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

Environmental Science Division

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

Acronyms, Initials, Symbols and Abbreviations

BLM   Bureau of Land Management
CAP   Central Arizona Project
CDWR   California Department of Water Resources
CHD   constant-head boundary/time-variant specified head package in MODFLOW
CRA   Colorado River Aqueduct
DEM   Digital Elevation Model
DOE   U.S. Department of Energy
DRN   drain package in MODFLOW
GIS   geographic information system
GMS   Groundwater Modeling System
K   hydraulic conductivity
PEIS   programmatic environmental impact statement
PEST   Parameter Estimation Tool
PVID   Palo Verde Irrigation District
RIV   river package in MODFLOW
SEZ   Solar Energy Zone
USGS   U.S. Geological Survey

Units of Measure

ac-ft   acre-foot (feet)
d   day(s)
ft   foot (feet)
ft^2 square foot (feet)
GW   gigawatt(s)
in.   inch(es)
km   kilometer(s)
km^2 square kilometer(s)
m   meter(s)
m^2 square meter(s)
m^3 cubic meter(s)
mi   mile(s)
yr   year(s)

Elevations are reported relative to mean sea level using the NAVD88 vertical datum.

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ACKNOWLEDGMENTS

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**A GROUNDWATER MODEL TO ASSESS WATER RESOURCE IMPACTS
AT THE RIVERSIDE EAST SOLAR ENERGY ZONE**

by

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1 INTRODUCTION

This study discusses the development of a groundwater flow model to use in examining the influence of potential groundwater withdrawal on the nearby environment. The groundwater withdrawal would be to support utility-scale solar energy development at the Riverside East Solar Energy Zone (SEZ) as a part of the Bureau of Land Management's (BLM's) solar energy program. The Riverside East SEZ groundwater model (referred to as the Riverside East SEZ Model, or the model) is a numerical model that was developed by using established software and hydrogeological principles and that relies on publicly available geospatial, geologic, and hydrologic data. Although the model focuses on the simulated drawdown effects of 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 modeling analyses. Because the basin hydrostratigraphy has been simplified into one layer, the model is intended to be used by water managers and others only as a general indicator of groundwater elevations and potential drawdown. The model was developed in three phases:

1. Calibration to steady-state, pre-1942 conditions (before the Colorado River Aqueduct began operations in 1942) to establish starting heads for the subsequent transient modeling;

2. Automated calibration of a transient model to assess the use of mining, municipal, and agricultural water from 1942 through 2010 (before the first solar facility began groundwater withdrawal related to construction in 2011); and

3. Development of a set of transient model scenarios in simulations to assess the simulated impact of 20 years of groundwater withdrawals for various development scenarios of the Riverside East SEZ.

This report describes the development of the Riverside East SEZ Model and summarizes the results from simulating the impacts from a full build-out of the Riverside East SEZ, considering three water-demand categories (high, medium, and low) based on technology-specific parameters. This report also suggests some approaches for improving the model as geologic and hydrologic data from individual project investigations associated with the siting, construction, and operation of utility-scale solar energy facilities become available.

1.1 Bureau of Land Management's Solar Energy Program

In 2012, the 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 established SEZs. The 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), including impacts on water resources (BLM and DOE 2012). Groundwater is the primary water resource available for solar energy development in most of the SEZs, and impacts of groundwater withdrawals were investigated qualitatively and semi-quantitatively in the Solar PEIS to assess the range of potential effects. The impacts of reduced groundwater flow to streams, springs, seeps, and wetlands would depend on the connectivity of surface water and groundwater in the region. These impacts would include a decreased supply of water 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, water requirements for cooling and/or washing at solar energy facilities were examined for different technologies and varying levels of development and compared 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 seven SEZs, including the Riverside East SEZ, for which three-dimensional groundwater models would be developed. The models are being used to examine potential groundwater impacts associated with the proposed development of the SEZs; the focus is on examining groundwater drawdown and potential loss of connectivity to surface water features, springs, and vegetation. In addition to these analyses, the developed numerical groundwater models are being made available through the Solar PEIS web site so that they can be used for project-scale review and for the development of long-term monitoring programs.

1.2 Riverside East Solar Energy Zone

The Riverside East SEZ covers approximately 150,000 acres (607 km^2) and is located along an east–west corridor that contains a stretch of I-10 extending between the towns of Desert Center and Blythe in southern California (Figure 1). Several utility-scale solar energy projects are under construction or proposed within this SEZ, which has a full build-out capacity of 13 to 24 GW based on assumptions stated in the Solar PEIS (BLM and DOE 2010, 2012). Five large transmission lines, plus one more that is under construction, pass through the SEZ, primarily in its southeastern and western portions (BLM and DOE 2010).

The Riverside East SEZ is within the Chuckwalla Valley and Palo Verde Mesa groundwater basins (Figure 1). These arid, alluvial basins are bounded by bedrock mountains, characteristic of the basin and range physiographic province. The SEZ has surface elevations ranging between 450 and 1,000 ft (137 and 305 m), and its general drainage pattern is from the northwest to the
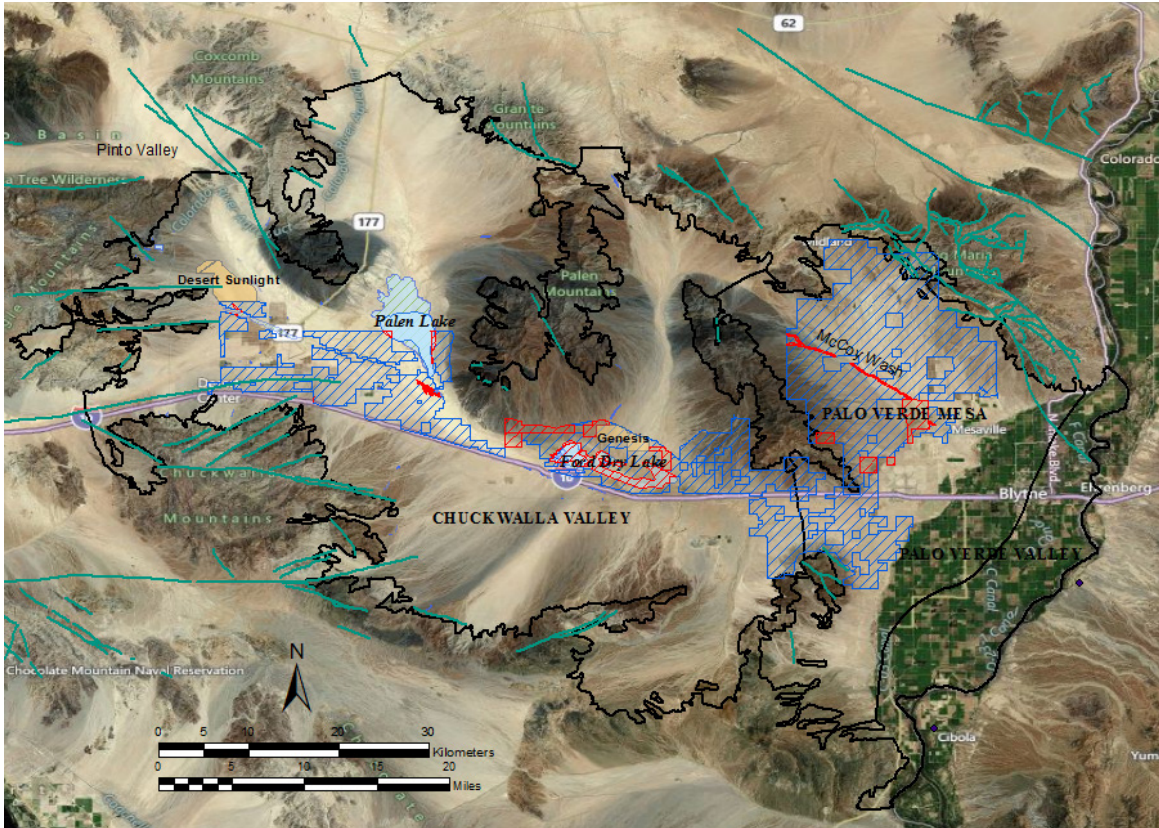
Figure 1 Riverside East SEZ That Spans the Chuckwalla Valley, Palo Verde Mesa, and Palo Verde Valley Groundwater Basins in Southern California (mapped geologic faults are in teal, SEZ development areas are in blue hatching, SEZ nondevelopment areas are in red hatching, groundwater basins are outlined in black)

southeast toward the Colorado River, which flows through the Palo Verde Valley basin to the east (Figure 1). The Colorado River and Palo Verde Irrigation District drainage ditches are within the Colorado River floodplain and serve as the primary groundwater discharge areas for the modeled region.

The primary consideration for groundwater management at the Riverside East SEZ relates to managing the allocations of water from the Colorado River, which is managed by an assemblage of compacts, federal laws, court decrees, and contracts that comprise the "Law of the River." The Colorado River "Accounting Surface" method was developed by the U.S. Geological Survey (USGS), in accordance with the Law of the River, to determine static groundwater elevations in contributing basins that replenish the Colorado River. The Chuckwalla Valley and Palo Verde Mesa groundwater basins are considered to be contributing basins (Wilson and Owen-Joyce 1994; Weile et al. 2008). The Accounting Surface elevation is between 238 and 240 ft (72.5 and 73 m) in the Chuckwalla Valley, and it is between approximately 218 ft (66 m) and more than 270 ft (82 m) in the Palo Verde Mesa area (Weile et al. 2008). From west to east across the Chuckwalla Valley and into the Palo Verde Mesa, recently measured groundwater elevations are approximately 488 ft (149 m) near Desert Center, 288 ft (88 m) near Palen Lake, and 245 ft (75 m) near the split between the two groundwater basins (USGS 2012).

The groundwater management implications of the Colorado River Accounting Surface elevations are beyond the scope of this study. In general, if groundwater elevations go below the Accounting Surface elevation, then subsequent groundwater withdrawals are considered Colorado River extractions and infringe on water rights established in the Law of the River. This interpretation does not necessarily represent the true physical nature of surface water–groundwater connectivity for the Colorado River, but it does allow for a basin-wide assessment of potential effects on Colorado River flows that are critical in supplying water users.

