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Pacific Gas & Electric Company

2022 Groundwater Flow and Solute Transport Model Update

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Topock Compressor Station

Needles, California

December 2022

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Acronyms and Abbreviations

BOD	Basis of Design
CACA	Corrective Action Consent Agreement
CD	Consent Decree
CERCLA	Comprehensive Environmental Response, Compensation, and Recovery Act
Cr6	hexavalent chromium
CSM	conceptual site model
DOI	Department of the Interior
DTSC	Department of Toxic Substances Control
gpm	gallons per minute
HSU	hydrostratigraphic unit
IM-3	Interim Measures 3
IRZ	in situ reactive zone
lbs	pounds
µg/L	microgram per liter
NTH	National Trails Highway
PG&E	Pacific Gas and Electric Company
TCS	Topock Compressor Station
TOC	total organic carbon
TRC	Technical Review Committee
TWG	Technical Working Group
USGS	U.S. Geological Survey

Executive Summary

Pacific Gas and Electric Company (PG&E) is implementing the final groundwater remedy for chromium in groundwater at the PG&E Topock Compressor Station (TCS) in San Bernardino County, California (the site). Remedial activities at the 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 United States (U.S.) 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 0.5 mile west of Topock, Arizona. This document, 2022 Groundwater Flow and Solute Transport Model Update, documents the updates made to the groundwater flow and solute transport model based on site data collected during Phase 1 well installation and testing through the Second Quarter of 2022. The model update included adjustments to model structure, hydraulic properties, and hexavalent chromium (Cr6) plume distribution. The groundwater flow model was calibrated to steady-state and transient conditions similar to those presented in the Addendum to the Development of Groundwater Flow and Solute Transport Models (Arcadis 2017) as well as to recent aquifer tests conducted at TW-03D and TW-01. The updated model was then used to qualitatively evaluate historical Cr6 transportation during Interim Measures No. 3 (IM-3) operation. Overall observations of Cr6 plume reduction in footprint, persistence of Cr6 source mass, and individual well concentration trends indicated that the updated model was able to represent the historical movement of the Cr6 plume reasonably well.

The updated and calibrated groundwater flow and solute transport model was then used to evaluate the remedy presented in the Basis of Design Report/Final (100%) Design Submittal (2015 BOD) versus an alternative proposed optimized remedy (2022 Optimized Design) (Arcadis 2022b). Modeling was used to assess the remediation of the Cr6 plume as well as the simulation of the potential remedy byproducts manganese and arsenic. The 2022 Optimized Design consisted of a lower rate of upgradient freshwater injection; freshwater injection locations closer to the western edge of the Cr6 plume; and focused on portions of the plume with greater Cr6 mass, less overall infrastructure/piping, and periodic short-term dosed injection in the plume core. Additional sensitivity analyses were conducted to evaluate the potential range in performance of the remedy using different hydraulic and transport parameters.

The results of the predictive groundwater flow modeling of the BOD remedy indicate that the model update did not have a significant impact on the overall remedy performance and projected cleanup timeframe. Approximately 98 percent of the Cr6 mass is removed after 26 years of simulated BOD remedy operation. The simulation of the 2022 Optimized Design indicated that this design is more efficient than the BOD remedy in that, with fewer upgradient injection wells in locations closer to the current western plume edge, a lower upgradient freshwater injection flow rate, and strategic dosed injection, 98 percent of the Cr6 mass is removed after 22 years. The 2022 Optimized Design also removed a greater amount of Cr6 mass in the earlier portion of the simulation, and the remaining alluvial Cr6 plume distributions exceeding 32 micrograms per liter (µg/L) are less aerially extensive than the BOD simulation.

Additional model updates are still planned based on continued refinement of the site hydrogeology, Cr6 plume distribution, and remedy operation and performance data. This includes data collected during Phase 2A and 2B construction.

1 Introduction and Objectives

This report has been prepared for Pacific Gas and Electric Company (PG&E) to present the updates made to the numerical groundwater flow and solute transport model using Phase 1 drilling and testing data collected through Second Quarter 2022 for the PG&E Topock Compressor Station (TCS, or the Compressor Station) in San Bernardino County, California. The model update was conducted as described in Section 3.1.5 of the 100% Basis of Design (BOD) Report (Arcadis 2015). This model update represents the first update during the remedy well construction and testing period and focused on the data collected during the installation of the Phase 1 wells.

On September 9, 2019, PG&E presented the planned procedures for updating the model, and on December 15, 2020, PG&E presented modeling of historical operation of Interim Measure 3 (IM-3) to provide context on model performance. The Technical Review Committee (TRC) provided comments on the evaluations and plans presented in these meetings in a memo titled TRC Comments and Recommendations on Recent Arcadis/PG&E IM-3 Modeling Efforts (TRC comment letter) on January 26, 2021 (TRC, 2021). PG&E has considered the recommendations in the TRC comment letter and appreciates the robust discussion of modeling issues at the Technical Working Group (TWG) meetings in 2020 and on March 10 and May 27, 2021 following the receipt of the TRC comment letter. The May 27, 2021 meeting was productive, established alignment on several modeling topics, and clarified areas where the TRC was recommending additional consideration of potential procedures and literature. In consideration of the modeling discussions at the TWG meeting and the recommendations in the TRC comment letter, a Proposed Path Forward on Model Updates memo (Arcadis 2021) summarizing PG&E's revised plans for updating the model and the supporting rationale was issued. This model update report is consistent with the 2021 model update memo and describes in further detail the updates made to the groundwater flow and solute transport model. The updated model was then used to evaluate the existing BOD remedy and a proposed optimized remedy to address the current hexavalent chromium (Cr6) plume distribution.

1.1 Site Location and Description

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 0.5 mile west of Topock, Arizona.

1.2 Initial Groundwater Flow and Solute Transport Model

The existing numerical flow model domain, constructed in MODFLOW, is three-dimensional, consisting of 425 rows, 389 columns, and 10 layers. The model consists of 1,653,250 total cells, covering an area of approximately 30,500 acres (47.7 square miles). The grid cell size varies throughout the model domain, with increased resolution in the site area, with the grid cell size as small as 25 feet by 25 feet. The grid spacing increases up to 200 feet at the model extents. The model grid axes were rotated 45 degrees counter-clockwise to align the major axes of the model with the major directions of groundwater flow in the vicinity of the site. The model was vertically discretized into 10 layers in 2017 based on consultation with the TWG and TRC. Details of the model domain, finite difference grid, and boundary conditions are shown in the model addendum report (Arcadis 2017).

The solute transport modeling was performed using the modular three-dimensional transport model referred to as MT3D. Solute transport modeling was performed to evaluate the migration and fate of Cr6 detected in the groundwater, as well as the fate and transport of potential in situ reactive zone (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. The solute transport model was used to evaluate the fate and transport of Cr6 as well as select byproducts (manganese and arsenic) to evaluate various potential remedial systems. Details of the solute transport modeling are provided in the model addendum report (Arcadis 2017).

The major inputs to MT3DMS for the modeling assessment are as follow:

- Mobile and Immobile Porosity: affecting the groundwater flow velocity and solute storage;
- Mass Transfer Coefficient: affecting the exchange of mass between mobile and immobile portions of the aquifer;
- Partition Coefficient: affecting the adsorption of Cr6 and byproducts to soil particles;
- Carbon Degradation Rate: affecting the rate of Cr6 reduction/precipitation;
- Initial Groundwater Concentrations: affecting the overall distribution and concentration of Cr6, manganese, and arsenic; and
- Byproduct Generation Coefficient: affecting the generation of manganese and arsenic from the introduction of carbon to the aquifer.

