Appendix A

Groundwater Flow Modeling Report, Cimarron Site (ENSR)

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

Groundwater Flow Modeling Report

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Groundwater Flow Modeling Report

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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.

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
	K_V	3.30E-01	ft/day	10% of K_H
	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
	Vertical Anisotropy (Kh/Kv)	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	30	%	Freeze & Cherry, 1979 Table 2.4
Silt	K_H	2.83E-01	ft/day	ENSR CSM Sec-3.2.1
	K_V	2.83E-02	ft/day	10% of K_H
	Horozontal Anisotropy	1.0	-----	No horizontal anisotropy
	Vertical Anisotropy (Kh/Kv)	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	20	%	Freeze & Cherry, 1979 Table 2.4
Sand	K_H	2.53E+02	ft/day	Average of pumping tests in alluvial wells
	K_V	2.53E+01	ft/day	10% 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	30	%	Freeze & Cherry, 1979 Table 2.4
Clay	K_H	5.00E-01	ft/day	Artificially high to improve model stability
	K_V	5.00E-02	ft/day	10% 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	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
	K_V	2.00E+00	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

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

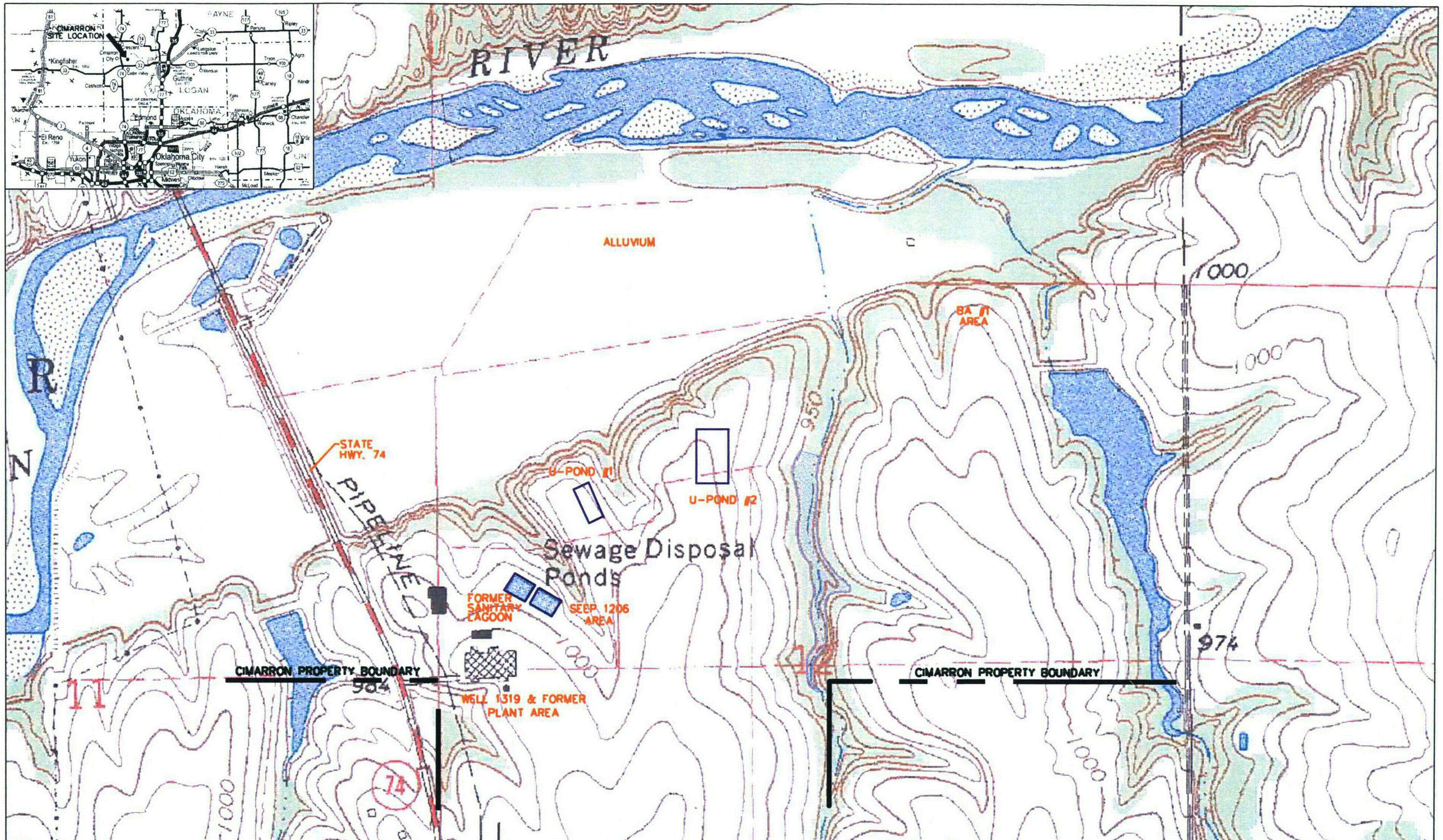
Table 4
WA Summary of Model Inputs
Cimarron Corporation
Crescent, Oklahoma

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

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
3.		6/8/05	JAS

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

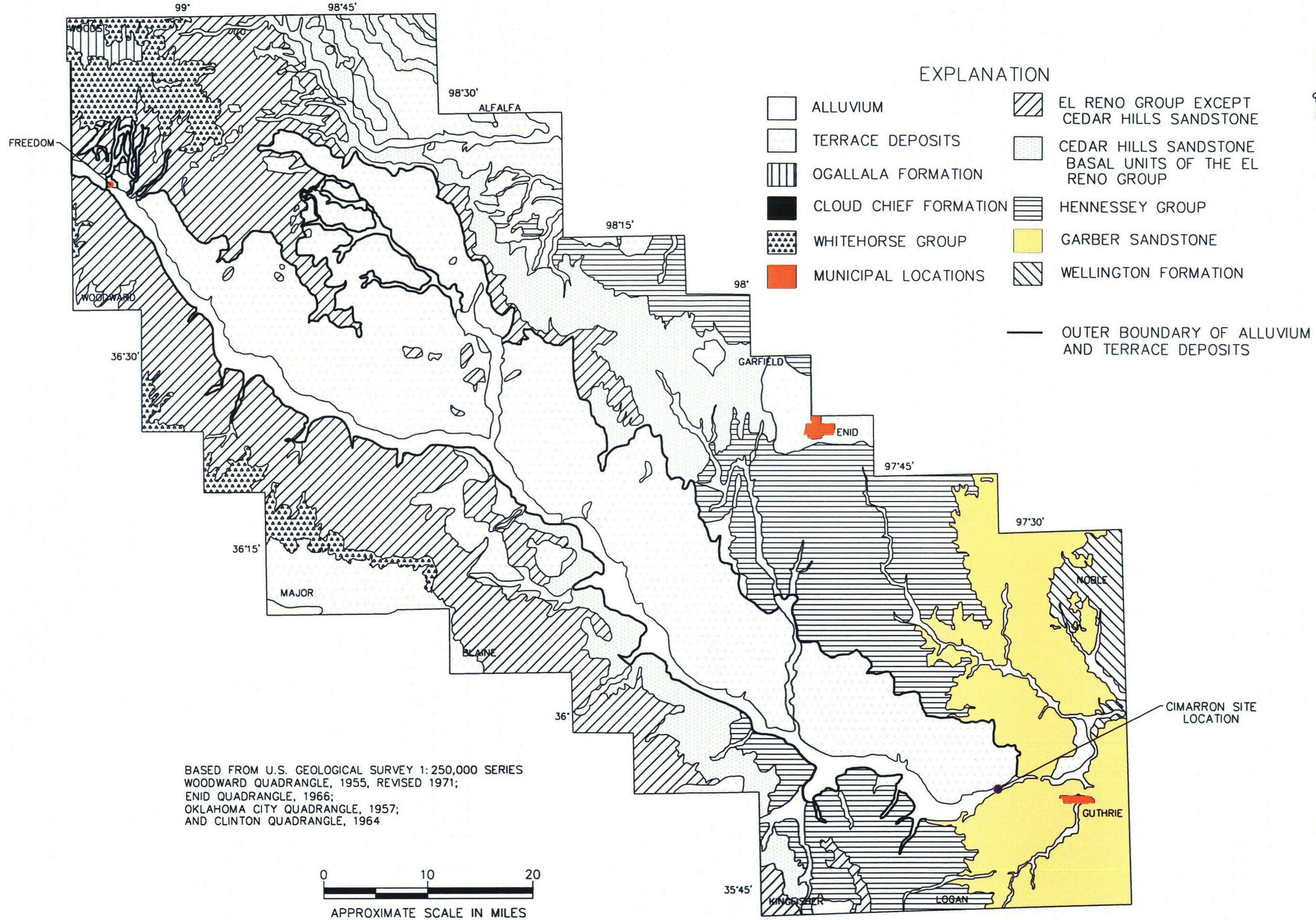
FIGURE 1
SITE LOCATION MAP
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

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

FIGURE NUMBER: 1

SHEET NUMBER: 1

DWG. NO. 040200056



BASED FROM U.S. GEOLOGICAL SURVEY 1:250,000 SERIES
WOODWARD QUADRANGLE, 1955, REVISED 1971;
ENID QUADRANGLE, 1966;
OKLAHOMA CITY QUADRANGLE, 1957;
AND CLINTON QUADRANGLE, 1964

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

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

ENSR | AECOM

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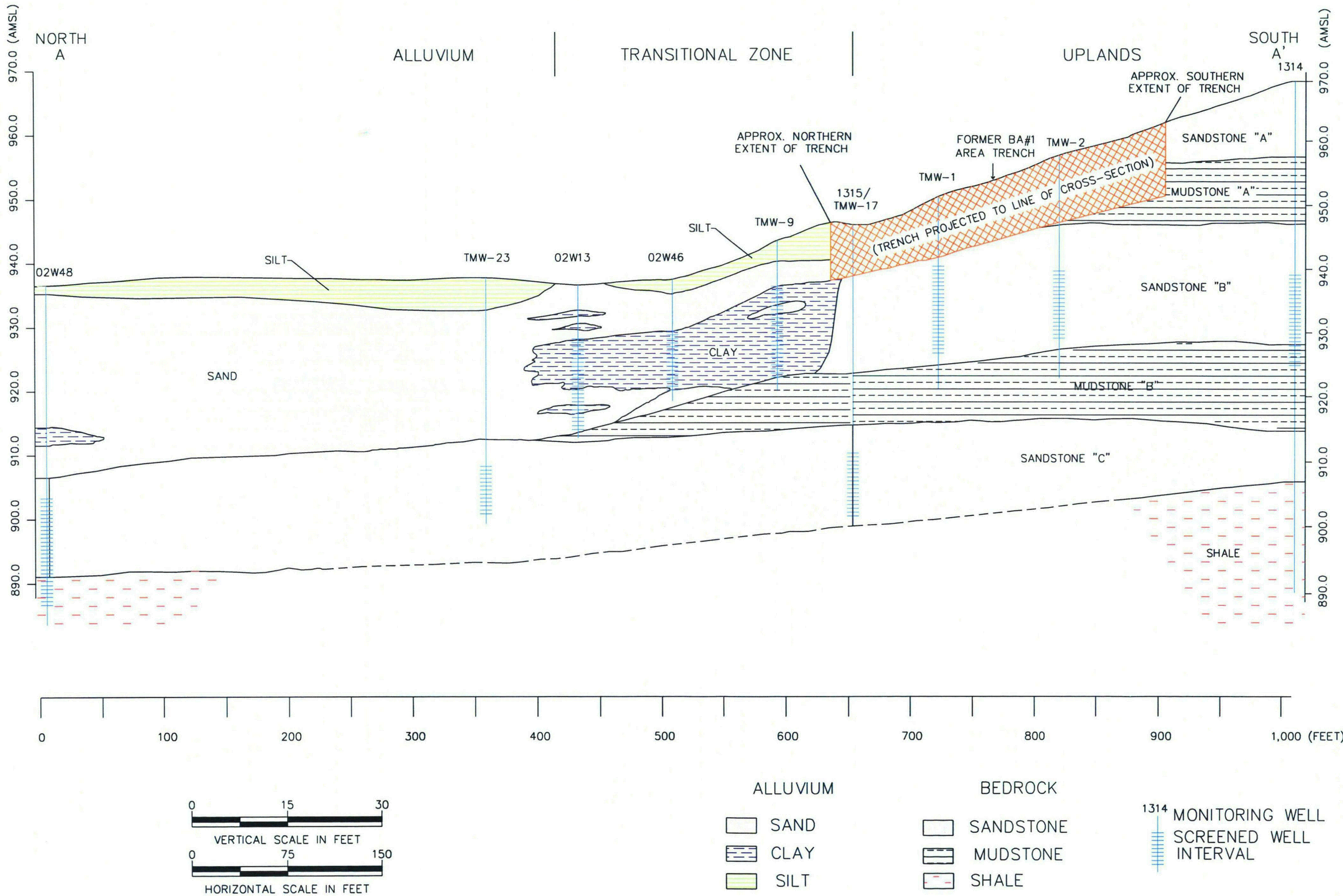
WEB: HTTP://WWW.ENSR.AECOM.COM

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. 04020012



DWG. NO. 040200005

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

REVISIONS

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

ENSR | AECOM

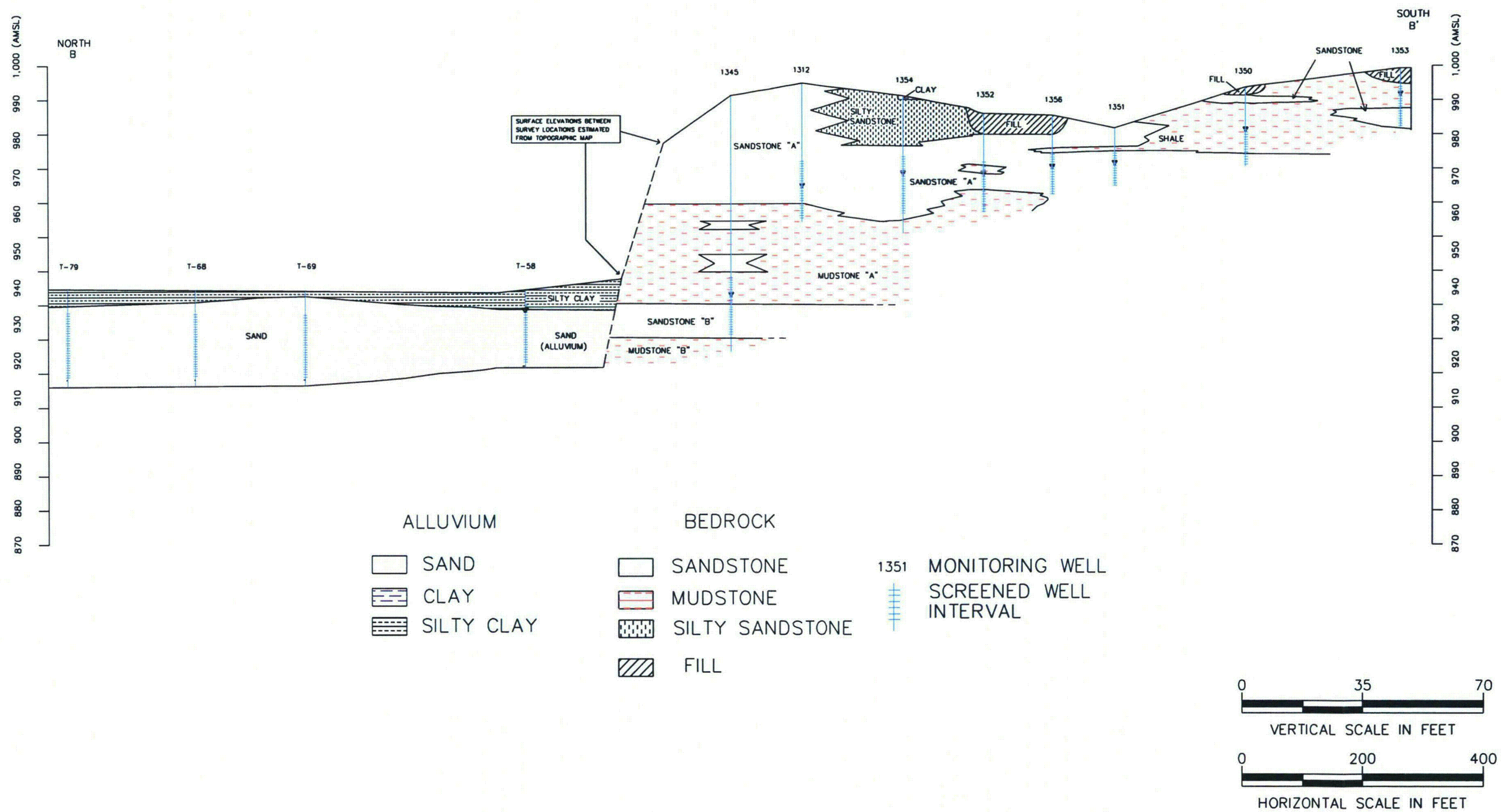
ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

FIGURE 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



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

ENSR | AECOM

ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
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FIGURE 4
REPRESENTATIVE GEOLOGICAL CROSS-SECTION WESTERN UPLAND AND ALLUVIAL AREAS CIMARRON CORPORATION CRESCENT, OKLAHOMA

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

FIGURE NUMBER: 4

SHEET NUMBER: 1

DWG. NO. 040200009

N

BA #1 Boundary

NOT TO SCALE

BA #1 Model Domain
Cimarron Corporation
Crescent, Oklahoma

DATE	PROJECT
October 2006	04020-044-300

ENSR | AECOM

Figure
5

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N

WA Area Boundary

NOT TO SCALE

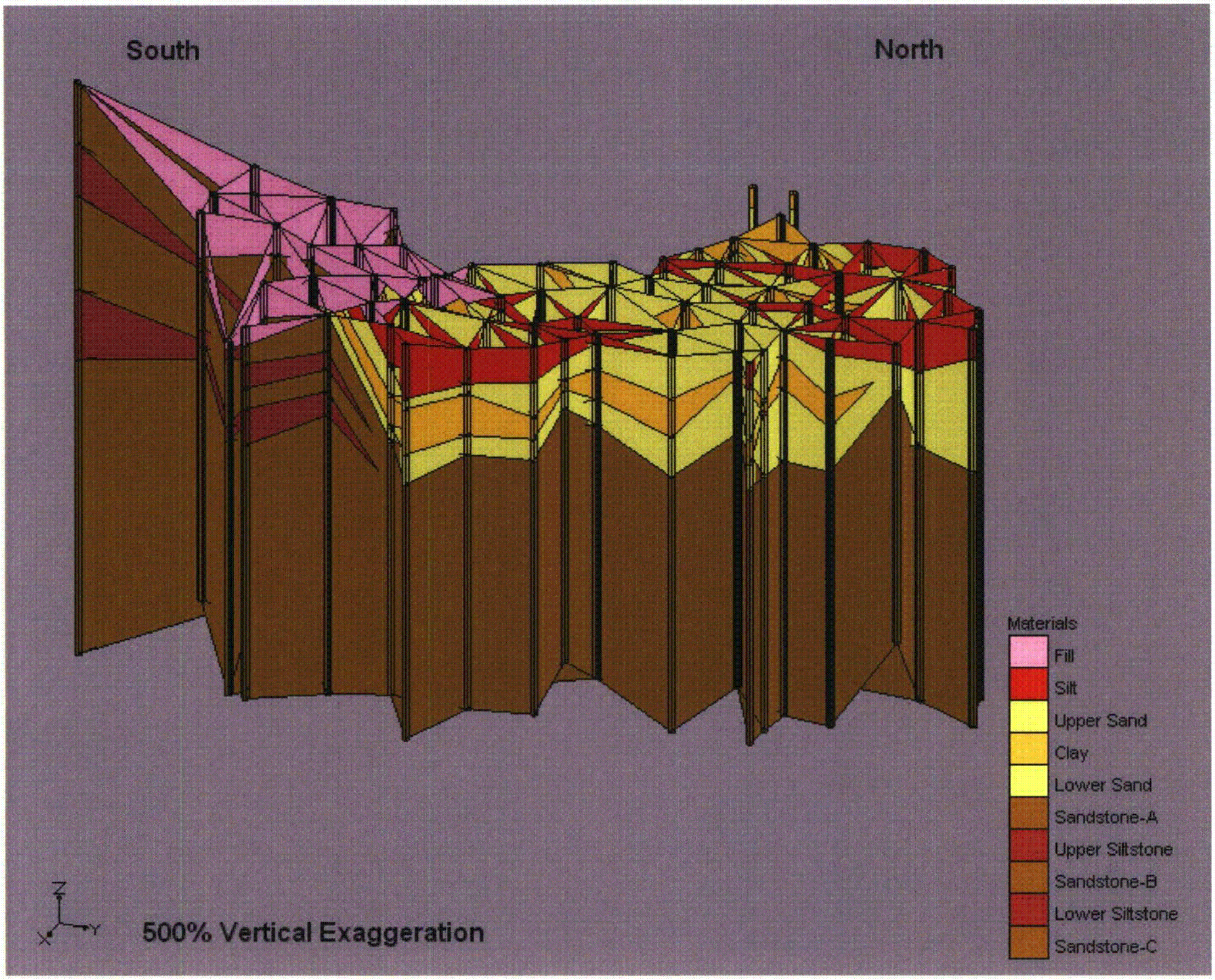
WA Area Model Domain
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	04020-044-300

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	Figure **7**
	October 2006	04020-044-300	

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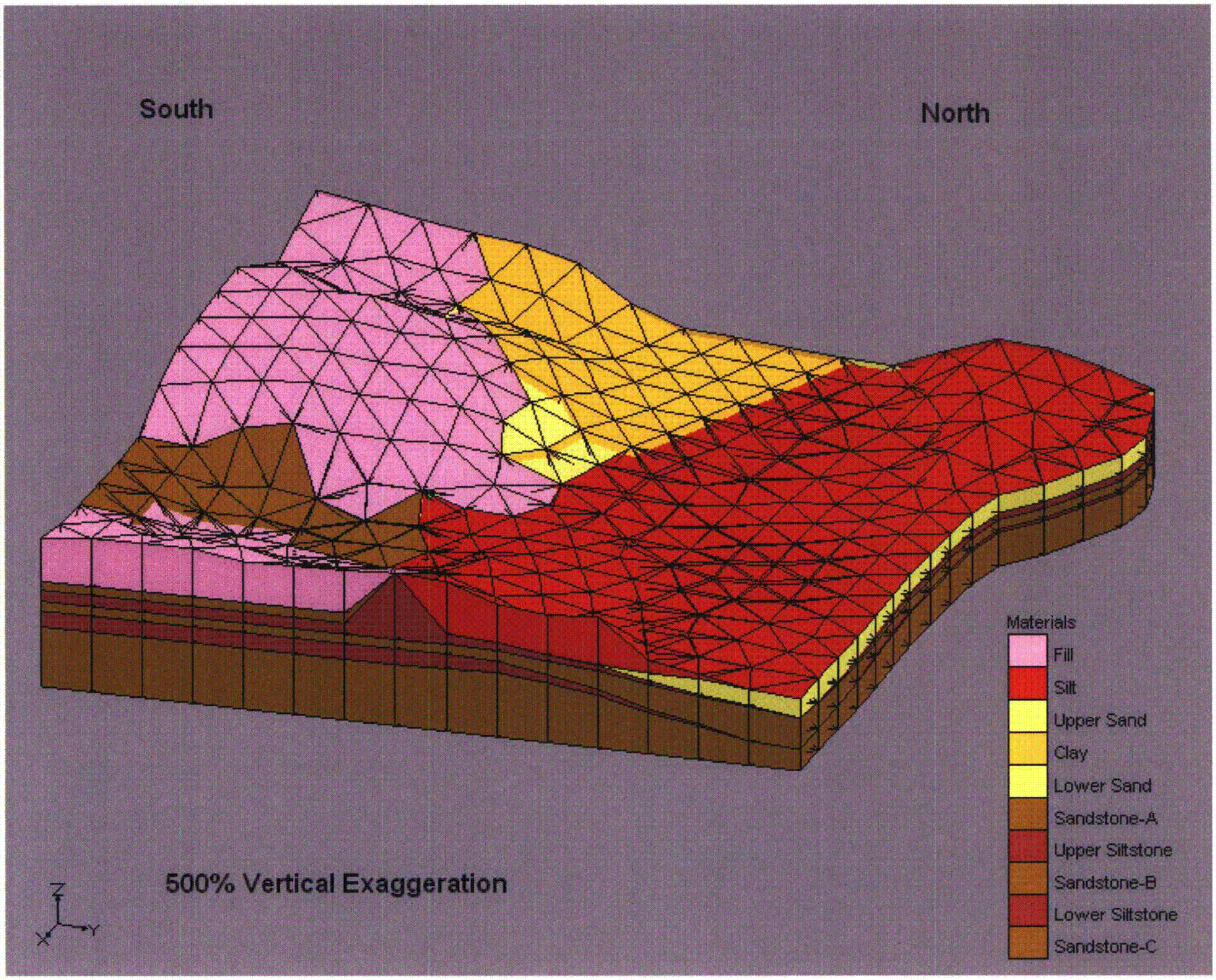