2 HYDROGEOLOGIC SETTING AND MODEL INPUT PARAMETERS

2.1 Landscape Characteristics

The Riverside East SEZ Model covers an aerial extent of the alluvial plain regions of the Chuckwalla Valley and Palo Verde Mesa groundwater basins. Ground surface elevations across the alluvial plain represented in the model range from about 1,942 ft (592 m) at the mountain-front intersection with the alluvial fan edge in the western Chuckwalla Valley to about 220 ft (67 m) at the downstream end of the Colorado River floodplain in the southeast (Figure 2). There is a change in elevation of up to 130 ft (40 m) along the mesa that divides the Palo Verde Mesa basin from the Palo Verde Valley basin (Colorado River floodplain). The Chuckwalla Valley basin receives ephemeral surface flow from Pinto Valley in the northwest but is a closed basin with surface drainage terminating in playa lakes (Palen Lake and Ford Dry Lake) in the central portions of the valley. The Palo Verde Mesa basin drains eastward toward the Colorado River
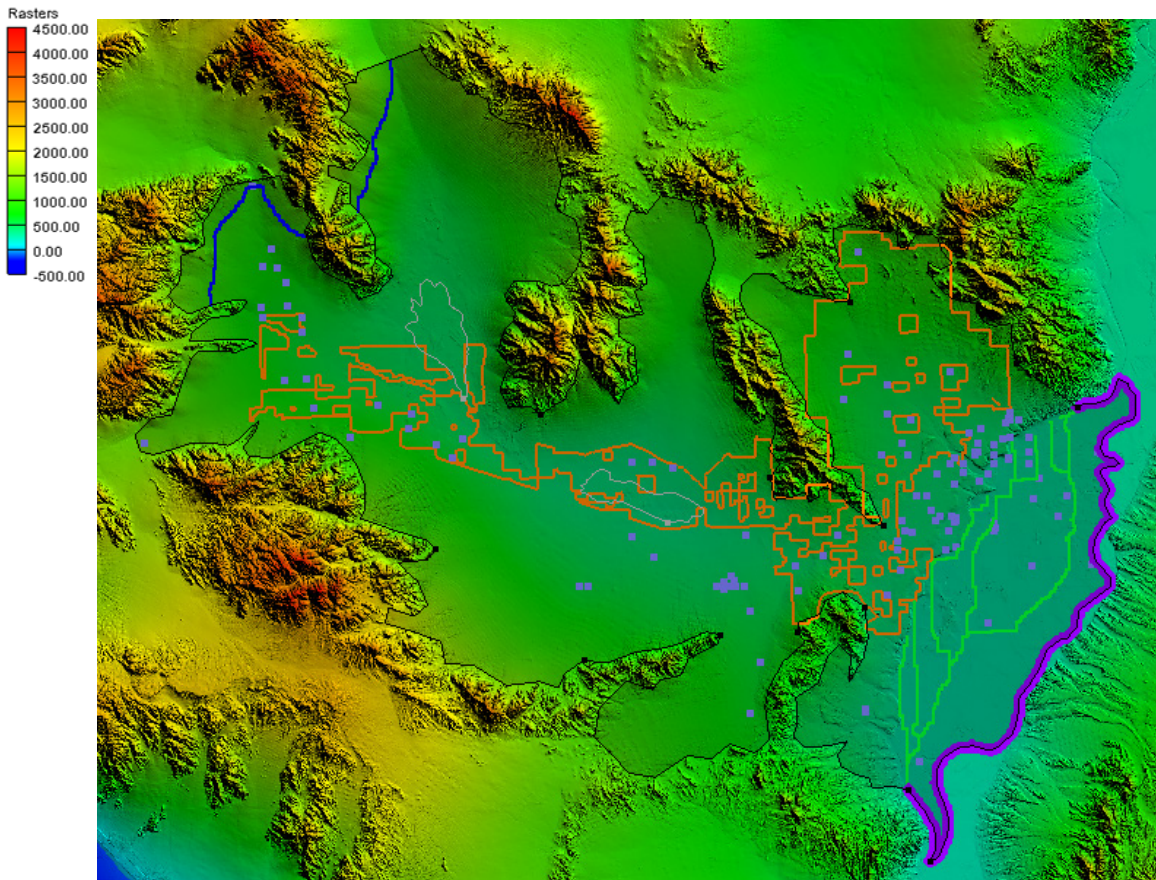
Figure 2 Riverside East Area Surface Elevations (in ft) and Numerical Model Grid Features (model grid is outlined in black, SEZ is outlined in red, present-day wells are represented by purple squares, irrigation canals are represented by drain cells [green line], the Colorado River is represented as a series of constant-head cells on the eastern edge of the model [purple line], and the Colorado River Aqueduct is represented by river cells [blue line] near the northwestern edges of the model)

floodplain by numerous ephemeral streams, primarily McCoy Wash in its northern portion. Segments of the Colorado River Aqueduct run through the western edges of the Chuckwalla Valley basin (Figures 1 and 2). The Kaiser mining area is near the Pinto Valley on the western edge of the Chuckwalla Valley, and scattered agricultural areas are located throughout the basins.

2.2 Aquifer Characteristics

The maximum thickness of the alluvial sediments in the basins, estimated from borehole logs, ranges from approximately 700 ft (213 m) to more than 1,200 ft (366 m) (Metzger et al. 1973; CDWR 1979). However, WorleyParsons (2009) presented an analysis of previously obtained USGS Bouger residual gravity data (see Mariano et al. 1986) that suggested greater depths to bedrock in some parts of the basins, up to over 1 mi (1.6 km) (e.g., in the pronounced local elevation low in the center of Chuckwalla Valley). For this study, the relationships among the gravity modeling results, the residual gravity data, and the observed elevations of the bedrock surface from borehole logs were all used to estimate the elevation of the bedrock surface across the three modeled groundwater basins (Figure 3). The estimated and observed bedrock elevations were used to define the lower boundary of this groundwater flow model.
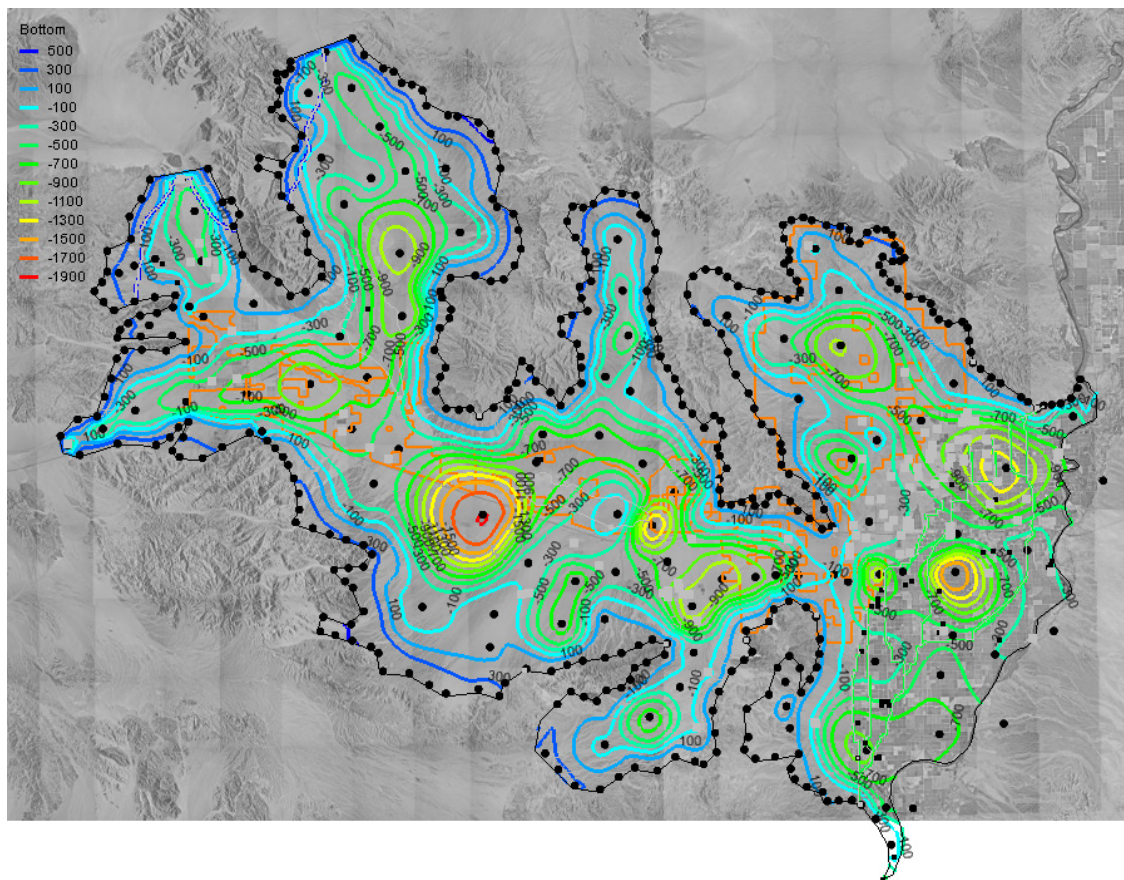
Figure 3 Interpolated Bedrock Elevation Contours Used as the Bottom Surface of the Model (contours are in m, and elevation control points are shown in black)

2.3 Hydraulic Conductivity of the Alluvial Fill

The principal aquifer consists of alluvium, marginal marine, and fanglomerate deposits on top of a metamorphic bedrock basement complex (Metzger et al. 1973; CDWR 2003). The Quaternary age alluvium sediments consist of alluvial fan and river deposits of fine to coarse sands intermixed with layers of gravel, silt, and clay. The underlying Bouse Formation consists of alluvial fan and marine deposits of limestone interbedded with clays, silt, and sand, and it overlies the late Tertiary age fanglomerate deposits (Wilson and Owen-Joyce 1994). These materials have a wide range of hydrogeologic properties, and the properties vary spatially depending on depth and proximity to mountains. Transmissivity values for the principal aquifer have been reported to range from 13 to 94,000 ft^2/d (1.2 to 8,733 m^2/d) (Metzger et al. 1973). When these values are translated into hydraulic conductivity (K) values across the range of estimated depths in this model, the range in K is approximately 0.026 to 9,400 ft/d (0.0002 to 873 m/d).

2.4 Water Budget Estimates

The Solar PEIS reported a groundwater budget for the Chuckwalla Valley and Palo Verde Mesa basins using the information from the California Department of Water Resources (CDWR) and environmental impact statements for solar developments in the Riverside East SEZ (BLM 2010a,b). CDWR Bulletin 118 characterizes the water budget information for the Chuckwalla Valley and Palo Verde Mesa groundwater basins as being "Type C," meaning few data are available (CDWR 2003). Further analyses have suggested that groundwater recharge is less than previously thought and that overdraft conditions (i.e., groundwater outflow and withdrawals exceeding inputs) have been occurring for decades (Godfrey et al. 2012). The development of the Riverside East SEZ Model involved updating the water budget for the Chuckwalla Valley and Palo Verde Mesa groundwater basins from the values reported in the Solar PEIS to better reflect recent analyses (Greer et al. 2013).

