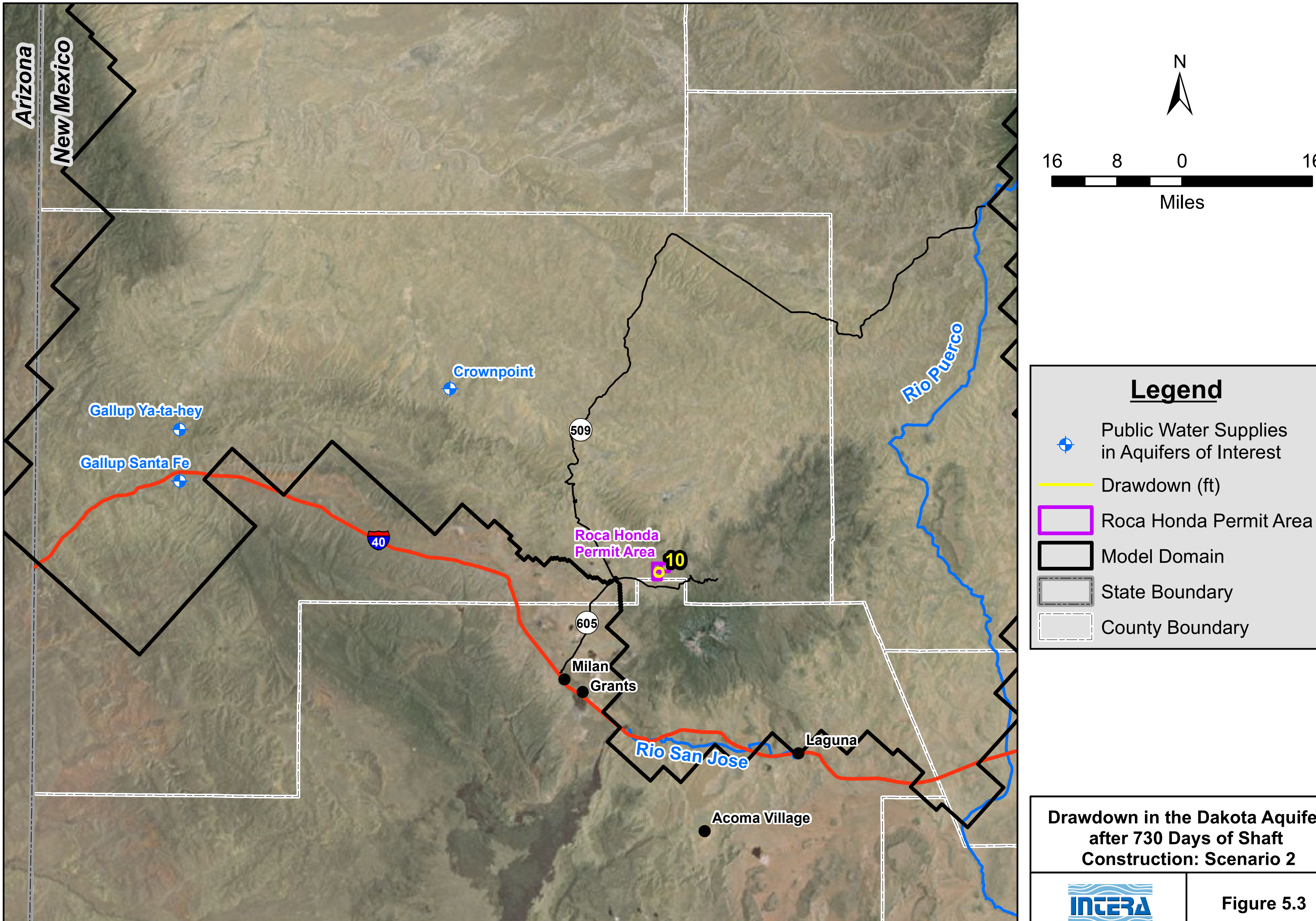

Drawdown in the Dakota Aquifer after 730 Days of Shaft Construction: Scenario 2

Figure 5.3

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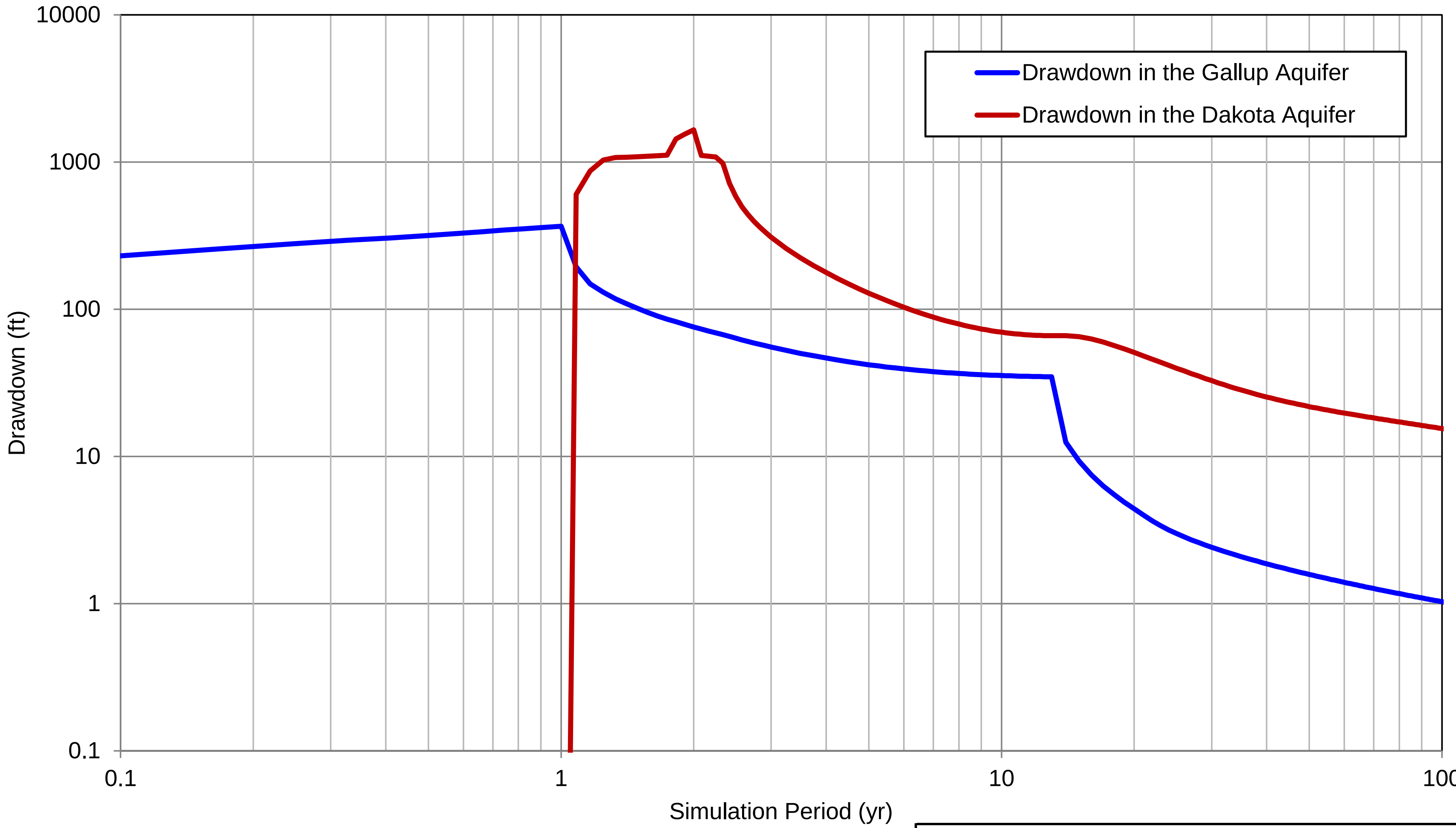

Drawdown at the RHR Production Shaft in the Gallup and Dakota Aquifers: Scenario 2

INTERA

Figure 5.4

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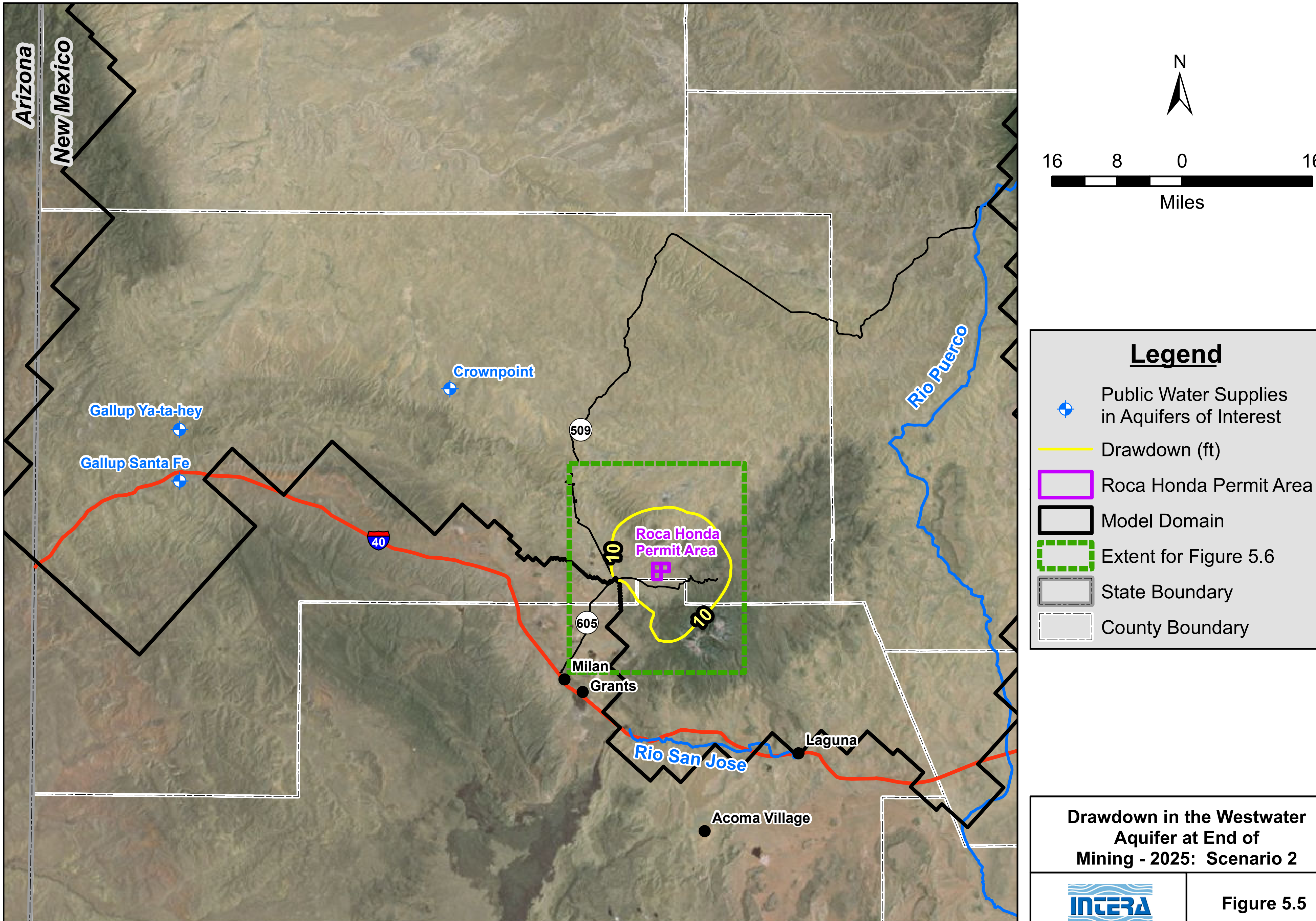
Figures 5.5 and 5.6 show the drawdown in the Westwater at the end of RHR mining. The maximum extent of the 10-foot contour of drawdown extends up to 7.5 miles beyond the permit area (Figure 5.5) by the end of mining. Within the permit area, drawdown reached a maximum of 1,806 feet (Figure 5.6). Figures 5.7 and 5.8 show the drawdown in the Westwater 40 years after the end of mining. The 10-foot contour of drawdown extends up to 15 miles from the permit area (Figure 5.7). By this time, the maximum drawdown within the permit area has decreased to 71 feet (Figure 5.8). Figures 5.9 and 5.10 show the drawdown in the Westwater 100 years after the end of mining. By this time, the maximum extent of the 10-foot drawdown contour is 16.6 miles from the permit area (Figure 5.9), but the largest drawdown is only 30 feet (Figure 5.10). The maximum extent of the 10-foot drawdown contour from the permit area begins to decrease after 100 years past the end of mining, so the farthest extent of groundwater impacts in the Westwater is 16.6 miles from the permit area, as shown in Figure 5.9.

The 10-foot drawdown contour in the Westwater will not reach the Acoma Pueblo, the Laguna Pueblo, the Crownpoint water supply, or the two City of Gallup well fields based on groundwater model simulations using the maximum dewatering rates. The model predicts that the groundwater level in the Westwater at the production shaft will recover to 90% of total drawdown 15 years after mining ends, and will recover to nearly 97% 100 years after mining ends. Public water supply wells located within the model domain included those for Crownpoint and the City of Gallup (Section 3.7).