BA #1 Solids Developed from Borehole Data Cimarron Corporation Crescent, Oklahoma		ENSR | AECOM
DATE	PROJECT	Figure **8**
October 2006	04020-044-300	

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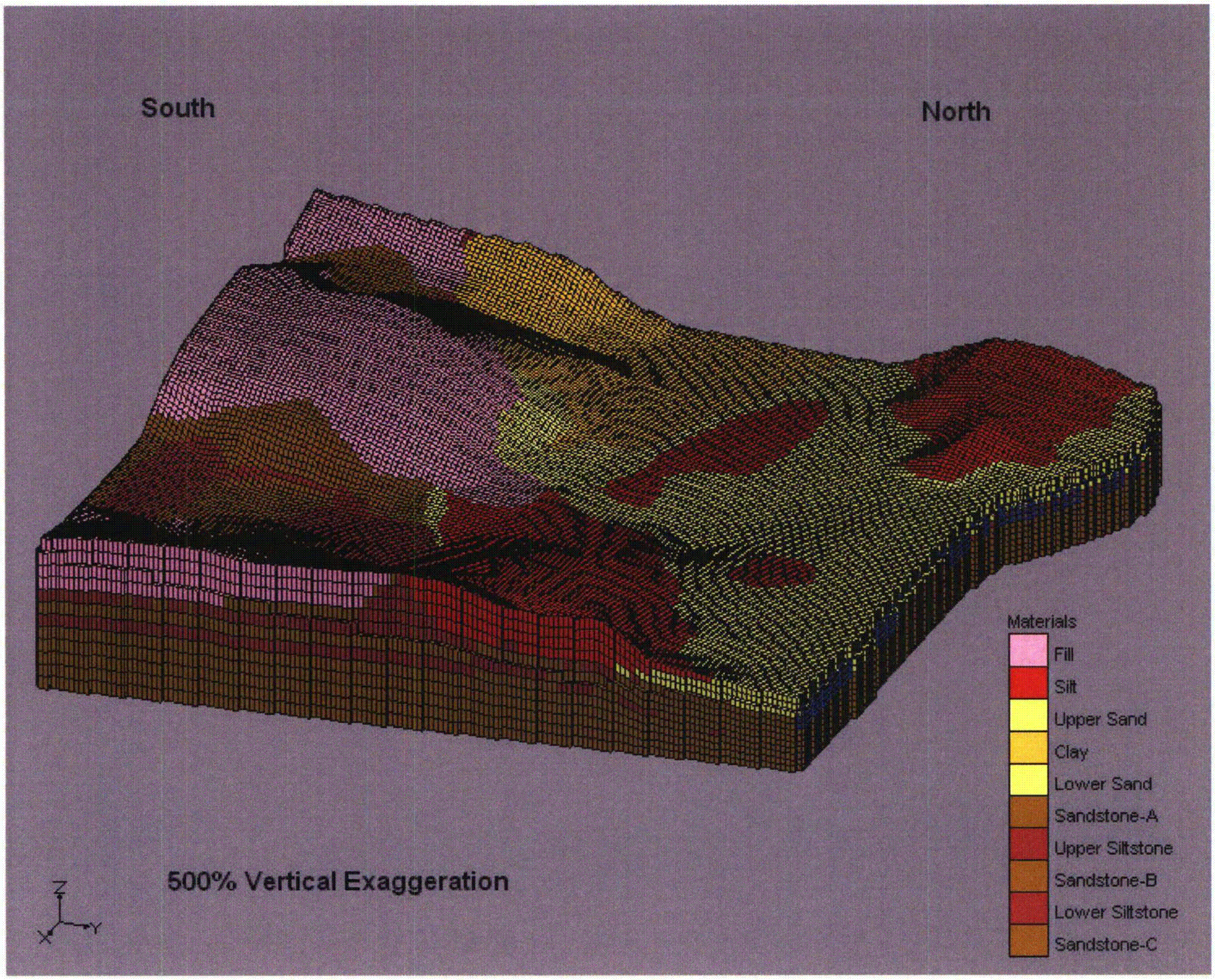
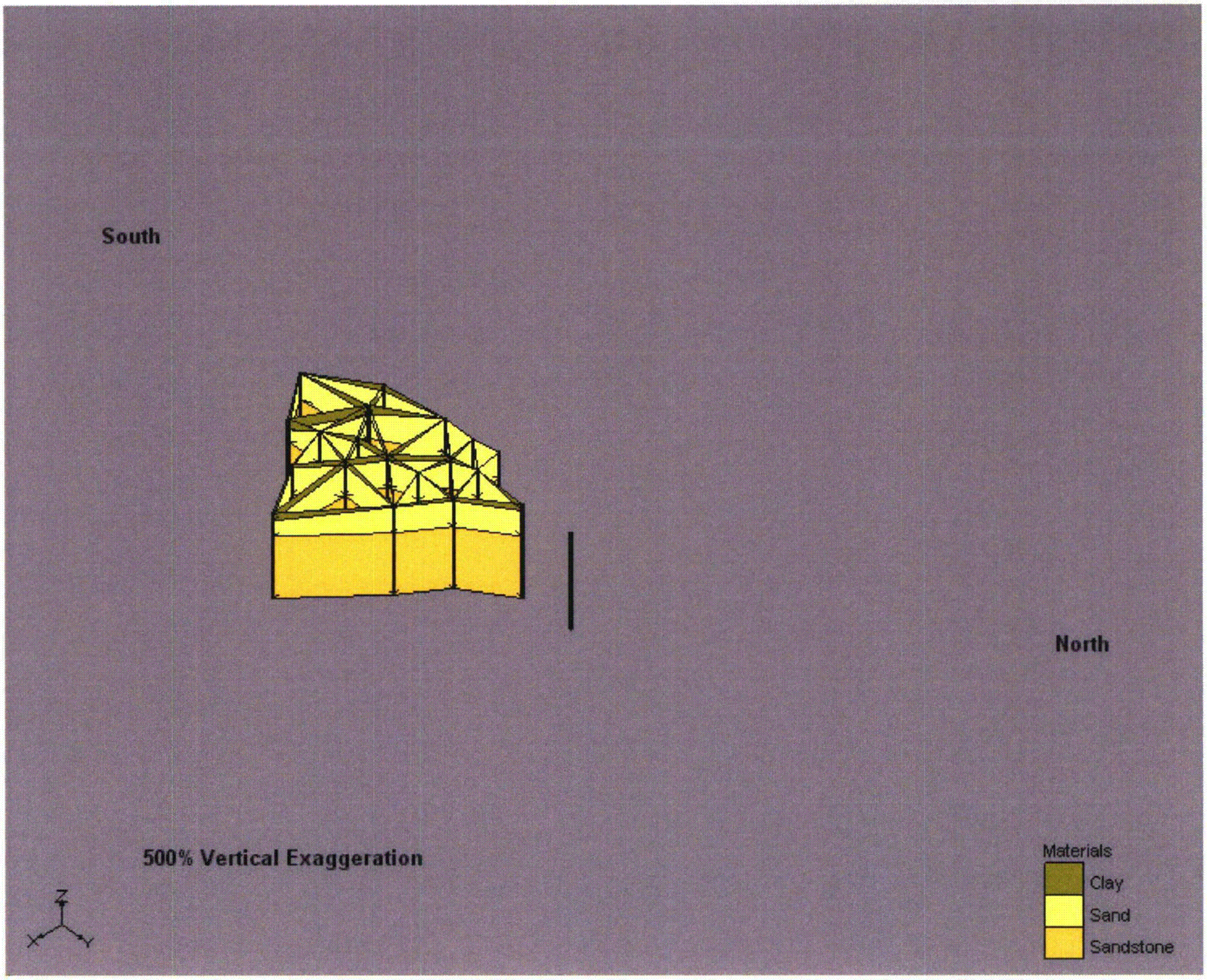


	BA #1 3D Grid Incorporating Geologic Information Cimarron Corporation Crescent, Oklahoma	ENSR | AECOM
	DATE: October 2006 / PROJECT: 04020-044-300	Figure 9

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure9.mxd



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

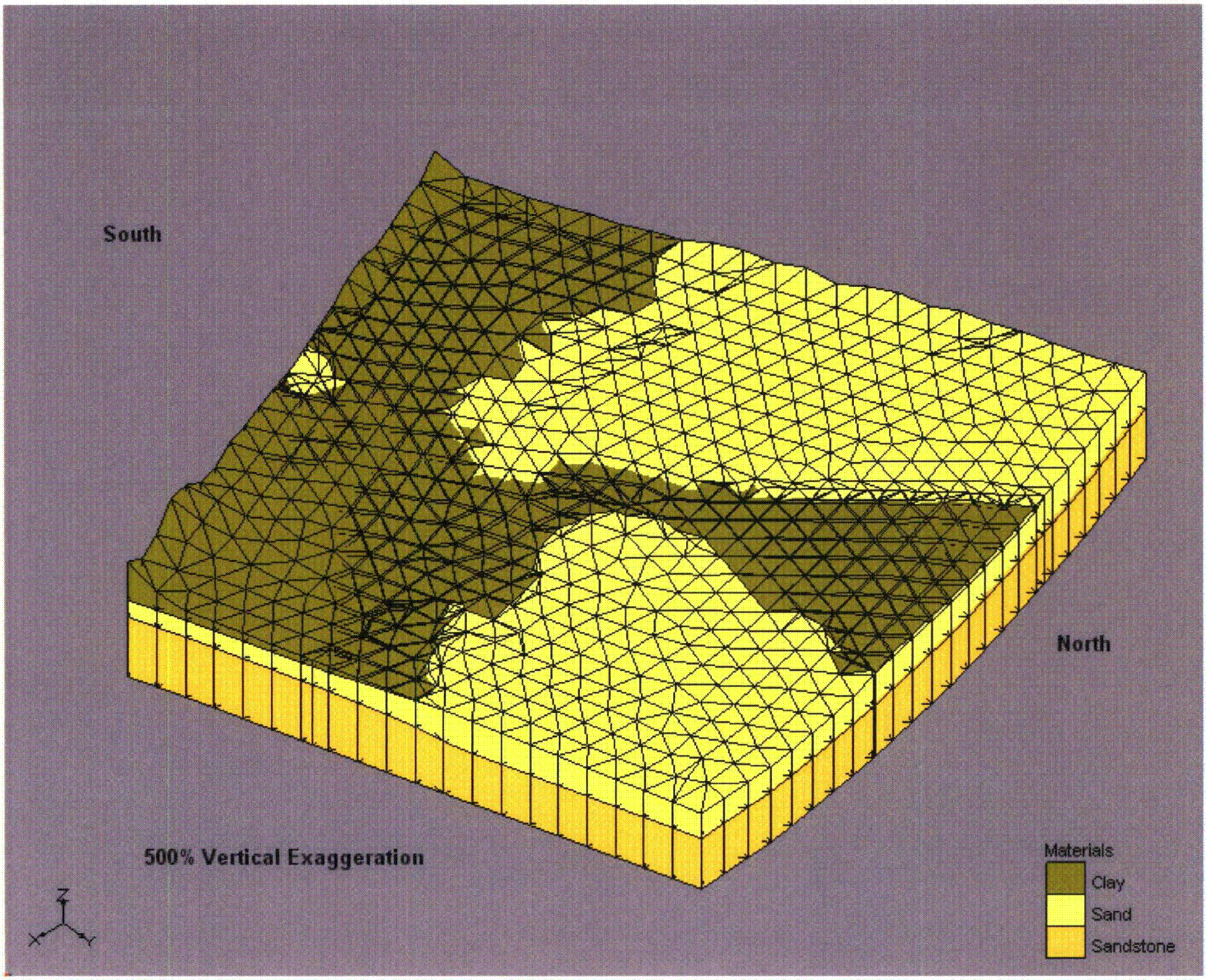
WA Area Boreholes and Cross-sections
Cimarron Corporation
Crescent, Oklahoma

ENSR | AECOM

DATE	PROJECT
October 2006	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
	DATE	PROJECT	Figure **11**
	October 2006	04020-044-300	

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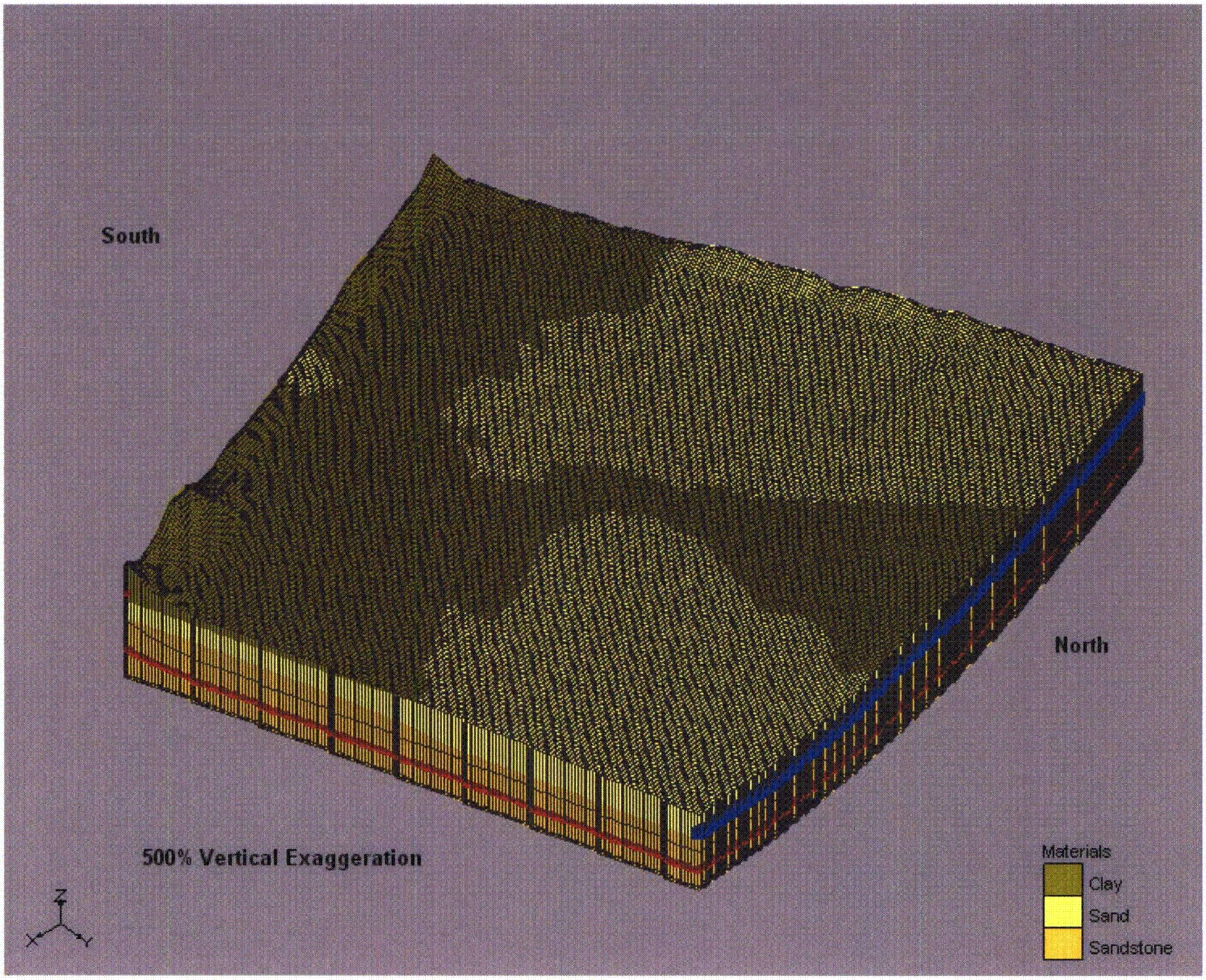
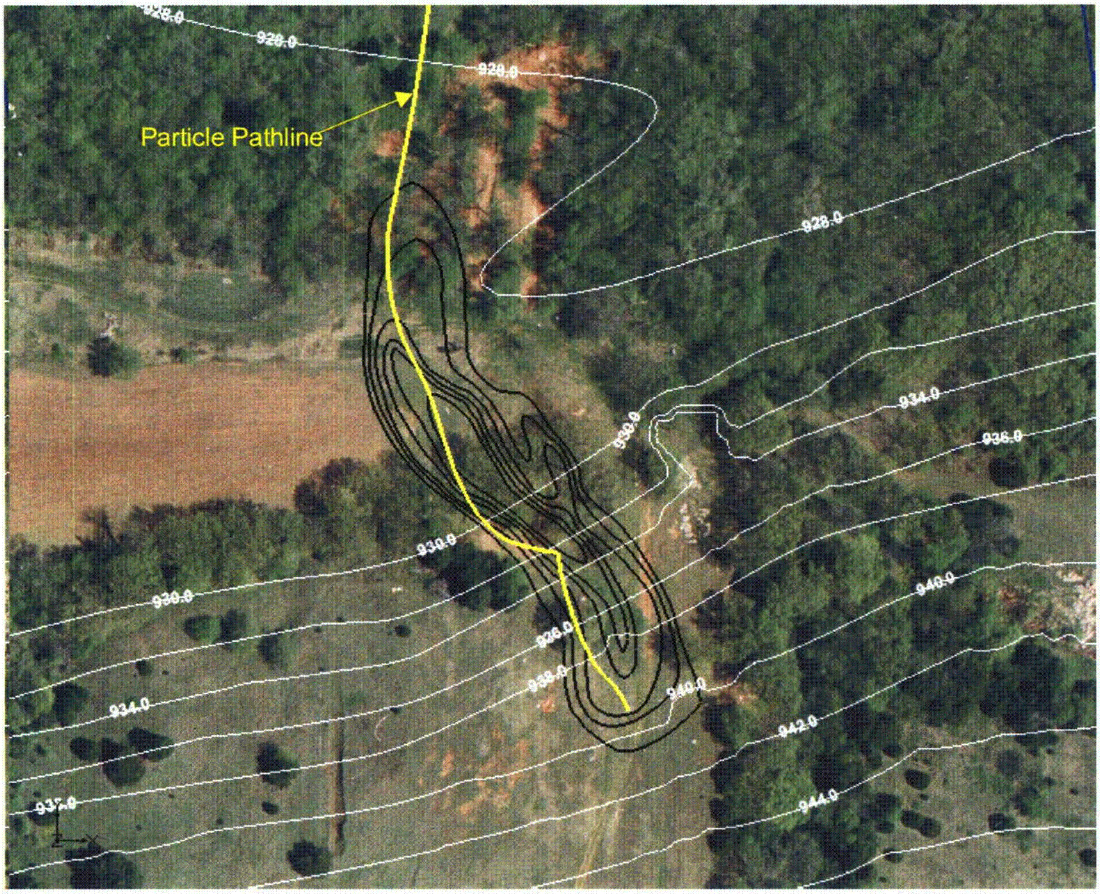
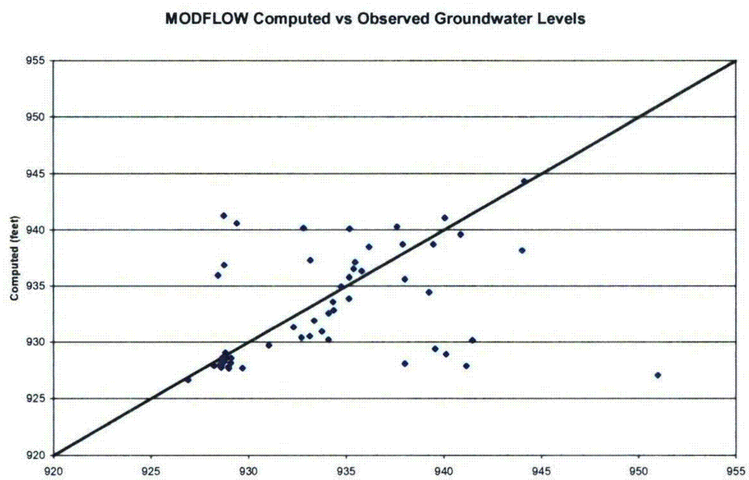


	WA Area 3D Grid Incorporating Geologic Information Cimarron Corporation Crescent, Oklahoma		ENSR AECOM
	DATE	PROJECT	Figure 12
	October 2006	04020-044-300	

J:\Water\PROJEC~2\P40\4020\044-CI~1\modeling\MODEL_~1\GIS\figure12.mxd

Predicted Groundwater Contours and Particle Pathlines





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

N

NOT TO SCALE

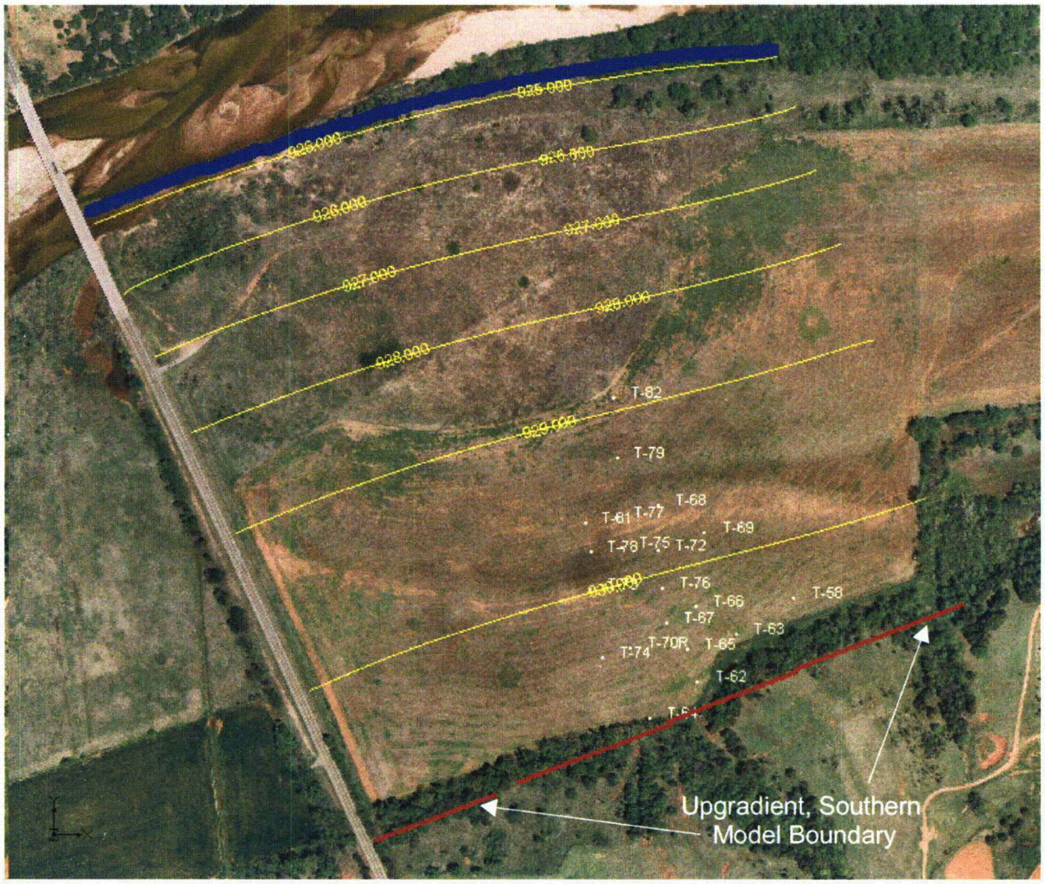
October 2006

ENSR | AECOM

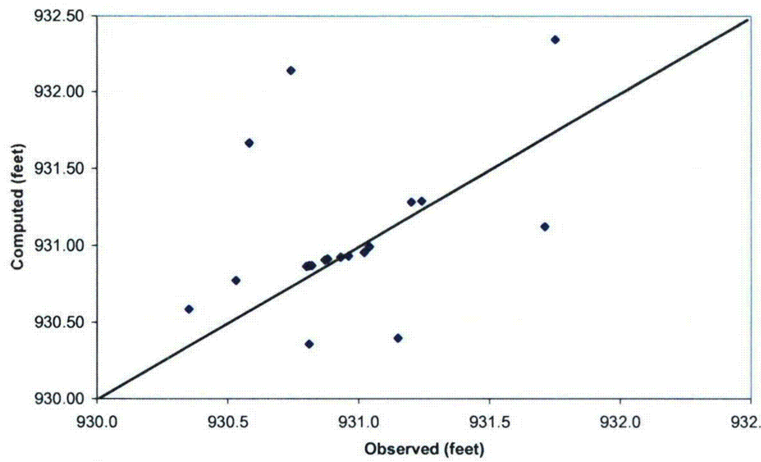
Figure 13

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

Hydrology Addendum (ENSR)

ENSR

Prepared for:
Cimarron Corporation
Crescent, Oklahoma

Hydrology Addendum
Cimarron Site, Crescent, Oklahoma
Final

ENSR Corporation
April 2008
Document No.: 04020-044-400

Contents

List of Tables

List of Figures

1.0 Introduction

In December 2006 Cimarron Corporation (Cimarron) submitted a License Amendment Request (LAR) to the NRC for the purposes of amending the Cimarron Site Decommissioning Plan (SDP) and addressing specific changes to the Cimarron license conditions. The SDP portion of the LAR included the following documents:

- Work Plan for In-Situ Bioremediation of Groundwater at the Cimarron Site (ARCADIS, 2006); and;
- Groundwater Flow Modeling Report (ENSR, 2006b).