Recharge to the basins occurs as 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, streamflow recharge, in-place recharge, and aqueduct leakage. Natural recharge in the Palo Verde Mesa groundwater basin is estimated to be 800 ac-ft/yr (2,702 m^3/d) (CDWR 1975). Assuming the same rate per unit area for the other two basins in the modeled area, the total natural recharge for the model area would be 3,200 ac-ft/yr (10,800 m^3/d).

Although not documented, leakage is likely from the Colorado River Aqueduct (CRA), which runs across the western edge of the Chuckwalla Valley basin. The CRA began operations in 1942. To estimate potential leakage from the CRA into the Chuckwalla Valley basin, leakage rates were assumed to be similar to leakage rates of the much younger Central Arizona Project (CAP) canal, completed in the early 1990s. In the Ranegras Plain groundwater basin in southwestern Arizona, the CAP canal leaks at an estimated rate of 2,000 to 3,000 ac-ft/yr (6,760 to 10,100 m^3/d) (ADWR 2010). For the Brenda SEZ Model of the Ranegras Plain basin (Quinn et al. 2013), CAP leakage was applied as a component of aerially distributed recharge at

a rate of 2,500 ac-ft/yr (8,440 m^3/d). Considering that the CRA is much older than the CAP and that both are of similar lengths within the Riverside East SEZ Model and Brenda SEZ Model, a reasonable initial estimate of CRA leakage in the Chuckwalla basin would be 80% of the CAP leakage or 2,000 ac-ft/yr (6,760 m^3/d). Split between the two segments within the model area, the rates are 900 ac-ft/yr (3,040 m^3/d) in the northern portion and 1,100 ac-ft/yr (3,720 m^3/d) in the northwest portion.

Documented groundwater inflows to the basins as underflow from adjacent basins are from the Pinto and Orocopia Valleys to the west. The values are presented in Table 1 (Godfrey et al. 2012).

The majority of groundwater withdrawals in the region of the Riverside East SEZ are for agricultural and domestic uses, with an unreported withdrawal from the former Kaiser mining wells in the western Chuckwalla Valley basin. There are 88 identifiable pumping wells in the USGS's National Water Information System (NWIS) database (USGS 2012) that are located within the Riverside East SEZ Model domain. The CDWR estimated that during dry and wet years occurring from 1998 to 2001, total well withdrawals in the basins ranged from 4,400 to 5,700 ac-ft/yr (14,860 to 19,250 m^3/d) (CDWR 2005). For Phases 1 and 2 of this study, pumping was assumed to be the average of the range presented by CDWR (2005), for a total of approximately 5,100 ac-ft/yr (17,200 m^3/d). The total pumping rate was divided among each of the 88 identifiable pumping wells, which resulted in a withdrawal rate of approximately 58 ac-ft/yr (196 m^3/d) per well.

Table 1 Estimates of Selected Components of Riverside East SEZ Model Inflows and Outflows

Groundwater Inflows		Groundwater Outflows	
Process	Value	Process	Value
Recharge	3,200 ac-ft/yr	Total withdrawals	Negligible in Phase 1, 5,100 ac-ft/yr in Phases 2 and 3[a]
Underflow	Pinto: 937 ac-ft/yr, Orocopia: 658 ac-ft/yr	Evapo-transpiration	350 ac-ft/yr at Palen Lake
CRA leakage	None in Phase 1, 2,000 ac-ft/yr in Phases 2 and 3		
Estimated inflow totals[b]	4,795 ac-ft/yr in Phase 1, 6,795 ac-ft/yr in Phases 2 and 3	Estimated outflow totals[b]	350 ac-ft/yr in Phase 1, 5,450 ac-ft/yr in Phases 2 and 3

[a] Withdrawal values for Phase 3 do not include water pumping estimates for solar facilities.

[b] Totals do not include contributions from the Colorado River.

Sources: CDWR (1975, 2005), Godfrey et al. (2012), ADWR (2010)

Evapotranspiration rates are estimated for Palen Lake on the basis of information presented in Godfrey et al. (2012). However, the observation of near-surface water levels adjacent to Palen Lake are associated with a local perched water table and are not indicative of the predominant aquifer system in the Chuckwalla Valley; they would not be simulated in this one-layer model structure.

As can be seen in Table 1, the estimated model inflows are larger than the outflows. This is mainly due to the omission of flows related to the Colorado River and Palo Verde Irrigation District (PVID) drainage ditches, which are expected to be predominantly outflows from the study area (through the PVID drainage ditches). Godfrey et al. (2012) summarized and evaluated a range of recharge and discharge estimates for the Chuckwalla Valley basin. There is greater certainty with regard to the recharge estimates on the lower end of the range, indicating that mining of groundwater may have been occurring for decades. For this study, individual inflow, recharge, and evapotranspiration components used in the groundwater model (see Table 1) are in the lower end of the previously reported ranges described by Godfrey et al. (2012).

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3 MODEL SETUP

Numerical groundwater modeling (using finite differences) was performed with the USGS code MODFLOW 2000. Several MODFLOW packages were used, including the river (RIV), drain (DRN), and constant-head boundary/time-variant specified head (CHD) packages. Pre- and post-processing was performed by using Groundwater Modeling System (GMS) software Version 8.3 with support from ArcMap 10.

3.1 Grid Design

The grid for the numerical model is designed with a constant cell size of 656 × 656 ft (200 × 200 m) across the model (Figure 2). The model is created with a single layer. Further groundwater modeling analyses could incorporate lithologic details in a multilayer model, with distributed properties in each layer. Ground surface elevations were obtained in Digital Elevation Model (DEM) format from the USGS (Gesch et al. 2002; Gesch 2007). Geographic information system (GIS) tools in ArcMap 10 were used to reduce the DEM data set to a manageable number of points for use in GMS. GIS tools were also used to determine the layer thickness/depth to bedrock in the model domain. A series of points were traced around the edge of the basins along the alluvium/bedrock boundary, and the ground elevation of each point was determined. Throughout the central portions of the basins, the bedrock elevations were determined at several locations (as described in Section 2.2). These two sets of points were combined, and the elevation of the top of the bedrock was interpolated by using the natural neighbor algorithm (Figure 3). In GMS, the bedrock surface and the ground surface created the boundary of the three-dimensional modeling domain.

3.2 Boundary Conditions

The bottom of the flow domain is a no-flow boundary represented by the bedrock surface. Subsurface flow is to the east, originating from a combination of inflows (described above) including the Colorado River Aqueduct (modeled as RIV cells) near the Eagle and Coxcomb Mountains. Subsurface flows discharge to the Palo Verde Irrigation District ditches in the Palo Verde Valley (modeled as DRN cells) and to the Colorado River (modeled as changing head, or CHD, cells). The ditch elevations (i.e., elevations of the DRN cells) were set based on the survey results from the USGS Colorado River Accounting Surface study (Weile et al. 2008). The Colorado River serves as a water source in its upstream portion and as a discharge source in its downstream portion. Other lateral boundaries are no-flow and generally follow the boundary between the alluvium and the bedrock mountains.

3.3 Layer Discretization

Aquifer tests performed in the Chuckwalla Valley and Palo Verde Mesa basins exhibited a range of behavior, but the alluvial fill aquifer is treated as unconfined, and this study uses only one model layer. In the Palo Verde Mesa, observation wells indicated both unconfined and semi-

confined conditions in the Quaternary alluvium and within the Bouse Formation (AECOM 2010b). Tests northwest of Desert Center indicated a similar mix of behaviors within the same formations (GEI Consultants, Inc. 2010). In the central portion of the SEZ near Ford Dry Lake, shallow observation wells in the Quaternary alluvium exhibited unconfined behavior, while deeper wells within the Bouse Formation indicated confined conditions beneath low-permeability sediments between 185 and 260 ft (56 and 79 m) below ground surface (WorleyParsons 2009). These low-permeability sediments are presumed to be related to lacustrine and playa deposits at the base of the Quaternary alluvium and/or distal estuarine deposits at the top of the Bouse Formation at the end of the California embayment (WorleyParsons 2009; Metzger et al. 1973). In either case, low-permeability sediments are present in the valley center, but they are likely to grade laterally into coarser sediments toward the basin margins (Buising 1990, WorleyParsons 2009) and not serve as a confining unit across the entire width of the valley. Using a one-layer approach is thus deemed to be acceptable for this study.

3.4 Initial Conditions

With the exception of the changing head boundary imposed along the Colorado River, starting heads in the Phase 1, steady-state, pre-1942 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 convert to dry cells, as expected. Starting conditions for Phase 2 were the hydraulic heads resulting from the Phase 1 steady-state simulation. Starting conditions for Phase 3 were the hydraulic heads resulting from the Phase 2 calibrated model at the simulation end point in 2011.

3.5 Calibration Targets

All field observations for wells within the Riverside East SEZ Model domain were downloaded from the USGS's NWIS database (USGS 2012). For the Phase 1 steady-state simulation, observed hydraulic heads at 5 wells scattered throughout the three basins were used as calibration targets. These were the only measurements found immediately prior to 1942 in the NWIS database. For the Phase 2 transient simulation between 1942 and 2010, 118 wells from the NWIS database and 6 additional wells associated with solar facility hydrogeologic analyses were used (WorleyParsons 2009; West Yost Associates 2011). Heads measured between 2000 and 2010 at these 124 wells were used as the observation points for calibration at the end of the Phase 2 simulation. This was considered sufficient for this study, since water levels were relatively stable in the 1990s and 2000s after partially recovering from relatively depressed levels in the 1980s.

