Pacific Gas & Electric

ADDENDUM TO DEVELOPMENT OF GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELS

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Topock Compressor Station

Needles, California

January 2017

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Our Ref.:

RC000753.0036

Date:

January 2017

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VERSION CONTROL, OPTIONAL

Issue	Revision No	Date Issued	Page No	Description	Reviewed by

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Acronyms and Abbreviations

ADWR	Arizona Department of Water Resources
af/y	acre-feet per year
CACA	Corrective Action Consent Agreement
CD	Consent Decree
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
Cr(VI)	hexavalent chromium
CSM	conceptual site model
DOI	Department of the Interior
DTSC	California Department of Toxic Substances Control
ET	evapotranspiration
ft^2	square feet
ft^3/day	cubic feet per day
gpm	gallons per minute
HSU	Hydrostratigraphic Unit
IM	interim measure
IRL	Inner Recirculation Loop
IRZ	*in-situ* reactive zone
K	hydraulic conductivity
$K_h:K_v$	Horizontal to vertical hydraulic conductivity
m^2/g	square meters per gram
NTH	National Trails Highway
NAVD 88	North American Vertical Datum of 1988
PG&E	Pacific Gas and Electric Company
RCRA	Resource Conservation and Recovery Act
SAV	submerged aquatic vegetation
TCS	Topock Compressor Station
µg/L	micrograms per liter
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

EXECUTIVE SUMMARY

Pacific Gas and Electric Company (PG&E) is implementing the selected groundwater remedy for chromium in groundwater at the PG&E Topock Compressor Station (TCS, or the Compressor Station) in San Bernardino County, California (Site). Remedial activities at the Topock site are being performed in conformance with the requirements of the Resource Conservation and Recovery Act (RCRA) Corrective Action pursuant to a Corrective Action Consent Agreement (CACA) entered into by PG&E and the California Department of Toxic Substances Control (DTSC) in 1996. In addition, PG&E and the United States executed a Remedial Design/Remedial Action Consent Decree (CD), on behalf of the Department of the Interior (DOI), under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 2012, which was approved by the U.S. District Court for the Central District of California in November 2013. The TCS is approximately 1,500 feet west of the Colorado River and ½ mile west of Topock, Arizona. This document, Addendum to Development of Groundwater Flow and Solute Transport Models documents the responses to the seven directives issued by the DTSC in a letter dated October 4, 2016 (DTSC 2016).

The groundwater flow model was updated in accordance with the seven agency directives. The model calibration was supplemented with additional regional groundwater level targets obtained from various sources published over the past 54 years. The initial Site targets represent 2015 steady-state conditions. Calibration results indicated the model was well calibrated to both regional and Site target sets. Although the focus of the groundwater flow model is the Site area, the regional targets helped further constrain the model calibration and better align simulated groundwater flow with flow patterns across the full model domain. The remediation design was re-evaluated using the updated groundwater flow model, and pathline and drawdown analyses were performed. The pathline analysis was consistent with the *Development of Groundwater Flow and Transport Models* report (Arcadis, 2016). The drawdown analysis for pumping at the freshwater supply wells (HNWR-1A and Site B) indicates a relatively minimal extent of drawdown from these two extraction wells with a maximum drawdown of only two feet at Topock-2 and -3 under the maximum 900 gpm freshwater extraction scenario.

The updated groundwater flow model was utilized to re-evaluate the remedial design and solute transport modeling presented in *Appendix B of the 100% Basis of Design* report (Arcadis 2015) and the *Development of Groundwater Flow and Transport Models* report (Arcadis 2016). Overall, the solute transport modeling results from the updated groundwater flow model were consistent with those presented in those two reports. Based on these results, no remedy design alterations are recommended.

Based on the modeling analyses and the results of the solute transport model, the planned remedy will be effective in remediating the current Cr(VI) plume distribution while minimizing the potential adverse impacts from byproduct generation. The solute transport model can be utilized as a tool to supplement monitoring of the implemented remedial system for assessing remedy effectiveness and optimizing operations. During installation and implementation of the remedial system, the additional hydrogeologic and groundwater quality data that will be generated can be utilized to update the groundwater flow and transport models and to further improve their effectiveness as tools for understanding site conditions and optimizing remedy performance.

1 INTRODUCTION AND OBJECTIVES

1.1 General

This report serves as an addendum to the *Development of Groundwater Flow and Transport Models* report (Arcadis 2016) and has been prepared for Pacific Gas and Electric Company (PG&E) to present responses to the seven agency directives from a letter dated October 4, 2016 (California Department of Toxic Substances Control [DTSC] 2016) for the PG&E Topock Compressor Station (TCS, or the Compressor Station) in San Bernardino County, California. The TCS is located approximately 1,500 feet west of the Colorado River and ½ mile west of Topock, Arizona (**Figure 1-1**).

Remedial activities at the Topock Site are being performed in conformance with the requirements of the Resource Conservation and Recovery Act (RCRA) Corrective Action pursuant to a Corrective Action Consent Agreement (CACA) entered into by PG&E and the DTSC in 1996. In addition, PG&E and the United States executed a Remedial Design/Remedial Action Consent Decree (CD), on behalf of the Department of the Interior (DOI), under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 2012, which was approved by the U.S. District Court for the Central District of California in November 2013.

1.2 Report Objectives and Organization

The objective of this modeling addendum report was to respond to the seven directives received from DTSC and DOI in the letter issued October 4, 2016 (DTSC 2016):

- Directive 1 – Adjust eastern and southeastern model boundaries to be consistent with the conceptual site model (CSM);

- Directive 2 – Review available data and computational methods for determining evapotranspiration (ET) rates, and with the assistance of Tribal representatives redefine the river cells and most likely areas for ET as well as ET rates and root extinction depths;

- Directive 3 – Ensure that mass balance is properly reported, illustrate inflows and outflows and compare against independent estimates;

- Directive 4 – Provide a hydraulic conductivity frequency histogram for each hydrostratigraphic unit (HSU) and discuss appropriateness of the distribution and assumed anisotropies with respect to measured values, depositional environments and diagenesis;

- Directive 5 – Describe the sources of data, data collection approach, available data, uncertainty, potential impacts on modeling results versus alternative conceptualizations, and justification for pumping wells in areas surrounding the Site, yet within the model domain;

- Directive 6 – Provide additional basis, associated uncertainty, potential impacts on modeling results versus alternative conceptualizations, and justification for the southwestern flux boundary; and

- Directive 7 – Provide additional basis, associated uncertainty, potential impacts on modeling results of the assigned vertical anisotropy in the lowest (bedrock) model layer versus different vertical anisotropies in this layer, and justification for the approach.

This document details the responses to the directives. To further illustrate the impacts on the flow and transport model, additional analyses were conducted and figures were generated using the updated groundwater flow model.

