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A Groundwater Model to Assess Water Resource Impacts at the Brenda Solar Energy Zone

Environmental Science Division

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by

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NOTATION

The following is a list of acronym, initials, symbols, and abbreviations (including units of measure) used in this document.

Acronyms, Initials, Symbols and Abbreviations

3-D	three-dimensional
ADWR	Arizona Department of Water Resources
BLM	Bureau of Land Management
b	aquifer saturated thickness
CAP	Central Arizona Project (a canal system)
CSP	concentrated solar power
DEM	Digital Elevation Model
DOE	U.S. Department of Energy
GIS	geographic information system
GMS	Groundwater Modeling System
K	hydraulic conductivity
MSL	mean sea level
NWIS	National Water Information System
PEIS	Programmatic Environmental Impact Statement
PEST	Parameter ESTimation
PV	photovoltaic
R	recharge
SEZ	Solar Energy Zone
Т	transmissivity
USGS	U.S. Geological Survey

Units of Measure

ac	acre
ac-ft/yr	acre-feet per year
d	day
ft	feet
in.	inch
km	kilometer
m	meter
m^2	square meter
m^3	cubic meter
mi	mile
mi ²	square mile
yr	year

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A GROUNDWATER MODEL TO ASSESS WATER RESOURCE IMPACTS AT THE BRENDA SOLAR ENERGY ZONE

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1 INTRODUCTION

The purpose of this study is to develop a groundwater flow model to examine the influence of potential groundwater withdrawal to support utility-scale solar energy development at the Brenda Solar Energy Zone (SEZ), as a part of the Bureau of Land Management's (BLM's) Solar Energy Program. The Brenda SEZ groundwater model (referred to as the Brenda SEZ Model or the model) is a numerical model developed using established software and hydrogeological principles that relies on publicly available geospatial, geologic, and hydrologic data. While the focus of the model is primarily on simulated drawdown effects caused by groundwater withdrawals, its construction is based on a detailed hydraulic "head" modeling approach, with true elevation control to provide a platform for more in-depth model is intended to be used by water managers and others only as a general indicator of groundwater elevations and potential drawdown. The model development consisted of three phases:

Phase 1 — Calibration to steady-state, pre-1940s conditions (before agricultural development began in the Ranegras Basin) to establish recharge and hydraulic conductivity values for the subsequent transient modeling;

Phase 2 — Development of a transient model to approximate the effect of agricultural water usage from the 1940s to present; and

Phase 3 — Development of transient model scenarios to assess the simulated impact of 20 years of groundwater withdrawals for various development scenarios, along with continued agricultural water use, in the Brenda SEZ.

This section of the report introduces BLM's solar energy program and briefly describes the Brenda SEZ. Section 2 describes the hydrologic setting and the input parameters used in the Brenda SEZ Model. Section 3 addresses the development of the model, and Section 4 provides a summary of results for simulated impacts associated with full buildout of the Brenda SEZ.¹ The study assumes three levels of water demand (high, medium, and low) based on technology-specific considerations. Section 5 presents a discussion of the results and provides suggested approaches to improve the model as geologic and hydrologic data become available from individual project investigations associated with the siting, construction, and operation of utility-scale solar energy facilities. References used in the report are listed in Section 6.

¹ Full buildout is assumed to correspond to solar development of 80 percent of the SEZ land area, as defined in the Solar Programmatic Environmental Impact Statement (Solar PEIS) (BLM and U.S. Department of Energy [DOE] 2012).

1.1 Bureau of Land Management's Solar Energy Program

In 2012, BLM officially established its Solar Energy Program, which facilitates permitting of utility-scale solar energy development on BLM lands in six southwestern states (Arizona, California, Colorado, Nevada, New Mexico, and Utah) in an environmentally responsible manner (BLM 2012). As a part of the Solar Energy Program, BLM has established 19 SEZs, which are areas that are well-suited for utility-scale production of solar energy where BLM will prioritize solar development. BLM, together with the U.S. Department of Energy (DOE), analyzed the potential environmental impacts of the Solar Energy Program in the Final Programmatic Environmental Impact Statement for Solar Energy Development in Six Southwestern States (Solar PEIS). The Solar PEIS included an assessment of impacts to water resources (BLM and DOE 2012); groundwater is the primary water resource available for solar energy development in most of the SEZs. Impacts of groundwater withdrawals were investigated both qualitatively and semi-quantitatively in the Solar PEIS to assess the range of potential effects. Impacts associated with reduced groundwater flows and timing of groundwater flows to streams, springs, seeps, and wetlands depend on the connectivity of surface water and groundwater in the region. These impacts include decreased water supply for downstream users; loss of wetland vegetation species; loss of habitat and forage for wildlife, wild horses, and livestock; and others.