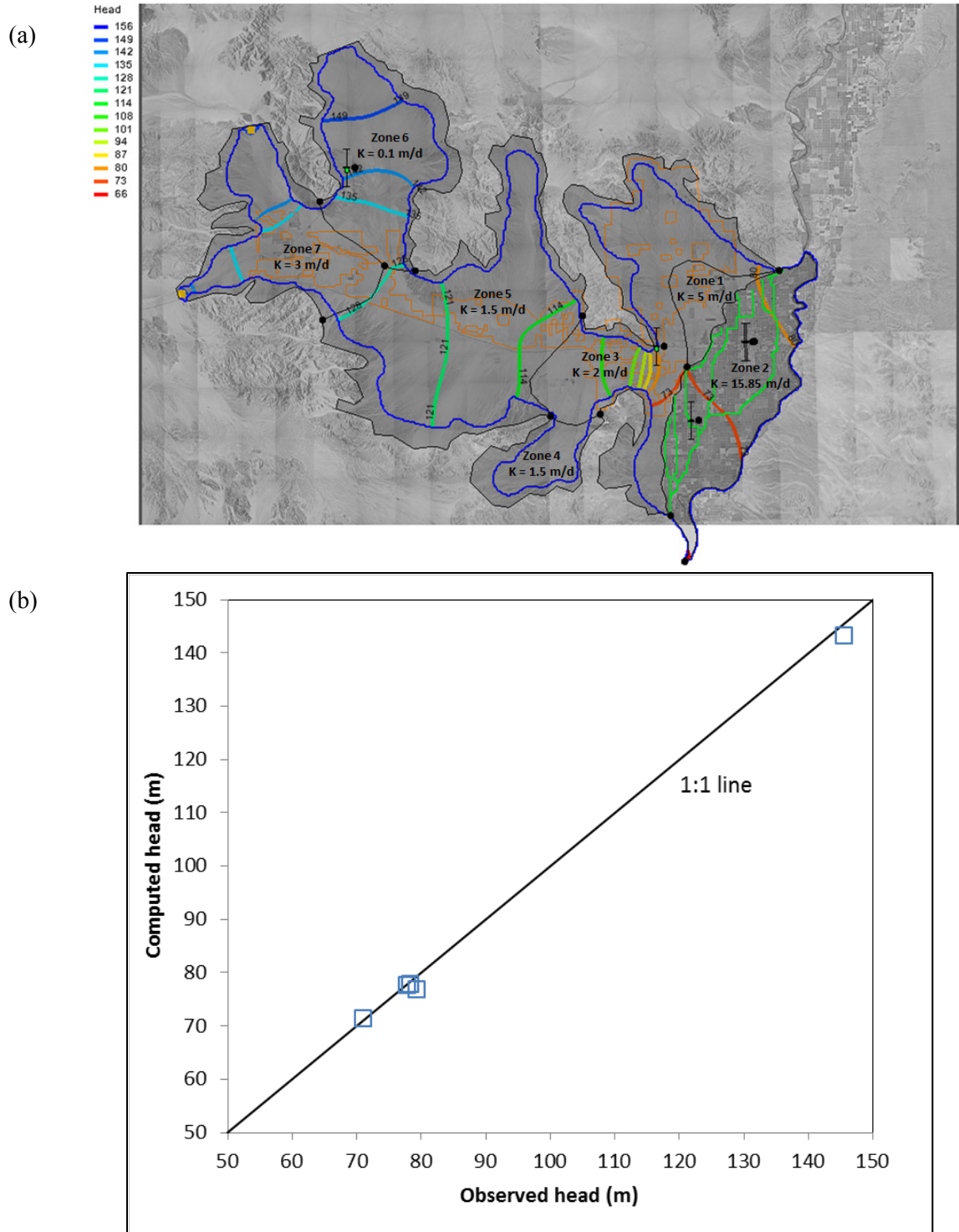# 4 RESULTS AND DISCUSSION

4.1 Phase 1 — Steady-State Model

Hydraulic conductivity, K, was varied manually across the model in seven zones in order to match the pre-1942 target hydraulic head values at five observation points in the basins and to optimize model convergence. Zones with similar K values were manually delineated, and K values were iteratively adjusted based on a combination of hydrostratigraphic information (e.g., higher K values in the Palo Verde Valley basin trending to lower K values away from the river) and optimization to corresponding observed heads (e.g., lower K values near Palen Lake to match a higher observed head) at the five observation points. The resulting K values ranged from 0.3 to 52 ft/d (0.1 to 15.85 m/d). Calibrated heads and K-zones are shown in Figure 4a. Recharge values were varied only slightly in the Phase 1 simulation, but no improvement in performance was seen. Therefore, calibration did not result in a change in recharge values from the initial estimate of 3,200 ac-ft/yr (10,800 m^3/d). The head targets for Phase 1 had minimal errors (Figure 4b). The water budget error for Phase 1 in the MODFLOW model was 0.00%.

4.2 Phase 2 — Transient Model

The Phase 2 transient model, representing decades of agricultural, mining, and municipal pumping, was used to simulate the changes in groundwater elevations between the start of CRA operation in 1942 and recent conditions (2000 to 2010). The transient model was designed with 69 one-year time steps representing 69 years of averaged annual agricultural, mining, and municipal pumping at 5,100 ac-ft/yr (17,200 m^3/d) (Table 2). This is a simplification of actual, annually varying pumping, but it is considered suitable for creating the initial conditions for the Phase 3 simulation.

A specific yield of 0.1 was applied to all model cells. This value is based on previous work (Weile et al. 2008; Leake et al. 2008; WorleyParsons 2009; AECOM 2010a,b; GEI Consultants, Inc. 2010) that used a range of 0.05 to 0.2 for specific yield within the three modeled basins (Table 2).

The spatially-variable K and recharge distributions were calibrated by using the MODFLOW Parameter Estimation Tool (PEST) utility. The pilot point method was used in the PEST utility; it interpolates values from a set of starting points (called pilot points) and inversely tries to match calculated head values with head values taken from monitoring wells (called observation points). Eighteen pilot points were chosen, and their starting K and recharge values were derived from the results of the Phase 1 simulation. The PEST inverse model initially interpolated between the starting pilot point values so that values varied from cell to cell throughout the model. When the inverse model ran, the values at the pilot points were iteratively adjusted and re-interpolated to the grid cells to produce a set of simulated heads calibrated to the 124 observation points described in Section 3.5. The majority of the Phase 2 model area had PEST-derived K values (Figure 5) that were similar to K values reported in aquifer tests or were from previous groundwater models calibrated to aquifer test results (Table 2; Leake et al. 2008; WorleyParsons 2009; AECOM 2010a,b; GEI Consulants, Inc. 2010).

(a)

(b)

Figure 4 (a) Calibrated Pre-1942 Steady-State Head Contours (in m) (blue outline defines the saturated extent, K-zones are outlined in black with labels, and the five observation points are identified by statistical error bars, +/–10 m, lined in black) and (b) Computed Versus Observed Heads at Observation Points for the Pre-1942 Steady-State Model

Table 2 Comparison of Selected Variables from Groundwater Flow Models Developed across the Riverside East SEZ

| Variable	This Study	Eagle Mountain Pumped Storage Project	Desert Sunlight Solar	Genesis Solar	Blythe Solar	USGS Accounting Surface
Citation		GEI Consultants (2010)	AECOM (2010a)	WorleyParsons (2009)	AECOM (2010b)	Leake et al. (2008)
Model type	1-layer head	Analytical: Taylor series approximation to the Theis nonequilibrium well function	1-layer superposition modified (Leake et al. 2008)	13-layer (L1–L13) superposition	1-layer superposition modified (Leake et al. 2008)	1-layer superposition
Notes		Low-K deposits (through 900 ft deep) were assumed to preclude a lower aquifer zone; thus, b is only 150 ft, but some wells there are up to 1,300 ft deep	Considered four zones: Zone 1: western Chuckwalla Valley, Zone 2: central Chuckwalla Valley, Zone 3: eastern Chuckwalla Valley, and Zone 4: Palo Verde Mesa	K's and T's derived using method described by Driscoll (1986). Confining unit interpreted from geophysical data in valley center and applied over valley width.	Considered two scenarios with a low and a high transmissivity	Considered two scenarios with a low and a high transmissivity
Hydraulic conductivity, K	0.002–505 ft/d; 90% of model is in 0.3–328 ft/d range	25–125 ft/d; Lakebeds: 0.02–7.1 ft/d	Zone 1: 12.6–57 ft/d Zone 2: 2–7 ft/d Zone 3: 12.6–42 ft/d Zone 4: 52–173 ft/d	Alluvium: 30 ft/d Bouse: 2×10^{-4} to 14 ft/d Fanglomerate: 15 ft/d	12.6 ft/d, 52 ft/d	12.6 ft/d, 52 ft/d
Transmissivity, T		7,486 ft^2/d	Zone 1: 6,300–8,500 ft^2/d Zone 2: 1,000 ft^2/d Zone 3: 6,300 ft^2/d Zone 4: 26,000 ft^2/d		6,300 ft^2/d, 26,000 ft^2/d	6,300 ft^2/d, 26,000 ft^2/d
Specific yield	0.1	0.05	Zone 1: 0.05–0.2 Elsewhere: 0.2	Alluvium: 0.15 Bouse & fanglomerate: 5×10^{-7} to 2×10^{-5}	0.2	0.2

Table 2 (Cont.)

Variable	This Study	Eagle Mountain Pumped Storage Project	Desert Sunlight Solar	Genesis Solar	Blythe Solar	USGS Accounting Surface
Aquifer thickness	Variable, 33 to >5,280 ft	150 to 300 ft	Two scenarios: 500 ft and 150 ft	Constant for L1–L11 (10 to 420 ft); varies with bedrock elevation for L12–L13 (<600 ft to bedrock surface range)	500 ft	500 ft
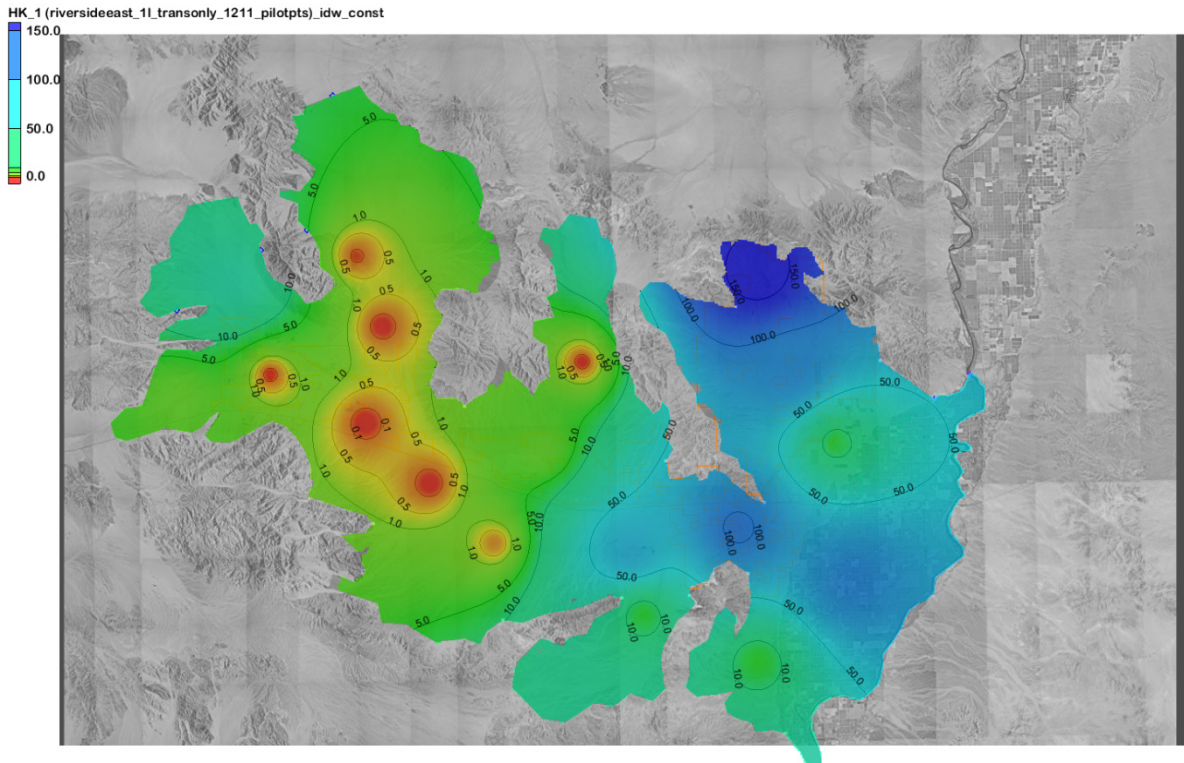
Figure 5 Distribution of Hydraulic Conductivity from the Calibration of the Transient 1942–2010 Model Using PEST (contours in m/d)

Due to the increased number of observation points and calibration parameters between the Phase 1 steady-state model (5 observation points and 7 K zones) and the Phase 2 transient model (124 observation points and 18 pilot points for both K and recharge), there is a wider variability in the calibrated K values for Phase 2, ranging from 0.002 to 505 ft/d (0.00061 to 158.6 m/d) (Figure 5), than in those for Phase 1 (Figure 4a). Only isolated locations immediately adjacent to PEST pilot points had K values that were either less than 0.3 ft/d (0.1 m/d) or greater than 328 ft/d (100 m/d) in the Phase 2 model. Recharge values did not change from the Phase 1 values as a result of the PEST process.

