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

Environmental Science Division

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FIGURES

NOTATION

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

Acronyms, Initials, Symbols, and Abbreviations

BLM	Bureau of Land Management
b	Aquifer saturated thickness
CAP	Central Arizona Project (a canal system)
CDWR	California Department of Water Resources
CHD	Constant-Head Boundary / Time-Variant Specified-Head MODFLOW package
CRA	Colorado River Aqueduct
DEM	Digital Elevation Model
DOE	U.S. Department of Energy
DRN	MODFLOW drain package
GMS	Groundwater Modeling System
K	Hydraulic Conductivity
L	Layer
MSL	Mean Sea Level
PEIS	Programmatic Environmental Impact Statement
PEST	Parameter Estimation Tool
PVID	Palo Verde Irrigation District
RIV	MODFLOW river package
SEZ	Solar Energy Zone
Sy	Specific Yield
T	Transmissivity
USGS	U.S. Geological Survey

Units of Measure

ac	acre
d	day
ft	feet
GW	gigawatt
in	inch
km	kilometer
m	meter
yr	year

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

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A GROUNDWATER MODEL TO ASSESS WATER RESOURCE IMPACTS AT THE IMPERIAL EAST 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 the utility-scale solar energy development at the Imperial East Solar Energy Zone (SEZ) as a part of the Bureau of Land Management's (BLM) solar energy program. The Imperial East SEZ groundwater model (referred to as the Imperial East model, or the model) is a flow model that utilizes established numerical simulation software based upon hydrogeological principles, publicly available characterization information, and several stated assumptions. Its development was initiated through modifications of an earlier, non-calibrated flow model of the Imperial and Mexicali Valleys described by Tompson et al. (2008). While the focus of the model is primarily on the projected drawdown effects, its construction is based on a detailed "head" modeling approach with true elevation control to provide a platform for more in-depth modeling. The model consists of three phases:

Phase 1 — Calibration to steady-state, pre-1942 conditions (before the All American Canal began operation) to establish starting heads for the subsequent transient modeling;

Phase 2 — Calibration of a transient model to assess municipal and agricultural water usage and the effects of irrigation canal linings through 2013; and

Phase 3 — Development of transient model scenarios to assess the simulated impact of 20 years of groundwater withdrawals for various development scenarios of the Imperial East SEZ.

This section of the report introduces BLM's solar energy program and briefly describes the development of the Imperial East SEZ Model. It also provides a summary of results for simulated impacts associated with a full buildout of the Imperial East SEZ considering three categories of water demands (high, medium, and low) based on technology-specific considerations. Section 2 describes the hydrogeologic setting for the Imperial East SEZ. Section 3 describes how this Imperial East SEZ Model is based on the modification of the Tompson et al. (2008) Model. Section 4 provides a summary of results for simulated impacts associated with the full buildout of the Imperial East SEZ Model. 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.

1.1 The 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 Imperial East 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 The Imperial East Solar Energy Zone

The Imperial East SEZ covers approximately 5,700 acres (23 km^2) and is located in southeastern California near the United States–Mexico border with I-8 running east-west along the northern edge of the SEZ (Figure 1). This region is known as the Imperial Valley, which is a flat, alluvium-filled basin with surface elevations typically at or below sea level over much of its area (Figure 1). The Imperial East SEZ is located on an elevated portion of the Imperial Valley called the East Mesa, which is a terrace of the Colorado River delta, and surface elevations within the Imperial East SEZ range between 75 and 125 ft (23 and 38 m).

The primary water management consideration in the Imperial Valley relates to imported water from the Colorado River via the All-American Canal, which is managed by the Imperial Irrigation District. The imported Colorado River water is primarily used for irrigation of the extensive agricultural fields located to the west of the Imperial East SEZ (Figure 1). The All-American Canal flows east to west from the Colorado River diversion at the Imperial Dam and along the southern boundary of the Imperial East SEZ. Annual average flows in the All-American Canal coming out of the Colorado River ranged between 2.8 million and 3.7 million ac-ft/yr (3.5 billion and 4.6 billion m^3/yr) for the period from 1962 to 1992 (USGS 2010). The canal has recently been lined with concrete to prevent seepage losses on a 23-mi (40-km) reach, which includes the portion along the southern boundary of the proposed SEZ (CDWR 2009; IID 2009). Diversions off the All American Canal include the Coachella Canal, East Highland Canal, and Central Main Canal, as well as numerous drainage ditches (Figure 1).

The SEZ has a potential full buildout capacity between 508 and 915 MW and potential groundwater withdrawals ranging from 26 to 13,734 ac-ft/yr (88 to 46,382 m^3/d) during the operations phase based on assumptions stated in the Solar PEIS. For the purposes of the analyses conducted in the Solar PEIS and in this study, all potential water supply for solar energy development at the Imperial East SEZ was assumed to come from groundwater sources.

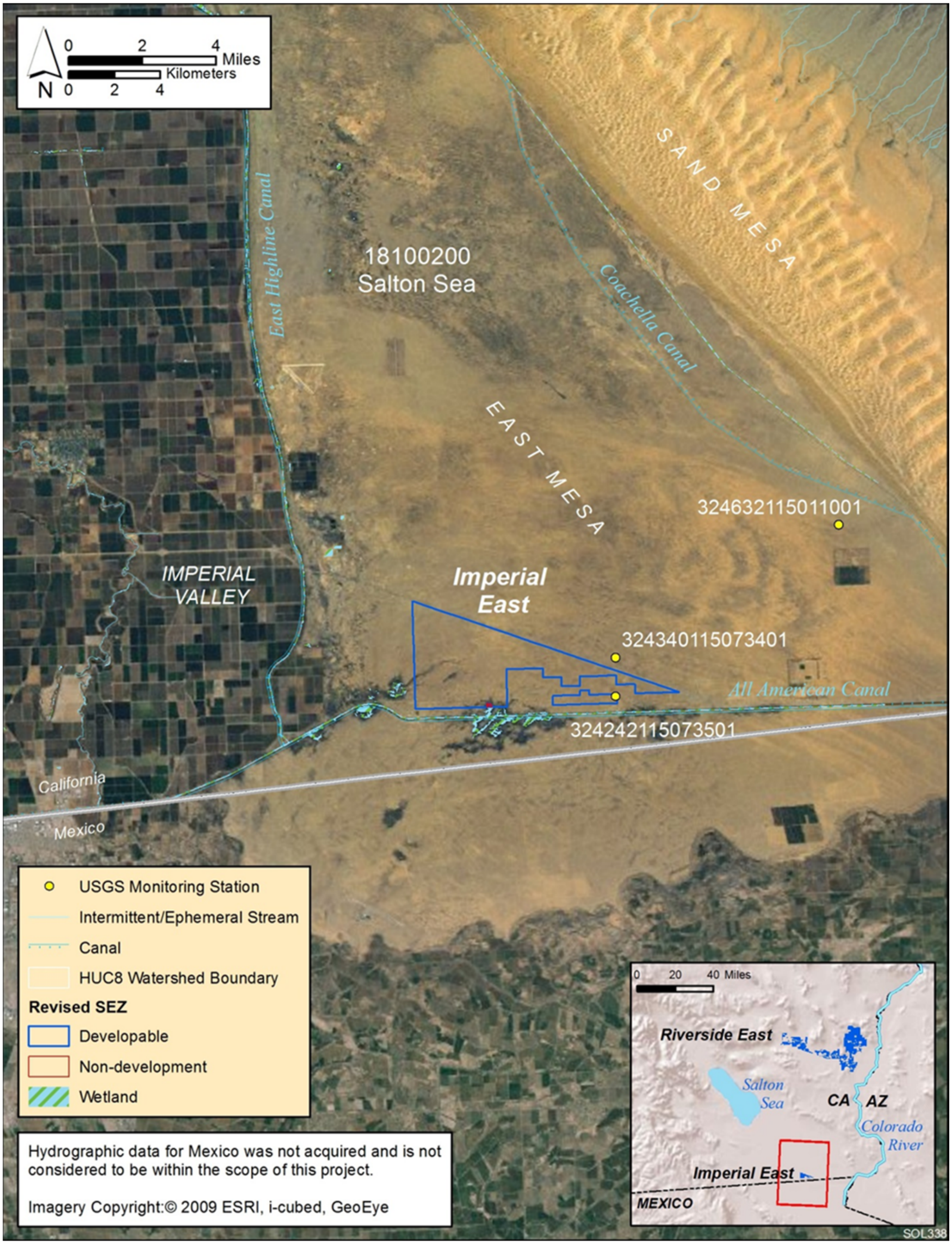

Figure 1 Location of the Imperial East Solar Energy Zone within the East Mesa Portion of the Imperial Valley (source: BLM and DOE 2012)

2 HYDROGEOLOGIC SETTING

2.1 Landscape and Aquifer Characteristics

The Salton Sea basin is the regional setting for the development of the Imperial East SEZ model (Figure 2). The extended Salton Sea basin encompasses the Imperial Valley, and extends further north into the Coachella Valley and further south into the Mexicali Valley of Baja California (CDPW 1954; Loeltz, et al. 1975; Tompson et al. 2008). The extended basin is surrounded on the north, east, and west by bedrock mountains. The Imperial and Mexicali Valley basins are underlain by alluvial and Colorado River delta and floodplain deposits. Ground surface elevations across the alluvial plain and mesa range from about 1,939 ft (591 m) at a mountain-front edge at the Sierra de los Cucapahs Mountains on the southwest edge of the model area to about -229 ft (-70 m) at the Salton Sea (Figure 2). There is an elevation change of up to 130 ft (40 m) along the edge of the East Mesa that divides the mesa from the Imperial Valley floodplain in the United States and from the Mexicali Valley floodplain to the south of the SEZ in Mexico.

Groundwater produced in the Imperial and Mexicali Valleys has typically been confined to a "shallow" system, extending to a depth of no more than 2,000 ft (61 m) in most areas, which is typically considered to be isolated from a "deeper" system that can extend to as much as 20,000 ft (6,096 m) in depth (Tompson et al. 2008). The ability to maintain groundwater pumping in the shallower system can range from very good to very poor.

The shallow system is the focus of this groundwater modeling study and it consists of two alluvial aquifers that are separated at depth by a semi-permeable aquitard that averages 60 ft (18 m) in thickness with a maximum thickness of 280 ft (85 m). The average thickness of the upper aquifer is 200 ft (61 m) with a maximum thickness of 450 ft (137 m), while the lower aquifer averages 380 ft (116 m) thick with a maximum thickness of 1,500 ft (457 m) (CDWR 2003). The aquifers consist mostly of alluvial deposits of late Tertiary and Quaternary age that are comprised of silts, sands, and clays that originate from the Colorado River mixed with locally derived coarse sands and gravels (Loeltz et al. 1975). As much as 80 ft (24 m) of fine-grained, low permeability prehistoric lake deposits have accumulated on the nearly flat valley floor and they cause locally confined aquifer conditions (Montgomery Watson 1995). The general groundwater flow path is towards the northwest and the Salton Sea, with transmissivity values generally decreasing moving west and north through the basin (Loeltz et al. 1975). The San Andreas, Algodones, and Imperial faults are present within the basin, but data on whether these faults control groundwater movement is lacking.