1.3 Report Objectives and Organization

The objectives of this modeling study were to update the groundwater flow and solute transport model as follows:

- Update the groundwater flow model structure to account for additional information collected during remedy and monitoring well installation, which refined the location of the contact between the alluvium and underlying bedrock.
- Update the average Cr6 plume using available data collected through Second Quarter 2021.
- Develop a potential maximum Cr6 plume honoring data collected through Second Quarter 2021.
- Update the distribution of evapotranspiration due to vegetation along the Colorado River.
- Evaluate sieve analysis data collected along the National Trails Highway (NTH) IRZ.
- Update the hydraulic conductivity distribution and values based on recent aquifer tests at TW-03D and TW-01.
- Calibrate the groundwater flow model to steady-state conditions and transient conditions: 1-year period, TW-03D aquifer test, and TW-01 aquifer test.
- Verify transport parameters using TW-01 tracer test data.
- Conduct IM-3 historical transport modeling to evaluate the model and inform the initial plume distribution for design modeling.
- Simulate Cr6 and remedy byproducts (arsenic and manganese) using the updated model under BOD Remedy Design conditions.

- Simulate Cr6 and remedy byproducts (arsenic and manganese) using the updated model under 2022 Optimized Design conditions.
- Perform sensitivity analysis of select flow and solute transport parameters.

2 Groundwater Flow and Solute Transport Model Updates

2.1 Model Structure Update

The model structure was updated to account for the additional data collected during the installation of the Phase 1 remediation and monitoring wells. The additional data were used to refine the contact between the alluvial aquifer and the bedrock primarily along the NTH IRZ, but also in several mid-plume and upland areas (i.e., bedrock elevations were higher than anticipated near MW-K). The updated bedrock contact elevation contours in the vicinity of the site are shown on **Figure 2-1.** The revised bedrock elevation in the site area was integrated into the regional interpreted bedrock surface, which extends throughout the model domain. Updating the bedrock contact allows the groundwater flow model to better simulate the saturated alluvium as well as better represent the Cr6 mass present in the alluvium. Additional updates to the model structure are anticipated as additional data are collected during the Phase 2 investigation and well installation.

2.2 Hexavalent Chromium Plume

One of the most significant updates to the groundwater flow and solute transport model is the update of the Cr6 plume using the available concentration data collected through Second Quarter 2021. A basis for initializing the mass in more permeable layers is not seen in the data, as more permeable layers were not identified in the Phase 1 drilling logs, nor were more permeable zones identified during the TW-03D and TW-01 aquifer tests. Mechanisms built into the dual-domain solute transport model (mass transfer coefficient, mobile porosity, and immobile porosity) account for the interaction of mass between the more and less mobile pore fractions. The detailed lithologic cross-sections are presented in the model update plan memo (Arcadis 2021). The high-concentration deep lobe of the plume is travelling within the typical heterogeneous deposits of gravelly sand with some silt, silty sands with gravel, and sandy silts/clays (i.e., the deep plume is not travelling in particularly sandier or more permeable deposits). Furthermore, similar gravelly sand with silt, silty sand, and sandy silt/clay lithologies are seen in the “gap” between the shallow and deep plumes and throughout much, but not all, of the shallow plume. Based on this evaluation of the CSM, Cr6 is not preferentially present in more permeable lithologies. Accordingly, the three-dimensional Cr6 mass was assigned through krigging based on the lateral and vertical distribution of the historical and recent observed Cr6 groundwater concentration data without preference to certain lithologies. It should be noted, though, that the solute transport between the more and less mobile fractions of the aquifer is accounted for with the dual-domain solute transport model.

The historical Cr6 concentration trends at individual wells was considered in selecting the appropriate Cr6 concentration to initialize the plume in the model at each location. If the recent Cr6 concentration data exhibit consistent trends, the most recent data point was used. If the recent Cr6 concentration data exhibit irregular trends, the highest recent Cr6 concentration was selected for that location. If data from adjacent wells varied significantly, plume delineation was biased to the higher Cr6 concentration. **Figure 2-2** show the monitoring well network used to delineate the Cr6 plumes. The updated average Cr6 plumes for model layers 1 through 5 are shown on **Figure 2-3**. Some of the key updates made in the Second Quarter 2021 plumes include elevated recent Cr6 concentrations near the source area (60,000 micrograms per liter [μg/L] at MW-68-180), elevated bedrock and low Cr6 concentrations at MW-98 (formerly MW-K), limited northern extent of the Cr6 plume in model layers 2 and 3, and refined Cr6 concentration based on the recently installed NTH IRZ remediation wells and monitoring wells (i.e., MW-L, MW-M, MW-N, and MW-R).

There is inherent uncertainty in the current distribution of Cr6 and therefore in the initial Cr6 distribution assigned for predictive solute transport modeling. This uncertainty may affect modeling predictions. To address this uncertainty, an additional maximum Cr6 plume was considered and evaluated as described in Section 5. This maximum Cr6 plume still honors the same dataset used to delineate the average Cr6 distribution; however, in portions of the plume where little to no data are available, the Cr6 plume was biased high to generate a maximum reasonable estimate of the Cr6 plume distribution. This maximum Cr6 plume distribution was also informed by historical solute transport modeling, which indicated the potential Cr6 mass transport from the source area into areas with limited data available.

2.3 Evapotranspiration

The original evapotranspiration distribution, rates, and extinction depths in the groundwater flow model were based on satellite imagery and U.S. Geological Survey (USGS) land cover studies as presented in the model addendum report (Arcadis 2017). These original evapotranspiration zones extended to the east and north of the TCS along the Colorado River and the Havasu National Wildlife Refuge. To the southeast of the site, the evapotranspiration was updated to reflect the observed vegetation along the Colorado River as shown on **Figure 2-4**. The locations of these additional evapotranspiration zones have minimal hydraulic influence on groundwater flow in the vicinity of the site because they are located on the eastern side of the bedrock knob. However, these evapotranspiration zones were still included in the model to improve the accuracy of the overall water balance.

2.4 Hydraulic Conductivity

Several approaches were pursued to gain better understanding of the hydraulic conductivity distribution in the alluvial aquifer in the vicinity of the TCS. These approaches included collection and analysis of sieve data during the installation of the NTH IRZ, aquifer testing at TW-03D (NTH IRZ area), and aquifer/tracer testing at TW-01 (near source area) (Arcadis 2022a). Results from these analyses and aquifer tests were used to inform the update of the hydraulic conductivity zones and values in the groundwater flow model. The details of the hydraulic conductivity analyses and flow model update are described below.

2.4.1 NTH IRZ Sieve Analysis

During the recent installation of the NTH IRZ remediation wells, 442 sieve analysis samples were collected at numerous depth intervals for each well location. The resultant sieve analysis for each well was then further analyzed using HydrogeoSieve XL (Devlin 2015 and 2016). HydrogeoSieve XL calculates hydraulic conductivity from grain-size distribution curves using 15 different methods. Based on the nature of the grain-size curve, the most appropriate hydraulic conductivity methods are selected, and a resultant average hydraulic conductivity value is computed. The resultant average computed hydraulic conductivity value per NTH IRZ sieve sample are presented in **Table 2-1** and are shown graphically by depth and location on **Figure 2-5**. Of the 442 grain size sample intervals analyzed along the NTH IRZ, 90 percent of the samples have hydraulic conductivity values less than 1 ft/d, and only three samples had computed hydraulic conductivity values greater than 10 ft/d. Additionally, the 442 grain-size samples from the NTH IRZ indicated no substantial variation in the grain-size curves to divide the samples into predominant lithofacies. These hydraulic conductivity values calculated from the grain-size results of the sieve analyses are lower than previous hydraulic conductivity values computed in the vicinity of the

NTH IRZ. Additional aquifer testing was conducted at TW-03D to further refine the hydraulic conductivities in the vicinity of the NTH IRZ.

