APPENDIX M – 2017 GROUNDWATER FLOW MODEL UPDATE REPORT

2016 Groundwater Flow Model Update
Cimarron Remediation Site

Cimarron Environmental Response Trust

Project No. 89761

Revision 0
1/25/2017

2016 Groundwater Flow Model Update Cimarron Remediation Site

Prepared for

Cimarron Environmental Response Trust
Crescent, Oklahoma

Project No. 89761

Revision 0
1/25/2017

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LIST OF ABBREVIATIONS

Abbreviation	**Term/Phrase/Name**
Burns & McDonnell	Burns & McDonnell Engineering Company, Inc.
amsl	above mean sea level
CSM	Conceptual Site Model
DCGL	Derived Concentration Goal Level
DEM	Digital Elevation Model
DEQ	Oklahoma Department of Environmental Quality
EPM	Environmental Properties Management LLC
Ft	foot/feet
GHB	General Head Boundary
in/yr	inches per year
KMNC	Kerr-McGee Nuclear Corporation
gpm	gallons per minute
MCL	maximum contaminant level
NRC	Nuclear Regulatory Commission
pCi/L	picoCuries per liter
Site	Cimarron Site
Trust	Cimarron Environmental Response Trust
USGS	United States Geological Survey
%	percent
µg/L	micrograms per liter

1.0 INTRODUCTION

Environmental Properties Management LLC (EPM), Trustee for the Cimarron Environmental Response Trust (the Trust), submits this 2016 Groundwater Flow Model Update for the Cimarron site (the Site), located at 100 N. Highway 74, Crescent, Oklahoma.

To evaluate groundwater remediation alternatives at two areas on the Cimarron Site, two existing groundwater flow models were updated. The areas include Burial Area #1 (BA #1) and the Western Alluvial (WA) area. These two models were originally developed as part of the *Groundwater Flow Modeling Report* (ENSR, 2006) included as Appendix A, and the *Groundwater Flow Model Update* (Burns & McDonnell, 2014) included as Appendix B.

The models were updated with new geologic and hydrogeologic data, based on additional assessment performed in 2014 and 2016. The WA model area was expanded to include a larger area including the Western Upland (WU). The WU hydrogeologic and water level information were added in the expanded model boundary area. The calibration of both models was confirmed using a comprehensive data set of groundwater elevations collected in August 2016. Accuracy of the model calibration was evaluated by comparing measured groundwater elevations, groundwater flow direction, and water budgets, with simulated elevations, flow paths, and budgets. Calibration goals included: 1) a mass balance error less than 1% of the water budget, 2) low residual error from the statistical testing of modeled and measured groundwater elevations, and 3) a qualitative match of model simulated potentiometric surface and observed potentiometric surface.

The updated groundwater models were linked to a particle tracking model (MODPATH) to evaluate alternative remediation scenarios. Groundwater extraction was modeled with both groundwater recovery trenches and extraction wells that were added to the models and will be used as the basis for design for the anticipated groundwater flow rates for the remediation efforts. Upon approval of these updated and revised flow models, they will be used for completion of the groundwater remediation design that will be included in a comprehensive license amendment request.

1.1 Background and Objectives

The Cimarron facility was formerly operated by Kerr-McGee Nuclear Corporation (KMNC), a wholly owned subsidiary of Kerr-McGee Corporation. The Cimarron facility was utilized for the production of mixed oxide fuel and uranium fuel including enriched uranium reactor fuel pellets, and eventually fuel rods. Enriched uranium fuel was produced at the facility from 1966 through 1975. Process facilities included a main production building; several ancillary buildings, five process related collection ponds, two original sanitary lagoons, one new sanitary lagoon, a waste incinerator, several uncovered storage areas, and three burial grounds.

Licensed material still present onsite exceeds decommissioning criteria for unrestricted release only in groundwater. The concentration of uranium in groundwater must be reduced to achieve unrestricted release of the site and license termination. The Derived Concentration Goal Level (DCGL) for the site is 180 picoCuries per liter (pCi/L) total uranium, and the Oklahoma Department of Environmental Quality (ODEQ) has approved a toxicological concentration release criterion of 110 micrograms per liter (μg/L) for uranium in groundwater. In addition to uranium, groundwater in portions of the Site contains two non-radiological chemicals of concern (COCs): nitrate and fluoride. DEQ has approved site-specific risk-based concentration limits of 52 milligrams per liter (mg/L) for nitrate and 4 mg/L for fluoride.

Uranium exceeds the license release criterion of 180 pCi/L in three areas: BA #1, the WU Area and the WA Area (ENSR, 2006a and Cimarron, 2007). These areas are illustrated in Figure 1-1. Uranium exceeds the DEQ criterion of 110 μg/L in these same areas, and the extent within those areas approximately matches the extent of uranium exceeding the NRC criterion. The extent of uranium impact to groundwater has been adequately delineated for the development of a groundwater remedy. Years of environmental monitoring have already demonstrated that nitrate and/or fluoride exceed DEQ criteria in the following areas: the WU Area, the WA Area, the Uranium Pond #1 (UP1) Area, the Uranium Pond #2 (UP2) Area, and the uranium plant storage yard (Well 1319 Area). The flow model domain covers all of the areas that exceed the Maximum Contaminant Level (MCL) and that will eventually require remediation.

These groundwater flow models will be used as a tool to assist in the design of groundwater recovery and reinjection systems to reduce the concentrations of COCs in groundwater to less than their release criteria.

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2.0 GROUNDWATER MODEL DESCRIPTION AND UPDATES

2.1 Conceptual Model

The Conceptual Site Model (CSM) of the Cimarron River flow system was developed and presented in the *Conceptual Site Model-Rev-01 Report* (ENSR, 2006b) prior to the development of the original groundwater models for the WU and WA areas and the BA #1 area. The CSM was then incorporated into the 2006 groundwater models to ensure that the models used existing information and an accepted interpretation of the site-wide geology. Appendix A (*Groundwater Flow Modeling Report* [ENSR, 2006a]) provides a summary of information on the CSM.

2.2 Groundwater Flow

The Site consists of gently rolling hills, leading northward to the floodplain of the Cimarron River. Ground elevation varies from approximately 925 ft above mean sea level (amsl) at the northeastern property line to approximately 1,045 ft amsl near the southern property line. Three surface water reservoirs are present on the Site. Unnamed ephemeral streams feed these reservoirs, which discharge to the floodplain of the Cimarron River.

Groundwater flow in the WU area is generally to the northwest with a gradient that ranges from 0.02 foot/foot in the central and western portions of the property, to 0.05 foot/foot in the eastern portion of the property (down gradient of Reservoir 3). This groundwater flow pattern continues until groundwater reaches the interface with the alluvial aquifer of the WA area, where the hydraulic gradient steepens. The groundwater flow direction and hydraulic gradient change significantly once groundwater enters the alluvial aquifer. The WA groundwater flow is generally northeastward toward the Cimarron River; flow is driven by a relatively flat hydraulic gradient of 0.001 to 0.002 foot/foot. Figure 2-1 presents a potentiometric surface map of Sandstone B beneath the WU and alluvium for the WA area based on groundwater level measurements during August 2016.

Additional wells installed in the WU and WA area have provided a more refined understanding of the groundwater flow and direction than was provided in the *2006 Groundwater Flow Modeling Report* (ENSR, 2006a). The current model update included the expansion of the domain to include the WU area where active remediation is planned. The August 2016 groundwater level measurements for upland wells screened in Sandstone B were used in the model expansion since Sandstone B and the alluvial deposits are in direct contact at the bluff that is the demarcation between the uplands and the WA area. Sandstone A was not included in this model since it is not in direct connection with the alluvial aquifer.

Groundwater in the vicinity of BA #1 flows across an escarpment that is an interface for the Sandstone B water-bearing unit and the Cimarron River floodplain alluvium, and finally into and through the floodplain alluvium to the Cimarron River. Figure 2-2 presents a potentiometric surface map of Sandstone B and the alluvium for the BA #1 area based on groundwater level measurements collected during August 2016. Flow in Sandstone B is mostly northward west of the transitional zone and northeastward along the interface with the transitional zone.

Flow is driven by a relatively steep hydraulic gradient (0.10 foot/foot) at the interface between Sandstone B and the floodplain alluvium. Once groundwater enters the transition zone of the floodplain alluvium, the hydraulic gradient decreases to around 0.02 foot/foot and flow is refracted to a more northwesterly direction. Once groundwater passes through the transitional zone, it enters an area where the hydraulic gradient is relatively flat and groundwater flow is toward the north. Data indicates that the gradient in the sandy alluvium is approximately 0.001 foot/foot.

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3.0 GROUNDWATER MODEL CONSTRUCTION

The two existing groundwater flow models developed for the Cimarron Site were updated as part of an effort to evaluate remedial alternatives at the Site. A detailed description of those groundwater models is provided in Appendix A (ENSR, 2006) and Appendix B (Burns & McDonnell, 2014). The primary modification to the existing groundwater models was the expansion of the model domain of the WA model to include the WU area. This model expansion was undertaken to better simulate the remedial activities that are proposed within the WU. No structural changes were made to existing groundwater models other than those related to the expansion of the WA model. No changes were made to the parameterization of input values in either model. The calibration of both models was checked using groundwater elevation data collected in August 2016. Once the model calibration check was completed, both models were used to evaluate the performance of the planned remedial system using injection and pumping rate data that are consistent with current remedial design concepts. Both groundwater models were run using steady state assumptions. The following sections describe the updates or new information in the model update.

3.1 Model Construction

MODFLOW-2000 (Harbaugh et al, 2000), a three-dimensional, finite difference groundwater flow computer code, was selected to update the groundwater flow models. Pre- and post-processing was performed using Groundwater Vistas 6 (Rumbaugh, 2011). Groundwater Vistas was used to create standard format MODFLOW file sets from graphically input data.

Model output was evaluated using Groundwater Vistas, Surfer® Version 12 (Golden Software, 2015), ArcMap 10 (ESRI, 2010) and Microsoft Excel. Groundwater Vistas was used when possible to provide contoured model results (model predicted heads and drawdown) and numerical data output. Additional data contouring and evaluation was completed using Surfer®. Surfer™ is a grid-based contouring and three-dimensional surface plotting program. Surfer® and ArcMap 10 were used to interpolate the irregularly-spaced, model-predicted data onto regularly spaced grids and to produce contoured results.

3.2 Model Domain

The numerical model domain for the WU and WA areas is shown on Figure 3-1. The primary objective of this model update was to expand the model domain to include the WU area, where extensive injection and pumping remediation will occur. The grid size remains 10 feet by 10 feet, but the model now contains 270,366 active cells which is a substantial increase from the 2006 model. The model origin (left-bottom corner) is located at X = 2,091,050 and Y = 319,455 in Oklahoma State Plane Coordinates. The model grid is rotated (minus) 20 degrees.

The numerical domain for BA #1 is shown on Figure 3-2 and covers the same area as the 2006 groundwater model. The northern boundary of the model domain is the Cimarron River and the southern boundary of the model is the extent of the transition zone. The grid size is 10 feet by 10 feet and contains 267,440 active cells. The model origin (left-bottom corner) is located at X = 2094550 and Y = 322150 in Oklahoma State Plane Coordinates. There is no rotation of the model grid. .

3.3 Model Layering

No adjustments were made to the number of model layers for either model. Some modifications to the layer elevations in the WA Model was required to accommodate the expansion of the model. The following section describes the layer development for both models.

3.3.1 WA Model

The WU/WA model domain includes two layers: Layer 1 represents the alluvium and Sandstone B (in the WU portion of the model domain), while Layer 2 represents the underlying bedrock. New model surfaces were imported to represent the WU area that was previously not included in the model. The top of Layer 1 was developed from a 10 meter resolution digital elevation model (DEM) obtained from the United States Geological Survey (USGS). The base of Layer 1 for the area which underlies the WU area was set at a constant elevation of 920 feet msl. This value represents the base of Layer 1 used in the 2006 model in the transition zone, which is the contact between the alluvium and the uplands.

3.3.2 BA#1 Model

Twelve layers are used to simulate the complex geology of the BA#1 area. No adjustments were made to the number of layers or the layer elevations for BA #1 model update. This complex model layering system setup was described in the *2006 Groundwater Flow Modeling Report* (ENSR, 2006a) and was not modified during the model update.

3.4 Boundary Conditions

The model boundary conditions represent the hydrologic interactions between the inside and outside of the model domain and simulate flow into and out of the groundwater model. The boundary conditions used in both the WA and BA#1 groundwater models were summarized in detail in the *Groundwater Flow Modeling Report* (ENSR, 2006), and in the *Groundwater Flow Model Update* (Burns & McDonnell, 2014). These documents are included as Appendix A and Appendix B, respectively.

The model conditions presented in the *Groundwater Flow Model Update* (Burns & McDonnell, 2014) were used as the point of departure for the model update presented within this document. No changes to the model boundary conditions were made to the BA#1 model. Boundary conditions for the WA model were not modified except in the portion of the model domain associated with the model expansion to include the WU area. Changes to the boundary conditions of the WA model are described below.

3.4.1 No Flow Boundaries

No flow boundaries are used to simulate impermeable boundaries, groundwater divides, or streamlines. Mathematically, no-flow boundaries occur when flux across a model cell is set to zero. The location of the active model domains are shown on Figures 3-1 and 3-2. Outside of the active domain are no flow cells that define the western and eastern boundary of both model domains. Within the active model domain all cells are active.

3.4.2 General Head Boundary

A new General Head Boundary (GHB) condition was established to represent the upgradient boundary of the WA groundwater model. The upgradient boundaries for both the WA area and BA #1 were represented as a GHB. This GHB was updated to account for the water level elevations observed in the wells during the August 2016 water level measurement event and to match the direction of groundwater flow observed with the recently installed wells in the WA area. No other GHBs were added to the WA model.

3.4.3 Constant Head Boundary

A Constant Head Boundary was added to the expanded WA model in order to simulate the impact of leakage from Reservoir 3 (the reservoir shown on Figure 3-1) on the groundwater elevations within the WU area. The impact of the reservoir on groundwater elevations can be seen upon examination of the groundwater elevations presented on Figure 2-1. The reservoir was simulated with a water surface elevation of 958 feet msl. The water surface elevation was based on specific data collected and reported by the design project team.

3.5 Hydrogeologic Properties

After review of new and existing data, no changes were made to the hydraulic conductivity parameters from the 2006 models. The WU expansion area within the WA model was simulated using the values presented in Table 3-1. These values are based on site-specific data or (where site data is not available), on values obtained from published literature.

3.6 Recharge

Based upon a review of precipitation data, 2016 appears to be slightly drier than a normal precipitation year. However, water levels at the site were similar to the 2006 model. No changes were made to the recharge values originally presented in the 2006 model because 2016 does not represent a typical year and the recharge values are meant to represent a long term average condition.

3.7 Model Calibration

Table 3-2 and Table 3-3 present the most recent water level measurements available from August 2016 for the WU and WA area and BA #1, respectively. All wells were used as calibration targets.

The WA model was recalibrated to water levels collected in August 2016 because the model domain was increased and new boundary conditions were added to the model. The calibration status of the BA#1 model was checked using water levels collected in August 2016. The BA#1 model was not recalibrated because no structural changes were made to that model. For both models, the calibration was evaluated by comparing measured groundwater elevations, groundwater flow direction, and water budgets, with simulated elevations, flow paths, and budgets. The calibration goals for the numerical model were as follows:

- A less than one (1) percent water balance error, which is considered appropriate for a calibrated groundwater model (Anderson and Woessner, 1992). The water balance error is defined as the total inflow minus the total outflow, divided by either the inflow or outflow, whichever yields the highest error.
- A Normalized Root Mean Square error (NRMS) of less than ten (10) percent. A NRMS of less than ten (10) percent is generally considered appropriate for a calibrated groundwater model (Anderson and Woessner, 1992). A lower NRMS indicates a better statistical model calibration.
- An Absolute Residual Mean (ARM) error of less than ten percent of the observed head change value across the model domain. The ARM can be described as the average error of the absolute value of the residuals.
- A qualitative match of model simulated potentiometric surface and observed potentiometric surface, evaluated by comparing contours. When calibrated, the model should be able to reproduce the direction and magnitude of the hydraulic gradient observed within the study area.

3.7.1 WA Model Calibration

The water level measurements that were collected in August 2016 were used to check the calibration status of the WU/WA model. The calibration data includes both alluvial wells and wells screened in

Sandstone B. Sandstone A wells were not included because the water level is significantly higher and this unit is not in direct connection with Sandstone B or the alluvial aquifer.

Approximately 70 water level measurements were available for comparison to the model predicted values for the August 2016 date. For comparison purposes, the previous WA area model (Burns & McDonnell, 2014) included water level measurements were collected from 43 wells. The results for these calibration checks are presented in Table 3-4 and are summarized below:

- Mass balance error of 0.09 percent.
- NRMS = 3.4 percent
- ARM = 0.6 feet

The percent error in the water budget for the WA model is significantly less than 1%, indicating a stable model. The calibration statistics are comparable to the statistics from the previous model (Burns & McDonnell, 2014) and indicate that the model is calibrated. A visual comparison between the model predicted and observed groundwater gradient indicates the model is a good match to the observed potentiometric surface and a good match to observed groundwater flow. The model predicted potentiometric surface and the residual error for each monitoring well is presented on Figure 3-2.

3.7.2 BA#1 Model Calibration Check

To check the calibration status of the BA #1 model, water level measurements that were collected in August 2016 were used. This calibration dataset included 68 wells and the range in observed water level elevations is 17.5 feet. The calibration goals for the BA#1 model were the same as those listed for the WA model:

The results for these calibration checks are presented in Table 3-5 and are summarized below:

- Mass balance error of 0.00003 percent.
- NRMS = 6.9 percent
- ARM = 0.7 feet

The percent error in the water budget for the BA#1 model is significantly less than 1%, indicating a stable model. The calibration statistics are comparable to the statistics from the previous model (Burns & McDonnell, 2014) and indicate that the model is calibrated. A visual comparison between the model predicted and observed groundwater gradient indicates the model is a good match to the observed potentiometric surface and a good match to observed groundwater flow. The model predicted potentiometric surface and the residual error for each monitoring well is presented on Figure 3-4.

3.7.3 Sensitivity Analysis

No structural changes or changes to the parametrization of the inputs were made to the BA#1 model as a result of this model update. Given these limited changes to the models, a sensitivity analysis was not performed as part of this modeling effort. A sensitivity analysis was conducted on the flow model for both the 2006 Groundwater Model (Appendix A) and the 2014 Groundwater Model (Appendix B). The parameterization of the WA model was not changed as part of this update; the only change was the expansion of the model domain. The conclusions presented in the 2006 Groundwater Model report regarding the sensitivity of the model to parameter inputs and boundary conditions remain valid for this update of the model.