2.2 Water Budget

This region of southern California is characterized as a hot and dry climate with summer high temperatures up to 120°F (48.8°C) and less than 3 in. (7.6 cm) of annual rainfall (ASDM 2010). The majority of the precipitation falls in the winter and spring months with occasional monsoonal thunderstorms (CDWR 2009). Evapotranspiration rates range between 57 and 75 in./yr (145 and 190 cm/yr) within the Imperial and Coachella Valleys (CIMIS 2010).

Precipitation-based groundwater recharge in the basin is generally not significant, given the low annual rainfall rates. Natural groundwater recharge to the East Mesa and Mexicali Valley portions of the basin are primarily from mountain-front recharge processes along the Chocolate Mountains, Cargo Muchacho Mountains, and Pilot Knob Mountains located in the eastern portion of the basin. Underflow from the Colorado River, as well as seepage under the many unlined irrigation canals in the Imperial Valley also provide groundwater recharge (CDWR 2003). Significant leakage from the All-American Canal and the Coachella Canal have been reported by previous studies (e.g., Loeltz et al. 1975), but starting in 1980 up until 2010 there has been a series of projects lining the majority of the All-American Canal and the Coachella Canal with concrete to prevent seepage losses. The most recent concrete lining project was on a 23 mi (37 km) reach of the All-American Canal, including the reach along the south portion of the proposed Imperial East SEZ, that is expected to save 67,700 ac-ft/yr (228,634 m^3/d) (BOR 2006; IID 2009).

Discharge of groundwater is primarily through irrigation withdrawals, losses to irrigation ditches that drain to the Salton Sea, and evapotranspiration (Tompson et al. 2008). Groundwater wells in the Imperial Valley are primarily used for irrigation and are located in the agricultural portion of the valley to the west of the SEZ. Withdrawal and injection of deep groundwater for geothermal energy production takes place in the East Mesa area (Tompson et al. 2008), with minor withdrawal amounts from the shallow zones. Reported groundwater well yields range between 45 and 1,550 gal/min (170 and 5,687 L/min) (Loeltz et al. 1975). Groundwater levels have remained steady in the region for several decades because of relatively constant recharge rates (CDWR 2003).

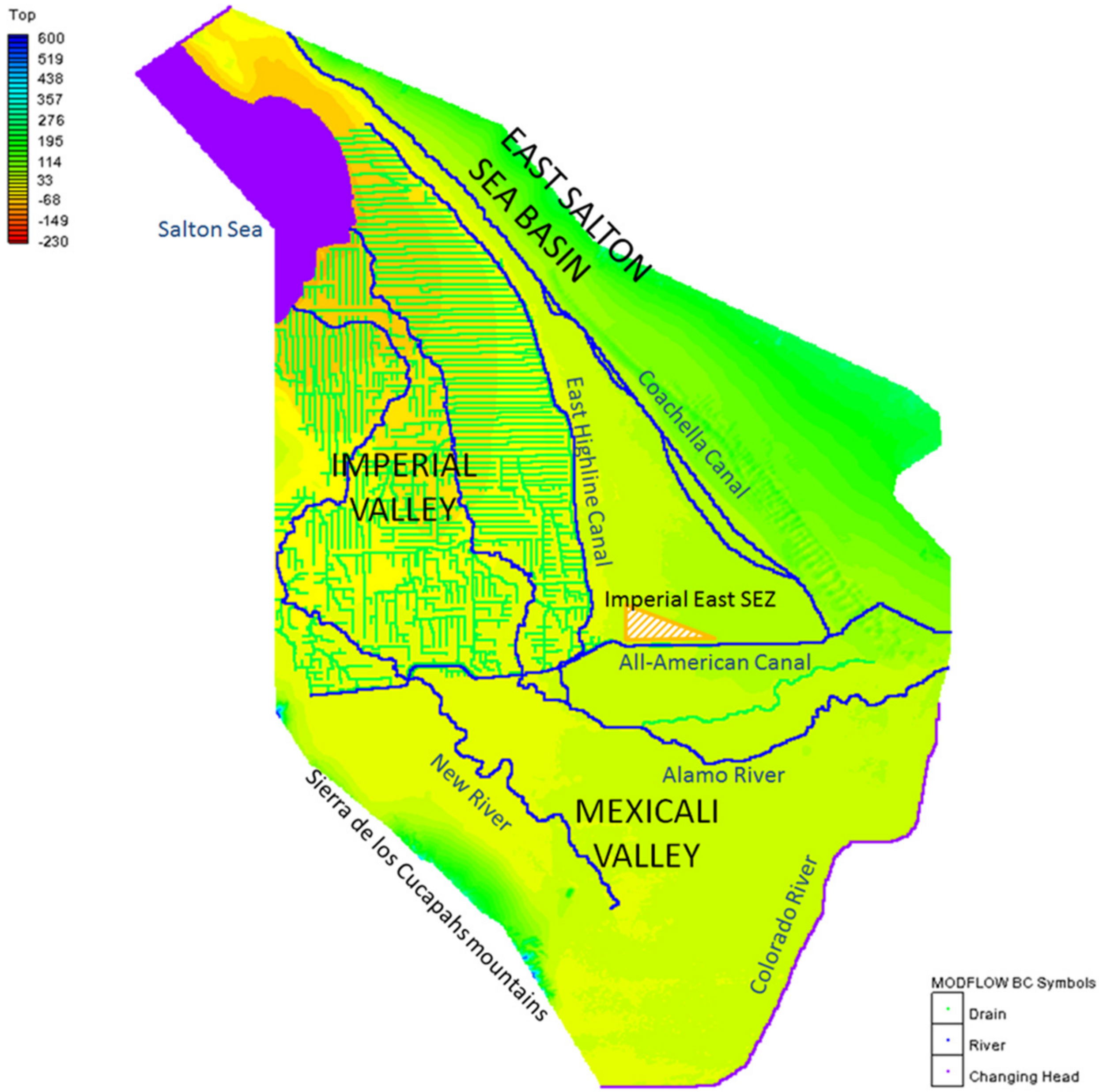

Figure 2 The Groundwater Modeling Domain of the Salton Sea Basin Showing Surface Elevations, Natural Rivers, Canals, and Irrigation Ditches

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3 MODEL DEVELOPMENT

3.1 Modification of the Tompson et al. (2008) Model

The groundwater model developed by Tompson et al. (2008) was not intended to be a fully calibrated numerical model, but to provide a preliminary conceptual framework for a steady-state model that could be further developed within a broader calibration framework (Tompson et al. 2008). The Imperial East model builds upon the framework developed by Tompson et al. (2008) to develop a series of calibrated modeling scenarios for assessing the impacts of groundwater requirements for utility-scale solar energy development. Phase 1 involves a steady-state model for the pre-1942 period to represent pre-development groundwater conditions. Phase 2 involves a transient model designed to replicate the accrual and loss of mounded groundwater derived from canal leakage and lining effects. The transient model calibration in Phase 2 includes the effects of recent (since the Tompson et al. model was published) canal lining activities that affect the overall water balance in the region. Phase 3 involves a forecast model to examine the effects of groundwater pumping from the SEZ.

The model domain and grid used for this application have been modified from the preliminary model of Tompson et al. (2008) in several ways:

- The deeper aquifer zones (2,000 to 20,000 ft [610 to 6,096 m] below ground surface) and the west Mesa portions of the Tompson et al. model were removed to reflect the SEZ study area with a focus on the shallow aquifers that were mentioned previously.

- The upper nine layers of the Tompson et al. model that represent the shallow aquifers were retained, with the exception of the ground surface portion (layer 1) that was modified using the digital elevation model (DEM) derived by Gesch et al. (2002) and Gesch (2007).

- The numerical grid cell dimensions were refined to a surface area of 200 m by 200 m (from the original 1,000 m by 1,000 m) to allow for a focus on impacts within and around the SEZ.

- The distribution of low- versus high-hydraulic conductivity (K) zones was preserved, but the K values within the high-permeability zone were adjusted during calibration of the pre-1942 steady-state model.

- Water surface elevations for the three canals surrounding the SEZ (All-American Canal, Coachella Canal and East Highline Canal) were included.

3.2 Hydrogeologic Considerations

3.2.1 Specification of Hydraulic Conductivity

The aquifer materials have a wide range in hydrogeologic properties, and these properties vary spatially depending on the depth and proximity to the low-permeability floodplain deposits. The distribution of high versus low K zones from the Tompson et al. (2008) model was used in both the steady-state and transient models (Figure 3). The low permeability zones had a horizontal hydraulic conductivity (K_h) of 0.56 ft/d (0.17 m/d) and vertical hydraulic conductivity (K_v) of 0.056 ft/d (0.017 m/d); the high permeability zones had K_h of 100.7 ft/d (30.68 m/d) and K_v of 10.07 ft/d (3.068 m/d). Changes to the K values during model calibrations are discussed below.

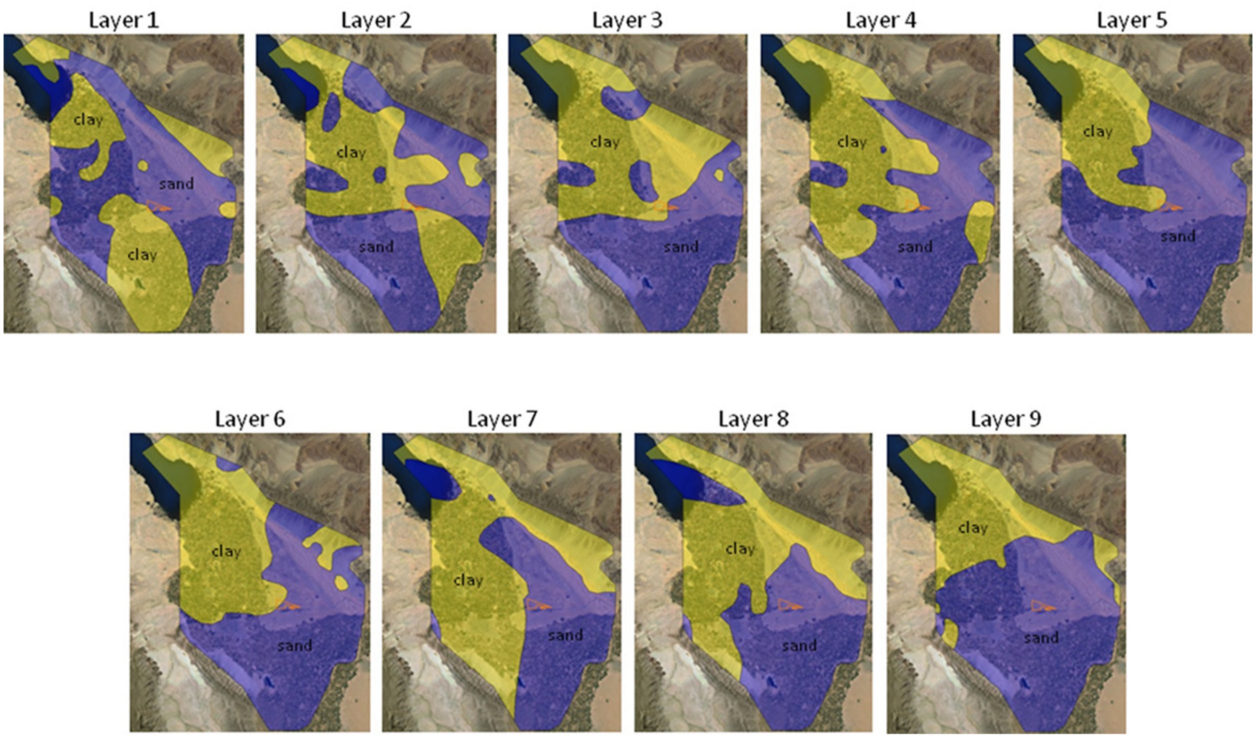

Figure 3 Distribution of High Permeability (e.g., Sand, in Purple) Versus Low Permeability (e.g., Clay, in Yellow) Materials in Model Layers 1-9. The Imperial East SEZ is Outlined in Orange.