Public water supply wells that pump from the Gallup and which are located within the model area include those for Crownpoint and the City of Gallup (Section 3.7). The public water supplies for the Village of Milan and the City of Grants are located within the model area, but their water supply wells are not constructed in hydrostratigraphic units that could be affected by RHR dewatering. In the vicinity of the RHR permit area, the San Mateo Community Water System pumps from the Point Lookout. Other wells pump water for mining purposes, domestic consumption, irrigation, or livestock watering from various hydrostratigraphic units, including the Gallup, Dakota, Westwater, and water-bearing sandstones located in younger hydrostratigraphic units (e.g., model layer 5).

Table D.1 in Appendix D shows the potential change in groundwater levels caused by RHR dewatering at each non-project well in the permit area vicinity as predicted by the model simulations. Monitoring and observation wells are not included. Groundwater levels are predicted to drop 12 feet at one domestic well in the Dakota, and between 27 and 53 feet at three wells in the Gallup, of which one is permitted for exploration, one is permitted for livestock, and the use of the remaining well is unknown. Maximum drawdown in the Gallup wells occurs in the first year of RHR dewatering and then declines thereafter. Maximum drawdown in the Dakota well occurs 61 years after the start of RHR dewatering and declines thereafter.



Drawdown in the Westwater Aquifer at End of Mining - 2025: Scenario 2

INTERA

Figure 5.5

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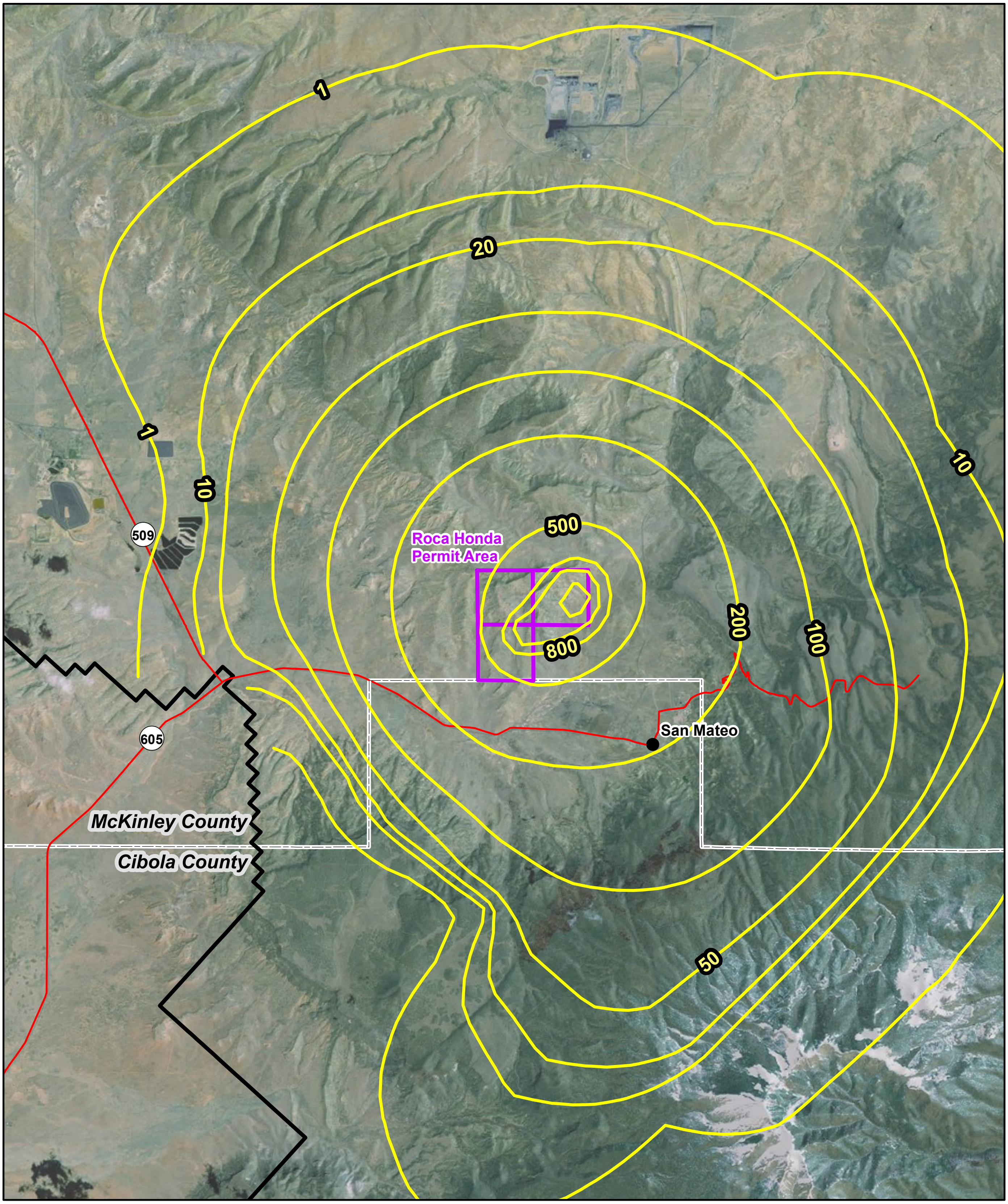

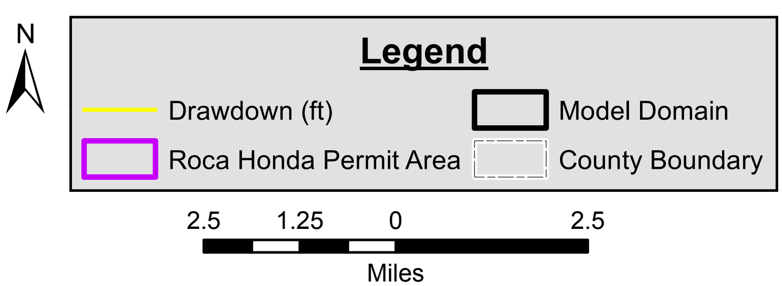

Maximum drawdown of 1,806 ft not shown.

Drawdown in the Westwater Aquifer at End of Mining - 2025: Scenario 2

INTERA

Figure 5.6

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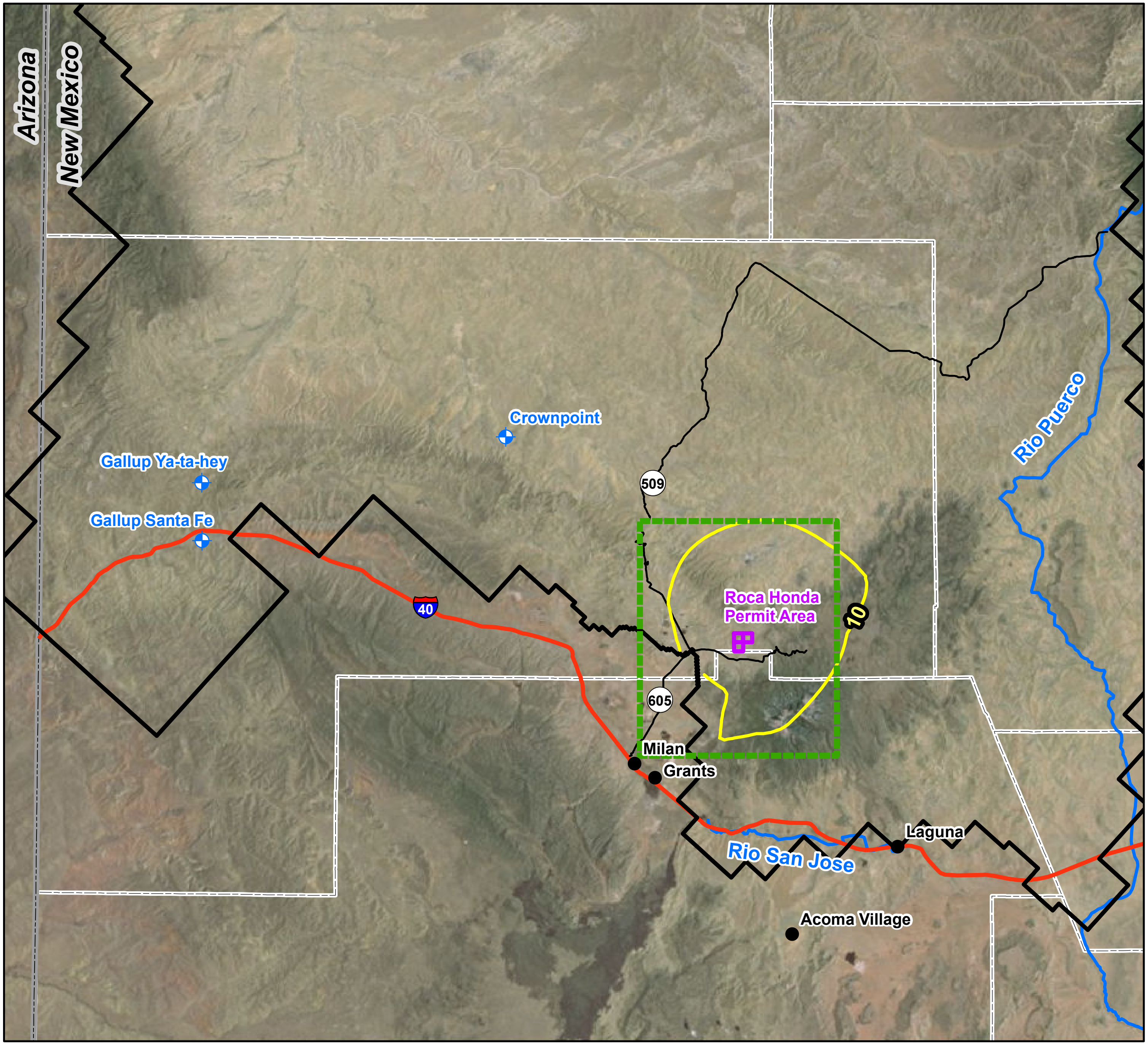

Drawdown in the Westwater Aquifer 40 Years After End of Mining - 2065: Scenario 2

INTERA

Figure 5.7

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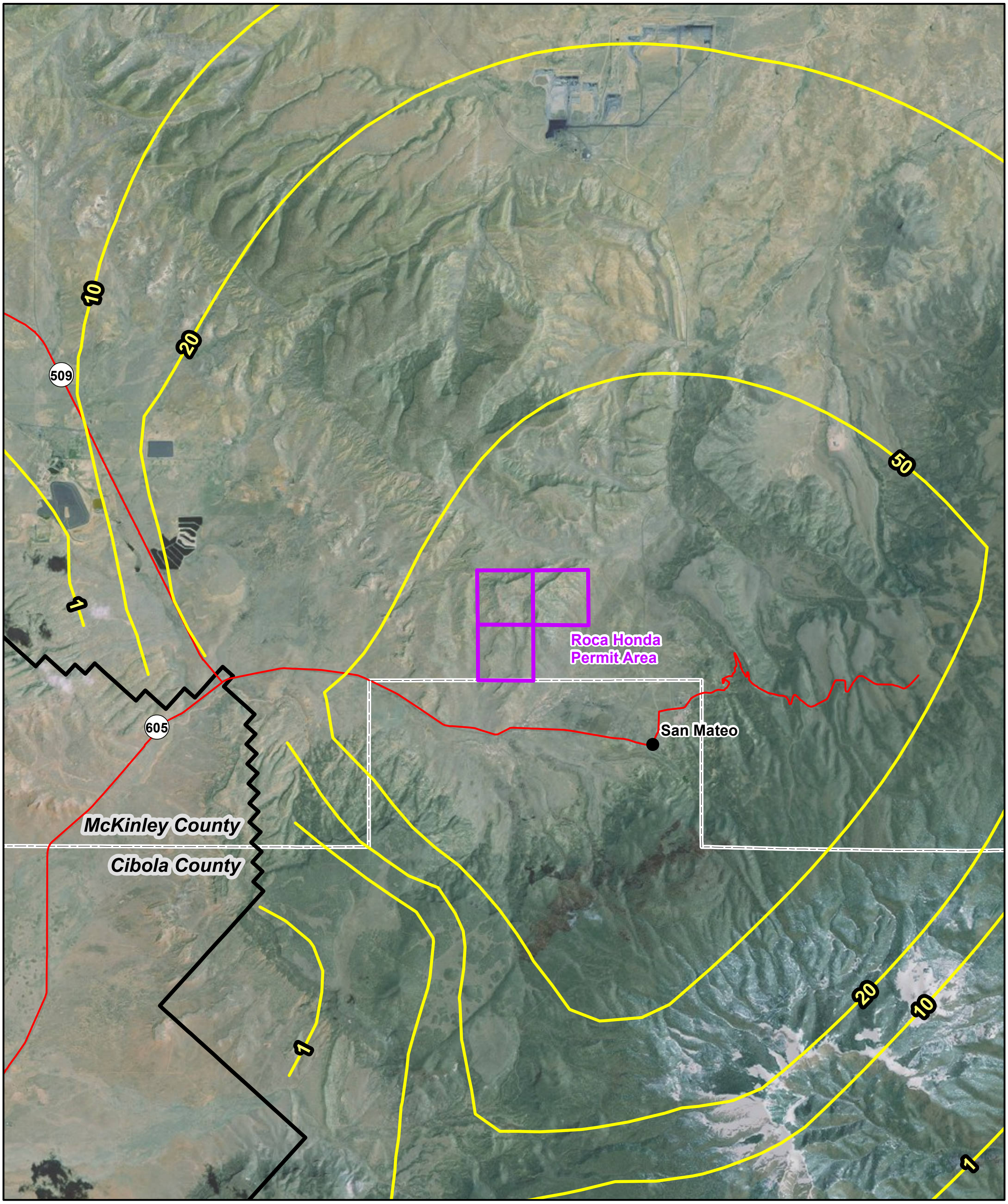