Final hydraulic heads from the Phase 2 transient model indicated a shallow gradient in the eastern half of the Chuckwalla Valley and a steeper gradient in the western half to match the higher groundwater elevations observed near Desert Center (Figure 6a). This finding is consistent with expectations. The target heads for Phase 2 are values from 124 wells scattered throughout the basin. However, the range of observation dates at each well varies between 2000 and 2010; the values do not represent a single snapshot in recent time. In addition, the head measurements may be affected by localized hydrogeology, perching, well construction, well depth, and proximity to localized concentrated recharge (e.g., from major washes or the CRA). Therefore, model results at the end of the 69-year period were inspected and compared to recent heads in the study area. Despite the noise in the target head values, it was determined that the
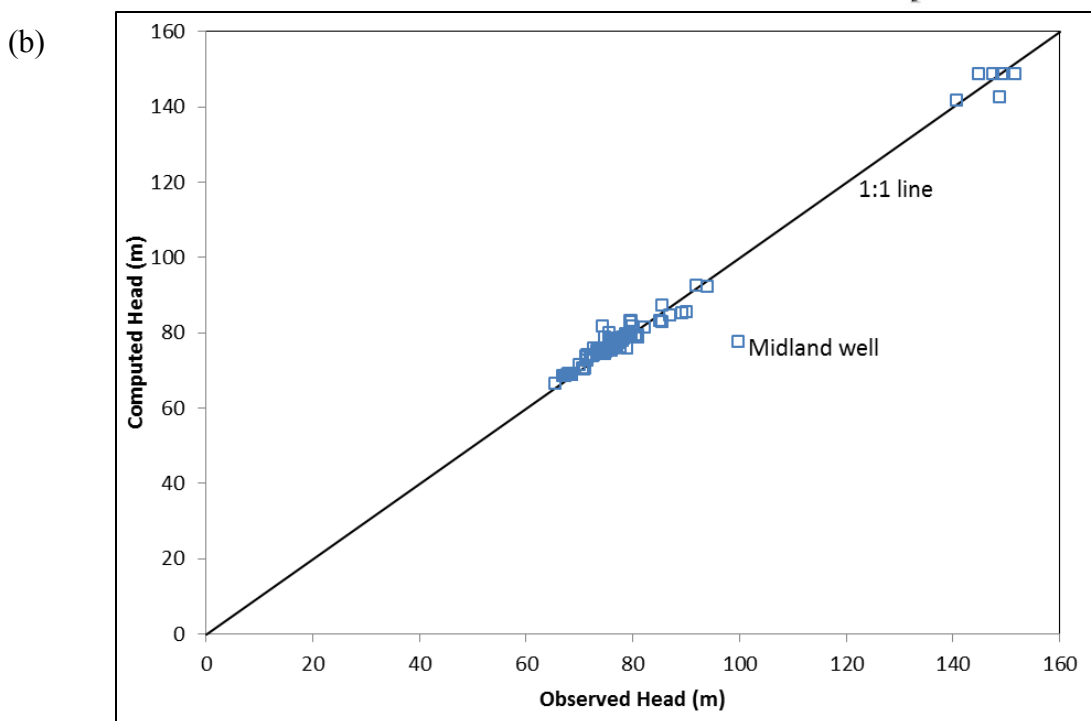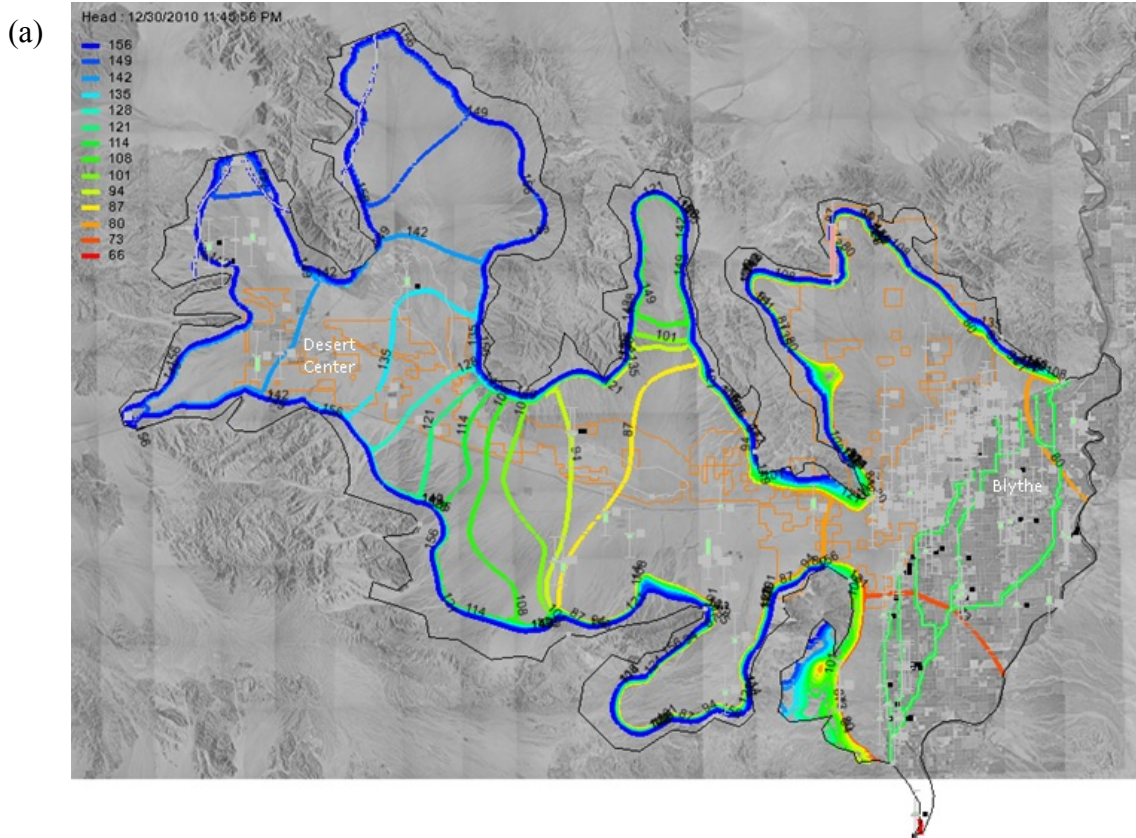
Figure 6 (a) Transient Model Estimated Heads after 69 Years of Agricultural, Mining, and Municipal Pumping (contours in m) between 1942 and 2010; (b) Calibration Results for the Final Time Step of the Phase 2 Model (the outlier point is from the Midland well at the northern border of the Palo Verde Mesa groundwater basin)

Phase 2 final heads (Figure 6b) matched the observed target heads adequately. An outlier value was identified (a well with a 99-m observed head) near the former town of Midland, located at the northern border of the Palo Verde Mesa.

Model Sensitivity

PEST is an optimization tool that aims to match 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 recharge). The linearization is conducted using a Taylor series expansion, where the partial derivatives of each model output with respect to every parameter must be calculated in each iteration. These derivatives provide a measure of the parameter sensitivities, and the "composite sensitivity" is provided by PEST.

Figure 7 shows the results of the sensitivity analysis for K and recharge values at each of the 18 pilot point locations. The model is most sensitive to K at the pilot points located along the central flow path through the Chuckwalla Valley and relatively insensitive to the recharge parameters.

4.3 Phase 3 — Transient Model with Solar Development

The potential groundwater withdrawal rates at an SEZ depend on the type of technology and the level of development at the SEZ. Three levels of withdrawals were considered for the Phase 3 simulations. The high-water-demand scenario has a total withdrawal of 16,898 ac-ft/yr (57,090 m^3/d), representing full build-out of dry-cooled, concentrated solar power facilities. The second scenario has a medium value of 8,450 ac-ft/yr (28,550 m^3/d), pumping half of the high-withdrawal scenario. The low-pumping scenario of 672 ac-ft/yr (2,270 m^3/d) is for full build-out of photovoltaic facilities. These rates are for the operational stage of solar facility implementation as defined in the Solar PEIS (BLM and DOE 2012); they do not include groundwater withdrawal estimates for construction and reclamation activities. In addition to the high-, medium-, and low-water-demand withdrawal rates, the baseline pumping from the Phase 2 calibrated transient model (i.e., 5,100 ac-ft/yr [17,200 m^3/d]) was included in the Phase 3 model.