In March of 2007, having reviewed the submittal, the NRC identified 17 deficiencies related to these submittals. Several of the deficiencies related to transient hydrologic processes which may impact a remediation design.

In response, ENSR has prepared this Hydrology Addendum, which provides a characterization of site hydrology. Based on this characterization, ENSR evaluated the impacts transient hydrologic events have on the water budget in the variably-saturated zone and, specifically on recharge to groundwater. Accordingly, ENSR considered the following hydrologic transient events: 1) periods of heavy rainfall; 2) river flood stage events; and 3) ponded water vertically infiltrating to the water table.

Terminology such as vadose zone, capillary zone, etc. may be used in the Work Plan and/or other documents; these have specific meanings in the context they are used. **Note that for the purposes of this document the variably-saturated zone is defined as the soil horizon that extends from the ground surface to the average groundwater level.** Among other topics, this report deals with the water budget in this zone.

1.1 Background & Overview

Cimarron's site near Crescent, Oklahoma, is a former nuclear fuel manufacturing facility. Since the cessation of operations, the site has been undergoing decommissioning. This decommissioning is being performed by Cimarron Corporation with oversight from the Nuclear Regulatory Commission (NRC) and the Oklahoma Department of Environmental Quality (Oklahoma DEQ).

The Conceptual Site Model (CSM Rev 01) prepared by ENSR and finalized in October 2006 updated the understanding of Cimarron Site's geology and hydrogeology based on site data. The CSM Rev 01 focused specifically on three areas where impacts have yet to be fully remediated: Burial Area #1 (BA #1 Area); the Western Upland Area; and the Western Alluvial Area. CSM Rev 01 (ENSR, 2006a) included information such as:

- Regional, site, and area specific stratigraphy;
- Regional, site, and area specific groundwater flow patterns (i.e., directions, gradients, sources and sinks of groundwater); and
- Regional, site, and area specific groundwater chemistry.

These three components were integrated into a conceptual model that describes the fate and transport processes that control impact to receptors in each of the three areas at Cimarron. Conclusions and recommendations identified that each of the three areas had been sufficiently characterized such that a remediation design could be completed.

One key assumption of the CSM Rev 01 was that the site could be confidently evaluated based on steady state conditions. That is, transient conditions such as changes in river stage and/or isolated precipitation events are short in duration. It was stated in the CSM Rev 01 report that these events may result in short term changes in groundwater velocities and directions, but that because they are short-term, their impacts are negligible relative to the long-term average groundwater conditions. Early remediation designs were based on the assumption that remediation would be required for a time frame consistent with long-term average groundwater conditions (i.e., greater than a few years). Thus, evaluating the site on a steady-state basis was considered acceptable.

However, the NRC expressed concern in their letter of deficiencies (March 2007) that in fact the transient hydrologic processes (changes in river stage and/or precipitation events) may have short-term impacts to groundwater and geochemical conditions during and after remediation is completed. Specifically the NRC expressed concern about the potential impact of water infiltration on sorbed uranium migrating to the water table. This infiltration could be caused by precipitation or flooding. The NRC also noted that the recharge water, which may have different geochemical characteristics from groundwater below, may impact groundwater quality. According to the NRC, these potential impacts needed to be accounted for in the development of a remediation design.

1.2 Objectives & Approach

To address the NRC's concerns, ENSR has prepared this hydrology addendum to evaluate the impacts transient hydrologic processes have on the water budget in the variably-saturated zone and specifically on recharge to groundwater. This document focuses on quantifying the water budget, although some conclusions are drawn regarding water quality based on the findings herein. In-depth discussions of water quality are addressed in the Site Decommissioning Plan – Groundwater Decommissioning Plan (ARCADIS, March 2008), submitted as part of the revised LAR along with this Addendum.

The specific objective of this Addendum is to characterize the impacts precipitation and surface water hydrology may have on variably-saturated soils and recharge to groundwater. The findings can be used, as necessary, to help develop a comprehensive remediation design.

To achieve this objective the following steps will be completed:

- Characterize regional climate;
- Characterize typical and extreme rainfall events;
- Characterize typical and extreme Cimarron River conditions; and
- Evaluate water budget in the variably-saturated zone soils during normal and extreme circumstances.

Starting in April 2007, the Cimarron Site experienced several months of high precipitation and river flows. This report includes overviews of the river and groundwater responses to the precipitation data collected over the spring and summer of 2007. These recent precipitation events were divided into four periods: late March/early April 2007, early May 2007, mid-June/late July 2007, and mid-August 2007; each of these periods are discussed individually.

Modeling was completed using the Hydrologic Evaluation of Landfill Performance (HELP) model to estimate recharge volumes to the variably-saturated zone and the water table. A summary of that modeling follows the discussion of the recent hydrologic events. The discussion of the background and set-up of the model is described as well as base case model runs. Several scenarios were then simulated to address: 1) extreme precipitation events and 2) ponding events.

A summary and conclusions section appears at the end of this document in which key points are highlighted both from the evaluation of the recent-past hydrologic events and the modeling conducted.

2.0 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 in Logan County, Oklahoma. The Cimarron Site is located approximately 30 miles north of Oklahoma City, OK. The site boundaries extend approximately one mile south from the south bank of the Cimarron River and approximately one mile east from Route 74 on the west (**Figure 2-1**).

2.1 Regional Climate

The Oklahoma Climatological Survey (OCS) collects and maintains a database of climatic conditions across Oklahoma and in Logan County. Oklahoma is located in the nearly flat to rolling Southern Great Plains. Within the plains are hillier areas, which contain as much as 600 feet of relief between higher hills and lower valleys. These hillier areas tend to be at the edges of the State: the Wichita Mountains in the southwest, the south central Arbuckle Mountains, the Ouachita Mountains in the southeast, the Ozark Plateau in the northeast, and the Black Mesa in the panhandle. The Red River and the Arkansas River are within the Mississippi River Basin and are the two major rivers in the State that both discharge directly to the Mississippi River.

Overall the climate of Oklahoma is strongly influenced by conditions that develop in the Gulf of Mexico. Summers tend to be long and hot compared to the northern Plains States; winters are shorter and milder. Annual average relative humidity ranges from 60% to 70%. Evapotranspiration and percolation are at least 80% of Oklahoma's precipitation; runoff and storage therefore account for the remaining 20%.

Average temperatures in the State range from 58°F to 62°F, with averages generally higher eastward. High temperatures (over 90°F) typically occur from 60 to 115 days per year, again depending on location. Temperatures exceeding 100°F occur frequently, generally between May and September. The hottest temperature on record, 120°F, occurred several times at several locations over the last 7 decades. Temperatures below 32°F occur 60 to 110 days per year, depending on location and elevation. The lowest temperature, -27°F, has occurred twice in 1905 and 1930. The growing season ranges from 175 to 225 days depending on location and elevation.

The spatial distribution of rainfall across the State is characterized by a sharp decrease in rainfall from east to west. In the far southeast, average annual rainfall is estimated at approximately 56 inches per year while the average annual rainfall in the far western panhandle may be as low as 17 inches per year. Rainfall typically falls in late spring, mainly May, except in the far west (panhandle). In much of the State, a second peak in rainfall occurs in September. In the western panhandle, the double peak pattern is not observed; most rainfall occurs in the June-July timeframe. Wintertime precipitation events tend to be a result of regional weather systems, while summertime precipitation results from mesoscale convective storms and other thunderstorms. Rainfall amounts up to 20 inches per day have also been reported, but these numbers are unofficial (i.e., non-standard).

The greatest snowfalls tend to be in the northwestern portion of the State where several events can occur in one year. In contrast, it can be several years between snowfall events in the southeast. The effects of snowfall in Oklahoma are generally short-lived; that is, snow melts within a few days of the event. Ice storms are possible, but ice accumulation is typically less than an inch.

Flooding along rivers and tributaries results from precipitation and for that reason occurs during the months of the highest precipitation. Impacts from droughts are linked to the duration of the drought. In the last century (approximately) there have been five multi-year drought events lasting six to ten years.

2.2 Local Climate

The Oklahoma Climatological Survey (OCS) collects and maintains a database of climatic conditions that have been used to characterize the climate across Logan County. Average annual precipitation ranges from 33 to 39 inches per year across the county. Temperatures average near 61°F with a typical yearly range of 95°F in the late summer to 26°F in January. Severe climatological events include periodic thunderstorms and tornadoes; 41 tornadoes have been documented in Logan County in the last 53 years. In depth summary statistics of climatological factors have been prepared by the OCS and can be found on line at http://climate.ocs.ou.edu/county_climate/Products/CountyPages/logan.html.

2.3 Geology & Soils

An in-depth description of the geologic setting of the Cimarron Site is included in the CSM Rev. 01 (ENSR, 2006a). In summary, the regional geology of the Cimarron area 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 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. Within each sandstone unit, there are frequent mudstone layers that are discontinuous and not correlative across the project area.

The soil distribution between the uplands and low lands differs considerably. The distribution of soil types is important for understanding the spatial variability in recharge and runoff. The Natural Resources Conservation Services (NRCS) provides an online soil mapping tool which was used for the following discussion (http://websoilsurvey.nrcs.usda.gov/app/). Lowland or floodplain soils tend to be in the Yahola Class while upland soils tend to be Ironmound-Coyle type soils. This is consistent with the origins of the soils. The flood plain soils may originate from both upland erosion and flood event deposition. The upland soils more likely originate from the local parent rock – mudstones and sandstones.

Specifically, the floodplain soils are characterized as follows:

- Soils are typically loams and sandy loams with smaller percentages of clay, resulting in high permeabilities consistent with the underlying alluvial materials.
- Slopes are around 10% or less.
- Because of the higher permeabilities and low slopes, recharge is expected to be higher and runoff lower than in the uplands.

In contrast, the upland soils (Burial Area #1 and Western Upland area) are characterized as follows:

- Soils generally contain a higher percentage of silts, clays, and fine sands, resulting in overall lower permeabilities, consistent with the parent rock, sandstones.
- Slopes tend to be steeper than in the floodplain, up to 45% grade.
- The lower permeabilities coupled with the steeper slopes yield lower recharge and higher runoff than that associated with the floodplain soils.

In general, based on NRCS descriptions of hydraulic conductivity, the permeability of the soils in the flood plain are greater than those in the uplands. It is estimated that floodplain soils have hydraulic conductivities in the range of tens of feet per day. The exception to this is where clays are present where conductivities may be one to two orders of magnitude less than the other floodplain soils. NRCS data indicates that conductivities of floodplain soils tend to increase with depth. In contrast, the upland soils tend to be in the ones of feet per day and conductivities decrease with depth, suggesting increased competency and decreased permeability of the sandstone units. The implications of these varying soil types impact the simulations of vertical infiltration. Sandier or loamier soils will tend to percolate water better than silty or clayey soils. Silty and clayey soils may percolate water so slowly that water will pond; i.e. infiltration is limited by the vertical transmissivity properties of the soils.

3.0 Site Hydrology

3.1 Water Budget

The purpose of this section is to summarize the components of the water budget, specifically how precipitation is expected to be partitioned among recharge, evapotranspiration (ET), and runoff. This discussion will provide a context for understanding the site and will form the basis for comparing expected site behavior to model results (Section 4.0).

The following table summarizes the values and ranges of each of these components based on literature review. The extreme-event precipitation depths have been included because they are important in understanding the extreme event recharge, which provides one basis for evaluating a remediation design.

	Value/Range	Source
Precipitation	24 inches/year near Freedom, OK (100 mi NW of Site)	Adams & Bergmann, 1995
	32-42 inches/year at Guthrie, OK	
	33-39 inches/year	Oklahoma Climatological Survey (OCS)
	35.93 inches/year average	
	2.65 inches; 24-hour, 2-year event	USGS, 2007b
	6.2 inches; 24-hour, 100-year	
	3.3 inches; 24-hour, 2-year event	Rea and Tortorelli, 1999
	9.5 inches; 24-hour, 100-year	
Recharge to the groundwater	8% of precipitation	Adams & Bergmann, 1995
	6.6-26% of precipitation	Reed, et. al., 1995
	2.5% of precipitation	Belden, 2000
	8% of precipitation	ENSR, 2006b
Evapotranspiration (ET)	Approaching equal to precipitation	Geraghty, et al., 1973
Runoff	7% of precipitation, 2-3 inches/year	Belden, 2000
	1-5 inches/year	Geraghty, et al., 1973

- Recharge is defined as that water that percolates into the soils and moves past the root zone, avoiding root uptake, ultimately reaching the groundwater table.

- ET is defined as the evaporation or transpiration of water from open bodies of water, the unsaturated soil zone, and the shallow saturated zone. Temperature, humidity, wind velocity, soil type, and depth to water are factors that control evaporation rates. Studies have shown that the principal controlling factor in evaporation is depth to water. As depth to water increases, evaporation decreases (Reed, et al., 1952). Transpiration is defined as the uptake by plant root zones and subsequent discharge of water to the atmosphere during growing. Quantifying ET is notoriously difficult because it can vary daily and over short distances, depending on soil types and land use. Oklahoma is especially challenging because of the highly variable temperature and precipitation distributions (Stadler and Walsh, 1983).

- Runoff is that portion of water that becomes part of the surface water hydrologic system; it does not recharge the aquifer nor is it part of the ET process.

3.2 Cimarron River

The Cimarron River and its floodplain, consisting of terrace deposits and alluvial floodplain gravels and sands, is the major hydrologic feature at the Cimarron Site. The headwaters of the Cimarron River are in Union County, New Mexico at an elevation of about 8,000 feet above mean sea level. It flows through areas of Colorado, Kansas, and Oklahoma and terminates at the Keystone Reservoir on the Arkansas River at an elevation of about 850 feet above mean sea level. Land along the course of the river is used mainly for farming, ranching, and residential development. 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).

3.2.1 River Flow

The Cimarron River is a gaining river over its entire course from Freedom to Guthrie, Oklahoma. In the vicinity of the Cimarron Site and Guthrie, the flow is perennial. Base flow from the alluvial and terrace aquifers and from the Permian sandstone units that border the river is highest in the winter months due to the higher water tables in these aquifers, which result from decreased evapotranspiration. Base flow is lowest from late summer through early winter because water tables are at their low point during that time. Because the Cimarron River is fed mainly by base flow from groundwater aquifers, base river flow in the Cimarron River parallels this seasonal fluctuation in groundwater levels.

From 1974 to 2006, the Dover gage, located approximately 30 miles west (upstream) of the site, recorded from 199 to 2,804 cubic feet per second (cfs) average annual flow rates (USGS, 2007). From 1938 to 2006, the Guthrie gage, located approximately 10 miles east of the site, recorded from 192 to 3,901 cfs average annual flow rates (USGS, 2007a). Adams and Bergman (1995) reported a low-water median flow rate of approximately 100 cfs and a high-water median flow rate of 600 cfs. Flood statistics for the Cimarron River have been compiled by the USGS (Tortorelli and McCabe, 2001) and indicate that peak flows at Guthrie range from a 2-yr flood with a discharge of 26,700 cfs to a 500-yr flood with a discharge of 237,000 cfs. These numbers are in general agreement with the numbers calculated by the USGS (2007b) of 27,800 cfs and 233,000 cfs, respectively, and with the values calculated using PKFQWin, described below. Floods most typically occur in this area in May-June or October, largely as a function of heavy rainfall in upstream portions of the watershed.

The National Weather Service (NWS, 2007) reports that the five highest flow events on the Cimarron River at Guthrie were in 1935, 1957, 1959, 1974, and 1986 and correspond with peak stages of 20.71 feet, 20.50 feet, 18.90 feet, 18.58 feet, and 18.58 feet, respectively. According to the NWS's ranking, Major Flooding is defined as flooding with crests greater than 20.0 feet and Moderate Flooding occurs with crests greater than 18.0 feet. Bankfull Stage, Flood Stage, and Minor Flooding all occur at 13.0 feet; and the action stage is 11.0 feet. The Action Stage as defined by the NWS as the stage at which a NWS partner/user needs to take some type of mitigation action in preparation for possible significant hydrologic activity.

At the Dover gage, the top five flow events occurred in 1986, 1957, 1995, 1982, and 1993 with water cresting at 26.10 feet, 25.70 feet, 23.10 feet, 22.87 feet, and 22.49 feet, respectively. All of these events are characterized as Major Flooding (22.0 feet). Moderate Flooding occurs at 20.0 feet. Bankfull Stage, Flood Stage, and Minor Flooding all occur at 17.0 feet; and the action stage is 15.0 feet.

For two water years in the early 1970s (from October 1970 to September 1972), there was a gage on the Cimarron River at Crescent, which is assumed to have been at the Route 74 bridge. The USGS does not report the stage for this site, but the daily discharges ranged from under 1 cfs to just over 6,000 cfs. These rates compared with the rates presented in **Table 3-1** and suggest that there were no flooding events during these two years and that flows were relatively low.

3.2.2 Statistical Flows

To date, flows for various recurrence intervals have not been developed for the site. Much of the site's response to high flows on the Cimarron River is based on anecdotal observations and lack a quantitative basis. To fill this data gap, an approach was developed to estimate river flows with different recurrence intervals on the Cimarron River at the site. The approach relied upon the use of PKFQWin 5.0.0 (Flynn, et.al, 2005) and historical flows at the USGS Dover and Guthrie Gages. The Dover gage is approximately 30 miles upstream of Route 74; the Guthrie gage is approximately 10 miles downstream of Route 74. Flows at the site were then estimated based on distance from the gages (assuming flow varied linearly with distance).

PKFQWin 5.0.0 is a USGS statistical tool that uses the log-Pearson Type III distribution for extreme event representation and annual peak flow data at each of the Dover and Guthrie to estimate flow events for different recurrence intervals. The background for PKFQWin is based on Bulletin 17B (IACWD, 1982). PKFQWin 5.0.0 is free and can be downloaded at http://water.usgs.gov/software/peakfq.html.

It is acknowledged that there are uncertainties associated with this approach. The use of annual peak flows, for instance, simplifies the dynamics of the river flows. However, in the absence of a gauging station at the site and associated historical data, this approach provides a reasonable estimate of flows with various recurrence intervals. These estimates are summarized in **Table 3-1**.

Critical to understanding vertical recharge through the variably-saturated zone is to estimate the extent of overtopping of the river banks during peak flows. PKFQWin was used to estimate recurrence interval *stage* events (instead of flow); these stage events were then converted to depths based on stage-depth relationships developed from historical actual flow measurement data at each of the gage station websites. Thus, recurrence interval depth-of-flow events were generated for each gauging station and these data were interpolated to give depth data at Route 74 adjacent to the site. Based on an estimated elevation of the river bed at Route 74 (925 feet), recurrence interval flood elevations could be estimated. These depths are summarized on **Table 3-2** and **Figure 3-1** maps the flood plain for three recurrence interval flood events based on these calculations.

Prior to this evaluation, a quantitative evaluation of flows and stages at different recurrence intervals had not been available for the site. This data helps to characterize depth and duration of ponding. To address this need, the above evaluation was completed. Despite some assumptions (regarding flows and stages changing linearly along the river, channel shape, etc.) and inherent contradictions in the results (higher upstream flows than downstream as shown in the shorter recurrence intervals), the estimated flood flows and elevations are considered appropriate to understand site flooding and ponding.

3.3 Recent Hydrologic Events – Site Response

The extreme precipitation and resultant surface water and groundwater events in spring and summer of 2007 provide valuable insight into the site's response to such events. This section will first discuss the data in general; subsequent sections will discuss four events in more detail.

3.3.1 Overview

3.3.1.1 Precipitation

According to the Oklahoma City weather station, between March 1 and August 21, 2007, 40.84 inches of rain fell in a number of intense storm events. This total rainfall represents significantly more than the average annual rainfall of 36 inches per year. A weather website, www.wunderground.com, provided the data to generate the following summary based on data at the Oklahoma City weather station. Rainfall data, recorded daily at the site, is summarized in the last column.

	Actual 2007 Rainfall (inches)	Normal Rainfall (inches)	Deviation from Normal %	Rainfall as measured at site
March	8.02	2.9	177	6.80
April	2.57	3	-14	3.00
May	8.49	5.44	.56	6.76
June	10.06	4.63	117	12.62
July	6.31	2.94	115	4.18
August (up to the 22nd)	5.39	1.78	203	4.34
Total	**40.84**	**20.69**	**97**	**37.70**

Figure 3-2 shows the daily precipitation data from the Oklahoma City weather station and the precipitation data from the site. The site precipitation data and the Oklahoma City weather station data are very similar indicating a general uniformity of regional precipitation patterns. Variability within the boundaries of the site is not expected to be significant.

In this six-month period, almost double the normal rainfall fell. Based on the precipitation record at Oklahoma City weather station, the greatest single precipitation event was 3.82 inches (August 19, 2007); this was preceded by 1.56 inches on August 18, 2007. On March 30, 2007 3.5 inches fell, preceded by 1.43 inches on March 29, 2007. Finally, 2.33 inches and 2.08 inches of rain fell on March 7 and 8, 2007, respectively. These precipitation events are the most comparable to a statistically based 24-hour, 2-year precipitation event of 3.3 inches (Rea and Tortorelli, 1999).

Based on site precipitation data, the greatest single precipitation event was 3.65 inches (August 19, 2007). Consistent with the Oklahoma City data, this was preceded by a fairly substantial rainfall of 0.7 inches on August 18, 2007. The rainfall on August 19, 2007 is consistent with the 24-hour, 2-year precipitation event of 3.3 inches (Rea and Tortorelli, 1999). Other high rainfall amounts occurred on June 29, 2007 (2.67 inches) and May 7, 2007 (2.60 inches).

3.3.1.2 Cimarron River Flow

Figures 3-3 and 3-4 show the daily average flow data for the Dover and Guthrie gages between March 1, 2007 and August 21, 2007. Also shown on these graphs is a plot of the median of the daily mean flow calculated based on available historical data. This data gives an indication of the magnitude of the flow events between March and August relative to daily median flows.

The first flow events during this time occurred in late March 2007. According to the flow data, peak flows were on March 30, 2007 in Dover and March 31, 2007 in Guthrie. These high flows were largely attributed to the large rainfall amounts measured at Oklahoma City in late March 2007. In response to this event, Cimarron began taking routine measurements of depth to water at a number of wells in the BA#1 area. Observations were also made with respect to the river's elevation relative to the site and to note if there were any areas of pooling water (due to overtopping or poor drainage). The next sections rely heavily on the data collected and observations made by Cimarron personnel. Unless otherwise noted, precipitation reported comes from the Oklahoma City weather station.

3.3.1.3 Groundwater Elevations

To provide some context for the following discussion and conclusions regarding groundwater it is useful to review concepts from the CSM Rev 01 (ENSR, 2006a) and the Groundwater Modeling Report (ENSR, 2006b). These reports present the site in a regional context and demonstrate that the Cimarron River is a regional discharge boundary. The river receives groundwater from the entire drainage basin, a portion of which must pass through the Cimarron site on its way to the Cimarron River. ENSR's groundwater model results indicate that as much as 50 million gallons of water pass through the BA#1 portion of the site annually (as modeled, ENSR, 2006b) and that more than three times that much pass through the WAA portion of the site annually (as modeled, ENSR, 2006b).

Three significant observations were made based on the groundwater data collected.

- Changes in groundwater elevations observed in wells in low permeability soils (Transition Zone and Sandstone) were similar regardless of whether or not the data was collected seasonally or almost daily. This indicates that, while gradients and fluxes in these soils may change in response to transient hydrologic events, the duration and magnitude of the changes is expected to be in the order of days or weeks and that the flux increases over this time is small relative to the overall flux of groundwater across the site annually.

- In the Alluvium wells, seasonally-collected groundwater elevation data did not capture the highs and lows that were observed when data was collected almost daily. The observed groundwater elevation rises and falls indicated that water levels change in parallel, yielding parallel gradients. Rises were observed to occur over the course of a few days, perhaps weeks. The increases in groundwater fluxes over these short time frames are not expected to be significant relative to the overall flux of groundwater across the site annually.

- An evaluation of groundwater data collected from April to August 2007 indicates that the changes in hydraulic gradients and flow directions result in small changes relative to the overall water budget of the site. The duration of these changes are on the order of days, perhaps weeks. Given this, rates and directions of contaminant transport are also unlikely to be significantly affected by transient events.

Figure 3-5 depicts the rise and fall of groundwater elevations from early April to August 20, 2007. **Figure 3-6** shows the locations of these wells. The groundwater response was measured routinely in 10 wells located in the BA#1 area. Three of these wells, TMW-02, TMW-08, and TMW-21, are screened in Sandstone B (red lines, red dots). Five wells are screened in Alluvium: 02W16, 02W24, 02W36, 02W43, and TMW-13 (green lines, green dots). Two wells are screened in Transition Zone soils: TMW-05 and TMW-09 (blue lines, blue dots).

Overall, the rise and fall of groundwater elevations indicate that the alluvial wells are most responsive to hydrologic events. The transition zone wells and two of the three Sandstone B wells were not as responsive as alluvial wells. The total head change seen over the period of record ranged from approximately 3.4 feet to just over 8 feet. The smallest overall changes were seen at the wells screened in transition soils and in two (TMW-02 and TMW-08) of the three sandstone wells. TMW-21 is fairly responsive, relative to the other Sandstone B wells, but its response is less than the alluvial wells. The greatest single change (8.08 feet) was observed at 02W43 between August 17 and 20 of 2007.