The report is organized into six main sections:

- Section 2 – Directive Responses

- Section 3 – Remediation Design

- Section 4 – Pathline Analysis

- Section 5 – Drawdown Analysis for HNWR-1A and Site B

- Section 6 – Solute Transport Model Results

- Section 7 – Model Uncertainty

2   DIRECTIVE RESPONSES

The responses to the seven directives listed in the letter from the DTSC and DOI issued October 4, 2016 (DTSC 2016) are described in the following sections. The responses are not in the sequential order of the directives, but rather are in the order in which they were completed. During the model update procedure, several meetings were held between PG&E, DTSC, DOI, and tribal representatives to discuss the model updates and solicit feedback from the group. These meetings were held on the following dates:

- October 31, 2016
- November 14, 2016
- November 22, 2016
- December 9, 2016

As per tribal requests during these meetings, additional regional targets were added to the model to help further constrain the model calibration. Regional targets were obtained from the United States Geological Survey (USGS) and Arizona Department of Water Resources (ADWR) databases, Brad Guay's Dissertation (Guay 2001), and the Topock Groundwater Study (GeoTrans 2006). These regional targets were located throughout the model domain. These data represent conditions from 1961 to 2015. Due to limited available data at some locations and local inconsistencies between water level data from different sources, the targets obtained from different databases were filtered to eliminate water level targets that were anomalous or suspect and retain those targets that were consistent with conceptual site model of overall groundwater flow patterns. Targets were not used in the model calibration if the well was dry or was a flowing artesian well, the well was an active pumping well, obstructed, depth unknown, and/or the reference elevation had an uncertainty greater than 2.5 ft. Data were further reduced by eliminating targets with values greater than a 10 foot difference from the median value of all targets (76% of targets fell within the range of 446 to 466 ft NAVD 88). Finally, targets with observed values that were inconsistent with values from proximate target locations were eliminated. Of the 343 targets obtained from the databases, 117 regional targets were added to supplement the 71 Site targets (total of 188 targets). The 71 Site targets are the 2015 steady-state calibration targets (Arcadis 2016).

2.1   Directive 1 - Eastern and southeastern boundary conditions

The eastern and southeastern model boundaries in the previous model version were no-flow boundaries (Figure 3.3-1 of *Development of Groundwater Flow and Transport Models* report [Arcadis 2016]). This configuration did not directly account for subsurface inflow from the direction of the Sacramento and Warm Springs Washes. To make the model more consistent with the conceptual site model, the boundary condition was revised first to a constant head then to a general head boundary. A general head boundary was selected over a constant head boundary because it more closely simulated the estimated flux of 2,400-4,000 acre-feet per year (af/y) for the Sacramento Wash as reported by the USGS (1971 and 2011) and more closely matched regional targets in the eastern portion of the model (discussed in Section 2.7). The head values in the general head boundary were interpolated water levels based on available regional groundwater data in the ADWR database (ADWR 2016). The general head boundary was added in model layers 1 through 9 in the alluvium. **Figure 2.1-1** shows the model boundary conditions. While water levels and flow conditions changed on the Arizona side to be more consistent with the conceptual site model (CSM), these modifications to the eastern and southeastern boundary conditions had minimal impact on water levels and flow conditions in the vicinity of the Site.

2.2   Directive 2 – ET and river cell update

The evapotranspiration (ET) rates, extinction depths, and locations for ET and river cells were updated based on the review of available data. The location of river cells and vegetation were further verified with January 2015 satellite imagery (Google Earth 2016; **Figure 2.2-1**) and 2015 land cover surveys (USGS 2016). These data sources were used to complete the following tasks:

- Locations of river cells in the model were edited based on USGS data files (USGS 2016)

- Verified types of vegetation and their locations using satellite imagery and land cover survey map

- A comparison of the USGS land cover survey map and the simulated ET distribution are shown on Figure 2.2-2. As the model domain was larger than the USGS landcover survey, estimates of vegetation types were made in these areas based on the satellite imagery. ET in the individual grid cells were assigned based on the dominant vegetation species located in each cell. The simulated ET distribution closely matches the ET distribution from the USGS landcover survey. The ET rates and extinction depths assigned to the model for different plant species are shown in Table 2.2-1. Defined values for ET rates and extinction depth based on plant species and regional studies (the effect of ET on groundwater may be overestimated as published ET rates typically neglect surface water contribution).

Table 2.2-1 Evapotranspiration Rates and Extinction Depths

Description	ET rate (in/yr)	Extinction Depth (feet [ft])	Reference
Open Water	0	0	None. Open water was not assigned an ET value.

Submerged Aquatic Vegetation (SAV)	0	10	None. SAV was not assigned an ET value because it is concurrent with open water observed on 2015 satellite imagery.
Cattail	68.05	10	US Department of the Interior Bureau of Reclamation-Lower Colorado Region. 2014.
Bulrush	68.05	10	US Department of the Interior Bureau of Reclamation-Lower Colorado Region. 2014.
Bare Ground	3.72	10	USGS 2006
Tamarix	36.24	30	USGS 2006
Arrowweed	25.68	10	USGS 2006
Phragmites	68.05	10	USGS 2006
Mesquite	42.35	30	US Department of the Interior Bureau of Reclamation-Lower Colorado Region. 2014.

Additional changes were incorporated to Topock Bay during the directive response. The stage of Topock Bay was adjusted to reflect the most recently reported average stage of Topock Bay from 2014 (USGS 2016). The average stage was corrected from 457.40 to 457.11 feet North American Vertical Datum of 1988 (NAVD 88). The conductance in Topock Bay was decreased to 10% of the previous model version value (Arcadis 2016) to better align with the site CSM, in which the slow moving waters of Topock Bay have led to deposition of finer sediment with lower hydraulic conductivity as compared to the riverbed sediment of the Colorado River.

As expected, the incorporation of the updated River and ET cells decreased simulated water levels by up to 2 feet in the area located between the Colorado River and the Topock Bay where the majority of the vegetation exists, and resulted in increased gradients in that local area. However, these modifications to the river and ET cells had minimal impact on water levels and flow conditions in the vicinity of the Site.

2.3 Directive 5 - Pumping wells

Directive 5 requested additional justification of regional pumping simulated within the model domain. The current ADWR database contains limited current pumping data for individual wells. In some cases, only well capacities are presented, which likely overestimate the pumping rates at individual wells. The majority of regional wells in the model domain do not have any reported rate information. Based on this limited data, regional pumping centers were assigned in approximate areas rather than using individual wells. Given the distance of the individual pumping wells from the Site, these regional wells do not have a significant impact on the flow conditions at the Site or the remedy design. Pumping rates at Golden Shores were re-evaluated and the collective pumping rate increased from 180 af/y to 550 af/y based on the Mohave County Water Authority Demand and Supply Assessment from June 2015 (ADWR 2015). The 550 acre-ft/yr rate is the current maximum demand for the Golden Shores Water Conservation District. The pumping data for Topock-2 and -3, and Park Moabi were maintained at 72 and 6 af/yr, respectively. The Golden Shores area is represented by a single pumping center within the residential area as the exact locations of individual active extraction wells within the Golden Shores Area were not readily available. As noted above, due to the distance of these pumping areas from the Site and the

buffering capacity of the surface water features, modifications to pumping rates had a minimal effect on water levels and flow conditions in the vicinity of the Site.

