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.

Fate and Transport Issues

It should be noted that this application is a flow model and, as such, only considers the movement of water in the subsurface. Constituents dissolved in groundwater may be subject to processes that result in migration that cannot be explained exclusively by groundwater velocity (i.e., advection).

Groundwater velocities generated by the model and presented in the CSM, Rev.1 (ENSR, 2006) require input of a value for porosity for each of the geologic materials. There are no site-specific data on porosities, and they are likely to be very variable. Literature values were used. It should be recognized that the calculated velocities are directly dependent on these input values of porosity. Changes to the porosity values could potentially change estimate velocities by more than an order of magnitude.

5.0 SUMMARY AND CONCLUSIONS

Numerical groundwater models for the BA #1 and the WA areas have been conceptualized, developed, and calibrated to provide tools by which groundwater flow can be evaluated and changes to groundwater flow can be assessed as different remedial alternatives are simulated. In particular, in consideration of a bioremediation approach, the model may be used design scenarios for injection of reagents that will enhance stabilization of U and to demonstrate the permanence of uranium stabilization in groundwater.

The objective was achieved by developing and calibrating the numerical models to include key data that characterize groundwater flow at the site consistent with the CSM-Rev 01 (ENSR, 2006). Specifically, the BA #1 model domain included portions of the uplands at the site, which are underlain by a series of sandstone and mudstone layers, the transition zone, which is characterized by silts and clays underlain by sandstone and mudstone, and the alluvial valley where the geology is predominantly sand with smaller fractions of silt and clay. The BA #1 model was bounded on the south, in part, by the reservoir and on the north by the Cimarron River. The WA model included only the alluvial materials (sands, silts, clay) from the escarpment that forms the northern edge of the uplands to the Cimarron River. In the WA area, the alluvial materials are underlain by sandstone. Upgradient sandstones in both models are assumed to contribute groundwater to the alluvial soils and overlying sandstone and mudstone units. The Cimarron River is a discharge boundary to which all modeled groundwater flows.

Calibration targets included measured groundwater elevations, flow budgets, and flow path data. The flow models achieved good calibration to the observed groundwater elevation data, to the estimated water budgets, and to observed flow path trajectories. Discrepancies between observed and predicted elevations were reasonable. The simulated water table configuration for each model was consistent with flow paths suggested by observations of U concentrations. Overall hydrogeological concepts as presented in the Conceptual Site Model, Rev 01 (ENSR, 2006) were captured by the numerical models. A sensitivity evaluation established that the model simulations will be most sensitive to boundary conditions, especially the recharge from upgradient sandstone units. Uncertainties, especially associated with boundary conditions, are important when interpreting and using model predictions in remedial designs.

Ultimately, the resulting numerical models have captured key hydrologic and geologic features that shape the groundwater flow directions, patterns, and rates, thus satisfying the objective to provide useful tools to consider remediation design options. For instance, groundwater extraction can be simulated to create capture zones that include areas of high U concentration. Injection scenarios can also be simulated to ensure adequate distribution of reagents. Even the calibrated model itself can yield valuable information about groundwater flow directions and rates. For instance, the design of the bioremediation system requires estimates of groundwater flux to the plume area, which can be extracted from the model. The calibrated BA #1 model indicates that there are 19 gpm to the plume area. The calibrated WA area model indicates that there are 31 gpm to the impacted area. ARCADIS will use the model further to help design the bioremediation effort; their uses of the model will be documented in their work plan.

6.0 REFERENCES

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Tables

Table 1
Summary of Slug and Aquifer Test Results
Cimarron Corporation
Crescent, Oklahoma

		Hydraulic Conductivity (cm/s)									
		Analysis Methodology									
Geology	**Well**	**Slug Test Bouwer & Rice**	**Slug Test Hvorslev**	**Sieve Analysis**	**Pumping Test - Jacob Straight Line**	**Pumping Test - t/t'**	**Pumping Test - distance-drawdown**	**Butler and Garnett**	**Cooper-Bredehoeft-Papadopulos**	**Geometric Mean (cm/s)**	**Geometric Mean (ft/day)**
Alluvium	TMW-09***	6.01E-03	1.20E-03							2.69E-03	7.61
	TMW-13	6.99E-02	6.20E-02							6.58E-02	186.61
	02W2*	1.92E-05								1.92E-05	0.05
	02W10*	3.36E-04	2.80E-04							3.07E-04	0.87
	02W11***	3.24E-03	4.00E-03	1.70E-03						2.80E-03	7.95
	02W15	1.09E-02	1.80E-02	1.00E-02						1.25E-02	35.49
	02W16	3.66E-02	3.90E-02	1.10E-02						2.50E-02	70.98
	02W17	3.25E-02	6.00E-02	6.00E-03						2.27E-02	64.35
	02W22				8.90E-02					8.90E-02	252.28
	02W33	1.30E-02	1.90E-02	1.70E-03						7.49E-03	21.23
	02W46*	3.56E-05	1.37E-05							2.21E-05	0.06
	02W56**	4.20E-02	7.10E-02	1.70E-02	8.30E-02	8.30E-02	8.60E-02			5.58E-02	158.04
	02W58				9.60E-02	8.60E-02				9.09E-02	257.56
	02W59	1.40E-02	3.30E-02		9.60E-02	8.00E-02				4.34E-02	123.03
	02W60				1.10E-01	8.60E-02				9.73E-02	275.70
	02W61	2.20E-02	2.30E-02		1.10E-01	8.90E-02				4.72E-02	133.73
	02W62							2.80E-02		2.80E-02	79.37
	TMW-24							4.13E-02		4.13E-02	117.07
Sandstone B	TMW-01	6.35E-05	2.70E-05							4.14E-05	0.12
	TMW-20	9.97E-04	4.10E-04							6.39E-04	1.81
	02W40								5.50E-04	5.50E-04	1.56
	02W51	7.10E-05	2.39E-05							4.12E-05	0.12
Sandstone C	02W48		7.85E-05							7.85E-05	0.22

Notes:
All data presented is summarized from the Burial Area #1 Groundwater Assessment Report (Cimarron Corporation, 2003).
* Clay present at or near this well; data excluded from calculating ranges, mean.
** Pumping Well
*** Some clays/silts present in well screen; data excluded from calculating ranges, means.

Table 2
Summary of Groundwater Elevation Data used for Calibration
Cimarron Corporation
Crescent, Oklahoma

Summary ID	9/16/03 Water Level (feet)	12/16/03 Water Level (feet)	Aug/Sep 04 Water Level (feet)	5/24/05 Water Level (feet)	Avg WL Elevation (feet)
**1206				n/a-SEEP	-----
**1206				n/a-SEEP	-----
**1208				n/a-SEEP	-----
**1208				n/a-SEEP	-----
1311	965.48	964.83	966.02	962.70	964.76
1312	962.66	963.64	964.48	964.66	963.86
1312				964.66	964.66
1313	963.60	963.19	964.04	963.97	963.70
1314	944.02	943.67	944.14	944.57	944.10
1315R	932.31	934.73	935.46	936.45	934.74
1315R				936.45	936.45
1316R	931.57	932.89	936.84	936.12	934.35
1319 A-1	969.86	969.63	970.37	969.88	969.93
1319 A-2	969.74	969.49	-	969.79	969.68
1319 A-3	968.46	968.56	968.45	968.35	968.45
1319 B-1	946.73	947.13	948.35	pumping	947.40
1319 B-1				pumping	-----
1319 B-2	947.73	948.25	949.44	950.06	948.87
1319 B-3	946.67	947.12	948.37	949.02	947.79
1319 B-4	946.18	946.52	947.84	948.54	947.27
1319 B-5	945.61	944.87	946.24	947.37	946.02
1319 C-1	942.27	943.81	946.01	pumping	944.03
1319 C-1				pumping	-----
1319 C-2	939.80	940.69	941.94	941.50	940.98
1319 C-3	939.06	939.78	941.07	940.85	940.19
1320	967.04	966.58	968.34	968.20	967.54
1321	935.97	936.45	937.74	938.07	937.06
1322	967.97	966.43	967.95	968.48	967.71
1323	941.84	942.49	943.29	944.19	942.95
1324	968.10	967.45	969.20	969.28	968.51
1325	971.25	970.62	972.44	972.31	971.66
1326	970.85	970.49	971.45	971.54	971.08
1327	966.02	965.95		966.62	966.19
1327B	966.05	965.55	966.01	966.63	966.06
1328	948.85	950.79	950.71	?	950.12
1329	968.26	967.97	968.00	968.62	968.21
1330	967.97	967.72	969.37	970.07	968.78
1331	965.80	965.30	967.02	966.63	966.19
1332	940.00	940.47	941.75	942.43	941.16
1333	967.92	967.16	968.48	969.03	968.15
1334	966.51	966.58	968.20	967.72	967.25
1335A	969.81	969.07	970.78	970.45	970.03
1336A	959.65	959.57	960.53	960.08	959.96
1337	965.90	965.48		966.95	966.11

Table 2
Summary of Groundwater Elevation Data used for Calibration
Cimarron Corporation
Crescent, Oklahoma

Summary ID	9/16/03 Water Level (feet)	12/16/03 Water Level (feet)	Aug/Sep 04 Water Level (feet)	5/24/05 Water Level (feet)	Avg WL Elevation (feet)
1338	943.71	943.62	945.25	939.32	942.98
1339	951.68	952.74	938.46	955.13	949.50
1340	961.49	961.42		962.42	961.78
1341	936.75	936.75		939.39	937.63
1342	929.95	930.13		930.40	930.16
1343	928.37	928.57		929.40	928.78
1344	925.84	926.22		928.62	926.89
1345	933.74	933.63	935.32	936.30	934.74
1346	937.60	937.31	938.81	939.22	938.23
1347	965.13	964.47		965.96	965.18
1348	975.27	975.26	977.96	977.50	976.49
1348			977.96	977.50	977.73
1349	971.74	971.23	973.71	973.83	972.63
1349			973.71		973.71
1350	974.98	974.69	977.08	980.01	976.69
1350			977.08		977.08
1351	969.93	969.78	971.33	970.80	970.46
1351			971.33		971.33
1352	966.49	966.06	967.89	967.50	966.99
1352			967.89	967.50	967.70
1352			967.89		967.89
1353	985.70	988.00	988.31	988.04	987.52
1353			988.31		988.31
1354	965.51	965.24	967.00	966.46	966.05
1354			967.00		967.00
1355	967.64	967.01	968.71	968.85	968.05
1355			968.71		968.71
1356	968.83	968.24	969.38	969.57	969.00
1356			969.38	969.57	969.47
1357	969.51	968.88	970.72	970.47	969.89
1357			970.72		970.72
1358	971.26	970.53	972.67	972.49	971.74
1358			972.67	972.74	972.71
1359			972.79		972.79
1359			972.79	974.82	973.80
1360			974.88		974.88
1360			974.88		974.88
02W01	930.56	932.92	934.49	934.51	933.12
02W02	928.87	930.72	932.30	932.25	931.03
02W03	926.43	927.99	930.33	930.40	928.79
02W04	927.64	928.09	929.64	929.81	928.79
02W04				929.81	929.81
02W05	927.43	927.86	929.56	929.77	928.65
02W06	927.37	927.77	929.56	929.78	928.62