3.8 Uncertainty

Site conditions and hydrogeologic properties were estimated through extrapolation of measured or estimated properties or inferences from data measured or estimated based on existing site data and professional judgment. Groundwater models are by definition a simplified version of the aquifer system. Therefore, these simplifications provide some model limitations.

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4.0 REMEDIATION SIMULATIONS

Remediation system simulations were completed using both groundwater models with injection rates and pumping rates that are representative of a design basis of each remediation system. A summary of the remedial system simulations is presented below.

4.1 Model Simulation of Injection and Extraction

Injection and extraction trenches were simulated as a line of boundary wells with the total pumping or injection flow rate was equally distributed amongst the wells. Injection or extraction wells were simulated as an individual boundary wells using their prescribed flow rate. Well boundaries in MODFLOW are specified flow boundary conditions, where the flow rate is assigned by the model. The impact to groundwater elevations that result from the injection or extraction of water in the well boundary cells is calculated by MODFLOW. The boundary wells were modeled using steady state conditions, meaning the extraction or injection flow rates are held constant through time.

4.2 Particle Tracking

The particle tracking code MODPATH (Pollock, 1989) was selected to perform the particle tracking analysis for both the WA and BA#1 models. MODPATH uses a semi-analytical particle tracking scheme and is based on the assumption that each directional velocity component for a particle of water varies linearly within a grid cell in its own coordinate direction (Pollock, 1989). This assumption allows an analytical expression to be derived that describes the flow path of water within a grid cell. Given the initial position of a particle anywhere in a cell, the pathline and travel time within the cell can be computed directly. Groundwater heads and intercell flow rates are first determined using MODFLOW. This information is then input to MODPATH along with effective porosity values and user-specified starting particle locations. MODPATH then calculates three-dimensional pathlines and time-of-travel information as particles are tracked individually through the simulated flow system using the calculated distribution of velocity throughout the flow system. MODPATH was selected for this modeling study because of its applicability and simple linkage with MODFLOW.

4.3 WA Remediation Simulation Setup

All wells and trenches located in the WU area were simulated regardless of their installation layer (Sandstone A or Sandstone B). The primary reason the Sandstone A trenches were included in the remedial simulations was to evaluate the potential mounding affects within the WU area, as the hydraulic properties of the two sandstone units are similar. A secondary reason for including the Sandstone A trenches in the remedial simulations was to evaluate the indirect travel path of injected water from Sandstone A into the alluvium. This approach is conservative, as it assumes that all water discharging from Sandstone A as a seepage face will eventually be captured by the wells installed in the alluvial transition zone. It should be noted that an unknown small percentage of the groundwater discharging at the seepage face will likely be lost to evaporation. The majority of this discharge however, will infiltrate into the alluvium after migrating down the seepage face surface or through joints and fractures.

4.4 BA#1 Remediation Simulation Setup

All wells and trenches located in the BA#1 model area were simulated in the model layer that corresponds to the geologic unit that the trench or well will be constructed in, based on the installation depth of the trench or well. A detailed cross section of the geology in the BA#1 area was presented in the 2006 *Groundwater Flow Model Report* (see Figure 3 in Appendix A).

The location of remediation well GE-BA1-04 was changed, compared to previous modeling efforts. This well was moved approximately 40 feet east to improve the capture of uranium impacted groundwater.

4.5 Remediation Simulation Results

Forward particle tracking was used to ensure that all areas of concern would be hydraulically contained by extraction pumping. This includes make sure that all water injected is later captured by an extraction well.

Prior to running the MODPATH simulation, a MODFLOW simulation that includes pumping and injection at full design scale was run. This MODFLOW simulation was used as the flow field for the MODPATH simulation. In the forward particle tracking simulations, particles were placed in each cell representing an injection trench and around specific areas of higher contaminant concentration that require containment. These particles were then tracked forwards using the MODPATH code. Particles were placed in the middle of a model cell and tracked forwards The results of the forward particle tracking model simulations are presented on Figure 4-1 (WA) and Figure 4-2 (BA#1).

The particle tracking simulation results shown on Figure 4-1 include injection and extraction trenches in the Western Upland that will be constructed in Sandstone A but were simulated in Sandstone B. Sandstone A is not included in the groundwater flow model since it is not directly interconnected with Sandstone B and the alluvium. The particle tracks depicted are nonetheless representative of groundwater and dissolved phase transport in Sandstone A, as the hydraulic properties of the two sandstone units are similar. All simulations show plume capture for the contaminants of concern.

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5.0 SUMMARY AND CONCLUSION

As presented in the 2006 modeling report and the 2014 model update for the WA and BA #1 models, the purpose of this work was to conceptualize, develop, and calibrate numerical models to provide tools to better evaluate changes in groundwater flow for assessment of different remedial alternatives through simulations.

The objective of this report was to describe updates to the two models that included the expansion of the domain in the WA model to include the western upland and update of water level elevations for both models. In addition to these updates, remediation simulations were evaluated using potential extraction and injection configuration scenarios using MODPATH forward particle tracking simulation.

Calibration targets including measured groundwater elevations and flow data were achieved in both models. Any variability between the observed and predicted groundwater elevations were acceptable and reasonable. The overall modeled simulations confirmed the hydrogeologic characteristics described in the *Conceptual Site Model* (ENSR, 2006). Sensitivity analysis was not performed since only limited changes were made to the models and did not impact the validity of the 2006 *Groundwater Flow Model Report* (ENSR, 2006) or the 2014 *Groundwater Flow Model Update Report* (Burns & McDonnell, 2014).

In conclusion the results of the updates to both numerical models have captured the characteristics of the hydrogeologic conditions in reference to groundwater flow and evaluation of potential remediation alternatives through generation of simulations of injection, pumping, and capture scenarios.

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TABLES

CIMARRON ENVIRONMENTAL RESPONSE TRUST

TABLE 3-1

GROUNDWATER MODEL INPUT VALUES

UPDATED WESTERN ALLUVIAL AREA MODEL

Subsurface Units:		**Value**	**Units**	**Source**
Sandstone-B (Layer 1)	Horizontal Hydraulic Conductivity (K_H)	3.00E+00	ft/day	Calibration
	Vertical Hydraulic Conductivity (K_V)	1.50E-01	ft/day	5% of K_H
	Specific Storage	0.01	-----	Default, not used in steady state model
	Specific Yield	0.01	-----	Default, not used in steady state model
	Porosity	5	%	Freeze & Cherry, 1979 Table 2.4

CIMARRON ENVIRONMENTAL RESPONSE TRUST

TABLE 3-2

WESTERN UPLAND and ALLUVIAL AREA WATER LEVEL MEASUREMENTS

August 2016

Well	Easting	Northing	Water Elevation (08/08/2016) (feet amsl)
T-51	2,091,962.33	322,775.32	929.40
T-52	2,092,329.67	322,774.93	929.33
T-53	2,092,658.89	322,773.47	929.20
T-54	2,092,870.51	321,927.51	929.90
T-55	2,093,119.60	322,069.59	928.46
T-56	2,093,377.95	322,211.21	927.75
T-57	2,092,460.78	321,788.04	930.23
T-58	2,092,165.08	321,742.39	930.42
T-59	2,092,954.88	322,773.96	929.18
T-60	2,093,281.83	322,773.99	929.20
T-61	2,093,609.54	322,774.36	929.03
T-62	2,091,852.83	321,470.61	930.69
T-63	2,091,976.65	321,623.17	930.50
T-64	2,091,690.89	321,341.87	930.85
T-65	2,091,814.49	321,568.90	930.65
T-66	2,091,841.97	321,712.17	930.53
T-67	2,091,742.89	321,657.32	930.61
T-68	2,091,713.09	322,052.25	930.25
T-69	2,091,871.69	321,961.92	930.35
T-70R	2,091,625.71	321,577.88	930.72
T-72	2,091,716.88	321,899.31	930.40
T-73	2,091,492.01	321,770.60	930.53
T-74	2,091,531.32	321,541.25	930.80
T-75	2,091,598.42	321,910.85	930.08
T-76	2,091,730.58	321,776.39	930.52
T-77	2,091,578.19	322,010.24	930.29
T-78	2,091,493.75	321,897.01	930.39
T-79	2,091,581.67	322,212.51	930.07
T-81	2,091,475.97	321,993.82	930.29
T-82	2,091,568.93	322,413.79	931.77
T-83	2,091,500.85	322,296.59	929.80
T-84	2,091,869.00	322,295.48	929.92
T-85	2,092,242.87	322,346.29	929.81
T-86	2,092,646.71	322,374.16	929.63
T-87	2,092,979.20	322,421.78	929.40
T-88	2,093,383.60	322,464.00	929.10
T-89	2,093,072.37	323,042.19	928.73
T-90	2,092,830.42	323,042.30	928.85
T-91	2,092,965.54	323,228.28	927.63
T-92R	2,093,120.51	323,143.29	925.85

CIMARRON ENVIRONMENTAL RESPONSE TRUST

TABLE 3-2

WESTERN UPLAND and ALLUVIAL AREA WATER LEVEL MEASUREMENTS

August 2016

Well	Easting	Northing	Water Elevation (08/08/2016) (feet amsl)
T-93	2,093,413.80	323,104.00	928.66
T-94	2,093,266.80	323,409.22	928.31
T-95	2,092,457.65	323,019.00	928.98
T-96	2091984.825	322557.2606	929.56
T-97	2092124.72	323343.533	928.78
T-98	2092176.49	323514.234	928.61
T-99	2092589.7	323746.24	928.25
T-100	2093060.29	323821.155	927.05
T-101	2093507.592	323599.274	927.99
T-102	2093581.063	323084.588	928.69
T-103	2094027.626	322867.406	928.86
Sandstone B Wells			
1314	2095467.354	322412.2216	944.45
1315R	2095504.061	322756.5123	934.62
1316R	2095438.451	322776.9811	933.38
1319B-1	2092053.325	320128.3468	947.62
1319B-2	2092077.815	319999.5928	948.71
1319B-3	2092004.745	320105.0462	947.82
1319B-4	2092053.333	320206.8577	947.11
1319B-5	2091860.113	320322.067	945.37
1338	2093545.835	321818.8511	944.27
1341	2092542.171	321354.7241	937.68
1345	2092346.655	321461.4806	934.66
1346	2093200.273	321854.3517	938.38
1382	2093127.503	321735.55	938.76
1384	2093398.84	321601.975	945.03
1386	2093375.507	321918.247	939.89
1388	2093709.911	321837.355	946.55
1390	2093720.086	322017.061	942.47
1391	2093820.096	321752.383	951.88
1392	2093115.047	321860.652	936.82
1394	2093370.33	321825.993	941.12
Alluvial Wells			
1342	2090179.195	322508.023	929.78
1343	2093597.568	323387.5216	928.27
1344	2095776.385	323500.3817	926.97
1361	2095439.831	323265.3712	927.53
1362	2095450.843	323186.9535	927.61
1363	2095357.605	323327.579	927.56
1364	2095504.527	323277.3096	927.51

CIMARRON ENVIRONMENTAL RESPONSE TRUST

TABLE 3-2

WESTERN UPLAND and ALLUVIAL AREA WATER LEVEL MEASUREMENTS

August 2016

Well	Easting	Northing	Water Elevation (08/08/2016) (feet amsl)
1365	2095455.832	323330.0953	927.49
1366	2095526.229	323327.8529	927.45
1367	2095208.626	323329.652	927.64
1368	2095262.386	323477.678	927.42
1372	2095590.485	323726.149	926.71
1373	2095689.267	323653.141	926.78

CIMARRON ENVIRONMENTAL RESPONSE TRUST
TABLE 3-3
BURIAL AREA #1 WATER LEVEL MEASUREMENTS
AUGUST 08, 2016

Well	Easting	Northing	Water Elevation (08/08/2016)
02W02	2095455.00	322885.00	930.53
02W03	2095375.00	322885.00	928.42
02W04	2095335.00	322905.00	927.88
02W05	2095315.00	322955.00	927.88
02W06	2095305.00	323005.00	927.87
02W07	2095345.00	323005.00	927.87
02W08	2095395.00	323015.00	927.85
02W09	2095595.00	322765.00	935.13
02W10	2095575.00	322825.00	933.81
02W11	2095445.00	323055.00	927.74
02W12	2095455.00	323035.00	927.73
02W13	2095475.00	322985.00	927.93
02W14	2095395.00	323055.00	927.76
02W15	2095285.00	322895.00	927.91
02W16	2095265.00	322945.00	927.90
02W17	2095255.00	323005.00	927.86
02W18	2095345.00	323095.00	927.74
02W19	2095325.00	323055.00	927.82
02W21	2095195.00	323055.00	928.41
02W22	2095215.00	322935.00	927.89
02W23	2095205.00	323005.00	927.89
02W24	2095265.00	323055.00	927.83
02W26	2095625.00	322715.00	935.88
02W27	2095395.00	322825.00	932.18
02W28	2095535.00	322835.00	933.91
02W29	2095555.00	322755.00	934.99
02W30	2095475.00	322765.00	934.91
02W31	2095505.00	322855.00	933.53
02W32	2095435.00	322965.00	927.87
02W33	2095255.00	322915.00	927.96
02W34	2095185.00	323105.00	927.84
02W35	2095255.00	323155.00	927.75
02W36	2095255.00	323105.00	927.78
02W37	2095325.00	323155.00	927.69
02W38	2095395.00	323095.00	927.70
02W39	2095575.00	322735.00	935.29
02W40	2095525.00	322665.00	939.37
02W41	2095575.00	322685.00	937.77
02W42	2095475.00	322725.00	937.06
02W43	2095325.00	323205.00	927.66
02W44	2095375.00	323155.00	927.65
02W45	2095285.00	323195.00	927.69
02W46	2095465.00	322905.00	929.07
02W47	2095525.00	322625.00	940.39
02W50	2095525.00	322565.00	940.91
02W52	2095555.00	322565.00	940.25
02W53	2095385.00	322825.00	932.28
02W62	2095205.00	323145.00	927.77
1314.00	2095465.00	322415.00	944.45
1344.00	2095775.00	323505.00	926.97
1361.00	2095435.00	323265.00	927.53
1362.00	2095455.00	323185.00	927.61
1315R	2095505.00	322755.00	934.62
1316R	2095435.00	322775.00	933.38
TMW-01	2095505.00	322695.00	942.72
TMW-02	2095505.00	322595.00	940.77
TMW-05	2095555.00	322885.00	932.30
TMW-06	2095635.00	322795.00	934.64
TMW-08	2095535.00	322725.00	935.37
TMW-09	2095485.00	322825.00	933.65
TMW-13	2095375.00	322955.00	927.90
TMW-17	2095495.00	322765.00	932.22
TMW-18	2095335.00	322865.00	928.12
TMW-19	2095335.00	322865.00	928.99
TMW-21	2095435.00	322705.00	937.22
TMW-24	2095435.00	323405.00	927.44
TMW-25	2095625.00	322655.00	937.22

CIMARRON ENVIRONMENTAL RESPONSE TRUST
TABLE 3-4
TARGET RESIDUALS
WESTERN ALLUVIAL AREA

Monitoring Well Target Name	X Coordinate	Y Coordinate	Layer	Observed Groundwater Elevation (ft msl)	Computed Groundwater Elevation (ft msl)	Residual Error (feet)
T-51	2091962.326	322775.3151	1	929.40	929.58	-0.18
T-52	2092407.077	321938.0561	1	929.33	930.03	-0.71
T-53	2092658.888	322773.4615	1	929.20	929.46	-0.26
T-54	2092870.502	321927.5107	1	929.90	929.95	-0.06
T-55	2093119.602	322069.5861	1	928.46	929.79	-1.33
T-56	2093377.955	322211.2088	1	927.75	929.66	-1.91
T-57	2092460.776	321788.0348	1	930.23	930.11	0.12
T-58	2092165.082	321742.3992	1	930.42	930.19	0.23
T-59	2092954.879	322773.9563	1	929.18	929.40	-0.22
T-60	2093281.825	322773.9903	1	929.20	929.37	-0.17
T-61	2093609.542	322774.3586	1	929.03	929.35	-0.32
T-62	2091852.827	321470.6111	1	930.69	930.35	0.34
T-63	2091976.646	321623.1701	1	930.50	930.27	0.24
T-64	2091690.893	321341.8723	1	930.85	930.60	0.25
T-65	2091814.49	321568.8962	1	930.65	930.30	0.35
T-66	2091841.967	321712.1639	1	930.53	930.24	0.29
T-67	2091742.889	321657.3199	1	930.61	930.27	0.33
T-68	2091713.086	322052.2542	1	930.25	930.08	0.17
T-69	2091871.687	321961.9211	1	930.35	930.11	0.24
T-70R	2091625.712	321577.8822	1	930.72	930.32	0.40
T-72	2091716.886	321899.31	1	930.40	930.16	0.24
T-73	2091492.007	321770.5945	1	930.53	930.24	0.29
T-74	2091531.319	321541.2486	1	930.80	930.34	0.46
T-75	2091598.425	321910.8499	1	930.08	930.16	-0.08
T-76	2091730.573	321776.3881	1	930.52	930.22	0.29
T-77	2091578.18	322010.2399	1	930.29	930.11	0.18
T-78	2091493.754	321897.016	1	930.39	930.18	0.21
T-79	2091581.67	322212.5118	1	930.07	929.99	0.08
T-81	2091475.972	321993.8223	1	930.29	930.12	0.16
T-82	2091568.929	322413.793	1	931.77	929.87	1.90
T-83	2091500.849	322296.5901	1	929.80	929.95	-0.15
T-84	2091868.998	322295.488	1	929.92	929.91	0.01
T-85	2092242.869	322346.2933	1	929.81	929.81	0.00
T-86	2092646.71	322374.1661	1	929.63	929.71	-0.08
T-87	2092979.208	322421.7784	1	929.40	929.60	-0.20
T-88	2093383.607	322463.997	1	929.10	929.52	-0.42
T-89	2093072.365	323042.1849	1	928.73	929.22	-0.49
T-90	2092830.417	323042.2904	1	928.85	929.25	-0.40
T-91	2092965.543	323228.2829	1	927.63	929.11	-1.48
T-92R	2093120.509	323143.2884	1	925.85	929.15	-3.30
T-93	2093413.803	323104.0018	1	928.66	929.17	-0.51
T-94	2093266.797	323409.2196	1	928.31	928.95	-0.64
T-95	2092457.655	323018.9933	1	928.98	929.33	-0.35
T-96	2091984.822	322557.2589	1	929.56	929.72	-0.16
T-97	2092038.592	323318.4229	1	928.78	929.18	-0.40
T-98	2092176.486	323514.2345	1	928.61	929.02	-0.41
T-99	2092589.694	323746.2418	1	928.25	928.79	-0.54
T-100	2093060.294	323821.1539	1	927.05	928.54	-1.49
T-101	2093507.595	323599.2793	1	927.99	928.83	-0.84
T-102	2093581.061	323084.5863	1	928.69	929.18	-0.49
T-103	2094027.623	322867.4018	1	928.86	929.34	-0.48
1319B-1	2092053.321	320128.3453	1	947.62	946.62	1.00
1319B-2	2092077.815	319999.588	1	948.71	947.85	0.86
1319B-3	2092004.75	320105.048	1	947.82	946.51	1.31