2.4   Directive 6 - Southwestern flux boundary

Directive 6 requested additional justification on the southwestern flux boundary located in the Chemehuevi Mountains. The southwestern flux boundary (see **Figure 2.1-1**) represents inflow from rainfall recharge in the mountain areas. The published estimate of rainfall in the mountain areas is approximately 10 inches per year (Metzger and Loeltz 1973), and 1 to 2 percent of this rainfall is assumed to infiltrate either directly into bedrock or into alluvium as mountain front recharge. The approximate drainage catchment area of Bat Cave Wash is 18,000 acres (CH2M Hill 2006). In this modeling exercise a flux of 171.5 af/y was used, which represents approximately 1 percent of the estimated rainfall in the mountain areas. This recharge rate produces a groundwater flux from the bedrock to the alluvium consistent with the CSM.

2.5   Directive 7 – Vertical anisotropy in bedrock

The previous model version produced groundwater flow patterns in the bedrock model layer (model layer 10) that were inconsistent with the CSM and the overlying alluvium, therefore different vertical anisotropies for the model layers representing bedrock were evaluated during this modeling exercise. Three vertical anisotropy ratios were evaluated: 10:1, 100:1, and 1000:1 (ratios are horizontal to vertical hydraulic conductivities [K_h:K_v]). The regional target statistics and the flux in Sacramento and Warm Springs Washes are presented in **Table 2.5-1** (note that these statistics reflect the groundwater flow model with all seven directive changes incorporated). The residual statistics and fluxes are not significantly different between the three anisotropy ratios. The simulated water levels for each ratio in the bedrock (model layer 10) are shown on **Figure 2.5-1**. The water levels for the 10:1 ratio more closely mimic the water levels simulated in the overlying alluvium, which is the expected CSM; therefore the vertical anisotropy ratio was changed from 1000:1 to 10:1. Due to the contrast between the hydraulic conductivities in the alluvium and bedrock, the flux contribution from the bedrock is still minimal relative to the regional fluxes in the alluvium.

Table 2.5-2 Regional Target Statistics for Various Vertical Anisotropies in the Bedrock

Parameter	K_h:K_v = 10:1	K_h:K_v = 100:1	K_h:K_v = 1000:1
Residual Mean (ft)	0.272	0.275	0.271
Residual Std. Deviation (ft)	1.964	1.963	1.964
Sum of Squares (square feet [ft^2])	805.75	805.51	805.85
Number of Observations	188	188	188
Range in Observations (ft)	25.19	25.19	25.19

Scaled Residual Std. Deviation	7.80%	7.79%	7.80%
Sacramento Wash Flux (af/y)	3,479.05	3,478.43	3,478.49
Warm Springs Wash Flux (af/y)	968.38	968.33	968.35

2.6   Directive 4 - Hydraulic conductivity values

2.6.1 Hydrostratigraphic Units

Directive 4 requested additional justification of the hydraulic conductivity (K) values simulated in the groundwater flow model. There are ten characteristic HSUs in the region (CH2M Hill 2006; Arcadis 2016). These HSUs, their range in estimated K values, and the average K used in the model are shown on **Table 2.6-1**. The HSUs are shown for each model layer on **Figures 2.6-1 and 2.6-2**. The groundwater flow model was initially calibrated to a single average K value in each HSU, and then heterogeneity within each HSU was approximated by applying a log-normal K distribution within each HSU. These hydraulic conductivities will be further refined in the future according to the model update procedure presented in Section 7 of the *Development of Groundwater Flow and Transport Models* report (Arcadis, 2016).

Table 2.6-3 Hydrostratigraphic Units

Index	Stratigraphic Age	Site HSU	Deposit	Description	Characteristics	Estimated Hydraulic Conductivity (ft/day) (CH2M Hill 2006)	Average Hydraulic Conductivity in the model (ft/day)
1	Holocene	Qr3	Fluvial	Upper Fluvial Sand and Silt	Unconsolidated sand and silty sand (no gravel), massive bedded, very well sorted; contains fine grained organic matter	3-22	41.3
2		Qr2	Fluvial	Middle Fluvial Deposits	Interbedded unconsolidated sand, clay, and minor gravelly sand; clay/silt lenses exhibit both brown and gray (reduced) appearance	5-110	60.0
3		Qr1	Fluvial	Lower Fluvial Deposits	Unconsolidated sandy gravel and gravelly sand with minor silty gravel (gravel content greater than 15%); subrounded to very well-rounded pebbles and cobbles from distant sources and fluvial deposits	20-50	31.5
4		Qr0	Fluvial	Colorado River Channel Fill	Fluvial channel fill sediments that occur below elevation 360 ft msl (deepest river deposits encountered in floodplain borings). Per Caltrans I-40 bridge borings includes moderately consolidated to dense, fine to coarse sand and sandy gravel	50	79.7
5	Pleistocene	Qoa	Alluvium	Older Quaternary Alluvium	Unconsolidated sandy gravel and silty/clayey gravel (alluvial fan deposits). Comprises moderately-dissected alluvial terraces' terrace/wash slopes are moderate angle (i.e., 45 degrees)	10-300	84.4
6	Pliocene	Tb	Alluvium	Bouse Formation	Pre-Colorado River lacustrine and deltaic deposits (well bedded, moderately indurated, green clay, siliceous claystone, sandstone, and basal marl)	1	8.2
7	Pliocene to Late Miocene	Toa2	Alluvium	Tertiary Alluvium - Upper	Moderately consolidated sandy gravel, gravelly sand, and silty/clayey gravel (oldest alluvial fan deposits). Comprises deeply-dissected alluvial terraces; terrace canyon walls are vertical/steep (Subdivision of Toa2 and Toa1 based on contrasts in hydraulic conductivity observed in TW-1, TW-2D, and IW-1).	1-85	37.5
8		Toa1	Alluvium	Tertiary Alluvium - Lower		1-85	77.8
9	Late Miocene	Toa0	Alluvium	Basal Alluvium	Moderately consolidated silty sand, clayey/silty gravel, and minor gravelly sand. Consists of 100% reddish detritus of Miocene conglomerate in floodplain area. In other areas, Toa0 is well-consolidated alluvium, lacks reddish-color, and exhibits high-induction geophysical log response	6-300	35.6
10	Middle Miocene	Bedrock	Bedrock	Miocene Conglomerate	Consolidated conglomerate, sandstone, metadiorite, gneiss, and granitic bedrock	0.003-0.03	0.11 (shallow)
	Pre-tertiary			Metamorphic/Igneous Bedrock			0.011 (deep)

2.6.1.1   Fluvial (River) Deposits

The Colorado River deposits (or fluvial deposits) lie from the Topock floodplain eastward to the edge of Topock Bay and Topock Marsh. The thickness of the fluvial deposits ranges from near zero to approximately 250 feet observed in the river seismic survey conducted by the USGS (Peter Martin, Technical Work Group meeting communications 2004). Four HSUs comprise the fluvial deposits: Qr3, Qr2, Qr1, and Qr0 (from the youngest to the oldest).