3.2.2 Specification of Groundwater Recharge

Recharge to the basin plains 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 recharge, in-place recharge, irrigation canal leakage and groundwater basin inflow. Recharge values in Table 7.2 from Tompson et al. (2008) were maintained in this model and adjusted for modifications in lateral model extent.

The value for natural areal recharge from the Tompson et al. (2008) model was adjusted to two values (1.3×10^{-5} ft/d and 1.6×10^{-3} ft/d, or 3.9×10^{-6} m/d and 5×10^{-4} m/d) during calibration of the pre-1942 steady-state model (phase 1), with the higher values aligned with the mountain-front areas along the mountains on the east edge of the model area (Figure 4). These values and their distributions were kept constant for the calibrated 1942-2013 transient model and the future projection scenario models (phases 2 and 3).

Leakage has been documented in the East Mesa from the All-American Canal, which runs east-west through the center of the model area (BOR, 2006; Tompson et al., 2008). The eastern 23 mi (37 km) of the All-American Canal were lined with concrete in 2008 (BOR, 2006). The southern 49 mi (79 km) of the Coachella Canal were lined in 1980 and the remainder of the Coachella Canal was lined in 2006. Values for conductance (the rate of leakage out of the canal bed to the underlying aquifer) were calculated for the pre-lined All-American Canal and Coachella Canal segments, and conductance values ranged from 82 to 1550 ft^2/d/ft (5 to 12 m^2/d/m) to match the total estimated pre-lining leakage. Once portions of these canals were lined, the conductance was assumed to become zero.

3.2.3 Specification of Pumping Stresses

The total groundwater withdrawal data from specific subregions in the modeling domain were obtained from Table 7.3 in Tompson et al. (2008) that specify groundwater withdrawals of 6 ac-ft/yr (20 m^3/d) in the East Salton Sea basin, 25,600 ac-ft/yr (86,513 m^3/d) in the Imperial Valley, and 740,300 ac-ft/yr (2.5 million m^3/d) in the Mexicali Valley. For the Imperial Valley and East Salton Sea regions, the numbers, locations, and depths (which model layer) of model wells were set according to information provided by the USGS National Water Information System (NWIS) database (USGS 2013); from a map of wells provided in Loeltz et al. (1975, Figure 12); and from the overlap of high K zones and the reported well extraction for the East Salton Sea basin from Tompson et al. (2008). For the Mexicali Valley, model wells were placed in layers 1, 3, and 9 at locations that mimicked the distribution of wells reported on Figure 1 in Gracia et al. (2011). One well was used in the East Salton Sea basin and the total valley withdrawals were distributed equally among 38 wells in the Imperial Valley and 238 wells in the Mexicali Valley (Figure 5).

Geothermal pumping is considered to be incorporated in the overall pumping tabulated by Tompson et al. (2008), primarily as the minor withdrawal of shallow groundwater as make-up water for the system. Deep groundwater withdrawals are assumed to be balanced by re-injection of the deep groundwater, plus cooling make-up water, during the energy generation process. Further, the deep groundwater extracted for geothermal purposes is considered to be hydrogeologically separated from the shallow flow system (Tompson et al. 2008) and the current modeling effort does not retain the deep model layers of the Tompson et al. model. This model relies on the withdrawal estimates through 2007 from Tompson et al. (2008). Any increases in the shallow withdrawal rates after 2007 are not included in this model.

Figure 4 Modeled Groundwater Recharge Values (in m/d) Across the Modeling Domain

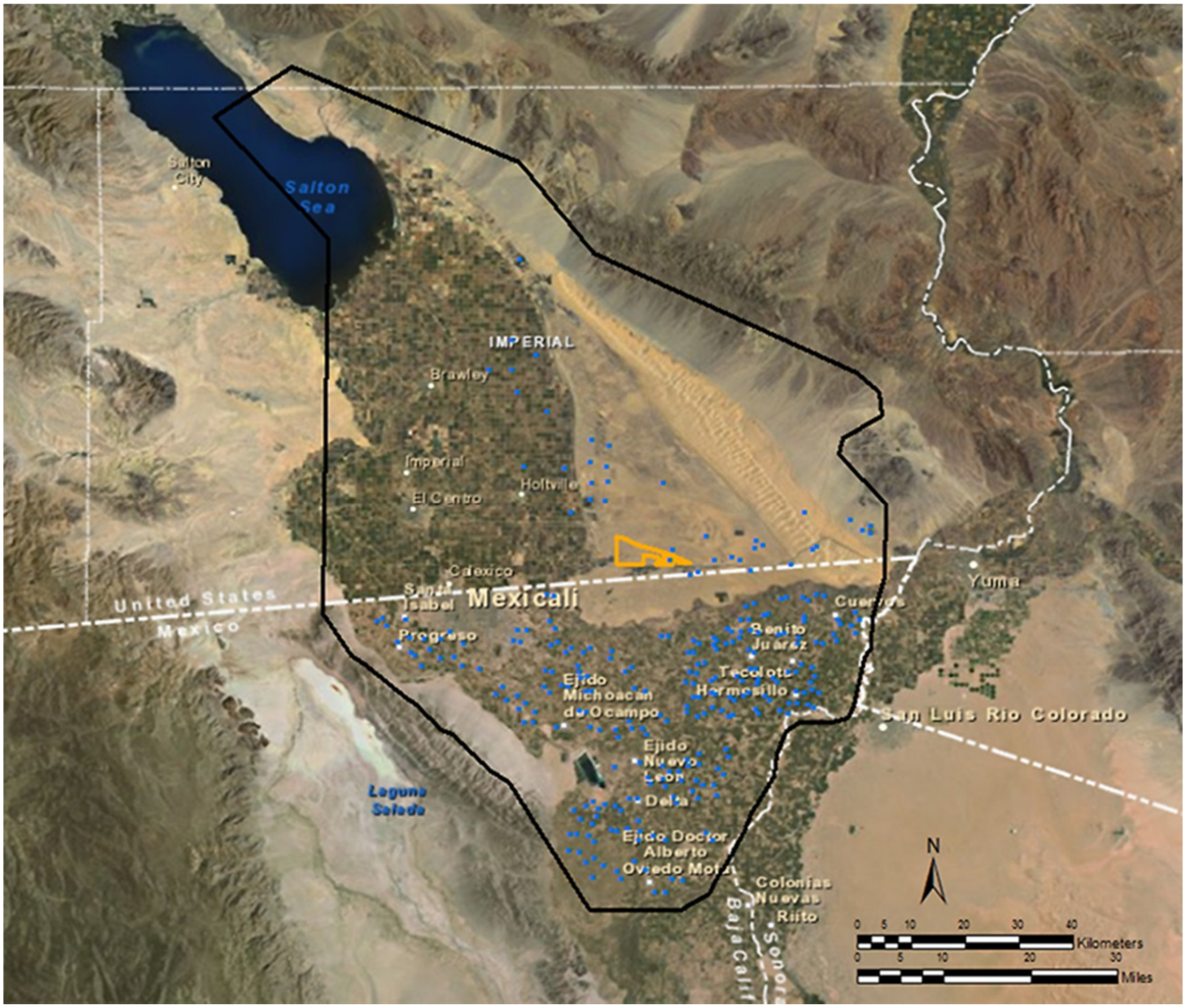

Figure 5 Location of Groundwater Pumping Wells (Blue Circles) within the East Salton Sea, Imperial Valley, and Mexicali Valley Regions

3.3 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 the time-variant specific head (CHD) packages. Pre- and post-processing were performed using Groundwater Modeling System (GMS) software version 8.3 with support from ArcMap 10.

The model was designed with a transient stress period with monthly time steps representing 71 years of agricultural and municipal pumping at total valley well withdrawal rates (from Table 7.3 in Tompson et al. 2008). This is a simplification of actual pumping rates that vary over time but is considered suitable for later testing the effect of SEZ pumping.

3.3.1 Grid Design

The numerical grid for the Imperial East model included a constant surficial area cell size of 656 ft by 656 ft (200 m by 200 m) across the model domain. The model was constructed using layers 1 through 9 from the Tompson et al. (2008) model and the vertical extent of the numerical grid was extracted from the individual layers of the Tompson et al. model. Geographic Information Systems (GIS) tools in ArcMap 10 were used to manage ground surface elevations obtained from the DEM (Gesch et al. 2002; Gesch 2007) and reduce the dataset to a manageable number of points for use in GMS. The area of the DEM just to the south of the SEZ contained errors as it was taken from a low-resolution (1:50,000 scale) map (Ejido Islas Agrarias, section I11-D66). The surface elevations incorporated into Layer 1 of the model for this region were obtained from a separate map produced by the Instituto Nacional de Estadistica y Geografia (INEGI).

3.3.2 Boundary Conditions

The vertical extent of the modeling domain is the bottom surface elevation in layer 9 of the Tompson et al. (2008) model. The surface flow in the Imperial Valley and Mexicali Valley discharges primarily northwest to the Salton Sea (modeled as CHD cells) through the Alamo and New Rivers (modeled as RIV cells) but also southward to the Colorado River and Hardy River (at the western edge of the Mexicali Valley floodplain) in Mexico. Subsurface flow is to the northwest, originating from a combination of mountain-front recharge, irrigation canal leakage (modeled as RIV cells), and the Colorado River (modeled as CHD cells) in the east portion of the model and discharging to the drainage ditches in the Imperial Valley (modeled as DRN cells) and to the Salton Sea. The irrigation canal elevations were set based on elevations obtained from the Imperial Irrigation District and Coachella Valley Irrigation District and ditch drain elevations were set based on an estimated average drain depth of 3 to 6 ft (1 to 2 m) below the ground surface.