As a part of the Solar PEIS analysis, BLM and DOE examined water requirements for cooling and/or washing at solar energy facilities for different technologies and varying levels of development and compared these requirements with basin-scale water budgets. In addition, one-dimensional groundwater modeling was performed to examine potential radial drawdown for different solar development scenarios. As a follow-on to the work done for the Solar PEIS, BLM identified a subset of SEZs, including the Brenda SEZ, for which three-dimensional groundwater models would be developed. The models are being used to examine potential groundwater impacts associated with proposed solar development of the SEZs, with a particular focus on examining groundwater drawdown and potential loss of connectivity to surface water features, springs, and vegetation. The developed numerical groundwater models are being made available through the Solar PEIS Web site (http://blmsolar.anl.gov) so that they can be used for project-scale review and for the development of long-term monitoring programs.

1.2 Brenda Solar Energy Zone

The Brenda SEZ covers approximately 3,348 acres (13.5 km^2) and is located in the Ranegras Basin in western Arizona (Figure 1). The SEZ is named for the town of Brenda, Arizona (population 676), located within 3 miles (5 km) of the SEZ boundary.

The Ranegras Basin is an arid, alluvial basin bounded by crystalline bedrock ranges on the north, west, and east; the basin contains several isolated bedrock hills, notably the Bear Hills. The town of Brenda is located near a gap between the Bear Hills. Elevations across the alluvial plain range from about 1,380 ft (420 m) above mean sea level (MSL) in the southeast to about 920 ft (280 m) above MSL near Bouse in the northwest (Figure 2). The elevation of the SEZ ranges from about 1,240 ft (380 m) along its southwest border to about 1,105 ft (340 m) at the northeast corner. The Ranegras Basin is drained by Bouse Wash, which trends northwest toward the town of Bouse.

The Central Arizona Project (CAP) canal trends through the basin northeast of and roughly parallel to the Bouse Wash. CAP construction began in 1973 and was mostly complete in 1993. Several agricultural areas are located in the basin.



Figure 1 Ranegras Basin Overview (Source: Modified from ADWR 2009)



Figure 2 Ranegras Basin Surface Elevations and Model Grid

2 HYDROGEOLOGIC SETTING AND MODEL INPUT PARAMETERS

2.1 Geology

The maximum thickness of the alluvial sediments in the Ranegras Basin is estimated to range from 1,100 to 1,493 ft (340 to 455 m) (Metzger 1951; Briggs 1969; Johnson 1990). The alluvial basin fill sediments include gravel, sand, silt, and clay. These materials have a wide range of hydrogeologic properties, and these properties vary spatially depending on depth and proximity to mountains.

Drilling data were obtained from the Arizona Department of Water Resources (ADWR) to assess the distribution of subsurface material types in the Ranegras Basin study area (ADWR 2013); ADWR maintains an online database of well information. Eighteen drilling logs from monitoring wells, government or commercial wells, or exploratory boreholes had coordinate information and sufficient logging descriptions to incorporate them into a three-dimensional (3-D) model for scientific visualization. The 3-D stratigraphic model demonstrates variability in the subsurface framework in the form of naturally complex assemblages of materials with widely differing properties.

2.2 Hydrogeology

Alluvial basin aquifers in the region may range from unconfined to confined. A study by Tillman et al. (2011) describes the Ranegras as generally unconfined, with a deep layer that is confined. Other reports focused on the Ranegras Basin do not discuss the degree of confinement of alluvial aquifer units (ADWR 2009, 2010; Johnson 1990; Metzger 1951). In a regional study that includes the adjacent Harquahala Basin, basin fill alluvium is generally considered unconfined but may be confined locally (Anderson and Freethey 1995). In the current study, the Ranegras Basin is assumed to be unconfined, although confined conditions may be encountered during construction of especially deep wells.

No hydrogeologic parameter value data are available for the Ranegras Basin. Anderson and Freethey (1995) modeled groundwater in the Harquahala Basin to the east. Because this basin is adjacent to the Ranegras Basin, the two basins are assumed to have similar hydrogeological properties. In the model, the Harquahala Basin had a hydraulic conductivity (K) of 2.2 ft/d (0.67 m/d) in upper alluvial units and roughly 27 ft/d (8.5 m/d) in lower units. Anderson and Freethey (1995) estimated a specific yield of 0.1 for the Harquahala Basin.

2.3 Pumping Stresses

At the town of Brenda, pumping for the potable water supply (assumed to be all of the potable pumping in the basin) is about 400 ac-ft/yr $(1,350 \text{ m}^3/\text{d})$ (Tillman et al. 2011).

The history of irrigation pumping in the Ranegras Basin is summarized by ADWR (2010). Highproduction agricultural wells began operation in the region in the 1940s, with the first two

agricultural wells installed in the Ranegras Basin in 1948. In 1957, 15 wells irrigated 5,200 acres (2,100 hectares). The peak of pumping and irrigated land area was in 1981, with 50,000 acre-feet $(6.2 \times 10^7 \text{ m}^3)$ of water used on 12,600 acres (5,100 hectares) of land. In 1988, 7,300 acres were irrigated with 28,000 ac-ft $(3.5 \times 10^7 \text{ m}^3)$ of water. Since that time, usage in the basin has not fluctuated significantly (ADWR 2009). Recent withdrawals (in 2005) totaled 27,500 ac-ft/yr $(92,900 \text{ m}^3/\text{d})$ (Tillman et al. 2011).