2.6.1.2   Quaternary Alluvium (Qoa)

The quaternary alluvial deposits overlie the Bouse Formation, where the Bouse Formation is present. Where the Bouse Formation is not present, the Quaternary and Tertiary Alluvial deposits are almost indistinguishable in Site borings. However, in outcrops, the difference between the Quaternary and Tertiary Alluvial deposits is apparent as the members of Quaternary Alluvium have a moderate angle (around 45 degrees). The average hydraulic conductivity in the model is 84.4 ft/day, falling within the measured hydraulic conductivity range of 10 to 300 ft/day (CH2M Hill 2006).

2.6.1.3   Bouse Formation

The Bouse Formation is located in the western portion of the model domain and consists of interbedded clay, claystone, and sandstone. This formation represents a lacustrine deposit left by a large portion of the Mohave Valley (Howard et al, 1997). However, much of the Bouse Formation was eroded away during the Pleistocene and Holocene Epochs. In Site boring logs, no saturated portion of the Bouse Formation has been encountered. Although no aquifer test data is available for the Bouse Formation, based on the hydrogeologic description, the average hydraulic conductivity was reduced from 81.6 to 8.16 ft/day.

2.6.1.4   Tertiary Alluvium

The tertiary alluvium consists of sandy gravel and silty/clayey gravel. The tertiary alluvium was divided into lower and upper units based on hydraulic permeability contrasts observed in well testing and variations in geophysical log responses. The average hydraulic conductivity of the lower and upper units is 77.8 and 37.5 ft/day, respectively. The measured range in hydraulic conductivity is 1 to 70 ft/day (CH2M Hill 2006).

2.6.1.5   Basal Alluvium

The basal alluvium has previously been described as either the "Basal Saline Unit" or "reworked Miocene Conglomerate" (CH2M Hill 2006). Geophysical induction logging indicates that there is much higher salinity and finer grained material in the basal alluvium than in most of the tertiary alluvium. The average hydraulic conductivity in the model for the basal alluvium is 35.6 ft/day, which is within the measured range of 20 to 300 ft/day (CH2M Hill 2006).

2.6.1.6   Bedrock

The bedrock at the Site consists of Pre-Tertiary igneous and metamorphic rock and the Miocene conglomerate. In general, both bedrock units are considered to produce very little water and to be locally fractured (CH2M Hill 2006). There is an upward hydraulic gradient between the bedrock units and the alluvial units. The bedrock can be divided into two separate units: shallow and deep. The shallow bedrock was conceptualized to be more weathered than the deeper bedrock, thus a larger K was assigned to the shallow bedrock than the deep.

2.6.1.7   Hydraulic Conductivity Distribution

The interpolated bedrock surface elevation and the thicknesses of the hydrostratigraphic units were utilized to determine where the individual hydrostratigraphic units intercepted the revised model layer structure. The hydrostratigraphic unit extents present in each model layer were used to define the hydraulic conductivity zonation. The hydrostratigraphic units for each model layer are shown in **Figures 2.6-1 to Figure 2.6-2**. Initial hydraulic conductivity values for the individual hydrostratigraphic units were assigned based on available aquifer test data. These initial values were further refined during the calibration process through manual adjustment and automatic parameter estimation using PEST. Hydraulic conductivity was allowed to vary within the range of recorded aquifer test values and previously modelled values using professional judgment. As there was limited regional hydraulic conductivity data available for the full model domain and the majority of the calibration targets are located in the immediate vicinity of the Site, the regional hydraulic conductivity values were dependent on the available Site data.

The initial calibration of the model to single hydraulic conductivity values for each hydrostratigraphic unit was then allowed to vary within each hydrostratigraphic unit by generating a stochastic distribution of hydraulic conductivity. This was approach is intended to represent the natural heterogeneity and variability of the aquifer. A two-dimensional spatially correlated log normal conductivity field, consistent with typical natural conditions (Law 1944; Bennion and Griffiths 1966; Freeze and Cherry 1979; Zheng and Bennet 2002; Belcher et al. 2002), was generated for the model using a Gaussian power spectrum (Robin et al. 1993). The distribution was constrained within the range of potential hydraulic conductivity values with the distribution varied by layer to represent the vertical heterogeneity within hydrostratigraphic units that span multiple model layers. While the hydraulic conductivity pattern and values varied within each hydrostratigraphic unit, the average value for each hydrostratigraphic unit is consistent with calibrated values. The use of these random generated fields allows for potential uncertainties associated with heterogeneities encountered in the aquifer while maintaining a well calibrated model. The hydraulic conductivity distributions per model layer are shown in **Figures 2.6-3 to 2.6-4**. Vertical hydraulic conductivity was not a sensitive parameter during the calibration and sensitivity analyses, so a horizontal to vertical hydraulic conductivity ratio of 10:1 was utilized throughout the model domain.

The statistics of the distributions are illustrated using histograms of hydraulic conductivity assigned in each cell in the model within the respective HSUs. These are shown on **Figures 2.6-5 to 2.6-7**. The calibration value (average), median, and mode for each distribution is shown on the figures. These values are not the same as the distribution is positively skewed. No histogram was created for the bedrock as the zone is represented in the model using uniform hydraulic conductivity.

Hydrogeologic systems are inherently anisotropic due to vertical stratification of layers with different hydraulic properties. These contrasts result in flow paths to be parallel to lithology and the vertical hydraulic conductivity to be significantly less than in the horizontal direction (Freeze and Cherry 1979; Zheng and Bennet 2002; Duque et al. 2012). As such, a horizontal to vertical anisotropy ratio of 10 to 1 was used for the alluvial and fluvial deposits.

2.7   Directive 3 – Water Balance and Model Calibration

Calibration of a groundwater flow model refers to the process of adjusting model parameters to obtain a reasonable match between observed and simulated water levels. Model calibration is an iterative procedure that involves adjustment of hydraulic properties and/or boundary conditions to achieve the best match between observed and simulated water levels. During model calibration, model parameters are varied over a narrow range set by Site-specific data using the CSM as a guide. During calibration of a groundwater flow model, use of point data (targets) eliminates the potential for interpretive bias that may result from attempting to match a contoured potentiometric surface (Konikow, 1978; Anderson and Woessner, 1992). This section describes the calibration results, simulated water levels, and the calibration water balance for 2015 Active Interim Measure (IM)-3 conditions (described in Section 3.5.1 of *Development of Groundwater Flow and Solute Transport Models* report [Arcadis 2016]). The final calibrated model incorporates the changes from all the other directives, described in Sections 2.1-2.6. A validation of the calibration results is provided in Section 2.7-4 for steady-state Pre Interim Measure (IM)-3 conditions in 2004 and for 2015 transient conditions.