N

Legend

Drawdown (ft)
Roca Honda Permit Area
Model Domain
County Boundary

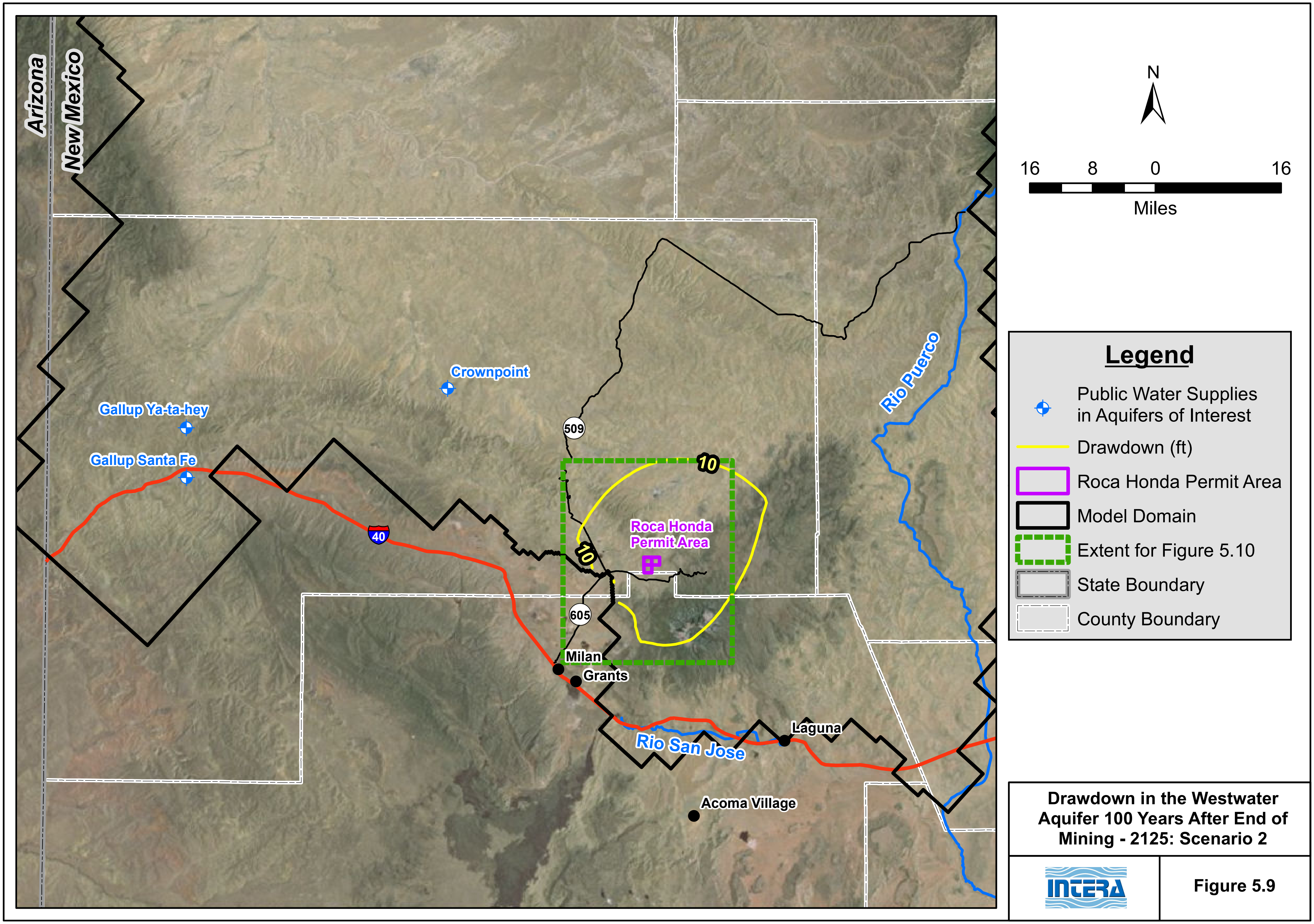
2.5 1.25 0 2.5
Miles

Maximum drawdown of 71 ft not shown.

Drawdown in the Westwater Aquifer 40 Years After End of Mining - 2065: Scenario 2

INTERA

Figure 5.8



Drawdown in the Westwater Aquifer 100 Years After End of Mining - 2125: Scenario 2

INTERA

Figure 5.9

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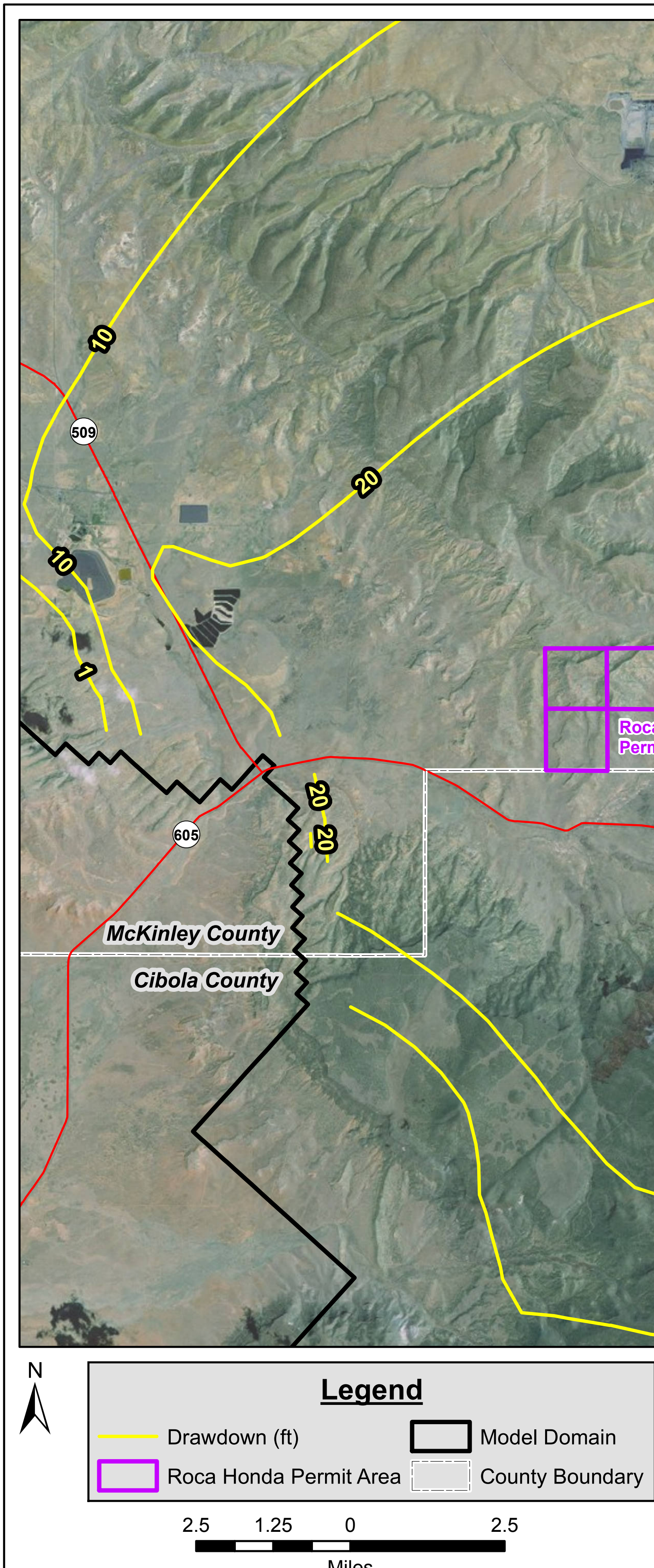

Maximum drawdown of 30 ft not shown.

Drawdown in the Westwater Aquifer 100 Years After End of Mining - 2125: Scenario 2

INTERA

Figure 5.10

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All six wells screened in the Mancos Shale (model layer 7) are predicted to have drawdown of less than 3 feet. Model layer 5, which represents the Point Lookout Sandstone and Menefee and Crevasse Canyon Formations, has 92 water supply wells, none of which is predicted to have drawdown greater than 10 feet, and only four wells are predicted to have drawdown greater than 5 feet. Nine Westwater wells are predicted to have drawdown that ranges between 27 and 258 feet, three of which are permitted for mining, three for domestic supply, one for livestock, and two for unknown uses. The three mining wells include two wells at the old Kerr-McGee Ambrosia Lake mine (now owned by BHP Billiton) and the mine shaft at the old Gulf Mt. Taylor (now Rio Grande Resources) mine. Maximum drawdown occurs at these wells between 14 and 29 years after the start of RHR dewatering and then declines.

5.1.2 Impacts at Springs and Rivers

Table 5.1 shows the predicted changes in groundwater levels at 23 springs located on Mt. Taylor or in the vicinity of the RHR permit area that will potentially be caused by RHR dewatering. Maximum drawdown is predicted to be 0.1 inches (0.01 foot) or less at 22 of the 23 springs. Maximum drawdown is predicted to be 8.8 inches (0.73 foot) at Bridge Spring 113 years after the start of mine construction. Located on private property, Bridge Spring is the nearest spring to the permit area.

All but a small portion of the 3 to 6 cubic feet per second (cfs) of water historically reported to be discharged at Horace Spring is supplied by the San Andres-Glorieta Formations, subsurface flow through the alluvium of the Rio San Jose valley, and subsurface flow from the basalts of the Malpais Valley (Risser, 1982; Baldwin and Anderholm, 1992; Frenzel, 1992; Wolf, 2010; Appendix E). A small fraction of water discharged at Horace Spring may be groundwater from the Cretaceous and Jurassic aquifers, e.g., Dakota, Westwater, and Zuni Sandstone aquifers (Baldwin and Anderholm, 1992; Frenzel, 1992; Appendix E). For the purpose of the impact assessment, approximately 3% of the 4 cfs present-day flow at Horace Spring was assumed to be derived from the Dakota and Westwater aquifers.

Dewatering at Roca Honda (Scenario 2) has a negligible effect (less than 0.3%) on the 3% of 4 cfs flow of groundwater from the Dakota and Westwater aquifers into Horace Spring. The groundwater discharge to Horace Spring is estimated to be 1,141 ac-ft during the first 13 years of Scenario 1 (no RHR dewatering). Under Scenario 2, the groundwater discharge to Horace Spring is estimated to be 1,144 ac-ft for the same time period, an apparent increase of 0.3% (0.23 ac-ft/yr on average). This small difference is not a real increase, but is caused by the way in which the output from the RHR model is processed by the post-processing model tool (Groundwater Vistas boundary reach report tool). This small difference, which is slightly more than a pint of water per minute, is not significant; that is, it is effectively zero. The error for measuring flow at Horace Spring is certain to be far larger.

Table 5.1
Potential Changes in Groundwater Levels at Springs

NAME	NAD 1983 UTM 13N		Model Row	Model Column	Model Layer	Spring Surface Elevation from DEM (ft)	Grid Maximum Elevation (ft)	Grid Minimum Elevation (ft)	Surface Geology	Elevation Difference Between Spring and Formation Top (ft)			Scenario 2[1] Maximum Drawdown (ft)	Scenario 3[2] Maximum Drawdown (ft)	Scenario 4[3] Maximum Drawdown (ft)
	Easting (m)	Northing (m)								Gallup	Dakota	Westwater			
Azabache, Ojo	287137	3944068	26	105	2	6398	7276	6292	Kmf	1011	2307	2730	0.00	0.00	0.01
Bridge Spring	255994	3913748	75	102	2	7043	7053	7037	Kmf	211	1429	1790	0.73	32.87	33.90
Burro Springs	268041	3934954	28	70	1	6563	6660	6499	Kmf	1118	2262	2682	0.00	0.01	0.00
Cerro Spring	266570	3925896	30	99	2	6844	6931	6601	Kmf	1345	2686	3101	0.00	0.00	0.00
Chamisa Losa Spring	298065	3935212	26	110	1	6518	8028	6122	Kmm	118	238	693	0.00	0.00	0.00
Dado Spring, El	271825	3933069	28	88	2	6597	6692	6535	Kmf	1118	2539	2975	0.00	0.01	0.01
Doctor Spring	268481	3933463	28	74	1	6603	6791	6574	Kmf	1137	2314	2734	0.00	0.00	0.00
Fort Miguel Ruins Spring	266081	3921652	31	105	1	7098	7460	6961	Kmf	1585	2901	3322	0.00	0.12	0.14
Jose Manuel Spring	305193	3889614	29	115	1	5823	6597	5600	Jsr	48	52	431	0.01	0.00	0.01
Marquez, Ojo	287501	3911593	29	111	1	7351	8503	6610	Kph	443	3385	3826	0.01	0.02	0.01
Montoya Spring	272974	3940595	27	70	1	6434	6745	6368	Kph	987	2320	2740	0.00	0.00	0.00
Ojo de las Yuges	273918	3930117	28	105	1	6739	7319	6702	Kmf	1252	2710	3146	0.01	0.02	0.00
Padre, Ojo del	304915	3935029	25	111	1	5878	7237	5728	Kml	329	862	1322	0.00	0.00	0.00
Pena Springs	267041	3936245	28	66	1	6545	6650	6519	Kmf	1136	2235	2655	0.01	0.00	0.01
Redondo, Ojo	266717	3933478	28	71	1	6596	6672	6509	Kmf	1146	2297	2717	0.01	0.01	0.01
Salazar Spring	269379	3935012	28	73	1	6595	6745	6558	Kmf	1134	2302	2722	0.01	0.01	0.01
San Jose Atarque Spring	258621	3891998	126	130	1	7578	8057	7454	Kmm	128	1428	1678	0.00	0.00	0.00
San Lucas Spring	262675	3924611	31	82	1	6901	7352	6899	Kmf	1146	2218	2638	0.01	0.01	0.01
San Ysidro Spring	263308	3932334	29	66	1	6646	6781	6604	Kmf	1153	2193	2613	0.04	0.04	0.04
Sap Hole Spring	264857	3922178	31	104	1	6923	7086	6902	Kmf	1389	2717	3138	0.00	0.00	0.00
Tecolote Springs, Ojo	284488	3903926	31	111	2	7793	8523	7099	Kpl	521	3047	3496	0.02	0.01	0.01
Unnamed Spring	262226	3892263	131	130	1	6935	7290	6397	Kcc	37	785	1035	0.01	0.00	0.01
Yeguas, Ojo de las	273918	3930086	28	105	1	6745	7319	6702	Kmf	1258	2716	3152	0.01	0.02	0.00