2.4.2 TW-03D Aquifer Test

In June 2021 a 72-hour constant rate aquifer test was conducted at TW-03D near the NTH IRZ. Extraction was maintained at TW-03D at a constant rate of 130 gallons per minute (gpm). Details of the TW-03D aquifer test are summarized in the text and Appendix H of the TW-01 aquifer test memo (Arcadis, 2022a). Water levels were monitored in 26 wells, and the resultant drawdown was analyzed using AQTESOLV 4.5 (Duffield 2007). The best drawdown curve fits selected were the Tartavkoski-Neuman and Neuman solutions. The summary of the TW-03D aquifer test results are presented in **Table 2-2** and are posted in plan-view and cross-section on **Figure 2-6**. The resultant hydraulic conductivity values varied within a relatively narrow range between 21.9 ft/d and 83.2 ft/d, with a geometric mean of 41.6 ft/d. A distance-drawdown analysis was also conducted and resulted in a hydraulic conductivity of 29.3 ft/d. The figure posting indicates that there is not a spatial bias vertically or in plan-view. Simulated hydraulic conductivity values in the alluvial aquifer in the vicinity of TW-03D are within the range of observed hydraulic conductivity values from the TW-03D aquifer test analysis.

2.4.3 TW-01 Aquifer Test

From June 2021 to December 2021, an aquifer test was conducted at TW-01 near the source area. Details of the TW-01 aquifer test are presented in a technical memorandum summarizing the aquifer test results that was submitted to the stakeholders on June 15, 2022 (Arcadis 2022a). Extraction occurred at TW-01 at a rate of 90 gpm for a period of approximately 6 months. Water levels were monitored in 17 wells, and the resultant drawdown was analyzed using AQTESOLV 4.5 (Duffield 2007). The best drawdown curve fit selected was the Neuman solution. The summary of the TW-01 aquifer test results are presented in **Table 2-3**. Similar to the TW-03D aquifer test, the resultant hydraulic conductivity values varied within a relatively narrow range between 17.8 ft/d and 61.7 ft/d, with a geometric mean of 30.6 ft/d. A distance-drawdown analysis resulted in a hydraulic conductivity of 33.9 ft/d. Simulated hydraulic conductivity values in the alluvial aquifer in the vicinity of TW-01 are within the range of observed hydraulic conductivity values from the TW-01 aquifer test analysis.

2.4.4 Hydraulic Conductivity Zone Updates

The hydraulic conductivity was updated considering results from historical aquifer tests and incorporating results from the aquifer tests at TW-03D and TW-01. The geologic and hydrogeologic conceptual site models (CSMs) have been updated with information collected during drilling and well testing as presented at TWG meetings on April 30, 2020, August 27, 2020, and March 10, 2021. The updated CSM provides the basis for the update to the model layering and hydraulic conductivity distribution in the model update. As presented at the detailed lithology TWG meeting on March 10, 2021, despite the relative heterogeneity observed in the lithologic descriptions across the site, the grain-size data indicate consistency in the grain-size distribution that would dictate groundwater flow. Further, both the TW-03D and TW-01 aquifer test results indicate a rather homogeneous distribution in observed hydraulic conductivity values. These aquifer tests are further summarized in both the TW-01 Pump Test Report (Arcadis, 2022a) and the design modification document (Arcadis, 2022b).

Although lithology and grain-size analyses indicated a fairly heterogeneous sediment distribution in the alluvial aquifer and hydraulic conductivity estimates from grain-size analyses suggested fairly low hydraulic conductivities (less than 1 ft/d), the aquifer testing conducted indicated bulk hydraulic conductivity values for the alluvial aquifer between 20 and 80 ft/d with geometric means between 34 and 42 ft/d. As the aquifer testing better represented the bulk behavior of the aquifer, the simulated hydraulic conductivity zones based on the hydrostratigraphic units used the hydraulic conductivity values within the range determined from the aquifer testing. Details are as follow:

- An evaluation of the grain size distributions from the NTH IRZ data indicates similar grain size distributions in the alluvium along the NTH IRZ despite variable lithologic descriptions. The grain size distribution information is presented in Section 2 of the design modification document (Arcadis, 2022b) .
- Appendix I of the TW-01 Pump Test Report (Arcadis, 2022a) shows the monitoring wells where transducer data were collected and analyzed during the TW-03D pump test as well as the range of lithologies (sands, gravelly silts, and silty sands) that is represented in these monitoring wells.
- **Figure 2.6** showing the Cr6 plume overlain on the detail lithologic description does not show the presence of lateral or vertical lithologic conduits, but rather a more uniformly heterogeneous aquifer matrix consistent with the nature of the alluvial depositional environment.
- The results of the TW-03D pump test yielded a relatively narrow range of hydraulic conductivity values from the set of monitoring wells that represented a range of lithologic descriptions (Appendix H and Appendix I of the TW-01 Pump Test Report (Arcadis, 2022a)). The data presented in these appendices indicate that the heterogeneous lithologic descriptions are behaving as a more homogeneous aquifer, yielding a limited range of observed hydraulic conductivities across various lithologies during aquifer testing.

The current groundwater flow model is composed of 10 layers with the upper eight layers being flat and extending into the shallow bedrock south of the site, and the bottom two layers having variable thickness to align with the alluvial bedrock contact north of the site. The individual hydrostratigraphic units (HSUs) assigned average hydraulic conductivity values based on available aquifer testing data and model calibration. In the 2017 modeling addendum, a conceptual gaussian distribution was added to model simulations after discussions with the TRC in 2016 to account for potential heterogeneity (Arcadis 2017). This allows the hydraulic conductivity to vary spatially within each HSU with the average hydraulic conductivity value consistent with the initial average hydraulic conductivity value of each HSU. However, one of the key observations made in the 2016 model update was how similar the long-term transport results were as compared to the original 100 percent BOD modeling as well as the intermediate step in which HSUs were assigned the average hydraulic conductivity values. All three versions of the model had similar bulk hydraulic parameters, resulting in similar long-term solute transport results (Arcadis 2017). This further indicates that the value of integrating lithologic layers, which in many cases are discontinuous and limited in extent, is minimal.

The concept to modify the model layering and assignment of hydraulic conductivities based on lithologic description was considered. However, given the consistency in grain size analysis and hydraulic conductivity measured in the TW-03D and TW-01 pump test across soils with various lithologic descriptions, modification of the existing model layering structure or assignment of new hydraulic conductivity values are not warranted. The lithologic descriptions in well logs extending from the NTH IRZ to the uplands show a similar consistently heterogeneous distribution of logged lithologies that are interpreted to have hydraulic properties similar to the areas near the aquifer test locations of TW-01 and TW-03D.

Based on the above described updated CSM, the model update for the hydraulic conductivity distribution used the existing 10-layer model, and the hydraulic conductivities in the existing model were refined with the results of the TW-03D and TW-01 pump tests. Using a bulk hydraulic property based on the TW-03D and TW-01 pump test results is representative of the aquifer. Simulations using these hydraulic parameters with the model is appropriate, as they align with actual computed hydraulic properties from the TW-03D and TW-01 tests. The updated hydraulic conductivity zonation and values in the site area are shown on **Figure 2-7**. The hydraulic conductivity zones align with the primary HSUs presented in the modeling addendum report (Arcadis 2017). The hydraulic conductivity values in the updated groundwater flow model were refined during model calibration and fall within the range of hydraulic conductivity values observed during the TW-01 and TW-03D aquifer tests.

While discrete heterogeneity is not represented in the groundwater flow model by a heterogenous cell-by-cell variation in hydraulic conductivity zone distribution, heterogeneity is represented using dual domain in the solute transport model. Dual domain allows for the simulation of the interaction of the more and less mobile pore fractions of the aquifer. The dual domain model allows for faster transport in the mobile fraction and slower transport in the less mobile fraction, allowing for both the fast arrival in mass and the tailing effect observed in many plumes. The use of the dual domain approach is further supported in the literature by Bianchi and Zheng (2016), who indicated that, in lieu of simulating a detailed representation of individual lithofacies, the dual-domain mass transfer rate approach was able to fit the observed plume spreading at the case study site.