2.4 Estimated Hydrologic Budget for the Ranegras Basin

Tillman et al. (2011) compiled estimates of groundwater input and output in the Ranegras Basin. These are presented in Table 1, and the components are discussed below.

Groundwater Inflow			Gr	ow	
Туре	Pre- Development	Post- Development	Туре	Pre- Development	Post- Development
Mountain front recharge	1,000 ac-ft/yr (3,380 m ³ /d)	1,000 ac-ft/yr (3,380 m ³ /d)	Underflow (at Bouse)	400 ac-ft/yr (1,350 m ³ /d)	860 ac-ft/yr (2,900 m ³ /d)
Irrigation return flow	None	2,800 ac-ft/yr (9,460 m ³ /d)	Irrigation withdrawals	none	27,500 ac-ft/yr (92,900 m ³ /d)
In-place recharge	0.01 in/yr or 400 ac-ft/yr (1,350 m ³ /d)	0.01 in/yr or 400 ac-ft/yr (1,350 m ³ /d)	Public withdrawal at Brenda	<300 ac-ft/yr (<1,010 m ³ /d) in 1980	400 ac-ft/yr (1,350 m ³ /d) in 2005
Underflow (from Butler Valley)	300 ac-ft/yr (1,010 m ³ /d)	300 ac-ft/yr (1,010 m ³ /d)	Evapo- transpiration of groundwater	Negligible	Negligible
CAP ¹ leakage	None	2,500 ac-ft/yr (8,450 m ³ /d)			
ESTIMATED INFLOW TOTALS:	1,700 ac-ft/yr (5,700 m ³ /d)	7,000 ac-ft/yr (24,000 m ³ /d)	ESTIMATED OUTFLOW TOTALS:	700 ac-ft/yr (2,400 m ³ /d)	28,760 ac-ft/yr (97,000 m ³ /d)

 Table 1 Ranegras Basin Groundwater Budget

Source: Tillman et al. 2011 ¹ Central Arizona Project canal.

Recharge to the Ranegras Basin plain is a combination of mountain-front recharge (the infiltration of water in drainages along mountain fronts and direct infiltration of precipitation into mountain blocks), agricultural return flow, stream-flow infiltration, in-place recharge, and groundwater basin underflow (Tillman et al. 2011). The in-place recharge of about 0.01 in./yr (0.0254 cm/yr) was related to the area of the Ranegras Basin (912 mi² or 2,360 km² per Tillman et al. 2011) to arrive at a total input of about 400 ac-ft/yr (500,000 m³/yr).

Because of the depth to groundwater in the basin, the evapotranspiration loss from groundwater is negligible (Tillman et al. 2011). Public withdrawal is assumed in the numerical model to be from a single well near Brenda, where nearly all of the people who live in the basin reside. The net of the 2005 irrigation withdrawals and the 2005 irrigation return flow (net amount of 24,700 ac-ft/yr or

 $3.05 \times 10^7 \text{ m}^3/\text{yr}$) were modeled as wells pumping equal amounts and located in the agricultural areas east and north of the Brenda SEZ.

The only groundwater inflow to the Ranegras Basin is from the Butler Valley to the north (Figure 2), beneath Cunningham Wash, which drains from Butler Valley to the Ranegras Basin (Tillman et al. 2011; Freethey and Anderson 1986).

Tillman et al. (2011) provide additional recharge estimates for the Ranegras Basin (determined by the ADWR) of 5,000 and 5,500 ac-ft/yr (6.2×10^6 to 6.8×10^6 m³/yr) (original references not currently available). These estimates agree with those provided in Metzger (1951). In Table 1, the sum of mountain-front recharge, in-place recharge, groundwater underflow, and 2005 irrigation return is 4,500 ac-ft/yr (5.6×10^6 m³/yr). However, the ADWR estimates compiled by Tillman do not mention leakage from the CAP canal, and the Metzger estimate predates the CAP. Leakage from this feature may be 2,000 to 3,000 ac-ft/yr (2.5×10^6 to 3.7×10^6 m³/yr) in the Ranegras Basin (ADWR 2010).

The post-development totals for inflow and outflow show outflow to be larger by a factor of four (Table 1). This is mainly attributable to the net effect of irrigation pumping and indicates mining of the groundwater because of irrigation requirements.