[1] Maximum drawdown for Scenario 2 equals the difference between the Scenario 2 groundwater level and the Scenario 1 groundwater level for the same location and time.
[2] Maximum drawdown for Scenario 3 equals the difference between the Scenario 3 groundwater level and the Scenario 1 groundwater level for the same location and time.
[3] Maximum drawdown for Scenario 4 equals the difference between the Scenario 4 groundwater level and the Scenario 1 groundwater level for the same location and time.

Dewatering at Roca Honda will have negligible changes in groundwater flow to rivers. The change in net groundwater flow into the river cells from Scenario 2 relative to Scenario 1 is much less than 1% during the 13-year mining period and the subsequent recovery period for the Rio San Jose, Rio Puerco, and San Juan River. The estimated change is less than 2% (37 ac-ft over 13 years) at the Puerco River during the mining period and less than 1% (12 ac-ft over 100 years) thereafter. Groundwater discharge to the Rio San Jose is estimated to have a net gain of 2 ac-ft over the first 13 years (0.07% of net discharge) and a net loss of 44 ac-ft (0.21% of net discharge) over the last 100 years of the simulation under Scenario 2 compared to Scenario 1. Similarly, groundwater discharge to the San Juan River is estimated to show a negligibly small net gain of 91 ac-ft (0.05% of net discharge) during the first 13 years and 162 ac-ft (0.01% of net discharge) during the last 100 years. Net groundwater discharge to the Rio Puerco is estimated to be a negligibly small loss of 51 ac-ft (0.17%) during the first 13 years and 93 ac-ft (0.04% of net discharge) during the last 100 years of the simulation. These estimates of changes in groundwater discharge to the rivers were made using the Groundwater Vistas boundary reach report tool. As with Horace Spring, the estimated differences are sufficiently small to be considered effectively zero. The estimated changes are smaller than the uncertainty surrounding any measurement of groundwater flow into the rivers.

RHR model estimates of the net groundwater flow to rivers reveal only small changes over the simulation periods. For example, net groundwater flow into the San Juan River during the 13-year mining period is estimated to be 165,241 and 165,332 ac-ft under Scenarios 1 and 2, respectively. These estimates yield an apparent negligibly small increase in groundwater discharge to the San Juan River under Scenario 2 compared to Scenario 1. This total discharge over the 13-year period equates to an average net groundwater flow rate into the river of roughly 35 ac-ft/day. When plotted for each model time step, the net groundwater discharge into the San Juan River is roughly 35 ac-ft/day and it varies by approximately ±1 ac-ft/day over the same 13-year period. During the 100-year recovery period, the net groundwater flow into the San Juan River for each model time step remains at roughly 35 ac-ft/day, and the variability in that groundwater flow rate is less than ±1 ac-ft/day. This demonstrates that the model simulations show an appropriately small level of variability in net groundwater flow into the San Juan River for each model time step, and confirms that the model is a valid tool for estimating impacts to the rivers.

5.1.3 Water Balance

Examination of the water balance for each of the three aquifers of interest reveals that the removal of water to dewater the Roca Honda mine is balanced by changes in storage and leakage from the adjacent aquitards. The water balance for each aquifer was calculated using the USGS ZONEBUDGET (Harbaugh, 1990; Harbaugh, 2008) tool to extract the fluxes between different zones (aquifers and aquitards) and boundary conditions. ZONEBUDGET reads the model output file that contains the flows between adjacent model cells for each time step. The USGS ZONEBUDGET tool only works with flux rates, not cumulative fluxes, so it is sensitive to the frequency with which results are written to the output files. Table 5.2a compares the water balances for Scenarios 1 and 2 in the Westwater aquifer for the 13-year mining period and the subsequent 100 years. Tables 5.2b and 5.2c provide similar comparisons for the Dakota and Gallup aquifers, respectively.

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 1,580 ac-ft larger than that for Scenario 1 (Table 5.2a). The amount of water stored in the Westwater aquifer decreased by 60,540 ac-ft under Scenario 2, and the 15,165 ac-ft increase in aquifer storage that would have occurred as water levels rebounded from historical pumping did not occur. The 79,000 ac-ft of RHR dewatering in the Westwater over 13 years was balanced by the following estimated fluxes:

- 60,540 ac-ft (76.6%) loss in groundwater stored in the Westwater aquifer.
- 15,165 ac-ft (19.2%) loss in groundwater that would have been added to storage in the Westwater aquifer as water levels rebounded from historical pumping.
- 30 ac-ft (0.04%) estimated to be reduced discharge to rivers.
- 1,600 ac-ft (2.0%) of increased leakage from the Brushy Basin aquitard.

The majority of water removed from the Westwater by RHR dewatering is from storage with approximately 2% coming from increased leakage from the Brushy Basin aquitard and an effectively zero (0.04%) percentage coming from groundwater discharge to rivers.

The small amount of water removed from the Dakota and Gallup aquifers is balanced by a change in storage and small changes in the groundwater fluxes to and from the adjacent aquitards. Table 5.2b demonstrates that the estimated 232 ac-ft removed from the Dakota for RHR dewatering is balanced by an 805 ac-ft net increase in flow to the adjacent aquitards, and an 89 ac-ft increase in discharge to rivers. Similarly, water removed from the Gallup aquifer is balanced by a change in storage and small changes in leakage from adjacent aquitards (Table 5.2c).

The water balance for the entire model domain shows the relative contributions of each flow component (Table 5.2d). This water balance is taken from the MODFLOW-SURFACT output listing and provides the most accurate water balance of the different methods used. Net groundwater discharge to rivers is the largest outflow component, followed by discharge to ephemeral drainages, whereas recharge and mountain-front recharge are essentially the same size (Table 5.2d). Mass balance errors are very small for both scenarios (Table 5.2d), reinforcing the validity of the RHR model.

Table 5.2a
Water Balance for Westwater Aquifer

	Water Balance Component (volume in AF) / Scenario		Mountain front recharge	Recharge at outcrops	Leakage from Brushy Basin aquitard	Water supply pumping	Discharge to ephemeral drainages	Discharge to rivers	Roca Honda dewatering	Total	Change in aquifer storage	Percent error
Mining Period: 2012 to 2025	Scenario 1	Inflow	16,006	128	46,649					62,782	15,165	1.3%
		Outflow				10,534	5,119	31,268	0	46,921		
	Scenario 2	Inflow	16,006	128	48,226					64,360	-60,635	-1.0%
		Outflow				10,534	5,119	31,238	79037	125,928		
Recovery Period: 2026 to 2125	Scenario 1	Inflow	72,432	983	345,253					418,668	55,743	0.4%
		Outflow				81,027	39,482	240,672	0	361,181		
	Scenario 2	Inflow	72,432	983	355,424					428,839	65,937	0.5%
		Outflow				81,027	39,481	240,571	0	361,079		

Table 5.2b
Water Balance for Dakota Aquifer

	Water Balance Component (volume in AF) / Scenario		Mountain front recharge	Recharge at outcrops	Leakage from Mancos Shale aquitard	Leakage from Brushy Basin aquitard	Water supply pumping	Discharge to ephemeral drainages	Discharge to rivers	Roca Honda dewatering	Total	Change in aquifer storage	Percent error
Mining Period: 2012 to 2025	Scenario 1	Inflow	81,383	40,744							122,127	-11,603	1.8%
		Outflow			83,055	45,415	212	0	2,724	0	131,405		
	Scenario 2	Inflow	81,383	40,744							122,127	-10,017	-0.3%
		Outflow			83,052	46,223	212	0	2,813	232	132,532		
Recovery Period: 2026 to 2125	Scenario 1	Inflow	626,023	313,416							939,439	-59,607	0.0%
		Outflow			638,447	338,660	1,634	0	20,522	0	999,262		
	Scenario 2	Inflow	626,023	313,416							939,439	-68,758	0.0%
		Outflow			638,303	347,899	1,634	0	20,603	0	1,008,439		

Table 5.2c
Water Balance for Gallup Aquifer

	Water Balance Component (volume in AF) / Scenario		Mountain front recharge	Recharge at outcrops	Leakage from Mancos Shale aquitard	Leakage from Layer 5 aquitard	Water supply pumping	Discharge to ephemeral drainages	Discharge to rivers	Roca Honda dewatering	Total	Change in aquifer storage	Percent error
Mining Period: 2012 to 2025	Scenario 1	Inflow	16,720	25,267	10,765	33,635					86,386	-7,762	1.4%
		Outflow					48,022	13,891	30,960	0	92,873		
	Scenario 2	Inflow	16,720	25,267	10,768	34,666					87,421	-11,042	4.7%
		Outflow					48,022	13,923	30,902	1,390	94,237		
Recovery Period: 2026 to 2125	Scenario 1	Inflow	128,612	194,359	82,800	280,304					686,076	-32,861	0.5%
		Outflow					369,398	107,040	239,070	0	715,508		
	Scenario 2	Inflow	128,612	194,359	82,794	280,442					686,208	-32,928	0.5%
		Outflow					369,398	107,082	238,862	0	715,343		

Table 5.2d
Water Balance for Entire Domain

	Water Balance Component (volume in AF) / Scenario		Mountain front recharge	Recharge at outcrops	Water supply pumping	Discharge to ephemeral drainages	Discharge to rivers	Roca Honda dewatering	Total Net	Change in aquifer storage	Percent error
Mining Period: 2012 to 2025	Scenario 1	Inflow	1.789E+05	1.791E+05					3.58E+05	-3.18E+04	0.1%
		Outflow			6.024E+04	1.332E+05	1.960E+05	0.000E+00	3.89E+05		
	Scenario 2	Inflow	1.789E+05	1.791E+05					3.58E+05	-1.13E+05	0.2%
		Outflow			6.024E+04	1.331E+05	1.959E+05	8.066E+04	4.70E+05		
Recovery Period: 2026 to 2125	Scenario 1	Inflow	1.325E+06	1.378E+06					2.70E+06	-2.7873E+05	0.0%
		Outflow			4.634E+05	1.022E+06	1.4956E+06	0.00E+00	2.98E+06		
	Scenario 2	Inflow	1.325E+06	1.378E+06					2.70E+06	-2.7878E+05	0.0%
		Outflow			4.634E+05	1.022E+06	1.4952E+06	0.00E+00	2.98E+06		

5.1.4 Drawdown Sensitivity to Changes in Westwater Hydraulic Properties

Standard practice for groundwater modeling requires an analysis of the sensitivity of model results to the model inputs, such as hydraulic properties (Anderson and Woessner, 1992). Such a sensitivity analysis examines whether the model results, e.g., drawdown in the Westwater, change as key model parameters change, e.g., hydraulic conductivity or specific storage in the Westwater. Nearly all pumping for dewatering will occur in the Westwater, and the Westwater is simulated to have the largest drawdown values, so INTERA carried out additional simulations to investigate how changes in Westwater hydraulic properties affected the simulated 10-foot drawdown contours in the Westwater. Given that drawdown increases as hydraulic conductivity or specific storage decrease, some of the additional simulations examined whether the 10-foot drawdown contour changed significantly if values for Westwater hydraulic conductivity and specific storage were reduced. The last set of sensitivity simulations tested whether the very low hydraulic conductivity assumed for the Mt. Taylor core volcanics prevented drawdown from propagating towards the Acoma or Laguna Pueblos.