In the steady-state pre-1942 model (phase 1), the Alamo River and Alamo Canal in Mexico served as the irrigation route from the Colorado River to the Imperial Valley (the Coachella Canal and All-American Canal were not yet operational). In the transient 1942-2013 model (phase 2), the Coachella Canal and All-American Canal were operational, with portions being lined and/or shifted in 1980, 2006, and 2008 (which served as transitions between the four stress periods in the 1942-2013 model). In 1980, the southern 49 mi (79 km) of the Coachella Canal were replaced with a lined canal on a slightly shifted alignment. In 2006 the remaining portion of the Coachella Canal in this model extent was lined in place. In 2008 the eastern 28 mi (45 km) of the All-American Canal were lined in place.

Other lateral boundaries include no-flow cells that are located along the boundary between the alluvium and the bedrock mountains, and at the groundwater confluence divide in the center of the Imperial Valley where groundwater flowing into the valley from the West and East Mesas meets before flowing north to the Salton Sea.

3.3.3 Starting Conditions

With the exception of the constant head boundaries imposed along the Colorado River and at the Salton Sea, starting heads in the steady-state pre-1942 model domain were set to the ground surface elevation or lower (3 ft [1 m] lower for each successive underlying layer) and allowed to decline during model iterations. Because of the depth to groundwater relative to the bottom of Layer 1, surficial model cells in a small area under the Algodones Dunes (Sand Mesa in Figure 1) in the East Mesa convert to dry cells.

3.3.4 Calibration Targets

All field observations for wells within the Imperial East SEZ model domain were downloaded from the USGS NWIS database (USGS 2013). For the steady-state pre-1942 scenario (phase 1), one measurement from each of five wells upgradient (to the east) of the SEZ were used as calibration targets. These were the only measurements in the 12 years prior to 1942 in the NWIS database. For the transient model between 1942 and 2013 (phase 2), transient-target datasets from 51 wells in the NWIS database were used. Hydrographs for NWIS wells in the East Mesa, with multiple measurements between 1942 and 2013, showed a rise in groundwater elevations from the 1940s and 1950s, following the beginnings of the operation of the Coachella Canal and All-American Canal, stable levels in the 1960s and 1970s, followed by decreases in groundwater elevations after portions of the Coachella Canal and All-American Canal were lined in 1980, 2006, and 2008. The general response of the simulated hydrographs (within +/- 2 m of observed transient data) were used as combined quantitative/qualitative calibration criteria.

3.3.5 Storage Terms

A storage coefficient (specific yield) of 0.15 was applied to all model cells, as a conservative estimate within the range of 10-30% provided in Tables 4.1 and 7.5 and Figure 7.7 in Tompson et al. (2008). A specific storage of 0.005 was used for all layers under confined conditions during the steady state and transient calibrated models. During the future high-withdrawal scenario, the specific storage was adjusted down to 0.0005 to test the model sensitivity. While the SEZ-related drawdowns were not sensitive to the specific storage over this range, the dry area in the northeast portion of the model increased nearly to the Coachella Canal with the lower specific storage value. This report presents all results with a specific storage of 0.005 for the confined layers below Layer 1.

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4 RESULTS

4.1 Phase 1 — Steady-State, Pre-1942 Model

For the steady-state model (used only to create starting heads for the transient model), the calibration to a limited set of 5 wells in the East Mesa (focusing on those closest to the Imperial East SEZ and All-American Canal) was manually performed and resulted in hydraulic conductivity values of K_h of 44.89 ft/d (13.68 m/d) and a K_v of 4.49 ft/d (1.37 m/d) for high-permeability regions shown in Figure 3. The hydraulic conductivity values for the low permeability regions in Figure 3 were initially varied, but the initial values of a K_h of 0.56 ft/d (0.17 m/d) and K_v of 0.056 ft/d (0.017 m/d) provided the best fit to calibration targets in the East Mesa region.

The resulting calibrated heads for Layer 1 are shown in Figure 6. This adjustment of the hydraulic conductivity values in the high permeability regions from those used in the Tompson et al. (2008) model is reasonable given the available knowledge about the study area. The recharge values were kept constant in the subsequent transient models. The head targets closest to the SEZ and All-American Canal had minimal errors (Figure 7), but one outlier point exists from a well on the other side of the Sand Mesa (Algodones Dunes) northeast of the Imperial East SEZ. The observed heads were measured from pumping wells that were allowed to equilibrate for more than one hour after the pumps were shut off to obtain an accurate measurement of the groundwater elevation in the surrounding formation. The model does not simulate pumping from these wells, so the computed heads tend to be higher — 10 to 33 ft (3 to 10 m) — than the observed groundwater elevations. The budget error in the MODFLOW model was -0.11%.

4.2 Phase 2 — Transient, 1942–2013 Model

A transient model representing decades of agricultural and municipal pumping was used to simulate the changes in groundwater elevations between the start of irrigation canal operation in 1942 and the present.

The hydraulic conductivity values for the high permeability zones were manually adjusted until the objective function (measuring the differences between observed and modeled heads) was minimized to produce a calibrated set of simulated heads. The final hydraulic conductivity values for the regions of high permeability (Figure 3) were a K_h of 164 ft/d (50 m/d) and a K_v of 16.4 ft/d (5 m/d). Due to the increased number of observation points between the steady-state model (5 points) and the transient model (over 1,100 points), there is a greater change in the calibrated K values for the transient model as compared to that of the steady-state model.

Results indicated flow originating from the mountain-front recharge, irrigation canal leakage and the Colorado River in the east portion of the model, and discharging to the drainage ditches in the Imperial Valley and to the Salton Sea (Figure 8). Similar to the Tompson et al. (2008) model

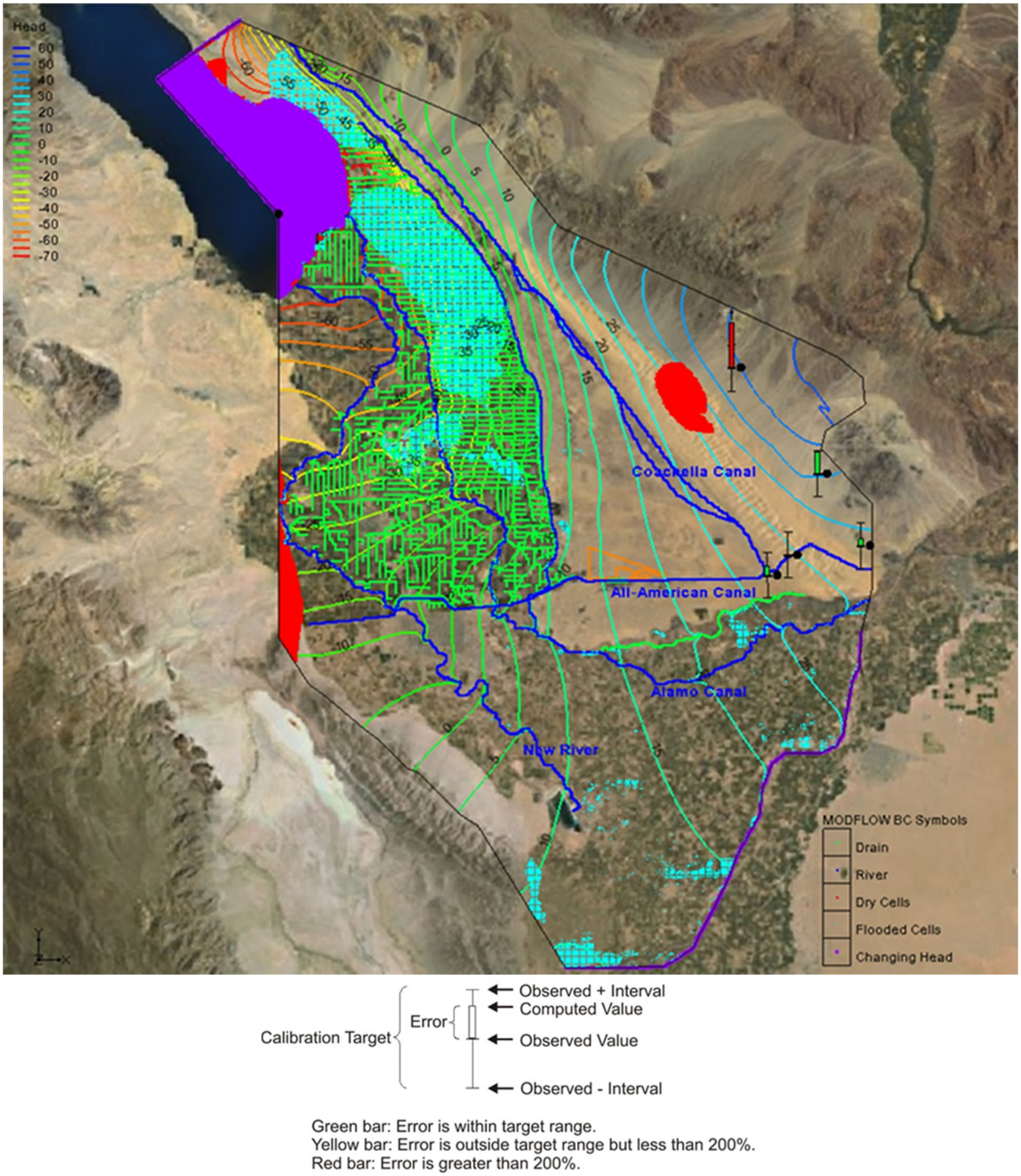

Figure 6 Calibrated pre-1942 Steady-State Heads (Contours in Meters) in Layer 1. The five observation points are identified by statistical error bars (Interval +/- 10 m) Lined in Black.

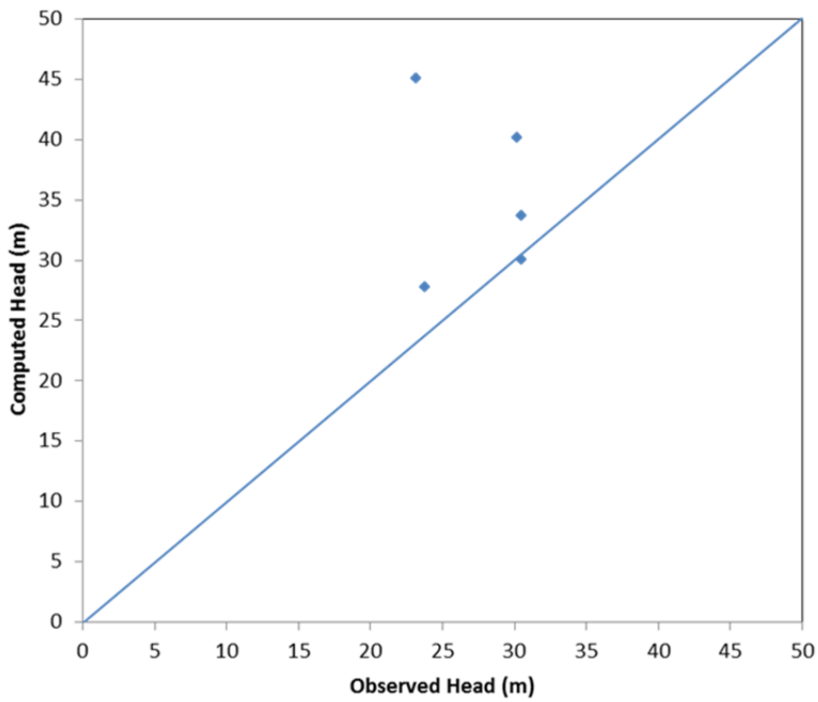

Figure 7 Computed Versus Observed Heads (in Meters) at Observation Points for the pre-1942 Steady-State Model (Phase 1)

results, flooding of cells occurs along the lower reaches of the Alamo and New Rivers indicating discharge of water into the rivers and into the densely irrigated lands in these areas. Flooded water would actually not pond as indicated, but would be captured and routed into the Salton Sea by the extensive drainage network in the floodplain area. Although the drainage ditches operated by the Imperial Irrigation District are included in this model, flooding in this model occurs in cells between the ditches where there are field tiles installed and maintained by individual farmers, which are not included in the model. This flooding tendency is consistent with continued perceived artesian conditions in this area (Tompson et al. 2008).