In the Ranegras Basin, pre-development conditions should be at quasi-steady-state, and estimated inflow totals should be approximately equal to estimated outflow totals. However, in Table 1, the sum of Tillman et al. (2011) pre-development inflow (1,700 ac-ft/yr or 2.1×10^6 m^{3}/yr) exceeds the pre-development outflow (700 ac-ft/yr or $8.6 \times 10^{5} m^{3}/yr$). The Tillman et al. values for underflow discharge at Bouse are not directly supported by its cited references of ADWR (2009) and Freethey and Anderson (1986). Determinations for the outflow at Bouse (or the inflow from Butler Valley) are not provided in other available references (Metzger 1951; Briggs 1969; Johnson 1990; or ADWR 2010). Tillman et al. also provide a post-development estimated outflow at Bouse (860 ac-ft/yr or 1.1×10^6 m³/yr) that is larger than the predevelopment value (400 ac-ft/yr or 4.9×10^5 m³/yr), which does not make sense given the significant net agricultural withdrawal compared with assumed CAP leakage. Because of the possible natural recharge processes for the basin (mountain front, in-place, underflow from Butler Valley, Bouse Wash infiltration), the predevelopment outflow at Bouse should exceed the inflow from the smaller Butler Valley. The accuracy of the relatively small recharge budget components is low, especially for reported values less than 1,000 ac-ft/vr $(1.2 \times 10^6 \text{ m}^3/\text{vr})$ (Tillman 2013).

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3 MODEL SETUP

Numerical (finite-difference) groundwater modeling was performed using the U.S. Geological Survey (USGS) MODFLOW 2000 modular groundwater model (Harbaugh et al. 2000). Pre- and post-processing were performed using Groundwater Modeling System (GMS) version 9.0.5 with support from ArcMap 9.3.

3.1 Grid Design

The grid for the numerical model is designed with 66 ft×66 ft (20 m×20 m) model cells in the center of the Brenda SEZ property. The cell size increases by a factor of 1.1, up to a maximum cell size of 820 ft×820 ft (250 m×250 m) (Figure 2). This method allows us to obtain more details in the area of interest.

As described in Section 2, alluvium varies in character in both the lateral and vertical directions. Because of the lack of subsurface data near the SEZ and throughout the Ranegras Basin and the complexity in the distribution of material types, the model is created with a single layer.

Ground surface elevations (Digital Elevation Model [DEM] data) were used in GMS to model the upper surface of the model domain. Geographic information system (GIS) tools were used to delineate a series of points along the alluvium/bedrock boundary around the edge of the Ranegras Basin (and along the internal Bear Hills), and the ground elevation of each point was determined. Regional information (presented in Section 2.1) about the depth of the Ranegras Basin was used to assign alluvium thicknesses at locations throughout the central portions of the basin. These two sets of points were combined, and the elevation of the base of the alluvial aquifer was interpolated using the natural neighbor algorithm. In GMS, this surface and the ground surface were used to bound the 3-D modeling domain.

3.2 Boundary Conditions

The bottom of the flow domain is a no-flow boundary represented by the estimated bedrock surface. The Ranegras Basin's surface and subsurface flows discharge to the northwest at a gap in the mountains at the town of Bouse. Here, a constant head boundary is assigned across this narrow zone to match the water level of 910 ft (277 m) shown by Johnson (1990). That boundary's head is used as a specified head boundary to enable generation of a model solution. The estimated groundwater outflow at Bouse is 860 ac-ft/yr (2,900 m³/d) (Tillman et al. 2011). This outflow is used as a budget check (flux target).

A narrow gap between mountain blocks and coinciding with the Cunningham Wash is assumed to be the location of the underflow from Butler Valley into the Ranegras Basin (Tillman et al. 2011). In the model, this constant flux input is modeled as a constant flux by the use of an injection well (300 ac-ft/yr or 1,010 m^3/d) located inside the modeling domain along the Cunningham Wash.

Other lateral boundaries are no-flow and approximately follow the boundary between the alluvium and the bedrock mountains.

3.3 Sources, Sinks, and Initial Conditions

The municipal pumping rate at the town of Brenda was applied in all model runs. For irrigation withdrawals, the assumed pumping well locations were distributed across the agricultural areas in northern and eastern portions of the basin on the basis of crop areas shown in aerial photography. The recent overall withdrawal rate of 27,500 ac-ft/yr (92,900 m³/d) (Tillman et al. 2011) was reduced by the estimated irrigation return flow of 2,800 ac-ft/yr (9,460 m³/d) (Tillman et al. 2011), for a net amount of 24,700 ac-ft/yr (83,000 m³/d). This net pumping amount was distributed evenly among five assumed well locations in the northern agricultural area of the basin and ten locations in the eastern agricultural area.

To factor the assumed components of recharge (excluding agricultural return flow) into the model, the sum of mountain-front recharge, in-place recharge, and the mid-range estimate of CAP leakage (a total of 3,900 ac-ft/yr or 4.8×10^6 m³/yr) was assigned as areally distributed recharge. (The irrigation return flux is accounted for in the net amount of assigned agricultural pumping.) This step was completed by assigning uniform recharge throughout the 912-square-mile (2,360 km²) basin, yielding a rate of 2.2×10^{-4} in./d (1.8×10^{-5} m/d). This simplification (i.e., uniformly distributed recharge) is made because, although the recharge is expected to be more focused along the edges of the basin and along the CAP, the detailed spatial distribution of recharge is complex. The uniform distribution is simple to implement and should not result in significant errors relative to the long-term evaluation of SEZ pumping.