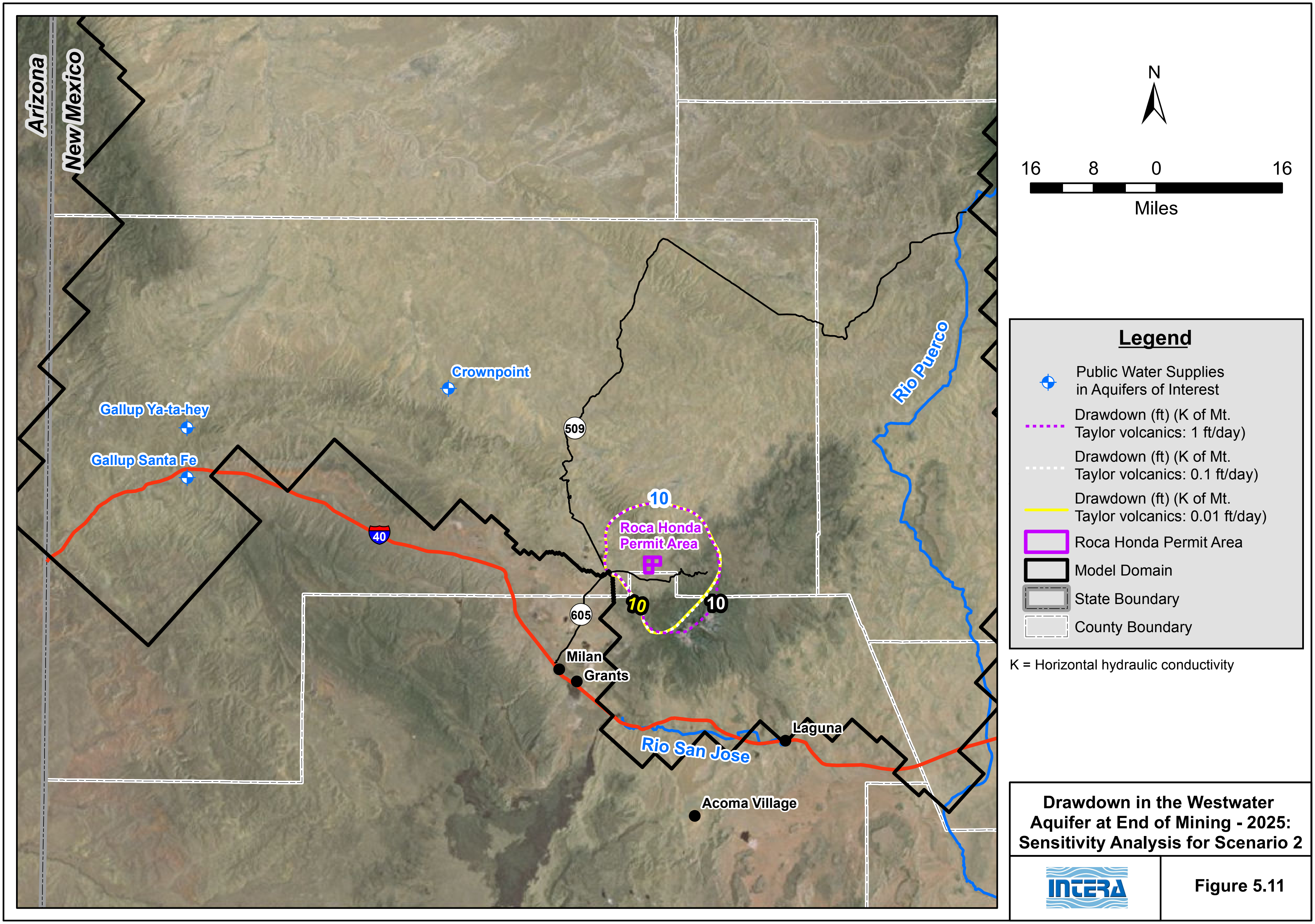
The first sensitivity simulations examined the changes in drawdown from decreasing the horizontal hydraulic conductivity and specific storage in part of the Westwater aquifer along the San Juan Basin's southern margin. This part of the Westwater aquifer is labeled as "Jmw2" in Table 4.1 and is depicted in Appendix B, Figure B.10. In the first simulation, the original horizontal hydraulic conductivity value of 1.25 f t/day was decreased to 0.125 f t/day. The simulation could not be completed because the reduced hydraulic conductivity could not support the maximum dewatering rate of 4,500 gpm. A follow-up simulation showed that reducing the hydraulic conductivity for the same part of the Westwater aquifer by 50% also could not be completed with the given maximum pumping rate. The other sensitivity simulations reduced the specific storage for the Westwater along the basin's southern margin to one-tenth and one-half of the original value (Table 3.2), but the simulations could not be completed because the reduced storage values also could not support the 4,500 gpm dewatering rate. If these lower specific storage or hydraulic conductivity values are indeed present in the Westwater, then the pumping rate that will be required to dewater the Roca Honda mine will be lower than the rates listed in Table 1.1.

The final sensitivity simulations increased and decreased the horizontal hydraulic conductivity (*K*) of the Mt. Taylor volcanic cores that were set within the Gallup, Dakota, and Westwater aquifers (Section 3.6). Represented as hydrostratigraphic units "Tnv" and "Tmv" in Table 4.1 and depicted in Appendix B, Figures B.6, B.8, and B.10, the Mt. Taylor volcanic cores were assigned a high hydraulic conductivity value of 0.1 ft/day in the original simulation (Section 3.6). The conservatism of this assumption was tested by running simulations in which the hydraulic conductivity of the volcanic cores was set to 1 and 10^{-2} ft/day, ten times larger and smaller, respectively, than the original *K* value.

Results at the end of RHR mining indicate that there is no significant difference between the locations of the 10-foot drawdown contours in the Westwater from the sensitivity simulations and the original simulation (Figure 5.11). The 10-foot drawdown contours for the two sensitivity simulations differ slightly from the original simulation 40 years after the end of mining: the contour for the 1 ft/day *K* value extends farther to the southeast than the other two simulations (Figure 5.12). At 100 years after mining, the 10-foot drawdown contours for the original simulation and for the two sensitivity simulations overlap to a large extent: the 10-foot contour for *K* = 1 ft/day extends only slightly farther to the southeast (Figure 5.13). Increasing or decreasing the *K* value for the original simulation by a factor of ten only results in a 10% increase and 8% decrease, respectively, in the area encompassed by the 10-foot drawdown contour. In all cases, the 10-foot drawdown contours in the Westwater for the sensitivity simulations will not reach the Acoma Pueblo, the Laguna Pueblo, the Crownpoint water supply, Horace Spring, any rivers, or the two City of Gallup well fields. Thus, the 10-foot drawdown contour is not sensitive to the tested changes in Westwater hydraulic properties.

5.1.5 Assessment of Predicted Impacts from RHR Dewatering

The impact analysis for the proposed Roca Honda mine over-estimates drawdowns because the analysis assumed that all dewatering occurred at the maximum permitted rate for the entire permitted duration. Actual dewatering will gradually increase in volume as mine workings are gradually developed away from the shaft and will not approach the maximum rate for a number of years. As a result, the specified flux boundary condition cells used in the RHR model to simulate this immediate maximum dewatering rate remove water from a much larger volume of Westwater aquifer than will actually need to be dewatered in order to mine. At the end of mining, this conservative approach causes an area of approximately 190,000,000 ft^2 to have drawdown of 500 ft or more, whereas the actual area of mine workings is only 1,230,000 ft^2, and the total volume of mine workings is estimated to be only 12,300,000 ft^3. The volume of water removed for dewatering is directly proportional to the area to be dewatered, so the volume of water estimated to be removed using the maximum permitted pumping rate is many times larger than the volume of water that will actually be removed from the Westwater during mining. For these reasons, the total volume of groundwater pumped during dewatering will likely be much less than has been simulated, and drawdowns will be commensurately less than those simulated by this impact analysis.



Drawdown in the Westwater Aquifer at End of Mining - 2025: Sensitivity Analysis for Scenario 2

INTERA

Figure 5.11

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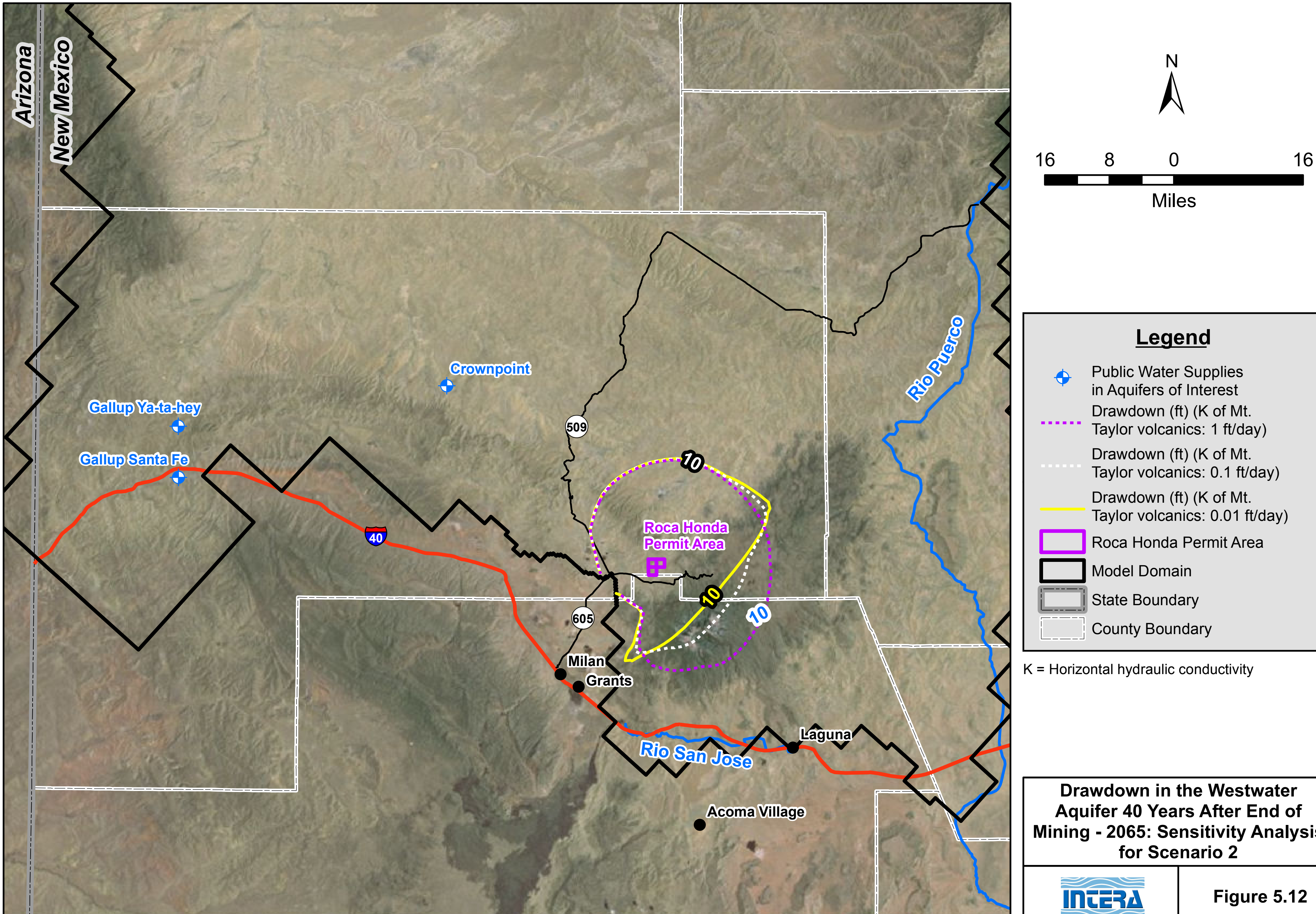

Drawdown in the Westwater Aquifer 40 Years After End of Mining - 2065: Sensitivity Analysis for Scenario 2