2.7.1   Calibration Results

The quality of the model calibration can be determined by a statistical analysis of the residuals, as shown in **Table 2.7-1** for the steady state 2015 Active IM-3 Site calibration targets and average regional calibration targets collected between 1961 and 2015. Residuals are defined as the difference between the model-simulated heads and the observed values. Positive residual values indicate that the model-simulated values are lower than the measured values, and negative residual values indicate that the model-simulated values are higher than the measured values. Residual statistics (**Table 2.7-1**) for the calibrated groundwater flow model indicate an acceptable agreement between simulated and measured groundwater elevations. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be 0.27 feet, 1.96 feet, and 805.75 square feet (ft^2), respectively. The residual standard deviation is less than 10% of the range in observed water levels. These statistics indicate a good agreement between the observed and simulated water levels. A plot of observed versus simulated groundwater elevations for the 188 calibration targets is presented on **Figure 2.7-1**. **Appendix A** includes a summary of the simulated and observed water levels for targets used in the model calibration. The target set was described in Section 2 of this document.

Table 2.7-1 Regional and Site Calibration Statistics

Residual Statistics	
Residual Mean (ft)	0.27
Residual Std. Deviation (ft)	1.96
Sum of Squares (ft^2)	805.75

Number of Observations	188
Range in Observations (ft)	25.19
Scaled Residual Std. Deviation	7.8%

The calibration was also evaluated for the conditions on Site only, as that is the focus of the remedial design. Residual statistics (**Table 2.7-2**) for Site targets only indicate an acceptable agreement between simulated and measured groundwater elevations. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be -0.01 ft, 0.38 ft, and 10.06 ft^2, respectively. The residual standard deviation is less than 10% of the range in observed water levels. These statistics indicate a good agreement between the observed and simulated water levels. A plot of observed versus simulated groundwater elevations for the 71 Site calibration targets is presented on **Figure 2.7-2**.

Table 2.7-2 Site Calibration Statistics

Residual Statistics	
Residual Mean (ft)	-0.014
Residual Std. Deviation (ft)	0.376
Sum of Squares (ft^2)	10.062
Number of Observations	71
Range in Observations (ft)	4.086
Scaled Residual Std. Deviation	9.2%

Simulated groundwater elevations in layer 1 and residuals for all layers are shown on **Figures 2.7-3, 2.7-4, and 2.7-5**. **Figure 2.7-3** shows regional targets outside the Site and Golden Shores areas, which are shown on **Figures 2.7-4 and 2.7-5**, respectively. Over-predictions in water levels are generally balanced with under-predicted water levels across the model domain. As the updated groundwater flow model remained well calibrated, no additional changes were made to hydraulic properties or boundary conditions.

2.7.2   Simulated Water Levels

Simulated water levels for all ten model layers are shown on **Figures 2.7-6 and 2.7-7**. Due to the contrast in permeabilities between the alluvium and the bedrock, the gradient steepens in the bedrock located south of the Site. The contact between the bedrock and the alluvium moves northward as the depth increases, therefore the location of the steep gradient between the bedrock and the alluvium also moves northward as the layers increase. In the bedrock in the vicinity of the Site, groundwater travels from south to north out of the bedrock and into the alluvium.

Figure 2.7-8 shows simulated regional groundwater pathlines under calibration conditions in model layer 1. These pathlines were delineated using MODPATH (Pollack 1989). MODPATH is a program that is used in conjunction with MODFLOW to track the advective movement of groundwater using the computed flow information from the MODFLOW model. Lines of particles were initialized at the active model domain extents and run with forward particle tracking. No time limit was specified for the pathlines. This figure helps to illustrate groundwater movement throughout the model domain. Groundwater in the eastern portion of the model domain moves from southwest towards the Colorado River and Topock Bay.

Groundwater in the bedrock in the vicinity of the Site travels from south to north out of the bedrock and into the alluvium. In the northwestern portion of the model domain, groundwater travels east/southeast towards the Colorado River.

2.7.3 Simulated Water Balance

The simulated layer-wise and full model water budget is shown in **Table 2.7-3** in cubic feet per day (ft^3/day). The water budget does not present the vertical flux between layers, but the vertical flux is accounted for in the total inflow and outflow values. The model wide water balance is also shown graphically on **Figure 2.7-9**. The inflow from Sacramento Wash was simulated as 3,479 af/y, which is within the range of estimated flux through Sacramento Wash of 2,400-4,000 af/y (USGS 1971 and USGS 2011). Warm Springs Wash was simulated as a flux of 968 af/y; there are no documented flux estimates for Warm Springs Wash.

Table 2.7-3 Simulated Water Balance

Description	Model Layer 1		Model Layer 2		Model Layer 3		Model Layer 4		Model Layer 5	
	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Flux	8,149	0	6,822	0	6,822	0	0	0	0	0
ET	0	1,044,972	0	0	0	0	0	0	0	0
Constant Head	11,988	3,470	8,290	2,475	13,564	4,711	17,919	5,651	17,180	7,110
General Head	57,620	0	57,584	0	61,371	0	65,024	0	61,255	0
River	501,264	157,686	0	0	0	0	0	0	0	0
Well	0	36,537	0	29,101	3,955	19,801	8,221	5,658	7,816	2,895
Storage	0	0	0	0	0	0	0	0	0	0
TOTAL	1,662,854	1,662,855	1,496,279	1,496,279	1,348,516	1,348,516	1,176,161	1,176,161	1,021,358	1,021,357
ERROR	-7.17E-05		2.28E-05		3.91E-05		4.20E-05		3.73E-05	
Description	Model Layer 6		Model Layer 7		Model Layer 8		Model Layer 9		Model Layer 10	
	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Flux	0	0	0	0	0	0	0	0	0	0
ET	0	0	0	0	0	0	0	0	0	0
Constant Head	9,123	2,744	8,059	2,304	7,691	2,598	270,354	239,669	11	83
General Head	55,836	0	48,150	0	59,170	0	195,310	0	1	0
River	0	0	0	0	0	0	0	0	0	0
Well	4,640	3,775	0	1,049	0	873	0	25	0	0
Storage	0	0	0	0	0	0	0	0	0	0
TOTAL	895,264	895,263	830,889	830,888	820,977	820,977	747,133	747,132	2,171	2,171
ERROR	2.74E-05		1.67E-05		1.21E-05		9.98E-05		4.83E-03	
Description	FULL MODEL									
	Inflow (ft^3/day)	Outflow (ft^3/day)								

Constant Flux	21,794	0
ET	0	1,044,972
Constant Head	364,179	270,813
General Head	661,318	0
River	501,264	157,686
Well	24,632	99,713
Storage	0	0
TOTAL	1,573,186	1,573,184
ERROR	**1.20E-04**	