CIMARRON ENVIRONMENTAL RESPONSE TRUST
TABLE 3-4
TARGET RESIDUALS
WESTERN ALLUVIAL AREA

Monitoring Well Target Name	X Coordinate	Y Coordinate	Layer	Observed Groundwater Elevation (ft msl)	Computed Groundwater Elevation (ft msl)	Residual Error (feet)
1319B-4	2092053.33	320206.8531	1	947.11	946.01	1.10
1319B-5	2091860.112	320322.0669	1	945.37	943.99	1.38
1338	2093545.832	321818.8544	1	944.27	943.19	1.08
1341	2092542.176	321354.7234	1	937.68	937.35	0.33
1345	2092346.652	321461.4784	1	934.66	934.00	0.66
1346	2093200.273	321854.3468	1	938.38	936.44	1.94
1382	2093127.504	321735.5542	1	938.76	937.53	1.23
1384	2093398.846	321601.9725	1	945.03	944.18	0.85
1386	2093375.507	321918.2437	1	939.89	937.96	1.93
1388	2093709.908	321837.3578	1	946.55	946.71	-0.16
1390	2093720.092	322017.0578	1	942.47	942.12	0.35
1391	2093820.098	321752.3799	1	951.88	952.16	-0.28
1392	2093115.048	321860.6481	1	936.82	934.86	1.96
1394	2093370.328	321825.9886	1	941.12	939.68	1.44
1342	2090179.201	322508.0204	1	929.78	929.66	0.12
1343	2093597.566	323387.5208	1	928.27	928.99	-0.72

SUMMARY STATISTICS	
Residual Mean	0.072692
Absolute Residual Mean	0.622272
Residual Std. Deviation	0.879194
Sum of Squares	54.47864
RMS Error	0.882194
Min. Residual	-3.301795
Max. Residual	1.960407
Number of Observations	70
Range in Observations	26.03
Scaled Residual Std. Deviati	0.033776
Scaled Absolute Residual M	0.023906
Scaled RMS Error	0.033891
Scaled Residual Mean	0.002793

CIMARRON ENVRONMENTAL RESPONSE TRUST
TABLE 3-5
TARGET RESIDUALS
BURIAL AREA #1

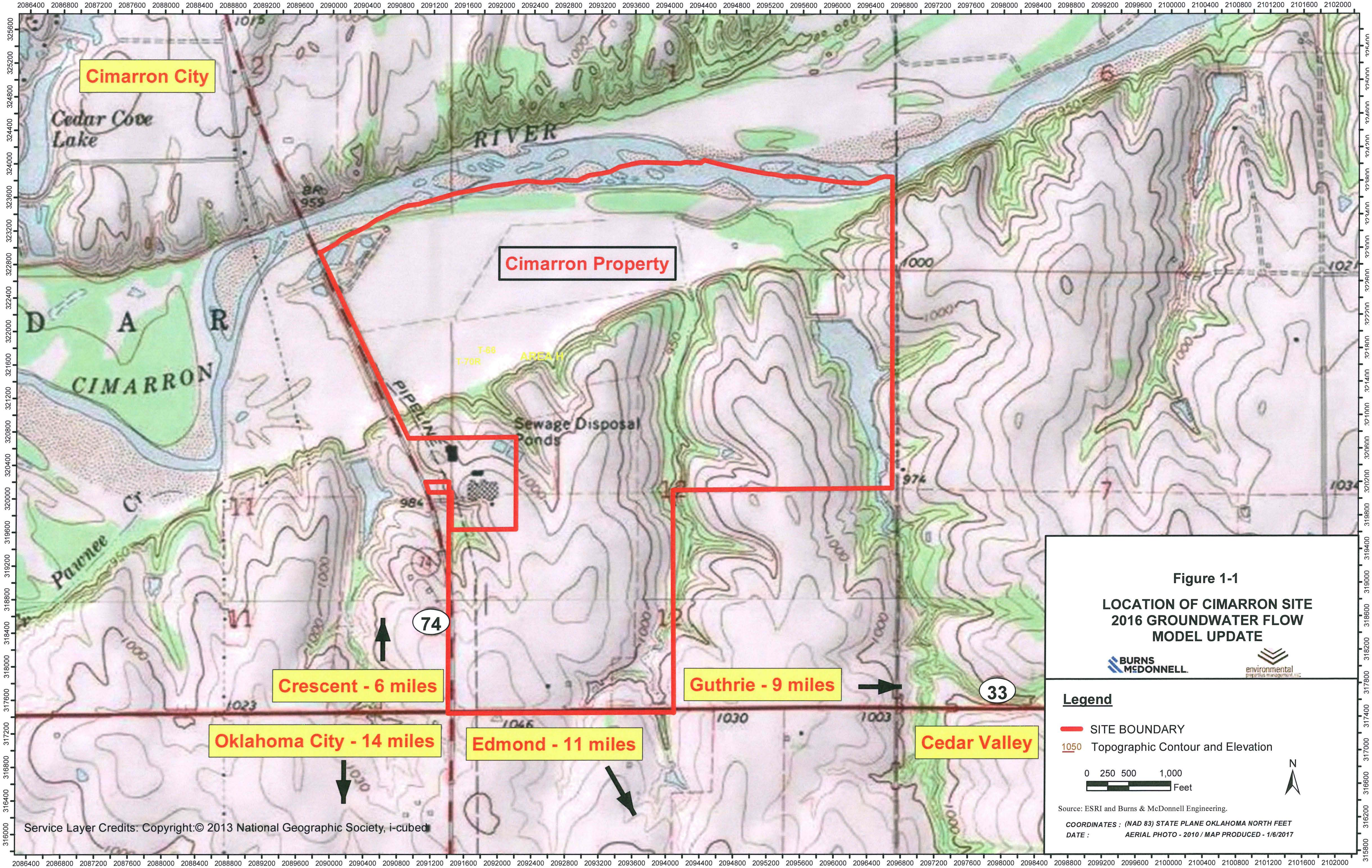
Monitoring Well Target Name	X Coordinate	Y Coordinate	Layer	Observed Groundwater Elevation (ft msl)	Computed Groundwater Elevation (ft msl)	Residual Error (feet)
02W02	2095455	322885	6	930.53	928.58	1.95
02W03	2095375	322885	5	928.42	928.51	-0.09
02W04	2095335	322905	6	927.88	928.42	-0.54
02W05	2095315	322955	5	927.88	928.23	-0.35
02W06	2095305	323005	7	927.87	928.06	-0.19
02W07	2095345	323005	7	927.87	928.05	-0.18
02W08	2095395	323015	7	927.85	928.00	-0.15
02W09	2095595	322765	6	935.13	935.40	-0.27
02W10	2095575	322825	6	933.81	933.00	0.81
02W11	2095445	323055	8	927.74	927.83	-0.09
02W12	2095455	323035	8	927.73	927.88	-0.15
02W13	2095475	322985	8	927.93	928.05	-0.12
02W14	2095395	323055	8	927.76	927.87	-0.11
02W15	2095285	322895	5	927.91	928.45	-0.54
02W16	2095265	322945	6	927.90	928.27	-0.37
02W17	2095255	323005	7	927.86	928.07	-0.21
02W18	2095345	323095	8	927.74	927.78	-0.04
02W19	2095325	323055	7	927.82	927.90	-0.08
02W21	2095195	323055	8	928.41	927.93	0.48
02W22	2095215	322935	6	927.89	928.31	-0.42
02W23	2095205	323005	8	927.89	928.07	-0.18
02W24	2095265	323055	8	927.83	927.91	-0.08
02W26	2095625	322715	5	935.88	936.93	-1.05
02W27	2095395	322825	6	932.18	930.41	1.77
02W28	2095535	322835	6	933.91	931.64	2.27
02W29	2095555	322755	5	934.99	935.63	-0.63
02W30	2095475	322765	7	934.91	934.82	0.09
02W31	2095505	322855	6	933.53	929.71	3.81
02W32	2095435	322965	7	927.87	928.18	-0.31
02W33	2095255	322915	6	927.96	928.38	-0.42
02W34	2095185	323105	8	927.84	927.80	0.05
02W35	2095255	323155	8	927.75	927.66	0.08
02W36	2095255	323105	8	927.78	927.78	-0.01
02W37	2095325	323155	7	927.69	927.64	0.05
02W38	2095395	323095	8	927.70	927.76	-0.06
02W39	2095575	322735	5	935.29	936.36	-1.07
02W40	2095525	322665	7	939.37	939.35	0.03
02W41	2095575	322685	6	937.77	937.97	-0.20
02W42	2095475	322725	7	937.06	937.05	0.02
02W43	2095325	323205	8	927.66	927.53	0.12
02W44	2095375	323155	8	927.65	927.62	0.04
02W45	2095285	323195	8	927.69	927.57	0.12
02W46	2095465	322905	6	929.07	928.49	0.58
02W47	2095525	322625	7	940.39	940.80	-0.41
02W50	2095525	322565	7	940.91	942.66	-1.75
02W52	2095555	322565	7	940.25	941.99	-1.75
02W53	2095385	322825	6	932.28	930.44	1.85
02W62	2095205	323145	8	927.77	927.70	0.07
1314	2095465	322415	8	944.45	947.88	-3.43

CIMARRON ENVRONMENTAL RESPONSE TRUST
TABLE 3-5
TARGET RESIDUALS
BURIAL AREA #1

Monitoring Well Target Name	X Coordinate	Y Coordinate	Layer	Observed Groundwater Elevation (ft msl)	Computed Groundwater Elevation (ft msl)	Residual Error (feet)
1344	2095775	323505	7	926.97	927.07	-0.10
1361	2095435	323265	8	927.53	927.38	0.15
1362	2095455	323185	10	927.61	927.14	0.47
1315R	2095505	322755	7	934.62	935.47	-0.85
1316R	2095435	322775	7	933.38	933.98	-0.60
TMW-01	2095505	322695	7	942.72	938.33	4.39
TMW-02	2095505	322595	7	940.77	942.18	-1.42
TMW-05	2095555	322885	7	932.30	930.35	1.95
TMW-06	2095635	322795	4	934.64	935.02	-0.37
TMW-08	2095535	322725	6	935.37	936.77	-1.41
TMW-09	2095485	322825	6	933.65	930.89	2.76
TMW-13	2095375	322955	6	927.90	928.24	-0.33
TMW-17	2095495	322765	12	932.22	934.50	-2.28
TMW-18	2095335	322865	6	928.12	928.56	-0.45
TMW-19	2095335	322865	4	928.99	929.19	-0.20
TMW-21	2095435	322705	6	937.22	938.13	-0.91
TMW-24	2095435	323405	7	927.44	927.22	0.22
TMW-25	2095625	322655	5	937.22	938.40	-1.18

SUMMARY STATISTICS	
Residual Mean	-0.02604
Absolute Residual Mean	0.735811
Residual Std. Deviation	1.199928
Sum of Squares	97.954333
RMS Error	1.20021
Min. Residual	-3.434028
Max. Residual	4.388739
Number of Observations	68
Range in Observations	17.4756
Scaled Residual Std. Deviatioı	0.068663
Scaled Absolute Residual Me;	0.042105
Scaled RMS Error	0.068679
Scaled Residual Mean	-0.00149

FIGURES



Path: Z:\Clients\ENV\CERT_ClientInfo\Sites\Database\Geospatial\Maps_Photos_Dwgs\ArcGIS\BMCD_Files\Arcdocs\2015\Decommissioning Plan\Fig1-1_Site_Location_11X17.mxd

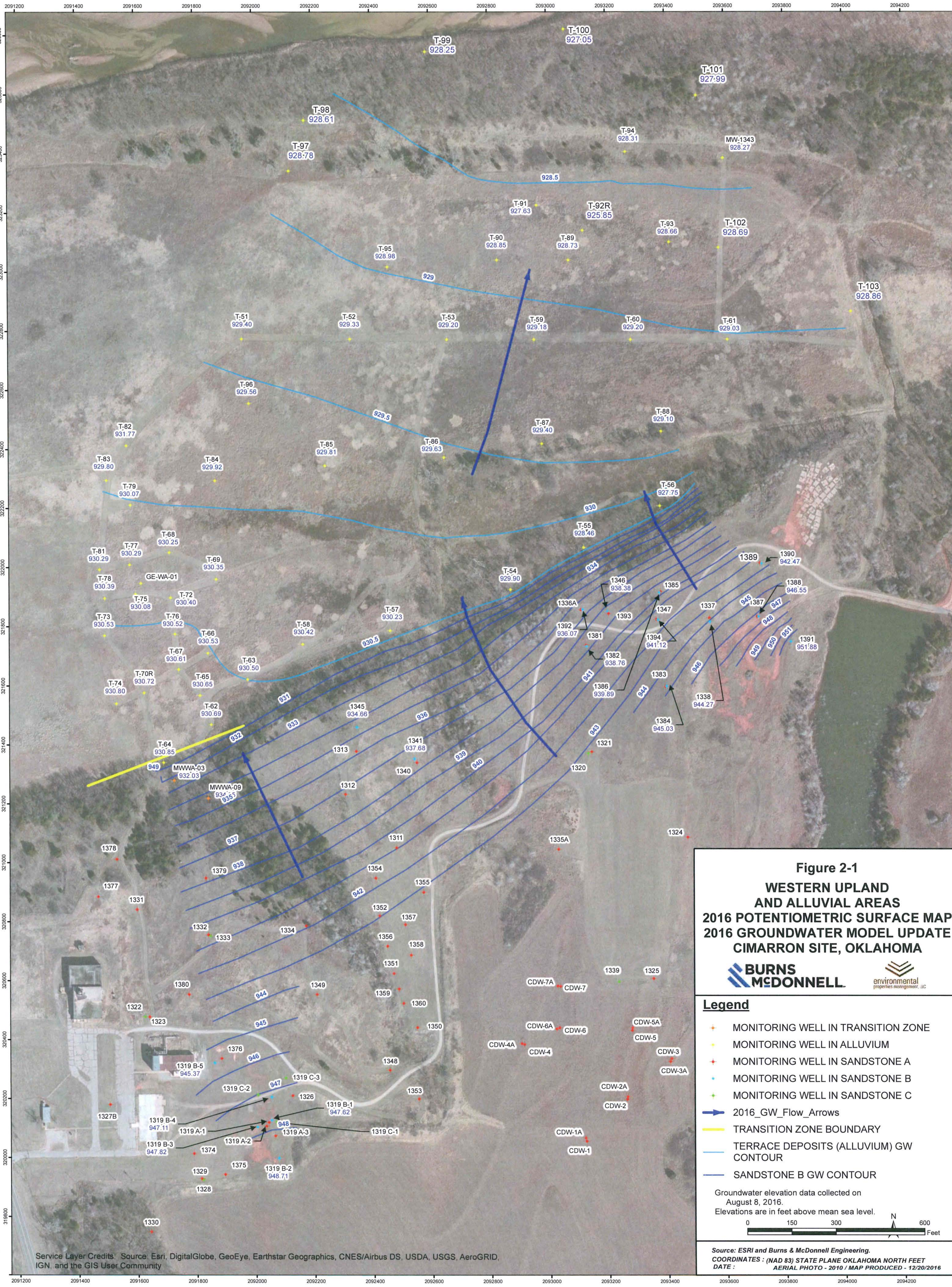


Figure 2-1
WESTERN UPLAND
AND ALLUVIAL AREAS
2016 POTENTIOMETRIC SURFACE MAP
2016 GROUNDWATER MODEL UPDATE
CIMARRON SITE, OKLAHOMA
BURNS McDONNELL
environmental properties management, LLC
Legend
MONITORING WELL IN TRANSITION ZONE
MONITORING WELL IN ALLUVIUM
MONITORING WELL IN SANDSTONE A
MONITORING WELL IN SANDSTONE B
MONITORING WELL IN SANDSTONE C
2016_GW_Flow_Arrows
TRANSITION ZONE BOUNDARY
TERRACE DEPOSITS (ALLUVIUM) GW CONTOUR
SANDSTONE B GW CONTOUR
Groundwater elevation data collected on August 8, 2016.
Elevations are in feet above mean sea level.
0 150 300 600 Feet
N
Source: ESRI and Burns & McDonnell Engineering.
COORDINATES : (NAD 83) STATE PLANE OKLAHOMA NORTH FEET
DATE : AERIAL PHOTO - 2010 / MAP PRODUCED - 12/20/2016
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

