# 3.0 Ground Water Model

This section presents a steady-state ground water flow model and a coupled solute transport model (ground water model) for the alluvial aquifer within OU III of the MMTS. Transport of uranium is simulated for a 50-yr period beginning October 2002. Uranium was selected among site COCs for transport modeling because it is the principal contributor to potential risk to human health. The model assumes stable ground water flow since completion of site restoration in July 2001.

The model was developed to accomplish the following objectives:

- Predict the length of time for natural processes to restore ground water to acceptable levels of uranium.
- Predict concentrations of uranium in ground water for human health risk evaluation.
- Provide a calibrated model with which to evaluate remedial alternatives for ground water other than Monitored Natural Attenuation.

COCs other than uranium (e.g., arsenic, vanadium) were not modeled because of their limited extent of concentrations above PRGs (generally limited to the area extending from the eastern portion of the Millsite to the PRB; Section 2.7.3), lower concentrations (less than about 1.5 times their respective PRGs), and much smaller contribution to potential future human health risk (Section 4.1). The concentrations of these COCs are expected to gradually decrease without significant transport beyond their present extent because they are less mobile than uranium. Recent increased levels of selenium in surface water and ground water, as distinct from the remaining COCs, is addressed as a component of ERA in Section 4.0.

Sections 3.2 through 3.7 present detailed analysis of the conceptual model for ground water flow and uranium transport, model construction and supporting data, and results of the flow and transport models. Section 3.8 presents a summary of the main topics addressed in Sections 3.2 through 3.7.

## 3.1 Background Information

The Monticello vanadium and uranium mill operated from about 1948 to 1960. Mill tailings were impounded at four former piles on the 110-acre site through 1999, resulting in contamination of soil, surface water, and the shallow water-table aquifer (alluvial aquifer). Removal of tailings contamination and subsequent site restoration extended from summer 1997 through summer 2001.

The model presented in the following sections replaces an earlier OU III model developed in 1998 prior to source removal and site reconstruction (DOE 1998a and 1998c). Significant impacts on the ground water system and contaminant distribution that were not represented in the previous model became apparent as remediation and restoration activities progressed. Other assumptions regarding non-site-specific input parameters also limited the accuracy of the 1998 model. As described in Section 1.0, an IRA was implemented in September 1998 to collect additional data and evaluate the effects of remediation and restoration. A full-scale PRB was also installed under the IRA (Section 2.6).

Except for ground water and surface water monitoring, all IRA tasks are completed. The results of the IRA, which provide input to the current model, have been reviewed by EPA and UDEQ and are reported in project documents (DOE 2000b, DOE 2001a, DOE 2002a). Other relevant information, obtained prior to the IRA, is included in the 1998 RI (DOE 1998a).

## 3.2 Hydrogeologic Conceptual Model

The hydrogeologic conceptual model summarizes the relationship between the physical environment and the occurrence and movement of ground water in the alluvial aquifer at MMTS. The following sections describe the current hydrogeologic setting of the study area as defined by the OU III boundary in Figure 1–2 (page 1–3) and provide an account for all inflows and outflows of water in this region.

### 3.2.1 Aquifer System

Relevant hydrostratigraphic units at MMTS are the alluvial aquifer and underlying bedrock formations, which from youngest to oldest are the Dakota Sandstone aquitard, Burro Canyon Fm. sandstone aquifer, and Morrison Fm. claystone aquitard. The Mancos Shale, which overlies the Dakota Sandstone, is present in the upland areas adjacent to the Millsite. It directly underlies the alluvial aquifer west of the study area. Montezuma Creek, the primary surface water feature, is in contact with the alluvial aquifer and portions of each bedrock unit as it flows west to east through the study area. A geologic map of the study area is provided in Section E1.0 of Appendix E. The hydrostratigraphic units and basic flow relationships at MMTS are shown schematically in Figures 3–1 and 3–2.

**Alluvial Aquifer**

Permeable sand and gravel alluvium within the paleochannel beneath the valley of Montezuma Creek constitutes the alluvial aquifer at the site. Alluvium is defined as the unconsolidated sediments deposited directly by the ancestral or recent Montezuma Creek. Abundant cobbles and up to 15 percent silt and clay are also present in the alluvium. The paleochannel is about 450 ft wide (north to south) at the eastern boundary of the Millsite and narrows to less than 200 ft about 1 mile east, where the valley becomes a steep-walled canyon (Figure 3–3). The bedrock erosional surface at the base of the alluvial aquifer slopes east to southeast and is relatively flat across the width of the aquifer. At the far western end of the Millsite, the alluvium is underlain by the Mancos Shale; on the remainder of the Millsite and in the upper canyon of Montezuma Creek, Mancos Shale has been eroded away, and the Dakota Sandstone underlies the alluvium. Approximately 1 mile east of the Millsite, the Dakota Sandstone has been eroded away, and the Burro Canyon Fm. underlies the alluvium (Figures 3–2 and 3–3).