3 Flow Model Calibration

3.1 Steady-State

A steady-state groundwater flow calibration was conducted using the original calibration dataset presented in the model addendum (Arcadis 2017). This calibration dataset represents active average IM-3 pumping conditions in 2015 using 71 site water level observations. The steady-state calibration residuals and residual statistics calculated with the model updates summarized in Section 2 are presented on **Figure 3-1**. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be 0.12 ft, 0.32 ft, and 8.0 ft^2, respectively. The scaled residual standard deviation is less than 8 percent of the range in observed water levels. The Pearson Correlation Coefficient was determined to be 0.92, and the Nash Sutcliffe Efficiency is 0.81. These statistics indicate a good agreement between the observed and simulated water levels.

3.2 Transient: 1-Year Period

A 1-year transient groundwater flow calibration was conducted using the original calibration dataset presented in the model addendum (Arcadis 2017). This calibration dataset represents observed conditions from November 2014 to October 2015 consisting of 827 calibration targets. Average variations in the Colorado River stage and pumping were computed monthly. Storage values are assigned consistent with the HSUs as presented in the model addendum (Arcadis 2017) and are within the range of observed storage values determined during the TW-01 and TW-03D aquifer tests. The 1-year transient calibration residuals and residual statistics are presented on **Figure 3-2**. The residual mean, residual standard deviation, and sum of squared residuals were calculated to be 0.32 ft, 0.5 ft, and 295 ft^2, respectively. The scaled residual standard deviation is less than 8 percent of the range in observed water levels. The Pearson Correlation Coefficient was determined to be 0.91, and the Nash Sutcliffe Efficiency is 0.73. These statistics indicate a good agreement between the observed and simulated water levels.

3.3 Transient: TW-03D Aquifer Test

To further verify the calibration of the groundwater flow model, the model was calibrated transiently to the observed drawdown measured using transducers during the TW-03D aquifer test. The simulated and observed drawdown curves for the observation wells screened in model layers 1 through 4 are presented on **Figure 3-3**. The curve fits indicate a good match between the observed and simulated drawdown trend and magnitudes in all four model layers.

3.4 Transient: TW-01 Aquifer Test

An additional transient model validation was conducted using the observed transducer drawdown data collected during the aquifer testing of TW-01 near the plume source area. The simulated and observed drawdown curves for the TW-01 aquifer test observation wells in the alluvial material are presented on **Figures 3-4 and 3-5**. The drawdown validation curves for wells located to the north of TW-01 (thicker alluvial aquifer wells) and to the south of TW-01 (thinner alluvial aquifer wells) both indicate a good fit between the simulated and observed drawdown, indicating that the model is well calibrated in the source area. **Figure 3-6** shows the simulated and observed drawdown in the four bedrock monitoring wells monitored by transducers during the TW-01 aquifer test. While the simulated bedrock drawdown validation curves reasonably represent the magnitude and the pattern of the observed drawdown, the curves do not match as well as the alluvial observation wells. This is likely due to the inherent complexity of simulating fractured bedrock as an equivalent porosity model.

3.5 Pathline Analysis: TW-01 Tracer Test

In addition to verifying the flow model calibration, the TW-01 aquifer test also had a tracer test component that was used to verify the groundwater flow model and solute transport parameters, specifically the simulated mobile porosity (Arcadis 2022a). Fluorescein was introduced at MW-38D (northwest of TW-01), and rhodamine was introduced at MW-67-185 (southeast of TW-01). A pathline analysis was conducted using MODPATH (Pollock 1989) by initializing particles at the two tracer injection wells. The MODPATH analysis indicated that the simulated tracer introduced at both wells had a simulated arrival time at TW-01 between 120 and 150 days, which is consistent with the observed tracer arrivals detected at TW-01 as shown on **Figure 3-7**. This tracer test analysis therefore further supports the calibrated hydraulic parameters in the groundwater flow model as well as the simulated mobile porosity of 12 percent used in the solute transport model.

4 IM-3 Historical Transport Modeling

To further evaluate the calibrated model and inform the initial Cr6 distribution for predictive model runs, the model was used to evaluate the historical transport of the Cr6 plume during IM-3 remedy operation from 2005 to 2021. An initial layer-wise Cr6 plume distribution was generated for 2005 as a starting plume distribution for the transport analysis. As the monitoring network was not as robust in 2005 as it is today, estimates of the 2005 plume distribution were based on both historical data as well as more recent Cr6 concentration trends. As the initial 2005 plume distribution was one of the more sensitive variables in this analysis, several variations of the 2005 plume were initialized to better represent observed trends over time but still honor the data available. The IM-3 historical transport modeling is a qualitative evaluation of the overall fate and transport of Cr6 to identify the relative consistency of the model and potential areas of significant deviation. In addition to the simulation of IM-3 operation, the historical transport modeling also included the operation of the uplands pilot test, which included extraction and carbon amended injection at both PTR-1 and PTR-2. The historical simulated layer-wise Cr6 plume footprints in Model Layers 1 to 4 from 2005 to 2021 are shown on **Figures 4-1** to **4-4**. The major observed consistencies between the observed and simulated Cr6 plumes are the retraction of the plume from the north and the west, preservation of elevated Cr6 concentrations in the plume source area and core, the western retraction of the Cr6 concentrations in the floodplain, and the treatment zone associated with the uplands pilot test. In addition to the evaluation of the bulk movement of the plume, observed and simulated Cr6 concentration trends were evaluated at individual monitoring wells throughout the TCS.

Figure 4-5 shows the simulated and observed Cr6 concentration trends in the vicinity of the uplands area. The primary Cr6 concentration trends are the declining trends at MW-37D and MW-25 due to flushing from the west because of the enhanced gradient from IM-3 injections, relatively stable to slightly increasing low concentrations at MW-37S, and declining trends at MW-24A/B due to flushing from the west and a dramatic concentration reduction due to the uplands pilot test at PTR-1 and PTR-2. The simulated Cr6 concentrations match the observed declining trends at MW-37D, MW-24A/B, and MW-25 both in magnitude and rate. The simulated data at MW-37S show an initial increase followed by a decrease, which does not match the stable to slightly increasing observed trend; however, the magnitude of the simulated concentration is comparable to the observed data. The initial increase in Cr6 concentration is likely due to the elevated simulated Cr6 concentrations at depth being immediately adjacent to the overlying cleaner zone, causing a slight vertical spread of the Cr6 plume.

Figure 4-6 shows the simulated and observed Cr6 concentration trends in the vicinity of the floodplain area. The initial elevated observed Cr6 concentrations in the floodplain (MW-44-115/125, MW-34-100, MW-46-175, MW-45-095) all have declining trends, indicating the retraction of the Cr6 plume in the floodplain due to IM-3 operations. Floodplain wells with observed low to non-detect Cr6 concentrations (MW-44-070 and MW-46-205) had continued low stable concentration trends. The simulated Cr6 concentrations match the observed concentrations in both magnitude and rate of decline in the floodplain area, indicating that the model performs well in the floodplain area.

Figure 4-7 shows the simulated and observed Cr6 concentration trends in the vicinity of IM-3 extraction, where the majority of observed Cr6 concentrations (MW-19, MW-20-70/100/1230, TW-2S, MW31-60/35, MW-50-95/200) declined during 15 years of IM-3 operation due to the extraction and Cr6 mass removal, causing the Cr6 plume to retract from the north and east. One well (MW-47-115) showed a slight increase in Cr6 that stabilized at a concentration of about 20 μg/L but still remained below 32 μg/L. The simulated Cr6 concentrations show a reasonable match to the overall observed reduction of Cr6 due to IM-3 operation with respect to relative trends and order of magnitude in concentration, as well as the slight increase at MW-47-115. In some areas with steep observed concentration trends with minimal upgradient data, it is difficult to attain an exact match with the model.