High-Water-Demand Withdrawal Scenario

To evaluate worst-case conditions from 20 years of SEZ pumping, the high-water-demand withdrawal rate was applied from 2011 to 2030 and divided equally among 19 assumed well locations within the SEZ boundary, resulting in a rate of 889 ac-ft/yr (3,000 m^3/d) per well. The locations of the assumed pumping wells in the SEZ can be seen in Figures 8, 9, and 10. The only portion of the Riverside East SEZ not containing simulated pumping wells in these scenarios is the SEZ area to the northeast of McCoy Wash on the Palo Verde Mesa.
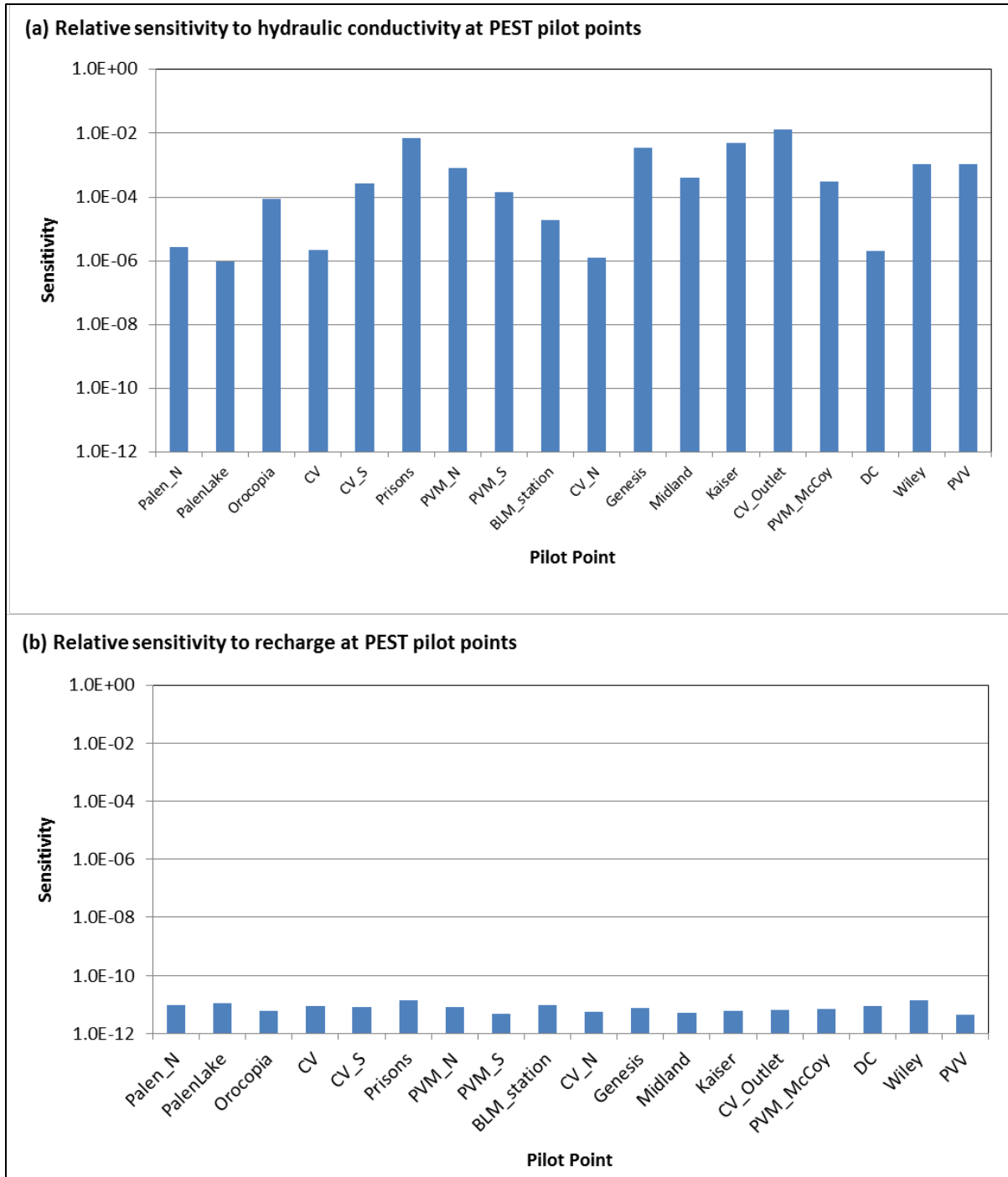
Figure 7 Relative Sensitivities of the Transient Model to (a) Hydraulic Conductivity and (b) Recharge at Pilot Points Used in the PEST Calibration Process

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The simulated distribution of hydraulic heads in 2030 resulting from the withdrawals associated with the high-water-demand scenario (Figure 8) indicates a general west-to-east flow, but with several deflections in the groundwater contours within the Chuckwalla Valley. There is a major decrease in groundwater elevations south of Palen Lake (as indicated by upgradient deflections in the elevation contours), with minor deflections north of Ford Dry Lake and east of the town of Desert Center. Additional modeling was conducted to examine the relative difference between the combined effect of SEZ pumping and baseline pumping (from agricultural, mining, and municipal wells) and the effect of baseline pumping alone during the Phase 3 time frame. The results show that after 20 years, the drawdown attributed to withdrawals from the SEZ may be up to 131 ft (40 m) at the center of the major cone of depression south of Palen Lake and over 6.5 ft (2 m) across most of the Chuckwalla Valley basin, with higher drawdown in the western portion of the basin (Figure 9). The simulated groundwater drawdown results are consistent with the one-dimensional analysis presented in the Solar PEIS that suggested there was a potential for
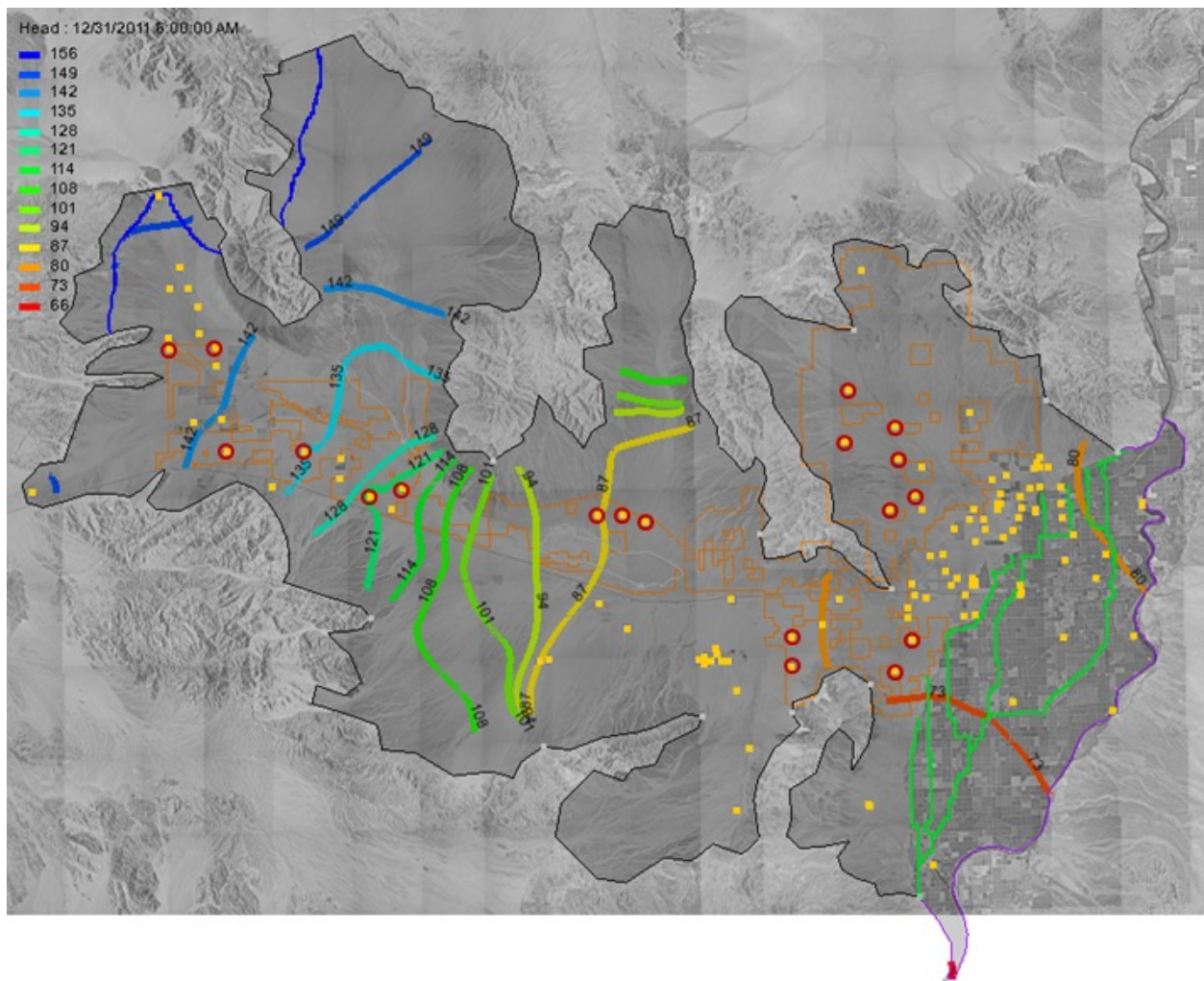
Figure 8 Calculated Heads after 20 Years of SEZ Pumping Considering the High-Water-Demand Scenario in Addition to Withdrawals for Agricultural, Mining, and Municipal Uses (contours in m) (pumping wells are yellow squares, with SEZ wells highlighted by red circles)
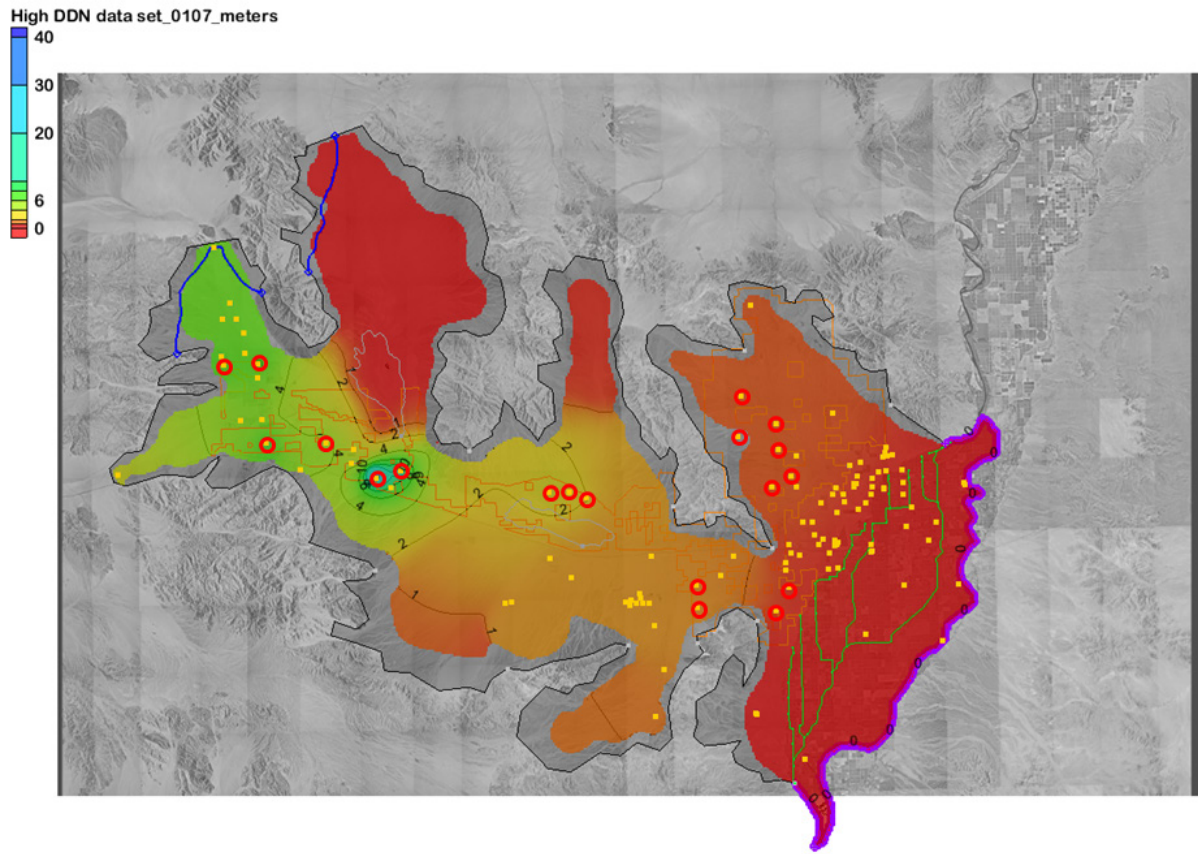
Figure 9 Additional Drawdown Due to a Simulated 20 Years of SEZ Pumping Considering the High-Water-Demand Scenario (contours in m) (pumping wells are yellow squares, with SEZ wells highlighted by red circles)