For this Brenda SEZ model, the assumed pre-development rate of outflow at Bouse was the rate that Tillman et al. (2011) consider to be the post-development rate (860 ac-ft/yr or 2,900 m³/d). This rate, when combined with the estimated pre-development municipal pumping, resulted in a total estimated pre-development outflow of 1,160 ac-ft/yr ($1.43 \times 10^6 \text{ m}^3/\text{yr}$) — a value closer to the estimated pre-development inflow total. The assumed groundwater outflow at Bouse of 860 ac-ft/yr ($2,900 \text{ m}^3/\text{d}$) was applied as the flux target in the Phase 1 modeling (pre-development scenario) conducted for parameter estimation of hydraulic conductivity (K) and recharge (R). While there is uncertainty in this parameter, the assumed value is adequate for creating a model and testing the impact of SEZ pumping on the model.

With the exception of the constant head boundary imposed at Bouse, initial heads in the model domain were set to the ground surface elevation and allowed to decline during model iterations. Because of the depth to groundwater, model cells along the edge of the model domain converted to dry cells, as expected.

3.4 Modeling Approach

The Brenda SEZ model relies on a three-phase approach, as follows.

Phase 1 — Steady-state modeling calibrated to pre-1940s conditions (before agricultural development began in the Ranegras Basin). The purpose of this phase was to determine, through parameter estimation techniques, the best estimates of K and R for the Ranegras Basin. Based on the locations of the four pre-development wells offering target head values, the modeling domain was divided into four zones (Figure 3) so that four K values would be determined across the basin (supported by the available head data). Based on the range of expected K values for alluvium described in Section 2.2, an initial K value of 9.8 ft/d (3.0 m/d) was assigned to each of the four K zones. An initial estimate for R of 1.8×10^{-5} ft/d (5.6×10^{-6} m/d) was distributed uniformly across the basin, as discussed in Section 3.3. These values for R and the K zones were adjusted during the modeling process, as described below.

As stated in Section 3.2, the groundwater outflow at Bouse (Tillman et al. 2011) was used as a flux target for calibration of the model. The water level at that boundary was used as a specified head boundary based on Johnson (1990) data to enable generation of a model solution.





Figure 3 Locations of Four Pre-Development Water Level Data Locations (from Johnson 1990) and Four Hydraulic Conductivity Zones

This phase was conducted using MODFLOW with the parameter estimation tool (PEST) (Watermark Numerical Computing undated). PEST is an optimization tool for matching the *simulated* groundwater elevations with an *observed* set of groundwater elevations by minimizing the weighted sum of squared differences between the two. The optimization problem is iteratively solved by linearizing the relationship between the model's output and its input parameters (in this case K and R). The linearization is conducted using a Taylor series expansion in which the partial derivatives of each model output (for every parameter) must be calculated for each iteration. PEST was used to evaluate model input possibilities and output, along with the four target head values and the discharge target at Bouse in order to determine optimum values for the four K zones and the basin's overall R rate. These K and R values were then used as fixed values for Phases 2 and 3.

Phase 2 — Development of a transient model to approximate the effect of agricultural water usage. This phase, focused on the timeframe from the 1940s to present, was completed using a transient model that relied on fixed values for the four K zones and the basin's R rate, as determined in Phase 1. The specific yield was assumed to be 0.1 (Anderson and Freethey 1995).

For the Phase 2 scenario, recent groundwater levels were obtained from the National Water Information System (NWIS) (USGS 2012) to serve as calibration targets for the transient model. To examine water levels for recent times, data from 1945 through 1989 were eliminated and the remaining data from 1990 through 2007 were retained. Multiple measurements at individual wells were averaged.

The model's initial condition was the set to the heads determined in Phase 1. The agricultural pumping distribution described in Section 3.4 was applied to the model, which was discretized into 40 annual time steps. Because the basin's complete history of changing pumping rates and locations is difficult to compile, the appropriate current pumping rate was applied to determine how many years would be required to reduce water levels in the Ranegras Basin from their predevelopment levels to their current levels. This step was completed by examining the modeled heads at the annual time steps and comparing them with the recent heads across the basin. Although this is a simplification of historical, annually varying pumping rates, it is suitable for later testing of the effect of SEZ pumping.

Phase 3 — Development of transient model scenarios to assess the simulated impact of 20 years of groundwater withdrawals for various development scenarios of the Brenda SEZ. This phase included continued agricultural water use as in Phase 2. By determining in Phase 2 how many years of current pumping rates would be needed to produce current water levels and then continuing the model for 20 years, the model assesses the future 20-year period of continued agricultural pumping combined with SEZ water use.