Table 2
Summary of Groundwater Elevation Data used for Calibration
Cimarron Corporation
Crescent, Oklahoma

Summary ID	9/16/03 Water Level (feet)	12/16/03 Water Level (feet)	Aug/Sep 04 Water Level (feet)	5/24/05 Water Level (feet)	Avg WL Elevation (feet)
02W07	927.53	927.98	929.53	929.76	928.70
02W07				929.76	929.76
02W08	927.57	928.02	929.57	929.80	928.74
02W08				929.80	929.80
02W09	933.09	935.51	936.32	936.57	935.37
02W10	931.73	934.39	935.54	935.62	934.32
02W11	927.27	927.85	929.57	929.73	928.61
02W12	927.29	927.83	929.69	929.71	928.63
02W13	927.41	927.91	929.71	929.89	928.73
02W14	927.27	927.77	929.50	929.70	928.56
02W15	927.34	927.81	929.60	929.80	928.64
02W16	927.37	927.81	929.50	929.77	928.61
02W17	914.25	927.87	929.55	929.80	925.37
02W18	927.30	927.75	929.47	929.69	928.55
02W19	927.56	927.95	929.47	929.41	928.59
02W19				929.41	929.41
02W20	936.42	937.88	938.04	937.99	937.58
02W21	927.43	927.84	929.46	929.74	928.62
02W22	927.42	927.85	929.50	929.72	928.62
02W23	927.42	927.74	929.56	929.79	928.63
02W23				929.79	929.79
02W24	927.32	927.75	929.53	929.75	928.59
02W25	940.60	941.84	947.51	946.01	943.99
02W26	934.13	936.34	937.00	937.14	936.15
02W27	930.37	931.97	934.48	933.97	932.70
02W28	931.52	934.17	935.30	935.41	934.10
02W29	932.59	935.12	936.19	936.65	935.14
02W30	932.19	934.13	937.03	937.17	935.13
02W31	931.19	933.83	934.97	935.02	933.75
02W32	927.31	927.84	929.61	931.65	929.10
02W33	927.44	927.85	929.52	929.77	928.65
02W33				929.77	929.77
02W34	927.44	927.71	929.39	929.66	928.55
02W35	938.70	927.92	929.36	929.60	931.39
02W36	927.42	927.83	929.46	929.71	928.60
02W37	934.00	934.40	935.82	936.03	935.06
02W38	926.67	927.10	929.47	929.64	928.22
02W39	933.00	935.46	936.43	936.90	935.45
02W40	938.36	939.05	940.18	940.18	939.44
02W41	936.42	937.80	938.62	938.66	937.88
02W42	934.42	936.09	941.05	940.34	937.98
02W43	927.35	927.91	929.29	929.53	928.52
02W43				929.53	929.53
02W44	929.23	927.77	929.35	929.55	928.97

Table 2
Summary of Groundwater Elevation Data used for Calibration
Cimarron Corporation
Crescent, Oklahoma

Summary ID	9/16/03 Water Level (feet)	12/16/03 Water Level (feet)	Aug/Sep 04 Water Level (feet)	5/24/05 Water Level (feet)	Avg WL Elevation (feet)
02W45	927.55	927.86	929.32	929.56	928.58
02W46	927.97	929.10	930.88	930.73	929.67
02W47	937.87	939.46	941.28	???	939.54
02W48	925.58	926.13		929.09	926.93
02W50	939.89	940.20	941.60	941.70	940.85
02W51	949.20	949.84	952.77	952.03	950.96
02W52	938.96	939.45	940.74	940.97	940.03
02W53	930.40	932.03	934.70	934.13	932.81
02W62	927.68	928.02	929.44	929.69	928.71
02W62				929.69	929.69
T-51	929.26	929.25		930.45	929.66
T-52	929.07	929.14		930.42	929.55
T-53	929.09	929.16		930.57	929.61
T-54	929.65	929.88	930.94	931.61	930.52
T-55	929.30	929.58		931.25	930.04
T-56	929.21	929.54		931.27	930.01
T-57	929.83	929.90	930.94	931.85	930.63
T-58	929.87	929.83	930.77	931.87	930.58
T-59	928.94	929.04		930.60	929.53
T-60	928.89	969.49		930.89	943.09
T-61	928.65	928.65		930.79	929.36
T-62	930.14	930.14	930.82	932.15	930.81
T-63			931.48	932.01	931.75
T-63	930.02	930.02	931.48	932.01	930.88
T-63			931.48		931.48
T-64	930.31	930.31	931.57	932.43	931.15
T-65	930.06	929.93	930.90	932.05	930.74
T-65				932.05	932.05
T-66			931.71		931.71
T-67			931.17		931.17
T-67			931.17		931.17
T-67			931.17		931.17
T-67			931.17		931.17
T-68			930.81		930.81
T-69			930.93		930.93
T-70					-----
T-70R			931.24		931.24
T-71					-----
T-72			930.96		930.96
T-73			931.02		931.02
T-74			931.20		931.20
T-75			930.88		930.88
T-76			931.04		931.04
T-77			930.82		930.82

Table 2
Summary of Groundwater Elevation Data used for Calibration
Cimarron Corporation
Crescent, Oklahoma

Summary ID	9/16/03 Water Level (feet)	12/16/03 Water Level (feet)	Aug/Sep 04 Water Level (feet)	5/24/05 Water Level (feet)	Avg WL Elevation (feet)
T-77			930.82		930.82
T-77			930.82		930.82
T-78			930.87		930.87
T-79			930.53		930.53
T-81			930.80		930.80
T-82			930.35		930.35
TMW-01	939.36	940.23	942.38	943.82	941.45
TMW-02	940.65	940.99	941.29	941.62	941.14
TMW-05	930.74	933.29	934.56	934.02	933.15
TMW-06	932.81	935.77	936.02	936.05	935.16
TMW-07	930.17	932.54	933.41	933.05	932.29
TMW-08	933.75	935.89	936.50	936.99	935.78
TMW-09	931.68	934.32	935.02	935.28	934.08
TMW-09				935.28	935.28
TMW-13	927.66	928.18	929.36	929.77	928.74
TMW-13				929.77	929.77
TMW-17	932.23	933.08	933.97	934.11	933.35
TMW-17			933.97		933.97
TMW-18	927.30	927.76	930.18	930.05	928.82
TMW-19	dry	dry		n/a	-----
TMW-20	938.43	939.35		939.91	939.23
TMW-21	936.45	937.09	944.33	942.49	940.09
TMW-23	928.33	928.87	929.94	930.37	929.38
TMW-24	927.71	928.05	928.73	929.19	928.42
TMW-25	936.83	938.41	938.42	938.32	937.99

Table 3
BA #1 Summary of Model Inputs
Cimarron Corporation
Crescent, Oklahoma

Burial Area (BA#1)				
Subsurface Units:		**Value**	**Units**	**Reference**
Fill	K_H	3.30E+00	ft/day	Average of Silt, Sand, & Clay
Fill	K_V	3.30E-01	ft/day	10% of K_H
Fill	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Fill	Vertical Anisotropy (Kh/Kv)	1.0	-----	No vertical anisotropy
Fill	Specific Storage	NA	-----	Not required for steady-state simulation
Fill	Specific Yield	NA	-----	Not required for steady-state simulation
Fill	Long. Disp.	NA	-----	Not required for flow model
Fill	Porosity	30	%	Freeze & Cherry, 1979 Table 2.4
Silt	K_H	2.83E-01	ft/day	ENSR CSM Sec-3.2.1
Silt	K_V	2.83E-02	ft/day	10% of K_H
Silt	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Silt	Vertical Anisotropy (Kh/Kv)	1.0	-----	No vertical anisotropy
Silt	Specific Storage	NA	-----	Not required for steady-state simulation
Silt	Specific Yield	NA	-----	Not required for steady-state simulation
Silt	Long. Disp.	NA	-----	Not required for flow model
Silt	Porosity	20	%	Freeze & Cherry, 1979 Table 2.4
Sand	K_H	2.53E+02	ft/day	Average of pumping tests in alluvial wells
Sand	K_V	2.53E+01	ft/day	10% of K_H
Sand	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Sand	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Sand	Specific Storage	NA	-----	Not required for steady-state simulation
Sand	Specific Yield	NA	-----	Not required for steady-state simulation
Sand	Long. Disp.	NA	-----	Not required for flow model
Sand	Porosity	30	%	Freeze & Cherry, 1979 Table 2.4
Clay	K_H	5.00E-01	ft/day	Artificially high to improve model stability
Clay	K_V	5.00E-02	ft/day	10% of K_H
Clay	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Clay	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Clay	Specific Storage	NA	-----	Not required for steady-state simulation
Clay	Specific Yield	NA	-----	Not required for steady-state simulation
Clay	Long. Disp.	NA	-----	Not required for flow model
Clay	Porosity	20	%	Freeze & Cherry, 1979 Table 2.4
Sandstone-A	K_H	4.00E+01	ft/day	Calibrated to high end of range in ENSR CSM Sec-3.2.1
Sandstone-A	K_V	2.00E+00	ft/day	5% of K_H
Sandstone-A	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Sandstone-A	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Sandstone-A	Specific Storage	NA	-----	Not required for steady-state simulation
Sandstone-A	Specific Yield	NA	-----	Not required for steady-state simulation
Sandstone-A	Long. Disp.	NA	-----	Not required for flow model
Sandstone-A	Porosity	5	%	Freeze & Cherry, 1979 Table 2.4

Table 3
BA #1 Summary of Model Inputs
Cimarron Corporation
Crescent, Oklahoma

Burial Area (BA#1)				
Subsurface Units:		**Value**	**Units**	**Reference**
Siltstone	K_H	8.43E+00	ft/day	
	K_V	4.22E-01	ft/day	5% of K_H
	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
	Specific Storage	NA	-----	Not required for steady-state simulation
	Specific Yield	NA	-----	Not required for steady-state simulation
	Long. Disp.	NA	-----	Not required for flow model
	Porosity	1	%	Freeze & Cherry, 1979 Table 2.4
Sandstone-B	K_H	5.00E+00	ft/day	Calibrated to high end of range in ENSR CSM Sec-3.2.1
	K_V	2.50E-01	ft/day	5% of K_H
	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
	Specific Storage	NA	-----	Not required for steady-state simulation
	Specific Yield	NA	-----	Not required for steady-state simulation
	Long. Disp.	NA	-----	Not required for flow model
	Porosity	5	%	Freeze & Cherry, 1979 Table 2.4
Sandstone-C	K_H	3.00E+00	ft/day	Slug test results at well 02W48
	K_V	1.50E-01	ft/day	5% of K_H
	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
	Specific Storage	NA	-----	Not required for steady-state simulation
	Specific Yield	NA	-----	Not required for steady-state simulation
	Long. Disp.	NA	-----	Not required for flow model
	Porosity	5	%	Freeze & Cherry, 1979 Table 2.4