Water level data had been collected previously at these wells and formed the basis of the calibration data set for the groundwater model (ENSR, 2006b). There are some interesting comparisons between the data collected in September 2003, December 2003, August 2004, and May 2005 to the data recently collected (quasi-daily). The following table summarizes the groundwater changes over the long term and over the spring and summer of 2007.

		Maximum groundwater change (ft) based on data from September 2003, December, 2003, August 2004, and May 2005	Maximum groundwater change (ft) based on data collected from April to August 2007
Sandstone B	TMW-02	0.97	3.82
	TMW-08	3.24	3.6
	TMW-21	7.88	7.91
Transition Zone	TMW-05	3.82	4.44
	TMW-09	3.6	4.38
Alluvial	02W16	2.39	7.03
	02W24	2.43	7.82
	02W36	2.29	7.84
	02W43	2.18	8.08
	TMW-13	2.11	7.81

The data indicates that at two of the Sandstone B wells (TMW-21 and TMW-08), recent fluxes in groundwater changes are consistent with what may be observed based on less frequent measurements. This is consistent with what was seen at the Transition Zone wells; long-term differences are consistent with short-term differences. In contrast, water level changes in the alluvial wells based on long-term measurements were far smaller than the changes seen over the spring and summer of 2007. At TMW-02, seasonal water level differences were also much smaller than the spring-summer 2007. It is possible that TMW-02 is screened across soils with different hydraulic conductivities compared to TMW-21 and TMW-08 and thus, is less responsive to short-term events. The graph of water elevations over time (**Figure 3-5**) suggests that water levels at TMW-02 were not as susceptible to precipitation events as at other wells.

The general consistency in water level changes in the Sandstone B and Transition Zone wells suggests that seasonal, infrequently recorded data tends to be as representative as short-term water level changes, even after extreme events such as those seen during the spring and summer of 2007. Alternatively stated, water level fluctuations are no greater whether they are measured frequently or infrequently. This is a significant observation as it implies a fairly stable flow field in the sandstone and transition soils. Water level changes resulting from transient hydrologic events are muted by the relatively low permeability soils such that they are consistent with longer term (seasonal) hydrologic events. This is consistent with what had been stated in the CSM Rev 01 (ENSR, 2006a): "the hydraulic gradients and flow directions do not change significantly over time. Therefore, rates and directions of contaminant transport are also unlikely to change significantly."

In the alluvial wells, only 2 to 2.5 feet of groundwater elevation relief were observed based on the seasonal data, but up to 8 feet of elevation relief were recorded based on the quasi-daily data. When considering the gradients and fluxes, however, it is the relative elevation differences between the wells that are important. In this case, whether groundwater elevations were low or high, for the most part the elevation differences between the most distant upgradient alluvial well (TMW-13) and the other alluvial wells were consistent – indicating parallel gradients.

The exception to this was between alluvial wells TMW-13 and 02W43 where the elevation differences based on seasonal data tended to be a few tenths of feet while the elevation differences based on the quasi-daily data tended to be on average approximately 0.6 feet (three times greater than the average elevation difference of 0.2 feet based on the seasonally-collected data). Elevation differences of 0.6 feet (between TMW-13 and 02W43) represent a two to three-fold increase in hydraulic gradient compared to the gradients in the alluvium reported in the CSM Rev 01 (ENSR, 2006a) and based on the seasonally collected data. The greatest elevation difference recorded based on the quasi-daily data was 1.14 feet, representing an approximate five fold increase in gradient. When elevation differences were up around one foot (between TMW-13 and 02W43), they persisted for at most eight days. In the context of evaluating water balances, the incremental increase in flux during periodic short term increases in gradient is small relative to the annual flux site-wide.

In summary, in the Sandstone B and Transition Zone soils, transient hydrologic events as seen during the spring and summer of 2007 are not expected to result in changes to the groundwater gradients and fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This suggests that groundwater elevations in Sandstone B and Transition Zone soils are fairly stable and that the zone of variably-saturated soils is, in general, thin relative to the zone of variably-saturated zone soils in the alluvial soils. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events; however, elevations generally responded uniformly indicating no change in groundwater gradients. Changes in flux will be small relative to the total water budget for the site. The exception to this was that some data suggested periodic change in groundwater gradients between TMW-13 and 02W43. These changes lasted at most eight days; this short duration may result in short-term increases of flux, but relative to the total water balance, these increases are considered insignificant.

3.3.1.4 Groundwater/Cimarron River Interaction

This section deals with the hydraulic connection between the river and the aquifer via the alluvial soils. **Figure 3-7** shows the daily water level data collected at 02W48 and TMW-24 using pressure transducers. For reference, the locations of these wells are shown in **Figure 3-6**; these wells are the most downgradient wells and are approximately 200 feet upgradient from the river bank. The most significant observation made based on this data is that there is no direct hydraulic connection via the aquifer between river water levels and groundwater elevations at or upgradient of TMW-24 and 02W48. Because there is no direct hydraulic connection via the aquifer, there are no anticipated water quality impacts of river water on groundwater at or upgradient of TMW-24 and 02W48. It is important to note that river water that overtops the river banks may impact groundwater elevations and water quality anywhere it can access via low-lying topography.

Because of a transducer malfunction, there is an incomplete data record for TMW-24. However it is clear from the available data that the water levels in TMW-24 and 02W48 closely parallel one another. By comparing the precipitation events to the groundwater response, it is also clear that the water levels respond quickly and in concert with the precipitation events.

In contrast, **Figure 3-8** shows the same transducer data plotted with the Guthrie flow data. The groundwater hydrographs and surface water hydrograph are not in concert. Where there are groundwater peaks, there are hydrograph troughs and vice versa. This inconsistency indicates that at these well locations, groundwater levels are not impacted by river water levels (via alluvial soils). If there was a direct hydraulic connection between the surface and groundwater at this location, the groundwater conditions would mirror surface water conditions, though with a time lag as the pressure wave of water moved through the porous media. This pattern is not observed.

As the findings indicate, there are no anticipated water quality impacts to the groundwater from river water, independent of possible impacts from river overtopping. Note that this conclusion is in agreement with what was presented in the CSM Rev 01 (ENSR, 2006a) wherein it was shown that river water quality and groundwater quality were, based on the preparation of stiff diagrams, quite different. It can be said that the river water levels and/or quality, independent of overtopping conditions, will not impact groundwater levels or quality at or upgradient of TMW-24 and 02W48.

3.3.2 Event-based discussion

3.3.2.1 Late March and April 2007

Between March 22 and March 30, 2007, 6.52 inches of rain fell at the Oklahoma City weather station (3.90 inches at the site). This rainfall caused a peak flow of 8,720 cfs at the Dover gage on March 31, 2007 and a peak flow of 24,400 cfs on March 31, 2007 at the Guthrie gage. At the Dover gage, flows returned to rates consistent with the median of the daily mean values about five days later on April 5, 2007. Flows at the Guthrie gage dropped down to 829 cfs on April 12, 2007, but never reached median values for that date (528 cfs).

A few days after the river flows dropped back down to median or near-median values, they rose again as a result of another April precipitation event. On April 10, 2007 0.09 inches fell, on April 13, 2007 0.86 inches fell, and on April 17, 2007 0.77 inches fell. For comparison, the site gage recorded 1 inch, 0.8 inch, and 0.65 inch on April 13, 14, and 17, 2007, respectively. The cumulative effect of this precipitation resulted in a peak flow of 6,420 cfs at Dover and 7,890 cfs at Guthrie; both peaks were on April 15, 2007. Flows returned to rates consistent with the median flow rates on April 21 and on April 30, 2007.

The shape of the hydrograph indicates that peak flows lasted one day with a steep increasing limb meaning that the response of the river to precipitation was fairly rapid, over one to two days. Flows decreased back down at lower rates as suggested by the less steep declining limb of the hydrograph. At the Dover gage, it took 5 to 6 days to return to median flow rates. At the Guthrie gage, it took 12 days and 15 days, respectively, for each of the two events to reach the lowest flow rate. The lengthy recovery rate is related to the large watershed that the gage at Guthrie represents. Also, there are contributing stream flows between Dover and Guthrie that, because of a different peak along those reaches, could have slowed the rate of overall flow rate decline.

According to PKFQWin calculations, a flow rate of 8,720 cfs at the Dover gage corresponds to a recurrence interval of approximately 1 year and corresponds approximately to a depth of flow of 5.8 feet (**Tables 3-1** and **3-2**). At Guthrie a flow rate of 24,400 cfs corresponds to a recurrence interval of less than 2 years and greater than 1.5 years and to a depth of flow of 12.2 feet. Based on these ranges of flows and depths, it is expected that the depth of flow at the site (Route 74) would be around 8.5 feet and flows in the range of 10,000 to 20,000 cfs depending on the contributions of other stream flows and bank storage capacity, among other factors. This rate and depth of flow is expected to have resulted in high flows approaching bankfull, but not necessarily significant overtopping. A photo taken at the Route 74 bridge (looking south, at the site) on April 2, 2007 confirms this understanding (**Figure 3-9**); a corresponding picture showing typical dry conditions is also shown in **Figure 3-9**. Though there was no observed overtopping of the banks at the site, there were some areas of the site where rainwater ponded and persisted for several days. **Figure 3-10**, taken on April 2, 2007 shows the flood plain area of BA#1; a corresponding picture showing typical dry conditions is also shown in **Figure 3-10**.

Ponded water occurs when a) topography is relatively flat or there is a low lying area in which water can collect and/or b) because of poorly draining soils, such as clay. As discussed in Section 2.3 there are some silty clays in the flood plain which may restrict vertical flow. When water ponds, some portion will evaporate, some may runoff, and some portion will drain vertically through the underlying soils to the root zone and potentially to the water table. When this occurs, the vertical flow rate is equal to the vertical hydraulic conductivity of the underlying soils.

Figure 3-5 shows the groundwater response to these rainfall events. In early April 2007 water levels in the wells were either declining or fairly steady. Small water level rises were observed starting on April 13, 2007. Given that there was a fairly immediate groundwater response to mid-April rainfall, occurring between April 10 and 14, 2007, it would appear that the rises are attributable to the mid-April rainfall as opposed to attributable to the late March/early April rainfall.

Among the wells, the rises in groundwater elevation between April 13 and April 18, 2007 ranged from 0.13 to 2.5 feet. The highest response was at TMW-21, a well screened in Sandstone B located in the uplands near the original burial trenches. Because of the distance to the river, the water table fluctuations at this location are assumed to be entirely attributable to site precipitation. The lowest response observed was at TMW-02, also located in the uplands in the former burial trench area. Response at TMW-08, a Sandstone B well located downgradient of TMW-02, was also low (0.31 feet). The muted responses of two of the three upland wells are attributable to heterogeneities in the Sandstone B formation.

In the transition zone wells, groundwater levels changed 0.68 and 0.53 feet. Responses in the alluvial wells were around one foot of groundwater elevation increase. Assuming that the water level response at TMW-21 is attributable entirely to rainfall, and that the rises in the alluvium are less than the responses seen at TMW-21, it can be concluded that the responses in the alluvium are also entirely attributable to rainfall. That is, changes in river elevation do not appear to be impacting groundwater elevations. This is true even at the most downgradient well 02W43, where elevations mirror patterns seen at other wells, not patterns seen in the river. This conclusion is confirmed by the transducer data collected at wells even closer to the river (see Section 3.3.1.3).

3.3.2.2 Early May 2007

There were several small rainfall events between mid-April 2007 and early May 2007. Based on data from the Oklahoma City weather station, five days of rainfall began on May 7, 2007 (2.33 inches) and continued through May 11, 2007 (2.06, 0.02, 0.29, 0.31 inches, respectively). According to site precipitation measurements, 3.9 inches of rain fell between May 7 and May 9, 2007. This rainfall resulted in rises on the Cimarron at Dover to 12,300 cfs (May 8, 2007) over the course of two days and rises to 33,700 cfs (May 9) at Guthrie over the course of three days. In the case of Dover, flow rates returned to median values in about six days. Even 20 days later, flows at Guthrie had not returned to median values and then flows went up again to 4,410 cfs on June 2, 2007 in response to a smaller rainfall event at the end of May 2007. Flows at Dover also responded to this late May rainfall by rising to 1,830 cfs also on June 2, 2007. This flow is less than the median flow for that date.

According to the PKFQWin calculations, 12,300 cfs at Dover corresponds to a 1.25 year recurrence event and 33,700 cfs at Guthrie corresponds to a 2.3 year recurrence event. Based on **Table 3-1** it is therefore estimated that flow at the site (Route 74) was likely around 23,000 cfs, a flow with recurrence interval of between 1.5 and 2 years. **Table 3-2** indicates that a river elevation corresponding to this flow may result in some bank overtopping depending upon factors such as antecedent moisture conditions, local scale topography, and bank storage availability. **Figure 3-11** is a photo taken on May 15, 2007 showing the river level relative to the banks; a corresponding picture showing typical dry conditions is also shown in **Figure 3-11**.

According to field notes, water was ponded around well 02W16 on May 9, 2007. **Figure 3-12** shows that ponding was extensive in the lower elevations of BA#1; a corresponding picture showing typical dry conditions is also shown in **Figure 3-12.** The extent of flooding looks similar to that observed in April 2007 (**Figure 3-10**). The ponding occurred after approximately 4-5 inches of rain. Observations made by Cimarron staff indicate that during high flow events, low-lying small drainage features will flood with Cimarron River water; in some instances, river water can reach as far south as the escarpment. For most of the storm/flow events observed over the spring and summer of 2007, ponding in the vicinity of BA#1 is attributed to both rainfall and river water.

Measurements of ponded depths were made at four locations (wells 02W05, 02W16, 02W22, and a stake just east of TMW-13) several times through mid-May. The data indicated that ponding was as deep as 19 inches and lasted as long as 16 days. Over this time, the average depth of ponding ranged from approximately 6 to 10 inches, depending on location and duration of ponding. By plotting ponded depth over time, the rate at which ponding decreased was estimated to be around 1.25 inches per day; this rate includes infiltration, runoff, and evapotranspiration as mechanisms for water removal. This rate applies when ponding exceeded approximately one foot. As ponding decreased, the removal rate appears to slow; this could be attributed to a reduced infiltration rate because of less hydrostatic head, less runoff, and/or reduced infiltration.

Groundwater rises were most pronounced in the wells screened in the alluvium (**Figure 3-5**). Over four days the average rise over all five alluvium wells was 6.55 feet and ranged from 6.13 to 6.94 feet. At TMW-21 water levels rose just over 4 feet. Water levels rose 0.17 and 1.22 feet at TMW-02 and TMW-08, respectively. Differences in response are attributed to local-scale heterogeneities. In the transition wells, water levels rose approximately 2.4 feet. However, the water levels at TMW-09 declined more slowly than the water levels at TMW-05 suggesting that the conductivity may be less at TMW-09.

3.3.2.3 Mid-June to Late July 2007

This period represents a protracted period of ongoing rainfall events. The total rainfall over this period (June 10 to July 31, 2007) was 16.2 inches, a value nearly half the normal total annual rainfall. **Figure 3-2** shows that there was no singularly high rainfall event, rather a series of heavy rainfalls day after day. Site precipitation data over the same time period was 15.68 inches.

The river responded accordingly by registering increased flows that were persistently high. Peak flows at Dover were recorded on June 16, 2007 (16,700 cfs), June 20 and 21, 2007 (10,200 cfs), June 30, 2007 (29,800 cfs), and July 14, 2007 (29,100 cfs). Unlike responses earlier in the year, some of the high flow peaks during this time occurred over two or more days. This is expected; the persistent rainfall results in accumulated runoff over several days. Peak flows at Guthrie were recorded on June 15, 2007 (31,200 cfs), June 21, 2007 (12,800 cfs), June 30, 2007 (61,000 cfs), and July 14, 2007 (40,300 cfs). It is interesting that Guthrie peaked on June 15, 2007, earlier than Dover did on June 16, 2007. This data may reflect large flows from tributaries influencing Guthrie before Dover. Spatial differences in precipitation may also cause the earlier peaks at Guthrie as compared to Dover. As with Dover, the peaks were spread over several days, as opposed to one or two days as in the events earlier in the spring.

The Dover flow of 29,100 cfs corresponds to a recurrence interval flow event of approximately 2.3 years. The Guthrie flow of 61,000 cfs corresponds to a recurrence interval flow event of approximately 7.5 years. Based on these flows, it is estimated that the flow at the site (Route 74) was approximately 45,000 cfs, which corresponds to an estimated flood elevation of approximately 939.0 feet elevation. It is expected that the banks would be overtopped and the flood plain would experience some flooding at this elevation. **Figure 3-13** (June 29, 2007) is a photo of the site from the Route 74 bridge; a corresponding picture showing typical dry conditions is also shown in **Figure 3-13**. Compared to similar photos taken in April 2007 (**Figure 3-9**) and May 2007 (**Figure 3-11**), this photo shows that the water is considerably higher and has obscured a sandy bank near the bridge's southern abutment previously visible. **Figure 3-14** shows considerable flooding (June 29, 2007), whether from accumulated precipitation or bank overtopping, in the Western Alluvial Area; a corresponding picture showing typical dry conditions is also shown in **Figure 3-14.**

Given the persistent high flows and the photos of the Western Alluvial Area, ponding is expected to have occurred in the low lying areas site-wide. Again this ponding is attributed to both intense, persistent rainfall as wells as inundation along low-lying drainage ways across the floodplain. Field notes suggest that there was ponding near 02W16 for at least a week.

Similar to early May 2007, the biggest groundwater responses were observed in the alluvial wells and in TMW-21. In the alluvial wells, there was an average increase of 6.33 feet between June 13 and June 29, 2007. At TMW-21 the water level increase was 6.00 feet. Water level increases at TMW-02 and TMW-08 were 1.24 feet and 2.73 feet, respectively; this pattern is consistent with what was discussed previously. Approximately three feet of water level increase was observed at the transition wells. Consistent with the persistent precipitation and high river flows, groundwater elevations remained high for about a month. Sometime around mid-July 2007, groundwater elevations began dropping and dropped to the lowest they had been since the measurements began in early April 2007. Similarly, flows at Dover dropped to levels consistent with median flow rates and Guthrie flows also receded, but not as low as the median rates.

3.3.2.4 Mid-August 2007

Based on data from the Oklahoma City weather station, between August 17 and 19, 2007, 5.39 inches of rain fell, with 3.82 inches falling on August 19, 2007. No precipitation fell at the site on August 17, 2007. At the site, on August 18, 2007, 0.69 inches fell and on August 19, 2007 3.65 inches fell. The resultant flows at Dover were remarkably low (1,870 cfs on the 19) even though this amount of precipitation had previously resulted in considerably higher flows. The low flow is attributed to spatial variability in precipitation amounts; in fact other weather stations reported considerably less precipitation over that same three-day period (0.39 inches at Enid Vance AFB). Guthrie, on the other hand, saw a substantial peak over two days to a peak flow of 33,700 cfs. Flows promptly declined to approximately one-tenth of that flow, but another rainfall event on August 24, 2007 (trace at OKC, but 0.37 inches at the site and 0.53 inches at Enid AFB) and flows appeared to be rising again.

A flow rate of 1,870 cfs at Dover is so low there is no calculated recurrence interval for it. A flow of 33,700 cfs is consistent with a 2 to 2.3 year recurrence interval flow event. Based on the spatially variable rainfall, it is difficult to estimate flows at the site (Route 74). Anecdotal evidence indicates that river water likely inundated the low-lying drainage features in the flood plain, but that most of the flood plain was otherwise dry. The flow at the site is estimated in the 5,000 to 10,000 cfs range.

In the wells screened in the alluvium, dramatic water table rises were seen between August 17 and 20, 2007 equaling, on average, 7.89 feet. This was the largest rise observed during the measurement period to date. Interestingly, the rises at TMW-21 have typically been consistent with alluvial well rises, but for this event, only slightly over a one-foot rise was observed and the peak occurred later than the peak in the alluvial wells. Unlike the previously discussed events where precipitation appears to be spatially well-distributed, for this event, the precipitation appeared to be spatially variable. Because of this, the rises in groundwater during this event are more of a reaction of the local rainfall depths as opposed to the accumulated impact of regional increases in groundwater as a result of regionally distributed precipitation. Groundwater rises in the other wells screened in Sandstone B were small, only 0.28 and 0.36 feet. Water level rises in the transition wells were 2.63 feet and 1.20 feet at TMW-05 and TMW-09, respectively. Unlike other events where the water levels in these two wells tended to parallel one another, in this event, the response at TMW-05 was more than double that of TMW-09. Similarly the decline of water levels at TMW-05 was rapid.

3.3.3 Event-Based Summary Observations

The precipitation, stream flow, and groundwater elevation data collected over the spring and summer of 2007 provide a unique opportunity to observe how the site responds to individual storm events, individual extreme events, and a series of extreme events. Cimarron will continue to collect this data at this time. Based on recent events, the following observations can be made:

- A total of 40.48 inches of rain fell between March 1and August 21, 2007. This represents an almost 100% increase over typical rainfall during the same time period, and roughly 5 inches above the normal amount received through the course of an entire year. Site precipitation data is consistent with data from the Oklahoma City weather station.
- Rainfall events resulted in a maximum flow rate at the Dover gage of 29,800 cfs on June 30, 2007 and resulted in a maximum flow rate at the Guthrie gage of 61,000 cfs also on June 30, 2007. It is estimated that during these flows, the flow rate at the site, Route 74, was approximately 45,000 cfs and resulted in flood elevations that caused low-lying drainage features to be inundated and river water to move into the floodplain as far south as the escarpment. This type of flooding (i.e., inundation of low-lying areas) was the typical mechanism for river water to move into the floodplain; there was no gross flooding of the floodplain wherein the entire flood plain was under water.
- Almost all of the events observed resulted in some amount of ponding around the low-lying poorly drained areas in the flood plain, for instance around well 02W16. The mechanism by which water ponded in the low-lying areas of BA#1 is a combination of factors: low permeability soils, intense rainfall, runoff from upland areas, and river water inundation along floodplain drainage ways.
- The water level data collected by the transducer at 02W48 and TMW-24 both located approximately 200 feet from the river showed groundwater hydrographs that are strongly influenced by precipitation and are not influenced by a hydraulic connection via the aquifer with the river. Stiff diagrams presented in the CSM Rev 01 identified that water quality at 02W48 and TMW-24 is consistent with Sandstone C and Alluvial well waters, respectively - that is, uninfluenced by river water quality. Data indicate that, independent of overtopping conditions, high river elevations will not impact groundwater elevations or water quality in the plume area as currently mapped (ENSR, 2006a).
- In general, based on groundwater levels measured in the Sandstone B and Transition Zone wells, the transient hydrologic events seen in the spring and summer of 2007 did not result in changes to the groundwater gradients and fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This conclusion indicates that groundwater elevations in Sandstone B and Transitions Zone soils are fairly stable. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events, however elevations generally responded uniformly indicating no change in groundwater gradients. Fluxes may change, but the largest changes lasted at most eight days; this duration may result in short-term increases of flux, but relative to the total water balance and the scope of the study, these increases are insignificant. Note that the zone of variably-saturated soils in the transition and upland areas is, in general, thin relative to the variably-saturated zone in the alluvial soils.
- Rainfall events were typically frontal storms that affected the region and resulted in regionally uniform responses in river flows and groundwater elevations. The most recent rainfall event was not as spatially uniform resulting in almost no flow response in Dover, but a fairly substantial response in Guthrie. In the groundwater, alluvial wells responded consistently with other events, but TMW-21, a Sandstone B well, registered a relatively low response. This suggests that the Sandstone B may be most responsive to regional events and less responsive to local scale rainfall events. The water levels

measured at wells screened in Sandstone B seemed most sensitive to geologic heterogeneities compared to the other wells.

4.0 Hydrologic Modeling

The specific objective of this report is to characterize the impacts surface water hydrology may have on the water budget of the variably-saturated soils and specifically on the recharge to groundwater. Thus far, the potential inputs to the variably-saturated zone have been characterized. Specifically, the report has discussed:

- General, specific, and extreme rainfall events;
- Land response to the rainfall events, including soil types that will control runoff and drainage, thus potential for ponding; and
- River response to these rainfall events, including bank overtopping.

It is the objective of this report to better understand the water budget of the variably-saturated zone and quantify potential groundwater recharge based on a number of rainfall, ponding, and river overtopping scenarios. It is the water that migrates to the water table, or recharge, that has the potential to impact the fate and transport through the variably-saturated zone.

The HELP (Schroeder, et al., 1994) model was chosen as it provides a robust, relatively simple method for evaluating the water budget of the variably-saturated zone including the discharge of water out of the variably-saturated zone. This discharged water becomes the recharge water to the groundwater system. There are other models and tools that may have performed the task equally well. However, some of these other models require sophisticated inputs and as the inputs become more sophisticated and assumptions are made to accommodate unknowns, the uncertainty of the model results increases. The HELP model is considered an appropriate tool to complete the evaluation given the objectives of this hydrologic evaluation.

The fate and transport component of the evaluation is discussed in the Groundwater Decommissioning Plan portion of the Site Decommissioning Plan (ARCADIS, March 2008) and will be used, in part, to support a remediation design.