The target heads for this transient model are values from 51 wells, located mainly in the East Mesa. However, the range of dates at each well varies between 1942 and 2013, and they 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 irrigation canals). Therefore, annual model results at the end of the 71-year period were inspected and compared to recent heads in the various portions of the study area. Despite the noise in the target head values, it was determined that the transient model's simulated results after 71 years of pumping (Figure 9) matched the observed target heads adequately, particularly in wells adjacent to the SEZ). The outlier point is a well that is located north of the dry area in layer 1, far from the SEZ, while the wells adjacent to the SEZ show good correlation between computed and observed heads. Descriptive statistics

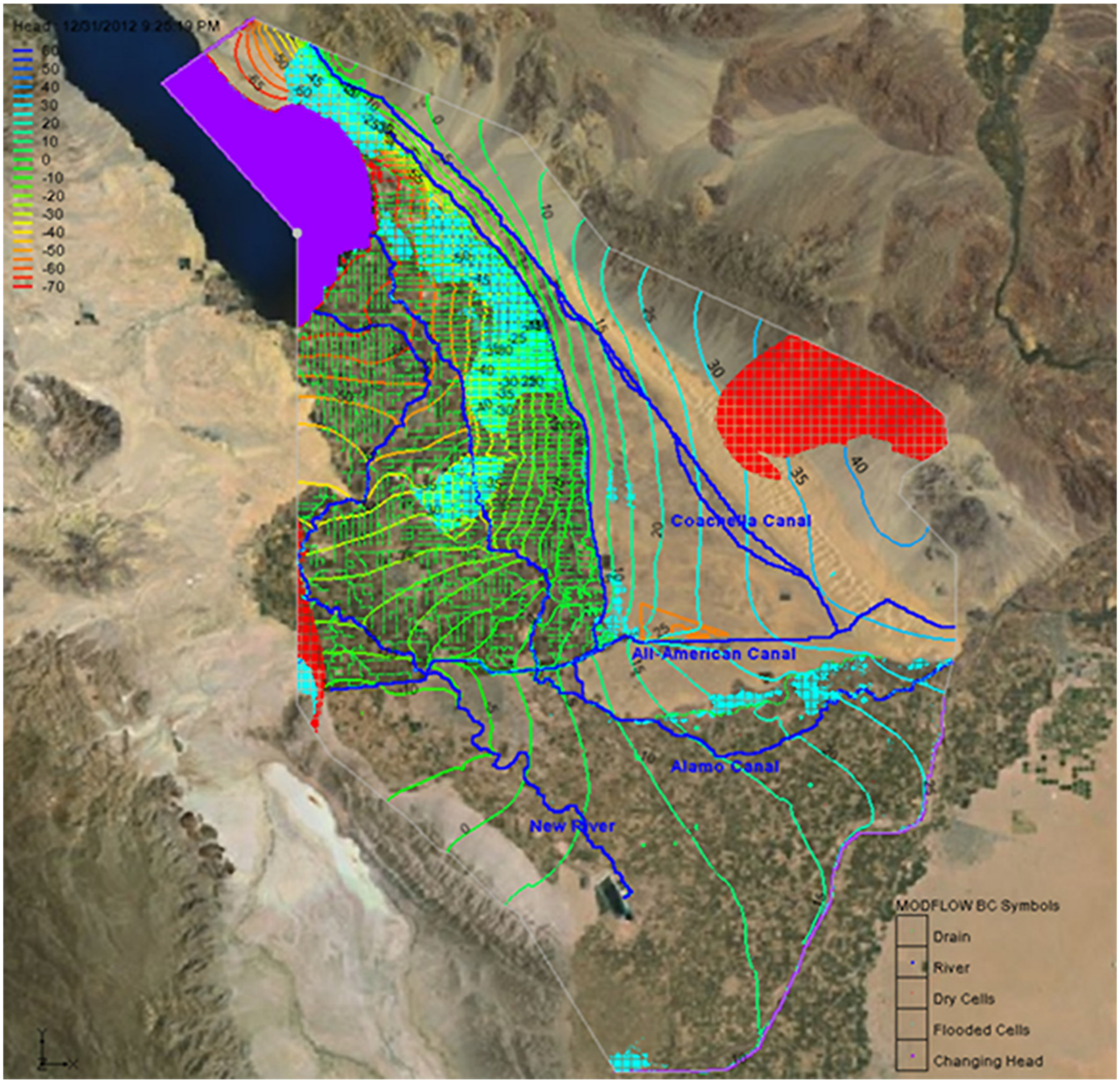

Figure 8 Calibrated Transient Heads in Layer 1 Following 71 Years of Agricultural and Municipal Pumping (Contours in Meters) Between 1942 and 2013 (Phase 2).The Coachella and All-American Canals are Operational, with Portions Being Lined or Shifted in 1980, 2006 and 2008.

of the calibration include a mean residual of 3.12 ft (0.95 m), a mean absolute value residual of 12.2 ft (3.7 m), and a root-mean-squared residual of 14.96 ft (4.56 m) that indicate a good overall correlation across the time period, depths, and area represented by the target wells. Comparison of time series in wells adjacent to the SEZ show a good fit between computed and observed groundwater elevations, within 3 to 6.5 ft (1 to 2 m) (Figure 10). The budget error in the MODFLOW model was 0.00%.

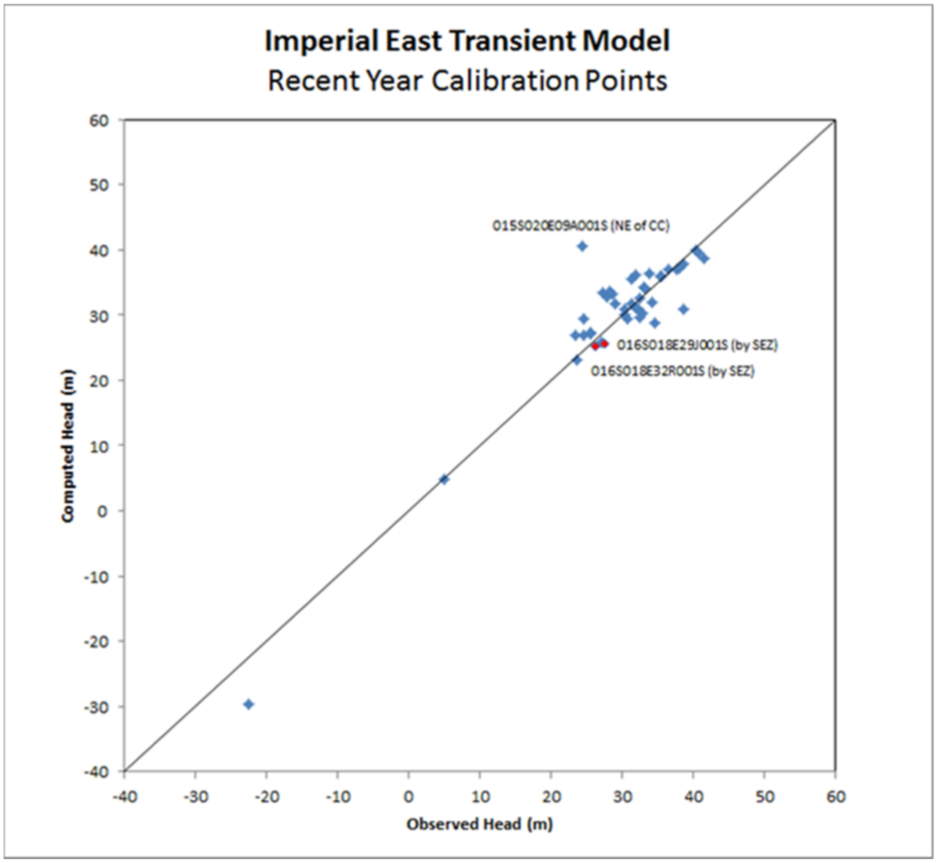

Figure 9 Calibration Results for the Final Time Steps of the Transient Model (Phase 2). The Outlier Point is from a Well on the Other Side of the Algodones Dunes from the Imperial East SEZ.

4.3 Phase 3 — Groundwater Pumping from Imperial East SEZ

The proposed withdrawal rates at an SEZ are dependent on the type of technology and the level of development at the SEZ. Three levels of withdrawals were considered to bracket the range of possible water use effectively. For the Imperial East SEZ model, the high-demand scenario has an assumed withdrawal of 4,591 ac-ft/yr (15,515 m^3/d) for full buildout of wet-cooled parabolic trough (BLM and DOE 2012). The medium-demand scenario has an assumed withdrawal of 654 ac-ft/yr (2,210 m^3/d) for full buildout of dry-cooled parabolic trough, while the low-demand scenario has an assumed withdrawal of 26 ac-ft/yr (88 m^3/d) for full buildout of photovoltaic. These rates are only for an 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 and reclamation stages of solar facility development.