Cimarron River:	**Value**	**Units**	**Reference**
Upstream Elevation	924.8	feet	Based on Dover and Guthrie gage datums
Downstream Elevation	924.8	feet	Based on Dover and Guthrie gage datums
Conductance	10,000	(ft^2/day)/ft	Estimate to for high river/aquifer connectivity

Areal Boundaries:	**Value**	**Units**	**Reference**
Recharge	5.48E-04	ft/day	ENSR CSM Sec-3.1.1 & 3.1.4

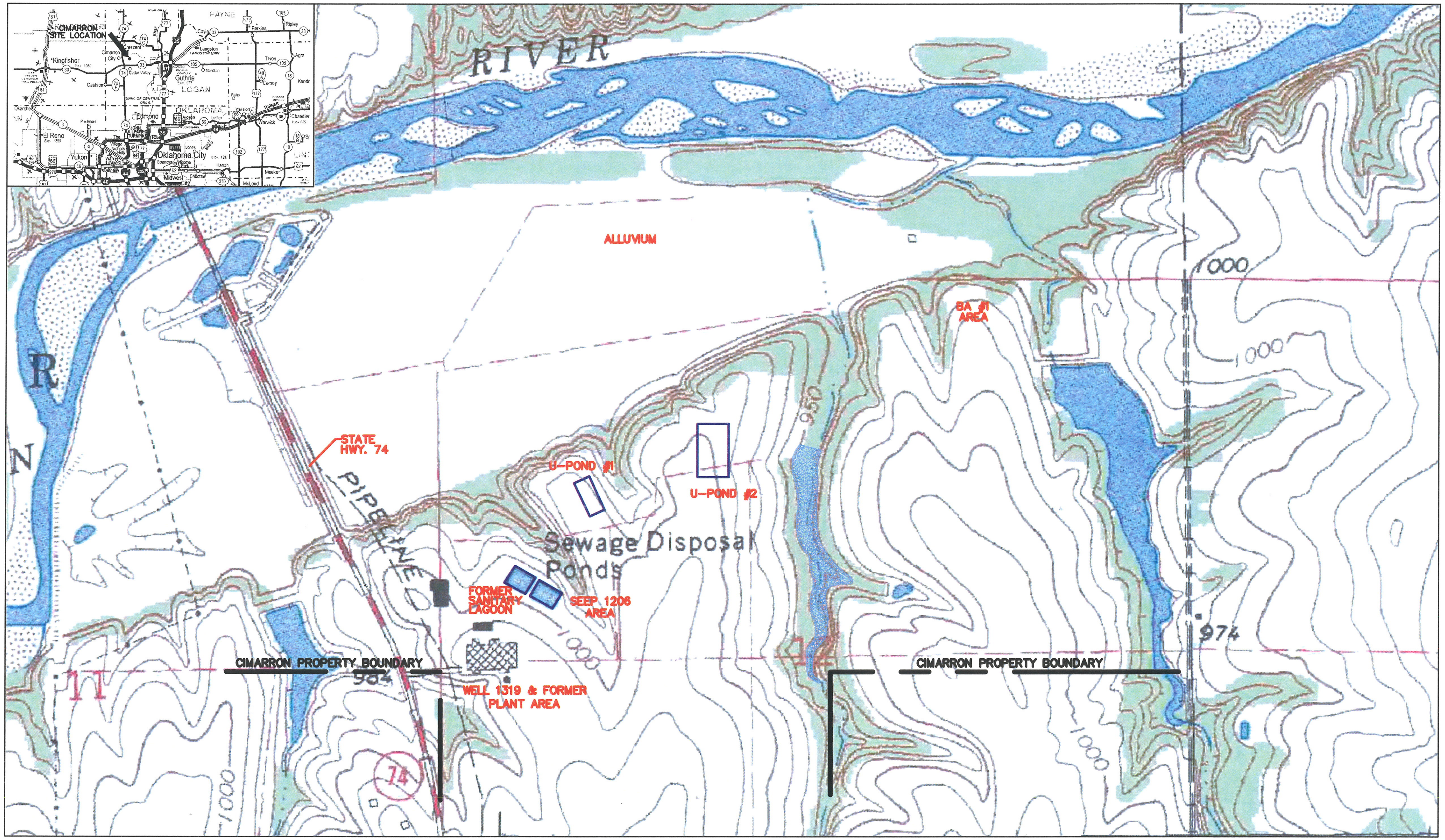
Table 4
WA Summary of Model Inputs
Cimarron Corporation
Crescent, Oklahoma

Western Alluvial Area (WA)				
Subsurface Units:		**Value**	**Units**	**Reference**
Clay	K_H	5.00E-01	ft/day	ENSR CSM Sec-3.2.1
Clay	K_V	5.00E-02	ft/day	10% of K_H
Clay	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Clay	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Clay	Specific Storage	0.001	-----	Default
Clay	Specific Yield	0.001	-----	Default
Clay	Long. Disp.	10	-----	Default
Clay	Porosity	20	%	Freeze & Cherry, 1979 Table 2.4
Sand	K_H	2.35E+02	ft/day	Average of pumping tests in alluvial wells
Sand	K_V	2.35E+01	ft/day	10% of K_H
Sand	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Sand	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Sand	Specific Storage	0.001	-----	Default
Sand	Specific Yield	0.001	-----	Default
Sand	Long. Disp.	10	-----	Default
Sand	Porosity	30	%	Freeze & Cherry, 1979 Table 2.4
Sandstone-C	K_H	3.00E+00	ft/day	Slug test results at well 02W48
Sandstone-C	K_V	1.50E-01	ft/day	5% of K_H
Sandstone-C	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
Sandstone-C	Vertical Anisotropy (K_H/K_V)	1.0	-----	No vertical anisotropy
Sandstone-C	Specific Storage	0.001	-----	Default
Sandstone-C	Specific Yield	0.001	-----	Default
Sandstone-C	Long. Disp.	10	-----	Default
Sandstone-C	Porosity	5	%	Freeze & Cherry, 1979 Table 2.4

Cimarron River:	**Value**	**Units**	**Reference**
Upstream Elevation	924.8	feet	Based on Dover and Guthrie gage datums
Downstream Elevation	924.8	feet	Based on Dover and Guthrie gage datums
Conductance	20,000	$(ft^2/day)/ft$	Medium estimate based on prior experience

Areal Boundaries:	**Value**	**Units**	**Reference**
Recharge	5.48E-04	ft/day	ENSR CSM Sec-3.1.1 & 3.1.4

Figures



REFERENCE: UNITED STATES GEOLOGICAL SURVEY
CRESCENT QUADRANGLE, OKLAHOMA–LOGAN CO.
7.5 MINUTE SERIES (TOPOGRAPHIC), 1970 (PHOTOINSPECTED 1981).

0 800 1600

SCALE IN FEET

DWG. NO. 040200056

NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS
3.		6/8/05	JAS

REVISIONS

DESIGNED BY:
DRAWN BY: JAS
CHECKED BY: DJF
APPROVED BY: DJF

ENSR | AECOM

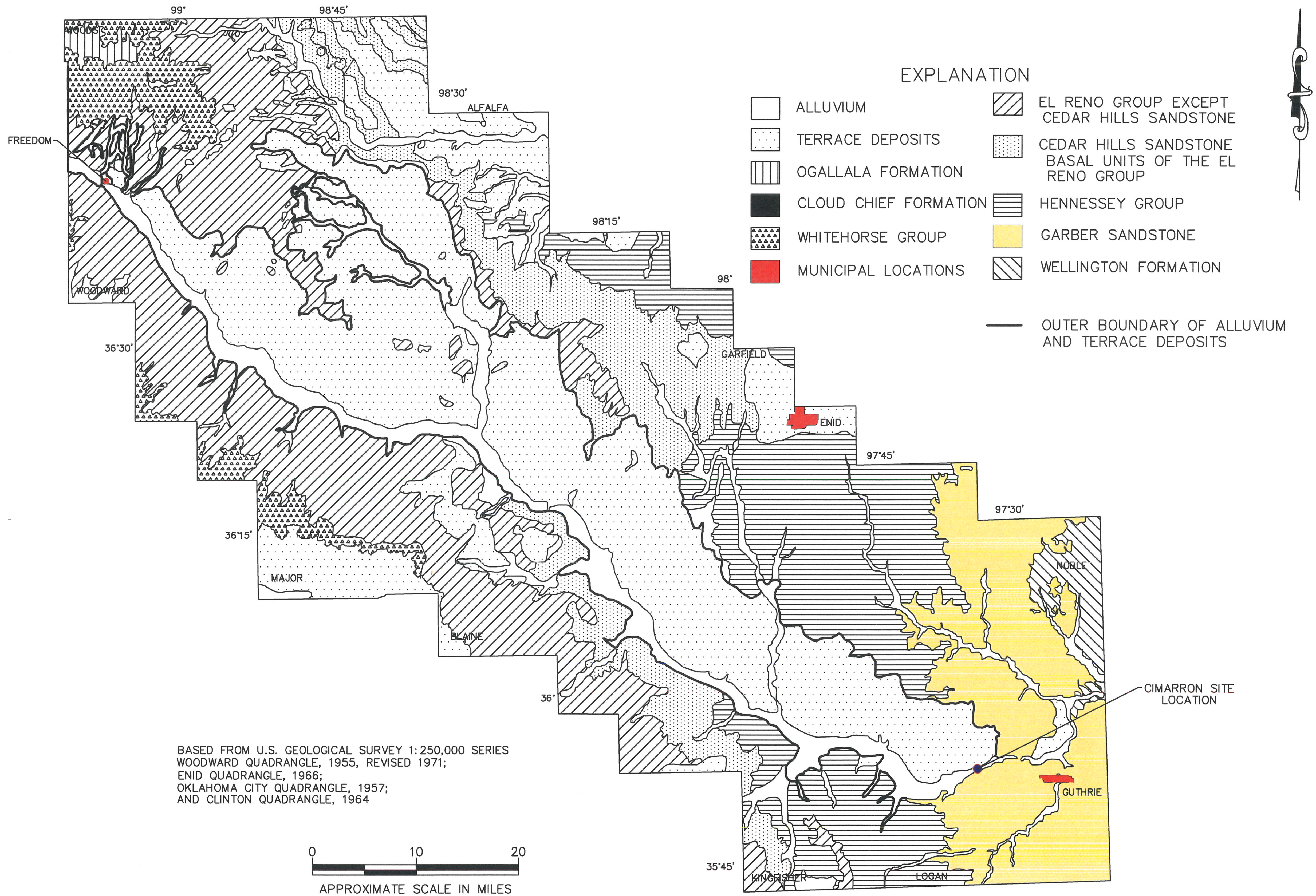
ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