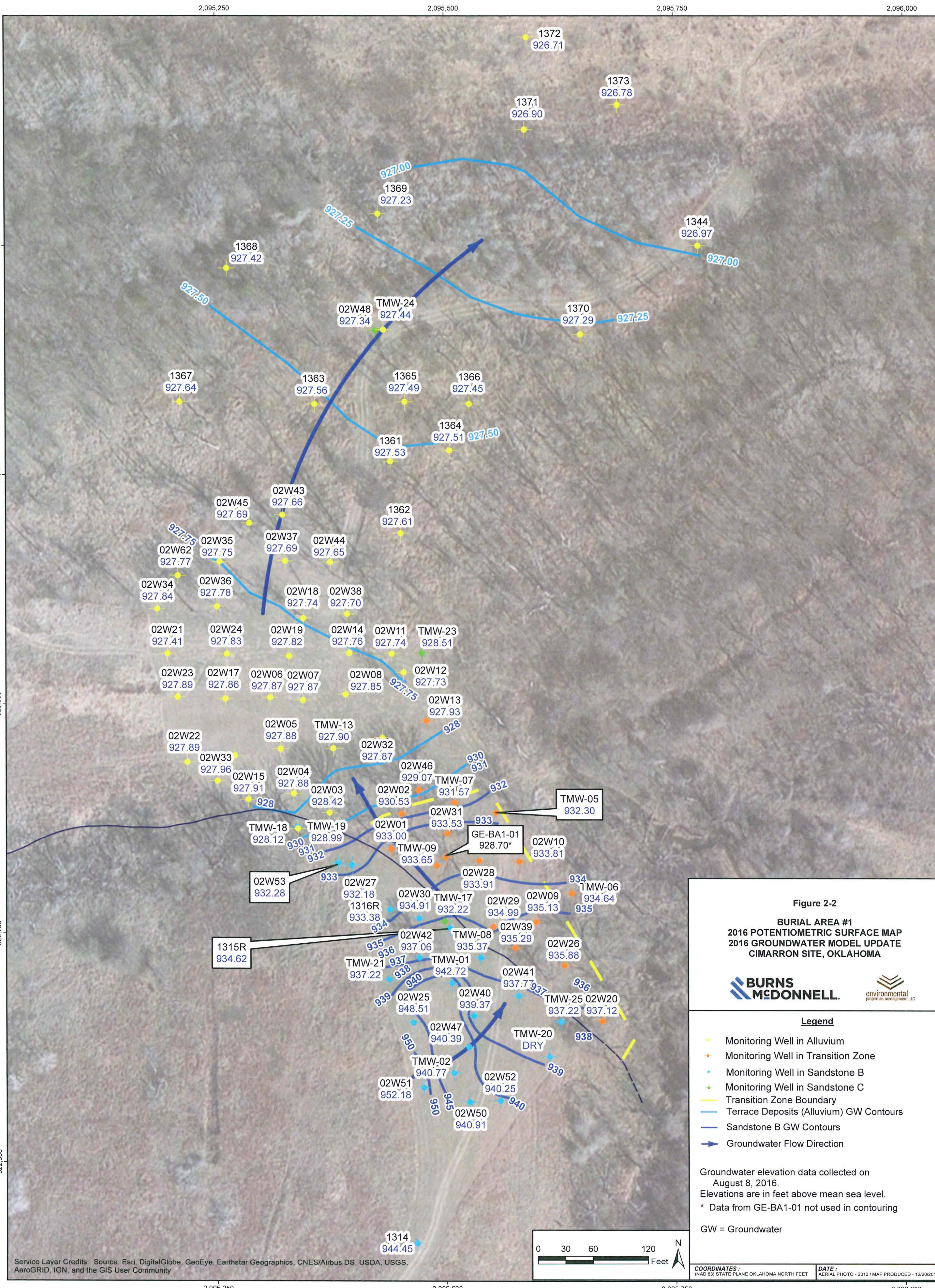


Figure 2-2
BURIAL AREA #1
2016 POTENTIOMETRIC SURFACE MAP
2016 GROUNDWATER MODEL UPDATE
CIMARRON SITE, OKLAHOMA
BURNS McDONNELL
environmental properties management, LLC
Legend
Monitoring Well in Alluvium
Monitoring Well in Transition Zone
Monitoring Well in Sandstone B
Monitoring Well in Sandstone C
Transition Zone Boundary
Terrace Deposits (Alluvium) GW Contours
Sandstone B GW Contours
Groundwater Flow Direction
Groundwater elevation data collected on August 8, 2016.
Elevations are in feet above mean sea level.
* Data from GE-BA1-01 not used in contouring
GW = Groundwater
0 30 60 120 Feet
N
COORDINATES : (NAD 83) STATE PLANE OKLAHOMA NORTH FEET
DATE : AERIAL PHOTO - 2010 / MAP PRODUCED - 12/20/2016
2,095,250
2,095,500
2,095,750
2,096,000
323,500
323,250
323,000
322,750
322,500
1372 926.71
1373 926.78
1371 926.90
1369 927.23
1344 926.97
1368 927.42
1370 927.29
02W48 927.34
TMW-24 927.44
1367 927.64
1363 927.56
1365 927.49
1366 927.45
1364 927.51
1361 927.53
1362 927.61
02W43 927.66
02W45 927.69
02W35 927.75
02W62 927.77
02W37 927.69
02W44 927.65
02W34 927.84
02W36 927.78
02W18 927.74
02W38 927.70
02W21 927.41
02W24 927.83
02W19 927.82
02W14 927.76
02W11 927.74
TMW-23 928.51
02W23 927.89
02W17 927.86
02W06 927.87
02W07 927.87
02W08 927.85
02W12 927.73
02W13 927.93
02W05 927.88
TMW-13 927.90
02W22 927.89
02W32 927.87
02W33 927.96
02W04 927.88
02W46 929.07
02W15 927.91
02W03 928.42
02W02 930.53
TMW-07 931.57
TMW-05 932.30
02W31 933.53
TMW-18 928.12
TMW-19 928.99
02W01 933.00
GE-BA1-01 928.70*
TMW-09 933.65
02W10 933.81
02W53 932.28
02W28 933.91
TMW-06 934.64
02W27 932.18
02W30 934.91
TMW-17 932.22
02W29 934.99
02W09 935.13
1316R 933.38
02W39 935.29
1315R 934.62
02W42 937.06
TMW-08 935.37
02W26 935.88
TMW-21 937.22
TMW-01 942.72
02W41 937.77
02W25 948.51
02W40 939.37
TMW-25 937.22
02W20 937.12
02W47 940.39
TMW-20 DRY
TMW-02 940.77
02W51 952.18
02W52 940.25
02W50 940.91
1314 944.45
927.00
927.25
927.50
927.75
928
930
931
932
933
934
935
936
937
938
939
940
945
950
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

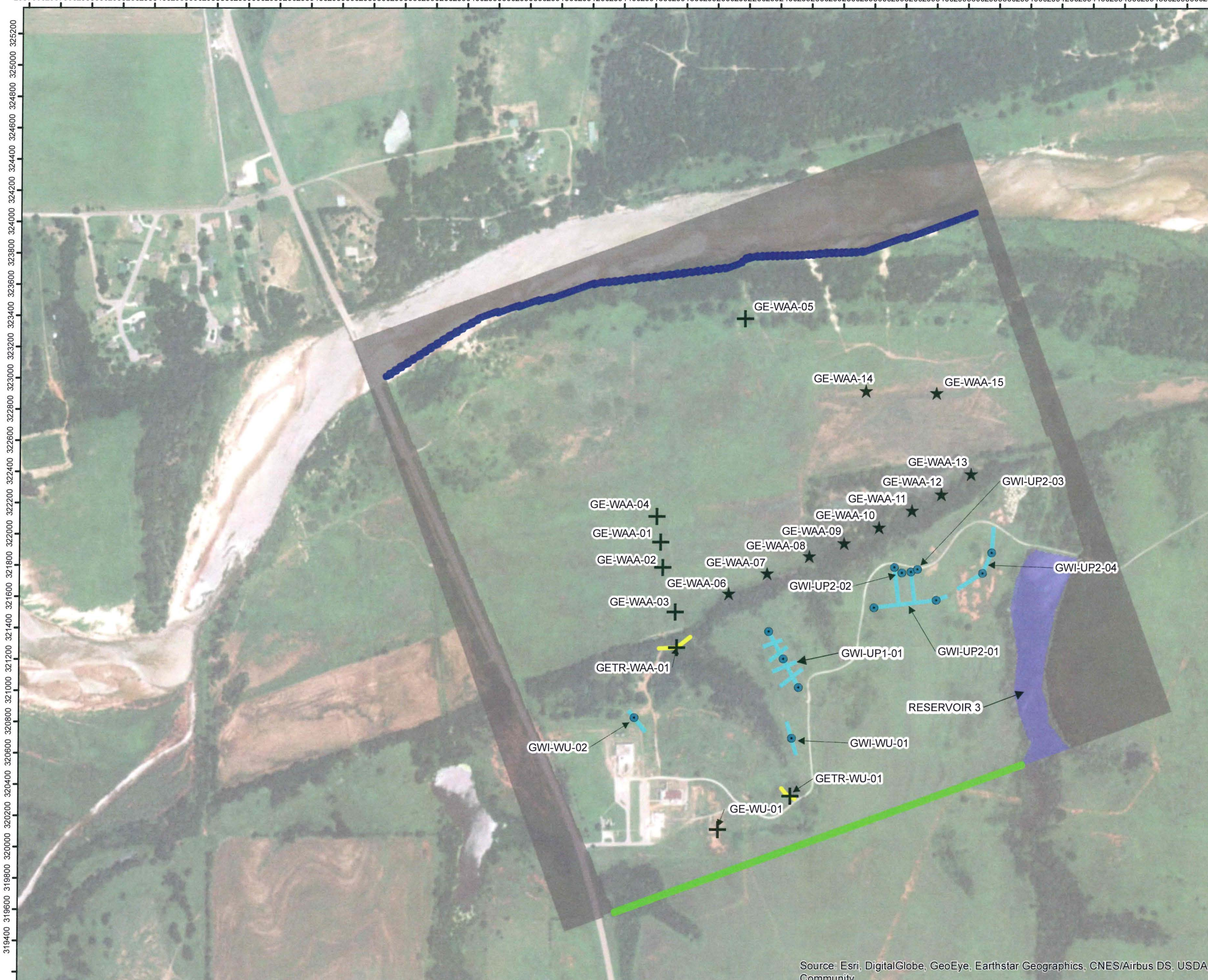


FIGURE 3-1
MODEL DOMAIN AND MODEL BOUNDARY CONDITIONS EXPANDED WESTERN ALLUVIAL AREA MODEL. CIMARRON SITE, OKLAHOMA

BURNS McDONNELL
environmental properties management, LLC

Legend

- TREATMENT TRAIN 1 PUMPING WELL OR TRENCH
- TREATMENT TRAIN 2 PUMPING WELL OR TRENCH
- PROPOSED INJECTION WELL
- PROPOSED GROUNDWATER EXTRACTION TRENCH
- PROPOSED INJECTION TRENCH
- MODFLOW GENERAL HEAD BOUNDARY CELLS
- MODFLOW RIVER CELLS
- MODFLOW NO FLOW CELLS
- MODFLOW CONSTANT HEAD BOUNDARY CELLS

0 250 500 1,000
Feet

N

Source: ESRI and Burns & McDonnell Engineering.

COORDINATES : (NAD 83) STATE PLANE OKLAHOMA NORTH FEET	DATE : AERIAL PHOTO - 2010 / MAP PRODUCED - 1/16/2017

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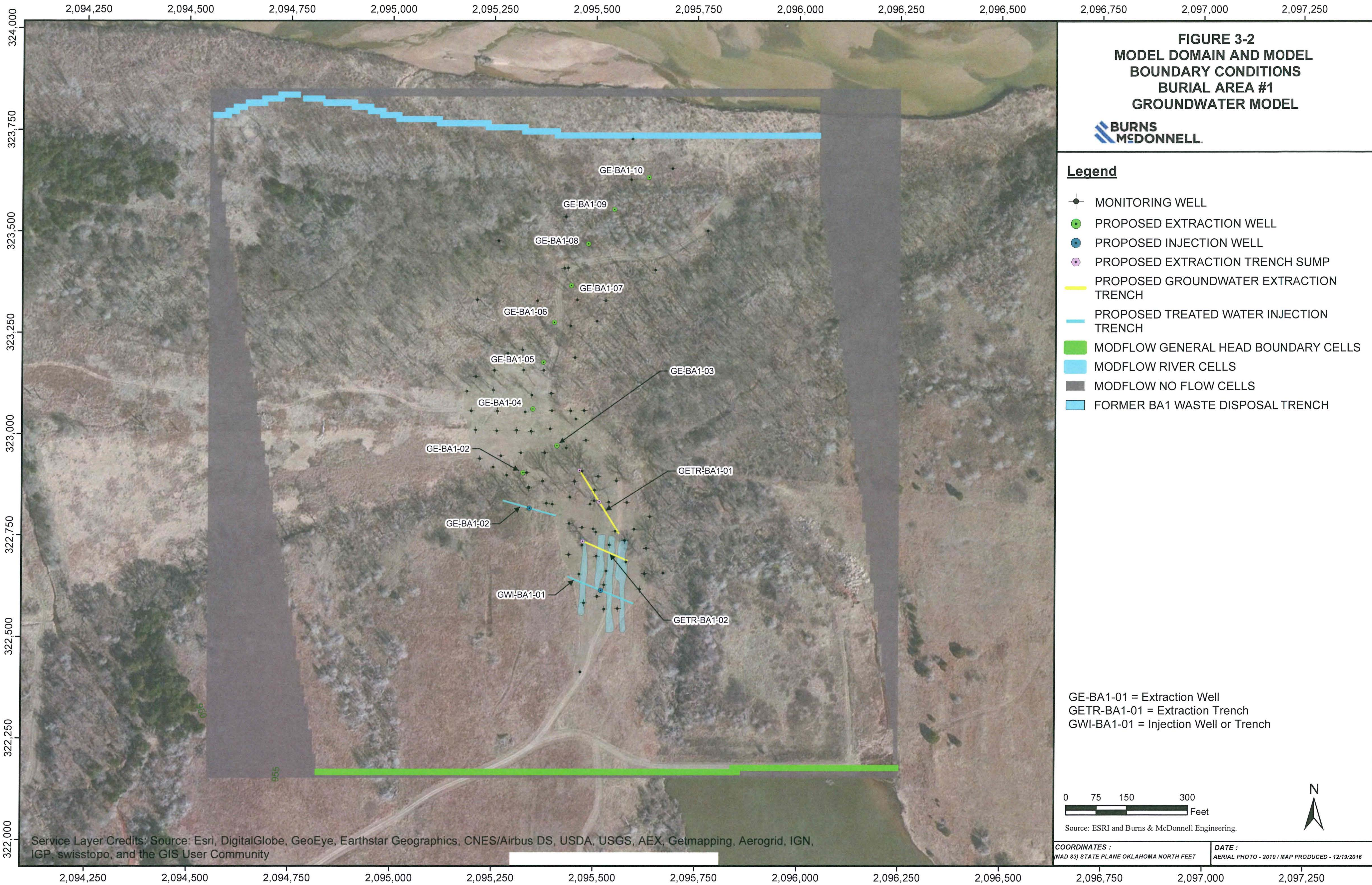


FIGURE 3-2
MODEL DOMAIN AND MODEL BOUNDARY CONDITIONS BURIAL AREA #1 GROUNDWATER MODEL

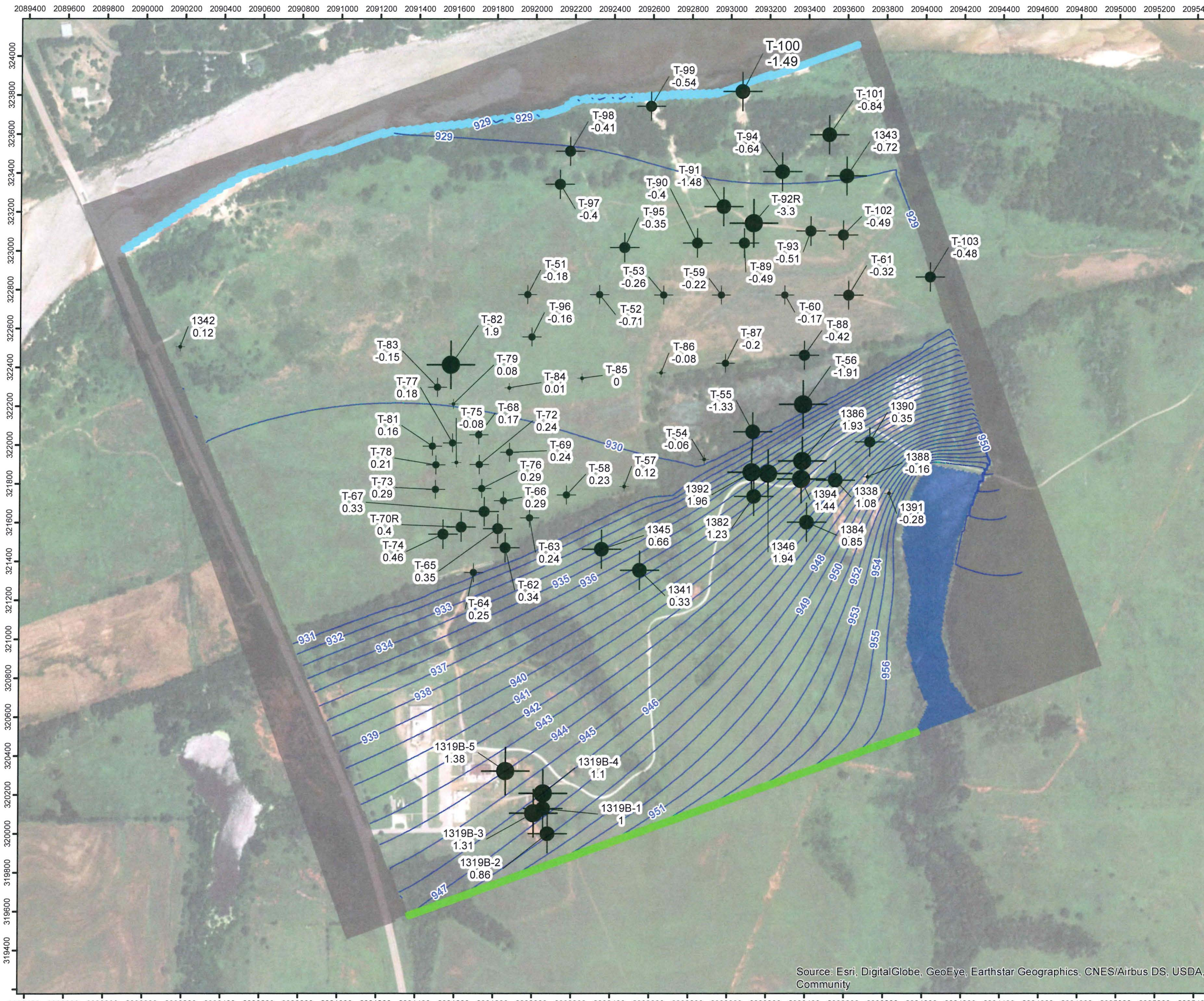


FIGURE 3-3
MODEL PREDICTED POTENTIOMETRIC SURFACE WITH CALIBRATION TARGET RESIDUALS
EXPANDED WESTERN ALLUVIAL AREA MODEL
CIMARRON SITE, OKLAHOMA

BURNS McDONNELL.

environmental properties management, LLC

Legend

1342 / 0.12 — MONITORING WELL WITH RESIDUAL ERROR (IN FEET)

930 — POTENTIOMETRIC SURFACE CONTOUR (IN FEET ABOVE SEA LEVEL)

MODFLOW GENERAL HEAD BOUDARY CELLS

MODFLOW RIVER CELLS

MODFLOW NO FLOW CELLS

MODFLOW CONSTANT HEAD BOUNDARY CELLS

NOTES

This figure illustrates:

1) The model predicted potentiometric surface for the Sandstone B and Alluvial Units.

2) The model predicted residual for each monitoring well. The residual is the measured water level (collected August 2016) minus the model computed water level.

3) Monitoring well size is proportional with the residual error in the model calibration.

0 250 500 1,000 Feet

N

Source: ESRI and Burns & McDonnell Engineering.