This section provides a conceptual discussion of the hydrology, which will set the stage for model runs.

4.1 Conceptual Model

As discussed in Section 3.0, rainfall is the primary input to the water budget of the variably-saturated zone. Once it has fallen, water will either run off, evaporate, or soak into the ground. Once in the ground, it can either be taken up by transpiration or it will bypass the root zone and reach the water table. Depending on the depth to water, evaporation may occur directly from the water table to the atmosphere.

How water gets partitioned to any of these components (runoff, ET, recharge) is dependent on intensity and duration of rainfall, land use, and soil properties. Also, when rainfall is especially intense or when rainfall results in river flows that cause inundation, water can pond on the land surface. This ponding results in a different boundary condition as the infiltration rate to the subsurface is controlled by soil properties and ponding characteristics, not necessarily rainfall rate. It should be noted that for the Cimarron site, ponding likely occurs as a result of a combination of precipitation and/or upland runoff and/or river inundation.

In quantifying the recharged water flux through the variably-saturated zone, there are conceptually three scenarios to consider:

1. Vertical infiltration due to rainfall;

2. Vertical infiltration due to ponded water. The mechanisms by which ponded water may occur and persist include, in some combination:
   a. Low permeability soils.
   b. Low-lying areas that may be inundated during high river flows.
   c. High intensity, long-duration rainfall.
   d. Runoff from upland areas.
3. Increased groundwater elevation as a result of increased river stages.

The first two scenarios are explored using the HELP model in the sections that follow. The evaluation of groundwater rises as a result of river stage rises did not require modeling and is discussed in Section 3.3.1.4.

4.2 Introduction

The use of the HELP model provided a means to evaluate how rainfall is partitioned into evapotranspiration, runoff, storage, and recharge. The HELP model was originally developed by the EPA (Schroeder, et al., 1994) to conduct water balance assessments of landfills, cover systems, and solid waste disposal containment facilities. However, the conceptual and mathematical basis of the model is not exclusive to landfill designs. The model can be used to evaluate water balance for any variably-saturated soil system.

The model uses weather and soil data and solution techniques that account for the water balance components, including surface storage, snowmelt, runoff, infiltration, ET, vegetation, soil moisture, and vertical drainage. Based on inputs, the model calculates the amounts of runoff, ET, and drainage that may occur through a given soil thickness.

The specific inputs used for HELP are described in detail in the Users Guide. Input and output files for each of the simulations presented in the following sections are included in the attached CD-ROM. In general, the two primary classes of inputs include:

- Weather data, including ET data, precipitation data, temperature data, and solar radiation data. In many instances modeling relied on a database and on model guidance to help select inputs for these values. The HELP model includes a tool to generate synthetic precipitation data based on a database of climatological data; this synthetic precipitation data was used in the simulations as well as measured precipitation data.
- Soil data, including area and thickness, soil characteristics, and runoff curve information. Site-specific data were used as inputs. Default values were used for some values for which site-specific data are not available.

Output from the model is essentially a water budget for the variably-saturated zone. Output can include daily, monthly, and yearly summaries of ET, runoff, and recharge proportions that make up a precipitation input. For the base-case simulations (Section 4.3.1), the yearly summaries were of primary interest as they provided confirmation that the model was behaving consistently with the conceptual model of site hydrology. For event-based simulations daily data were output and summarized so that recharge could be calculated based on an extreme precipitation event.

4.3 Simulations

4.3.1 Base-case simulations

The purpose of the base case run was to see how the water balance simulated by the model compared to the understanding presented in Section 3.0. For the first simulations, model inputs and outputs are provided. Discussion of subsequent simulations will then discuss only the changes in inputs from the base case. **Table**

4-1 lists all the input parameters and output for the base case runs. Site-specific input parameters were used when available; default values were used in lieu of site-specific values, when site-specific values were not available.

In the first base case simulation, synthetically-generated precipitation data was used. Based on these input parameters, the output indicates that precipitation was on average 27.47 inches per year with a range of 20.50 to 35.97. This range seems a little low compared with what OCS presents for Logan County of 33 to 36 inches per year, but is considered reasonable. Model output indicates that recharge to the water table (percolation/leakage through Layer 2) was on average 1.25 inches or approximately 4.5% of the total precipitation. This rate is low relative to that presented by Adams and Bergmann (1995) who suggested that recharge represents 8% of the total precipitation. However, their estimate may have been based on soils that did not include as much silt and clay as have been simulated here. Furthermore, the ET was simulated to be 95.5% of total precipitation, a rate consistent with expectations.

For comparison purposes a second base case simulation was run where actual rainfall observations were used as model input. These rainfall observations were made at the Oklahoma City weather station from 2002 to 2006 (5 years). Note that the Oklahoma Water Resources Board considers these years to be drought years because of the lower than normal precipitation rates (OWRB, 2007). The change to precipitation input represents the only change in the input values. The model simulation output indicated that the annual average precipitation was 27.47 inches per year with a range of 22.00 to 36.62 inches per year. The simulated recharge rate was 6.9% (range from 1.5-10.1%) and the ET represented on average approximately 93% of the total rainfall. The differences in recharge rates are attributed to the more natural rainfall patterns as compared to the synthetic precipitation data. This recharge rate is consistent with the 8% presented by Adams and Bergmann (1995).

Finally, for further comparison, the 2007 (through August 20) precipitation data was added to the 2002-2006 series and the model was re-run to see how the extreme events of 2007 impacted the model output. This run indicated that recharge was dramatically higher than other years, 29.2% (approximately 13 inches of the approximately 44 inches of precipitation). These results indicate that the plants were obtaining sufficient water such that any additional water could flow vertically past the root zone to the water table. ET was reduced to around 74% compared to a higher percentage in other years.

These base case runs provide a frame of reference for the response of the model. The following runs will build on this understanding to explore hypothetical extreme events.

4.3.2 Simulate recharge based on site soil variability

This series of model runs explored the variability in recharge depending on soil type. There were three main soil types to consider. Note that the soils of interest are those between the land surface and the water table, not below the water table. Silty-clay underlain by sand is prevalent in the alluvium. A mix of silt and clay with a relatively low percentage of sands, but no underlying sands is typical of soils at transition wells and some upland wells. A few locations indicate as much as five feet of unsaturated fill; these are located in the uplands near the former burial trenches.

Table 4-2 shows that though there are differences in recharge rates in the model output based on varying the input soil types, the recharge rate variations are relatively small and fall within the general understanding of the relative portion of precipitation that actually recharges the aquifer on an annual basis.

4.3.3 Simulate recharge based on extreme precipitation events

The next series of simulations evaluated recharge rates after a single extreme precipitation event. Depth-duration-frequency maps (Rea and Tortorelli, 1999) were used to estimate extreme precipitation depths; these are summarized on **Table 4-2**. For these simulations, soil types were assumed to be consistent with the alluvial soils in the base case. For the 24-hour duration events, the precipitation rate was applied to a hypothetical July 1 of the sixth year of precipitation, which was preceded by 5 years of measured rainfall inputs. In the sixth year, precipitation data for the rest of the year was synthetically based to provide average, representative conditions. For the 7-day duration events, the precipitation rate was applied to a hypothetical July 1 through 7 of the sixth year of precipitation, which was preceded by 5 years of measured rainfall inputs. In the sixth year, precipitation data for the rest of the year was synthetically based to provide average, representative conditions.

Recharge was simulated to total 0.41 inches over the 30 days following a 24-hour, 2-year storm event of 3.3 inches (Rea and Tortorelli, 1999). The 24-hour, 500-year storm event of 10 inches yielded a model estimate of 5.94 inches of total recharge over the 30 days following the storm event. It should be noted that for some of the most intense storm events such as the 24-hour, 500-year event, ponding is simulated to occur. Ponding under these scenarios is assumed to be due entirely to precipitation; this scenario is unlikely as the river would also be responding to such rainfall and likely to overtop and create ponding. These numbers are intended to give a frame of reference for site response, not necessarily to be precise. Details of ponding are discussed in the next section.

Table 4-2 shows the results of these model runs. As expected, the greater the rainfall, the greater the recharge, though the intensity of the storm was also important. The recharge from the 24-hour precipitation events tended to peak quicker than the 7-day precipitation events, which is consistent with the differences in intensities of rainfall events. It is interesting to note that a 10-inch rainfall over 24 hours produces a similar recharge rate to a 12-inch rainfall event over 7 days.

4.3.4 Simulate recharge based on impacts of ponding

Conceptually, ponding on the land surface occurs because the mechanisms for water removal (i.e., runoff, recharge, ET, and removal to storage) do not cumulatively happen at a rate as fast as water can accumulate and/or the ponded area is replenished via upland runoff, additional precipitation, or ongoing inundation. Based on the HELP output, a daily water balance can be calculated in which runoff, recharge and ET are subtracted from precipitation. When the result is negative, it indicates that the water removal mechanisms are greater than the precipitation rate. When the result is positive, it indicates that the there is "residual water" for that day (i.e., precipitation > runoff + recharge + ET). This residual water is defined as the surplus water that includes both water that goes to storage and the water that can be considered ponded water. HELP output does not distinguish between the two. If steady state is reached – as demonstrated by a constant recharge rate – storage in will equal storage out and any residual water can be assumed to be entirely ponded water.

When HELP calculates residual water the program assumes that pressure head is uniformly dissipated in the low permeability layer (i.e., land surface) that is restricting the flow. The recharge rate is then calculated based on a hydraulic gradient and unsaturated hydraulic conductivity. The hydraulic conductivity is a function of soil water content, residual water content, and saturated soil water content. The hydraulic gradient becomes a function of the depth of ponded water. Thus, the recharge rate is a function of the variably unsaturated hydraulic conductivity and the depth of ponded water.

In relation to infiltration of water through the variably-saturated zone and ultimately to the groundwater, the process by which the ponded water recharges the groundwater is the same whether ponding occurs from excessive precipitation or from inundation of low-lying area. The critical factors for calculating recharge when ponding occurs are the depth of ponding and the duration of ponding.

The HELP model was used to evaluate the recharge depth given a scenario where water may pond on the land surface. Ponding in the alluvial area was observed several times during the 2007 period. Observed ponding lasted from a day or two to as much as 16 days. Average ponding depths were estimated to be between 6 and 10 inches over the days in which ponding occurred. These recent observations were used as a basis for formulating an appropriate scenario and simulating ponding and thus, estimating recharge to the groundwater table using the HELP model.

Uniform daily precipitation depths were input to the HELP model to achieve a variety of ponded depths. In general, steady state ponded depths were reached within a few days of the beginning of rainfall. Recharge rates that result from ponded water were dependent on the depth of ponded water. Based on the observations, a ponding depth was conservatively set to 1 foot and was simulated to last as much as 14 days. Simulations indicated that one foot of ponding (constant head) on each of 14 consecutive days would result in 6 inches of recharge per day. The ponded area that also overlays the BA#1 uranium plume area was estimated to be approximately 24,000 square feet yielding a total recharge volume of 170,000 cubic feet (1.3 million gallons) over 14 days.

The HELP model was also used to evaluate ponding that resulted from river overtopping. Note, over the spring and summer of 2007, no observations indicate that the floodplain was entirely overtopped. Therefore, this scenario is conservative. River overtopping that would reach the BA#1 plume area was estimated to occur at an elevation of 940 feet, resulting in a ponding depth of 1 to 2 feet over the plume area. Based on data presented by Tortorelli (1999) the duration of a flooding event was evaluated to be 7 to 10 days. Recharge over the duration of river-generated ponding was calculated to be 6 inches per day; however, the area over which this might occur would include the entire northern lobe of the BA#1 uranium plume area (at elevations less than approximately 940 feet). This ponded area is estimated to be 39,100 square feet, yielding a recharge volume of 195,500 cubic feet (1.5 million gallons) over 10 days.

4.3.5 Sensitivity

It is acknowledged that there are input variables for which site-specific data are not completely known. To attempt to understand how changes in some of the variables may affect predicted recharge depths an informal sensitivity analysis was completed using the base case run wherein five years of actual precipitation were used.

The results indicated that the model's prediction of recharge was fairly sensitive to wilting point and evaporative zone depth producing recharge percents up to approximately 40% and down to approximately 4%. The model was relatively insensitive to many of the other parameter including leaf area index, soil thickness, curve number, and hydraulic conductivity.

4.4 HELP Model Results

The use of the HELP model provided a means to evaluate how rainfall is partitioned into evapotranspiration, runoff, storage, and recharge. The recharge component is particularly useful for evaluating the extent of mobilization of sorbed uranium from variably-saturated zone soils.

Model simulations indicate that, based on soil type, recharge ranges from 4.3 to 7.2 percent of annual average rainfall. These rates are consistent with what has been observed and reported by others (**Section 3.1**). Additional model simulations were run to evaluate the inches of recharge that would occur given a statistically based storm event. For instance, recharge was simulated to total 0.0155 inches over the 30 days following a 24-hour, 2-year storm event of 3.3 inches (Rea and Tortorelli, 1999). The 24-hour, 500-year storm event of 10 inches yielded a model estimate of 4.24 inches of total recharge over the 30 days following the storm event.

Modeling was also performed to estimate recharge from ponding scenarios. It was found that steady state ponding was reached quickly and in turn, steady state recharge rates were also established quickly. A relationship between steady state recharge and ponding was established. Based on this relationship, it was estimated that one foot of ponding with a two-week duration would result in approximately 6 inches per day recharge. This scenario is consistent with observations made during the spring and summer of 2007.

Based on transducer data collected at the most distant downgradient wells (TMW-24 and 02W48), changes in groundwater levels were shown to be unrelated to changes in river stage via alluvial soils, independent of river overtopping. If the focus of future work remains upgradient of TMW-24 and 02W48 as it has been to date, it is expected that the river will not impact groundwater conditions in the treatment area.

5.0 Summary and Conclusions

The conclusions of the hydrology assessment of recent and historical data are summarized as follows:

1) A total of 40.48 inches of rain fell between March 1and August 21, 2007. This total represents an almost 100% increase over typical rainfall during the same time period. Site precipitation data is consistent with data from the Oklahoma City weather station. The extreme precipitation and the consequent response in surface and groundwater were evaluated to draw conclusions regarding the site during transient hydrologic events.

2) The evaluation suggested that flows at the site would have to be around 45,000 cfs for bank overtopping to occur, which corresponds to a recurrence interval of between 4.5 and 5 years. Except for the mid-August 2007 hydrologic event, all the other events appear to have been driven by regional (frontal) precipitation events. With these events, there is a fairly uniform response in river levels and flow rates and in groundwater elevations. The mid-August 2007 event appears to have had a different rainfall pattern; river responses at Dover were far less than at Guthrie and groundwater responses in the upland sandstone wells were small relative to the other events. This information suggests that the sandstone wells are more influenced by regional groundwater boundary conditions as opposed to short-duration local precipitation events.

3) The water level data collected by transducer at 02W48 and TMW-24, 200 feet from the river, showed groundwater hydrographs that are strongly influenced by precipitation and are not influenced by river water levels, independent of river overtopping. In turn, it is expected that water quality at 02W48 and TMW-24 would be consistent with Sandstone C and Alluvial well waters, respectively, that is, uninfluenced by river water quality. It is expected that high river elevations alone will not impact groundwater elevations in the plume area as currently mapped (CSM Rev 01, ENSR 2006a).

4) In general, in the Sandstone B and Transition Zone soils, transient hydrologic events such as seen in the spring and summer of 2007 are not expected to result in changes to the groundwater gradients or the groundwater fluxes that are dramatically different from the changes that might be seen based on seasonally collected water elevations. This suggests that groundwater elevations in Sandstone B and Transitions Zone soils are fairly stable. Groundwater elevations in alluvial zone soils were far more responsive to transient hydrologic events, however elevations generally responded uniformly indicating no net change in groundwater gradients and fluxes. The exception to this was that some data suggested periodic change in groundwater gradients between TMW-13 and 02W43. These changes lasted at most eight days; this short duration may result in short-term increases of flux, but relative to the total water balance, these increases are insignificant.

5) Throughout the spring and summer 2007 season, ponding was frequently observed in the BA#1 area. This ponding occurred and persisted because of the poorly-draining soils in that area that receive water from precipitation, upland runoff, and river water that inundated low-lying drainages.

6) All of the data collected over spring and summer of 2007 were from the BA#1 area. Though there is no data from the Western Alluvial Area, the following conclusions can be drawn:

   - Small site-scale differences in precipitation are not expected to have been significant.
   - Groundwater rises and falls are expected to be consistent with what was observed in the wells screened in alluvial soils in the BA#1 area. Groundwater rises and falls may be as much as 5 to 10 feet, but the rises and falls occur concurrently so there is no change in gradient. Short-term changes in flux are small relative to the total water budget for the site.

- In the BA#1 area, rises and falls in the river did not impact groundwater elevations or water quality 200 feet from the river. Groundwater impacts from uranium in the Western Alluvial area occur at a much greater distance than 200 feet from the river. Therefore, the rises and falls in the river are not expected to impact the WAA where uranium occurs.
- The mechanisms that cause ponding in the Western Alluvial are the same as for the other floodplain areas of the site. Site observations indicate that there is a low-lying drainage feature that runs next to Route 74 that may serve as a conduit of river water to the southern area of the escarpment when river water levels are high.

The HELP model was used with precipitation and soil characteristics to estimate a depth of recharge based on a variety of soil characteristics and depths of rainfall. Factors that control recharge to the water table are the intensity, frequency, and duration of rainfall as well as soil properties. Results of the HELP model can be summarized as follows:

- Average annual recharge rates, regardless of soil type, were fairly consistent with one another (4.3 to 7.2%) and are consistent with what is reported in the literature. A sensitivity evaluation indicates that the model is not that sensitive to soil thickness and therefore, to depth to water.
- For an extreme statistical rainfall event, 7-day, 500-year rainfall (total precipitation of 15.5 inches), recharge was simulated to be almost 8 inches of recharge over 30 days. Over the BA#1 plume area this amounts to 48,200 cubic feet or 361,000 gallons over 30 days.
- The HELP model was used to simulate ponding and consequent recharge that occurred from extreme precipitation and accumulated runoff. The simulations relied on observations made during spring and summer 2007. Ponding of 1 to 2 feet lasting approximately 14 days was estimated to result in a recharge volume over the BA#1 plume area of 170,000 cubic feet or 1.3 million gallons over 14 days.
- The HELP model was used to simulate ponding and consequent recharge that occurred from river bank overtopping that would reach elevation 940 feet, thus causing 1 to 2 feet of ponding in the BA#1 plume area. Statistical studies indicated a flooding event of this magnitude may last for 7 to 10 days. Model output estimated a recharge volume of 195,500 cubic feet or 1.5 million gallons over 10 days.

HELP modeling was conducted not necessarily to provide a precise estimate of recharge for any of the given scenarios discussed above, but rather to provide bounds on data heretofore uncharacterized. This study has helped to better conceptually characterize the site especially in terms of transient hydrologic processes.

6.0 References

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Crescent: http://waterdata.usgs.gov/nwis/dv?referred_module=sw&site_no=07159400

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TABLES

Table 3-1
Hydrology Addendum
Summary of PKFQWin Results for Flow (cfs)

Exceedance Probability (1/year)	Calculated Dover flow (cfs) (1)	Calculated Guthrie flow (cfs) [1]	Estimated flow (cfs) at Rte 74 [2]	Recurrance Interval Flood (year)
0.995	3,468	2,462	2,714	1.005
0.99	4,160	3,248	3,476	1.010
0.95	6,870	6,651	6,706	1.053
0.9	9,002	9,512	9,385	1.111
0.8	12,520	14,350	13,893	1.25
0.6667	17,080	20,620	19,735	1.5
0.5	23,730	29,520	28,073	2
0.4292	27,200	34,020	32,315	2.3
0.2	45,440	55,870	53,263	5
0.1	64,090	75,550	72,685	10
0.04	92,780	101,800	99,545	25
0.02	118,000	122,000	121,000	50
0.01	146,800	142,400	143,500	100
0.005	179,300	162,900	167,000	200
0.002	228,800	190,300	199,925	500

Notes
1 - Based on PKFQWin.
2 - Based on linear interpolation with distance.

Table 3-2
Hydrology Addendum
Summary of PKFQWin Results for Depth (feet)

Exceedance Probability (1/year)	Calculated Dover stage (ft) [1]	Calculated Dover depth (ft) [2]	Calculated Guthrie stage (ft) [1]	Calculated Guthrie depth (ft) [2]	Estimated depth (ft) at Route 74 [3]	Estimated elevation (ft) at Route 74 [4]	Estimated Flow (cfs)	Recurrance Interval Flood (year)
0.995	13.6	3.9	4.4	3.5	3.6	928.6	2,714	1.005
0.99	14.0	4.3	4.8	4.1	4.1	929.1	3,476	1.010
0.95	15.1	5.2	6.2	6.1	5.9	930.9	6,706	1.053
0.9	15.8	5.8	7.0	7.2	6.9	931.9	9,385	1.111
0.8	16.7	6.6	8.1	8.8	8.3	933.3	13,893	1.25
0.6667	17.6	7.4	9.2	10.4	9.6	934.6	19,735	1.5
0.5	18.6	8.2	10.5	12.2	11.2	936.2	28,073	2
0.4292	19.1	8.7	11.1	13.1	12.0	937.0	32,315	2.3
0.2	20.9	10.2	13.5	16.5	15.0	940.0	53,263	5
0.1	22.3	11.4	15.2	19.0	17.1	942.1	72,685	10
0.04	23.9	12.8	17.2	21.8	19.6	944.6	99,545	25
0.02	25.1	13.9	18.6	23.8	21.4	946.4	121,000	50
0.01	26.1	14.7	19.9	25.7	23.0	948.0	143,500	100
0.005	27.2	15.7	21.1	27.4	24.5	949.5	167,000	200
0.002	28.6	16.9	22.6	29.6	26.4	951.4	199,925	500

Notes:
1 - Based on PKFQWin.
2 - Based on stage-depth relationship, assumes rectangular channel.
3 - Based on linear interpolation with distance.
4 - Bottom Elevation of Cimarron River at Rte 74 Estimated at 925 feet.