FIGURE 1
SITE LOCATION MAP
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE: 1" = 800'
DATE: 9/22/06
PROJECT NUMBER: 04020-044-327

FIGURE NUMBER: 1

SHEET NUMBER: 1



NO.:	DESCRIPTION:	DATE:	BY:
1.		4/10/05	JAS
2.		6/17/05	JAS

REVISIONS

DESIGNED BY:
DRAWN BY: JAS
CHECKED BY: DJF
APPROVED BY: DJF

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HOUSTON, TEXAS 77081-2214
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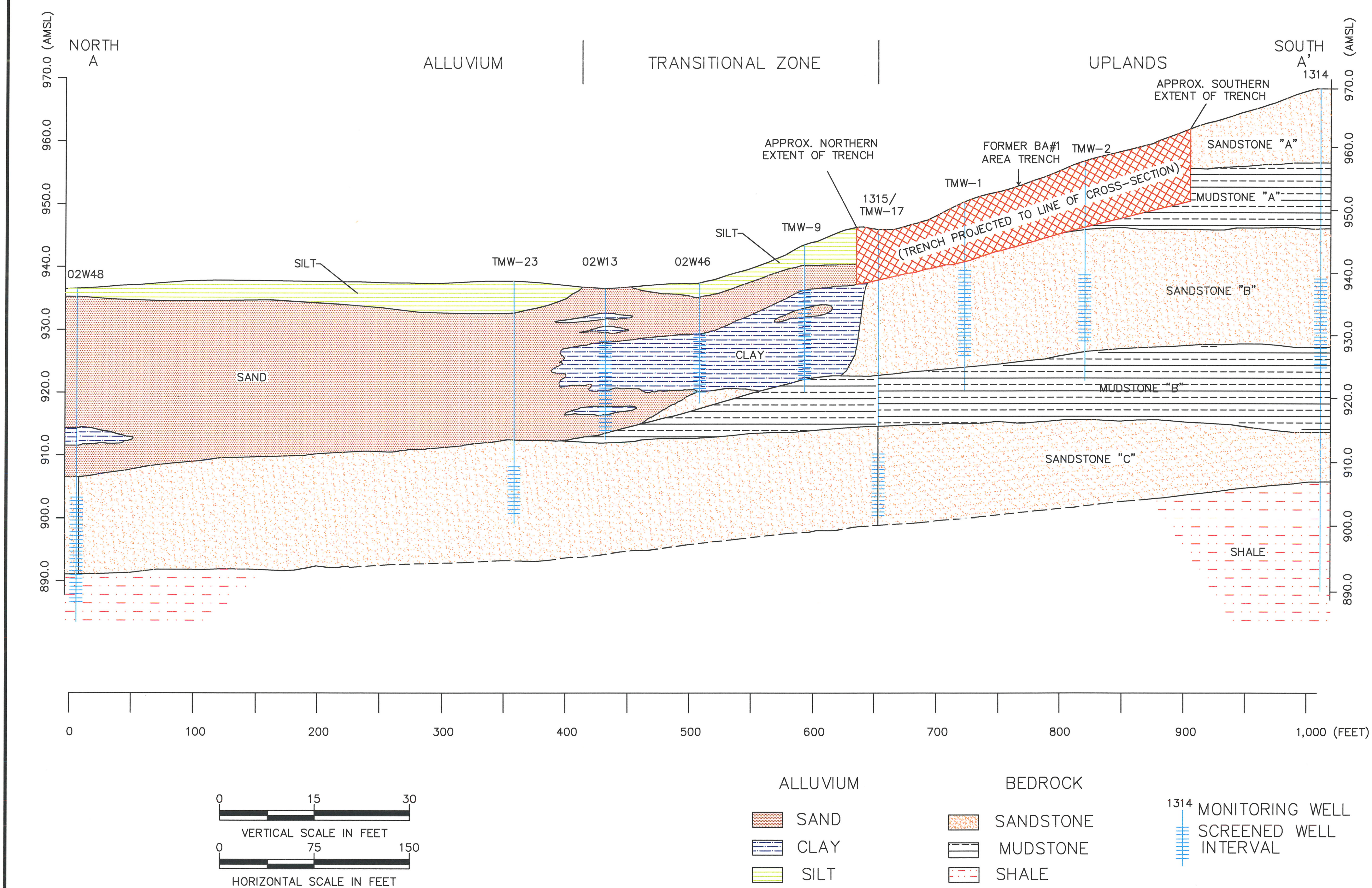
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

FIGURE 2
GEOLOGY ALONG THE CIMARRON RIVER
FROM FREEDOM TO GUTHRIE, OKLAHOMA
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE: 1"=10 miles
DATE: 9/22/06
PROJECT NUMBER: 04020-044-327

FIGURE NUMBER: 2
SHEET NUMBER: 1

DWG. NO. 040200012



DWG. NO. 040200005

REVISIONS			
NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS

DESIGNED BY:
DRAWN BY: JAS
CHECKED BY: DJF
APPROVED BY: DJF

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ENSR CORPORATION
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HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

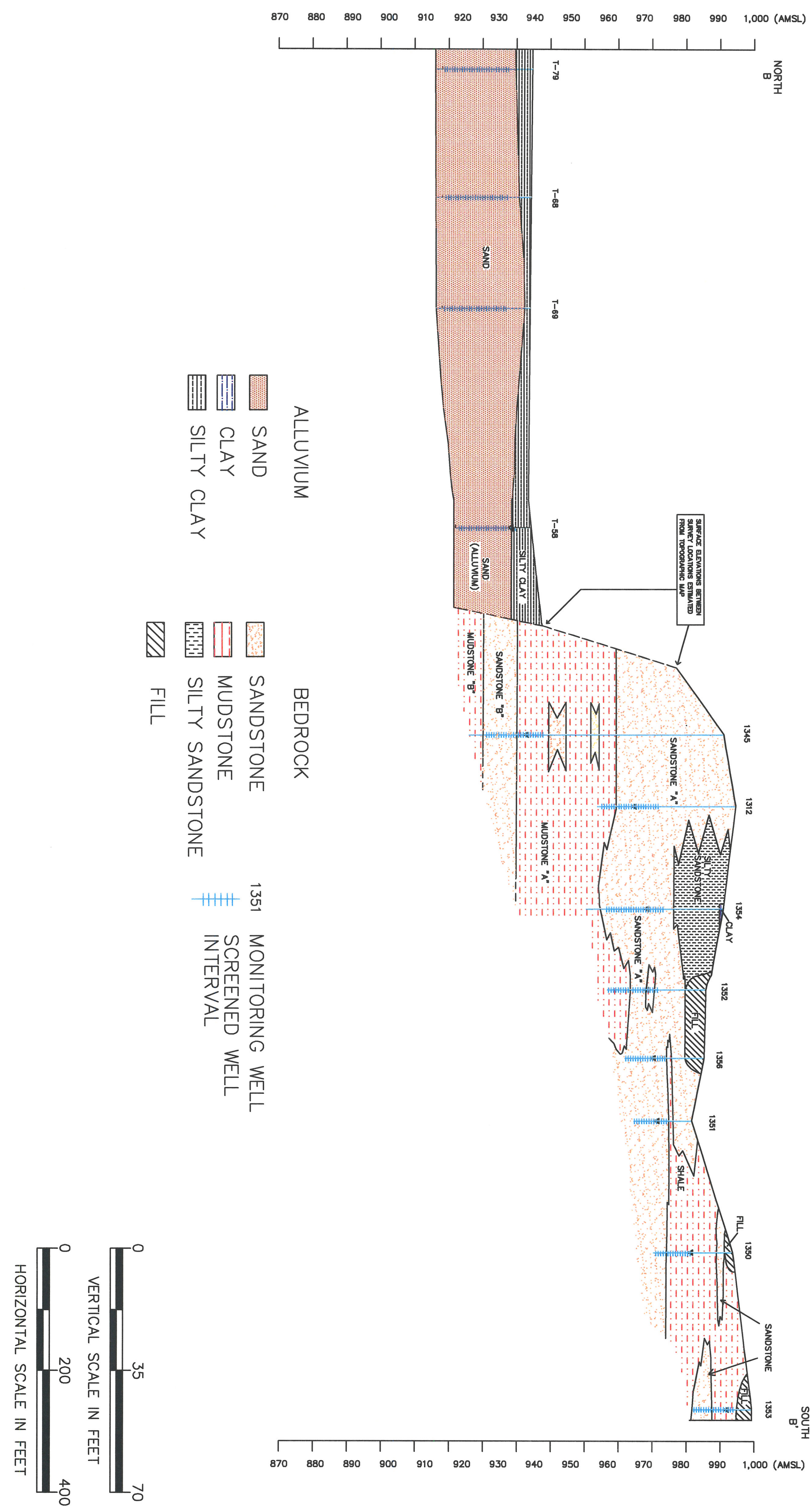
FIGURE 3
BA #1 AREA
REPRESENTATIVE GEOLOGICAL CROSS-SECTION
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE: 1" = 75'
DATE: 9/22/06
PROJECT NUMBER: 04020-044-327

FIGURE NUMBER: 3

SHEET NUMBER: 1

DWG. NO. 040200009



SHEET NUMBER:	FIGURE NUMBER:
1	4

FIGURE 4
REPRESENTATIVE GEOLOGICAL CROSS-SECTION WESTERN UPLAND AND ALLUVIAL AREAS CIMARRON CORPORATION CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1" = 200'	9/22/06	04020-044-327