Interaction between groundwater and surface water is shown graphically on **Figure 2.7-10**. This figure does not illustrate the magnitude of the flux, but gives a general understanding of the interaction of groundwater and surface water. Locations where the Colorado River and Topock Bay are losing (flow from the river to groundwater) are shown in red. Locations where the Colorado River and Topock Bay are gaining (flow from groundwater to the river) are shown in blue. Areas that show a stippled pattern of red and blue typically indicate where the surface water feature is transitioning between gaining and losing, and the simulated flux is generally near neutral. This neutral flux area is evident in the southern portion of the Colorado River where the river is bounded by bedrock and flow between groundwater and surface water is minimal. The Colorado River transitions between gaining and losing throughout the model domain. The river is mostly losing in the Site area due to the influence of the current IM3 extraction. Topock Bay is losing on its western side primarily due to the influence of the introduced ET but also due to water level differences between the Bay and the Colorado River. On the eastern side of Topock Bay, the bay is primarily gaining except in the vicinity of the Golden Shores community due to induced leakage from groundwater extraction.

2.7.4 Calibration Validation

To further evaluate the updated groundwater flow model, the updated groundwater flow model was validated against Site groundwater flow levels from two additional periods: steady-state Pre IM-3 conditions (2004) and transient conditions from November 2014 thru October 2015.

2.7.4.1   Pre IM-3 Conditions

The updated groundwater flow model was validated against steady-state Pre IM-3 conditions (2004). The quality of the model calibration validation can be determined by a statistical analysis of the residuals, as shown in **Table 2.7-4**. Residual statistics (**Table 2.7-4**) for the calibrated groundwater flow model indicate an acceptable agreement between simulated and measured groundwater elevations. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be -0.152 feet, 0.397 feet, and 4.695 ft^2, respectively. The residual standard deviation is less than 21% of the range in observed water levels. These statistics indicate a good agreement between the observed and simulated water levels and the results are consistent with those presented in the *Development of Groundwater Flow and Transport Models* report (Arcadis 2016). A plot of observed versus simulated groundwater elevations for

the 26 calibration targets is presented on **Figure 2.7-11**. The Pre IM-3 Conditions were considered a validation of the model calibration rather than the primary target set since Site 2004 data was fairly limited. The simulated layer-wise and full model water budget is shown in **Table 2.7-5**.

Table 2.7-4 Pre IM-3 Water Level Targets and Residuals

Name	X	Y	Layer	Observed Water Level (ft NAVD 88)	Computed Water Level (ft NAVD 88)	Residual (ft)
MW-09	7614780.27	2100673.29	1	456.46	456.05	0.47
MW-10	7614886.60	2100984.20	1	455.35	455.99	-0.59
MW-11	7614865.33	2101557.09	1	455.75	455.91	-0.12
MW-12	7615923.61	2101429.49	1	455.71	455.74	0.01
MW-13	7614848.07	2103135.17	1	456.15	455.70	0.46
MW-14	7614081.09	2102738.09	1	455.86	455.90	-0.01
MW-15	7613164.94	2100844.08	1	456.08	456.31	-0.15
MW-20-070	7615893.48	2102493.39	1	455.35	455.48	-0.09
MW-21	7616099.26	2101486.75	1	455.48	455.66	-0.14
MW-22	7616359.75	2101566.69	1	454.58	455.33	-0.70
MW-23	7616448.53	2101286.15	1	455.21	456.15	-1.20
MW-24A	7615114.47	2101451.00	1	455.50	455.89	-0.36
MW-27-020	7616557.66	2102294.73	1	455.75	455.22	0.58
MW-30-030	7616141.26	2102499.58	1	455.35	455.38	0.01
MW-16	7610980.32	2100697.20	1	456.47	456.73	-0.14
MW-17	7610243.29	2103135.56	1	455.73	456.48	-0.66
MW-18	7612598.61	2102894.59	1	455.70	456.13	-0.38
MW-20-100	7615881.03	2102506.33	2	455.22	455.48	-0.23
MW-30-050	7616150.98	2102503.83	2	455.12	455.38	-0.22
MW-34-055	7616444.49	2102542.45	2	455.23	455.28	-0.02
PGE-06	7615050.86	2101525.07	2	455.76	455.89	-0.09
MW-20-130	7615881.52	2102493.68	3	455.53	455.48	0.07
MW-24B	7615069.38	2101436.41	3	455.98	455.90	0.12
MW-34-080	7616444.98	2102535.25	3	455.47	455.28	0.21
IW-03	7613237.80	2103007.18	4	455.17	456.02	-0.81
PGE-07	7615034.78	2101350.19	4	456.50	457.13	0.04

Residual Statistics	
Residual Mean (ft)	-0.152
Residual Std. Deviation (ft)	0.397
Sum of Squares (ft^2)	4.695
Number of Observations	26

Range in Observations (ft)	1.920
Scaled Residual Std. Deviation	20.7%

Table 2.7-5 Pre IM-3 Conditions Water Balance

Description	Model Layer 1		Model Layer 2		Model Layer 3		Model Layer 4		Model Layer 5	
	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)
Constant Flux	8,149	0	6,822	0	6,822	0	0	0	0	0
ET	0	1,045,123	0	0	0	0	0	0	0	0
Constant Head	11,929	3,570	8,231	2,553	13,453	4,884	17,746	5,895	17,026	7,402
General Head	57,315	0	57,278	0	61,054	0	64,695	0	60,933	0
River	484,699	169,450	0	0	0	0	0	0	0	0
Well	0	11,849	0	9,461	0	418	0	256	0	2,887
Storage	0	0	0	0	0	0	0	0	0	0
TOTAL	1,632,627	1,632,629	1,446,125	1,446,125	1,293,182	1,293,184	1,134,841	1,134,843	989,892	989,893
ERROR	-1.51E-04		-6.41E-05		-1.26E-04		-1.30E-04		-9.93E-05	

Description	Model Layer 6		Model Layer 7		Model Layer 8		Model Layer 9		Model Layer 10	
	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)	Inflow (ft³/day)	Outflow (ft³/day)
Constant Flux	0	0	0	0	0	0	0	0	0	0
ET	0	0	0	0	0	0	0	0	0	0
Constant Head	9,036	2,881	8,020	2,423	7,653	2,722	267,682	247,853	11	83
General Head	55,532	0	47,881	0	58,874	0	194,587	0	1	0
River	0	0	0	0	0	0	0	0	0	0
Well	0	3,764	0	1,046	0	871	0	49	0	0
Storage	0	0	0	0	0	0	0	0	0	0
TOTAL	872,453	872,453	815,832	815,832	809,364	809,364	744,487	744,488	2,172	2,172
ERROR	-6.85E-05		-3.50E-05		-1.84E-05		-4.39E-05		-1.67E-04	

Description	FULL MODEL	
	Inflow (ft³/day)	Outflow (ft³/day)
Constant Flux	21,794	0
ET	0	1,045,123
Constant Head	360,787	280,266
General Head	658,151	0
River	484,699	169,450
Well	0	30,601
Storage	0	0