Table 4-1
Hydrology Addendum
HELP Model Inputs/Outputs for
Base Case Runs

BASE CASE 1 - 5 Year Simulation Using Synthetic Rainfall

INPUTS			
Weather Data			
Evapotranspiration Data			Source
City:	OKC		
State:	OK		
Latitude:	35.88		Adjusted for site
Evaporative Zone Depth:	25	inches	Based on guidance document
Maximum Leaf Area Index:	4.5		4.5 recommended by guidance document.
Growing Season Start Day:	86		Default based on location
Growing Season End Day:	310		Default based on location
Average Wind Speed:	12.5	MPH	Default based on location
First Quarter Relative Humidity:	64	%	Default based on location
Second Quarter Relative Humidity:	66	%	Default based on location
Third Quarter Relative Humidity:	63	%	Default based on location
Fourth Quarter Relative Humidity:	66	%	Default based on location
Precipitation Data			
5 year synthetic	30.89	in/year	Using default monthly means.
OR			
Actual data from 2003-2007			Using actual measurements from OKC
Temperature Data			
5 year synthetic			Using default monthly means.
Solar Radiation Data			
5 year synthetic	35.88	degrees	Latitude to generate data.
Soil and Design Data			
General Information			
Area:	1	Acre	Assume a unit area of 1 acre in BA#1 flood plain
Percent of area were runoff is possible:	100	%	None is water
Specify initial soil moisture:	No		Over long simulations, soil moisture will come to steady state regardless of initial inputs.
Soil Layer Information:			
Soil Layer 1 - Layer Type	1		Type 1 address vertical percolation
Soil Layer 1 - Layer Thickness	52.08	inches	Thickness of flood plain silty-clay based on data from TMW-23, 02W48, 02W46, TMW-09
Soil Layer 1 - Soil Texture	12		Silty-clay soil type
Soil Layer 1 - Total Porosity	0.471	vol/vol	Default values for soil type 12
Soil Layer 1 - Field Capacity	0.342	vol/vol	Default values for soil type 12
Soil Layer 1 - Wilting Point	0.21	vol/vol	Default values for soil type 12
Soil Layer 1 - Saturated Hydraulic Conductivity	1.20E-03	cm/sec	Based on slug test data in wells with silty clay (see Table 1, GW Modeling Report)
Soil Layer 2 - Layer Type	1		Type 1 address vertical percolation
Soil Layer 2 - Layer Thickness	50	inches	Thickness of flood plain sands based on data from TMW-23, 02W48, 02W46, TMW-09
Soil Layer 2 - Soil Texture	2		Sand soil type
Soil Layer 2 - Total Porosity	0.437	vol/vol	Default values for soil type 12
Soil Layer 2 - Field Capacity	0.062	vol/vol	Default values for soil type 12
Soil Layer 2 - Wilting Point	0.024	vol/vol	Default values for soil type 12
Soil Layer 2 - Saturated Hydraulic Conductivity	4.80E-02	cm/sec	Based on slug test data in wells with sand (see Table 1, GW Modeling Report)
Runoff Curve Number Information			
User Specified Runoff Curve Number	50		Based on soil type 2 and fair grass condition

Table 4-1
Hydrology Addendum
HELP Model Inputs/Outputs for
Base Case Runs

BASE CASE 1 - 5 Year Simulation Using Synthetic Rainfall				
OUTPUT				
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	27.85	5	100	
Runoff	0.04	0.0439	0.07	
Evapotranspiration	26.603	4.3104	95.53	
Percolation/Leakage Through Layer 2	1.07	0.96	3.84	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	0.154	1.46	0.55	
BASE CASE 2 - 5 Year Simulation Using Actual Rainfall from 2002-2006				
INPUTS				
Same as above except rainfall inputs				
OUTPUT				
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	27.47	6.232	100	
Runoff	0	0	0	
Evapotranspiration	25.44	4.03	92.99	
Percolation/Leakage Through Layer 2	1.98	0.91	7.2	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.053	3.13	-0.195	
BASE CASE 3 - 6 Year Simulation Using Actual Rainfall from 2002-2006 and partial 2007				
INPUTS				
Same as above except rainfall inputs				
OUTPUT				
2007	Total	Std. Dev.	Percent (%)	
Precipitation	43.92		100	
Runoff	0.14		0.32	
Evapotranspiration	32.63		74.31	
Percolation/Leakage Through Layer 2	12.08		27.5	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.936		-2.13	
Average Annual Totals (inches)	Total	Std. Dev.	Percent (%)	
Precipitation	30.21	8.728	100	
Runoff	0.023	0.0572	0.077	
Evapotranspiration	26.695	4.58	88.361	
Percolation/Leakage Through Layer 2	3.71	4.19	12.29	Water exiting the bottom of the sand layer, thus reaching the water table.
Change in Water Storage	-0.22	2.92	-0.729	

Table 4-2
Hydrology Addendum
Summary of HELP Model Simulation Results

Variability in recharge rates based on Soil Type using 2002-2006 rainfall data. See Section 4.3.2

	Average Annual Recharge inches	Average Annual Recharge percent	
1 - Floodplain with overlying silty-clay, Base Case	1.89	6.9	
2 - Silty-clayey-sand with no underlying sand	1.42	5.2	As seen at transition wells, among other locations
3 - Fill underlain by sandstone	1.21	4.4	As seen at TMW-21, TMW-08

Variability in recharge rates based on alluvial soils and different recurrence interval precipitation events. See Section 4.3.3

		Precipitation on July 1st or July 1st to 7th (inches)[1]	Recharge totaled over 30 days after extreme rainfall event (inches)
a	24-hour duration, 2 year-recurrence interval	3.3	0.41
b	24-hour duration, 100 year-recurrence interval	9.5	5.49
c	24-hour duration, 500 year-recurrence interval	10	5.94
d	7-day duration, 2 year-recurrence interval	4.9	0.013
e	7-day duration, 100 year-recurrence interval	12.4	6.24
f	7-day duration, 500 year-recurrence interval	15.5	9.67

1 - From Rea and Tortorelli, 1999

Table 4-3
Hydrology Addendum
Duration of Statistical High Flows

DOVER - Magnitude and probability of annual high flow based on period of record 1974-1999.
Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent

Period (consecutive days)	2 years 50%	5 years 20%	10 years 10%	25 years 4%	50 years 2%	100 years 1%
1	18,400	34,700	49,100	72,100	93,000	117,000
3	12,800	23,900	33,500	48,700	62,300	78,000
7	7,520	13,900	19,500	28,400	36,500	45,800
10	6,240	11,500	15,900	22,800	28,900	35,800
30	3,390	5,900	7,790	10,400	12,500	14,600
60	2,330	3,890	5,020	6,540	7,720	8,930

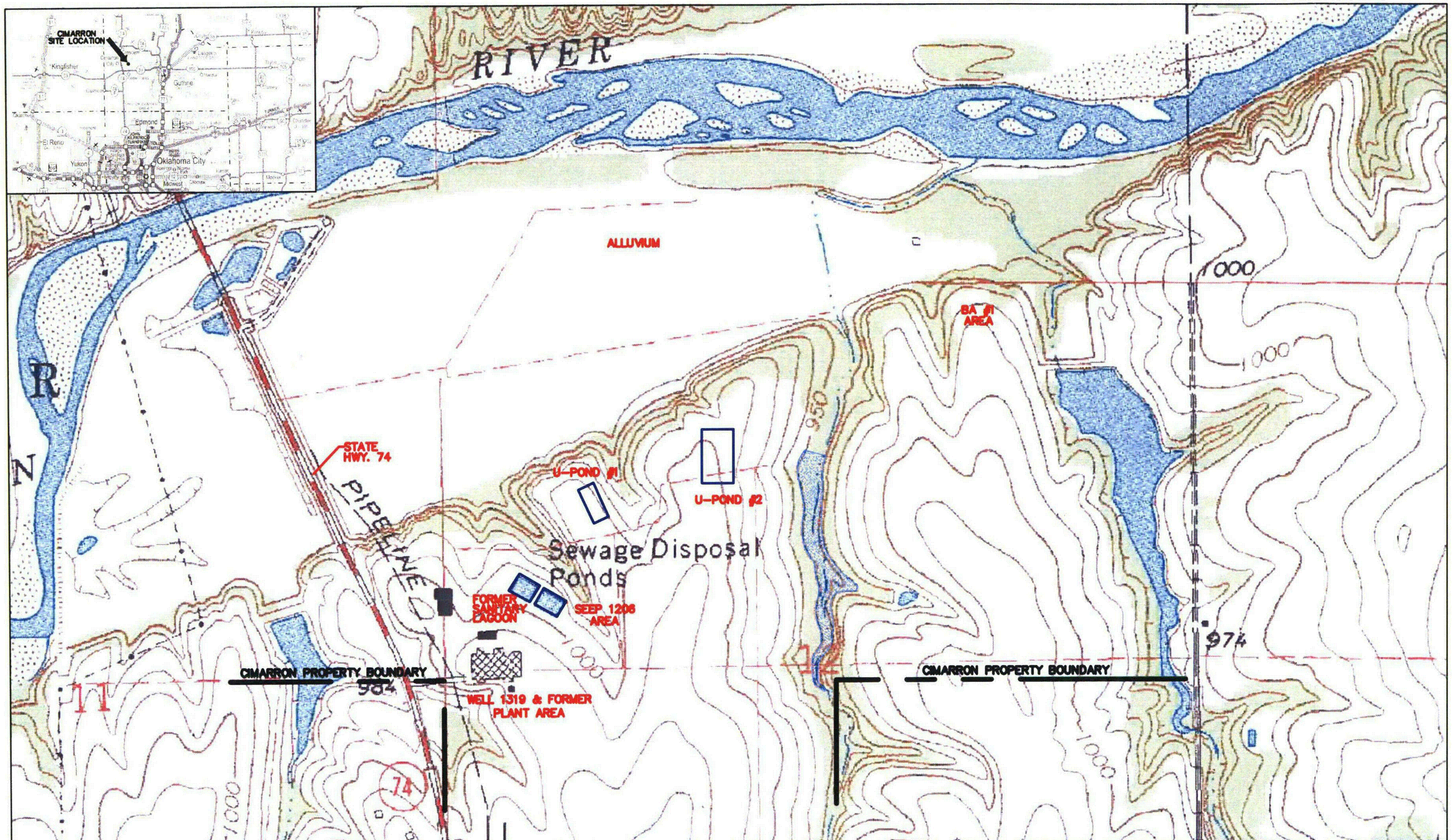
GUTHRIE - Magnitude and probability of annual high flow based on period of record 1974-1999.
Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent

Period (consecutive days)	2 years 50%	5 years 20%	10 years 10%	25 years 4%	50 years 2%	100 years 1%
1	24,400	46,600	62,600	83,500	99,000	114,000
3	16,400	32,100	44,300	61,300	74,800	88,800
7	9,660	19,600	27,900	40,200	50,600	61,900
10	7,510	15,500	22,300	32,700	41,800	51,900
30	3,750	7,460	10,600	15,400	19,600	24,300
60	2,570	5,110	7,280	10,600	13,400	16,500

CIMARRON SITE AT RTE 74 - Magnitude and probability of annual high flow based on period of record 1974-1999.
Discharge in cfs, for indicated recurrance interval, in years, and exceedance probability, in percent

Period (consecutive days)	2 years 50%	5 years 20%	10 years 10%	25 years 4%	50 years 2%	100 years 1%
1	22,900	43,625	59,225	80,650	97,500	114,750
3	15,500	30,050	41,600	58,150	71,675	86,100
7	9,125	18,175	25,800	37,250	47,075	57,875
10	7,193	14,500	20,700	30,225	38,575	47,875
30	3,660	7,070	9,898	14,150	17,825	21,875
60	2,510	4,805	6,715	9,585	11,980	14,608

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. 04020056

DESIGNED BY:	REVISIONS			
DRAWN BY: JAS	NO.:	DESCRIPTION:	DATE:	BY:
CHECKED BY: DJF	1.		4/01/05	JAS
APPROVED BY: DJF	2.		6/17/05	JAS
	3.		6/8/05	JAS

ENSR | AECOM

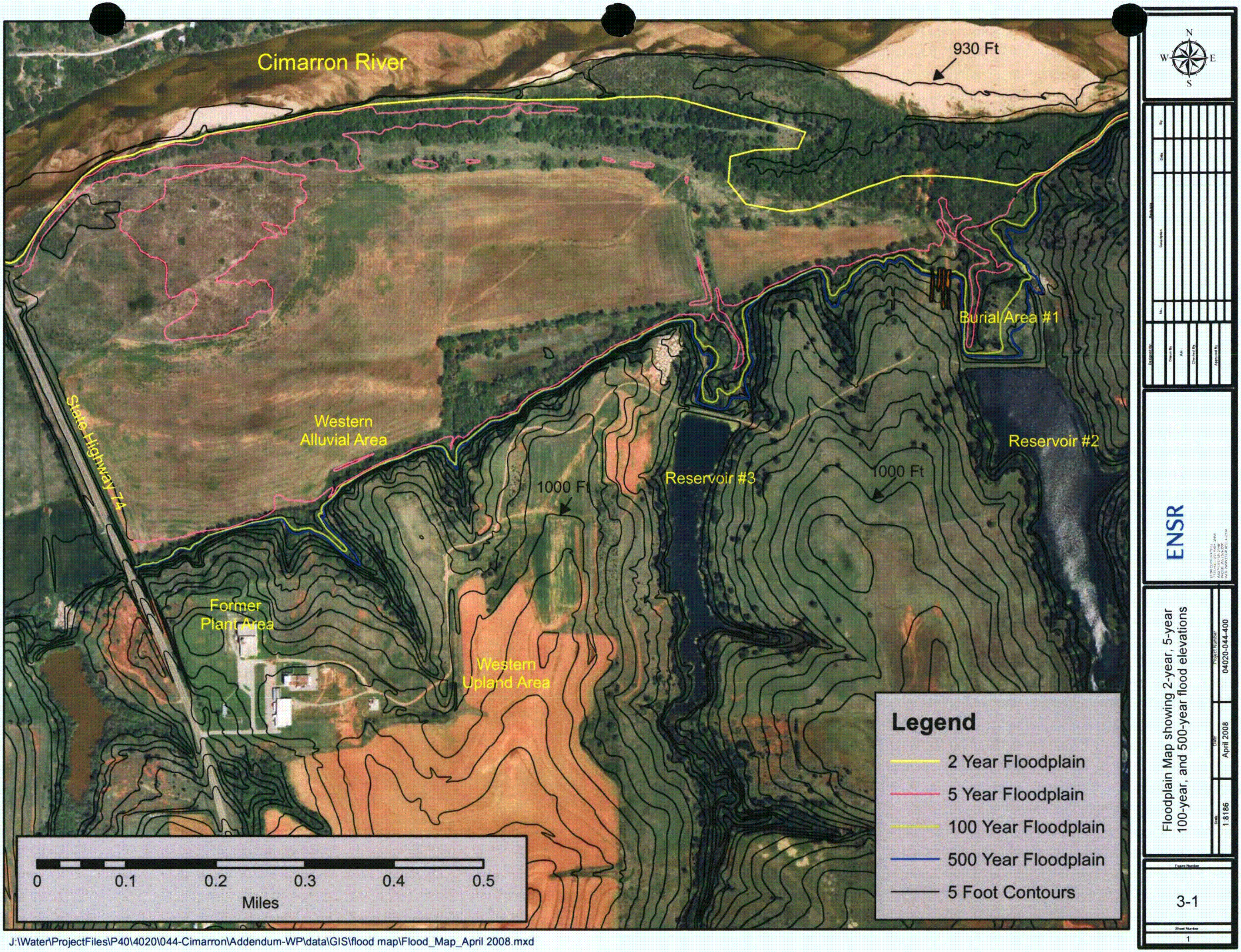
ENSR CORPORATION
4888 LOOP CENTRAL DRIVE, SUITE 600
HOUSTON, TEXAS 77081-2214
PHONE: (713) 520-9900
FAX: (713) 520-6802
WEB: HTTP://WWW.ENSR.AECOM.COM

FIGURE 2–1
SITE LOCATION MAP
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

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

FIGURE NUMBER: 2–1

SHEET NUMBER: 1



J:\Water\ProjectFiles\P40\4020\044-Cimarron\Addendum-WP\data\GIS\flood map\Flood_Map_April 2008.mxd

Figure 3-2
Hydrology Addendum
Precipitation measured
March 1, 2007 to August 21, 2007

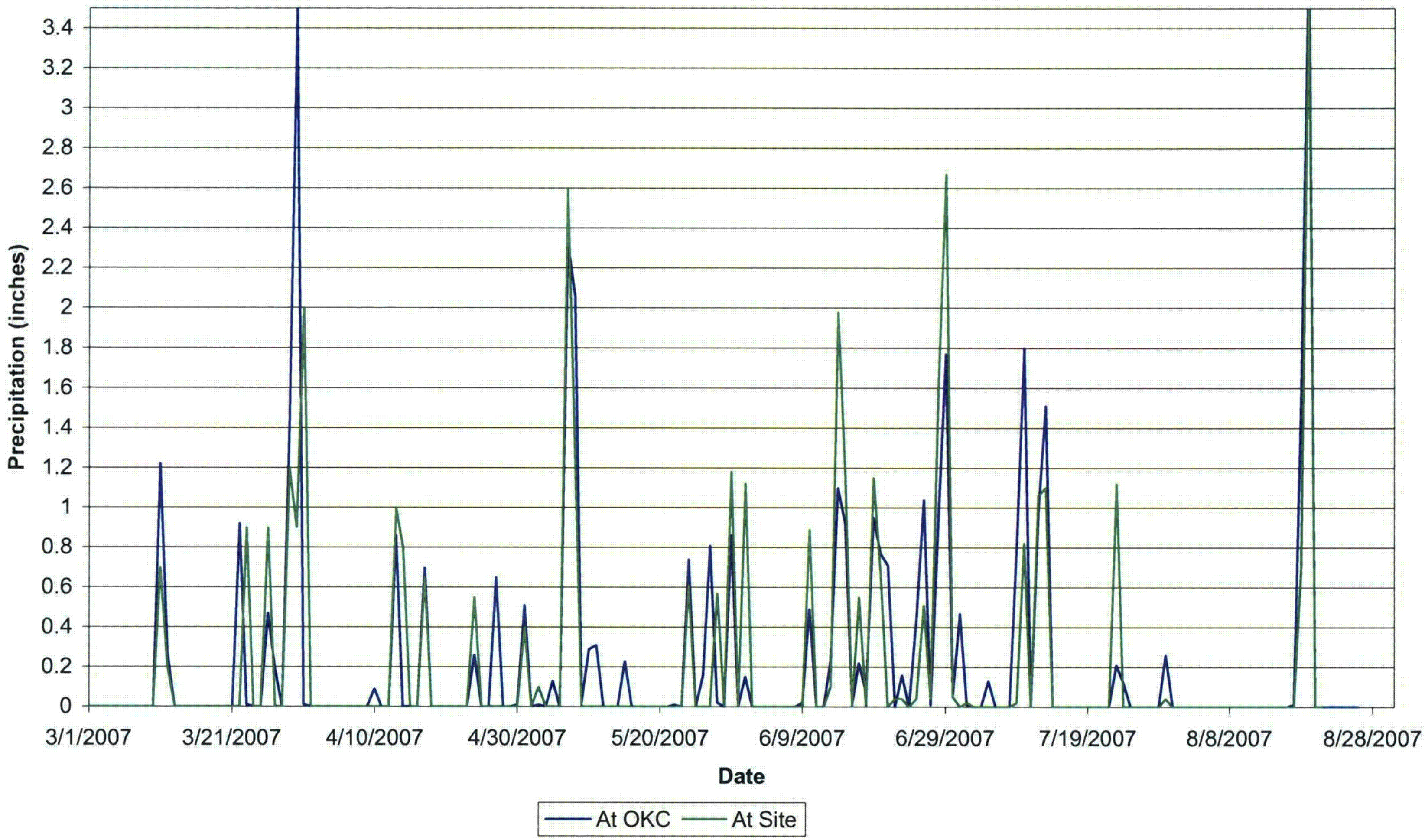


Figure 3-3
Hydrology Addendum
Flows on the Cimarron River between March 1, 2007 and August 21, 2007
at Dover

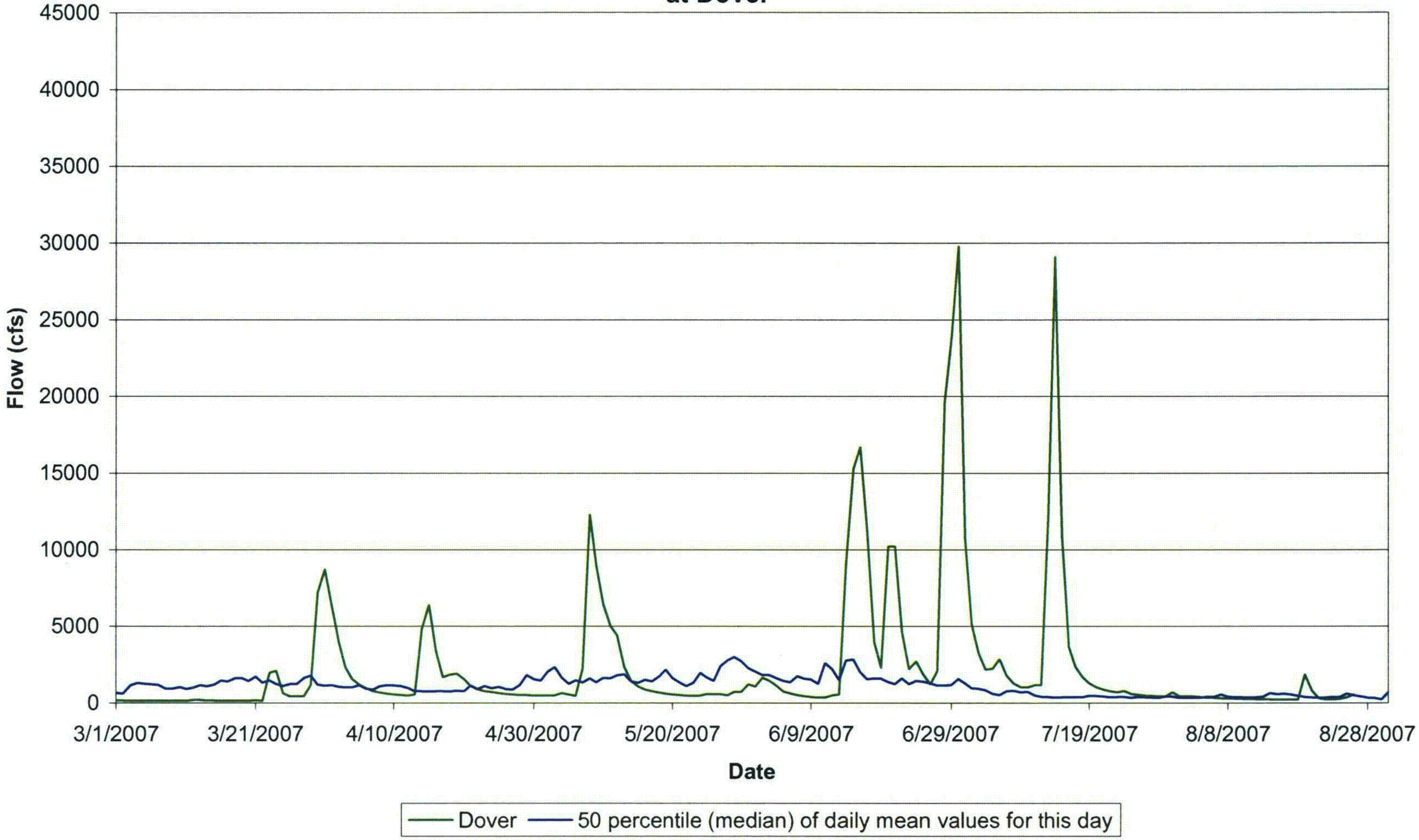


Figure 3-4
Hydrology Addendum
Flows on the Cimarron River between March 1, 2007 and August 21, 2007
at Guthrie

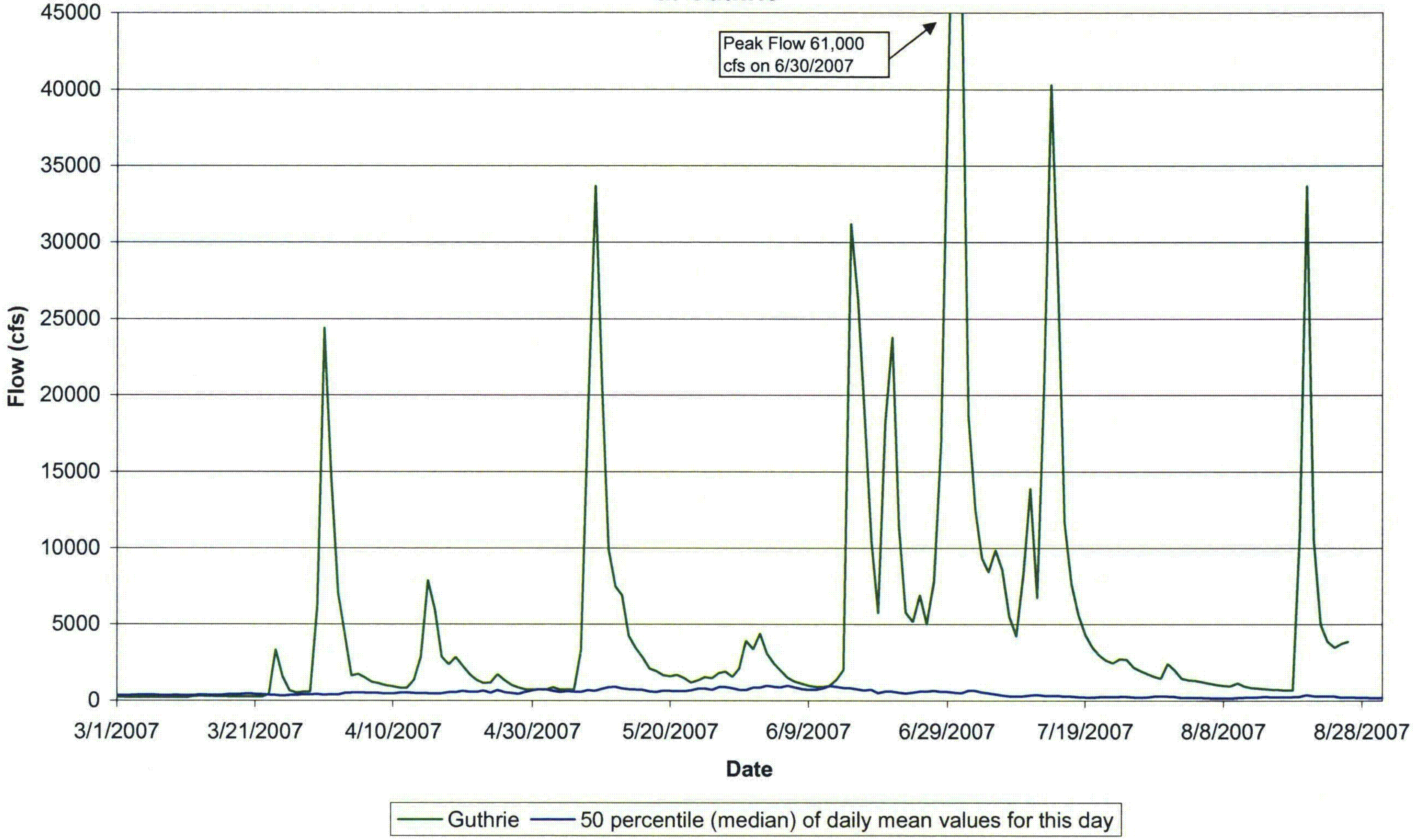
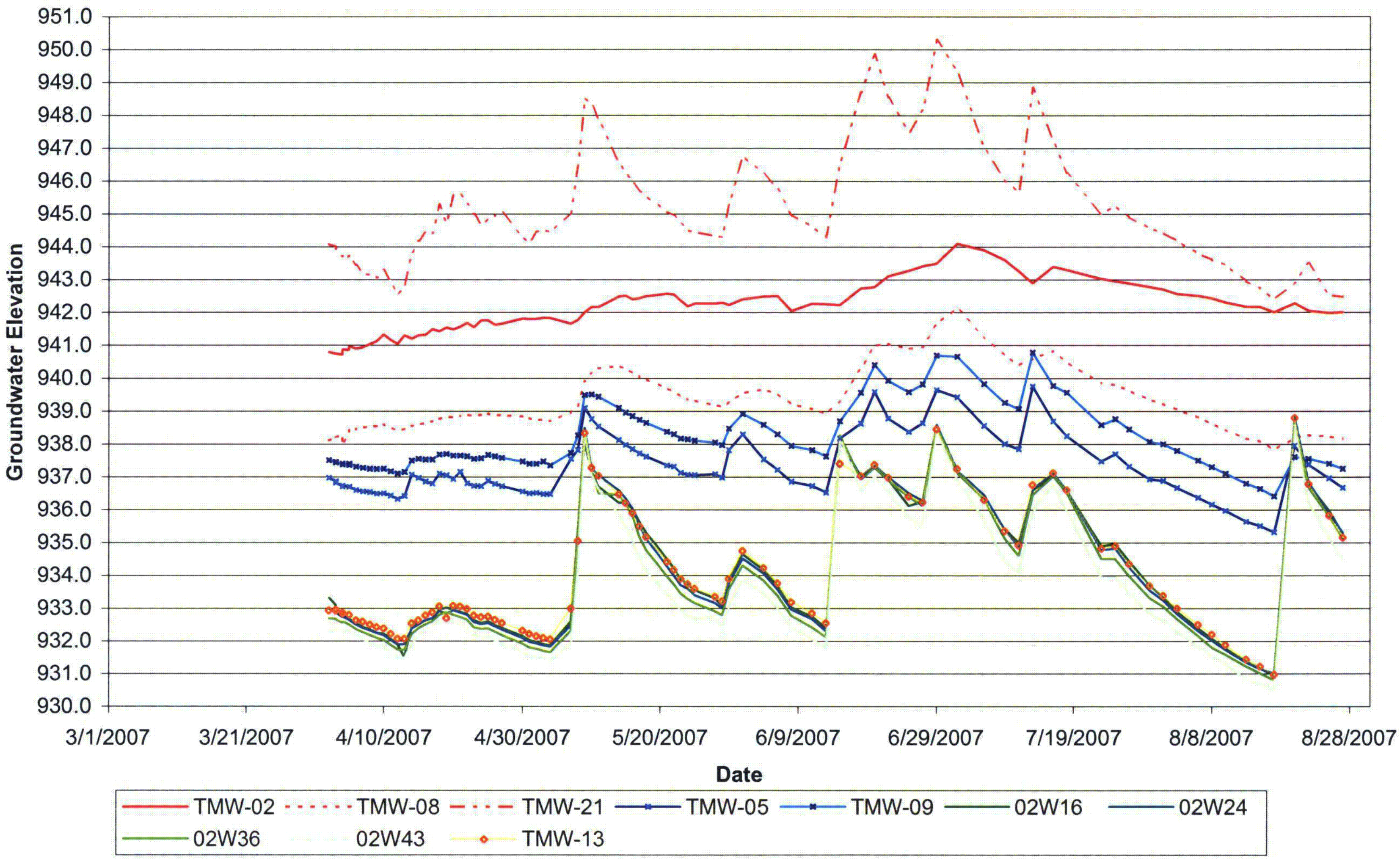