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DESIGNED BY:	
DRAWN BY:	JAS
CHECKED BY:	DJF
APPROVED BY:	DJF

REVISIONS

NO.:	DESCRIPTION:	DATE:	BY:
1.		4/01/05	JAS
2.		6/17/05	JAS

N

BA #1 Boundary

NOT TO SCALE

BA #1 Model Domain
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

Figure
5

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N

WA Area Boundary

NOT TO SCALE

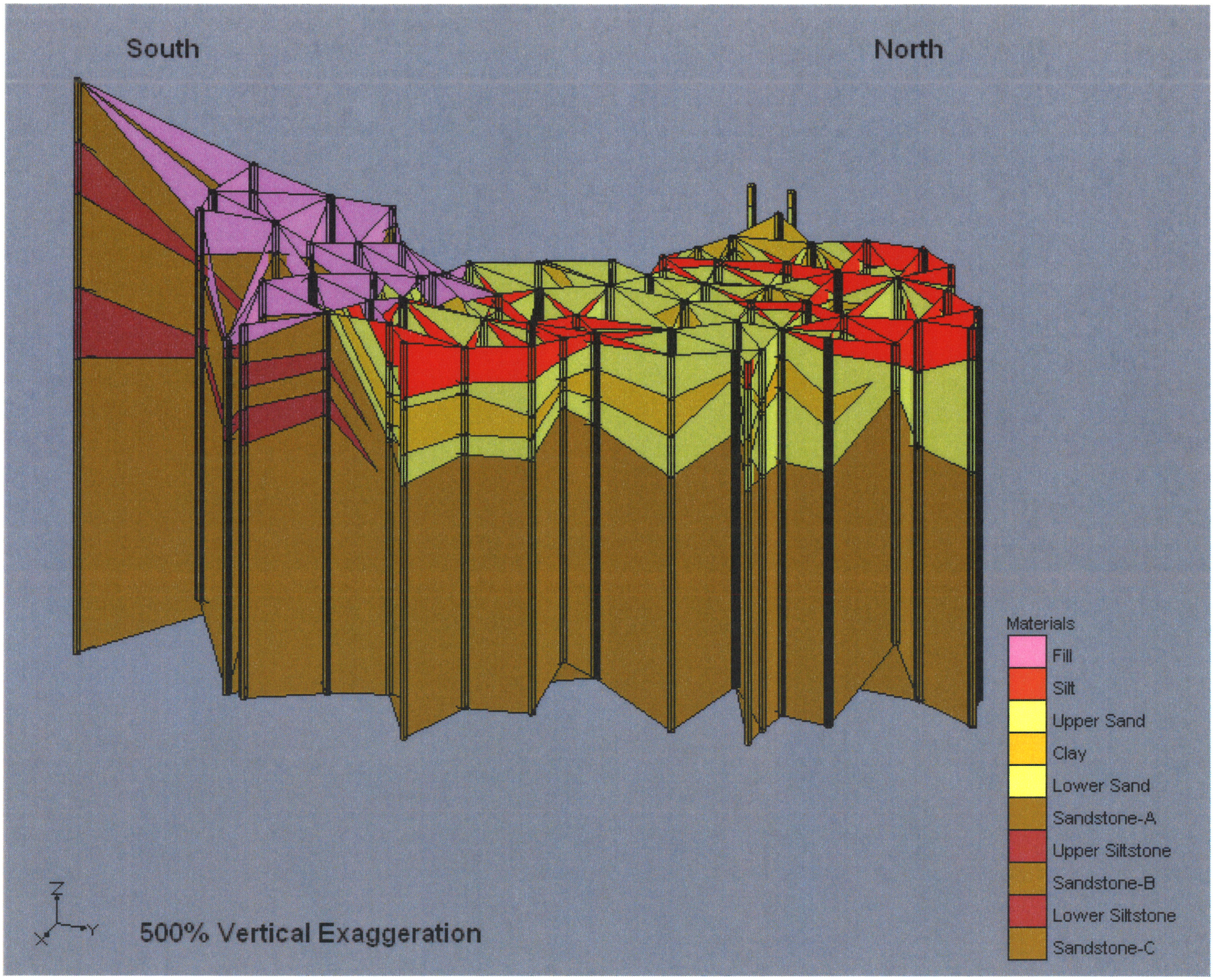
WA Area Model Domain
Cimarron Corporation
Crescent, Oklahoma

DATE	PROJECT
October 2006	04020-044-300

ENSR | AECOM

Figure
6

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\FI0BD2~1.MXD



BA #1 Boreholes and Cross-sections
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

Figure
7

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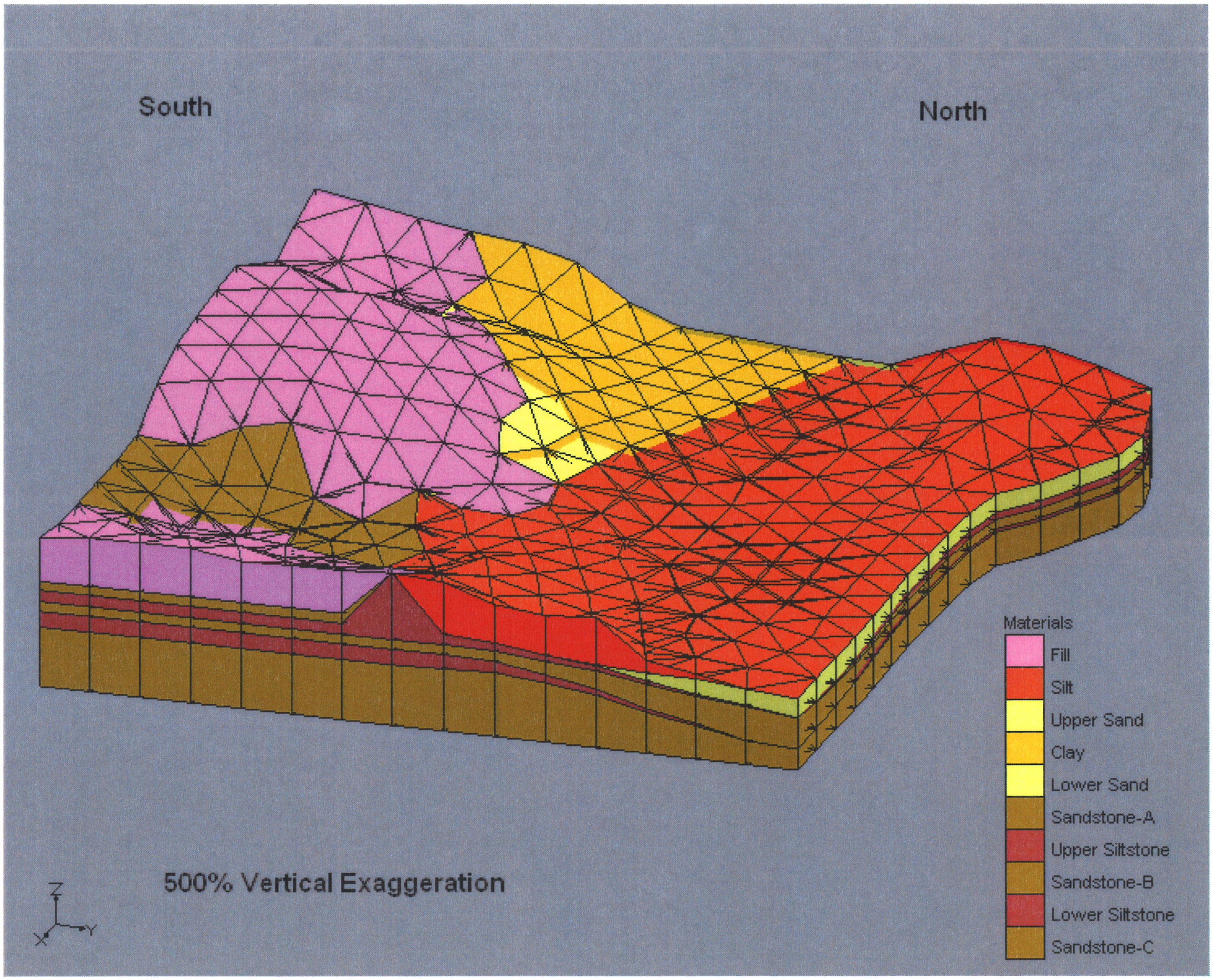


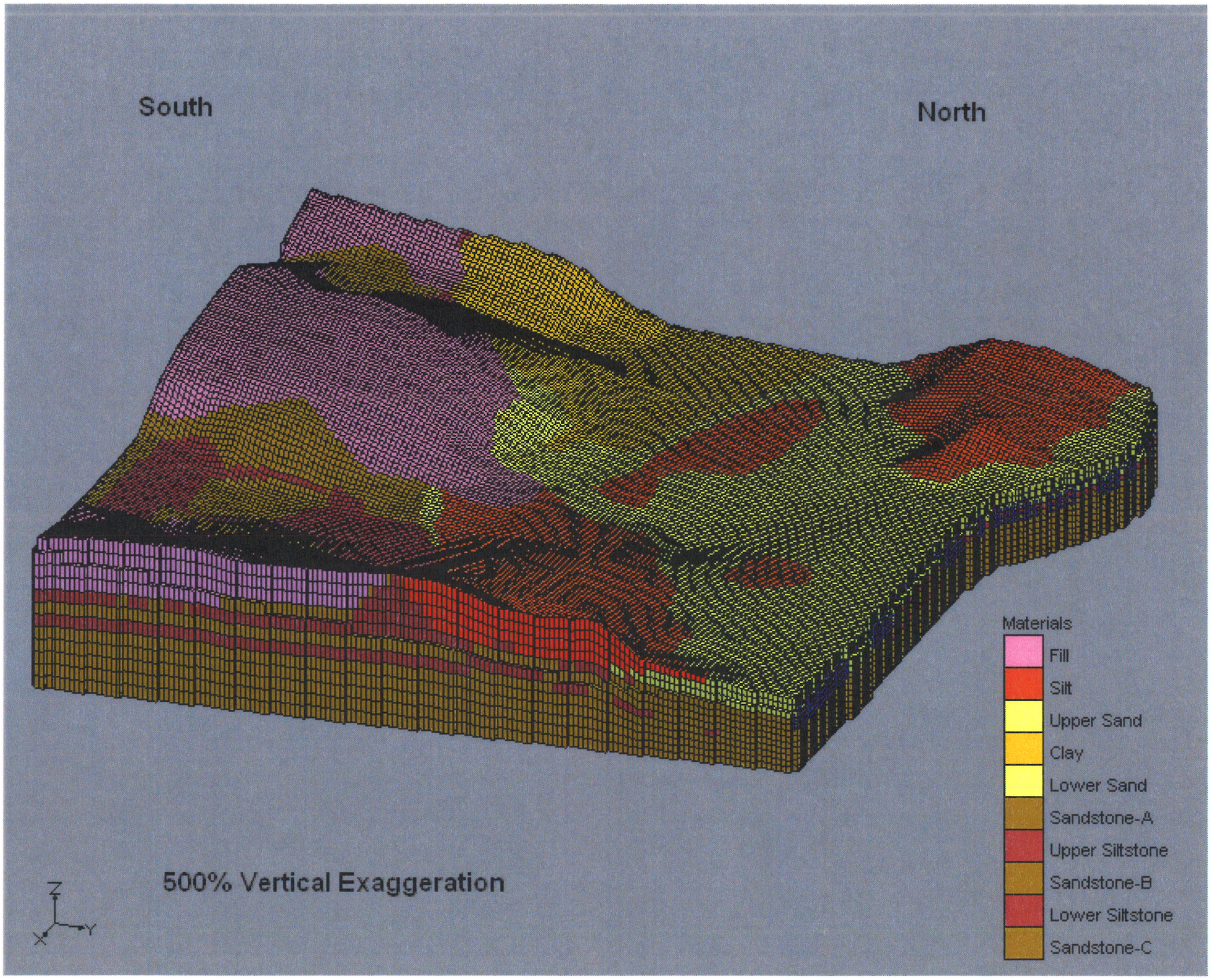
BA #1 Solids Developed
from Borehole Data
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