Figure 3–4 illustrates water table contours and saturated thickness of the alluvial aquifer from October 2001 measurements. Regional ground water flow is east to southeast down the valley. The hydraulic gradients of the water table and creek downstream of the Millsite are approximately 0.02 ft/ft. Depth to ground water ranges from about 5 to 10 ft below ground surface beneath the valley floor and 20 to 30 ft below ground surface on the flanking slopes. Saturated thickness varies between about 2 and 9 ft in the center of the valley and thins to zero toward the margins, where the coarse channel deposits pinch out against bedrock or fine-grained hill-slope colluvium.

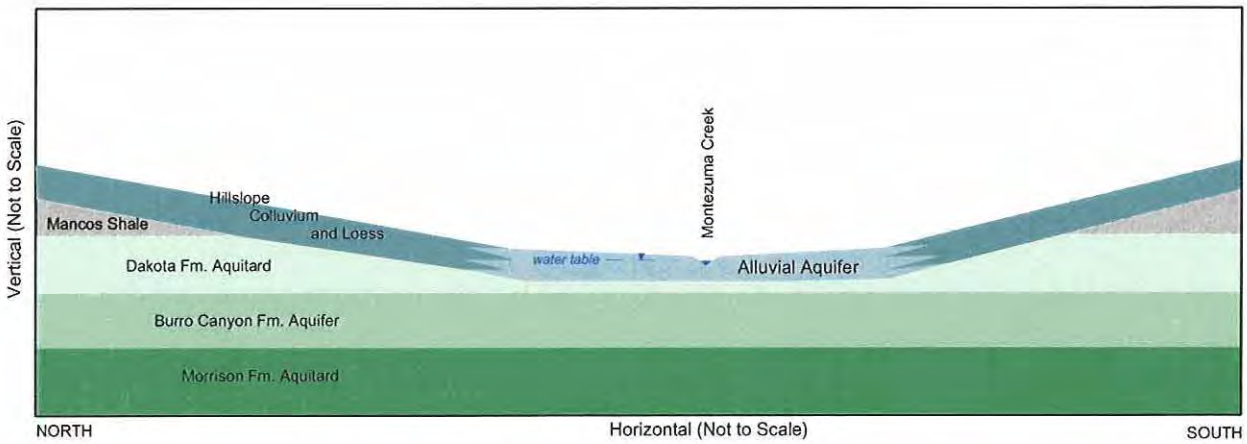


*Figure 3–1. Schematic North to South Cross-Sectional View of Hydrostratigraphic Units at MMTS*