drawdown to exceed 100 ft (30 m) but that the majority of the SEZ would see drawdown values on the order of tens of feet (BLM and DOE 2012). The sharp increase in drawdown south of Palen Lake is directly attributable to the rate of pumping combined with the decrease in hydraulic conductivity in the western half of the Chuckwalla Valley during the PEST calibration process. Groundwater and geophysical investigations near Ford Dry Lake (WorleyParsons 2009) indicate that there is a considerable thickness of low-permeability sediment between 185 and 260 ft (56 and 79 m) below the ground surface in the center of the valley in this area. The Genesis solar wells are installed below this low-permeability zone. The effect shown in this model scenario likely overstates the maximum drawdown effect due to the simplification of the basin hydrostratigraphy. Any additional hydrogeological information obtained in the basins and incorporated into the model would change the outcome of this simulation and the estimate of drawdown from pumping.

Even under conditions representing withdrawal rates for the high-water-demand scenario, the final simulated heads are above the Colorado River Accounting Surface. As seen in Figure 8, the elevation contour (73 m, or 239.5 ft) equivalent to the Accounting Surface elevation for the Chuckwalla Valley (238–240 ft) is located downgradient in the Palo Verde Mesa and Palo Verde Valley groundwater basins.

The simulated groundwater elevations in the Palo Verde Mesa portion of the SEZ (242.8–282.2 ft or 74–86 m) are also above the Accounting Surface elevations for that area (218–274 ft or 66–84 m).

Decreases in the water level in the western portion of the Chuckwalla Valley could potentially affect phreatic vegetative communities in this region, particularly in the area to the south of Palen Lake that shows significant drawdown as a result of the high-water-demand scenario.

Medium- and Low-Water-Demand Withdrawal Scenarios

For the medium-water-demand scenario, each of the 19 SEZ pumping wells was assumed to pump at a rate of 445 ac-ft/yr (1,500 m^3/d) from 2011 to 2030. After 20 years of groundwater withdrawals from the SEZ under the medium-water-demand scenario, the additional drawdown in the basin was a maximum of 39 ft (12 m) south of Palen Lake but less than 6.5 ft (2 m) elsewhere in the SEZ (Figure 10). Although the drawdown is less than that seen in the high-water-demand scenario, there could be impacts on phreatic vegetation in areas that experience large drawdowns as a result of the pumping for the medium-water-demand scenario.
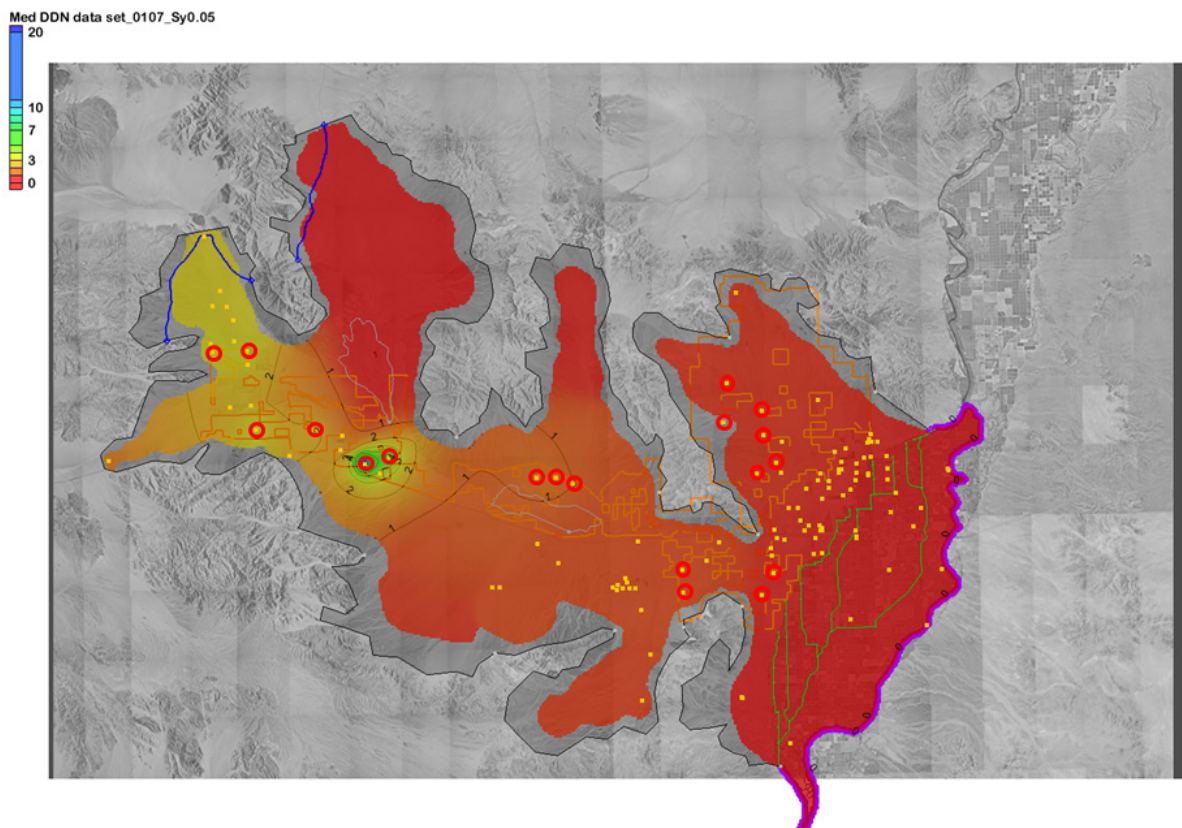
Figure 10 Additional Drawdown Due to a Simulated 20 Years of SEZ Pumping Considering the Medium-Water-Demand Scenario (contours in m) (pumping wells are yellow squares, with SEZ wells highlighted by red circles)

For the low-water-demand scenario, the per-well withdrawal rate was 35 ac-ft/yr (118 m^3/d). After 20 years when there were withdrawals from the SEZ under the low-water-demand scenario, the additional groundwater drawdown was small (Figure 11). Impacts are anticipated to be very small as a result of pumping for the low-water-demand scenario.

4.4 Summary

The Riverside East SEZ Model is a single layer model that simplifies the geology of the Chuckwalla Valley and the Palo Verde Mesa groundwater basins. The model was developed by using available data on the aquifer characteristics and on hydrologic processes that establish initial and boundary conditions. Recent analyses and additional information about the groundwater budget that differs from the information presented in the Solar PEIS were incorporated into the model development (BLM and DOE 2012). In particular, the recharge and underflow values given in previous presentations are now thought to be too high; the values presented here are lower and represent the BLM's most current understanding of the basins (Godfrey et al. 2012). The Riverside East SEZ Model provides a three-dimensional representation of groundwater drawdown that was not accounted for in the Solar PEIS analysis. The Solar PEIS presented a one-dimensional analysis of drawdown. This effort, however,
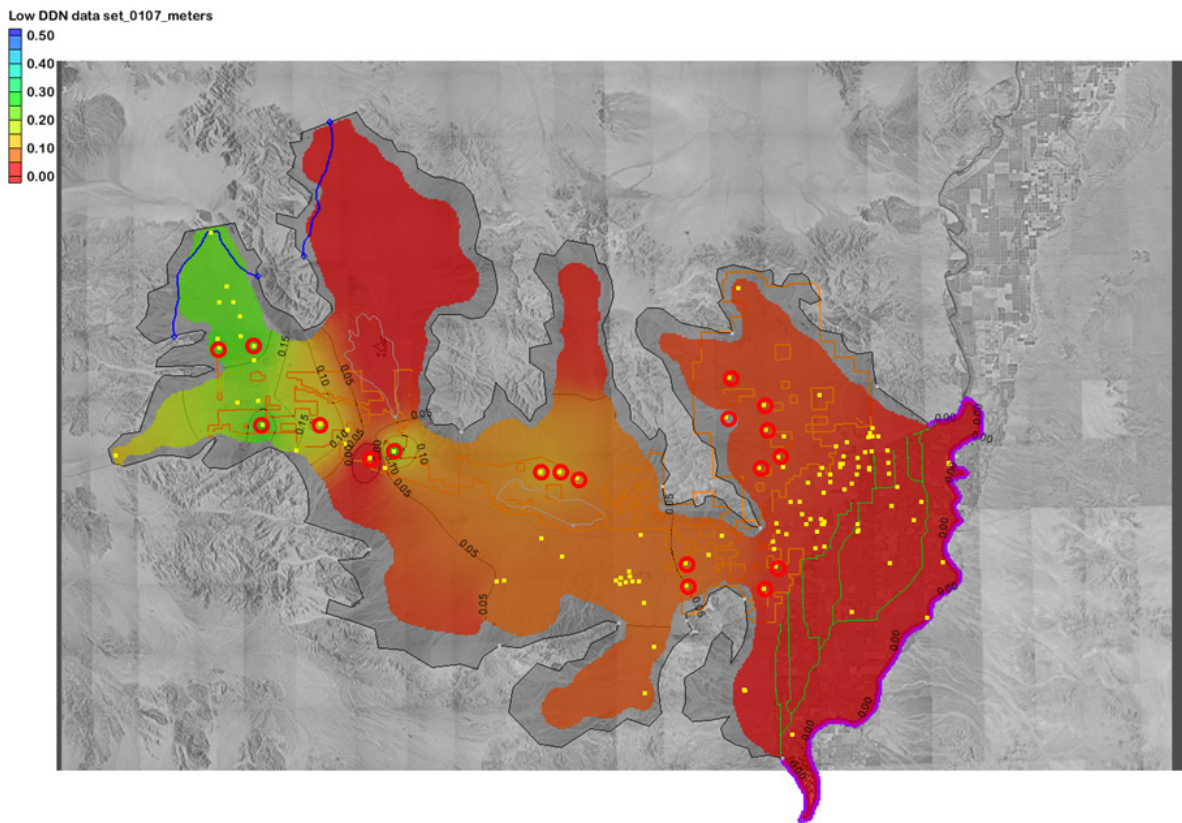

Figure 11 Additional Drawdown Due to a Simulated 20 Years of SEZ Pumping Considering the Low-Water-Demand Scenario (contours in m) (pumping wells are yellow squares, with SEZ wells highlighted by red circles)

provides a more detailed approach, including representation of variable hydraulic conductivity throughout the model domain.