TOTAL	1,525,431	1,525,439
ERROR	**-5.79E-04**	

2.7.4.2   Transient Calibration

The transient calibration was conducted with 827 Site water level targets from November 2014 to October 2015. Average variations in the Colorado River stage and pumping were computed on a monthly basis. As the transient calibration model is a time dependent simulation, storativity (storage) needed to be incorporated into the model. Storage values were varied per hydrostratigraphic unit and were adjusted during the transient calibration. The recalibrated storativity values for the individual hydrostratigraphic units are shown in **Table 2.7-6**. The storativity values presented in **Table 2.7-6** are less than those presented in the *Development of Groundwater Flow and Transport Models* report (Arcadis 2016). Adjustments to the simulated storativity was necessary due to the changes made to the model boundary conditions and properties presented in Section 2.1 through 2.5 of this report. No other changes were made to the steady state hydraulic parameters during the transient calibration process. As the solute transport modeling is conducted as a long term steady state run, the storage values are not used in the solute transport model.

Table 2.7-6 Hydrostratigraphic Unit Storativity Values

Hydrostratigraphic Unit	Description	Average Storativity Value
Qr3	Upper Fluvial Sand and Silt	6.5E-03
Qr2	Middle Fluvial Deposits	1.9E-03
Qr1	Lower Fluvial Deposits	1.4E-03
Qr0	Colorado River Channel Fill	1.5E-03
Qoa	Older Quaternary Alluvium	5.1E-03
Tb	Bouse Formation	6.0E-03
Toa2	Upper Tertiary Alluvium	1.9E-03
Toa1	Lower Tertiary Alluvium	8.1E-06
Toa0	Basal Alluvium	2.8E-06

Tmc	Miocene Conglomerate	2.2E-05

Residual statistics (**Appendix B**) for the calibrated groundwater flow model indicate an acceptable agreement between simulated and measured groundwater elevations. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be -0.01 feet, 0.42 feet, and 142.88 ft^2, respectively. The residual standard deviation is 6.2% of the range in observed water levels. These statistics indicate a good agreement between the observed and simulated water levels. A plot of observed versus simulated groundwater elevations for the 827 calibration targets is presented on **Figure 2.7-12**. Example hydrographs for the floodplain and upland areas are shown in **Figures 2.7-13 and 2.7-14**, respectively. Each hydrograph shows good fit between observed and simulated conditions as the river stage and IM-3 pumping rates varied over time.

3 REMEDIATION DESIGN

As described in the *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016) report, there are seven components of the remediation design that are simulated concurrently with the solute transport model to effectively remediate the hexavalent chromium plume while reducing the impact of potential byproducts:

- NTH IRZ (NTH IRZ Injection and Extraction Wells)

- River Bank extraction (River Bank Extraction Wells)

- Uplands injection (Inner Recirculation Loop [IRL] Injection Wells)

- Transwestern Bench extraction (Transwestern Bench Extraction Wells)

- East Ravine extraction (East Ravine Extraction Wells)

- TCS injection (TCS Injection Wells)

- Freshwater injection (Freshwater Injection Wells)

Details of each component is presented in the *100% Basis of Design* report (Arcadis 2015). The remediation design is shown in **Figure 3-1**.

4 PATHLINE ANALYSIS

Figures 4-1 to 4-10 show simulated groundwater pathlines under active remedy flow conditions in model layers 1 through 5, respectively. Each model layer has 2 figures to represent the different time periods

with the NTH IRZ, active or inactive. These pathlines were delineated using MODPATH (Pollack 1989). A ring of particles was initialized at each of the uplands injection, freshwater injection and TCS injection wells in each layer and run with forward particle tracking for a period of 30 years. These figures help to illustrate the movement of the injected water during the remedy operation and should not be used independently from the solute transport model in order to best evaluate remedy performance. For evaluation of hexavalent chromium, manganese and arsenic migration, the solute transport model is a more useful tool as it is able to account for mechanisms that would influence the behavior of these species in groundwater (i.e., sorption, reduction, oxidation, precipitation, etc.). These pathlines are very similar to those presented in *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016) indicating the changes made to regional model pumping, boundary fluxes, bedrock anisotropy, and evapotranspiration had little to no impact of the simulated flow in the vicinity of the Site under simulated active remedy conditions.

5 DRAWDOWN ANALYSIS FOR HNWR-1A AND SITE B

Drawdown was analyzed for HNWR-1A and Site B under two different pumping conditions (HNWR-1A at 450 gpm and a bounding worst case scenario of HNWR-1A and Site B at 450 gpm each) with the NTH IRZ inactive. The simulated water levels obtained for each of the two pumping scenarios were subtracted from the calibrated water levels (described in Section 2.7) to yield groundwater drawdown at each well. Pathlines were delineated using MODPATH (Pollack 1989). Particles were initialized in a ring around HNWR-1A and a ring around Site B in layers 3 and 4 (the well screen interval) and run with reverse particle tracking for a period of 30 years. Particles were not initialized around Site B when it was not pumping.

5.1   HNWR-1A at 450 gpm

Figure 5.1-1 shows the groundwater drawdown and simulated groundwater flow pathlines for HNWR-1A pumping at 450 gpm. This represents the nominal extraction rate used in the remedial design (Section 3 of the *100% Basis of Design* report [Arcadis 2015]). Drawdown at HNWR-1A is localized, with the potential drawdown from HNWR-1A is relatively limited and the drawdown at Topock 2 and 3 less than 2 feet. The pathlines indicate that over a 30 year timeframe, the majority of the water extracted by HNWR-1A is from the northeastern portion of the model domain.

5.2   HNWR-1A and Site B at 450 gpm each

Figure 5.2-1 presents the groundwater drawdown and simulated flow pathlines for HNWR-1A and Site B each extracting at 450 gpm, representing a bounding and worst-case scenario for the remedial design. The cones of depression for HNWR-1A and Site B are merged between 1 and 2 feet of drawdown. The potential drawdown from HNWR-1A and Site B is still relatively localized and the drawdown at Topock 2 and 3 is approximately 2 feet. The pathlines indicated that over a 30 year timeframe, the majority of the water extracted by both HNWR-1A and Site B is form the northeastern portion of the model domain.

6 SOLUTE TRANSPORT MODEL RESULTS

To further evaluate the updated groundwater flow model, solute transport modeling was performed to evaluate the migration and fate of hexavalent chromium (Cr(VI)) detected in the groundwater, as well as the fate and transport of potential IRZ byproducts (i.e., manganese and arsenic). The solute transport model used the results from the calibrated groundwater flow model to simulate solute transport under average flow conditions.

All parameter values for the solute transport model and software are consistent with Section 4 of *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016). The solute transport modeling in this assessment was performed as a confirmation of results obtained in *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016) and the *100% Basis of Design* (Arcadis 2015).