For the Brenda SEZ, full buildout of utility-scale solar energy facilities was assumed. Three different solar technologies, each with different water requirements (Table 2), were explored. At the high end of the expected range is full buildout of wet-cooled concentrated solar power (CSP) facilities. CSP technology relies relatively intensively on water for cooling. Medium water

demand is associated with a scenario of full buildout of dry-cooled CSP facilities. Low water demand is associated with full buildout of photovoltaic (PV) facilities, for which water is required to clean the equipment. These rates are only for the operational stage of solar facility implementation, as defined in the Final Solar PEIS. They do not include the estimated rates or durations for the construction or reclamation stages of solar facility development.

Water Demand		Actual Water Demand		
Level	Technology	ac-ft/yr	m ³ /d	
High	Full buildout of wet-cooled CSP ¹	2,860	9,070	
Medium	Full buildout of dry-cooled CSP ¹	380	1,290	
Low	Full buildout of PV ²	15	51	

Table 2 High-, Medium-, and Low-Demand Proposed SEZ Groundwater Pumping Requirements for the Brenda SEZ

¹ Concentrated solar power.
 ² Photovoltaic.

By assessing the operational water requirements of these three technologies, the Brenda SEZ model assesses the range of expected water requirements and associated impacts.

3.5 Calibration Targets

Measurements of hydraulic head and calculated estimates of groundwater discharge served as calibration targets for a groundwater model. For the Phase 1 steady-state, pre-development scenario, heads were available from Freethey and Anderson (1986) for four wells scattered throughout the Ranegras Basin (Figure 3). As described previously, the groundwater discharge at Bouse is 860 ac-ft/yr (2,900 m³/d) (Tillman et al. 2011), which serves as a flux target for model calibration. Groundwater levels from recent years were obtained from the NWIS (USGS 2012) and used in the transient model.

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4 RESULTS

4.1 Phase 1 — Steady-State Model

The groundwater model relied on PEST for parameter estimation of the four K zones and the distributed recharge to match the four pre-development target heads in the basin, as well as the flux discharge at Bouse. PEST determined optimal K value for each zone, along with an optimal R value, to minimize calibration errors at these locations and at the discharge target (groundwater outflow at Bouse).

Figure 4 shows the resulting heads, and Table 3 lists the optimal K and R values. The head errors at the four pre-development wells were zero (Figure 5), and the calculated groundwater discharge at Bouse matched exactly the target of 860 ac-ft/yr (2,900 m³/d). MODFLOW provides a summary of all model input and output values and compares them as a validation of the water budget. The error determined for this model was 0.00%.



Figure 4 Heads of Calibrated Pre-Development Model

	Initial Input		PEST Output	
Parameter	ft/d	m/d	ft/d	m/d
Hydraulic conductivity zone 1	9.8	3.0	14.60	4.45
Hydraulic conductivity zone 2	9.8	3.0	4.13	1.26
Hydraulic conductivity zone 3	9.8	3.0	2.59	0.79
Hydraulic conductivity zone 4	9.8	3.0	1.54	0.47
Recharge (m/d)	1.8×10^{-5}	5.6×10 ⁻⁶	1.33×10 ⁻⁵	4.06×10 ⁻⁵

 Table 3 Initial Model Input and PEST-Derived Output for Hydraulic Conductivity

 and Recharge Values



Figure 5 Calculated Heads vs. Observed Heads at the Four Pre-Development Targets

Model Sensitivity

Model sensitivity is evaluated by examining the change in model output when calibrated model input values are varied. GMS includes an option to scale an input value (or spatially distributed input values, as in the situation with four K zones). The sensitivity of modeled heads was evaluated in the form of mean head in the model domain; the sensitivity of the outflow at Bouse was also evaluated. The sensitivity of the model's mean head to changes in R was very low across a reasonable range of tested R values (Figure 6). The sensitivity to K was also very low



Figure 6 Sensitivity of the Pre-Development Model's Mean Head to K and R

across a wider range of changes in K (Figure 6). Increase in K beyond 100% had little effect on mean head, while decreases of 75% or more produced unacceptable heads in the domain. The calculated discharge of the system at Bouse showed different sensitivities to K and R (Figure 7). The sensitivity to changes in K was modest with respect to increased K or slight decreases in K, but increased rapidly when K was less than 50% of the calibrated values. In contrast, the model

was highly sensitive to changes in the R input. PEST also produces a measure of sensitivity on the basis of derivatives of model output with respect to parameter values. The high observed sensitivity to changes in R is consistent with output from PEST.



Figure 7 Sensitivity of the Pre-Development Model's Groundwater Discharge at Bouse to K and R

4.2 Phase 2 — Transient Model for Agricultural Development

A transient model representing decades of agricultural pumping was required for the Ranegras Basin, because a steady-state model that includes the current stresses would dewater essentially the entire modeling domain.