Additionally, in some areas, the variability of the observed concentration data distribution is a finer scale than both the later and vertical finite difference grid resolution. The poor fit at MW-31-135 is likely due to the vertical movement of the plume from the overlying layer through numerical dispersion, but the simulated Cr6 concentration is declining closer to recent observed concentrations.

Figure 4-8 shows the simulated and observed Cr6 concentration trends in the vicinity of the source area, where several concentration trends were apparent with northern well pair MW-38S/D showing a declining trend, bedrock wells showing a stable low concentration trend (MW-68BR-280 and MW-66-270BR), and centrally located source area wells showing stable to increasing trends (MW-68-180/240, MW-66-165/230, MW-67-185/225). Wells such as MW-68-180, which have recently shown a dramatic increase in Cr6 concentrations higher than all historical concentrations, are difficult to match, as it points to a historical source mass that may have not been fully delineated. This area was accounted for in predictive modeling by making sure the initial average and maximum Cr6 plumes account for this maximum observed concentration in the vicinity of the source area. The observed Cr6 increase at well MW-65-160 that is not represented well by the simulated Cr6 concentrations suggests there may be mass migrating upward from deeper layers, as this well is located upgradient from the source area. The observed decreasing Cr6 at MW-67-260 is not represented well by the simulated Cr6 concentrations due to the higher initial Cr6 values initialized in model layer 3 to account for the higher observed Cr6 concentrations at nearby well MW-66-230 which also resulted in an overprediction of Cr6 at MW-67-260. Simulated Cr6 concentration wells show a reasonable match to the stable low concentration trends in the bedrock wells and persistent elevated Cr6 concentrations in the source area.

Observed IM-3 treatment operations estimated that IM-3 removed approximately 9,970 pounds (lbs) of Cr6 mass. Based on the second quarter 2021 Cr6 plume delineation, the observed mass removed by IM-3 represents approximately 40% of the initial plume has been extracted by IM-3 operations. The IM-3 historical transport modeling indicates that the conceptual 2005 Cr6 plume mass was reduced by approximately 56% during operation of IM-3. This percentage in total Cr6 plume mass reduction is reasonably comparable given that the total simulated Cr6 mass removal accounts for not only IM-3 operation, but also the Cr6 mass treated during the 2008 uplands pilot test, and the natural attenuation of the Cr6 mass in the vicinity of the naturally occurring reducing rind. The larger simulated fraction of mass removal also indicates the simulated initial 2005 plume may have been overly conservative with sustained elevated concentrations near IM-3 extraction, as well as an overestimate of Cr6 mass throughout the saturated thickness to the north where more recent data has shown the plume is bifurcated with a significant portion of the middle of the aquifer with lower concentrations than the shallow and deep portions. Given the uncertainty in the 2005 timeframe historical plume, the recent second quarter 2021 plume informed by Phase 1 data is the best Cr6 distribution to use for predictive modeling exercises, rather than the inferred 2005 plume used to initialize the IM-3 historical modeling exercise. The historical modeling exercise will be used to inform a maximum Cr6 mass and distribution in predictive modeling sensitivity analysis.

The historical IM-3 transport modeling was conducted as a qualitative, rather than quantitative, assessment of model performance. The results indicate that the model reasonably represents the overall observed plume movement during 15 years of IM-3 operation. **Figure 4.9** shows the simulated layer-wise plume footprints at the end of IM3 historical transport run compared to the observed 2021 Cr6 plumes. The major components of the Cr6 plume movement that the model successfully simulated were the flushing of the western portion of the Cr6 plume, Cr6 mass reduction in the vicinity of the uplands pilot test, persistent elevated concentrations in the source area, northern retraction of the Cr6 plume near the NTH IRZ, and the westward retraction of the observed Cr6 plume in the floodplain at depth. Uncertainty is associated with the initial 2005 Cr6 plume distribution, as it was based on a more limited dataset than our current more robust monitoring network. All future predictive modeling will be based on the more recent Cr6 plume delineations, which reflect recent Cr6 concentrations, but also consider the simulated historical plume movement in areas of the Cr6 plume with limited data.

5 Predictive Transport Modeling

The updated groundwater flow model was used for the predictive solute transport modeling of Cr6, manganese, and arsenic to evaluate the original 100% BOD remedy as well as the 2022 Optimized Design. The 2022 Optimized Design is being proposed in order to achieve remedial action objectives (RAOs) while using fewer remedy wells, less piping/land disturbance, and less freshwater demand than the BOD. Details of the 2022 Optimized Design are presented in the Draft Design Modification (2022 Optimized Design) Basis for Final Groundwater Remedy report (Arcadis 2022b). Both remedy deigns simulate the current Phase 1 NTH IRZ operations for the first 4 years followed by their respective Phase 2 operations.

5.1 Hexavalent Chromium

5.1.1 Average Hexavalent Chromium Plume

The updated average Second Quarter 2021 Cr6 plume described in Section 2.2 is used as the starting plume distribution for both remedy designs (**Figure 5-1**). The simulation results of the average Cr6 distribution are discussed in the following sections.

5.1.1.1 Basis of Design Remedy

The BOD remedy average Cr6 simulated plume distributions are presented for years 4 (at the end of Phase 1), 10, 15, 20, 25, 30, and 35 by each layer on **Figures 5-2 to 5-5**. Consistent with the original model, the updated groundwater flow and solute transport model indicates that the BOD remedy successfully addresses the majority of the Cr6 in the alluvial aquifer. The primary BOD design components are still effective including upgradient freshwater injection flushing the Cr6 plume eastward, the TCS dosed injection reducing elevated Cr6 concentrations in the vicinity of the source area, and the NTH IRZ producing an effective reducing zone to remediate Cr6 and prevent further Cr6 migration into the floodplain. After 35 years of simulated transport, with the first 4 years simulated with the Phase 1 NTH IRZ only, there only remains a relatively small footprint of alluvial Cr6 concentrations greater than 32 µg/L in model layers 1 through 3 upgradient of NTH IRZ well IRZ-23 and downgradient of the TWB extraction wells. Model layer 4 has the largest remaining Cr6 alluvial footprint in a thin zone along the bedrock between the source area and the NTH IRZ. These remaining Cr6 alluvial footprints are generally consistent with the predicted Cr6 concentrations from the original BOD modeling. By year 35, there are still Cr6 concentrations in the bedrock in all layers due the relatively low permeability of the bedrock compared to the alluvium. The BOD remedy achieves 98 percent Cr6 mass removal within approximately 26 years of Phase 1 startup.

5.1.1.2 2022 Optimized Design

The 2022 Optimized Design remedy average Cr6 simulated plume distributions are for years 4 (at the end of Phase 1), 10, 15, 20, 25, 30, and 35 by each layer on **Figures 5-6 to 5-9**. Similar to the BOD, the 2022 Optimized Design addresses the majority of the Cr6 in the alluvial aquifer; however, the 2022 Optimized Design is more efficient than the BOD in that it uses less freshwater, requires less infrastructure/piping, and achieves 98 percent Cr6 mass removal in only 22 years of Phase 1 startup. The freshwater injection wells are located closer to the western edge of the Cr6 plume and are focused more towards the central and southern portions of the Cr6 plume, where the majority of the Cr6 alluvial mass is located. The periodic short-term dosed injection into wells IRL-6 and

IRL-7 aggressively reduces Cr6 concentrations in the plume core without adversely impacting the overall flow pattern of the Cr6 plume. The NTH IRZ produces an effective reducing zone that prevents additional Cr6 migration into the floodplain. The only active riverbank extraction well is RB-5, operated at rates up to 25 gpm to hydraulically control the existing Cr6 impacts in the deeper portion of the floodplain (specifically in model layer 3). As there is no Cr6 simulated migrating from upgradient into the floodplain, the other riverbank extraction wells remain off during the full duration of the remedy. By year 35, in model layers 1 through 3, only a smally footprint of C6 greater than 32 µg/L in the alluvium is present between the TWB extraction wells and the downgradient bedrock. In model layer 4, all Cr6 alluvial groundwater concentrations are below 32 µg/L. These simulated remaining alluvial Cr6 groundwater concentrations at year 35 of the 2022 Optimized Design are significantly smaller than those simulated in the BOD remedy.