Figure
8

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure8.mxd



	BA #1 3D Grid Incorporating Geologic Information Cimarron Corporation Crescent, Oklahoma		ENSR | AECOM
	DATE	PROJECT	Figure 9
	October 2006	04020-044-300	

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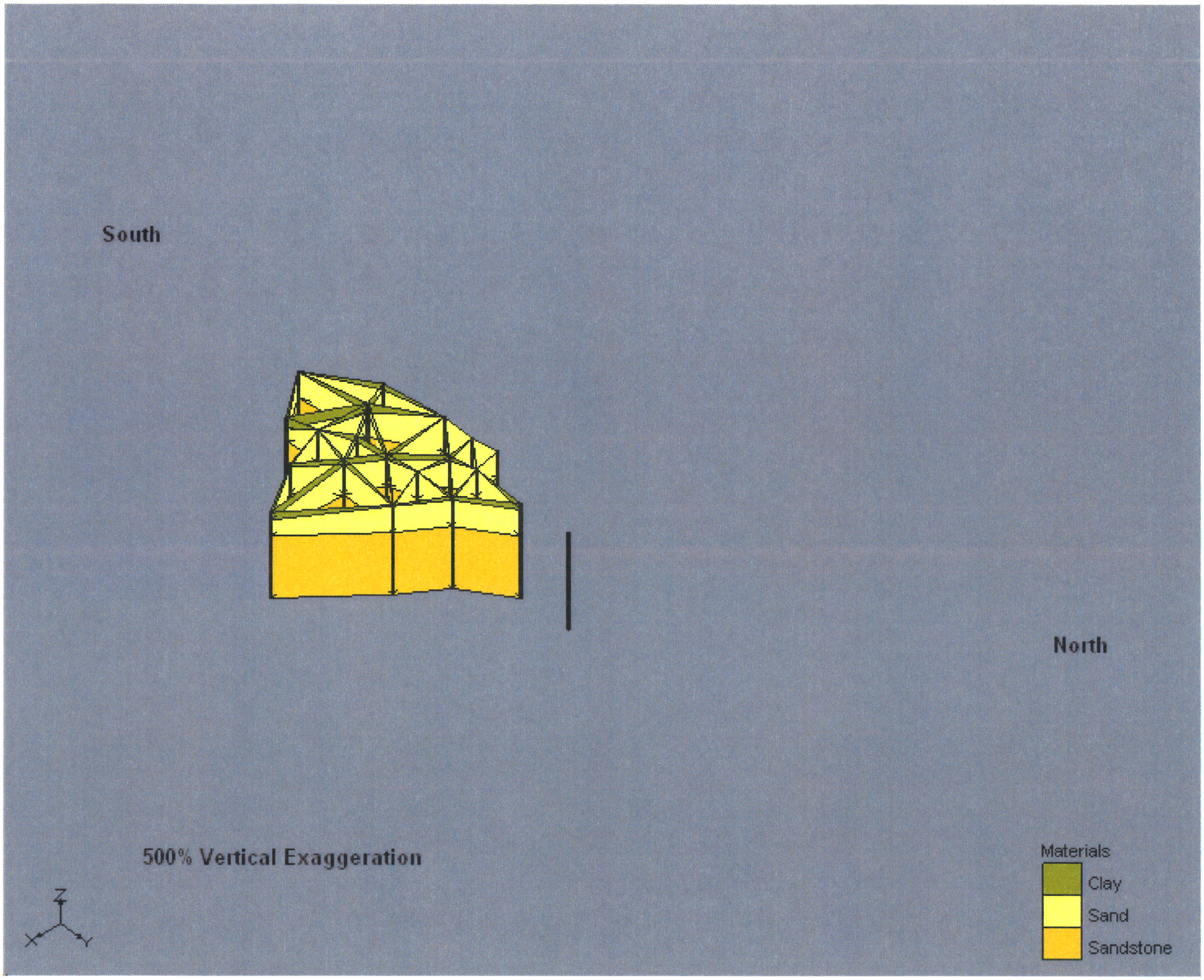
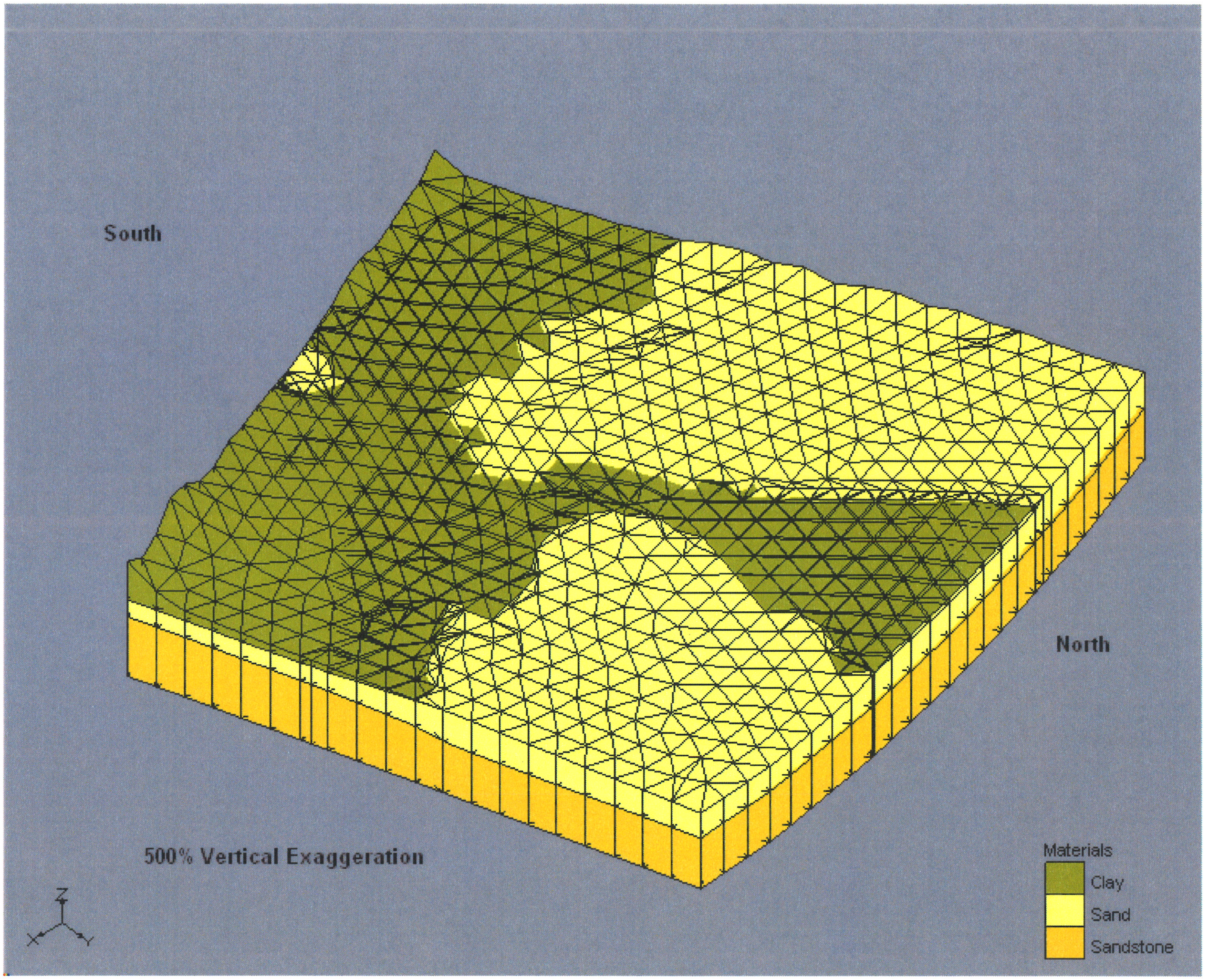


Note:
Shows extent of borings
and cross-sections.
Figure 11 shows extrapolation
of geology to model domain.

	WA Area Boreholes and Cross-sections Cimarron Corporation Crescent, Oklahoma	ENSR | AECOM
	DATE: October 2006 / PROJECT: 04020-044-300	Figure **10**

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure10.mxd



WA Area Solids Developed
from Borehole Data
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

Figure
11

DATE	PROJECT
October 2006	04020-044-300

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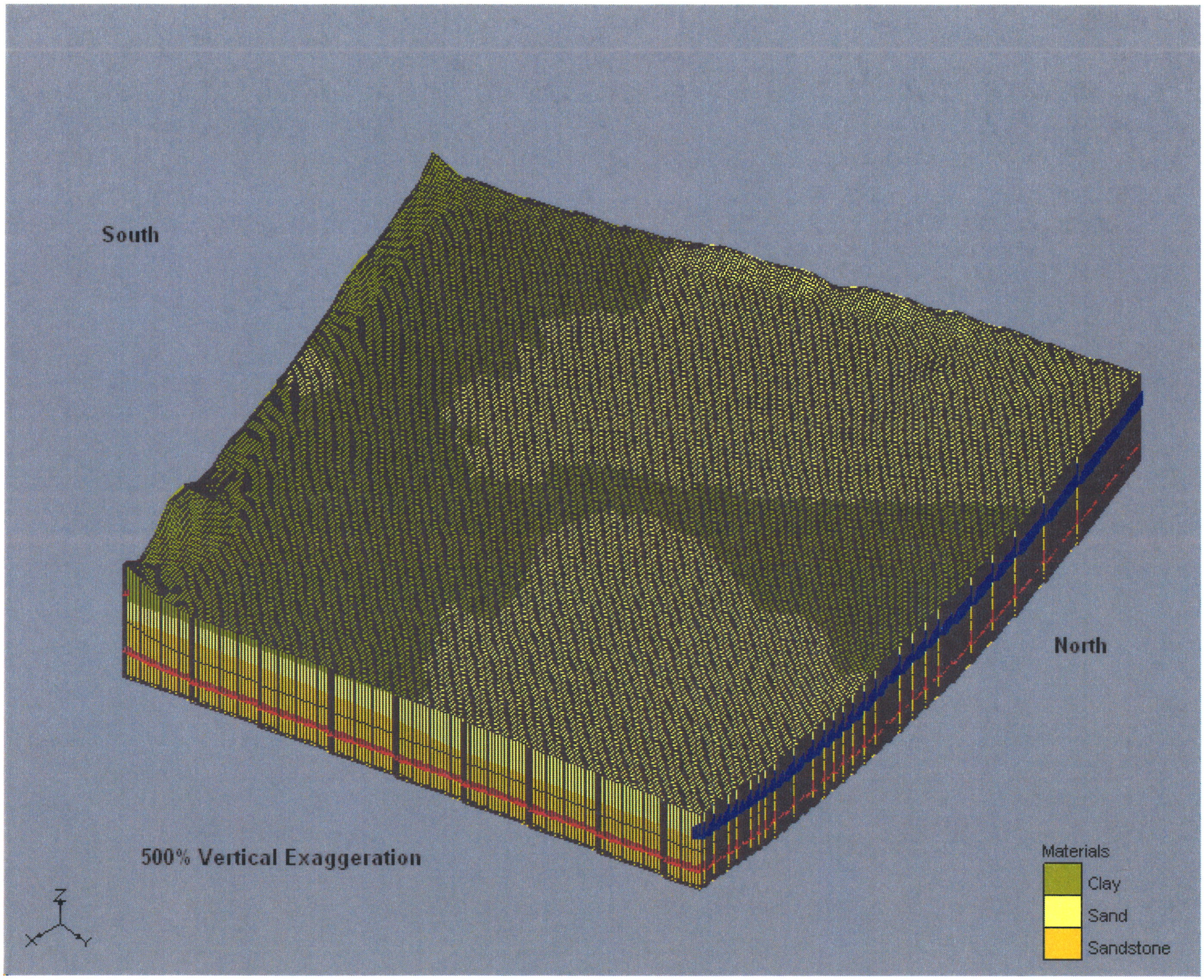