Results indicated large cones of depression developing around the two agricultural pumping centers. The target heads for this scenario are from 40 wells scattered throughout the basin (Figure 8). This is not a perfect data set. All values considered were from 1990 or more recent. In some cases, a single measurement was available from a well, while in other cases, multiple measurements were averaged. The head measurements may be affected by localized hydrogeology, perching, well construction, nearby pumping, well depth, and proximity to localized concentrated recharge (e.g. from Bouse Wash, tributary washes, or the leaking CAP). Despite the limitations of the target head data, they are considered adequate for the transient calibration.

The annual model results for the 40-year period were inspected and compared with overall heads in the various portions of the study area. Despite the nature of the target head values, it was determined, through careful comparison, that the transient model's results after about 20 years of pumping (Figure 8) matched the target heads. The adequacy of the calibration is shown in Figure 9. The modest correlation to the 1:1 line is consistent with the noisy target heads. Many of the observed target values were likely affected by factors described above. During the calibration process, the annual model results were inspected individually to determine which year's output best matched the bulk of the target values. In Figure 9, if several of the outlying points were to be ignored, the correlation is much improved.

The 20-year mark was therefore selected as the point to turn on SEZ wells in the final model scenario. The model's calculated drawdown at the 20-year point compared to pre-development conditions was about 56 ft (17 m) in the northern agricultural area and about 190 ft (58 m) in the eastern agricultural area.

4.3 Phase 3 — Transient Model with Solar Development

High-Water-Demand Withdrawal Scenario

The results for the high-water-demand SEZ scenario indicate a developing cone of depression (Figure 10). The relative difference between the 20 years of combined effect associated with agricultural pumping plus high-demand SEZ pumping was compared with the effect of agricultural pumping alone during that timeframe. The results (Figure 11) show that after 20 years of maximum-demand SEZ operations, the additional drawdown attributed to SEZ pumping is 20 to 66 ft (6 to 20 m) across the SEZ property and about 8 ft (2.5 m) across the basin to its eastern side.



Figure 8 Calculated Heads after 20 Years of Agricultural Pumping



Figure 9 Calculated vs. Recent Observed for the Phase 2 Transient Analysis



10 km

Figure 10 Calculated Heads after 20 Years of Agricultural Pumping Followed by 20 Years of Agricultural Pumping Plus High-Demand SEZ Pumping





Figure 11 Additional Drawdown Due to 20 Years of High-Demand SEZ Pumping

Medium- and Low-Water-Demand Withdrawal Scenarios

After 20 years of SEZ pumping, the additional drawdown in the basin resulting from the medium pumping rate was about 3 to 10 ft (1 to 3 m) within the SEZ and almost 1.2 ft (0.4 m) across the basin to the east (Figure 12).

The low SEZ pumping rate showed additional drawdown of 0.3 ft (<0.1 m) in the SEZ after 20 years of operations.

Water Level (m above MSL)





Figure 12 Additional Drawdown Due to 20 Years of Medium-Demand SEZ Pumping

5 DISCUSSION

5.1 Comparison of Numerical Model with Solar PEIS Analytical Model

In the Solar PEIS, an initial assessment of drawdown associated with the low-, medium-, and high-demand SEZ scenarios using a one-dimensional analytical model adapted from standard methods for long-duration analyses was explored. The analytical model assumed an unconfined alluvial aquifer with a thickness of 1,493 ft (455 m), K of 3.5 ft/d (1.1 m/d), and specific yield of 0.05. The numerical model relied on a variable thickness, because the base of the alluvium was a modeled surface. Its calibrated K values in four zones varied from 1.5 to 14.6 ft/d (0.47 to 4.45 m/d); the zone containing the SEZ had a value of 4.13 ft/d (1.26 m/d) (Table 3). The specific yield of 0.1 was based on the mid-range literature value obtained for an adjacent valley. Another difference was the number of wells considered (one well for the analytical model and two wells for the numerical model, although the drawdown effect attributable to this issue decreases with distance from the SEZ).

For the high-demand scenario, results from the one-dimensional model (BLM and DOE 2012) suggest additional drawdown attributable to the SEZ of about 15 to 70 ft (5 to 21 m) within the SEZ boundary and about 5 ft (1.5 m) at the eastern side of the basin, which is about 5 miles (8 km) from the center of the SEZ. These results are similar to those obtained using the numerical model described in this report (i.e., drawdown of 20 to 66 ft [6 to 20 m] within the SEZ boundary and about 8 ft [2.5 m] in the basin to its eastern side), despite the simplifying assumptions of the one-dimensional model. The close comparison supports the use of the analytical model as a conservative screening tool. Changing the analytical model's input for K and specific yield to match those of the numerical model had only a small effect on the model output.

For the medium-demand scenario, the one-dimensional model indicated that the additional drawdown due to the SEZ would be about 3 to 10 ft (1 to 3 m) within the SEZ and almost 1.2 ft (0.4 m) across the basin to the east. Again, these results are very similar to those obtained using the numerical model.