5.1.2 Maximum Hexavalent Chromium Plume

A maximum initial Cr6 plume was developed using the same dataset as was used for the average Second Quarter 2021 Cr6 plume; however, additional mass was added into the plume, primarily in the plume core between the source area and IRZ-23, where there is limited available data due to access restrictions. This maximum Cr6 plume distribution was also informed by the historical transport modeling by looking at the resultant Cr6 plume distribution after 15 years of simulated transport under IM-3 pumping conditions, which showed additional potential Cr6 mass between the source area and the IM-3 extraction wells. The layer-wise maximum Cr6 plumes are shown on **Figure 5-10**.

5.1.2.1 Basis of Design Remedy

The BOD remedy maximum Cr6 simulated plume distributions are presented for years 4 (at the end of Phase 1), 10, 15, 20, 25, 30, and 35 by each layer on **Figures 5-11 to 5-14**. Although there is additional Cr6 mass initialized in the maximum plume, the resultant simulated Cr6 plume distributions by year 35 under BOD remedy conditions are consistent with the average Cr6 plume scenario in both magnitude and extent. The areas of increased Cr6 mass are effectively flushed with the freshwater injection, addressed by the dosed TCS injection wells, and treated by the NTH IRZ. The maximum Cr6 plume BOD scenario also indicates that the NTH IRZ successfully reduces the Cr6 concentrations, and no further migration of Cr6 mass occurs into the floodplain. The controlling portions of the plume remediation total timeframe appears to be the mass in the vicinity of Interstate 40, which aligns with the widest portion of the plume. The similarity of the BOD performance between the average and maximum Cr6 plume distributions indicates that the BOD remedy concept and components will effectively address the maximum Cr6 plume, and further updates or modifications to the BOD remedy are not necessary to achieve comparable results.

5.1.2.2 2022 Optimized Design

The 2022 Optimized Design remedy maximum Cr6 simulated plume distributions are presented for years 4 (at the end of Phase 1), 10, 15, 20, 25, 30, and 35 by each layer on **Figures 5-15 to 5-18**. Similar to the BOD remedy evaluation, the additional Cr6 mass in the maximum Cr6 simulations did not adversely affect the overall performance of the 2022 Optimized Design. By year 35, the simulated Cr6 mass remaining under 2022 Optimized Design conditions are similar between the maximum and average Cr6 scenarios. The majority of the additional Cr6 mass in the maximum Cr6 scenario is addressed in the first 15 years of remedy operation. The similarity of the 2022 Optimized Design performance between the average and maximum Cr6 plume distributions indicates that the 2022 Optimized Design remedy concept and components will effectively address the maximum Cr6 plume, and further updates or modifications to the 2022 Optimized Design remedy are not necessary to achieve comparable results.

5.2 Manganese

In addition to Cr6, a potential remedy byproduct (manganese) was simulated with the updated groundwater flow and solute transport model. Under reducing conditions induced by the dose injection components of the remedy, naturally occurring manganese in the formation has the potential to be released and migrate with the groundwater. There is naturally occurring manganese concentrations in groundwater observed at the TCS before implementation of the proposed remedial options, with the majority of impacts observed in the floodplain and portions of the bedrock. The initial naturally occurring manganese distribution in model layers 1 through 4 was generated using manganese data presented in the Fourth Quarter 2021 Quarterly Progress Report (Arcadis 2022c) and is shown on **Figure 5.19**. The updated flow and solute transport model was used to simulate the generation and transport of manganese under both the BOD and 2022 Optimized Design conditions. No modifications were made to the manganese generation and sorption parameters used in the solute transport model as documented in previous modeling exercises (Arcadis 2015, 2016, and 2017).

5.2.1 Basis of Design Remedy

The BOD remedy simulated and naturally occurring manganese distribution in model layers 1 through 4 for years 10 and 35 are presented on **Figures 5-20 and 5-21**, respectively. Similar to the original model, the only areas where simulated manganese is generated is at the dosed injection wells of the NTH IRZ and the TCS dosed injection wells. Low concentrations of byproduct manganese reach the riverbank extraction wells by year 35 and are injected into the IRL injection wells IRL-1 and IRL-2, resulting in simulated manganese byproduct at these well locations. The simulated byproduct manganese concentrations fall within the range of observed naturally occurring manganese concentrations in the floodplain.

5.2.2 2022 Optimized Design

The 2022 Optimized Design remedy simulated and naturally occurring manganese distribution in model layers 1 through 4 for years 10 and 35 are presented on **Figures 5-22 and 5-23**, respectively. In addition to the simulated manganese byproduct distribution at the dosed injection wells of the NTH IRZ and TCS dosed injection wells, there is manganese generated at the two periodic short-term injection wells IRL-6 and IRL-7. As the majority of the riverbank extraction wells are off in this scenario and are no longer injected into upgradient recirculation wells, no additional manganese footprints are generated throughout the site. As the NTH IRZ is operating the same in both the BOD and the 2022 Optimized Design (same rates and carbon dosing), the difference in the manganese distribution is most likely attributable to the difference in groundwater flux in the floodplain between the two remedies. The same amount of byproduct manganese mass is generated in both remedy designs. However, due to the additional freshwater/northern upgradient injection in the BOD and the active riverbank extraction, the groundwater flux in the floodplain under BOD conditions is higher, causing the manganese byproduct to migrate faster, resulting in a larger manganese byproduct footprint with lower average concentrations than the 2022 Optimized Design. However, similar to the BOD remedy, all of the generated byproduct manganese concentrations fall within the range of observed naturally occurring manganese concentrations in the floodplain.

5.3 Arsenic

Arsenic was also simulated with the updated groundwater flow and solute transport model. The two simulated sources for arsenic in the model are arsenic generated as a byproduct due to dosed injection and arsenic associated with the freshwater source in Arizona (HNWR-1/1A for the BOD scenario and Topock 2 and 3 for the 2022 Optimized Design Scenario). Arsenic naturally occurred in groundwater observed at the TCS before implementation of the proposed remedial options, with the majority of impacts observed in the floodplain and portions of the bedrock. The initial naturally occurring arsenic distribution in model layers 1 through 4 was generated using arsenic data presented in the Fourth Quarter 2021 Quarterly Progress Report (Arcadis 2022c) and is shown on **Figure 5.24**. The updated flow and solute transport model was used to simulate the generation and transport of arsenic under both the BOD and 2022 Optimized Design conditions. No modifications were made to the arsenic generation and sorption parameters used in the solute transport model as documented in previous modeling exercises (Arcadis 2015, 2016, and 2017).

5.3.1 Basis of Design Remedy

The BOD remedy simulated and naturally occurring arsenic distribution in model layers 1 through 4 for years 10 and 35 are presented on **Figures 5-25 and 5-26**, respectively. Under BOD remedy conditions, it is assumed that the freshwater injection water originates from HNWR-1/1A in Arizona and has an average arsenic concentration of 16.5 µg/L based on observed concentrations. The freshwater arsenic concentration remains at this fixed concentration throughout the duration of the remedy. This results in the radial arsenic footprints emanating from wells FW-1, FW-2, IRL-3, and IRL-4. The largest freshwater injection arsenic footprints occur at IRL-4, which is operating at a rate of 200 gpm, and FW-2, which is only operating at a rate of 50 gpm, but is located in a thinner portion of the alluvial aquifer. The byproduct arsenic generated near dosed injection wells due to the development of reducing conditions and release from the aquifer materials is very limited in magnitude and extent, and concentrations typically remain below 5 µg/L. This is under the range of observed naturally occurring arsenic in the floodplain. These results are consistent with the original groundwater flow and solute transport model, indicating that the model updates did not significantly impact the solute transport model results with respect to arsenic.