Figure 3-5
Hydrology Addendum
Groundwater Elevations at BA#1 Wells April 1, 2007 and August 20, 2007



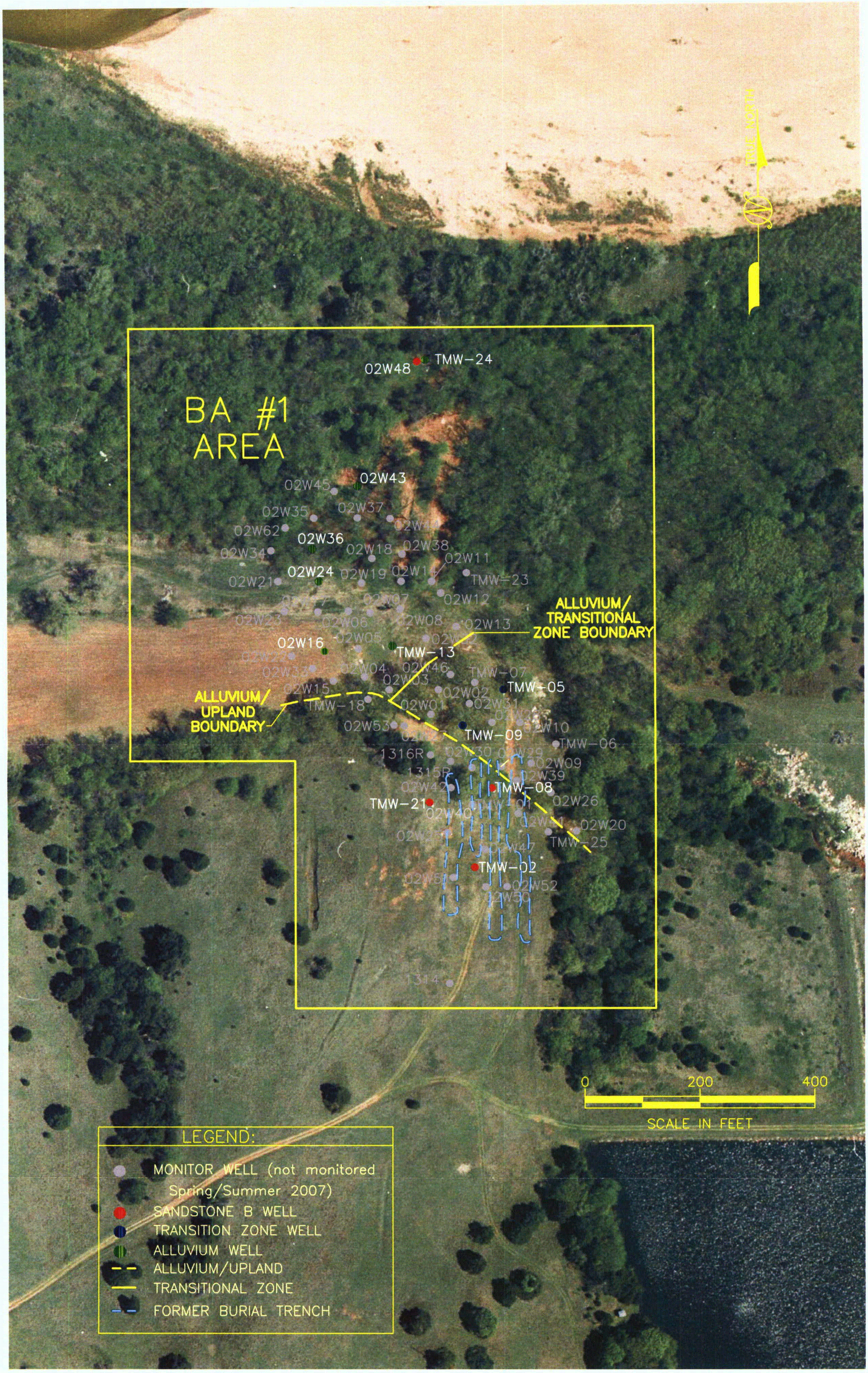


FIGURE 3-6
BA #1
LOCATION OF WELLS MONITORED FOR
GROUNDWATER ELEVATION APR.-AUG. 2007
CIMARRON CORPORATION
CRESCENT, OKLAHOMA

SCALE:	DATE:	PROJECT NUMBER:
1"= 200'	10-31-07	04020-044-400

SHEET NUMBER: 1

FIGURE NUMBER: 3-6

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

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	

Figure 3-7
Hydrology Addendum
Water level data as measured at the transducers in TMW-24 and 02W48 and site rainfall
March 1, 2007 to August 21, 2007

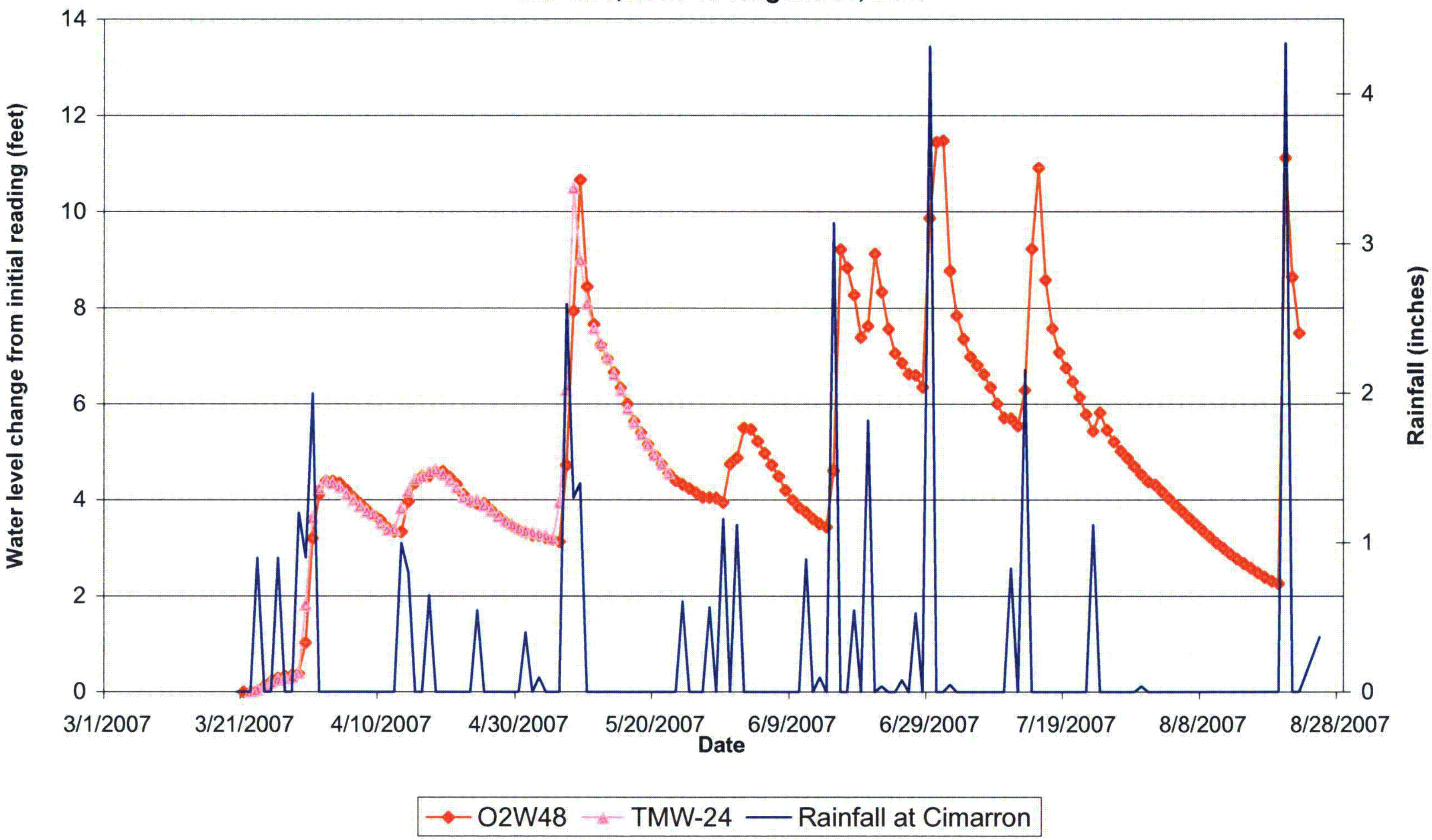
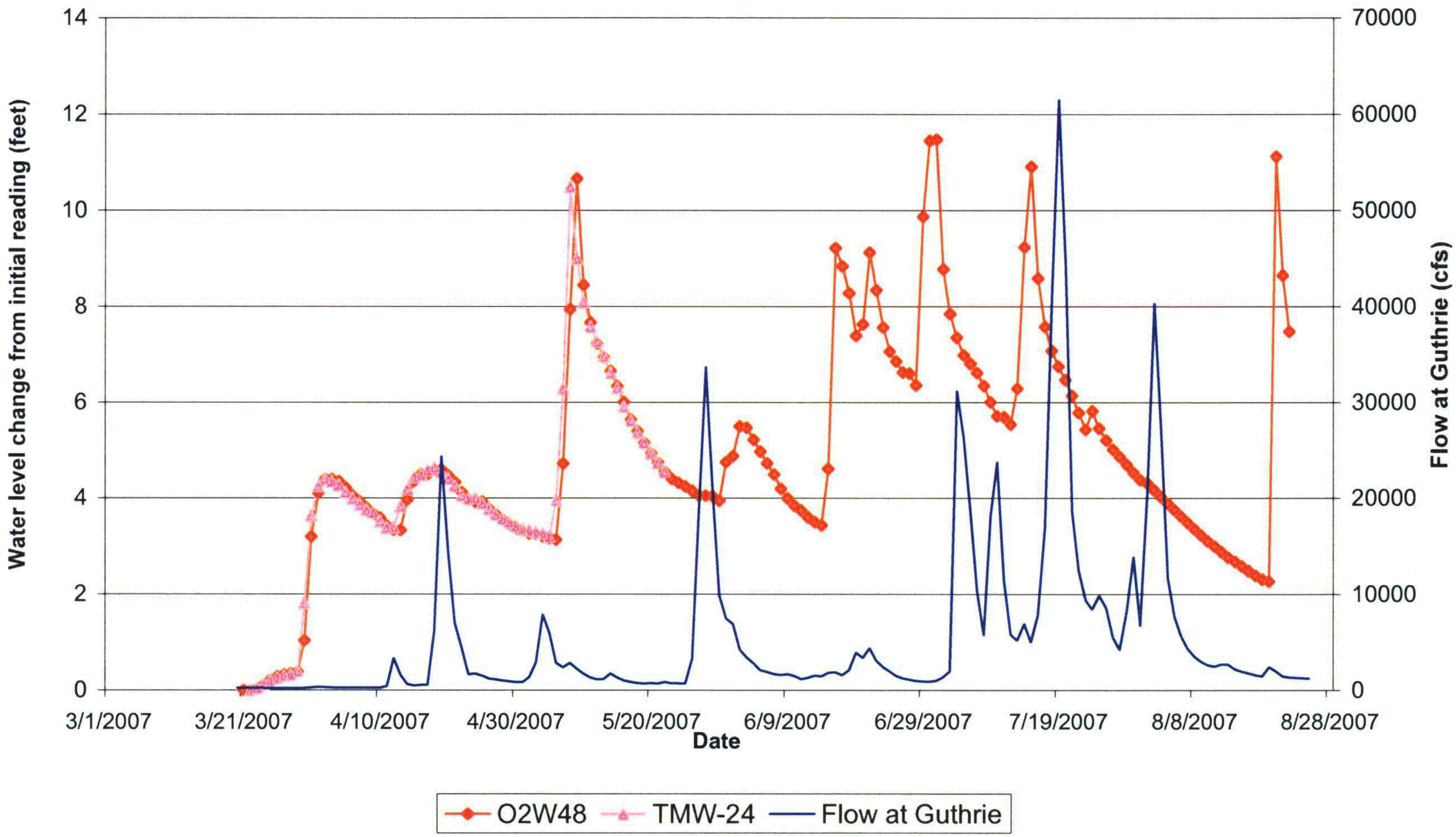
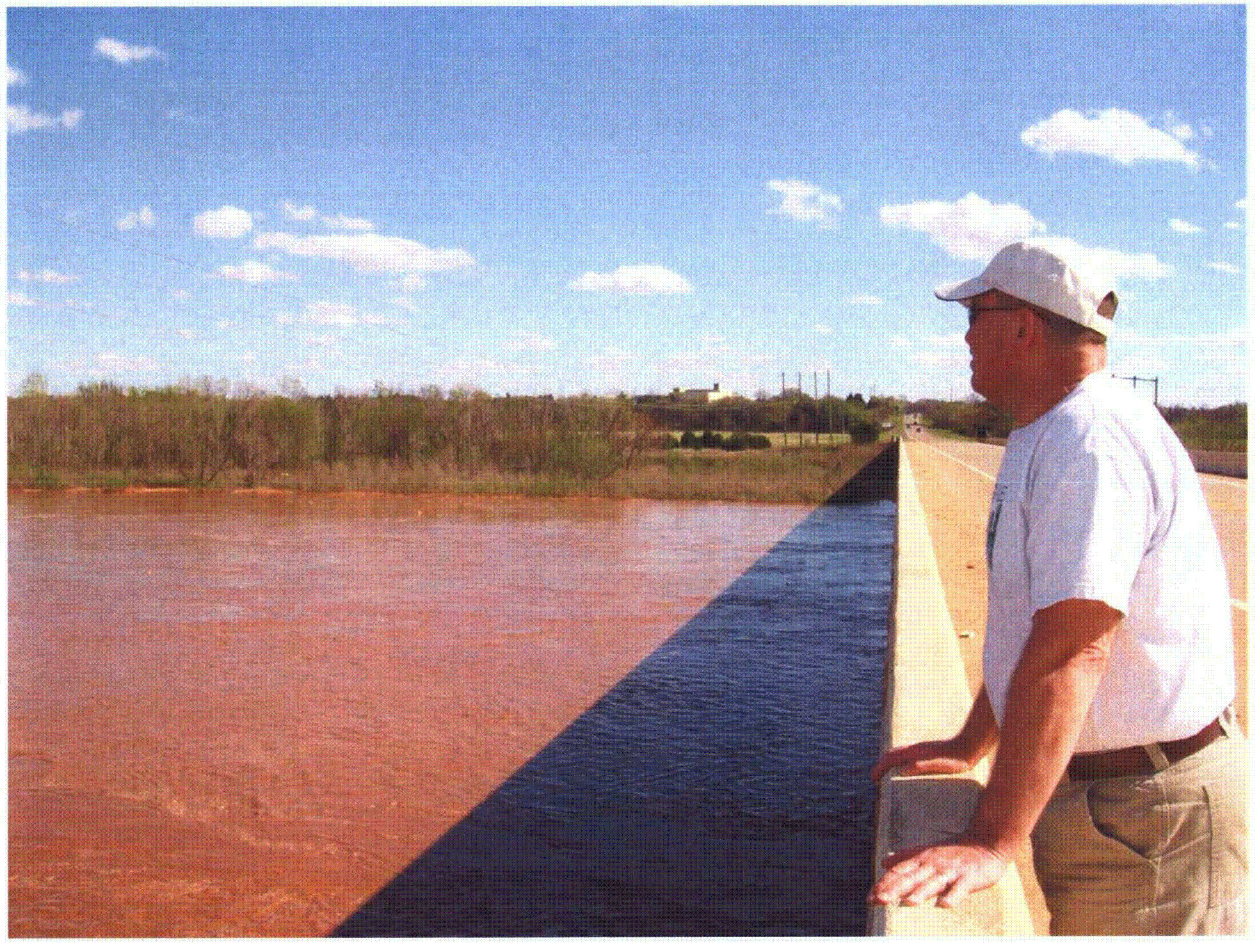


Figure 3-8
Hydrology Addendum
Water level data as measured at the transducers in TMW-24 and 02W48
and Guthrie flow data
March 1, 2007 to August 21, 2007





April 2, 2007

October 18, 2007

Cimarron River at Route 74 Looking South

April 2008 Job No. 04020-044-400

Figure 3-9

www.ensr.aecom.com

April 2, 2007

October 18, 2007

BA#1 Floodplain Area April 2008 Job No. 04020-044-400	Figure 3-10 www.ensr.aecom.com

May 15, 2007

October 18, 2007

Cimarron River at Route 74 Looking South

April 2008 Job No. 04020-044-400

Figure 3-11

www.ensr.aecom.com

May 15, 2007

October 18, 2007

BA#1 Floodplain Area	Figure 3-12
April 2008 Job No. 04020-044-400	www.ensr.aecom.com

July 26, 2007

October 18, 2007

Cimarron River at Route 74 Looking South

April 2008 Job No. 04020-044-400

Figure 3-13

www.ensr.aecom.com

July 26, 2007

October 18, 2007

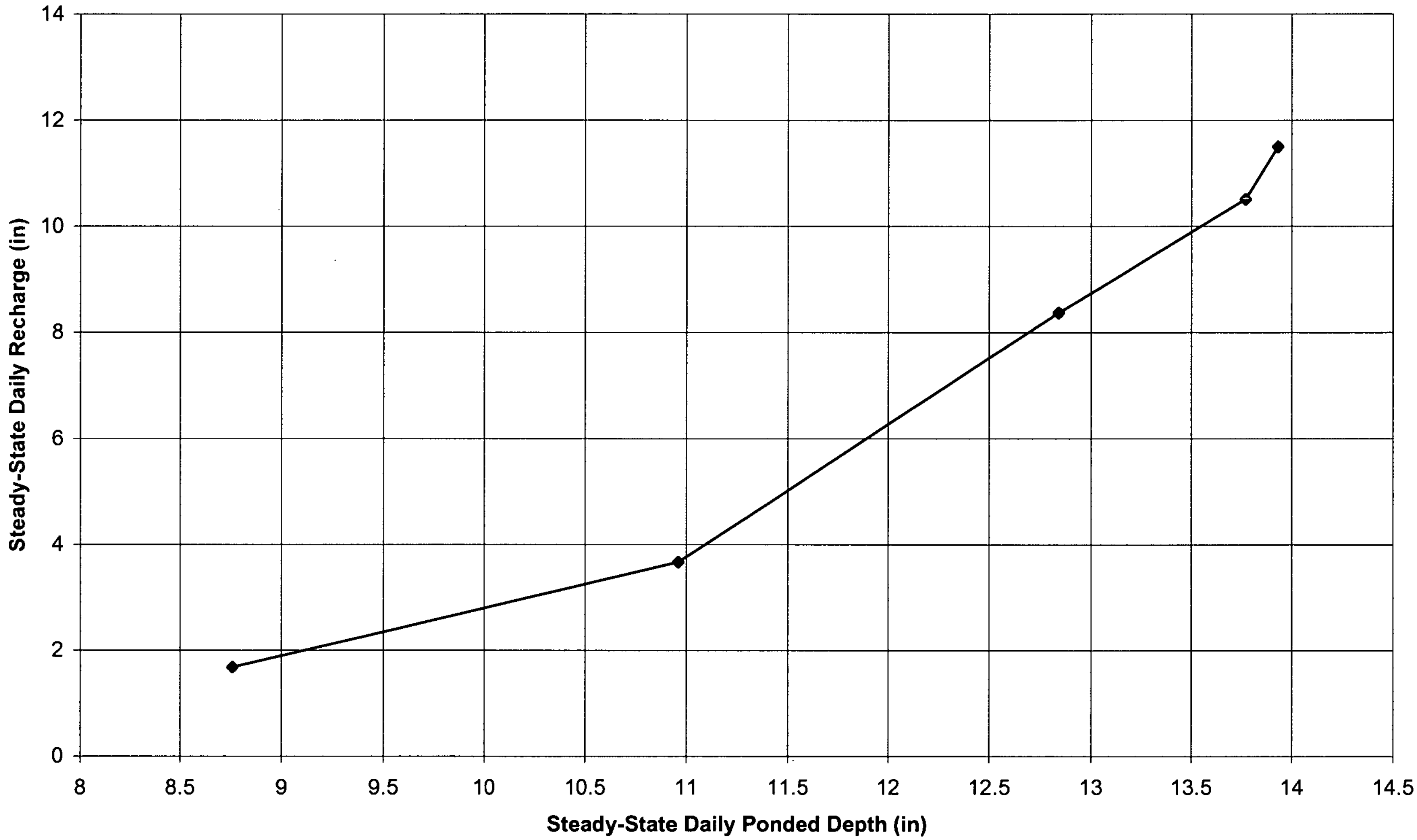
Western Alluvial Area

April 2008 Job No. 04020-044-400

Figure 3-14

www.ensr.aecom.com

Figure 4-1
Hydrology Addendum
Simulated Daily Ponded Depth versus Simulated Daily Recharge



Appendix C

Data Quality Objectives

Appendix C
Data Quality Objectives
Groundwater Decommissioning Plan

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
1: Development of Groundwater Decommissioning Plan and Approval (by the NRC and ODEQ)	A. Evaluate uranium precipitation and immobilization; evaluate the mass of iron sulfide required for remediation system	1) Collect groundwater and soil geochemical data	ARCADIS sampling procedures	Water level data to ±1 foot, sample according to low-flow methods
		2) Update thermodynamic database 3) Perform model runs 4) Analyze output	Defined in peer-reviewed literature	Verification and validation for off-the-shelf (commercial) software is not required.
2: Baseline Sampling and Initial Treatment System Installation	A. Determination of the baseline iron mineralogy, including iron sulfide	1) Soil sampling	ARCADIS sampling procedures Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.	Sample to prevent air oxidation using gloved bag for handling samples at surface; seal samples to protect from oxidation and ship on dry ice for analysis.
		2) Soil digestions and analysis	EPA Protocol 3050B and 3052	Not applicable
		3) Selective extraction	ARCADIS Procedures, procedures published in the peer-reviewed literature	Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.
		4) Acid-volatile sulfide measurement	EPA Draft Protocol 821R91100	Reporting limits set prior to analyses and based upon method detection limits and requirements of the geochemical modeling and remediation system.
		5) X-ray diffraction	Defined in peer-reviewed literature	Not quantitative (detection only)
		6) SEM/EDS	Defined in peer-reviewed literature	Not quantitative (detection only)
		7) XAS	Defined in peer-reviewed literature	Not quantitative (detection only)
	B. Additional field characterization, including groundwater	Field parameters: 1) pH	ARCADIS procedures	± 0.2 standard units