COORDINATES :	DATE :
(NAD 83) STATE PLANE OKLAHOMA NORTH FEET	AERIAL PHOTO - 2010 / MAP PRODUCED - 12/20/2016

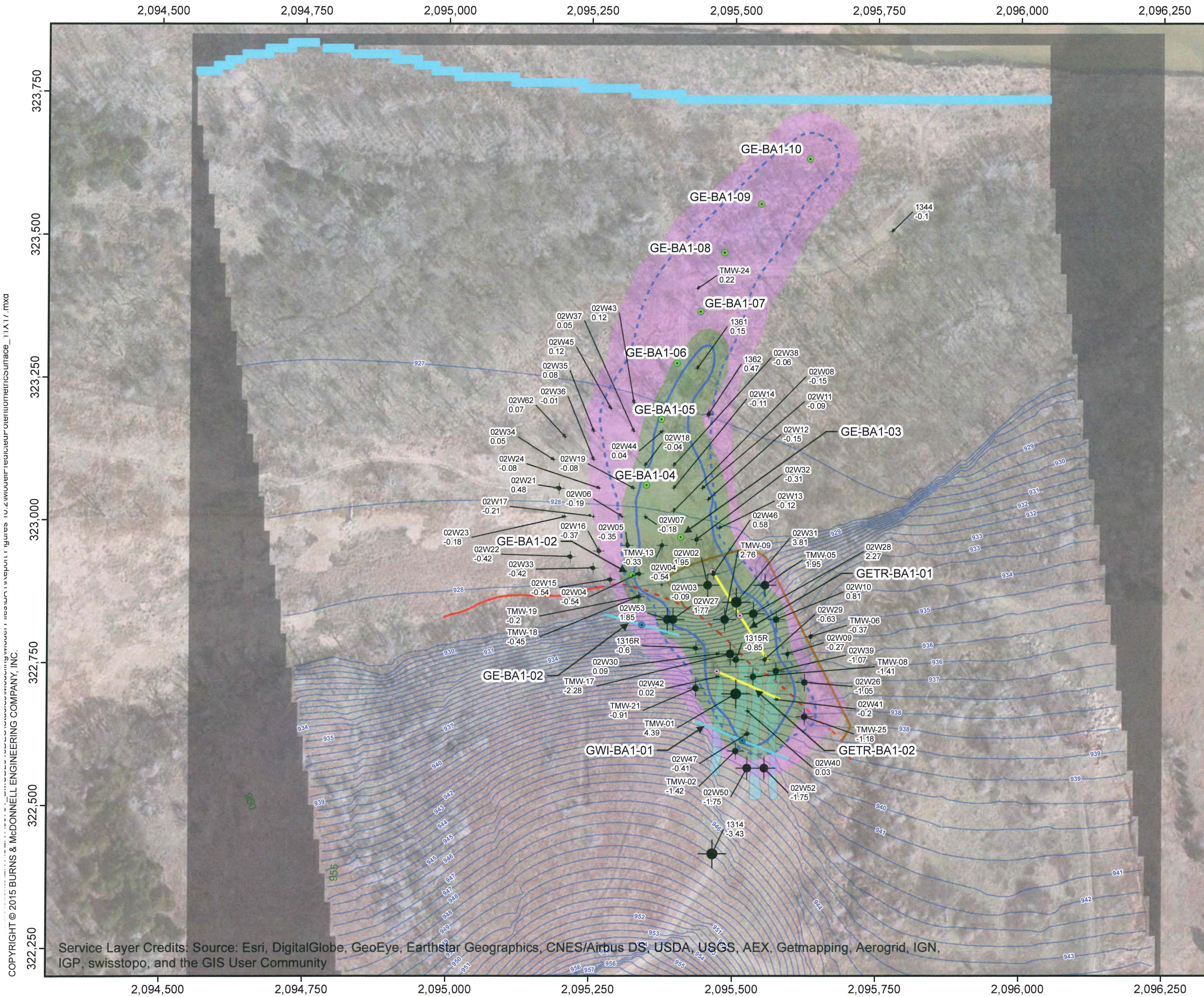


FIGURE 3-4
MODEL PREDICTED POTENTIOMETRIC SURFACE WITH CALIBRAITON TARGET RESIDUALS

BURNS McDONNELL

Legend

Name

- MONITORING WELL WITH RESIDUAL ERROR (IN FEET)
- PROPOSED EXTRACTION WELL
- PROPOSED INJECTION WELL
- PROPOSED EXTRACTION TRENCH SUMP
- PROPOSED GROUNDWATER EXTRACTION TRENCH
- PROPOSED TREATED WATER INJECTION TRENCH
- MODFLOW GENERAL HEAD BOUNDARY CELLS
- MODFLOW RIVER CELLS
- MODFLOW NO FLOW CELLS
- URANIUM > 180 PICOCURIES PER LITER (pCi/L)
- URANIUM > 30 MICROGRAMS PER LITER (ug/L)
- BA1 U > DCGL REMEDIATION AREA
- BA1 U < DCGL REMEDIATION AREA
- FORMER BA1 WASTE DISPOSAL TRENCH
- BA1 ESCARPMENT
- BA1 ESCARPMENT (INFERRED)
- TRANSITION ZONE BOUNDARY
- POTENTIOMETRIC SURFACE CONTOUR (IN FEET ABOVE MEAN SEA LEVEL)

GE-BA1-01 = Extraction Well
GETR-BA1-01 = Extraction Trench
GWI-BA1-01 = Injection Well or Trench

0 75 150 300 Feet

N

Source: ESRI and Burns & McDonnell Engineering.

COORDINATES :	DATE :
(NAD 83) STATE PLANE OKLAHOMA NORTH FEET	AERIAL PHOTO - 2010 / MAP PRODUCED - 12/19/2016

FIGURE 4-1
FORWARD PARTICLE TRACKING SIMULATION EXPANDED WESTERN ALLUVIAL AREA MODEL CIMARRON SITE, OKLAHOMA

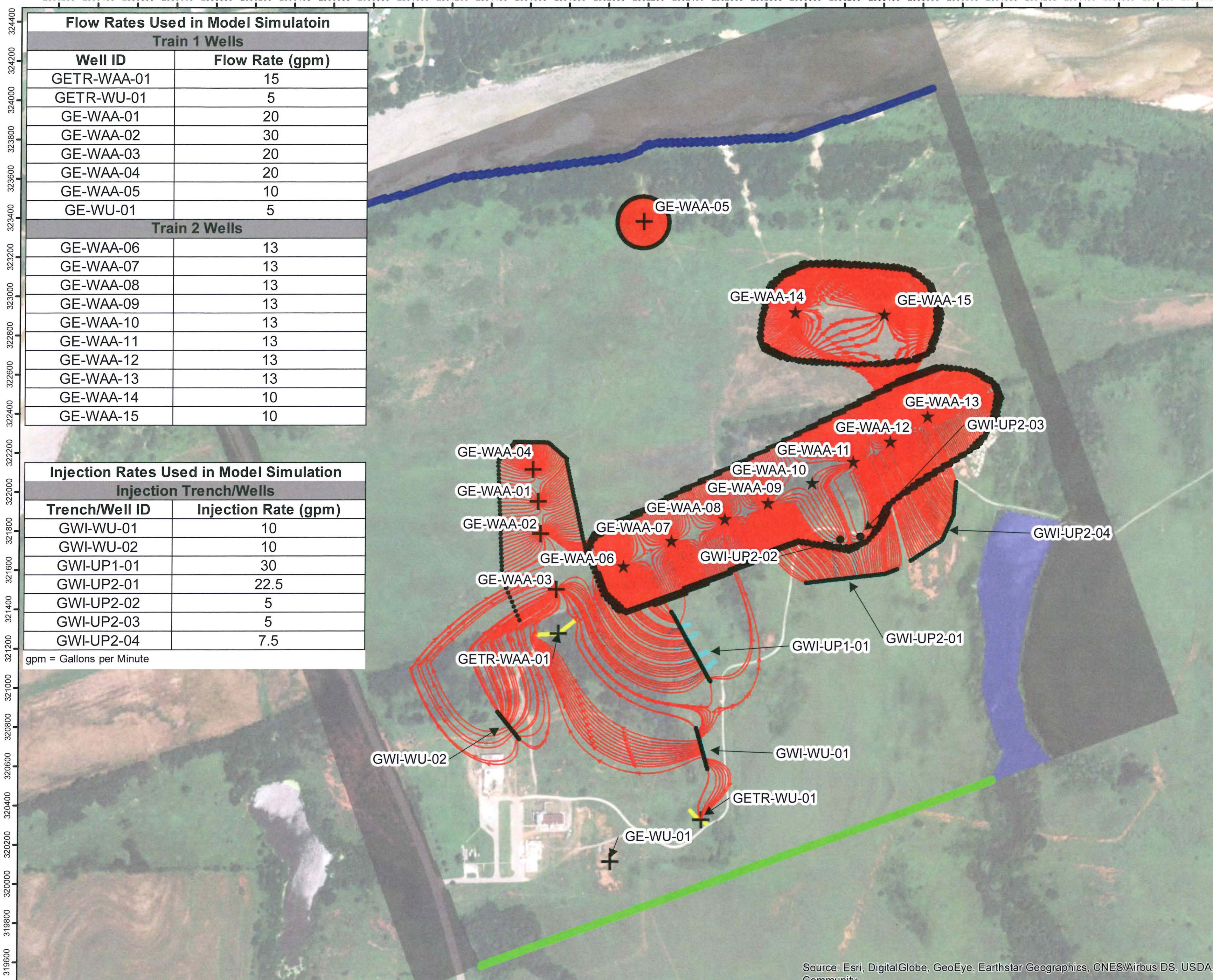
BURNS McDONNELL

environmental properties management, LLC

Flow Rates Used in Model Simulatoin	
Train 1 Wells	
Well ID	**Flow Rate (gpm)**
GETR-WAA-01	15
GETR-WU-01	5
GE-WAA-01	20
GE-WAA-02	30
GE-WAA-03	20
GE-WAA-04	20
GE-WAA-05	10
GE-WU-01	5
Train 2 Wells	
GE-WAA-06	13
GE-WAA-07	13
GE-WAA-08	13
GE-WAA-09	13
GE-WAA-10	13
GE-WAA-11	13
GE-WAA-12	13
GE-WAA-13	13
GE-WAA-14	10
GE-WAA-15	10

Injection Rates Used in Model Simulation	
Injection Trench/Wells	
Trench/Well ID	**Injection Rate (gpm)**
GWI-WU-01	10
GWI-WU-02	10
GWI-UP1-01	30
GWI-UP2-01	22.5
GWI-UP2-02	5
GWI-UP2-03	5
GWI-UP2-04	7.5

gpm = Gallons per Minute



Legend

- INJECTION PARTICLES
- TREATMENT TRAIN 1 PUMPING WELL OR TRENCH
- TREATMENT TRAIN 2 PUMPING WELL OR TRENCH
- MODPATH PARTICLE TRACK WITH ARROW SHOWING FLOW DIRECTION
- PROPOSED INJECTION WELL
- PROPOSED GROUNDWATER EXTRACTION TRENCH
- PROPOSED INJECTION TRENCH
- MODFLOW GENERAL HEAD BOUNDARY CELLS
- MODFLOW RIVER CELLS
- MODFLOW NO FLOW CELLS
- MODFLOW CONSTANT HEAD BOUNDARY CELLS

NOTES

This figure illustrates:
1) The model predicted particle tracking for the wells that send water to Treatment Trains 1 and 2. The simulaiton inlcudes injection through trenches and wells in the Sandstone A and B upland areas.
2) Pumping and injection rates used in the simulation are summarized on the figure.
3) The groundwater model used was calibrated to August 2016 groundwater measurements for the Sandstone B and Alluvial monitoring wells.

0 250 500 1,000 Feet

N

Source: ESRI and Burns & McDonnell Engineering.

COORDINATES : (NAD 83) STATE PLANE OKLAHOMA NORTH FEET

DATE : AERIAL PHOTO - 2010 / MAP PRODUCED - 1/16/2017

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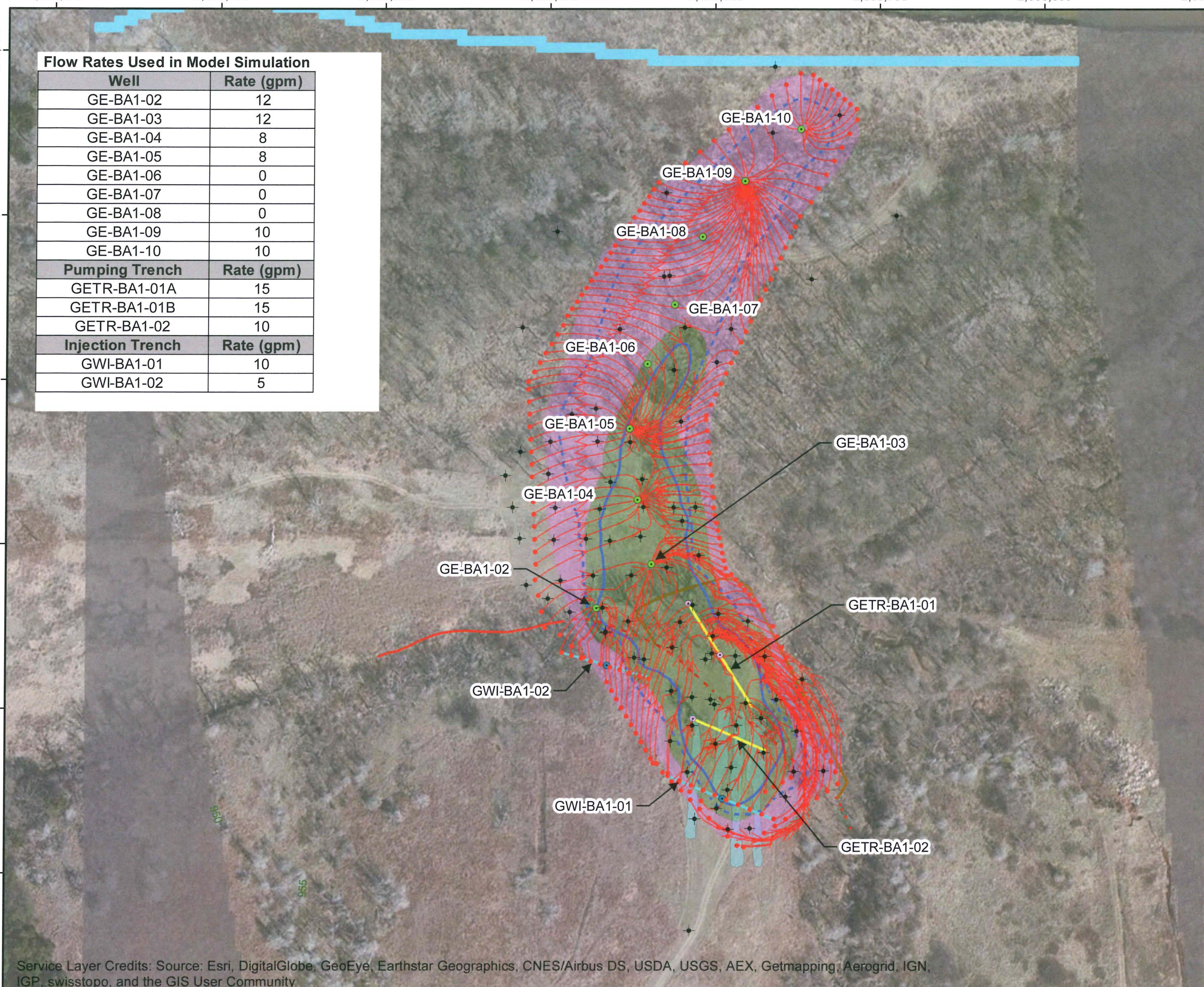
FIGURE 4-2
FORWARD PARTICLE TRACKING SIMULATION
BURIAL AREA #1
GROUNDWATER MODEL

BURNS McDONNELL

Flow Rates Used in Model Simulation

Well	Rate (gpm)
GE-BA1-02	12
GE-BA1-03	12
GE-BA1-04	8
GE-BA1-05	8
GE-BA1-06	0
GE-BA1-07	0
GE-BA1-08	0
GE-BA1-09	10
GE-BA1-10	10
Pumping Trench	**Rate (gpm)**
GETR-BA1-01A	15
GETR-BA1-01B	15
GETR-BA1-02	10
Injection Trench	**Rate (gpm)**
GWI-BA1-01	10
GWI-BA1-02	5



Legend

- FORWARD PARTICLES
- MONITORING WELL
- PROPOSED EXTRACTION WELL
- PROPOSED INJECTION WELL
- PROPOSED EXTRACTION TRENCH SUMP
- PARTICLE TRACK WITH ARROW SHOWING FLOW DIRECTION
- PROPOSED GROUNDWATER EXTRACTION TRENCH
- PROPOSED TREATED WATER INJECTION TRENCH
- MODFLOW GENERAL HEAD BOUNDARY CELLS
- MODFLOW RIVER CELLS
- MODFLOW NO FLOW CELLS
- URANIUM > 180 PICOCURIES PER LITER (pCi/L)
- URANIUM > 30 MICROGRAMS PER LITER (ug/L)
- BA1 U > DCGL REMEDIATION AREA
- BA1 U < DCGL REMEDIATION AREA
- FORMER BA1 WASTE DISPOSAL TRENCH
- BA1 ESCARPMENT
- BA1 ESCARPMENT (INFERRED)
- TRANSITION ZONE BOUNDARY

GE-BA1-01 = Extraction Well
GETR-BA1-01 = Extraction Trench
GWI-BA1-01 = Injection Well or Trench

0 75 150 300 Feet

N

Source: ESRI and Burns & McDonnell Engineering.

COORDINATES :	DATE :
(NAD 83) STATE PLANE OKLAHOMA NORTH FEET	AERIAL PHOTO - 2010 / MAP PRODUCED - 1/16/2017

APPENDIX A GROUNDWATER FLOW MODEL REPORT (ENSR, 2006)

Prepared for:
Cimarron Corporation (Tronox)
Oklahoma City, Oklahoma

Groundwater Flow Modeling Report

ENSR Corporation
October 2006
Document No.: 04020-044

TRONOX

ENSR | AECOM

Prepared for:
Cimarron Corporation (Tronox)
Oklahoma

Groundwater Flow Modeling Report

Maya Desai and Ken Heim

Maya C. Desai Ken Heim

Prepared By

Michael Meenan and James Cao

Michael Meenan James Cao

Reviewed By

ENSR Corporation
October 2006
Document No.: 04020-044-327

TRONOX

ENSR | AECOM

Contents

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List of Tables

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1.0 INTRODUCTION

1.1 Overview

In order to depict and predict groundwater flow and to evaluate groundwater remediation alternatives, two groundwater flow models were developed for the Cimarron Site. These two models address two of the three areas on site that require remediation of Uranium (U) in the groundwater. The two models included Burial Area #1 (BA #1) and the Western Alluvial (WA) area.

Calibration was evaluated by comparing measured groundwater elevations, flow path data, and water budgets, with simulated elevations, paths, and budgets. Both flow models achieved adequate calibration to the observed groundwater elevation data, to observed flow path trajectories, and to the estimated water budgets. Discrepancies between observations and predictions are considered reasonable. The overall water table configuration for each model was consistent with expectations based on observations of U concentrations. Overall hydrogeological concepts as presented in the Conceptual Site Model (CSM), Rev 01 (ENSR, 2006) were captured by the numerical models.