5.3.2 2022 Optimized Design

The 2022 Optimized Design remedy simulated and naturally occurring arsenic distribution in model layers 1 through 4 for years 10 and 35 are presented on **Figures 5-27 and 5-28**, respectively. Under 2022 Optimized Design remedy conditions, it is assumed that the freshwater injection water originates from wells Topock 2 and 3 in Arizona and has an average arsenic concentration of 12.75 µg/L based on observed concentrations. The freshwater arsenic concentration remains at this fixed concentration throughout the duration of the remedy. This results in the radial arsenic footprints emanating from wells FW-2, FW-3, and FW-4. Although of the three freshwater injection wells, FW-3 has the highest injection rate of 150 gpm, FW-02 and FW-04 have larger simulated arsenic footprints due to being screened in thinner portions of the alluvial aquifer. With respect to byproduct arsenic generated near dosed injection wells (NTH IRZ dosed injection wells, source area dosed injection wells TCS-1 and TCS-2, and periodic short-term dosed injection wells IRL-6 and IRL-7), simulated concentrations are very limited in extent and magnitude, and typically remain below 5 µg/L. This is under the range of observed naturally occurring arsenic in the floodplain. With respect to byproduct arsenic, the simulated

2022 Optimized Design does not result in any additional adverse impacts, as these simulated arsenic results are relatively consistent with those of the BOD remedy.

5.4 Pathline Analysis

To further illustrate the average groundwater flow pattern during the operation of the BOD and 2022 Optimized Design remedies, a pathline analysis was conducted using MODPATH (Pollock 1989). For each remedy design and in each model layer, particles were initialized around each active freshwater injection well, the source area dosed injection wells (TCS-1 and 2), and around the simulated 4-year Cr6 plume footprint greater than 32 µg/L. The pathline analysis was also run during NTH IRZ active conditions and NTH IRZ inactive conditions to highlight the hydraulic influence of the NTH IRZ. While the pathline analysis does not account for solute transport mechanisms, such as sorption, precipitation, degradation, and redox reactions, it does provide a general understanding of the flow path of a particle of water in the area of concern. This means that simulated particles that reach or flow under the Colorado River do not represent Cr6 mass discharging to the river, and the Cr6 plume would be treated by the proposed remedies. To attain a better understanding of the fate and transport of Cr6, the analysis and figures presented in Section 5.1 are more appropriate.

5.4.1 Basis of Design Remedy

The simulated pathlines for model layers 1 through 4 under BOD remedy conditions with the NTH IRZ on and off are shown on **Figures 5-29 and 5-30**, respectively. Under NTH IRZ on conditions, the pathline indicates that the western edge of the plume is pushed towards the NTH IRZ. Pathlines are captured by the active NTH IRZ extraction wells as well as the TWB extraction wells and East Ravine Extraction wells. Some simulated particles pass through the NTH IRZ line, although this does not indicate plume breakthrough. Viewed in conjunction with the Cr6 solute transport modeling results, it is apparent that the particles that pass through the NTH IRZ will pass through the generating reducing zone, allowing for the reduction of precipitation of the Cr6 plume. Shallow particles in the floodplain in model layer 1 indicate that the active riverbank extraction wells (which are screened in the deeper portion of the alluvial aquifer, below the naturally occurring reducing rind) are not hydraulically controlling the shallow groundwater flow in this area, which is consistent with the original BOD modeling (Arcadis 2015, 2016, and 2017).

In the deeper portion of the aquifer, the active riverbank extraction wells control the majority of pathlines passing through the NTH IRZ. Under NTH IRZ off conditions, the pathlines that were previously hydraulically controlled by the NTH IRZ extraction wells now pass through the NTH IRZ reducing zone. The BOD pathline analysis also helps to illustrate some of the inefficiency of the original BOD with respect to the updated Cr6 plume distribution. The Cr6 plume based on 2013 and 2015 datasets had a larger more continuous plume distribution in the northern portion of the plume that helped drive the proposed higher freshwater injection to the north. The updated Second Quarter 2021 Cr6 plume has a much smaller and lower concentration Cr6 distribution in the norther portion of the plume, as well as a relatively clean mid-depth zone. This reduction in plume size was due to both the additional 7 years of plume reduction resulting from IM-3 activities as well as additional plume distribution refinement through the installation of new monitoring and remediation wells. Many of the simulated northern freshwater injection particles no longer pass through the more recent Cr6 plume distribution and therefore do not provide as much value for remedy success. These pathlines help to identify these areas of potential remedy inefficiency and support the optimization of the original BOD remedy design, which led to the 2022 Optimized Design.

5.4.2 2022 Optimized Design

The simulated pathlines for model layers 1 through 4 under 2022 Optimized Design remedy conditions with the NTH IRZ on and off are shown on **Figures 5-31 and 5-32**, respectively. Similar to the BOD pathline analysis, under NTH IRZ on conditions, the pathline indicates that the western edge of the plume is pushed towards the NTH IRZ. Pathlines are captured by the active NTH IRZ extraction wells, as well as the TWB extraction wells and East Ravine Extraction wells. Some simulated particles pass through the NTH IRZ line, although this does not indicate plume breakthrough. Viewed in conjunction with the Cr6 solute transport modeling results, it is apparent that the particles that pass through the NTH IRZ will pass through the generating reducing zone, allowing for the reduction of precipitation of the Cr6 plume. In the 2022 Optimized Design, the only active riverbank extraction well is RB-5, which is intended to hydraulically control deeper Cr6 impacts in the floodplain that are already downgradient of the NTH IRZ. The simulated pathlines in model layer 3 indicate that RB-5 hydraulically controls these Cr6 impacts located downgradient of the NTH IRZ.

Under NTH IRZ off conditions, pathlines that were previously hydraulically controlled by the NTH IRZ extraction wells pass through the NTH IRZ reducing zone. Under NTH IRZ off conditions, RB-5 still hydraulically controls the Cr6 impacts in the floodplain in model layer 3. As the simulated pathlines of the alluvial Cr6 plume footprint in all layers pass through the NTH IRZ reducing zone, the operation of other riverbank extraction wells is not proposed in the 2022 Optimized Design. However, these riverbank extraction wells can still be operated as contingency wells if Cr6 or byproduct concentration trends indicate that they are needed. The upgradient freshwater injection pathlines indicate that the reduced freshwater infrastructure of the 2022 Optimized Design still effectively, and more efficiently, hydraulically flushes the plume from west to east through the NTH IRZ without causing adverse Cr6 plume expansion.

6 Sensitivity Analysis

In order to evaluate the potential range in simulated remedy results, a sensitivity analysis was conducted similar to that conducted in Appendix B of the 100% BOD report (Arcadis 2015). Sensitivity analyses are conducted to describe how the model reacts to a change in a given parameter. The sensitivity analysis is an important tool when describing the uncertainty of the model (Johnson 2010). The sensitivity of the initial Cr6 plume distribution was evaluated in Section 5.1 in the discussion of the simulation of the initial average and maximum Cr6 plume distributions. Although the total mass in the maximum Cr6 plume was increased, the results of the remedy performance for both the BOD and 2022 Optimized Design were not sensitive to the range of Cr6 plume concentrations and still effectively controlled and treated the Cr6 plumes over the same simulated timeframes. As the updated modeling of the BOD design scenario was very similar to the original BOD modeling, it is anticipated that the previously performed sensitivity analyses would yield comparable results. For this reason, the sensitivity analysis conducted in this report focused on the 2022 Optimized Design. The results of the sensitivity analyses conducted on the 2022 Optimized Design are presented in **Appendix A**. The sensitivity analyses focus on the following flow and transport parameters:

- Hydraulic conductivity;
- Cr6 sorption;
- Total organic carbon (TOC) degradation;
- Manganese oxidation;
- Manganese sorption;
- Manganese generation;
- Arsenic precipitation;
- Arsenic sorption; and
- Arsenic generation.