To evaluate the worst-case conditions from 20 years of SEZ pumping, the high-demand rate was applied from 2013 to 2033, divided equally between two assumed well locations within the SEZ boundary (2,296 ac-ft/yr or 7,758 m^3/d per well) (Figure 11). It was assumed that only one facility could be constructed within the Imperial East SEZ. The locations were chosen to

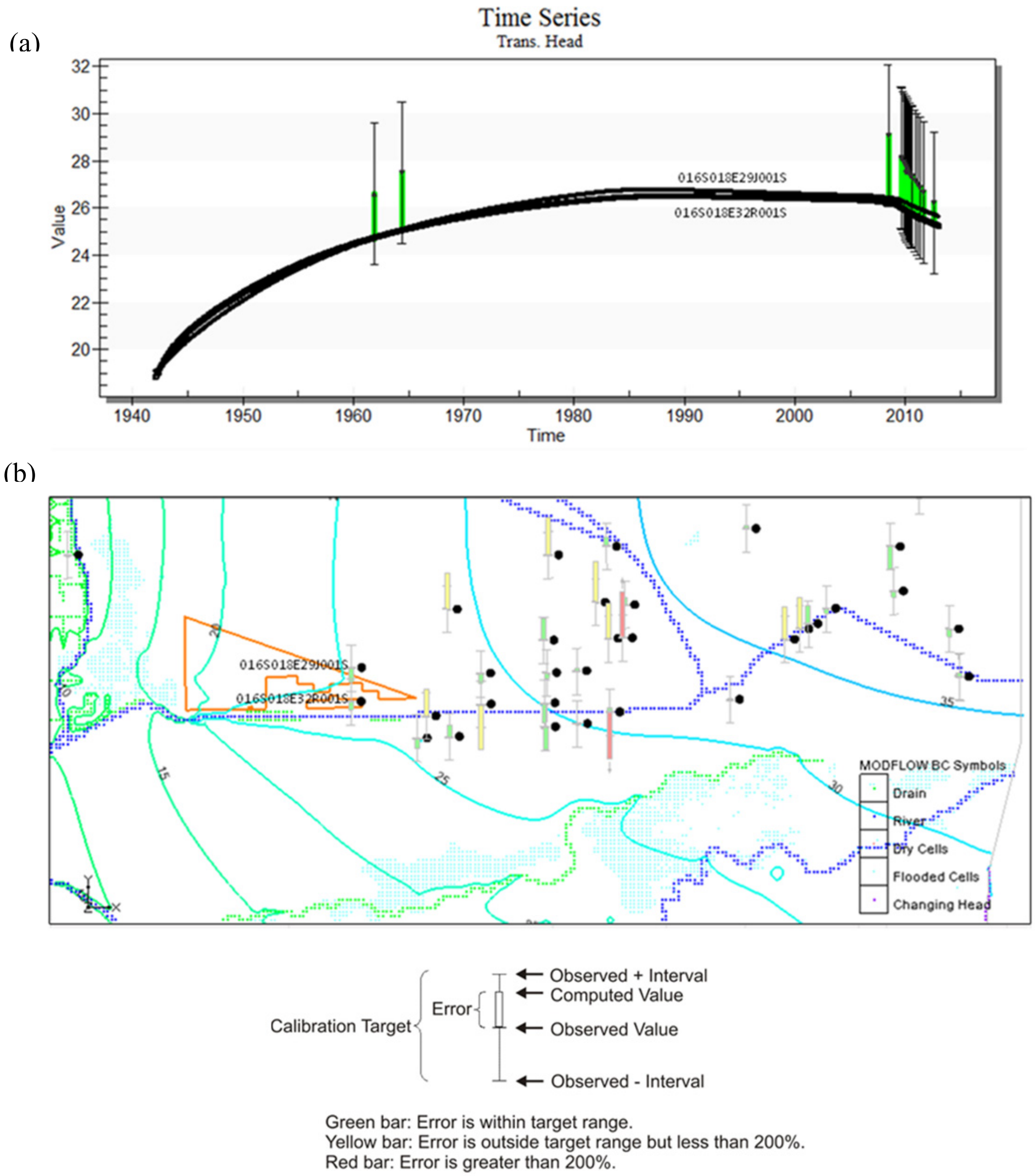

Figure 10 (a) Time Series of Monthly Computed Groundwater Elevations (in Meters) Versus Observed Elevations for the Two Wells Adjacent to the SEZ (016S018E29J001S and 016S018E32R001S). (b) Error Bars (in Gray) Across the Observation Points Represent a +/- 10 ft (3 m) Interval.

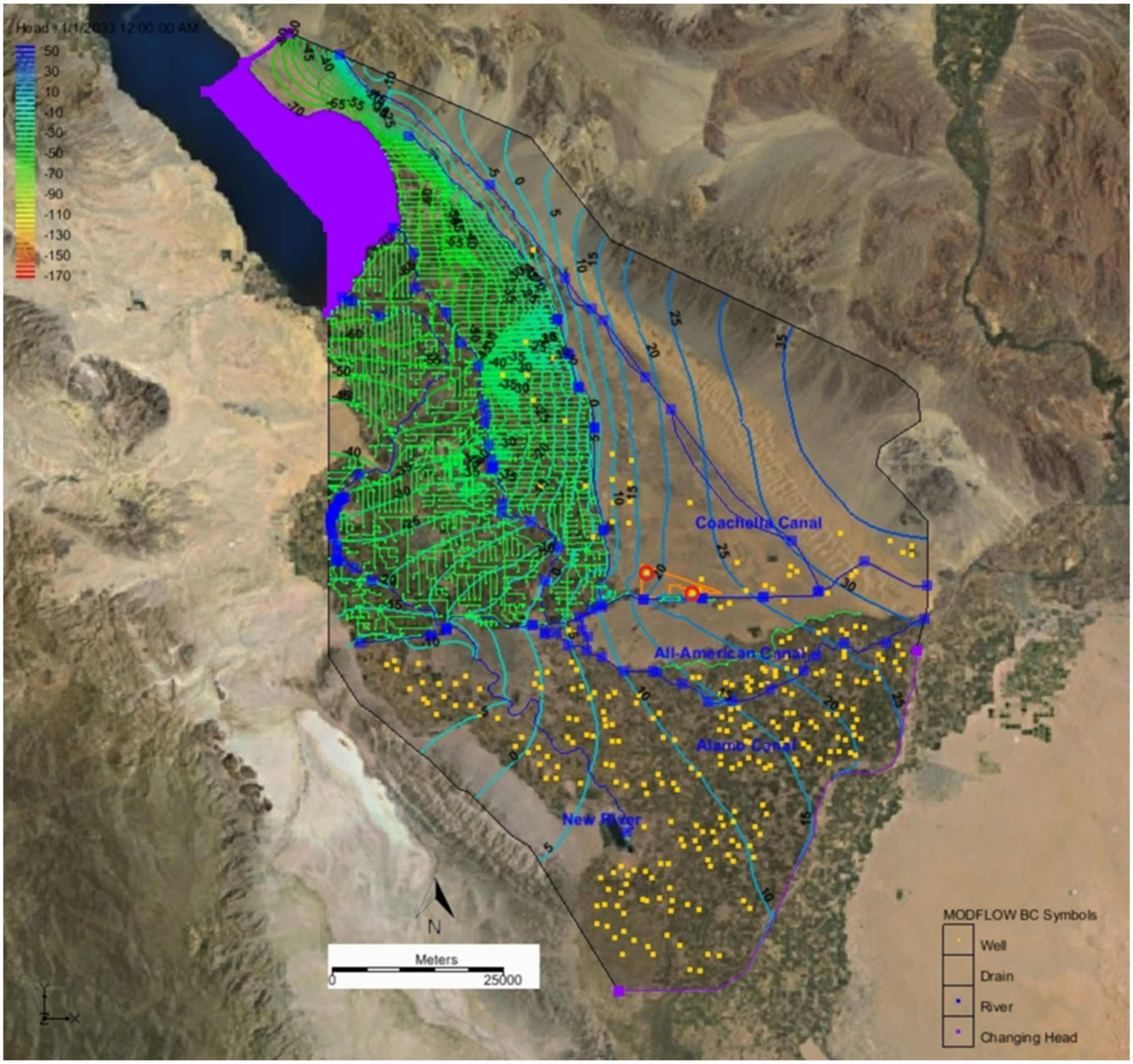

Figure 11 Calculated Heads Following 20 Years of Projected Agricultural, Municipal, and High-Demand SEZ Pumping from Full Buildout of Wet-Cooled Parabolic Trough Solar Technology (Contours in Meters). Pumping Wells are Yellow Squares, with SEZ Wells Highlighted by Red Circles.

approximate possible water services required across the SEZ and to examine the impacts at variable distances from the AAC. Different well depths were investigated. In one scenario, the wells were placed in model layer 1; in the other scenario they were both in model layer 7. Both of the well locations were in high-K material (see Figure 3). It is anticipated that site characterization and/or well installation programs would determine suitable depths for well screen placement in sandy rather than clayey units.

During the Phase 3 scenarios, the withdrawals of other groundwater users continued at the same rate as in the transient 1942-2013 model.

The resulting distribution of hydraulic head from the high-demand SEZ scenario indicated continued general westerly flow with minimal deflections in the groundwater contours in the SEZ vicinity (Figure 11). Additional modeling was conducted to examine the relative difference between the combined effect of baseline pumping (from agricultural and municipal wells) with SEZ pumping versus baseline pumping alone during that time frame. These results were dependent on the depth of pumping wells. The results when both wells were screened in model layer 1 (the uppermost layer) indicated additional drawdown in that layer of 14 ft (4.4 m) at the northwest SEZ well and 11 ft (3.2 m) at the southeast SEZ well (Figure 12). Less drawdown is observed at the southeast well, presumably due to the influx of water from the leaking canal. The results when both wells were screened in model layer 7 (a deep layer) indicated additional drawdown in that layer of 2.2 ft (0.68 m) at the northwest SEZ well and 1.6 ft (0.50 m) at the southeast SEZ well (Figure 13). The less significant drawdown is attributed to semiconfining effects in the deeper aquifer material.

To assess the medium-demand drawdown effects, the same two SEZ well locations were used. The northwest well was assumed to be in model layer 1 while the southeast well was assumed to be in model layer 7. Because of the reduced pumping demand in this scenario, the modeled drawdown was reduced.

The maximum additional drawdown after 20 years is 1.9 ft (0.58 m) where the shallow SEZ well is in layer 1 (Figure 14) and 0.23 ft (0.07 m) where the deeper SEZ well is in layer 7 (Figure 15).

The SEZ drawdown in the low-demand SEZ pumping scenario was negligible, with less than 0.3 ft (0.1 m) drawdown at the assumed northwest SEZ well screened in model layer 1.