The resulting models are useful tools to evaluate groundwater flow characteristics (velocities, flux rates, etc.) and to evaluate different remediation scenarios including, but not limited to, understanding the permanence of the proposed remedial technique and to design the injection of reagents.

1.2 Background and Objectives

Cimarron Corporation's site near Crescent, Oklahoma is a former nuclear fuel manufacturing facility. Since stopping operations, the site has been undergoing decommissioning under the oversight of the Nuclear Regulatory Commission (NRC) and the Oklahoma Department of Environmental Quality (ODEQ). As a result of the facility processes there are several areas at the Cimarron Site that have residual concentrations of Uranium (U) in the groundwater. Cimarron Corporation is currently considering remedial actions in Burial Area #1, the Western Alluvial Area, and the Western Uplands area. To support the design of these remedial systems, numerical groundwater flow models were developed for two of these areas. These models, based largely on data and concepts presented in the Conceptual Site Model (Rev 01, ENSR, 2006), serve as tools to evaluate remediation strategies.

The overall objective of this modeling effort was to provide tools by which remediation alternatives could be evaluated. This objective was achieved by setting up the numerical models to include geologic and hydrologic conditions as observed and documented in the CSM-Rev 01 (ENSR, 2006). The models were then calibrated to specific targets. This calibration process yielded two models that compared well to observations and therefore could provide a frame of reference with which to evaluate impacts from remediation alternatives.

These models were initially developed to support ENSR's remediation via pump and treat. While Cimarron was considering remediation via pump and treat, they were also considering bioremediation. In this latter process, via additives, the geochemical conditions in the aquifer would be converted to a reducing environment which would immobilize the U. This process has been conceptualized and proposed by Arcadis. Data from these calibrated models and simulations using these numerical models can help to design either these or other remediation alternatives.

Note that even though there are detectable concentrations of U in the Western Upland area of the site, a numerical model was not constructed for that area. The conceptual site model for the WU area is presented in the CSM Rev 01 (ENSR, 2006). This conceptual site model forms the basis for ARCADIS' evaluation and selection of remedial design for this area. Given the extent of the U concentrations, complex numerical modeling for this area may not be necessary based on the remedial approach.

2.0 HYDROGEOLOGIC FRAMEWORK

Much of the following has been extracted and paraphrased from the CSM-Rev 01 Report (ENSR, 2006). This section largely focuses on the parts of the CSM that were directly used in the modeling effort.

2.1 Site Setting

The Cimarron Site lies within the Osage Plains of the Central Lowlands section of the Great Plains physiographic province, just south of the Cimarron River (**Figure 1**). The topography in the Cimarron area consists of low, rolling hills with incised drainages and floodplains along major rivers. Most of the drainages are ephemeral and receive water from storms or locally from groundwater base flow. The major drainage included in the models was the Cimarron River, which borders the site on the north. This river drains 4,186 square miles of Central Oklahoma from Freedom to Guthrie, Oklahoma (Adams and Bergman, 1995). The Cimarron River is a mature river with a well-defined channel and floodplain. The stream bed is generally flat and sandy and the river is bordered by terrace deposits and floodplain gravels and sands (Adams and Bergman, 1995). In the area of the Cimarron Site, the ancestral Cimarron River has carved an escarpment into the Garber-Wellington Formation. Floodplain alluvial sediments currently separate most of the river channel from the escarpment. Surface elevations in the Cimarron area range from 930 feet above mean sea level (amsl) along the Cimarron River to 1,010 feet amsl at the former plant site. Between the river and the escarpment, the ground surface is flat relative to the variable topography of the escarpment and leading up to the uplands. Vegetation in the area consists of native grasses and various stands of trees along and near drainages. Soil thickness in the project area ranges from about one to eight feet.

2.2 Precipitation

Adams and Bergman (1995) summarized the precipitation for the Cimarron River Basin from Freedom to Guthrie, Oklahoma. Their study showed that precipitation ranges from an average of 24 in/yr near Freedom, Oklahoma, in the northwest part of the Cimarron River floodplain in Oklahoma, to 32–42 in/yr at Guthrie, Oklahoma. Wet weather years occurred between 1950 and 1991, 1973–1975, 1985–1987, and 1990–1991. The wettest months of the year are May through September, while the winter months are generally the dry months. The period from 1973 through 1975 had a total measured rainfall that was 23 inches above normal (Carr and Marcher, 1977). Precipitation data collected by the National Oceanic and Atmospheric Administration (NOAA) for Guthrie County, Oklahoma, from 1971 to 2000 indicates that the annual average precipitation is 36.05 inches.

2.3 General Geology

The regional geology of the Cimarron area and the site-wide stratigraphic correlations for the project area can be combined into a general geological model for the Cimarron Site (Figure 2). The site consists of Permian-age sandstones and mudstones of the Garber-Wellington Formation of central Oklahoma overlain by soil in the upland areas and Quaternary alluvial sediments in the floodplains and valleys of incised streams. The Garber sandstones dip gently to the west and are overlain to the west of the Cimarron Site by the Hennessey Group. The Wellington Formation shales are found beneath the Garber sandstones at a depth of approximately 200 feet below ground surface in the project area. The Garber Formation at the project site is a fluvial deltaic sedimentary sequence consisting of channel sandstones and overbank mudstones. The channel sandstones are generally fine-grained, exhibit cross-stratification, and locally have conglomeratic zones of up to a few feet thick. The sandstones are weakly cemented with calcite, iron oxides, and hydroxides. The silt content of the sandstones is variable and clays within the fine fraction are generally kaolinite or montmorillonite. The mudstones are clay-rich and exhibit desiccation cracks and oxidation typical of overbank deposits. Some of the mudstones are continuous enough at the Cimarron Site to allow for separation of the sandstones into three main units, designated (from top to bottom) as Sandstones A, B, and C. Correlation of these three sandstone units is based primarily on elevation and the presence of a thick mudstone unit at the base of Sandstones A and B that can be correlated between borings. Within each sandstone unit, there are frequent mudstone layers that are discontinuous and not correlative across the project area.

The Cimarron Site is located on part of an upland or topographic high between Cottonwood Creek and the Cimarron River. The project site is dissected by shallow, incised drainages that drain northward toward the Cimarron River. Groundwater base flow and surface water runoff during storms have been ponded in two reservoirs (Reservoirs #2 and #3) on the project site. The Cimarron River is a mature river that has incised the Garber Formation, forming escarpments that expose the upper part of the Garber sandstones. Within the Cimarron Site, the Cimarron River has developed a floodplain of unconsolidated sands, silts, and clays that separate the Garber sandstones exposed in an escarpment from the main river channel. Surface drainages within the project site flow toward the Cimarron River. Geological features of each modeled area of the Cimarron Site are as follows:

- BA #1 Area – The upland is underlain by a sequence of sandstone and mudstone units, namely, from top to bottom, Mudstone A, Sandstone B, Mudstone B, and Sandstone C. The alluvium can be divided into a transitional zone located within the erosional drainage area and an alluvial zone located north of the escarpment line. The transitional zone consists predominantly of clay and silt and overlies Sandstone B or Mudstone B. A paleochannel appears to exist in the transitional zone, which may control the flow of groundwater in the vicinity of the upland in this area. The alluvium consists of mainly sand and overlies Sandstone C and Mudstone B. Additional descriptions of the geology of this area are included in the CSM-Rev 01 Report (ENSR, 2006).
- Western Alluvial Area – Alluvial sediments in this area consist of predominantly sand with minor amounts of clay and silt. Sandstone B and Mudstone B exist beneath the alluvial sediments near the escarpment and Sandstone C underlies the alluvial sediments farther out in the floodplain. Additional descriptions of the geology of this area are included in the CSM-Rev 01 (ENSR, 2006).

2.4 Site-Specific Geology

2.4.1 BA #1 Area

Geologic logs from seventy-five boreholes were used to describe the subsurface geology in the immediate vicinity of the Uranium (U) plume at the BA #1 area. The lithologic logs collected from borehole cuttings described the subsurface geology as a sequence of interbedded layers of near surface unconsolidated alluvial material and deeper consolidated sandstones and mudstones. The logs identified twenty-seven unique material types, which included unconsolidated materials of varying degrees of sand, silt, and clay, anthropogenically disturbed surficial deposits, and sedimentary rock. In an effort to simplify the conceptualization of the subsurface geology these twenty-seven different material types were collapsed into nine distinct material types representing strata with significantly different hydrogeologic characteristics. The four unconsolidated materials include, fill, sand, silt, and clay, and the underlying consolidated units include Sandstone A, Sandstone B, and Sandstone C, interbedded with two distinct mudstone layers (**Figure 3**). The simplified lithologic units describe, from the surface downward, fill material in the uplands and widely scattered silt in the upland and alluvial areas. In the alluvial areas this is underlain by a thick sandstone unit with a relatively thick bed of clay within the unit. The upland areas and beneath the alluvium consist of interbedded sandstone and mudstone. Because of varied topography and elevation the exposure of materials at the site varies widely. In the upland areas most of the exposed material is either sandstone or mudstone while in the alluvium most of the exposed material is either sand or to a lesser extent silt and clay. All data in the lithologic logs was used in the development of the model

2.4.2 Western Alluvial Area

The subsurface geology at the WA area was depicted by geologic logs from twenty boreholes near the escarpment. In contrast to the geology of the BA#1 area, the subsurface of the WA area is a relatively flat, "pancake" geology where Sandstone C, the lowest sandstone indicated in the BA #1 area, is overlain by a continuous unit of unconsolidated alluvial sand, which is overlain by a intermittent unit of unconsolidated clay

(**Figure 4**). A simplification of the information from the lithologic logs was not necessary for the WA and the inconsistent distribution of clay around the site was largely due to topography and the erosion of the clay in the low lying areas. All data in the lithologic logs was used in the development of the model

2.5 Hydrogeology

Groundwater flow through above-described regional geologic units is governed by recharge areas and discharge areas.

Regionally, recharge is precipitation (rain, snow, etc) that infiltrates past the root zone to the water table. As discussed above, the average annual precipitation rate is approximately 30 in/yr. Recharge to the alluvium and terrace deposits along the Cimarron River was estimated to be 8 percent of precipitation based on baseflow calculations and the assumptions of steady-state equilibrium in the alluvium and terrace sands (Adams and Bergman, 1995). Rainfall recharge to groundwater is therefore estimated to be approximately 2.4 in/yr (5.5×10^{-4} ft/day).

Discharge of groundwater occurs at low points in the watershed and generally coincides with streams and lakes. At this site the Cimarron River is a local and regional discharge boundary. Average annual baseflow in the Cimarron River should equal average annual recharge indicating that the recharge and discharge rates are balanced.

Recharge to the groundwater system typically occurs at topographic highs. The application of this water to the groundwater system results in downward gradients in the recharge areas; that is, there is a component of flow downward in addition to horizontal. Conversely, discharge from the groundwater system occurs at the topographic low points in any given watershed, for instance at a stream, river, or lake. Because of this, groundwater gradients tend to be upward in these areas; that is, there is component of flow upward in addition to horizontal. The flow path of any given unit of groundwater depends on where in the watershed it originates as recharge and how far it has to flow to discharge.

2.6 Hydrologic Implications

The site-specific geology suggests several hydrologic implications including:

- The alluvial material was largely deposited by the historical meandering of the Cimarron River and the deposition of overbank deposits that result from intermittent floods on the river. This inconsistent and repeating depositional cycle resulted in a series of inter-bedded unconsolidated material types that are collectively referred to as alluvium, which on a small scale can exhibit variable hydrogeologic characteristics but on a larger scale can be considered collectively.
- Groundwater discharged from the Garber-Wellington formation largely discharges through the alluvial deposits on its way to its final destination, the Cimarron River.
- Since both the WA and the BA #1 areas are within the Cimarron River alluvial valley, both areas receive groundwater from both upgradient discharge of groundwater to the alluvial deposits and from subsurface discharge of water from the deeper aquifer to the alluvium and river system. In general, flow from the southern upgradient sandstones to the alluvium is characterized as horizontal flow and flow from the sandstone underlying the alluvium is characterized as having a component of vertical (upward) flow.
- The sandstone and siltstone/mudstones of the Garber-Wellington formation are relatively impermeable when compared to the unconsolidated alluvial sands adjacent to the river. This suggests that the water table gradient in the sandstone would be relatively steep when compared to the alluvial sand. This would further suggest that water could be more easily withdrawn from the alluvial sand than from the consolidated sediments occurring both beneath, and upgradient of the alluvial material.

- In addition, within the bedrock, the sandstone units have higher permeability relative to the mudstones. Therefore, more groundwater flow is expected to take place horizontally within these water bearing units, with less flow between the units.

The hydrogeologic characteristics of the Cimarron River alluvial system are typical of a relatively permeable aquifer system receiving groundwater from an adjacent, less permeable bedrock aquifer and transferring the groundwater to the discharge zone, in this case the Cimarron River.

2.7 Conceptual Model of Site Groundwater Flow

The Conceptual Site Model (CSM) of the Cimarron River flow system was developed prior to the development of groundwater models for the WA area and the BA #1 area. The CSM was incorporated into the groundwater models to ensure that the models used existing information and an accepted interpretation of the site-wide geology. The conceptual models for the WA area and the BA #1 area were developed separately and as such are discussed separately. However, it is recognized that the conceptual models for the two areas must be consistent.

2.7.1 The Cimarron River

The Cimarron River is a significant hydrogeologic boundary for the entire Cimarron Site. The headwaters of this river are in New Mexico and from there it flows through Colorado, Kansas, and Oklahoma. In the vicinity of the Site (Freedom to Guthrie, OK) the Cimarron River is a gaining river. That is, it is a discharge zone for groundwater. Groundwater flow into the river is controlled by the difference in elevation of groundwater and in the river and by the conductivity of the river bottom sediments. The elevation of the river changes seasonally, but this can be represented as an average annual elevation for this steady-state modeling effort. Changes in the elevation of the river may result in short-term changes in the groundwater flow directions and gradients in the nearby alluvial materials. However, over the long-term, an average elevation is appropriate to reflect the average groundwater flow system. Cimarron River streamflows and associated water level elevations in the immediate vicinity of the Western Alluvial area and BA#1 model domains has not been historically measured. The variability in river water levels at the site were estimated using long term flow records (1973 through 2003) from the USGS stream gages at Dover (30.0 miles upstream to the west) and Guthrie (10.3 miles downstream to the east). Daily averaged water level elevations at each of the two sites were averaged and the average water level elevation for the area of the model domains was determined through linear interpolation to be 925.0 feet. A further statistical evaluation indicated that the 5^{th} percentile of water level elevations at the site was 924.1 feet and the 95^{th} percentile of water level elevations was 927.7 feet; therefore, 90% of the time the Cimarron River water level at the site varies within a range of 3.60 feet.

2.7.2 BA #1 Area

Groundwater in the vicinity of the BA #1 Area originates as precipitation that infiltrates into the shallow groundwater in recharge zones, both near the BA #1 area and in areas upgradient of the BA #1 area. The amount of water flowing from the sandstones into the modeled area and into the alluvial material is controlled by the changes in groundwater elevation and hydraulic conductivities between the two units.

Local to the BA #1 area, infiltrated rainwater recharges the shallow groundwater in the area of the former disposal trenches and then flows into Sandstone B. The reservoir also contributes water to the groundwater system. This groundwater then flows across an escarpment that is an interface for the Sandstone B water-bearing unit and the Cimarron River floodplain alluvium, and finally into and through the floodplain alluvium to the Cimarron River. Flow in Sandstone B is mostly northward west of the transitional zone and northeastward along the interface with the transitional zone. Flow is driven by a relatively steep hydraulic gradient (0.10 foot/foot) at the interface between Sandstone B and the floodplain alluvium. Once groundwater enters the transition zone of the floodplain alluvium, the hydraulic gradient decreases to around 0.023 foot/foot and flow is refracted to a more northwesterly direction. The decrease in hydraulic gradient is due in part to the much higher overall hydraulic conductivity in the floodplain alluvium compared to Sandstone B (10–3 to 10–2 cm/s in alluvium versus 10–5 to 10–4 cm/s in Sandstone B). The refraction to the northwest is primarily due to a paleochannel in the floodplain alluvial sediments. The direction of this paleochannel is to the northwest near the buried escarpment and then is redirected to the north as it extends farther out into the floodplain. Once groundwater passes through the transitional zone, it enters an area where the hydraulic gradient is relatively flat. Data indicates that the gradient in the sandy alluvium is approximately 0.0007 ft/ft. **Figure 3-4** in the CSM-Rev 01 Report (ENSR, 2006) presents a potentiometric surface map of Sandstone B and the alluvium for the BA #1 area based on groundwater level measurements during August/September 2004. Seasonal data between 2003 and 2005 indicate that although groundwater levels may change seasonally, the hydraulic gradients and groundwater flow directions do not change significantly over time (ENSR, 2006).

2.7.3 Western Alluvial Area

Groundwater in the vicinity of the WA area originates as precipitation that infiltrates into the shallow groundwater in recharge zones both near the WA area and in areas upgradient of the WA area. Most of the groundwater in the WA area comes from the discharge of groundwater from Sandstones B and C to the alluvial materials. The amount of water flowing from the sandstones to the alluvial material is controlled by the difference in groundwater elevation and hydraulic conductivities between the two geologic units. Groundwater flow in the WA area is generally northward toward the Cimarron River; flow is driven by a relatively flat hydraulic gradient of 0.002 foot/foot. **Figure 3-6** in CSM-Rev 01 Report (ENSR, 2006) presents a potentiometric surface map of the alluvium for the WA area based on groundwater level measurements during August/September 2004. As with the BA#1 Area, although groundwater levels may change seasonally, there is little change over time in hydraulic gradient and groundwater flow directions.

3.0 MODELING APPROACH

Groundwater flow at the two Cimarron sites (BA #1 and WA areas) was simulated using the three-dimensional MODFLOW model (McDonald and Harbaugh, 1988). The MODFLOW model uses a block-centered finite-difference method to simulate groundwater flow in three dimensions. The MODFLOW model was selected because of its wide acceptance by the technical community, because of its robustness, and because several Windows® based applications support the model, including the GMS 6.0® modeling package, which was used for this project. The GMS 6.0® software package is a visualization package that facilitates easy manipulation of the MODFLOW input and output files. In addition to using the MODFLOW groundwater model, the MODPATH particle tracking program was used to simulate the transport of groundwater particles within the model domain as a direct result of a flow field predicted by MODFLOW.

3.1 Groundwater Model Domain

The domains of the BA #1 area and WA groundwater models were set up to include the specific areas of interest and all important boundary conditions.