Results of each of these sensitivity analyses are presented for model layers 2 and 4 after 10 years and 30 years of simulated transport. These layers and timeframes were selected to provide representative results in the shallow (model layers 1 and 2) and deep portions (model layers 3 and 4) of the aquifer at short- and long-term intervals of the active remedy. The relative sensitivity of each of the simulated parameters is listed in **Table 6-1** below:

Table 6-1: Relative Simulation Sensitivity Summary

Sensitivity Model Run	Hexavalent Chromium	Manganese	Arsenic
Hydraulic Conductivity Sensitivity	**Moderate Sensitivity**	**Moderate Sensitivity**	**Moderate Sensitivity**
Cr6 Sorption Sensitivity	**Moderate Sensitivity**	NA	NA
TOC Degradation Sensitivity	High Sensitivity	Low Sensitivity	Low Sensitivity
Manganese Oxidation Sensitivity	NA	Low Sensitivity	NA
Manganese Sorption Sensitivity	NA	High Sensitivity	NA
Manganese Generation Sensitivity	NA	High Sensitivity	NA

Sensitivity Model Run	Hexavalent Chromium	Manganese	Arsenic
Arsenic Precipitation Sensitivity	NA	NA	Low Sensitivity
Arsenic Sorption Sensitivity	NA	NA	**Moderate Sensitivity**
Arsenic Generation Sensitivity	NA	NA	Low Sensitivity

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 results of the historical IM-3 modeling and this sensitivity analysis show that, although there is uncertainty associated with hydraulic conductivity, Cr6 sorption and the Cr6 plume distribution, the model simulates Cr6 fate and transport at the site well and the model is appropriate for evaluating implementation of the remedy with variations in well layouts and flowrates, i.e. the differences in the sensitivity analysis for hydraulic conductivity, Cr6 sorption and base case versus maximum case initial plume would not drive the selection of one design over another. Parameters governing IRZ behavior, such as TOC degradation and manganese reactions and transport had greater sensitivity in the sensitivity analysis. Given this uncertainty, the IRZ was designed with an initial set of recirculation wells, ethanol dosing rate, and flowrates and data collecting during operations will guide changes in flowrates and ethanol dosing and determine whether the provisional wells reserved in the design are needed.

7 Conclusions

The groundwater flow and solute transport model was updated using additional site data collected during Phase 1 of remedy construction through Second Quarter 2021. Updates to the groundwater flow model included updates to the model structure, evapotranspiration, and hydraulic conductivity distribution and magnitude. The groundwater flow model was calibrated to steady-state conditions and transient conditions over a period of 1 year, and the model calibration was further validated transiently using drawdown data collected during aquifer tests conducted near the NTH IRZ (TW-03D) and near the source area (TW-01). Although lithology and grain size analyses indicated a fairly heterogeneous sediment distribution in the alluvial aquifer, and hydraulic conductivity estimates from grain size analyses suggested fairly low hydraulic conductivities (less than 1 ft/day), the aquifer testing conducted indicated bulk hydraulic conductivity values for the alluvial aquifer between 20 and 80 ft/d, with geometric means between 34 and 42 ft/d. As the aquifer testing better represented the bulk behavior of the aquifer, the simulated hydraulic conductivity zones based on the HSUs used the hydraulic conductivity values within the range determined from the aquifer testing. Tracer testing conducted during the TW-01 aquifer test was also further used to verify aquifer parameters as well as the mobile porosity values used in the solute transport modeling. The solute transport model was primarily updated by refining the initial Cr6 plume distribution based on data collected through Second Quarter 2021.

A qualitative historical transport modeling analysis was conducted to compare the overall simulated and observed plume behavior and trends during 15 years of IM-3 operation. The objective of the historical transport modeling was not to attain an exact match to observed concentration trends, but rather to validate the bulk movement of the Cr6 plume and identify general areas of increasing, decreasing, or stable Cr6 concentrations. As a more robust dataset is available to delineate the current Cr6 plume, the recent Cr6 plume delineation was used to evaluate the predicted Cr6 transport, although general observations from the historical transport modeling were used to inform the Cr6 plume distribution in areas with limited data availability.

The updated and calibrated groundwater flow and solute transport model was then used to evaluative the predictive transport under the BOD remedy and a new 2022 Optimized Design remedy. The BOD remedy was consistent with the BOD presented in previous modeling reports (Arcadis 2015, 2016, and 2017), except that the NTH IRZ was modified to represent the current modified operation of Phase 1 (Arcadis 2022b). The 2022 Optimized Design remedy is a modified version of the BOD design that consists of less freshwater injection, freshwater injection wells relocated closer to the western edge of the plume and focused further south in the area of greater Cr6 mass, periodic short-term dosed injection into IRL-6 and IRL-7, and reduced riverbank extraction well pumping. Additional 2022 Optimized Design details are provided in the Phase 2 report (Arcadis 2022b). The updated predictive modeling indicates that the BOD simulated performance is comparable between the updated model and the original modeling, indicating that the modeling updates did not substantially change the predicted simulated transport and the BOD still adequately addresses the Cr6 plume with respect to the RAOs. The 2022 Optimized Design transport simulations indicate that the proposed design optimization more aggressively reduces Cr6 concentrations, is more efficient, and requires less infrastructure than the BOD remedy. The modeling supports that the 2022 Optimized Design is a viable remedy approach to achieve RAOs with less infrastructure and less freshwater demand.

With respect to simulated byproducts of manganese and arsenic, as well as arsenic associated with freshwater supply wells in Arizona, both remedies produced consistent results. Byproduct arsenic generation was minimal, and the arsenic freshwater injection footprints were smaller than the maximum radius of 225 ft. Manganese byproducts differed slightly with respect to manganese footprints downgradient of the NTH IRZ in the 2022

Optimized Design due to a lower groundwater flux than what was simulated in the BOD remedy. The 2022 Optimized Design also had limited manganese generation footprints near the periodic short-term dosed injection wells IRL-6 and IRL-7. However, all of the manganese byproduct concentrations in both remedy designs fell within the range of observed naturally occurring groundwater manganese concentrations in the floodplain. Pathline analyses for both remedies also supported that the proposed remedial actions will not expand the Cr6 plume, and the alluvial Cr6 plume will be pushed through the NTH IRZ induced reducing zone for treatment before entering the floodplain. The pathline analysis also indicates that the Cr6 impacts that currently extend into the floodplain (in model layer 3) are hydraulically contained by riverbank extraction well RB-5.

The sensitivity analysis conducted on the 2022 Optimized Design indicated a potential range of remedy performance with respect to Cr6, manganese, and arsenic. The original or baseline simulated parameters for Cr6, manganese, and arsenic still represent the most appropriate parameters based on available site geochemical data and literature data, but the range in values was evaluated to provide a potential range in transport results that may occur. Detailed monitoring data are being collected during current Phase 1 operations and will be collected during Phase 2 operations to further quantify and refine flow and solute transport model parameters during future model updates.

Additional model updates are still planned based on continued refinement of the site hydrogeology, Cr6 plume distribution, and remedy operation and performance data. In addition to the actual performance data, the model will continue to be used to evaluate proposed remedy operations.

8 References

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Tables

Figures

Appendix A

2022 Optimized Design Sensitivity Analysis

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