Appendix C
Data Quality Objectives
Groundwater Decommissioning Plan

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
		2) ORP	ARCADIS procedures	± 10%
		3) DO		± 10%
		4) Conductivity		± 10%
		5) Temperature		± 10%
		Analytical laboratory	EPA Protocols	
		6) Total Organic Carbon	EPA 415.1	RL = 0.2 mg/L
		7) Anions (nitrate, sulfate)	EPA 300.0	RL = 0.1 mg/L
		8) Major Cations	EPA 200.8	RL = 0.1 mg/L
		9) Total and dissolved iron	EPA 200.8	RL = 0.025 mg/L
		10) Sulfide	EPA 376.1	RL = 0.1 mg/L
		11) Alkalinity	EPA 310.1	RL = 5 mg/L
		12) Isotopic uranium	LNST & DOE EML procedures	LNST Minimum Detectable Activities: 18 pCi/L total U, total alpha, total beta 9 pCi/L U-234 and U-238 5 pCi/L U-235 LNST precision: 6 pCi/L at 1 σ or 6% at 1 σ, whichever is greater

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
		13) Total uranium	EPA Protocol 6020	RL = 0.001 mg/L
	C. Install initial treatment system including remediation wells and performance monitoring wells.	1) Well/boring location selection and determination	ARCADIS procedures	± 2 ft from bottom of well screen
		2) Boring lithologic logging		Standard USCS
		3) IDW Management		Collection of saturated soils and radiological characterization
		4) Well construction		Screened at top of impacted interval
		5) Survey of wells		Industry standard (± 2 ft laterally and ± 0.1 ft vertically)
		6) Water level gauging		± 1 ft
		7) Extraction Pump Installation		± 10% of proposed spacing
		8) Hydraulic evaluation of sustainable injection and extraction yields		Defined in procedure
		9) Injection tracer test		Defined in procedure
		10) Determination of mobile porosity		Defined in procedure
		11) Determination of groundwater velocity		Defined in procedure

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
	D. Operate initial treatment system.	1) Carbon substrate delivery	ARCADIS procedures	± 20% of proposed amendment dose
		2) Amendment (iron sulfate) delivery		± 20% of proposed TOC dose
		3) Adjust flow rates and frequency of injection		Defined in procedure
	E. Collect system performance data for groundwater and soil iron mineralogy data	Same as Task 1A, 2A, and 2B	Same as Task 1A, 2A, and 2B	Same as Task 1A, 2A, and 2B
	F. Update/adjust Geochemical Model	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4
3: Full-scale Systems Operation/Active Treatment	A. Expand treatment systems to complete functionality	Same as Tasks 1A, and 2A-F	Same as Tasks 1A, and 2A-F	Same as Tasks 1A, and 2A-F
	B. Continue to operate and optimize systems	1) Perform semi-annual (seasonal) groundwater monitoring	Same as Task 2B	Same as Task 2B
		2) Soils mineralogy demonstration testing	Same as Task 2A	Establishment of at least 1 part uranium to 80 parts iron (by mass).
		3) Oxidative aging testing	ARCADIS procedure will be prepared for this testing	MQOs will be defined in the procedure
	C. Update/adjust Geochemical Model	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4	Same as Task 1A, Subtasks 2-4

In-Situ Bioremediation System				
Stage	**Task**	**Sub-Task or Measurement**	**Guidance/Procedures**	**Measurement Quality Objectives**
4: Remedy Completion Demonstration and License Termination	A. Collection of groundwater uranium concentrations and statistical trend analysis	1) Groundwater sampling and analysis	Same as Tasks 2B, 12 and 13	Same as Tasks 2B, 12 and 13
		2) Statistical analysis of trends over 8 quarters	EPA Guidance and Sen's Slope Estimator; ARCADIS procedure will be prepared for this assessment	To be described in ARCADIS procedure
	B. Soils demonstration	1) Demonstration of iron mineralogy (already completed in Stage 3) sufficient to maintain insoluble uranium mineral stability	Same as Task 2A	Same as Task 2A
		2) Demonstration of conversion of iron minerals to iron oxyhydroxides (oxidative aging already completed in Stage 3)	Same as Task 3A-3.	Same as Task 3A-3
		2) Final geochemical modeling using site-specific data (iron mineralogy and uranium concentrations in groundwater/soils)	Same as Task 1A	Same as Task 1A

Appendix D

Soil Analytical Methods

Appendix D

Soil Analytical Methods

A variety of methods will be used to provide a comprehensive characterization of the soil in the aquifer in order to verify that iron minerals are transformed to iron sulfide. A description of these methods, with reference to their application for similar purposes, is provided as follows:

Selective chemical extraction: This method involves the use of chemical extractants that target specific mineral phases in the soil (Tessier, 1979). Various iron mineral phases are quantified according to their crystallinity, for example amorphous (poorly crystalline iron) is extracted using a solution of hydroxylamine hydrochloride in dilute hydrochloric acid and crystalline iron is extracted with a solution of citrate-bicarbonate-dithionite (Chao and Zhou, 1983; Poulton and Canfield, 2005). Poorly crystalline iron is the most accessible form of iron for microbial transformation, however with time the crystalline iron fraction will be altered. The shift in iron speciation during the course of remediation will be quantified using this technique (Figure D-1). Ferrous iron that is released due to reductive dissolution of iron oxyhydroxides in the aquifer, and subsequently re-adsorbed, will be determined by extraction with dilute (0.25N) hydrochloric acid (Gleyzes et al., 2002). Acid-volatile sulfide, combined with analysis of simultaneously-extractable metals (AVS-SEM), will be used to quantify sulfide, iron and the production of iron sulfide in the soil during remediation (Cooper and Morse, 1999). Finally, total metal content of the soil will be determined by EPA Method 3050 (acid digestion) and inductively-coupled plasma mass spectrometry (ICP-MS, EPA Method 6010) in order to understand the fraction of total iron that is available for biotransformation.

X-Ray Diffraction: This method will provide information about the bulk mineralogy at baseline and during treatment. Soil (~1 gram) is loaded into a sample holder for analysis using a powder x-ray diffractometer; mineral phases are identified based upon their x-ray diffraction (XRD) pattern. Patterns are matched against standards available in a powder diffraction database provided by the International Centre for Diffraction Data (ICDD). Iron mineral phases, if present at concentration greater than 1 percent by weight can be detected and the method can provide semi-quantitative information about these minerals and their transformation over time. Bulk minerals, such as quartz, feldspar, plagioclase, amphibole, and clay, will likely comprise most of the aquifer soil at baseline; the method will be used to screen the samples for the iron minerals. This method will also be used to detect iron sulfides, if present in sufficient quantity (>1% by weight) (Wilkin and Barnes, 1996). Synchrotron-based XRD will be used to examine mineralogy of the samples at a higher resolution and will provide information about microscopic crystalline phases that may not be detected by bulk XRD. The advantage of synchrotron-based XRD is the ability to maintain the sample in a sample holder sealed from contact with air thereby preserving the air-sensitive minerals. This method is available at high-energy x-ray sources, including the National Synchrotron Light Source at Brookhaven National Laboratory (New York), and the Advanced Photon Source at Argonne National Laboratory (Illinois). These resources can be accessed through appropriate arrangements with these Federal "user-facilities." The x-ray microprobe XRD method can also be used to obtain x-ray fluorescence (XRF) information (to identify elements in a sample and the co-association of elements (such as iron and uranium) has been applied to examine mineralogy at the scale of 10-microns in a sample, and for understanding the biotransformation of radionuclides in the environment (Lanzirotti and Sutton, 2006; Fuhrmann and Lanzirotti, 2005). Sulfide phases, and mineral phases present below the detection of bulk-XRD methods, have been identified in environmental samples using this method (Walker et al., 2005).

Microprobe Methods: In addition to synchrotron-based micro-XRD, other microprobe methods will be used to characterize the soil during the performance monitoring phase including scanning-electron microscopy (SEM) with energy-dispersive x-ray spectroscopy (EDS) (Figure D-2). This method provides even finer resolution (sub-micron resolution, down to nanometer scale). Samples will be analyzed using an environmental-SEM (ESEM); this instrument provides the capability to analyze the soil without the need for ultra-high vacuum (UHV). The UHV instruments require soil to be coated with a fixative (e.g., gold) or embedded so that the samples can withstand the UHV environment. The ESEM analysis will provide images (allowing identification of iron mineral based upon morphology) as well as elemental information from the EDS (providing for the detection of co-located iron-uranium-sulfur). Mackinawite has been characterized by SEM, as well as other forms of iron sulfide (Rickard, et al., 2006). Microprobe XRF and micro-x-ray absorption near-edge spectroscopy (μ-XANES) (synchrotron-based methods) will also be used to examine iron-uranium-sulfur associations and co-location within the soil (Reeder, et al., 2001) (Figure D-3).

References:

Chao, T.T., and L. Zhou. 1983. Extraction techniques for selective dissolution of amorphous iron oxides from soils and sediments. Soil Science Society of America Journal. 47: 225-232.

Fuhrmann, M., and A. Lanzirotti. 2005. ^{241}Am, ^{137}Cs, Sr and Pb uptake by tobacco as influenced by application of Fe chelators to soil. Journal of Environmental Radioactivity. 32: 33-50.

Gleyzes, C., S. Tellier, and M. Astruc. 2002. Fractionation studies of trace elements in contaminated soils and sediments: a review of sequential extraction procedures. Trends in Analytical Chemistry 21(6,7): 451-467.

Lanzirotti, A., and S. Sutton. 2006. Synchrotron X-ray microbeam techniques in assessing metal bioavailability in the environment. Geochimica et Cosmochimica Acta, 70: 343-346.

Poutlon, S.W., and D.E. Canfield. 2005. Development of a sequential extraction procedure for iron: implications for iron partitioning in continentally derived particles. Chemical Geololgy 214: 209-221.

Reeder, R.J., M. Nugent, C.D. Tait, D.E. Morris, S.M. Heald, K.M. Beck, W.P. Hess, and A. Lanzirotti. 2001. Coprecipitation of uranium(VI) with calcite: XAFS, micro-XAS, and luminescence characterization. Geochimica et Cosmochimica Acta 65(20): 3491-3503.

Rickard, D.T. 1975. Kinetics and mechanism of pyrite formation at low temperatures. American Journal of Science. 275: 636-652.

Tessier, A., P.G.C. Campbell, M. Bisson. 1979. Sequential extraction procedure for the speciation of particulate trace metals. Analytical Chemistry, 51: 844-851.

Walker, S.R., H.E. Jamieson, A. Lanzirottie, C.F. Andrade, and G.E.M. Hall. 2005. The speciation of arsenic in iron oxides in mine wastes from the Giant Gold Mine, N.W.T.: Application of synchrotron micro-XRD and micro-XANES at the grain scale. The Canadian Mineralogist, 43(4): 1205-1224.

Wilkin, R.T., and H.L. Barnes. 1996. Pyrite formation by reactions of iron monosulfides with dissolved inorganic and organic sulfur species. Geochimica et Cosmochimica Acta 60(21): 4167-4179.

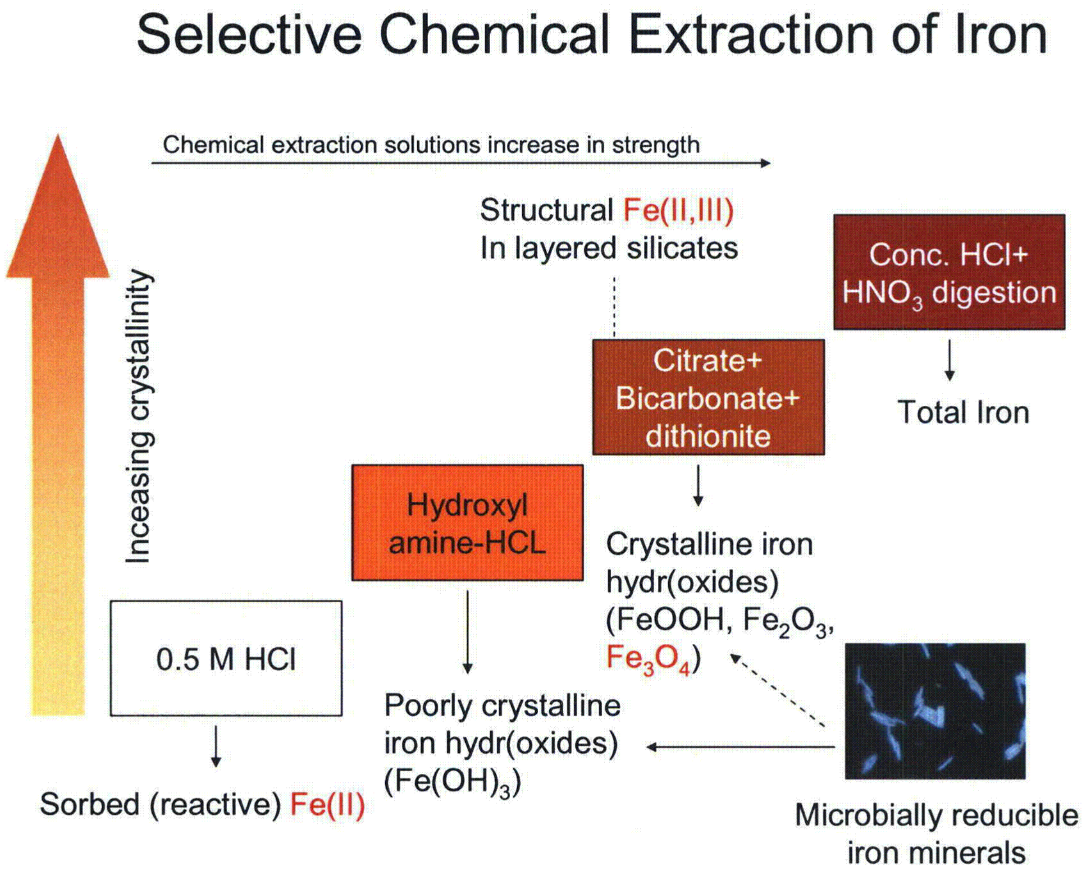
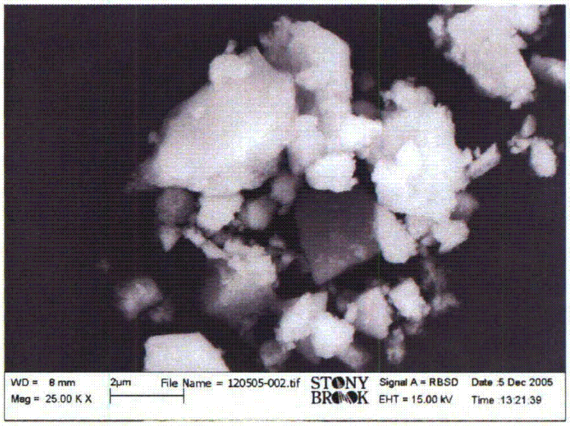
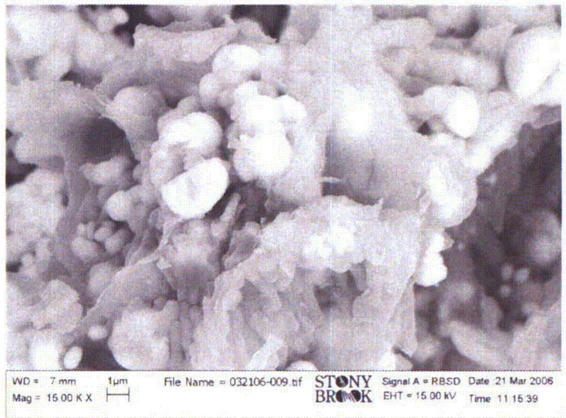


Figure D-1. Selective Extraction Scheme for Determining the Microbially Accessible Iron in the Aquifer During the Performance Monitoring Phase.



<u>Prior to Microbial Activity</u>: SEM of ferrihydrite ("2-line ferrihydrite" $Fe_5HO_8 \cdot 4H_2O$; surface area: 331± 2 m^2/g; 592 ± 1 ug Fe/mg)



<u>After Microbial Activity</u>: SEM analysis shows magnetite spherules (Fe_3O_4 (mixed-valent iron)), bacterial cells and exopolymer. Bacteria were grown on glucose.

Figure D-2. Scanning Electron Microscopy of Ferrihydrite (A) and Biogenic Magnetite Formed After Metabolism of Glucose (B) (from Gillow, in preparation).

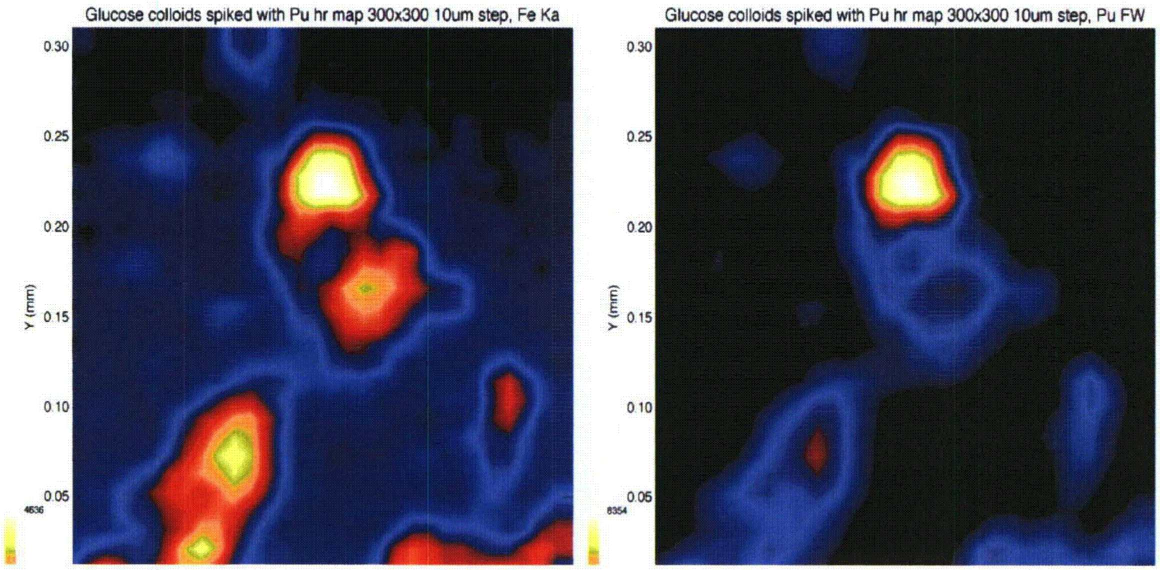


Figure D-3. Synchrotron Micro-x-ray Fluorescence of Iron Particles Spiked with Plutonium. Left panel (A) shows the iron distribution (false color image, yellow represents the highest concentration of Fe). The right panel (B) shows the Pu distribution. This method can identify spatial distribution of elements on a microscale in a sample (these images are 300 micron x 300 micron); each spot can be studied by μ-XANES to understand oxidation state and chemical speciation. (from Gillow, in preparation).

Appendix E

Quality Assurance Program Attachments

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Quality Assurance Program Attachments

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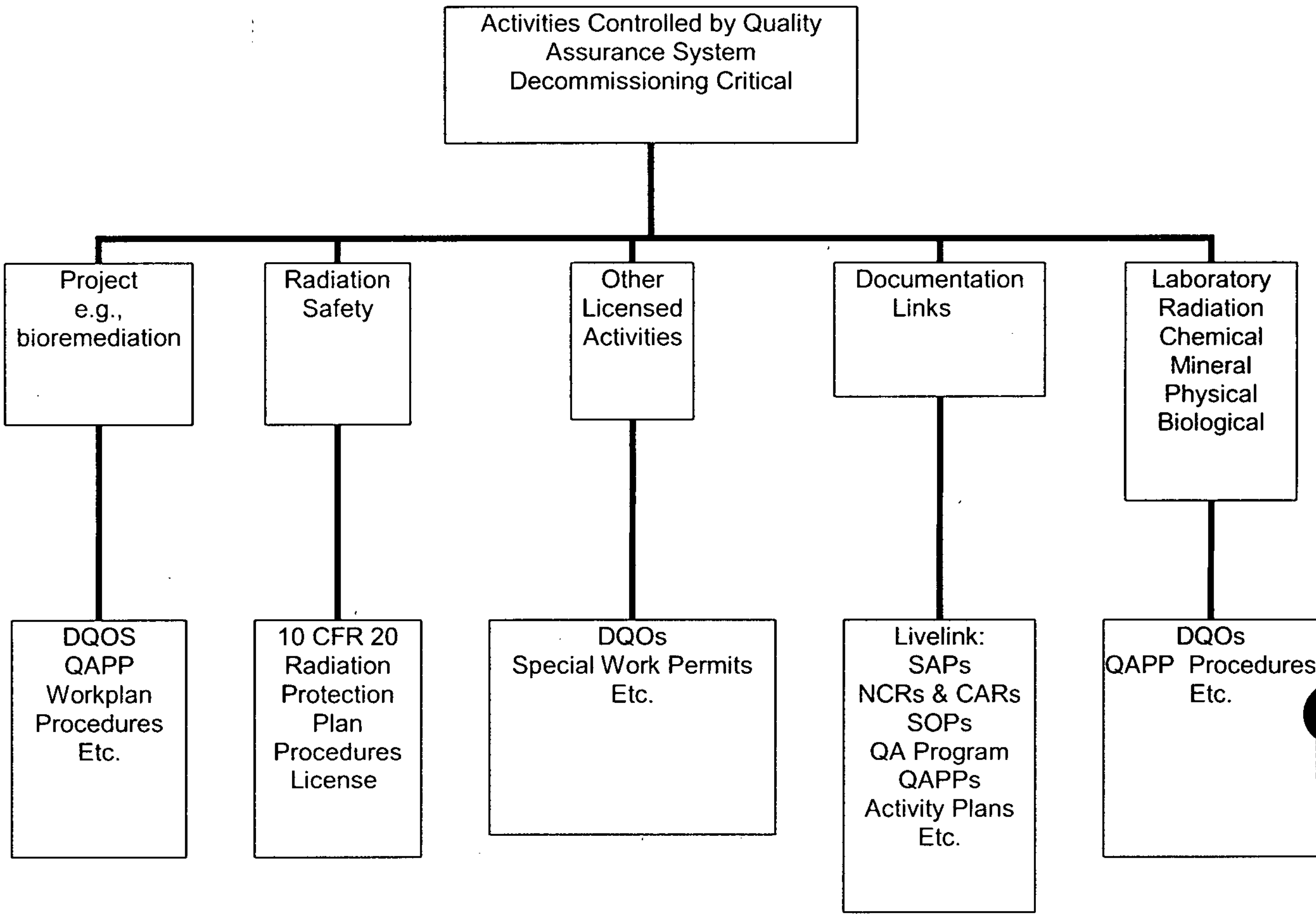
Quality Assurance Program Attachments

Table E-1
QA Cross References

Item Description	NQA-1 1994	RegGuide 4.15 Rev. 2	NUREG 1757, vol. 1	Cim QA System	ANSI/ASQ E4-2004
Organizational Structure and Responsibilities of Managerial and Operational Personnel	BR 1	C.1	17.6.1	1.0	5.2
Quality Assurance Program	BR 2	C, C.2	17.6.2	2.0	5.3,5.4
Design Control	BR 3	C.8	N/A	3.0	5.8,6.2, 6.3,7.2,7.3
Procurement Document Control	BR 4	N/A	N/A	4.0	5.5
Instructions, Procedures, and Drawings	BR 5	C.3	N/A	5.0	5.9,6.4.2
Document Control	BR 6	C.3	17.6.3	6.0	5.6
Control of Purchased Items and Services	BR 7	N/A	N/A	7.0	5.5
Identification and Control of Items	BR 8	N/A	N/A	8.0	
Control of Processes	BR 9	C.3	N/A	9.0	5.9
Inspection	BR 10	C.3	N/A	10.0	5.10
Test Control	BR 11	C.8	N/A	11.0	5.7,6.6,7.7
Control of Measuring and Test Equipment (MT&E)	BR 12	C.6.1	17.6.4	12.0	6.4.3,7.4.4, 7.5.5
Handling, Storing and Shipping	BR 13	C.3	N/A	13.0	6.4.4
Inspection, Test and Operating Status	BR 14	C.3	N/A	14.0	6.4.3
Control on Nonconforming Items	BR 15	C.10	N/A	15.0	
Corrective Action	BR 16	C.10	17.6.5	16.0	
Quality Assurance Records	BR 17	C.4	17.6.6	17.0	5.6
Audits	BR 18	C.9	17.6.7	18.0	5.10
Quality Control in Environmental Sampling	N/A	C.5	N/A	19.0	
Quality Control in the Radioanalytical Laboratory	N/A	C.6	N/A	20.0	
Internal Quality Control Samples and Analysis	N/A	C.6.2	N/A	21.0	
Performance Evaluation Program	N/A	C.6.3	N/A	22.0	
QAPP (Quality Assurance Project Plan)	N/A	B, para. 3	N/A	23.0	6.3.2 7.2.2

Appendix E
Quality Assurance Program Attachments

Chart E-1
Quality Assurance System



Appendix F

Modeling Output Files