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Figure 5.12

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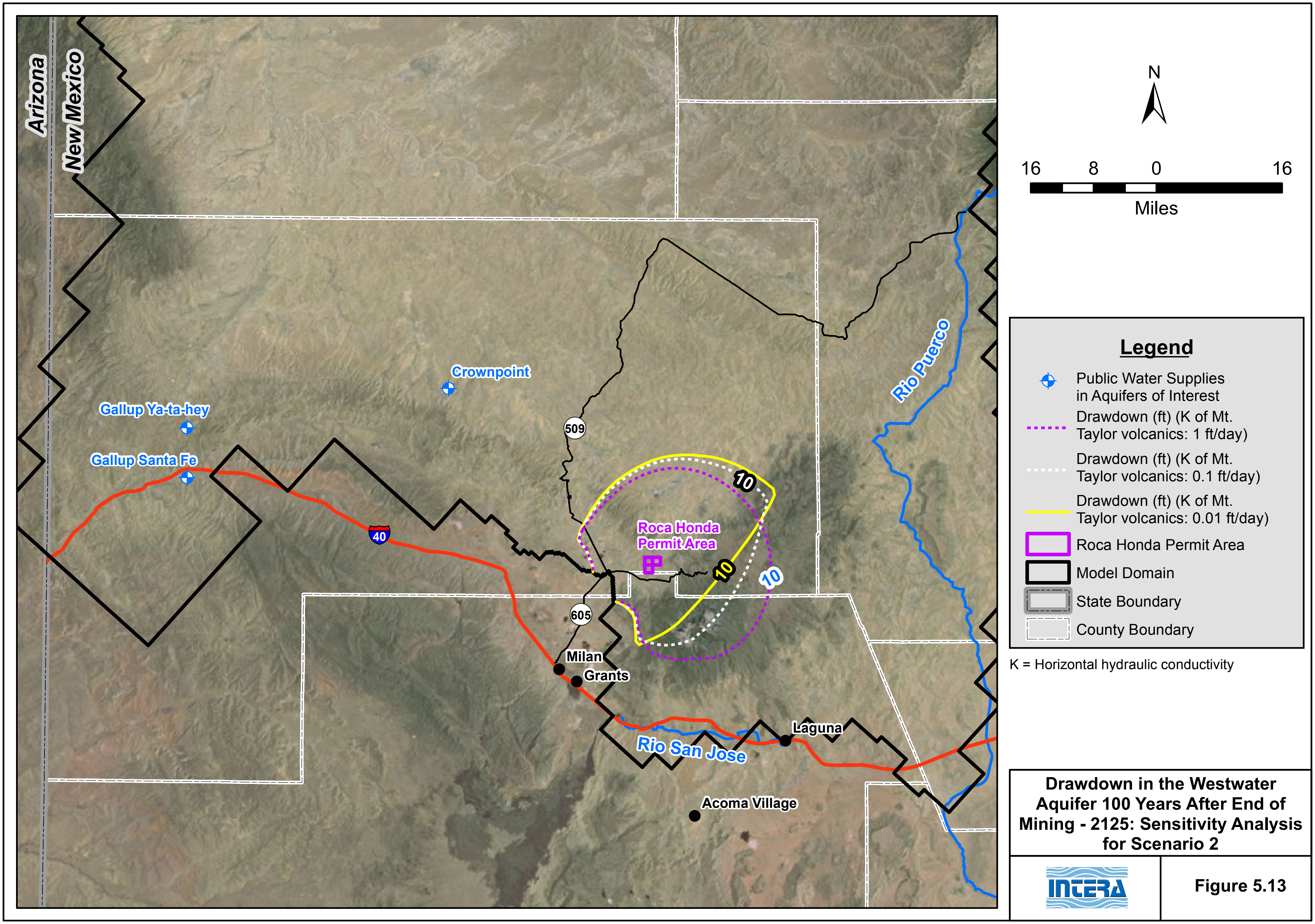

Drawdown in the Westwater Aquifer 100 Years After End of Mining - 2125: Sensitivity Analysis for Scenario 2

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Figure 5.13

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The simulated rates and total volume to be dewatered compare very well with data from historical uranium mining operations in the Westwater. The RHR dewatering volume over 13 years is estimated to be approximately 79,000 ac-ft. Approximately 76,000 ac-ft were pumped at the nearby Johnny M mine (Figure 4.16). At the Gulf Mt. Taylor mine, historical pumping rates reached 9,000 gpm and stabilized at about 4,500 gpm, the maximum RHR rate, and more than 660,000 ac-ft of water was pumped over 27 years (Figure 4.15). The total volume of water dewatered in the Ambrosia Lake district was roughly 1.4 million ac-ft during a 31-year period (Figure 4.13).

The RHR model estimates that the maximum water level decline during RHR dewatering will be 1.7 feet for wells screened in the Point Lookout Sandstone, which is part of model layer 5. Maximum drawdown under Scenario 2 is 0.5 feet at the San Mateo community water supply well, which is screened across the Point Lookout Sandstone and the Menefee Formation and is labeled B-428 in Appendix D, Table D.1. Maximum drawdown reaches 1.7 feet under Scenario 2 at public supply well B-428S (Appendix D, Table D.1). These results are consistent with the little that is known about water level declines in the area of the Mt. Taylor mine during historical dewatering. There is no historical evidence that historical dewatering of the Mt. Taylor mine affected water levels in local shallow domestic, stock, and water supply wells in the San Mateo area, all of which were completed in the Point Lookout Sandstone and the overlying Menefee Formation or alluvium. The potable water supply wells for both the Mt. Taylor mine and the community of San Mateo, completed in the Point Lookout Sandstone in the immediate vicinity of the mine, continued as viable water supply wells during the period of time the mine was dewatered, suggesting that any water level changes were not significant. Water level data available for Mt. Taylor mine monitor wells in the Point Lookout Sandstone indicate that water levels in this aquifer were affected minimally, if at all, by Mt. Taylor mine dewatering (NMED, Gulf Mineral Corporation Discharge Permit DP-61).

In summary, the RHR model overestimates the area and volume of the Westwater aquifer to be dewatered because the pumping rates employed are the maximum rates expected. Thus the model provides a conservative assessment of potential impacts from RHR dewatering. That is, the model over-estimates impacts. Simulated dewatering of the Westwater provides a good match to historical mine dewatering data for the same general area and geology. The predictive simulations show small variability in groundwater discharge to rivers and very good water balance errors (e.g., $\leq$1%). Sensitivity analyses revealed no significant changes in the maximum extent of the 10-foot drawdown contour even if the hydraulic conductivity value for the volcanic cores is assigned an unrealistically high value.

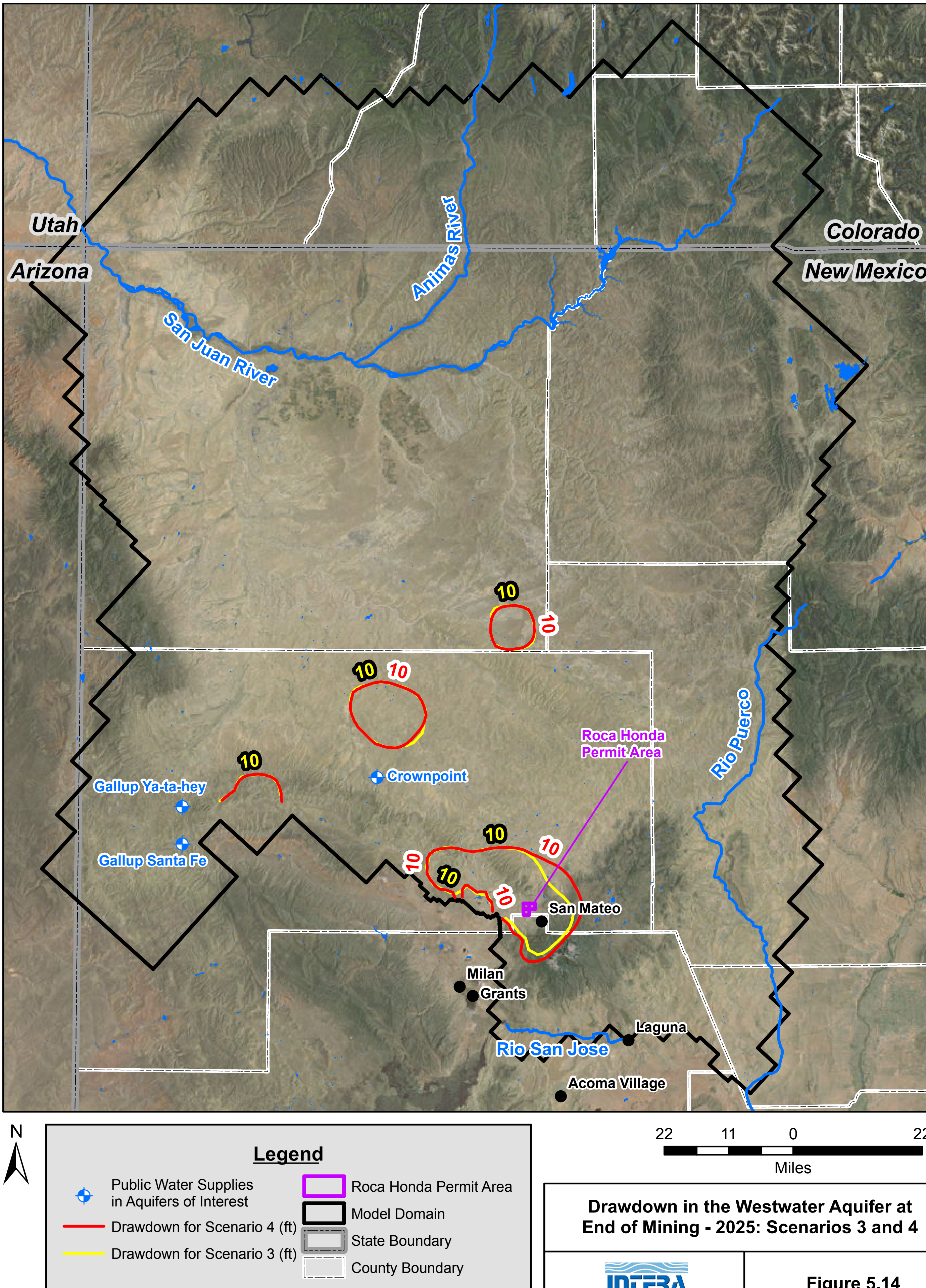
5.2 Changes in Groundwater Levels from Scenario 3

Scenario 3 estimates the changes in Westwater groundwater levels from pumping of large water rights in the Westwater, Gallup, and Dakota aquifers near the RHR permit area (Table 3.5) at rates equal to the permitted or declared diversion rates (see OSE WATERS) without any RHR dewatering. The purpose of Scenario 3 is to calculate water level declines caused by existing potential groundwater pumpers during the 113-year period that the RHR dewatering and recovery is projected to encompass (refer to Scenario 2). As described below, drawdown in the Westwater, Gallup, and Dakota aquifers from pumping of large water rights, **without any RHR dewatering**, will affect groundwater levels at the public water supplies for Crownpoint and probably for the City of Gallup, but not for the pueblos of Laguna and Acoma. The Scenario 3 simulation predicts that the pumping of large water rights at their maximum amount, exclusive of RHR dewatering, could cause a drawdown of 32.9 feet at Bridge Spring and a drawdown of 10 feet or more at nine wells screened in the Westwater, two wells screened in the Dakota, four wells screened in the Gallup, four wells screened in the Mancos Shale (model layer 7), and 82 wells screened in model layer 5 (Point Lookout Sandstone and Menefee and Crevasse Canyon Formations). Drawdown at these wells increases throughout the entire simulation period, reaching the maximum at the end.

5.2.1 Aquifer Drawdown

The Scenario 3 simulation predicts that drawdown of 10 feet or greater will occur within the Westwater in four areas 13 years after the start of the simulation (Figure 5.14). As is shown on Figure 5.14, these areas include the Ambrosia Lake area, the southeast corner of San Juan County, the Crownpoint vicinity, and east of Gallup. After 40 more years, one of these areas with 10 feet or more of drawdown will have expanded to affect the Crownpoint public water supply (Figure 5.15). After 60 more years, the areas with 10 feet or more of drawdown will have all merged so that the Crownpoint public water supply and the Yah-ta-hey well field for the City of Gallup would be affected (Figure 5.16). The 10-foot drawdown contour is not predicted to reach the pueblos of Laguna and Acoma. Scenario 3 pumping, absent any RHR pumping, would cause a water level decline in the Westwater aquifer of roughly 50 feet within the RHR permit area 13 years after the start of the simulation without any pumping by RHR.

Table D.1 in Appendix D shows the drawdown at each well in the permit area vicinity predicted for Scenario 3. Many more wells are predicted to have impacts than those impacted by RHR dewatering alone (Scenario 2), especially wells simulated in model layers 5 and 7. Drawdown is predicted to range between 30 and 455 feet at four wells in the Gallup (one livestock well, two exploration wells, and one well with unknown use) and between 19 and 54 feet in two wells in the Dakota (one domestic well and one well with unknown use).



Drawdown in the Westwater Aquifer at End of Mining - 2025: Scenarios 3 and 4

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Figure 5.14

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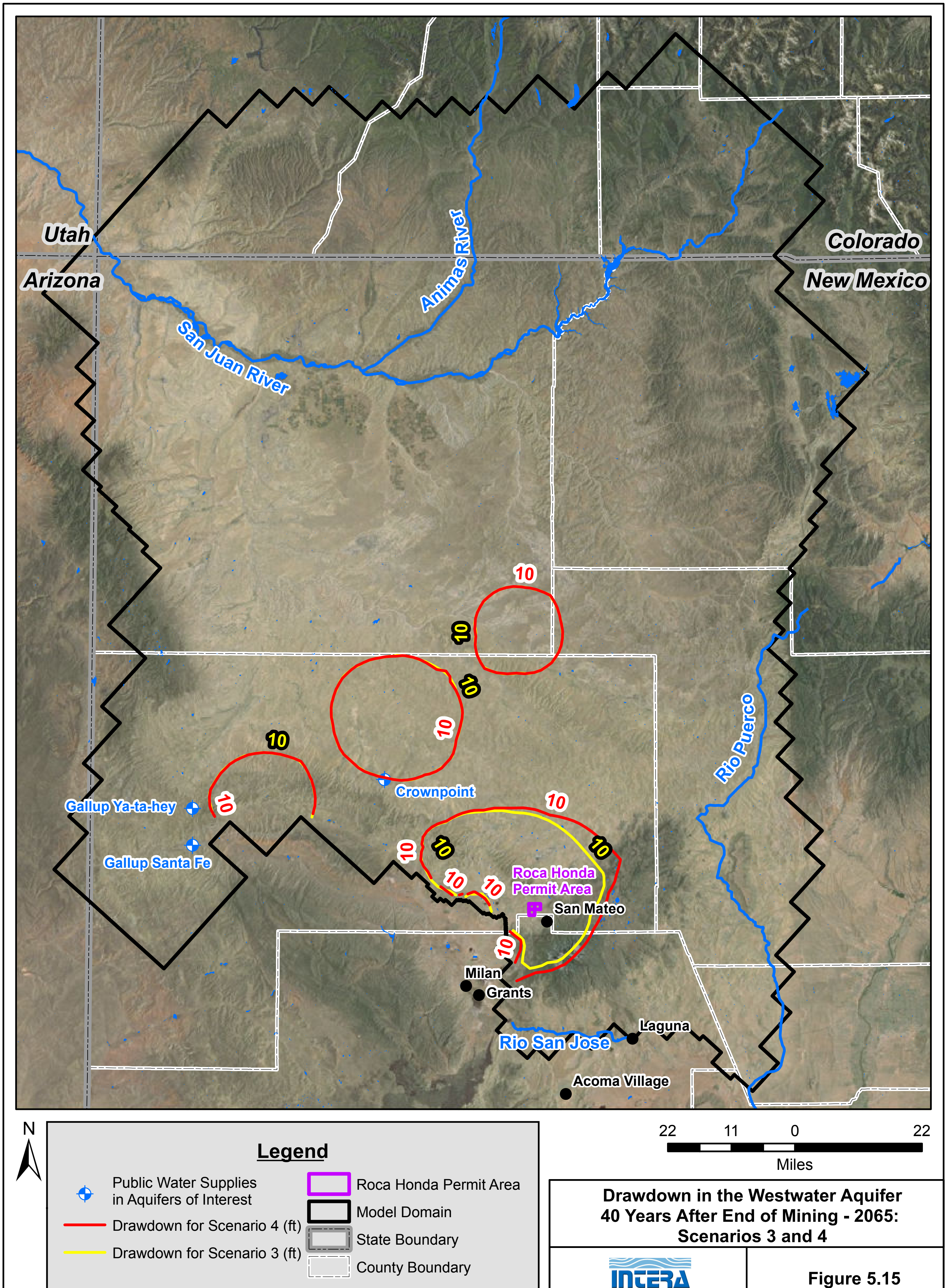