5.2 Summary of Numerical Model Results

The modeling analysis of solar energy operations at the Brenda, Arizona, SEZ represents the predevelopment conditions and the significant drawdown caused by agricultural pumping in the Ranegras Basin. Having a flux target in addition to the scattered head targets strengthens the accuracy of the model's parameter estimation calculations. The optimal K and R values determined through the use of PEST in the model calibration process were similar to the initial values, which were consistent with information in the literature for the study area (Table 3). The calibrated K and R values determined during Phase 1 are very reasonable given the available knowledge about the study area; they were used as fixed values in the subsequent transient models.

Analysis of the pumping requirements for the high-demand scenario suggests that after 20 years of operations, the additional drawdown would be 20 to 66 ft (6 to 20 m) across the SEZ property

and about 8 ft (2.5 m) across the basin to its eastern side. The additional drawdown was found to be significantly less for the medium-demand scenario (about 3 to 10 ft (1 to 3 m) within the SEZ and almost 1.2 ft (0.4 m) across the basin to the east). The additional drawdown for the low-demand scenario was negligible.

This numerical model represents a significant improvement over the one-dimensional analytical model for the Brenda SEZ presented in the Solar PEIS in terms of level of detail, understanding of the hydrogeologic system, and ability to evaluate the effects of SEZ pumping and other water uses in the Ranegras Basin.

5.3 Implications for Future Model Development

The inspection of available drilling data in the Ranegras Basin indicated a large degree of complexity in alluvial basin deposits. These materials vary widely in terms of their hydrogeologic properties, resulting in a large degree of uncertainty in the subsurface distribution of material types. For this reason, the one-layer approach is suitable as a means of overall assessment. The current model could be improved with the incorporation of future data regarding the hydrogeological framework and aquifer parameter values; for example, new site-specific drilling data from the SEZ obtained through site characterization efforts or from the logging of SEZ groundwater extraction well(s). The model's basal elevation selected for flow modeling could be adjusted in light of new information, and the degree of confinement locally could be evaluated. Drilling data could be used to support discretization of multiple model layers. Zonal and vertical changes could be made in the assignment of parameter values for alluvial materials. Site-specific data would improve the design and accuracy where such improvements are most needed for assessing drawdown impacts.

This model may be used by regulators in the planning and assessment of future water resources needs in the Ranegras Basin on the basis of permit applications. It may also be used by developers to evaluate the potential impact to groundwater levels from SEZ pumping. Model runs could assess the cumulative effect on groundwater levels from changes in water usage by others in the Ranegras Basin. It should be noted that although the Ranegras Basin can supply the water necessary to meet needs in the Brenda SEZ over a 20-year window, water use even at current agricultural use levels is not sustainable over the longer term.

5.4 Disclaimer for Use of the Brenda SEZ Model

This numerical groundwater modeling study was performed to analyze the potential impacts of groundwater pumping associated with utility-scale solar energy development. The models used for these analyses rely on established hydrogeologic principles and established groundwater modeling software. While efforts were made to develop modeling tools for proper assessment of impacts from groundwater pumping to support solar energy development, the models are not intended to be exact predictors of groundwater impacts over time in the study areas. Hydrogeologic information obtained as individual solar projects are developed should be used to refine, modify, and update the models and analyses used for this study. The reports associated

with each groundwater modeling study provide recommendations for the further development of the groundwater models as information becomes available.

MODFLOW-based modeling was performed using particular versions of GMS, as described above. The model files associated with the groundwater modeling studies may be usable by older or newer versions of GMS or by other commercial graphical user interfaces; however, functionality cannot be guaranteed.

5.5 Summary of Brenda SEZ Model Files and Future Use

Modeling was performed using GMS version 8.3.4.16592 (64-bit) with a build date of August 24, 2012. The files are packaged in a single zip file. When unzipped, they may be usable by older or newer versions of GMS or by other commercial graphical user interfaces; however, functionality cannot be guaranteed.

Within GMS, the project explorer includes MODFLOW-related items under the 3D Grid Data. For the Brenda work, the solution file sets include the following:

- **brendav9-2013-0516a** is the pre-development, steady-state model with parameter estimation for K and recharge.
- **brendav9-2013-0517a** is the transient model including agricultural development pumping, consisting of an initial steady-state model of pre-development conditions, followed by approximate agricultural pumping for 40 years.
- **brendav9-2013-0517b** is the model of the effect of high-demand SEZ pumping. It includes an initial steady-state stress period of pre-development conditions, a 20-year transient period of agricultural development, and a 20-year period of agricultural pumping and high-demand SEZ pumping.
- **difference at 40yr** is a data set created using the GMS Data Set Calculator tool to determine the difference in drawdown between the **0517b** results at the 40-year mark (20 years agricultural plus high-demand SEZ pumping) and **0517a** results at the 40-year mark (40 years of agricultural pumping).

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