WA Area 3D Grid Incorporating Geologic Information Cimarron Corporation Crescent, Oklahoma		ENSR | AECOM
DATE	PROJECT	Figure **12**
October 2006	04020-044-300	

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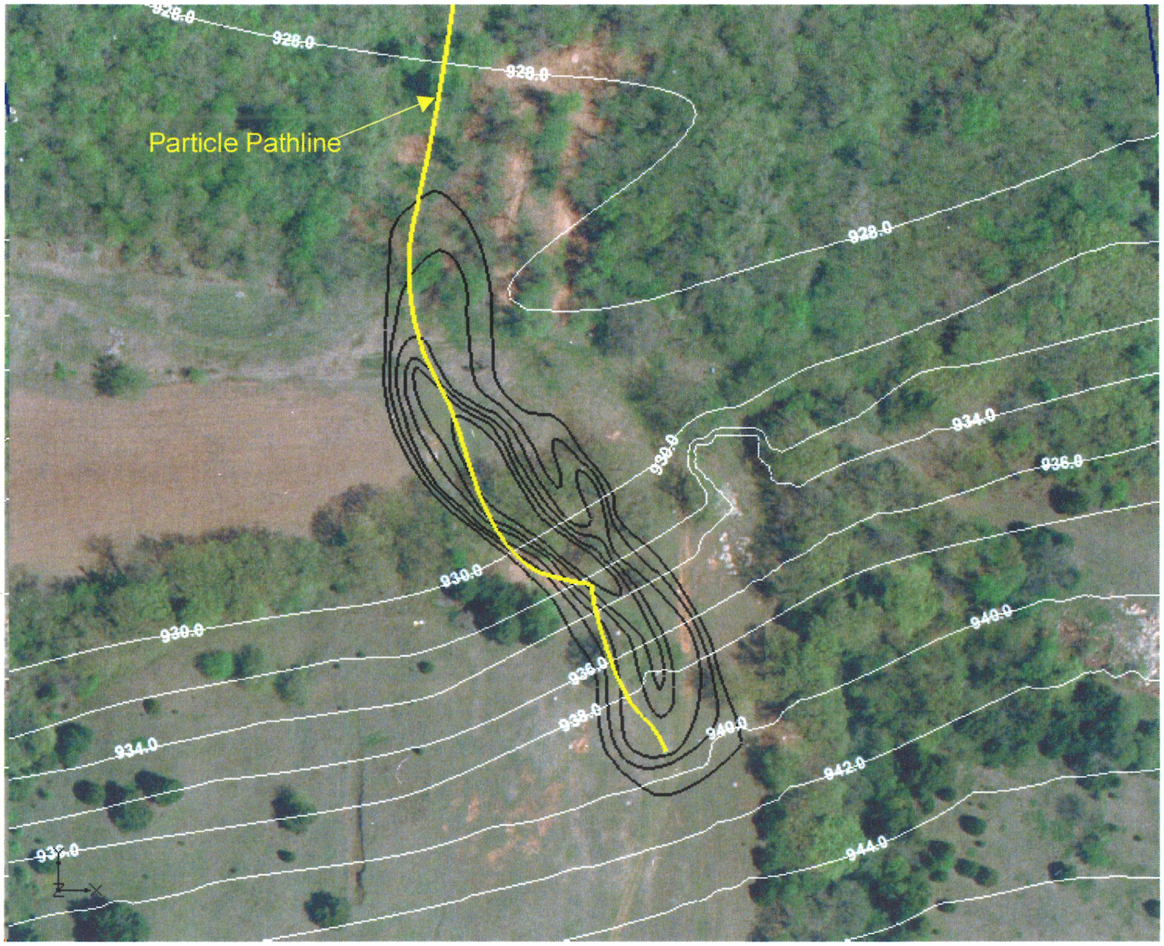
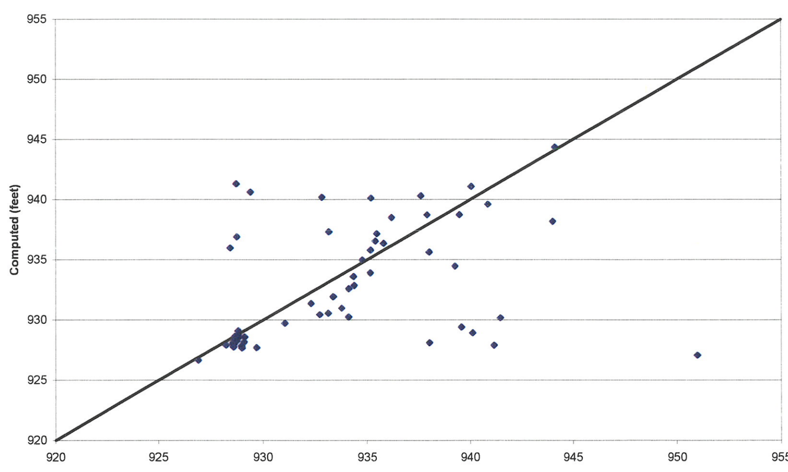
Predicted Groundwater Contours and Particle Pathlines



MODFLOW Computed vs Observed Groundwater Levels



NOT TO SCALE

N

Results of Burial Area #1 Model Calibration:
Predicted Groundwater Contours with Pathline
and Measured vs Predicted Water Levels

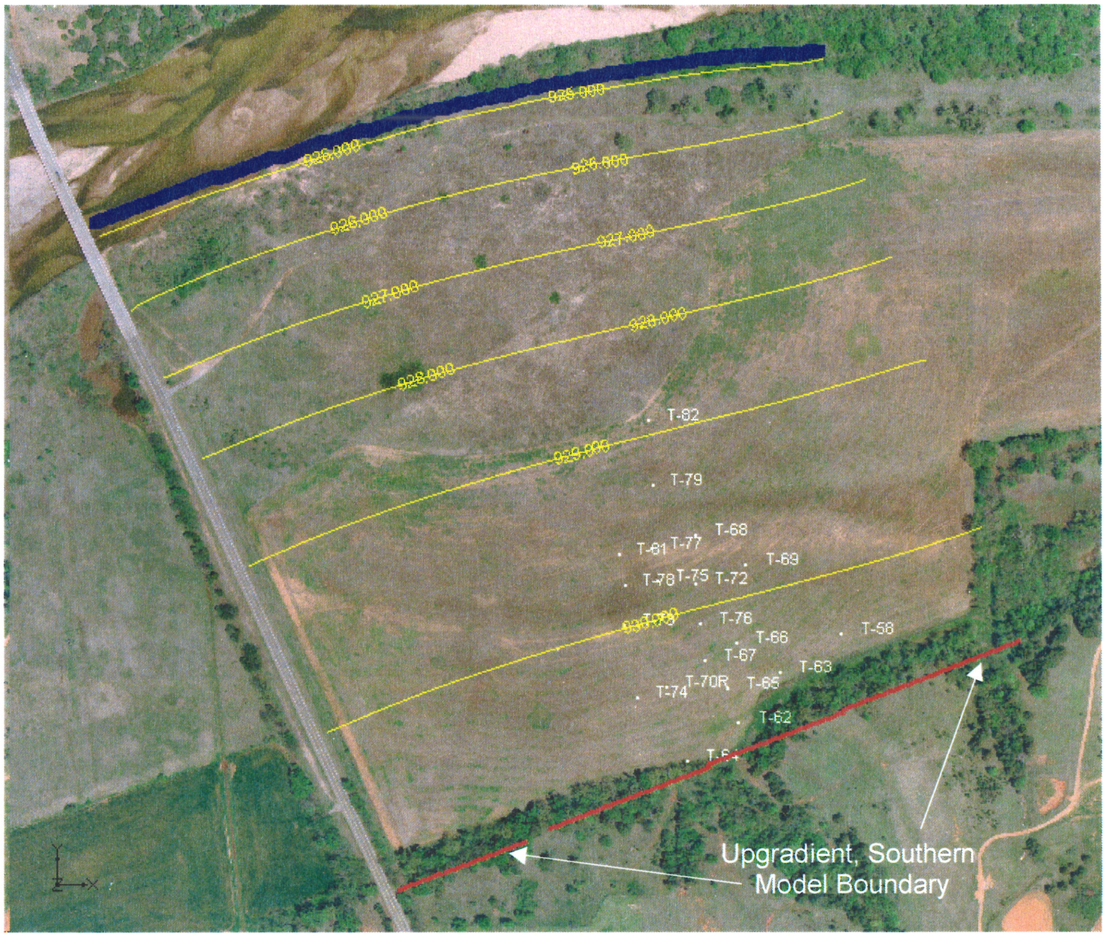
October 2006

ENSR | AECOM

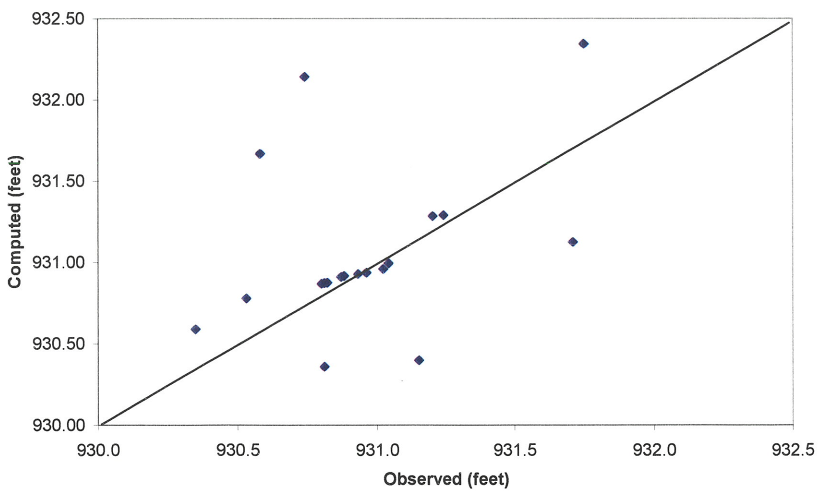
Figure
13

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\FIFF2A~1.MXD

Predicted Groundwater Contours



MODFLOW Computed vs Observed Groundwater Levels



N

NOT TO SCALE

Results of Western Alluvial Area Model Calibration:
Predicted Groundwater Contours and
Measured vs Predicted Water Levels