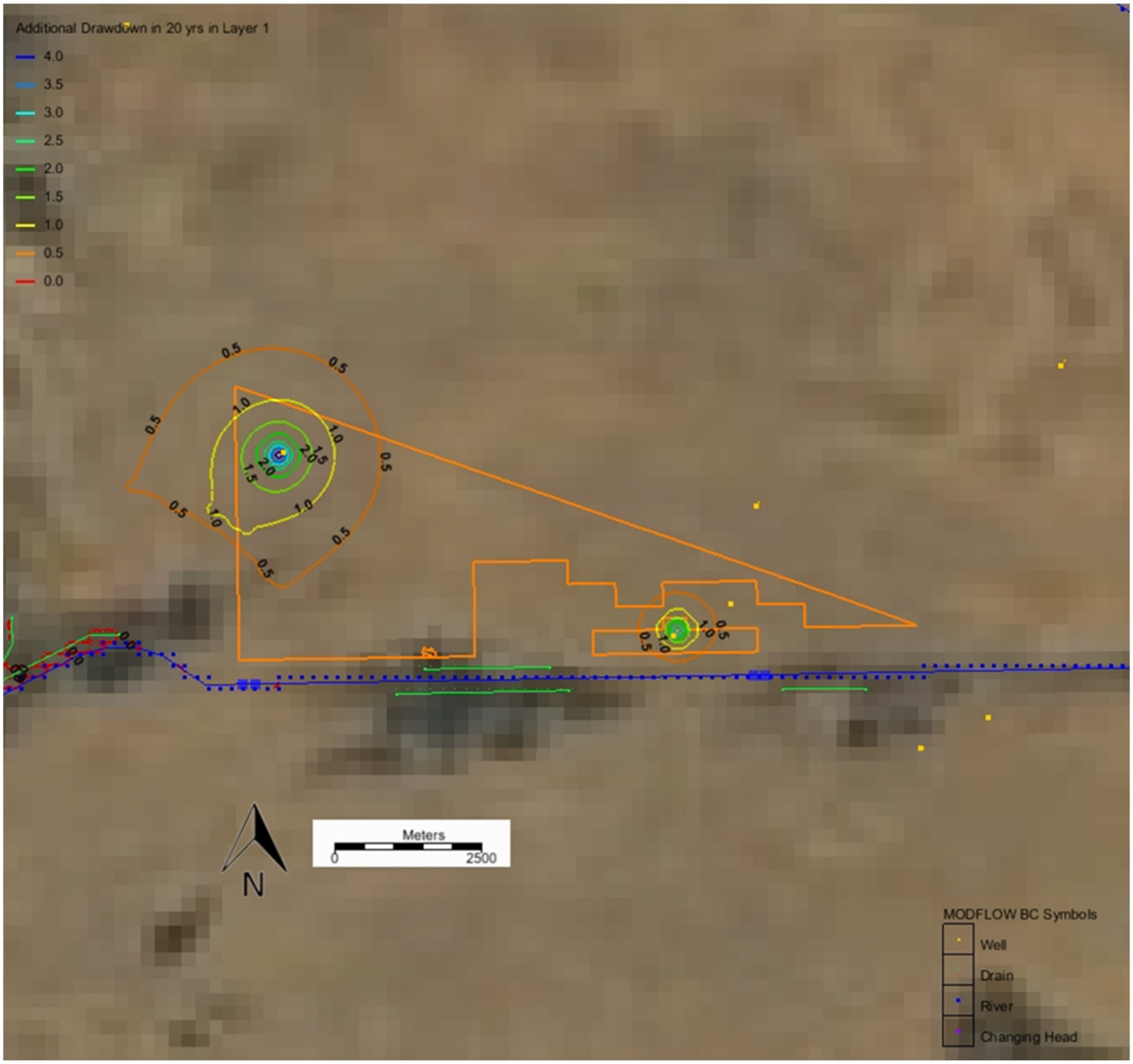

Figure 12 Additional Drawdown from SEZ Wells Screened in Model Layer 1 Due to a Projected 20 Years of High-Demand SEZ Pumping from Full Buildout of Wet-Cooled Parabolic Trough Solar Power Technology (Contours in Meters). The Maximum Drawdown is in Layer 1 and as Shown is 14 ft (4.4 m) at the Northwest SEZ Well and 11 ft (3.2 m) at the Southeast SEZ Well. Other Pumping Wells are Marked with Yellow Squares.

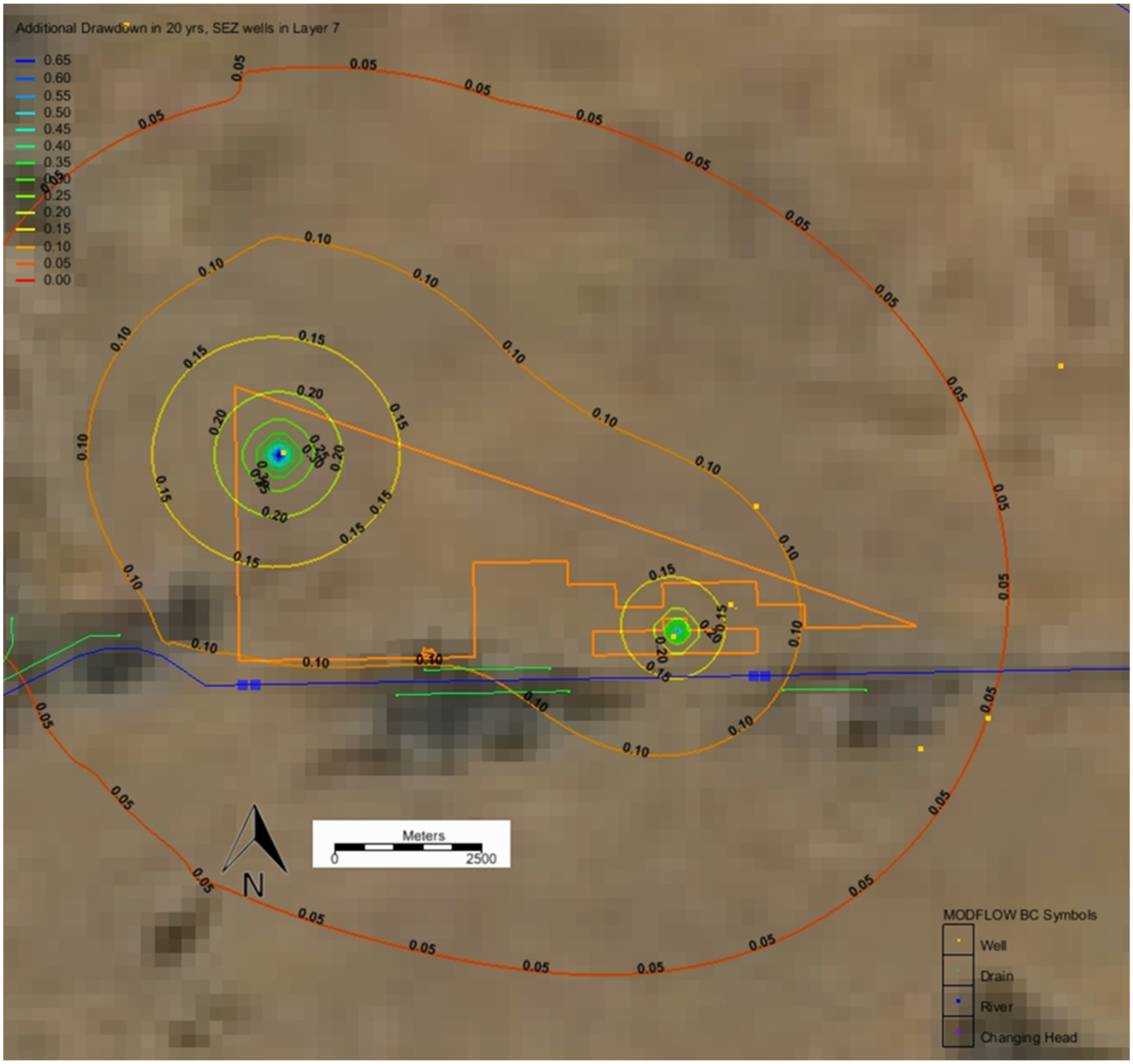

Figure 13 Additional Drawdown from SEZ Wells Screened in Model Layer 7 Due to a Projected 20 Years of High-Demand SEZ Pumping from Full Buildout of Wet-Cooled Parabolic Trough Solar Power Technology (Contours in Meters). The Maximum Drawdown is in Layer 7 and as Shown is 2.2 ft (0.68 m) at the Northwest SEZ Well and 1.6 ft (0.50 m) at the Southeast SEZ Well. Other Pumping Wells are Marked with Yellow Squares.

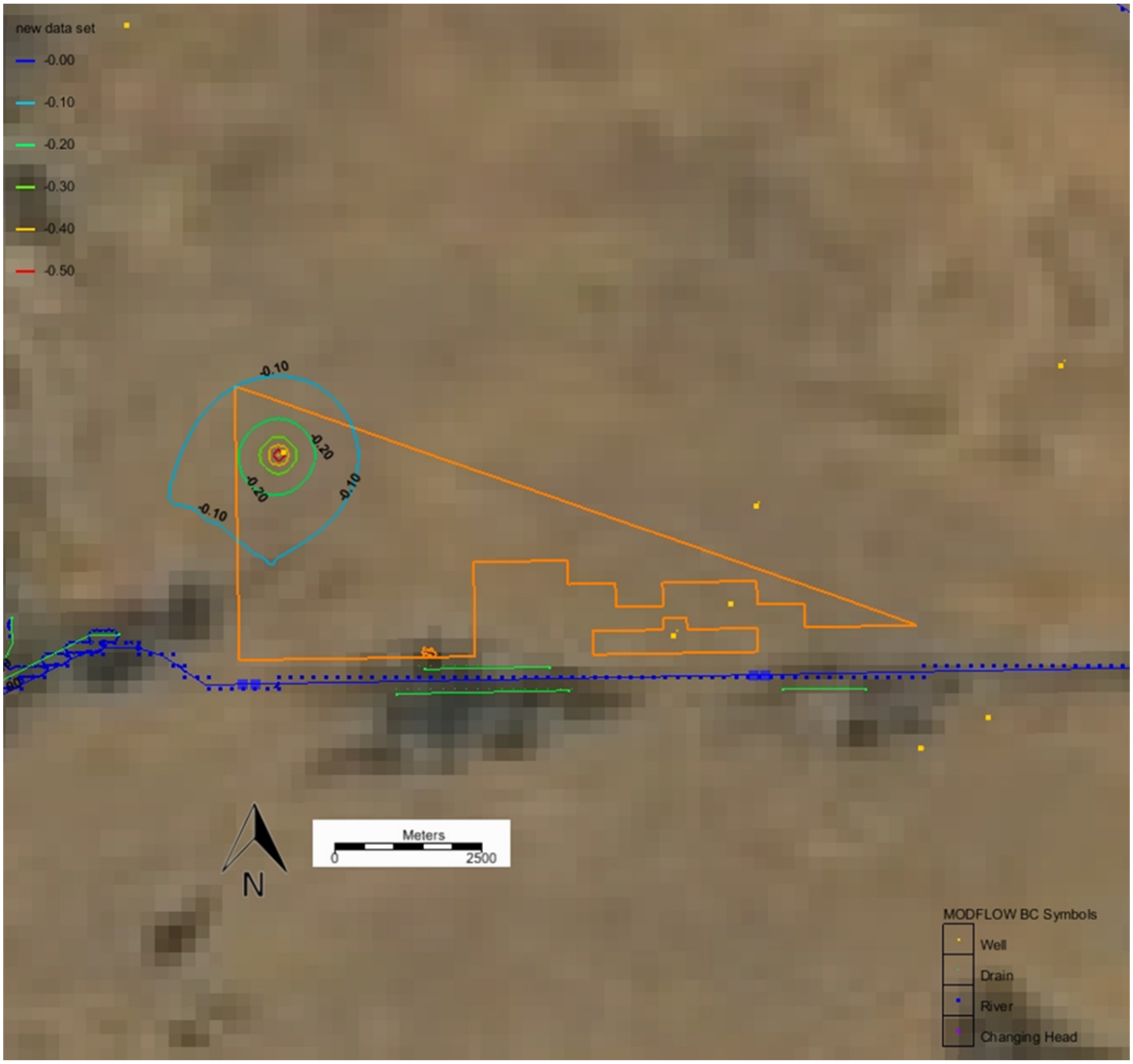

Figure 14 Additional Drawdown from SEZ Wells Screened in Model Layer 1 Due to a Projected 20 Years of Medium-Demand SEZ Pumping from Full Buildout of Dry-Cooled Parabolic Trough Solar Power Technology (Contours in Meters). The Maximum Drawdown is in Layer 1 and as Shown is 1.9 ft (0.58 m) where the Shallow Assumed SEZ Well is in Layer 1. Other Pumping Wells are Marked with Yellow Squares.