For the BA #1 area, the specific area of interest was located northwest of the Reservoir #2 from the source area in the uplands, downgradient through the transition zone, and into the alluvial sands (**Figure 5**). The downgradient boundary was the Cimarron River and the upgradient boundary was along an east-west line coincident with the Reservoir #2 dam. Groundwater flow is primarily northward, so boundaries parallel to groundwater flow were set up at locations upstream and downstream along the Cimarron River far enough away from the high U concentrations and parallel to flow lines to not influence the interior of the model domain during pumping simulations. The lower boundary (i.e., bottom) of the BA #1 model domain was fixed at elevation 900 feet, well below the lower extent of the alluvial aquifer.

In the case of the WA area, the specific area of interest was located just downgradient of the escarpment along a north-trending line of high U concentrations (**Figure 6**). The downgradient boundary was the Cimarron River and the upgradient boundary was set at the escarpment. Groundwater flow is primarily northward so boundaries parallel to groundwater flow were set up at locations upstream and downstream along the Cimarron River far enough away from the high U concentrations to not influence the interior of the model domain during pumping simulations. The lower boundary (i.e., bottom) of the WA area model domain was fixed at 870 feet, well below the lower extent of the alluvial aquifer.

The model domain for the BA #1 area was set up to include the area from the upgradient reservoir to the south, to the Cimarron River to the north, and to distances east and west adequate enough to have a negligible effect on the interior of the model domain. The model was developed with grid cells that are 10 feet square in the X-Y plane and with 12 layers extending from the land surface down to a depth of elevation 900 feet, resulting in approximately 270,000 grid cells within the model domain.

The model domain for the WA area was set up to include the area from the escarpment to the south to the Cimarron River to the north and east and west to distances adequate enough to have a negligible effect on the interior of the model domain. The model was developed with grid cells that are 10 feet square in the X-Y plane and with 2 layers extending from the land surface down to a depth of elevation 870 feet, resulting in 97,830 grid cells within the model domain. The high density of grid cells within each model domain was selected for two reasons including: 1) to provide for a finely discretized model within the area of the U plume for testing the effects of groundwater pumping, and 2) to provide for adequate representation of the subsurface geology into discrete geologic material types, particularly for the BA#1 area.

3.1.1 BA #1 Area

The model layers for the BA #1 area were developed directly from the lithologic information from the seventy-two boreholes that were available for the site. A simplification of the original borehole data, which had originally described 27 unique lithologic types, was imported directly into the GMS 6.0® modeling platform, as the basis for the groundwater model. The simplified geology included the following geologic units/materials: 1) fill, 2) silt, 3) an upper sand unit, 4) clay, 5) a lower sand unit, 6) an upper sandstone unit (Sandstone A), 7) an upper mudstone (A), 8) a middle sandstone unit (Sandstone B), 9) a lower mudstone (B), and 10) a lower sandstone unit (Sandstone C). Each of the boreholes was reviewed in light of the surrounding boreholes to ensure that the inter-relationships between boreholes were realistic and representative of the CSM-Rev 01 (ENSR, 2006) developed for the site. Following the importation and adjustment of the borehole information, each layer in each of the seventy-two boreholes was assigned a Horizon ID to indicate the layer's position in the depositional sequence at the Site. The GMS 6.0® modeling platform was then used to "connect" the boreholes to form cross-sections based on the Horizon IDs assigned to each of the boreholes. Since a cross-section was developed for every adjacent borehole, this resulted in a total of one hundred sixty-five cross-sections; each of which was reviewed to ensure the sensibility of the interpretations. In cases where the cross-section did not make geologic sense, the cross-section was manually modified (**Figure 7**).

Once the cross-sections were developed and checked for accuracy, the GMS 6.0® program was used to develop three-dimensional solids of each material type within the intended model X-Y model domain. Each of the 3-D solids was represented by upper and lower TIN (triangularly integrated network) surfaces and was created using the previously developed cross-sectional data. Each of the solids types corresponded to the nine geologic units indicated by the lithologic information for the boreholes (**Figure 8**).

The model boundaries were identified and incorporated into the GMS 6.0® platform, including the location of the river boundary, the general head boundary, and the recharge boundary (discussed in the next section). One of the last steps in the development of the BA #1 area groundwater model was to develop a generic, twelve layer 3D grid that encompassed the model domain on a 10 ft by 10ft horizontal spacing. The next step in the development of the model was to assign hydrogeologic properties to each of the material types and boundaries and then transition all of the 3-D solids information to the 3-D grid that is used by the MODFLOW and MODPATH models (**Figure 9**). The final step was to make modifications to the distribution of material types (i.e., hydraulic conductivities) to adjust for the discrepancies between the mathematically interpreted version of the distribution of soil types and the interpretation of soil types based on the CSM (ENSR, 2006).

3.1.2 WA Area

The model layers for the WA area were developed directly from the lithologic information from the twenty boreholes that were available for the site. The borehole data was imported directly into the GMS 6.0® modeling platform as the basis for the groundwater model. Each of the boreholes was reviewed in light of the surrounding boreholes to ensure that the inter-relationships between boreholes were realistic and representative of the CSM, Rev.1 (ENSR, 2006) developed for the site. Following the importation and adjustment of the borehole information, each layer in each of the twenty boreholes was assigned a Horizon ID to indicate the layer's position in the depositional sequence at the site. The GMS 6.0® modeling platform was then used to "connect" the boreholes to form cross-sections based on the Horizon IDs assigned to each of the boreholes. Since a cross-section was developed for every adjacent borehole, this resulted in a total of forty-one cross-sections; each of which was reviewed to ensure the sensibility of the interpretations. In cases where the cross-section did not make geologic sense, the cross-section was manually modified (**Figure 10**).

Once the cross-sections were developed and checked for accuracy, the GMS 6.0® program was used to develop three-dimensional solids of each material type within the intended model X-Y model domain. Each of the 3-D solids was represented by upper and lower TIN (triangularly integrated network) surfaces and was created using the previously developed cross-sectional data. Each of the solids types corresponded to the three geologic units indicated by the lithologic information for the boreholes (**Figure 11**). It should be noted that the geologic materials in the WA area consisted only of sandy alluvium and the underlying bedrock (Sandstone C), so this process was much simpler than for the BA#1 area.

The model boundaries were identified and incorporated into the GMS 6.0® platform including the location of the river boundary, the general head boundary, and the recharge boundary (discussed in the next section). One of the last steps in the development of the WA area groundwater model was to develop a generic, two layer 3D grid that encompassed the model domain on a 10 ft by 10 ft horizontal spacing. The final step in the development of the model was to assign hydrogeologic properties to each of the material types and boundaries and then transition all of the 3-D solids information to the 3-D grid that is used by the MODFLOW and MODPATH models (**Figure 12**).

3.2 Hydrogeologic Physical Properties

The physical property most commonly used to characterize subsurface permeability is the hydraulic conductivity. This parameter is applied to Darcy's Law as a proportionality constant relating groundwater flow rate to groundwater gradient and cross-sectional area, and is a measure of the ability of a soil matrix to transport groundwater through the subsurface. Hydraulic conductivity values are required to describe the permeability of each cell in the MODFLOW groundwater model because Darcy's equation is used by the model to solve for groundwater head in each model cell. If hydraulic conductivity values in the model area were spatially the same, the multiple model layers could act as a single layer. However, this degree of uniformity is not evident at the Cimarron site, so each model layer was assigned a unique horizontal and vertical hydraulic conductivity value consistent with the geology assigned to that layer.

In the case of the BA #1 area model, the MODFLOW model represents the complicated ten layer geologic system of largely continuous material types with twelve model layers. From the surface downward these include, 1) fill, 2) silt, 3) an upper sand unit, 4) clay, 5) a lower sand unit, 6) an upper sandstone unit (Sandstone A), 7) an upper mudstone (A), 8) a middle sandstone unit (Sandstone B), 9) a lower mudstone (B), and 10) a lower sandstone unit (Sandstone C). A single, constant hydraulic conductivity value was assigned to each of these 10 material types.

In the case of the WA area model, the MODFLOW groundwater model represents the (simple relative to the BA #1 model) subsurface by assigning the two dominant material types (sand and sandstone) to two different model layers. (Note: even though clay was present in the boring logs, it was not saturated, therefore was not modeled). These are 1) a sandy alluvium layer beneath the clay layer and exposed at several locations throughout the site and 2) an underlying sandstone layer beneath the sandy alluvial aquifer (Sandstone C). A single, constant hydraulic conductivity value was assigned to each of the two layers.

Hydraulic conductivity values for both the alluvium and the sandstone were derived from slug and pumping tests conducted during the field investigations, as described in the Burial Area #1 Groundwater Assessment Report (Cimarron Corporation, 2003). **Table 1** summarizes the findings from these tests. Results for the alluvium ranged from 0.04 to 312 ft/day with a median value of 38 ft/day. Results for the sandstones ranged from 0.07 to 2.83 with a median value of 0.35 ft/ day. The conductivity values are consistent with literature (Freeze & Cherry, 1979).

In general, the vertical hydraulic conductivity is assumed to be less than the horizontal because of the inter-bedding that occurs during sedimentary deposition. While relatively small layers and lenses of fine material do not significantly effect the lateral movement of groundwater they can effect the vertical movement by creating more tortuous pathway for groundwater flow, and resistance to vertical flow. In general, the vertical hydraulic conductivity in sedimentary or alluvial deposits can be 1 to 30% of the horizontal hydraulic conductivity.

The alluvial materials (sand, clay, silt) were assumed to have vertical components of flow consistent with a sedimentary environment. Therefore, the vertical hydraulic conductivity of the alluvial materials was set to 10% of horizontal hydraulic conductivity. For the sandstones and mudstones, the vertical hydraulic conductivity was set to 5% of horizontal hydraulic conductivity. The groundwater flow in sandstone and mudstone may be controlled not only by primary (matrix) pathways, but also secondary (remnant fracture) pathways. However, there is no data (i.e., groundwater elevation data) to suggest that fractures flow is significant at this site, especially on the scale of the entire model domain. Note that the conceptual understanding of fractures at this site is that most of fractures occur on bedding planes (i.e., in the horizontal direction); thus, flow in the stone fractures would be controlled by horizontal hydraulic conductivity, not the vertical.

Anisotropy values are used if there is some reason to believe that the aquifer has a substantially different permeability along one horizontal axis than another. This is not believed to be the case in either the WA area or the BA #1 model domain and therefore the horizontal anisotropy was assumed to be unity.

3.3 Boundary Conditions

The boundary conditions at the perimeter of the model domain play an important role in the outcome of a groundwater simulation because of the dependence of hydraulic behavior within the interior of the model on the water levels and fluxes fixed at the model boundaries. Ideal model boundaries are natural hydrogeologic features (i.e., groundwater divides, rivers). Recharge to groundwater is also a boundary condition. Model predictions can be inaccurate when the areas of interest in the model domain are too close to a poorly selected boundary condition. In the absence of natural hydrogeologic boundaries, boundaries are chosen at distances great enough such that they do not affect the outcome of simulations in the area of interest. In the groundwater models of the Cimarron Site, the downgradient boundary was selected to coincide with the Cimarron River, a natural hydrogeologic boundary. Since there are no nearby natural features for the other boundaries, the domain was extended to distances sufficient such that simulations would not be significantly affected by the model boundaries.

3.3.1 Recharge

Recharge to groundwater is simulated using the MODFLOW Recharge Package. This package can be used to apply a spatially and temporally distributed recharge rate to any layer within a model domain. In general, the recharge package is used to represent the fraction of precipitation that enters the subsurface as rainfall recharge directly to the groundwater water table. In model domains representing relatively small geographic regions, and without significant variability in site wide precipitation, the recharge package is applied uniformly throughout the model domain. The recharge package can be temporally varied in unsteady simulations to predict system response to unique or seasonal events but can be applied at a constant rate for steady state simulations. For the steady-state simulation of groundwater flow at the two Cimarron sites the recharge package was applied uniformly over the entire model domains at a constant rate. Since the model was steady-state and no losses of groundwater were assumed, the recharge rate, determined through model calibration, was expected to be similar to the rate indicated in the CSM-Rev 01 (ENSR, 2006) of 8% of precipitation or 2.4 in/yr.

3.3.2 Surface Water/Groundwater Interactions

The Cimarron River is included in each of the models, as it is the regional groundwater discharge point. The Cimarron River is represented in the model domain using the MODFLOW River Package. The channel bed elevations at these sites were linearly interpolated from the gage datum of 999.2 feet at the USGS stream gage at Dover, OK (#07159100) located about 30 miles upstream, and the gage datum of 896.5 feet at the USGS stream gage at Guthrie, OK (#07160000) located about 10 miles downstream. The resulting value of 922.8 feet was assigned as the river bed elevation for both the BA #1 and WA areas. The surface water elevations were assumed to be 2 feet higher than the bed elevations at both locations resulting in a constant water surface elevation of 924.8 feet.

Depending on the difference between the measured river surface elevation and the predicted groundwater elevation in the cells adjacent to the river cells, the river will either be simulated to lose water to the aquifer or gain water from the aquifer. Based on the topography and hydrogeology of the site, the streams and rivers are generally expected to gain groundwater. The rate of water gain or loss from the Cimarron River is represented in MODFLOW using three parameters that include (1) the river bed area, (2) the channel bottom thickness, and (3) the hydraulic conductivity of the river bed sediments. While the product of the hydraulic conductivity and the riverbed area divided by the bed thickness results in a conductance term (C), this value was established through model calibration rather than being calculated, due to a lack of site-specific information.

Model cells that were assigned river properties are shown with blue dots on **Figures 9** and **12** for the BA #1 and WA models, respectively.

The reservoir south of the BA#1 area was incorporated into the General Head Boundary condition as described below. None of the other intermittent surface waters, such as the drainageways, were included in the model, as their influence on the groundwater system is local and sporadic.

3.3.3 Upgradient General Head Boundary

The upgradient boundaries for both the BA #1 and the WA area were represented as a General Head Boundary (GHB) in MODFLOW. Unlike a constant head boundary, which holds the water level constant and offers no control over the amount of water passing through the boundary, the GHB offers a way to limit the supply of upgradient water entering the model domain. This limitation provides a better representation of the system that is limited by the transfer of groundwater from the upgradient aquifer to the upgradient model boundary. The general head boundary requires the designation of a head, or groundwater elevation along the boundary, and conductivity. The head assigned to the GHB defines the groundwater level at the boundary and largely dictates the downgradient water levels and the gradients. The conductivity of the GHB defines the permeability of the boundary and controls the amount of water that can pass through the boundary. Water can pass into or out of the model domain through the general head boundary, depending on the relative hydraulic heads.

3.3.4 Underlying General Head Boundary

In addition to representing the upgradient boundary using a GHB, the upward hydraulic gradient from the underlying bedrock described in the site CSM-Rev 01 (ENSR, 2006) can also be represented this way. Because the Cimarron River is a major discharge area, the discharge of deep groundwater through the alluvium and into the river is an expected phenomenon. To simulate this upward flow of groundwater a GHB was used in both model domains to varying degrees to represent a higher water level at depth than in the alluvial aquifer. The volumetric flow rate of water into the alluvial aquifer was limited by adjusting to a relatively low conductance during the calibration process.

Some of the model cells that were assigned general head boundary properties are shown with brown dots on **Figures 9** and **12** for the BA #1 and WA models, respectively. Other cells were also assigned this boundary type, but are not visible in this view of the model domain. Basically, all cells at the base of the models and at the southern limit were assigned GHB boundaries.

3.4 Summary of Modeling Approach

Model parameters used to setup the groundwater models for the BA #1 and WA areas were developed from measured information and from interpretations made based on material characteristics. These parameters largely control the predictions made by the groundwater and pathline models.

4.0 MODEL CALIBRATION

4.1 Calibration Approach

Once the model domain was established, the model grid developed, and the model inputs entered, the calibration process began. The calibration process is a quality control step used to provide a frame of reference for evaluating simulation results. The calibration of groundwater models proceeds by making adjustments to the boundary conditions and the hydraulic conductivities until the simulated groundwater elevations adequately match the observed groundwater elevations. In addition to comparing model predicted elevations to observed elevations, a good calibration was also dependent on capturing gradients and flow directions such that simulated flow paths were congruent with inferred flow paths from U concentration data. The overall regional water balance was also considered. The following sections (**4.1.1**, **4.1.2**, and **4.1.3**) discuss the three ways the model calibration was evaluated.

4.1.1 Measured and Predicted Water Levels

Comparing model predicted groundwater levels with measured levels is a rigorous, obvious, and straightforward way to evaluate the ability of a groundwater model to meet the project objectives. In steady-state models the groundwater predictions are generally compared with representative average groundwater water levels at several locations around the site. Since a single round of groundwater elevation measurements may not be representative of the average water table due to seasonal variations, it is preferable to use the results of several temporally distributed water level surveys to provide a better representation of the average water table.

The water level data used to evaluate the BA #1 and WA groundwater model calibrations was from each of the wells/boreholes used to develop the models. Water levels from each of four surveys including September 2003, December 2003, during August and September of 2004, and in May of 2005 were averaged to arrive at a set of average water levels for comparison to model predictions. **Table 2** summarizes the average groundwater elevations from four sampling rounds. This data set served as the calibration data set.

During the calibration, the model calibration parameters were adjusted in order to reach a quantitative target: the mean absolute difference between the predicted and measured water levels within 10% of the measured site-wide groundwater relief.

For the BA #1 area, the maximum groundwater elevation was 950.96 feet at Well 02W51 and the minimum elevation was 925.37 feet at Well 02W17; therefore, the calibration target is 10% of that difference or approximately 2.6 feet.

For the WA area, the maximum groundwater elevation in the model domain is 931.75 feet (at T-63) and the minimum elevation is 930.35 feet (at T-82), then the calibration target of 10% of the difference is approximately 0.14 feet.

In addition, it is recognized that the two models, although developed separately, must be consistent with each other. That is, values for inputs between the two models cannot be significantly different from each other.

4.1.2 Volumetric Flow-Through Rate

Both of these models are dominated by the boundary conditions, that is, the boundary conditions have a strong influence on the model results. Therefore, in addition to simply matching steady-state water levels in the model domain by successive adjustment of aquifer properties and boundary conditions, comparing estimated steady-state flow-through rates was also considered as a means for evaluating calibration. There are a variety of ways to estimate a flow-through rate based on drainage area, baseflow, recharge, etc. This section discusses one of the methods using one set of input values. Though not a rigorous calibration target, it is important to be mindful of the water budget, or flow-through volumes for the models. Therefore, the estimate of flow-through rate presented here is intended to provide a general, again not rigorous, frame of reference by which to evaluate the calibration.

One estimate of the steady-state flow rate through each model domain was made by multiplying an estimate of rainfall recharge by the total drainage area to arrive at an annual recharge rate. This recharge volume represents the water that enters the groundwater system over the entire watershed – not just the model domain and/or immediate site vicinity. However, this entire volume will pass through the model domain on its way to the regional discharge boundary – The Cimarron River. During the calibration process, the model boundary conditions were adjusted in consideration of this calculated annual flow-through rate. Note that in making this estimate, it is assumed that the surface water divides as represented from the topographic contours coincide with groundwater divides.