The results of this analysis depend on assumptions about the hydrologic and geologic characteristics, as well as the locations of proposed pumping wells and water-demand scenarios associated with potential development. As solar facilities are planned, constructed, and begin operations, it is expected that new wells will be constructed and new data will be collected to refine the hydrologic and geologic assumptions used to build the Riverside East SEZ Model. Any new information incorporated into the model will change the results presented here. In addition, assumptions regarding the development of solar facilities should be revisited when improvements to the Riverside East SEZ Model are made, to provide a more accurate estimate of potential impacts on the basins.

The simulations performed for the high-, medium-, and low-water-demand scenarios that assume full build-out of the SEZ yielded results comparable to those from the more simplistic analyses used in the Solar PEIS (BLM and DOE 2012). Groundwater pumping has the potential to cause significant drawdown of groundwater elevations, but this effect would vary across the Riverside East SEZ, which was not represented in the Solar PEIS analyses. The aquifer characteristics in the region just to the south of Palen Lake (to the extent they are currently understood) lead to a significant cone of depression in groundwater elevations in the high- and medium-water-demand scenarios. Our preliminary modeling simulations suggest that groundwater drawdown would not affect the Colorado River Accounting Surface but could affect phreatic vegetative communities and sand dunes that are near Palen Lake. Further characterization of the hydrogeologic characteristics of this region is needed to improve the predictive capabilities of the Riverside East SEZ Model.

4.5 Implications for Future Model Development

Improvements to this assessment-level model could be made by incorporating new data regarding the hydrogeological framework and aquifer parameter values. The model's hydrostratigraphy could be changed. It is recommended that future models incorporate multiple layers to account for the lateral and vertical changes in hydraulic conductivity and aquifer behavior. Potential changes would be to include the (1) semi-confining units above the Bouse Formation in the northern portion of the Palo Verde Mesa and northwest of Desert Center and (2) confining low-permeability deposits in the eastern Chuckwalla Valley near Ford Dry Lake and the Genesis solar facility. Further, the inclusion of underlying confining layers would be accompanied by the need for a sensitivity analysis of the storage coefficient on the predicted groundwater drawdown related to solar operations. Drilling data could be used to support local discretization of multiple model layers. Also, the basal elevation surface could be adjusted in light of new information. Zonal and vertical changes could be made in the assignment of parameter values for alluvial materials. Some of this information could be obtained through SEZ site characterization during facility planning and development stages and through the logging of SEZ groundwater extraction wells or aquifer testing. The alluvium in the study area is highly spatially variable. Site-specific data would improve the design and accuracy of the model for assessing drawdown impacts.

Midland and Palo Verde Mesa Considerations

The majority of the residual calibration error in the Phase 2 model was due to the head difference at the Midland well. While no inflows have been documented in the northern portion of the Palo Verde Mesa groundwater basin, CDWR (1979) listed subsurface inflow as a possible source of recharge. The simulated head of 255 ft (77.7 m) at the Midland well observation point at the northern valley edge in the Palo Verde Mesa groundwater basin is 72 ft (22 m) below the observed head of 327 ft (99.7 m) in 2010. Without an influx of water upgradient (north) of Midland, the only substantial source of water to this well to be considered (outside of precipitation/mountain-front recharge) is from the Colorado River. However, the river stage is at a maximum elevation of only 283 ft (86.4 m), which is far below the observed head of 327 ft (99.7 m). It is possible that there is a small influx of groundwater from the Rice Valley to the north, across a low point in the gap between the Little Maria and the Big Maria mountain ranges or through fractures or carbonates in the basement rocks. Groundwater near Midland could also be "mounded" north of an unmapped low-flow fault that creates a hydraulic separation from the remainder of the Palo Verde Mesa groundwater basin.

According to the USGS NWIS database, the ground surface elevation at the Midland well is only 10 ft (3 m) lower than the ground surface elevation at wells immediately on the north side of the "divide" in the basin to the north (Figure 12; USGS 2012). However, the groundwater elevation at the Midland well (approximately 330 ft [100 m] above mean sea level) is 270 ft (82 m) lower than the greatest groundwater elevations in wells on the north side of the divide in the Rice Valley. This is similar to the elevation drop of more than 330 ft (100 m) from the documented Pinto Valley inflow location into the western Chuckwalla Valley, which involves alluvial inflow, groundwater "mounding" behind a fault zone, and possible interaction with basement carbonates in the area (USGS 2007, 2012). A similar groundwater inflow could exist from the Rice Valley at Midland. However, whether the depths/screen elevations of the Rice Valley wells are comparable to that of the Midland well is not known. The potential influx could be comparable to flows into the Chuckwalla Valley from the Pinto Valley and would significantly change (lower) the PEST-derived hydraulic conductivity in this area of the Palo Verde Mesa. This, in turn, could significantly increase the effect of solar facility pumping on groundwater and ephemeral surface water in the upper reaches of the northern Palo Verde Mesa, as well as on the Colorado River Accounting Surface.

4.6 Summary of Riverside East SEZ Model Files and Future Use

Modeling was performed by 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 useable by older or newer versions of GMS or by other commercial graphical user interfaces; however, their functionality cannot be guaranteed.

Within GMS, the project explorer includes MODFLOW-related items under the three-dimensional grid data. The solution file sets include:

- RiversideEast_1L_1107.gpr is the Phase 1, pre-1942, steady-state model.
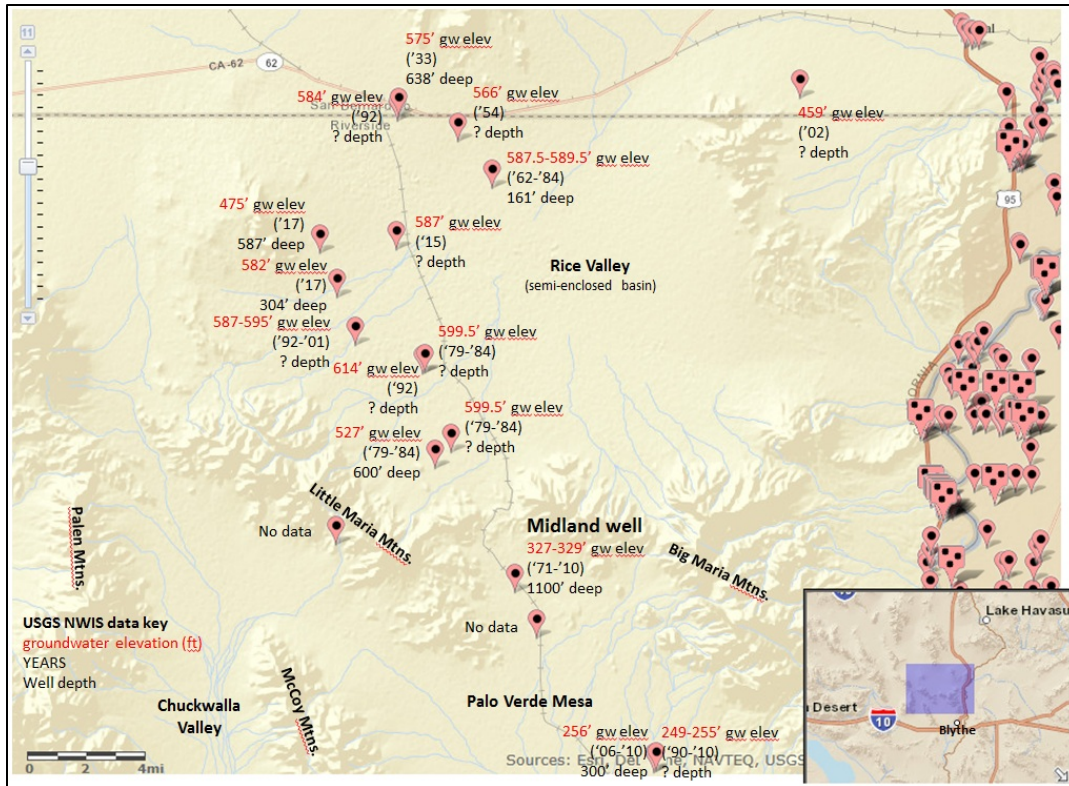
Figure 12 USGS NWIS Data for the Midland Well and Surrounding Wells in the Palo Verde Mesa and Rice Valley Groundwater Basins

- RiversideEast_1L_transONLY_1211_PilotPts.gpr is the Phase 2 transient model calibrated with parameter estimation for hydraulic conductivity, including baseline (i.e., agricultural, mining, and municipal) pumping for 69 years.

- RiversideEast_1L_transFWD_0107high.gpr is the Phase 3 model incorporating the effect of SEZ pumping. It uses the final heads from the calibrated transient model as starting heads and simulates a 20-year period of continued baseline pumping and maximum SEZ pumping.

- RiversideEast_1L_transFWD_0107_baseline.gpr is the same as RiversideEast_1L_transFWD_0107high.gpr except that only baseline pumping is simulated (i.e., no SEZ-related pumping).

- "High DDN data set_0107"is a data set created using the GMS Data Set Calculator tool to determine the difference in drawdown between the 0107high results at the 20-year mark (with maximum SEZ pumping) and 0107_baseline results at the 20-year mark (without SEZ pumping).

Disclaimer on the Use of the Riverside East SEZ Model

The numerical groundwater modeling studies were performed to analyze the potential impacts of groundwater pumping associated with utility-scale solar energy development. The models used for these analyses have relied on established hydrogeologic principles and established groundwater modeling software. The approaches taken have ranged from the development of new models based on existing data sources to the evaluation and modification of models already created by various agencies. While efforts were made to develop modeling tools for proper assessment of impacts from groundwater pumping to support solar energy, the models are not intended to be exact predictors of groundwater impacts that could be present over time in the study areas. Hydrogeologic information that is 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 make recommendations for the further development of the groundwater models as information becomes available.

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

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