October 2006

ENSR | AECOM

Figure
14

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure14.mxd

APPENDIX B GROUNDWATER FLOW MODEL UPDATE REPORT (BURNS & MCDONNELL, 2014)

GROUNDWATER FLOW MODEL UPDATE
CIMARRON REMEDIATION SITE

Prepared for

CIMARRON ENVIRONMENTAL RESPONSE TRUST

Prepared by

Burns & McDonnell Engineering Company, Inc.
Kansas City, Missouri

Project No. 72454

January 2014

GROUNDWATER FLOW MODEL UPDATE
CIMARRON REMEDIATION SITE

Prepared for

CIMARRON ENVIRONMENTAL RESPONSE TRUST

January 2014

Project No. 72454

Prepared by

Burns & McDonnell Engineering Company, Inc.
Kansas City, Missouri

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LIST OF ACRONYMS AND ABBREVIATIONS

amsl	above mean sea level
CSM	Conceptual Site Model
DCGL	Derived Concentration Goal Level
DEQ	Oklahoma Department of Environmental Quality
EPM	Environmental Properties Management LLC
ft	foot/feet
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 Groundwater Flow Model Update for the Cimarron site (the Site), located at 100 N. Highway 74, Guthrie, 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.

The models were updated with new geologic and hydrogeologic data, based on additional assessment performed in 2012 and 2013. The WA model area was expanded to include a larger area. The base of the alluvial aquifer was updated with new geologic information. The porosity was also updated in both models. Both models were recalibrated to a more comprehensive round of groundwater levels collected in November 2013. 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 mean, and 3) a qualitative match of model simulated potentiometric surface and observed potentiometric surface evaluated by comparing contours.

Upon Nuclear Regulatory Commission (NRC) and Oklahoma Department of Environmental Quality (DEQ) approval, the updated models will be used to evaluate alternative remediation scenarios using a particle tracking model (MODPATH). Groundwater extraction with both groundwater recovery trenches and extraction wells will be added to the models, and these will be resubmitted with anticipated groundwater flow rates for both Phase I and Phase II remediation efforts. Upon approval of these revised flow models, a groundwater remediation design will be prepared; this will be included in a comprehensive license amendment request.

1.1 BACKGROUND AND OBECTIVES

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 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 DEQ 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 Western Upland (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 roughly 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. Once the flow models are approved, two phases of groundwater extraction and injection will be evaluated: Phase I will address uranium exceeding NRC's release criteria, and Phase II will address COCs exceeding MCLs.

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.

* * * * *

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 WA area 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 WA area is generally northeastward toward the Cimarron River; flow is driven by a relatively flat hydraulic gradient of 0.002 foot/foot. Figure 2-1 presents a potentiometric surface map of the alluvium for the WA area based on groundwater level measurements during November 2013. Additional wells installed in the 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).

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 November 2013. 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. 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 0.0007 ft/ft.

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3.0 GROUNDWATER MODEL CONSTRUCTION

A detailed description of the groundwater model construction is provided in Appendix A. 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 V (Rumbaugh, 2007). Both groundwater models were run using steady state assumptions.

The numerical model domain for the WA area is shown on Figure 3-1; the model was expanded eastward to address remedial alternatives in the entire area of the nitrate plume as defined by the 10-mg/L isoconcentration contour; it therefore covers a larger area than the 2006 groundwater model. The northern boundary of the model domain remains the Cimarron River and the southern boundary of the model is the extent of the transition zone. The grid size remains 10 feet by 10 feet and contains 159,343 active cells. The model origin (left-bottom corner) is located at X = 2090530 and Y = 320886 in Oklahoma State Plane Coordinates. The model grid is rotated (minus) 20 degrees. The WA model domain includes two layers: Layer 1 represents the alluvium and Layer 2 represents the underlying bedrock.

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. There are twelve layers in the model. 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.

No adjustments were made to the number of model layers for either model. For the WA area the base of Layer 1 was adjusted with new bedrock depth data. For BA #1 new boring data collected in the alluvium suggested the model layer elevations for the sandstone needed to be adjusted, therefore slight adjustments were made to the bedrock elevation in the model. No additional changes were made to the top or base of layers.

3.2 BOUNDARY CONDITIONS

The model boundary conditions represent the hydrologic interactions between the inside and outside of the model domain. The boundary conditions simulate flow into and out of the groundwater model.

3.2.1 No Flow Boundaries

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.

3.2.2 General Head Boundaries

The upgradient boundaries for both the WA area and BA #1 were represented as a General Head Boundary. The upward hydraulic gradient from the underlying bedrock described in the site *Conceptual Site Model Revision 01* (ENSR, 2006b) was represented as a General Head Boundary. 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 upward flow of deep groundwater through the alluvium a General Head Boundary was used in the lowest layer in both model domains to represent a higher water level at depth than in the alluvial aquifer (ENSR, 2006a). The General Head Boundary along the southern edge of the model for the WA area was updated to account for the water level elevations observed in the wells during the November 2013 water level measurement event and to match the direction of groundwater flow observed with the recently installed wells in the WA area. No changes were made to the groundwater elevations in Sandstone B.

The general head boundaries for BA #1 were updated during model calibration to enable more accurate prediction of groundwater flow direction in the Sandstone and Alluvium. The general head boundary along the southern boundary of the model, which represents the upgradient boundary was adjusted (in some cases the head was higher, and in some cells the head was decreased). The general head boundary in layer 12 (representing an upward gradient from the lowest bedrock layer) was also adjusted slightly as part of model calibration to match the direction of groundwater flow. These adjustments were reasonable and were made to enable a better calibration to the larger data set available for this model update.

3.2.3 River Boundaries

River boundary conditions were updated based on U.S. Geological Survey (USGS) monitoring station data, groundwater level measurements close to the river and as part of model calibration. Data from the

USGS monitoring stations at Dover (30.0 miles upstream to the west) and Guthrie (10.3 miles downstream to the east) were downloaded to determine river elevations at the time of the November water level measurement event. It was determined that the water levels in the area of the Site were on the order of 930 ft amsl to 933 ft amsl, from east to west. Small variations in river boundary heads were made during model calibration. No changes were made to the boundary conductance or the riverbed elevation.

3.3 HYDROGEOLOGIC PROPERTIES

Pneumatic slug tests were performed on select wells in the Western Alluvium to collect data to supplement and verify hydraulic conductivities values used in the 2006 WA model. In addition, conventional slug testing was also performed on select Burial Area #1 wells during the hydrogeologic investigation. After review of new and existing data, no changes were made to the hydraulic conductivity parameters from the 2006 models. The parameters used for each of the areas are provided in Table 3-1. The porosity was updated and is also presented in Table 3-1. These values are based on either site-specific data or (where site data is not available) on values obtained from published literature, as listed in Table 3-1.

3.4 RECHARGE

Based upon a review of precipitation data from 2013, this year appears to have been a higher than normal precipitation year and water levels at the site were higher than in the 2006 model in accordance with the higher recharge. The calendar year 2013 was the 9th wettest year on record for Central Oklahoma, with 41.1 inches of rainfall through October, compared to mean annual precipitation of 37 inches (Oklahoma Climatological Survey, 2013). No changes were made to the recharge values originally presented in the 2006 model because this year does not represent a typical year and the recharge values are meant to represent a long term average condition.

3.5 MODEL CALIBRATION

Table 3-2 and Table 3-3 present the most recent water level measurements available from November 2013 for the WA area and BA #1, respectively. All wells were used as calibration targets except BA #1 wells 02W25 and 02W51, which are screened over multiple zones represented by multiple layers in the BA #1 model.

Both models were recalibrated to water levels collected in November 2013. 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) absolute residual mean error of less than 5% of the range of water level measurements, and 3) a qualitative match of model simulated potentiometric surface and observed potentiometric surface evaluated by comparing contours. Discrepancies between observations and predictions are more pronounced in BA#1 near the transition zone where the groundwater gradient is steep.

3.5.1 Water Budget

The first model calibration goal is to evaluate the mass balance error. A model simulated water budget provides a picture of the flow volumes into and out of the model domain. Water budgets for BA #1 and the WA area for the calibration condition are provided in Table 3-4. General head boundaries account for the highest inflow and the head boundaries and river accounts for the largest outflow. The percent error in the water budget for both models is significantly less than 1%, indicating a stable model.

3.5.2 Comparison of Hydraulic Heads

Comparison of observed heads and simulated heads was conducted in two different ways including a statistical evaluation of the direct measurement of water level versus the simulated water level at the model targets and through a qualitative examination of simulated potentiometric surface and measured potentiometric surface.

For the WA area model, water level measurements were collected from 43 wells. Simulated and observed hydraulic heads for the steady-state model are compared in Table 3-5 and graphed on Figure 3-3. Both the river boundary elevation and the general head boundary condition were adjusted from the 2006 Model to account for the water elevations observed in November 2013. The simulated elevations near the river are influenced by the river and the exact stage of the river near the WA area is unknown, therefore there may be a slight bias to the water levels but the overall direction of groundwater flow matches the observed conditions. The residual mean is less than 0.1 feet.

For the BA #1 model water level measurements were collected from 70 wells. Simulated and observed hydraulic heads for the steady-state model are compared in Table 3-6 and graphed on Figure 3-4. The residual mean is less than 0.1 feet.

The model simulated potentiometric surface and the observed potentiometric surface were compared visually (Figures 3-5 and 3-6). The overall simulated surface is similar to the observed, with some differences to data density especially near the transition zone of BA#1. Discrepancies between observations and predictions are more pronounced in BA#1 near the transition zone where the groundwater gradient is steep.

3.5.3 Sensitivity Analysis

In the 2006 Groundwater Model (Appendix A), a sensitivity analysis was conducted on the flow model. The only parameters adjusted in this update in the WA area model were bedrock elevation (base of Layer 1), general head boundary, and river boundary stage. The only parameters adjusted in the BA#1 model were general head and river boundary stage. Therefore, sensitivity analysis was not repeated for hydraulic conductivity which was addressed in the 2006 Groundwater Model. Modifying the river stage +/- 1 foot changed the model calibration, indicating river stage (elevation) is a sensitive parameter (see Table 3-7). This parameter controls flows out of the groundwater models. In the WA area model modifications to the southern boundary general head changed the model calibration. In BA#1 the southern boundary general head was a relatively insensitive parameter.

3.6 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 REFERENCES

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