For the BA #1 area, the total drainage area upgradient and including the model domain is approximately 2.1 square miles. Based on an annual recharge rate of 2.4 in/yr over the BA #1 watershed, the total flow through rate for the BA #1 model domain was estimated to be approximately 32,000 ft^3/day. For the WA area, the total upgradient drainage area and model domain is 0.32 mi^2 resulting in an estimated total flow through rate of the WA model domain of approximately 5,000 ft^3/day.

During the calibration process, adjustments of hydrogeologic characteristics and boundary conditions were made in light of these estimates of flow. Comparing these estimates with the calibrated results provides one way to evaluate calibration.

4.1.3 Plume Migration

In addition to accurately reproducing water levels and volumetric flow rate through the groundwater system, a pathline analysis was conducted to demonstrate an accurate representation of groundwater movement in the system. This was especially important for BA #1 area where there is ample water quality data by which to infer flow paths. In the case of the BA #1 site, the current distribution of the U plume was compared to predicted particle pathlines developed from particles initiated in the original U source area. By demonstrating that particles seeded in the source area would effectively follow the path of a measured plume, the pathline simulation can illustrate the accuracy of the model in representing flow directions and groundwater gradients.

For the BA #1 area, the MODPATH model was used to predict the fate of particles seeded at the approximate location of the initial U source. The results of the steady-state MODFLOW model were used as the groundwater flow driver for the MODPATH simulation and the predicted paths of the particles were compared with the plume map for U at the BA #1 area. For the simpler WA model, a pathline comparison was not required.

4.2 Calibration Parameters

For both of these models there are strong boundary conditions. These are the general head boundary at the upgradient (south) edge of each of the models to simulate water entering the model domain from the sandstones, the general head boundary along the bottom of the models to simulate flow up from the sandstone into overlying soils, and the river where groundwater discharges. Flow and elevations in the model are dominated by the flow entering the model through the general head boundaries and flow leaving the model through the river. When models are so strongly influenced by these boundary conditions, calibrated solutions can result from a variety of non-unique combinations of boundaries and hydraulic conductivities.

Early in the calibration process, adjustments to hydraulic conductivity, recharge rate, and river conductance were made to simulate groundwater elevations similar to measured groundwater elevations. Once these initial adjustments were made, calibration focused on adjusting the head and conductance of the general head boundaries.

The general head boundary uses two variables to control the transfer of water across a model boundary including a water level (head) and a conductance term. The assigned groundwater elevation indicates the pressure head along the boundary. This is essentially the starting point for predicted heads along the boundary and adjacent water levels in the model are either higher or lower depending on boundary conditions and the additions or losses of water elsewhere within the model domain. The rate at which water enters the model through the general head boundary is controlled by the conductance term. A high conductance indicates a relatively limitless supply of water to the aquifer when the water table downgradient of the boundary is stressed and a low conductance indicates a limited supply of water to the aquifer. Limiting the conductance is of particular importance if only a portion of the total aquifer is included within the model domain and it is unrealistic to assume that the upgradient supply of water is limitless.

Each groundwater model was re-run several times with successive adjustment to the calibration parameters (general head boundaries) until the models were satisfactorily calibrated.

4.3 Calibration Results

In the following sections the results of each model's calibration is discussed with respect to the calibration targets discussed in Section 4.1.

4.3.1 BA #1

In the calibration process, hydraulic conductivity, recharge, and river elevation and conductance were adjusted; the final calibration values are summarized in **Table 3**. The other adjusted parameters were the elevation and the conductance of the general head boundaries both at the back edge and on the bottom of the model. **Table 3** also includes the calibrated values for these inputs.

Through successive adjustment of the general head boundary parameters, the mean absolute error (MAE) between the measured and predicted water levels was calculated to be 1.2 feet. This value is much less than the 2.6 feet which is 10% of the total water table relief at the site; this indicates an acceptable model calibration. Additional adjustments to the shape and orientation of the underlying general head boundary were made to simulate flow paths (using MODPATH) consistent with that which is inferred from the concentrations downgradient of the burial area. Finally, adjustments to the general head boundary were also made to simulate an approximate flow-through volume consistent with what is expected based on the drainage area size and recharge rate. The following are calibration results that indicate transfer rates of groundwater through the BA #1 model domain.

- Calibrated transfer rate of water from the model domain to the Cimarron River is 19,100 ft^3/day.
- Calibrated inflow rate from upgradient sandstone/mudstone units to the model domain is 16,900 ft^3/day.
- Recharge rate to the aquifer is 1,200 ft^3/day.

The difference between the total inflow (18,100 ft^3/day) and the total outflow (19,100 ft^3/day) equals ~1,000 ft^3/day, which represents less than a 5% error in the water balance and is considered acceptable. **Figure 13** summarizes the calibration results showing the measured versus predictefd groundwater elevations, the static simulated groundwater contours and a comparison of the particle pathlines originating from the burial area with the plume map as drawn from concentrations measured in August 2004. In the calibration process, targets with the best data (i.e., water level, flow path) are given preference over targets with less data (i.e., flow through rates). Thus, a good match of water levels, flow paths, and gradients is achieved, but justifiably at the expense, somewhat, of the flow-through match. The total calibrated flow through value above is less than the calculated flow-through rate based on drainage area and recharge presented in **Section 4.1.2**.

One of Arcadis' bioremediation design objectives is to estimate flux (dissolved oxygen) through the plume. Based on the calibrated flow-through rates, ZoneBudget (Harbaugh, 1990) was used in conjunction with the

MODFLOW output to calculate the flux through the plume areas only. The 2004 plume area for the BA #1 area is depicted on Figure 4-11 (CSM, Rev.1, ENSR, 2006); the plume was assumed to extend to the bottom of model Layer 7, which coincides with the lowest elevation where concentrations over 180 pCi/L were detected in August 2004. The flux was estimated at 19 gpm.

4.3.2 WA area

In the calibration process, hydraulic conductivity, recharge, and river elevation and conductance were adjusted and the final calibration values are summarized in **Table 4**. The other adjusted parameter was the elevation and the conductance of the general head boundaries both at the back edge and on the bottom of the model. **Table 4** also includes the calibrated values for these inputs.

Conceptually the interaction of the sandstones with the alluvial materials should be very similar regardless of model area. That is, the conductance of Sandstone B and Sandstone C should be the same for the BA #1 model and for the WA model. Because the BA #1 model is so much more complicated, it was calibrated first and then the calibrated conductance values were applied to the WA model. In effect, calibration of the WA model relied almost exclusively on changing the elevations assigned to the general head boundaries.

Through successive adjustment of the general head boundary elevation the average absolute error between the measured and predicted water levels was determined to be 0.31 feet. This value is more than the target of 0.14 feet, which is 10% of the total water table relief at the site. When the gradient is very flat as it is in this case measured groundwater elevation differences over short distances can be very difficult to simulate, especially when spatial variations in hydraulic conductivity are not considered. Furthermore, because the calibration data set is averaged over several rounds of data, seasonal differences may be more apparent.

The flow paths generated based on the MODFLOW head field and the MODPATH model indicates that groundwater flow paths are generally from the south to the north, consistent with the conceptual model and with the inferred flow paths based on U concentrations from August 2004.

The following are calibration results that indicate transfer rates of groundwater through the WA area model domain.

- Calibrated transfer rate of water from the aquifer to the Cimarron River is 57,000 ft^3/day.
- Calibrated inflow rate from upgradient sandstone/mudstone units to the model domain is 54,300 ft^3/day.
- Recharge rate to the aquifer is 2,600 ft^3/day.

The difference between the total inflow (56,900 ft^3/day) and the total outflow (57,000 ft^3/day) equals ~100 ft^3/day, which represents less than a 1% error and is considered acceptable. **Figure 14** summarizes the calibration results showing the measured versus predicted groundwater elevations and the static simulated groundwater contours. In the calibration process, targets with the best data (i.e., water level, flow path) are given preference over targets with less data (i.e., flow through rates). Thus, a good match of water levels, flow paths, and gradients is achieved, but justifiably at the expense, somewhat, of the flow through match. The total flow through value presented above is more than the flow-through rate calculated based on drainage area and recharge presented in **Section 4.1.3**.

One of Arcadis's bioremediation design objectives is to estimate flux (dissolved oxygen) through the plume. Based on the calibrated flow-through rates, ZoneBudget (Harbaugh, 1990) was used in conjunction with the MODFLOW output to calculate the flux through the plume areas only. For the WA model the total U distribution was assumed to be an area that extends from near the base of the escarpment northward toward the Cjmarron River, apparently originating where the western pipeline entered the alluvium north of the former Sanitary Lagoons. Uranium concentrations that exceeded 180 pCi/L in August 2004 are presented in Figure 4-15, CSM-Rev 01, ENSR, 2006). This impacted area extended only to the bottom of model Layer 1 since there were no concentrations of U detected in the sandstone (i.e., Layer 2). The flux for this plume area was 31 gpm.

4.3.3 Discussion

In addition to evaluating the calibration of the model from the standpoint of quantitative targets, another way to evaluate the model is how well it aligns with the conceptual model. Because there is often aquifer test data (i.e., slug tests, pumping tests), comparison of calibrated and measured hydraulic conductivities is a good way to evaluate how well the model corresponds with the conceptual model. **Table 1** summarizes the measured hydraulic conductivities and **Tables 3** and **4** summarize the calibrated hydraulic conductivities. **Tables 3** and **4** also summarize the calibrated inputs for the river, recharge, and general head boundaries.

There are no measured hydraulic conductivity data for Fill, Silt, Clay, and Sandstone A. For Alluvium, the measured hydraulic conductivity values range from about 20 to more than 275 ft/day. Pumping tests generally provide a better estimate of aquifer hydraulic conductivity than slug tests. Focusing on just pumping test results, the hydraulic conductivity ranges from about 120 to about 275 ft/day. The calibrated value, 235 ft/day, is consistent with this range.

Slug test data was also available from four wells screened in Sandstone B. The hydraulic conductivity results ranged from approximately 0.1 to 2 ft/day. The calibrated value for Sandstone B was 5 ft/day. One slug test was completed in Sandstone C and the result was 0.2 ft/day, less than the calibrated value of 3 ft/day. In both instances, the calibrated values are higher than the measured. Values derived from pump tests and values from calibrated models are often higher than slug test data. The locations of slug tests represent only a tiny fraction of each Sandstone B and C. During model calibration, the values are adjusted upward and may ultimately be more representative of site conditions than just a few data points may indicate.

In some instances, the hydraulic conductivities were adjusted upward to provide numerical stability to the model. The model can become numerically unstable when there are large changes (in hydraulic conductivity, groundwater elevation, etc) over short distances. In the BA#1 model this happens, for instance where clay (hydraulic conductivity less than 1 ft/day) comes into contact with sand (over 200 ft/day). This instability can be mitigated by smoothing those contrasts. Sometimes this is done at the expense of making a perfect match with measured data. As long as the adjustments are consistent with the conceptual model, the conceptual understanding of how different soils transmit water, and are mindful of the project objectives, smoothing typically does not impact simulations. The model will simulate this general behavior whether the contrast is 100 or 1000 times different. This change was evaluated in the sensitivity analyses, discussed below.

In the absence of data for fill, silt, clay and Sandstone A, estimates were made based on literature values and on qualitative site observations. Adjustments to these values were made during the calibration to encourage a good match of simulated and measured groundwater elevation and to encourage numerical stability.

Figures 13 and **14** summarize the calibration results. The graph shows the measured versus predicted groundwater elevations. Each point represents the groundwater elevation at a particular well. The closer the point is to the line, the less difference there is between the simulated and observed groundwater elevation. These figures also show the simulated groundwater contour map. Overall these match well for both models. For the BA#1 model, **Figure 13** also shows a comparison of a particle pathline originating from the Burial Area with the plume map as drawn from U concentrations measured on August 2004. As discussed above, these pathlines are a good match for the groundwater flow paths suggested by the distribution of U in groundwater.

4.3.4 Summary of Calibration Results

Three calibration targets were set as objectives prior to model calibration: achieve a good match between simulated and measured groundwater elevations and gradients, achieve a good match with the site conceptual model, and yield relatively consistent correlation of water budget estimates. For the most part, the first two objectives were achieved without difficulty. The measured and simulated groundwater elevations are in concert and especially for the BA#1 model, the simulated flow directions agree with flow directions indicated by U concentrations. Discrepancies between measured and simulated groundwater elevations, flow paths, and water budgets are explainable and can be accounted for when interpreting simulation results. Ultimately, the discrepancies in estimated flow-through volumes and simulated flow-through volumes are explained by ranges in recharge to and discharge from the site as well as uncertainties inherent in the modeling.

4.4 Sensitivity Analysis

In order to characterize the effects of uncertainty in the modeling parameters (recharge, hydraulic conductivity, and general head boundaries) on model predictions, sensitivity runs were conducted. In these runs, each parameter was varied from the base run (calibrated model). Differences were noted and these differences help in understanding the range of possible predictions, and how uncertainties in these parameters may affect model predictions.

Rainfall recharge, hydraulic conductivity and the general head boundary were the three primary variables tested in the sensitivity evaluation. Rainfall recharge has a direct impact on the amount of water moving through the aquifer and an impact on the amount of water that can be withdrawn from an aquifer. The conductivity is the fundamental parameter describing how effectively groundwater is transmitted in an aquifer. The sensitivity evaluation was focused on the hydraulic conductivity of the sand. The upgradient head boundary and the aquifer bottom boundary in the model of the BA #1 area were both represented using the general head boundary (GHB) in MODFLOW. This boundary fixes a water level at a specific group of cells in a model domain and uses a conductance term to facilitate the calculation of the volume of water that can be moved across the general head boundary. Like recharge, the general head boundary has a significant effect on the hydrologic budget and can largely control the amount of water entering or leaving the model domain. Therefore the models' sensitivity to this parameter was evaluated also.

One parameter was adjusted to complete the sensitivity analysis of the BA #1 area to enable this already complex and numerically sensitive model to iterate to a solution under the range of conditions imposed by the sensitivity analysis. During the sensitivity analysis, the horizontal hydraulic conductivity of the clay was increased from the 0.5 ft/day that was used during the model calibration, to 10 ft/day. By increasing the hydraulic conductivity of the clay, the gradients were decreased resulting in a smoother transition across adjacent model cells and therefore, a more stable model.

With the parameters selected for the sensitivity analysis a sequence of model scenarios were developed and run to evaluate the effect of varying the magnitudes of the selected parameters on the calibration. The results are as follows.

For the BA #`1 area, with the increased hydraulic conductivity of the clay, calibration results were marginally different results then when the original calibrated clay conductivity value was used.

Modification of the recharge rate by a factor of 50% and 200% resulted in only minor changes to the steady-state head calibration. This is largely because of the relatively small component of the hydrologic budget that surface recharge represents in the calibrated model, which is less than 10% of the overall budget.

Changing the hydrologic conductivity in the sand aquifer by a factor of 50% and 200% resulted in a relatively minor change to the steady state calibration. Small differences in the Mean Absolute Error (MAE) between the calibration run and the sensitivity runs are primarily because the Mean Absolute Error value is calculated using several wells outside of the sand aquifer that were relatively unaffected by the change and because the flow regime is so strongly controlled by the recharge and discharge boundary conditions.

Changes made independently to the head and the conductance of the subsurface general head boundary by factors of 50% and 200% resulted in fairly substantial changes to the steady state calibration. This is because water flowing into the model through the subsurface general head boundary represents a significant portion of the total water budget in the model. Both the elevation and the conductance are strong controllers of how much water is permitted to enter the model, thus have obvious impacts to model predictions.

4.5 Uncertainties and Assumptions

In order to fully understand the predictions and simulations, it is important to understand the factors that contribute to model uncertainty. Addressing these uncertainties allows users to understand and interpret the results of the simulations.

Flow-Through Volumes

As discussed above, estimates of flow-through volume were made based on drainage area and recharge rates. Comparing these estimates to simulated flow-through volumes was one way calibration was evaluated. Other methods can also be used to estimate flow-through volumes. For instance, one method varies recharge rates based on the ranges of annual precipitation rates of 24 inches, 30 inches, 32 inches, and 42 inches (CSM-Rev 01, ENSR, 2006). Another method uses streamflow measurements collected by the USGS on the Cimarron River at Dover (upstream) and Guthrie (downstream) and basin scaling to estimate the rate of groundwater discharge from the Western Alluvial area and the Burial Area #1. These approaches indicated that flow-through volume estimates may range over more than an order of magnitude depending on the methodology for making the estimate. In turn, depending on the technique to calculate flow-through volumes, different groundwater fluxes through the plume areas may be calculated.

Equivalent Porous Media Assumption

The MODFLOW model assumes that flow is through a porous media. That is, MODFLOW is designed to model groundwater flow through unconsolidated materials. MODFLOW is often used to model consolidated soils and bedrock, but flow through these materials may be governed by fractured flow, not porous media flow. The presence of fractures may greatly affect the direction and rate of groundwater flow especially on a local scale. For example, if the local groundwater flow system is dominated by a single fracture, the orientation of the fracture will control the direction of travel. Depending on the fracture's size, groundwater velocity through the fracture may be higher than would occur in more diffuse flow through a porous media even if the flux is the same. There is no evidence that groundwater flow and contaminant transport at the Cimarron Site are necessarily controlled by fracture flow. However, there may be local effects associated with fracturing the bedrock units. It is beyond the capabilities of the current model to accurately predict the time of travel through fractures in the consolidated soils or bedrock. Travel times through the consolidated units (sandstones and mudstones) can be calculated by MODPATH based on the assumption that the consolidated units are an equivalent porous media. The use of equivalent porous media assumptions are best suited for predictions over the scale of the model and may not provide accurate predictions local to a fracture or fracture system. Despite this uncertainty, groundwater flow is still likely to coincide generally with the surface water catchments and groundwater will discharge to the surface waters located within and adjacent to the site.

Steady-State Assumption

If the model should be used to simulate either groundwater extraction or injection, it should be noted that the groundwater model assumes that steady-state is reached instantaneously. In fact, there will be some time that will elapse before steady-state will be reached. Simulated pumping or injection also assumes that groundwater will be extracted from or injected into the entire cell saturated thickness. In fact, depending on where the well screen is placed and where the pump is set, this may not hold true. Simulated pumping or injection also occurs throughout the entire 10 foot by 10 foot cell. For these reasons, pumping and injection scenarios implemented in the field may result in drawdown and flow rates different from what has been predicted. Because the model accurately represents the conceptual model and overall observed flow rates, directions, and gradients, overall capture zones should be relatively accurate. As field data become available, they may be used to update and refine the model.