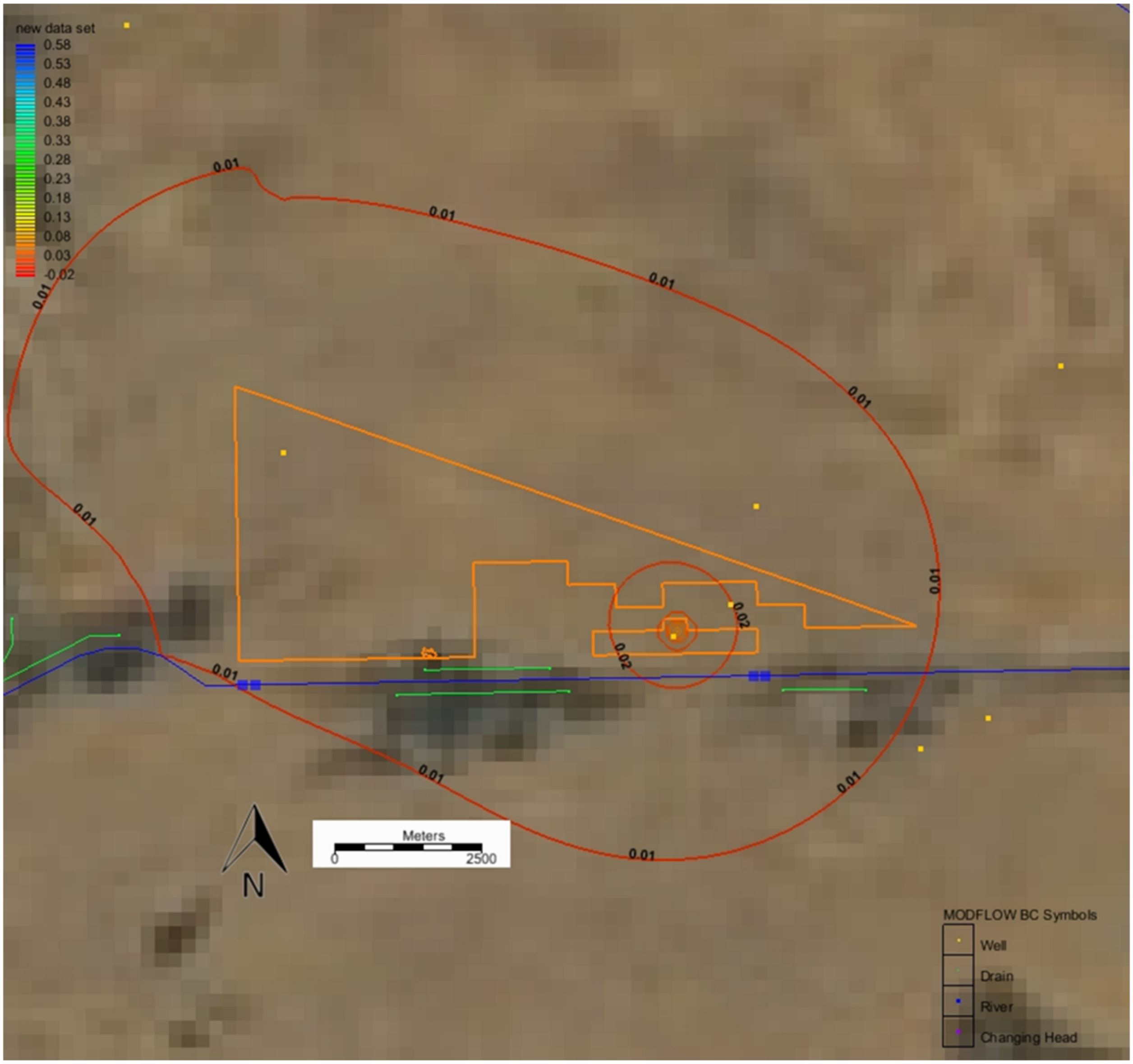

Figure 15 Additional Drawdown from SEZ Wells Screened in Model Layer 7 Due to a Projected 20 Years of Medium-Demand SEZ Pumping from Full Buildout of Dry-Cooled Parabolic Trough Solar Power Technology (Contours in Meters). The Maximum Drawdown in Layer 7 is 0.23 ft (0.07 m) and is Located where the Deeper Assumed SEZ Well is in Layer 7. Other Pumping Wells are Marked with Yellow Squares.

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 was explored using a one-dimensional analytical model adapted from standard methods for long-duration analyses. For the Imperial East SEZ, the analytical modeling effort considered a single well supporting the SEZ's water demands. Two scenarios were examined: a well completed in an unconfined basin fill aquifer and a well completed in a confined basin fill aquifer.

In the unconfined scenario, the analytical modeling described in the Solar PEIS used a thicker aquifer (200 ft or 61 m) than the numerical model's saturated thickness of layer 1, which was approximately 79 ft (24 m), though deeper model layers could contribute to the pumped water as a function of the layering and vertical hydraulic conductivity of the three-dimensional flow model. The analytical model assumed a hydraulic conductivity of 345 ft/d (105 m/d), while the numerical model's calibration process led to a value of 164 ft/d (50 m/d). The numerical model relied on a smaller value of specific yield than the analytical model (0.15 vs. 0.2). The drawdown estimates for high-, medium-, and low-demand pumping were for a single well, whereas the numerical model approach included the assumption of pumping divided between two wells. In the end, the numerical model's drawdown estimates at each of the two wells exceeded the estimate of the analytical approach for the high-demand scenario. This is attributed to the differing input values and modeling approaches. For the medium- and low-demand cases, the drawdown results were very similar between the two methods.

In the confined scenario, the analytical modeling assumed a confined aquifer 380 ft (116 m) thick. Model layer 7 in the numerical model (targeted by the pumping wells) is 328 ft (100 m) thick, though adjacent model layers could contribute to the pumped water as a function of the layering and vertical hydraulic conductivity of the three-dimensional flow model. The analytical model assumed a hydraulic conductivity of 100 ft/d (30 m), while the numerical model's calibration process led to a value of 164 ft/d (50 m/d). The numerical model relied on a smaller storativity value than the analytical model (0.005 vs. 0.01). As with the unconfined scenario, the drawdown estimates for high-, medium-, and low-demand pumping were for a single well, whereas the numerical model approach included the assumption of pumping divided between two wells. In the end, the numerical model's drawdown estimates at each of the two wells were significantly less than the estimate of the analytical approach for both the high- and medium-demand scenarios. This is attributed to the differing input values and modeling approaches.

5.2 Summary of Numerical Model Results

The modeling analysis of solar energy operations at the Imperial East SEZ included an analysis of pre-development and development (municipal and agricultural) pumping to estimate aquifer parameters. Analysis of the pumping requirements for the high-demand SEZ scenario indicates that the drawdown associated with SEZ wells would be dependent on the depth of the well(s) installed. In the model, two SEZ wells were installed, although practical considerations may result in pumping demands distributed among a larger number of wells in the SEZ. With the high-demand pumping split evenly between two wells, additional drawdown due to SEZ operations of up to 14 ft (4.4 m) was noted in the uppermost model layer, if pumping wells were screened in that unit. If deeper aquifer units were targeted by the wells, additional drawdown of up to 2.2 ft (0.68 m) was calculated. The reduced drawdown from deeper units is attributed to semiconfining effects in the hydrogeologic system. Slightly less additional drawdown was observed closer to the canal. This is attributed to the availability of additional water due to canal leakage.

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

5.3 Implications for Future Model Development

Improvements to this assessment-level model could be made with the incorporation of new data regarding the hydrogeological framework and aquifer parameter values. The model's layer boundaries selected for flow modeling could be adjusted in light of new information, particularly to alleviate the drying of cells. 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 and through the logging of SEZ groundwater extraction and/or monitoring well(s). The nature of the alluvium is that it is highly variable spatially. 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 SEZ vicinity 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 modeling domain.

Further evaluation of the decrease in groundwater elevations as a result of lining of the All-American Canal in the vicinity of the Imperial East SEZ may also improve the assessment of potential drawdown impacts from solar-related withdrawals in the SEZ.

5.4 Summary of Model Files

Modeling was performed using GMS version 9.0 (64-bit) with a build date of January 10, 2013. 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, functionality cannot be guaranteed.

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

- ImperialEast_0524.gpr is the pre-1942 steady-state model.

- ImperialEast_0628_transient_cal.gpr is the transient model calibrated with hydraulic conductivity including agricultural and municipal pumping for 71 years.

- ImperialEast_0628_transFWD_baseline.gpr is the baseline model for the future effects of SEZ pumping. It uses the final heads from the calibrated transient model as starting heads and simulates a 20-year period of continued agricultural and municipal pumping.

- ImperialEast_1113_transFWD_high.gpr is the same as ImperialEast_0628_transFWD_baseline.gpr except that SEZ pumping at the high-demand (wet-cooling of CSP) rate occurs during the 20 years of modeled agricultural and municipal pumping. Within this GMS file, "High SEZ drawdown (m)" is a data set created using the GMS Data Set Calculator tool to determine the difference in drawdown between the high results after the 20-year time step (with maximum SEZ pumping) and baseline results at the 20-year time step (without SEZ pumping).

- ImperialEast_1113_transFWD_medium.gpr is the same as ImperialEast_0628_transFWD_baseline.gpr except that SEZ pumping at the medium-demand rate (dry-cooling of CSP) occur during the 20 years of modeled agricultural and municipal pumping. Within this GMS file, "Medium SEZ DDN (Ss=0.005)" is a data set created using the GMS Data Set Calculator tool to determine the difference in drawdown between the medium results after the 20-year time step (with medium SEZ pumping) and baseline results at the 20-year time step (without SEZ pumping).

- ImperialEast_0628_transFWD_low.gpr is the same as ImperialEast_0628_transFWD_baseline.gpr except that SEZ pumping at the minimum (PV) rates occur during the 20 years of modeled agricultural and municipal pumping. Within this GMS file, "Low SEZ DDN (Ss=0.005)" is a data set created using the GMS Data Set Calculator tool to determine the difference in drawdown between the low results after the 20-year time step (with minimum SEZ pumping) and baseline results at the 20-year time step (without SEZ pumping).

5.5 Disclaimer on the Use of the Imperial East 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 have relied 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 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 above. 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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