Drawdown in the Westwater Aquifer 40 Years After End of Mining - 2065: Scenarios 3 and 4

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Figure 5.15

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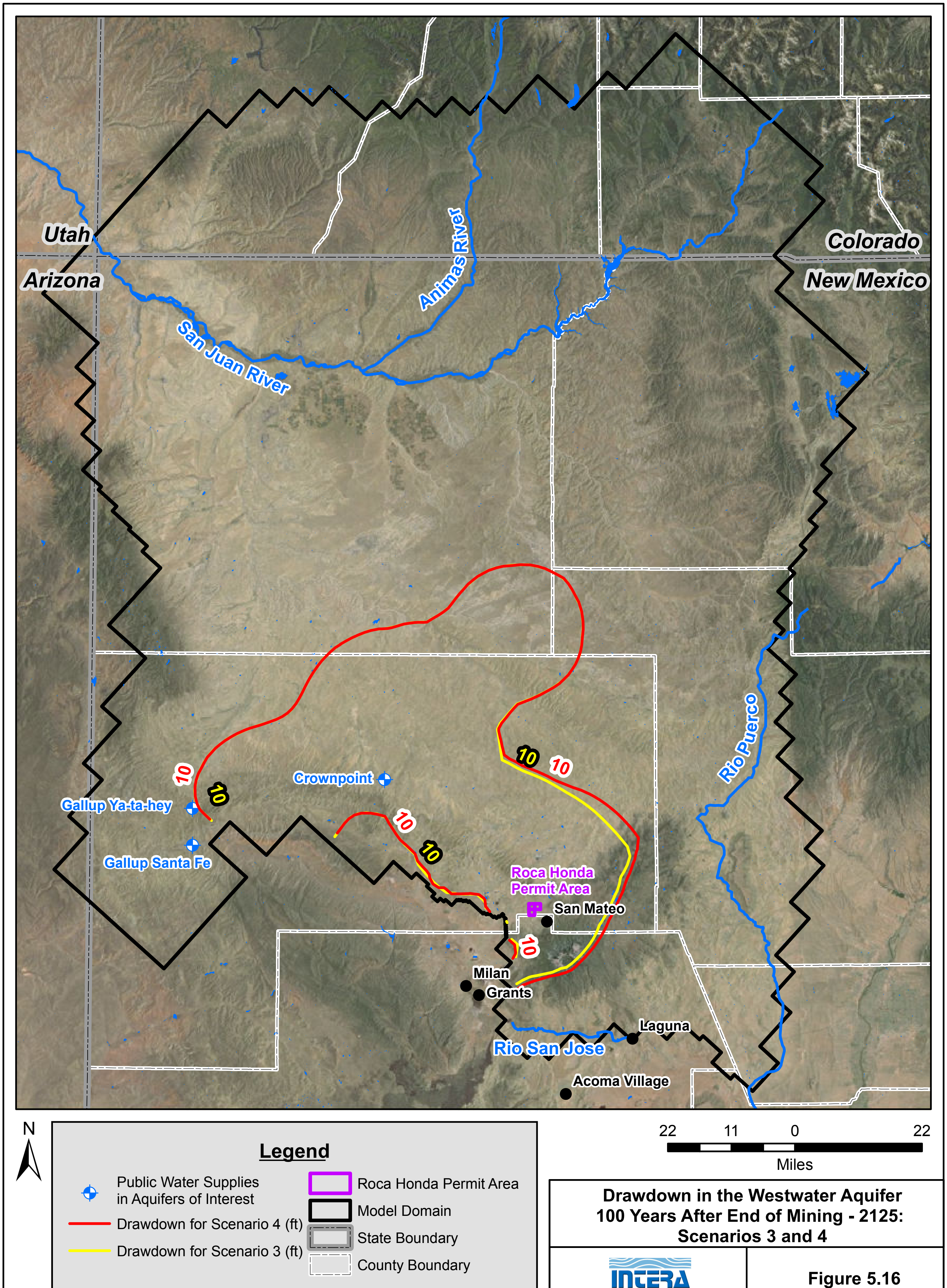

Drawdown in the Westwater Aquifer 100 Years After End of Mining - 2125: Scenarios 3 and 4

INTERA

Figure 5.16

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Revised March 8 and August 7, 2012

Drawdown is predicted to range between 63 and 423 feet at nine wells in the Westwater: three are permitted for mining, three for domestic supply, one for livestock, and two for unknown uses. Four of the six wells screened in the Mancos Shale (model layer 7) are predicted to have drawdown greater than 10 feet. Of the 92 wells screened in model layer 5, which includes the Menefee and Crevasse Canyon Formations and Point Lookout Sandstone, 82 wells are predicted to have drawdown greater than 10 feet. Drawdown at all wells continues to increase throughout the entire simulation period, reaching a maximum at the end of the simulation.

5.2.2 Drawdown at Springs

The column labeled "Scenario 3" in Table 5.1 shows the predicted changes in groundwater levels for Scenario 3 at 23 springs located in the vicinity of the RHR permit area. The drawdown is predicted to be 0.2 feet or less at 22 of the 23 springs. Drawdown is predicted to be 32.9 feet at Bridge Spring 113 years after the start of the simulation. Scenario 3 pumping is predicted to cause a negligibly small decrease in groundwater discharge to Horace Spring of 0.11 ac-ft per year (0.07 gallons per minute).

5.3 Changes in Groundwater Levels from Scenario 4

Scenario 4 estimates the changes in Westwater groundwater levels from pumping of large water rights in the Westwater, Gallup, and Dakota aquifers at rates equal to the permitted or declared diversion rates (NM OSE WATERS) **including RHR dewatering**. Drawdown in the Westwater, Gallup, and Dakota aquifers under this scenario would affect groundwater levels at the public water supplies for Crownpoint and probably the City of Gallup, but not at the pueblos of Laguna and Acoma. A drawdown of 33.9 feet is predicted for Bridge Spring. Drawdown at wells in the vicinity of the RHR permit area is predicted to equal or exceed 10 feet or more at nine wells screened in the Westwater, two wells screened in the Dakota, four wells in the Gallup, four wells screened in the Mancos Shale (model layer 7), and 82 wells screened in model layer 5 (Point Lookout Sandstone and Menefee and Crevasse Canyon Formations). Adding the RHR dewatering, which is the only difference between Scenarios 3 and 4, does not increase the number of wells or springs affected compared to Scenario 3 (Section 5.2). Drawdown at all wells would continue to increase throughout the entire simulation period, reaching the maximum at the end of the simulation.

5.3.1 Aquifer Drawdown

Changes in groundwater levels for Scenario 4 are very similar to those predicted for Scenario 3. Drawdown varies between 63 and 423 feet in the Westwater under Scenario 4 and would be localized in four areas at the end of mining (Figure 5.14). One of these areas with 10 feet or more of drawdown would expand to affect the Crownpoint public water supply 40 years after the end of mining (Figure 5.15). By the end of the simulation, 100 years after the end of mining, the areas with 10 feet or more of drawdown would all merge so that the Crownpoint public water supply would still be affected and the Yah-ta-hey well field for the City of Gallup would also be affected (Figure 5.16). The 10-foot drawdown contour does not reach the pueblos of Laguna and Acoma.

Table D.1 in Appendix D shows that the predicted drawdown at each well in the permit area vicinity for Scenario 4 is the same as or greater than the drawdown for Scenario 3 and much greater than the drawdown predicted for Scenario 2 (RHR dewatering only). Drawdown is predicted to range between 32 and 454 feet at four wells in the Gallup (one livestock well, two exploration wells, and one well with unknown use) and range between 24 and 55 feet at the two wells in the Dakota (one domestic well and one well with unknown use). Drawdown is predicted to range between 67 and 450 feet for nine wells in the Westwater: three are permitted for mining, three for domestic supply, one for livestock, and two for unknown uses. Four of the six wells screened in the Mancos Shale (model layer 7) are predicted to have drawdown greater than 10 feet. Of the 92 wells screened in model layer 5, which includes the Menefee and Crevasse Canyon Formations and Point Lookout Sandstone, 82 are predicted to have drawdown greater than 10 feet. Drawdown at all wells continues to increase throughout the entire simulation period, reaching the maximum at the end of the simulation.

5.3.2 Drawdown at Springs

The column labeled "Scenario 4" in Table 5.1 shows the predicted changes in groundwater levels for Scenario 4 at 23 springs located in the vicinity of the RHR permit area. The drawdown is predicted to be 0.2 foot or less at 22 of the 23 springs. Drawdown is predicted to be 33.9 feet at Bridge Spring 113 years after the start of the simulation. Scenario 4 pumping will cause a negligibly small decrease in groundwater discharge to Horace Spring of 0.05 ac-ft/yr (0.3 gpm).

5.4 Comparison of JSAI and RHR Models

As described in Section 3.2, the consulting firm of John Shomaker & Associates, Inc. (JSAI) constructed a groundwater flow model to assess the impacts from long-term pumping at the Gulf Mt. Taylor mine for the City of Gallup (Carpenter and Shomaker, 1998). The original 1998 model predicted that pumping at a rate of 4,000 ac-ft/yr between 2001 and 2033 at the Gulf Mt. Taylor mine would cause a 72 ac-ft/yr depletion of groundwater discharge to the Rio San Jose (Carpenter and Shomaker, 1998). Results from the JSAI model were later cited in DBSAI (2001) and the model was recently revised (Miller, 2012a). In contrast, the RHR model estimated that depletion of the Rio San Jose from 13 years of RHR dewatering in Scenario 2 would be a net gain of 0.15 ac-ft/yr during the first 13 years or net depletion of 0.36 ac-ft/yr over the entire 113-year simulation period (Section 5.1.2). The JSAI model was therefore evaluated to determine the reasons for this difference in potential impact to the Rio San Jose from dewatering of the Westwater, and to evaluate which of the two models better represented the hydrogeologic system. INTERA reviewed the model report and MODFLOW input and output files made available by a third party (Miller, 2012b); however, the review did not include actually running the JSAI model because one or more input files were missing. The review compared selected model input parameters to the report description and also compared how the JSAI and RHR models represented groundwater flow between the three aquifers of interest and the Rio San Jose.

The model review revealed that the JSAI model employs an overly simplified and overly conservative representation of the groundwater flow between the aquifers of interest and the Rio San Jose. The JSAI model represents the Morrison Formation as a single model layer. The RHR model represents the Brushy Basin aquitard and Westwater aquifer as separate layers. The JSAI model omits a critical hydrogeologic feature for the Westwater aquifer, the Brushy Basin aquitard, an extensive, thick, aquitard. The Brushy Basin aquitard maintained a 100- to 200-foot head difference between the Dakota and Westwater units in predevelopment conditions (Ganus, 1980; Bostick, 1985). The JSAI model could not simulate this head difference because it allows unrealistically high vertical leakance between the two units. In contrast, the RHR model does simulate this head difference in the predevelopment model. Consequently, the JSAI model is not an adequate tool for assessing dewatering impacts from mining in the Westwater.

The JSAI model incorrectly represents the hydrogeology near Horace Spring and the Rio San Jose. By not capturing the synclinal fold and omitting the Brushy Basin aquitard, it severely overestimates the hydraulic connection between the Westwater and the Rio San Jose by creating an 11-mile-long contact between the Morrison Formation and the Rio San Jose. This contact is more than 100 times longer than the contact in the RHR model, which is based on detailed geologic mapping (Appendix E). By omitting the Brushy Basin aquitard, allowing unrealistically high vertical flux out of the Morrison Formation, and forcing an unrealistically long contact between the Morrison Formation and the Rio San Jose, the JSAI model causes unrealistically high groundwater flux rates between the Rio San Jose and the underlying aquifer. The JSAI model cannot therefore provide a defensible assessment of impacts to the overlying aquifers, wells, springs, and rivers from dewatering in the Westwater.