6.1 Hexavalent Chromium

The solute transport model was run for a period of 30 years utilizing the transport parameters and flow conditions described in Section 4 of *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016) for the simulated Cr(VI). The results are shown for years 0.5, 1.5, 3, 5, 10, 20, and 30 for each of the five model layers in which Cr(VI) was initialized on **Figures 6.1-1 through 6.1-5**.

The solute transport model was rerun with the 2015 Cr(VI) plumes initialized in model layers 1 through 5. The results are shown on **Figures 6.1-6 through 6.1-10**, respectively. There was no simulated hexavalent chromium present in model layers 6 through 10, so these layers were not presented. As there were only minor changes to the Cr(VI) plume distribution between 2013 and 2015, the 2015 Cr (VI) simulation results are similar to predictions using the 2013 initialized plume. The simulated magnitude and extent of Cr(VI) using the revised groundwater flow model are generally consistent with simulated Cr(VI) in the *100% Basis of Design* report (Arcadis 2015) and *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016) using both the 2013 and 2015 initialized plumes (presented in Figures 5.1-1 to 5.1-10).

6.2 Manganese

Figure 6.2-1 shows the maximum manganese in all layers generated as a byproduct from the injection of carbon-amended groundwater for the 30-year simulation period. The simulated magnitude and extent of byproduct manganese using the revised groundwater flow model are consistent with simulated manganese in the *100% Basis of Design* report (Arcadis 2015) and Figure 5.2-1 of *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016).

6.3 Arsenic

Figure 6.3-1 shows the maximum simulated arsenic transport in all layers for the 30-year simulation period. The simulated magnitude and extent of freshwater arsenic and byproduct arsenic using the revised groundwater flow model are generally consistent with simulated arsenic in the *100% Basis of*

Design report and Figure 5.3-1 of *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016).

7 UNCERTAINTY

As with all mathematical models of natural systems, the groundwater flow and solute transport model is limited by factors, such as scale, accuracy of the estimated hydraulic properties and/or boundary conditions, and the underlying simplifications and assumptions incorporated into the model. These factors result in limitations to the model's appropriate uses and to the interpretations that may be made of the simulation results. The remedy design and range of operation were based on the conceptual Site model, calibrated groundwater flow model, the predictive solute transport modeling and sensitivity analysis, and professional judgment.

Several strategies were employed to address the uncertainties inherent to the predictive model. As discussed in Section 2, the flow model was calibrated against: (a) Pre IM-3 steady state conditions, (b) active IM-3 operating steady state conditions (2015), and (c) average monthly Site conditions responding to fluctuating river levels and pumping during 2015. This calibration procedure utilized a stochastic approach that resulted in a highly heterogeneous distribution of hydraulic conductivity to represent the identified hydrostratigraphic units. Rates for regional pumping wells (Section 2.3) were verified against available data. Pumping rates in the Golden Shores wells were increased from rates presented in *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016). Since regional pumping centers are relatively far away from the Site, changes in pumping rates had little to no effect on remedy performance. The southwestern flux boundary (Section 2.4) was justified using the catchment area and estimates of recharge in the Chemehuevi Mountains. The southwestern flux value used fell within the published range of 1 to 2 percent of rainfall assumed to infiltrate as mountain front recharge. The vertical anisotropy in the bedrock (Section 2.5) was evaluated at three different ratios (1000:1, 100:1, and 10:1); changing the anisotropy ratio had little effect on the model calibration. A ratio of 10:1 was chosen because it most closely aligned with the flow pattern for the bedrock in the CSM and still provided low flux from the bedrock to the overlying alluvium. All of these changes had minimal impact on remedy design.

A dual domain mass-transfer approach was used to model solute transport in the heterogeneous aquifer system as the small-scale preferential flow pathways cannot be fully and explicitly represented by the spatial discretization in a numerical model for practical reasons. Additional details about uncertainty was presented in Section 6 of *Development of Groundwater Flow and Solute Transport Models* (Arcadis 2016).

8 SUMMARY AND CONCLUSIONS

The groundwater flow model was updated in accordance with the seven agency directives. The model was calibrated with additional regional and Site groundwater targets obtained from several sources. Regional targets were collected between 1961 and 2015, and Site targets represent 2015 steady-state conditions. Calibration results indicated the model was well calibrated to both regional and Site target sets. The regional targets helped further constrain the model calibration. To further evaluate the updated

groundwater flow model, the updated groundwater flow model was validated against Site groundwater flow levels from two additional periods: steady-state Pre IM-3 conditions (2004) and transient conditions from November 2014 thru October 2015. Pathline analyses were conducted and were consistent with the *Development of Groundwater Flow and Transport Models* report (Arcadis 2016) under simulated active remedy conditions. A regional model pathline analysis was also conducted to illustrate the alignment of the simulated regional flow with the CSM. Simulated drawdown analyses at HNWR-1A and Site B wells were conducted and indicated that drawdown from these two extraction wells is relatively minimal and can be expected to induce approximately 2 feet of drawdown in Topock 2 and 3.

The updated groundwater flow model was then utilized to examine the remedial design and solute transport modeling presented in the *100% Basis of Design* report (Arcadis 2015). Overall, the solute transport modeling conducted with the updated groundwater flow model results were very similar to those of the *100% Basis of Design* report (Arcadis 2015) and the *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016). Hexavalent chromium footprints were very similar over the simulated 30 year transport period with the exception of more persistent hexavalent chromium concentrations initialized in the bedrock due to the enhanced simulation of the alluvium/bedrock contact. Byproduct manganese and arsenic results were very similar in extent and magnitude in the floodplain and downgradient of the TCS injection wells as those presented in the *100% Basis of Design* (Arcadis 2015) the *Development of Groundwater Flow and Solute Transport Models* report (Arcadis 2016). The simulated arsenic footprints associated with the freshwater injection into the upland wells also were essentially identical in extent and magnitude as presented in the *100% Basis of Design* (Arcadis 2015) and the *Development of Groundwater Flow and Solute Transport Models* (Arcadis 2016). These analyses indicate that while model updates were effective in better aligning the simulated groundwater flow with the CSM of regional groundwater flow, the impact on groundwater flow and solute transport in the vicinity of the Site is minimal. Based on this model update, no additional changes were recommended to the remedial design.

The solute transport model results indicate that the planned remedy will be effective in remediating the current Cr(VI) plume distribution while minimizing the potential adverse impacts from byproduct generation. The solute transport model can be utilized as a tool to supplement monitoring of the implemented remedial system for assessing remedy effectiveness and optimizing operations. During installation and implementation of the remedial system, the additional hydrogeologic and groundwater quality data that will be generated can be utilized to update the groundwater flow and transport models and to further improve their effectiveness as tools for understanding site conditions and optimizing remedy performance.

9   REFERENCES

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TABLES

FIGURES

APPENDIX A

Regional and Site Water Level Targets

APPENDIX B
Transient Calibration Data