According to Carpenter and Shomaker (1998), the JSAI model predicted a depletion of groundwater discharge (72 ac-ft) to the Rio San Jose after more than 30 years of pumping and with the unrealistically large vertical leakance between the Morrison and Dakota layers. The

RHR model sets the vertical leakance to a more realistic value and reduces the length of the Rio San Jose that is in contact with the Morrison to a more realistic value. These appropriate changes, which are based in the actual hydrogeology of the area, reveal a negligible impact on groundwater discharge to the Rio San Jose caused by RHR dewatering of the Westwater aquifer.

Compared to the JSAI model, the RHR model is a more accurate tool for assessing potential impacts from dewatering in the Westwater for the following reasons:

- The RHR model captures more of the structure and important hydrogeologic features of the San Juan Basin, including geology specific to the RHR site. The JSAI model is a series of six flat layers. That is, the model cells in each layer do not change in elevation and do not incorporate relevant geologic structure. Only the transmissivity, vertical leakance, and storage properties are specified for each cell. The RHR model represents the complex geology in the southern San Juan Basin by specifying top and bottom elevations and by specifying horizontal and vertical hydraulic conductivities and storage properties for each cell. Therefore, the RHR model more realistically captures groundwater flow and exchange with surface water bodies along the basin margin than the JSAI model.
- The JSAI model does not account for the Brushy Basin as an aquitard between the Morrison and the Dakota. A single model layer is used to represent the entire Morrison Formation in the JSAI model, whereas the RHR model sets the Westwater Canyon Member (aquifer) of the Morrison in one layer and the Brushy Basin Member (aquitard) in another layer. The Brushy Basin has a thickness of 200 to 300 feet in the area which includes the McCartys Syncline, Horace Spring, and the Rio San Jose, whereas the Westwater is only 20 to 50 feet thick and could even be absent on the eastern limb of the McCartys Syncline (Appendix E). If the Westwater is in contact with the Rio San Jose on the eastern limb of the syncline, that contact is limited to 150 to 200 feet (Appendix E). In contrast, the JSAI model has the Rio San Jose in direct contact with the Morrison Formation for 11 miles. Therefore, the RHR model provides a much more realistic representation of groundwater flow in and out of the Morrison Formation than the JSAI model, which overly simplifies the hydrogeology of the Morrison Formation and so generates overly conservative estimates of river depletion.
- By ignoring the thick Brushy Basin aquitard, the JSAI model allows groundwater flow rates between the Morrison and the Dakota that are 100 times larger than are realistic given the geology. The JSAI model specifies a vertical leakance of 10^{-6} ft^{-1} between the Morrison layer and the overlying Dakota layer. The RHR model estimated a vertical leakance between the Westwater layer and the Brushy Basin layer of approximately 10^{-8} ft^{-1},

which is also the value of the vertical leakance between the Brushy Basin layer and the overlying Dakota layer. Thus, the RHR model provides a much more accurate and defensible characterization of the hydrogeologic features governing flow in and out of the Westwater than the JSAI model, which underestimates the effects of the Brushy Basin on groundwater leaving or entering the Westwater by a factor of 100.

- The JSAI model uses an overly conservative method to represent the Rio San Jose. The JSAI model represents the Rio San Jose as specified head boundary conditions in model cells in layers 3, 4, 5, and 6, which correspond to the Mancos Shale, Dakota Sandstone, Morrison Formation, and San Raphael Group in this area. These Rio San Jose model cells vary in size, but are generally on the order of 2 miles by 0.75 miles, all of which are much larger than the dimensions of the river itself. The RHR model represents the Rio San Jose (and Horace Spring – see Section 3.2) using the head-dependent river boundary condition in model cells located in model layers 7 (Mancos), 8 (Dakota), 9 (Brushy Basin), and 10 (Westwater). RHR cells that represent the Rio San Jose have sizes that are generally similar to those in the JSAI model, but some are larger and others are smaller (Appendix A), but the boundary conditions for the river in these cells employ a conductance that is defined by the river dimensions and riverbed hydraulic conductivity in each cell. Kernodle (1996) used river boundary conditions to represent the perennial river reaches in the San Juan Basin. Frenzel (1992) represented the Rio San Jose using the stream boundary condition, which is a head-dependent boundary condition that is defined by a conductance in similar fashion to the river boundary condition. The conductance used in stream and river boundary conditions acts to restrict the flow between the aquifer and the surface water body to the dimensions of the surface water body. Specified head boundary condition cells do not have a conductance, therefore the groundwater-surface water exchange occurs over the entire cross-sectional area of the cell. River boundary conditions can and have been used in a superposition model by setting the river stage to zero (e.g., Leake, et al. 2008). Consequently, the JSAI model overestimates the amount of water that flows from the aquifer to the Rio San Jose because it assumes that the Rio San Jose is nearly two miles wide. In contrast, the RHR model represents the Rio San Jose as a river boundary condition that uses an estimated river width of 25 feet and so simulates the groundwater-surface water exchange in a much more realistic fashion than the JSAI model because 25 feet is much closer to the actual width of the Rio San Jose than the roughly 10,000-foot width used in the JSAI model.
- Calibration of the JSAI model was limited to attempting to match predicted to observed groundwater levels in seven wells in the Westwater over the period from 1978 to 1990.

As described in Section 4, calibration of the RHR model used 69 wells in the predevelopment steady-state simulation and 27 different wells in all three aquifers of interest in the transient calibration simulation, which spanned the time period from 1930 to 2012. As a result, the RHR model is calibrated over a much larger area and much longer time period than the JSAI model. Consequently, the RHR model has been tested more completely than the JSAI model and so is more likely to capture the observed behavior in these aquifers.

- No water balance is provided for the JSAI model, nor are mass balance errors even mentioned in the report. Without the water balance, it is not possible to compare the JSAI model against previous models or the RHR model to see if the overall flows in and out of the San Juan Basin are commensurate with these other models. Without the mass balance errors, it is not possible to determine the credibility of the groundwater level predictions or the river depletion estimates. Without all the input files, it was not possible to determine whether the JSAI model had unrealistically large oscillations in fluxes between aquifer cells and the constant head boundary condition cells used to represent the rivers. In contrast, the water balance for the RHR model fell in the middle of previously published water balances for the San Juan Basin (Section 4.12). Moreover, the mass balance errors for the RHR model are very small (Section 4.1.2 and INTERA, 2012). Therefore, the RHR model is a much more credible and defensible tool for assessing impacts from dewatering in the Westwater.
- The JSAI model was designed for a different purpose and used to answer different questions than the RHR model. Drawdown impacts simulated by the JSAI model do not represent dewatering at the Roca Honda mine for a period of 13 years; instead they represent dewatering of the Gulf Mt. Taylor mine, located closer to the Rio San Jose and Horace Spring than to the Roca Honda mine, for a period of 30 years. Thus, drawdown and stream depletions for the JSAI model should be larger than those for the RHR model because the JSAI stresses operated closer to the spring and river and nearly twice as long as the RHR stresses.

6.0 SUMMARY AND CONCLUSIONS

INTERA has constructed a three-dimensional groundwater flow model of the San Juan Basin for the purpose of estimating impacts on groundwater and surface water resources potentially caused by the construction and dewatering of the proposed Roca Honda underground mine. The RHR model is the most reliable and accurate tool constructed to date for estimating the effects of proposed RHR dewatering. The following summary and conclusions are discussed and defended in detail in this report:

1. The proposed Roca Honda mine will pump water from the Gallup Sandstone and the Westwater Member of the Morrison Formation during a 13-year period of mine construction and operation, and from the Dakota Sandstone during construction only for one year. All dewatering will cease with the end of mining. Almost all of the water pumped will come from the Westwater aquifer.

2. The RHR groundwater flow model is based on a reasonable and appropriate conceptualization of the San Juan Basin hydrogeology, incorporates the most recently available hydrogeologic information and data, and has been calibrated to both pre-development and transient conditions using a larger number of calibration measurements than any other model of the San Juan Basin.

3. The RHR model significantly improves on previously constructed numerical models of the San Juan Basin. The RHR model incorporates more appropriate boundary conditions than those used in earlier models and uses new data on aquifer parameters and stratigraphy in the vicinity of the RHR permit area.

4. The RHR model is the best available tool for assessing the impacts of RHR mine dewatering on Horace Spring and the Rio San Jose. The RHR model represents the Rio San Jose and Horace Spring better than any other available numerical model because it is the only available model to accurately represent the hydrogeology of the spring, the Rio San Jose, the Brushy Basin aquitard, the Westwater, and the McCartys Syncline.

5. The RHR model captures more of the key hydrogeologic features for assessing impacts from dewatering the Westwater near Ambrosia Lake, including the Brushy Basin aquitard and mountain-front recharge around Mt. Taylor, than any previous model of the San Juan Basin. Model calibration included many more wells, especially wells in and around the Ambrosia Lake district, and a far longer calibration period than any other available model. The RHR model assesses impacts on all the rivers of concern, including the perennial reaches of the Rio San Jose and the springs in the vicinity of Mt. Taylor, including Horace Spring.

6. The calibrated RHR model is the best available tool for predicting potential groundwater level changes from proposed dewatering at the Roca Honda mine. The following key results support this conclusion:

   a. Calibration statistics revealed an NRMSE of 4.45%, indicating a very good steady-state calibration (Spitz and Moreno, 1996).

   b. The model mass balance error was very low, -0.21%, and a mass balance error of less than 1% indicates a good mass balance calibration (Anderson and Woessner, 1992).

   c. Water balance calculations for the calibrated predevelopment model showed that the total groundwater inflow was within the range of previous models and closely agreed with an estimate from Lyford and Stone (1978).

   d. Comparison of simulated groundwater levels over time for the Dakota and Westwater aquifers from the transient numerical flow model with groundwater levels measured at over two dozen locations demonstrated a good fit between simulated and actual groundwater data. Comparison of contours of simulated groundwater levels in 1979, 2007, and 2010 demonstrate a close match to observed groundwater levels. Simulated dewatering rates and volumes for Ambrosia Lake mines, the Church Rock mine area, the Gulf Mt. Taylor mine, and the Johnny M mine all closely matched rates from Stone et al. (1983) and other data sources.

7. The RHR model predicts that RHR dewatering will have negligible impacts on groundwater levels at the public water supplies for Crownpoint and Gallup, or at the pueblos of Laguna and Acoma.

8. The RHR model predicts that there will be essentially no impact on springs, including Horace Spring, from RHR dewatering. The RHR model predicts that dewatering will have no impact on groundwater discharge to rivers with perennial reaches, including the San Juan River, Rio San Jose, Puerco River, and Rio Puerco.

9. The maximum extent from the RHR permit area boundary of the 10-foot drawdown contour in the Westwater aquifer is predicted to be 17 miles. Drawdown at wells in the vicinity of the RHR permit area is predicted to range from 27 to 258 feet or more at nine wells screened in the Westwater, three of which are used for mining, three for domestic supply, one for livestock, and two for unknown uses. Drawdown is predicted to be 12 feet or more at one domestic well screened in the Dakota, and to range between 27 and 54 feet at three wells in the Gallup, of which one is permitted for exploration, one for livestock, and one with an unknown use.

10. The water removed by RHR mine dewatering will be balanced by changes in aquifer storage and leakage from the various aquitard units: Brushy Basin, Mancos Shale, and upper Mesaverde group sediments.

11. The pumping rates and pumping time periods used to represent RHR dewatering Scenario 2 result in larger drawdowns than those that are expected to actually occur. Actual RHR dewatering rates will increase gradually over the 13-year mining period, resulting in a smaller volume of water removed, whereas the model simulations assumed the maximum anticipated dewatering rate for the maximum permitted time. This modeling approach results in a larger area than is necessary for mining to be dewatered. Realistically, actual pumping rates over time will be significantly less.

12. The water level declines that will occur from maximum pumping of existing water rights will greatly exceed impacts from proposed RHR dewatering. The RHR model predicts that maximum pumping of all water rights in the vicinity of the permit area together with RHR mine dewatering (Scenario 4) will result in groundwater level drawdown of 10 feet or greater for Crownpoint and the City of Gallup water wells 40 years after the end of mining, but not the groundwater levels near the Acoma and Laguna Pueblos. Bridge Spring is predicted to have a water level decrease of 34 feet.

13. The RHR model predicted that proposed RHR dewatering will not adversely affect the water resources of the Village of Milan, Acoma Pueblo, Laguna Pueblo, the City of Grants, the community of San Mateo, the Crownpoint area, or the City of Gallup. RHR mine dewatering will not have any adverse impacts on area springs, including Horace Spring, or on perennial river reaches. The model predicts that RHR mine dewatering may cause water level declines between 0.5 and 1.7 feet at or near the end of mining in the area of the public water supply wells for the community of San Mateo, which pump from the Point Lookout Sandstone.

14. The public water supplies for the Village of Milan and the City of Grants will not be affected by RHR dewatering because they pump groundwater from aquifers that are stratigraphically much lower than the Westwater aquifer, and are separated from the Westwater aquifer by thick shale with low hydraulic conductivity.

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