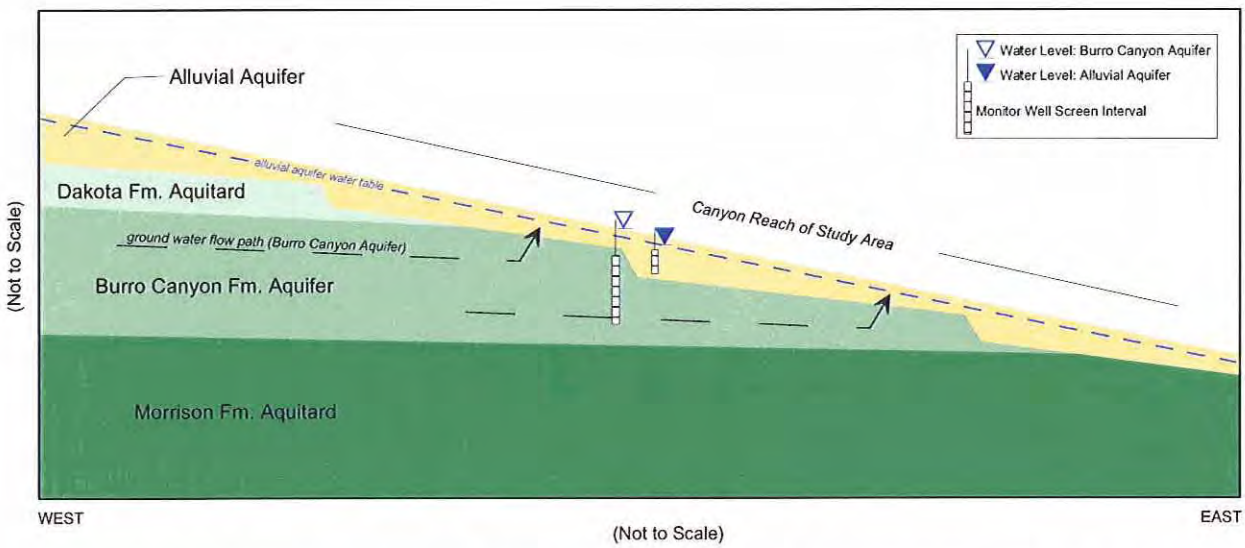


*Figure 3–2. Schematic West to East Cross-Sectional View of Hydrostratigraphic Units at MMTS*

The colluvium, which represents soil and rock materials deposited by surface runoff at the base of a slope, is primarily silty clay with sparse, matrix-supported sand, gravel, and cobbles.

Intervals of sheetwash deposits of sorted sand, gravel, and imbricated shale clasts are common, and on the south side of the valley, several horizons of red loess are present. Total combined thickness of the colluvium and loess is 30 to 40 ft. Ground water is generally absent from these deposits, although thin, intermittent lenses of saturation occur beneath the cropland and pastures east of the Millsite and north of Montezuma Creek. This water is separate from the underflow off the Millsite.

Most of the native alluvium beneath the tailings impoundments was removed to bedrock during remediation. A narrow ground water conduit was subsequently constructed of remnant and

borrowed alluvium. This artificial corridor extends 20 ft on either side of the creek and is about 3 ft thick. Native alluvium is present in some areas outside the corridor; in others, common fill was placed against its edge.

In June 1999, a PRB was installed across the alluvial aquifer about 600 ft east (downgradient) of the east boundary of the Millsite (Figure 3–3). The PRB is an engineered zone of reactive media (ZVI) measuring 105 ft in length (perpendicular to ground water flow) by 6 ft wide. The reactive zone is keyed into bedrock and extends to within 3 ft of ground surface. Ground water is funneled to the PRB by low-permeability slurry walls also keyed into bedrock. The slurry walls extend 97 ft northwest and 240 ft south from the PRB and are about 4 ft wide. A detailed analysis of the hydraulic and geochemical performance of the PRB is presented in the PRB performance evaluation report (DOE 2002a) (see also Section 2.6 of this report).

**Surface Water**

The MMTS is located in the valley of Montezuma Creek. The creek forms at the confluence of North and South Creeks about 0.5 mile upstream (west) of the Millsite. Its watershed includes portions of the east flanks of the 11,000-ft Abajo Mountains, 4 miles farther west. An earth dam 1.5 miles upstream of the Millsite impounds South Creek in Loyd's Lake reservoir. Baseflow in Montezuma Creek is maintained by leakage through the dam and from flows in North Creek, which joins Montezuma Creek about 0.5 mile below the dam. Natural flow in North Creek is interrupted by the operation of the municipal water treatment plant and irrigation diversions. Flow in Montezuma Creek, as measured since November 1992, is typically less than about 0.5 cfs (1 cfs $\approx$ 450 gpm).

Montezuma Creek was realigned during remediation and restoration of the Millsite (summer 1997 to July 2001) to its present configuration on the Millsite and in the area of the PRB. Relative to its position prior to Millsite remediation, to about 1955, its elevation is now as much as 25 ft lower through the eastern half of the Millsite, where it generally occupies the lowest part of the bedrock valley. In some areas, a narrow trough was cut into the bedrock to accept the new creek. A 3-ft layer of alluvial fill typically separates the creek and bedrock in the artificial corridor, although the creek flows directly on bedrock at several locations.

Three basins were excavated partially into bedrock to allow establishment of wetland habitat on the Millsite. Portions of the center and eastern wetland excavations extended several feet into bedrock. Engineered fill was placed within the depressions to provide the desired hydraulic and substrate properties. By design, surface and ground water within the restored alluvial system enters through infiltration galleries on the upstream side of the wetlands; however, perennial ground water seepage from native deposits along the northwest and north aspects of the wetlands provides much or most of the inflow. This seepage is maintained by ground water sources above the valley floor along the north margin of the Millsite. Surface water flows from the wetlands to the creek through a downstream outlet at each basin. Recent observations of seepage inflow to Wetland 3 but no surface outflow suggest some leakage from the wetland to the aquifer, likely along its eastern edge where the basin may not have been excavated as deeply into bedrock.

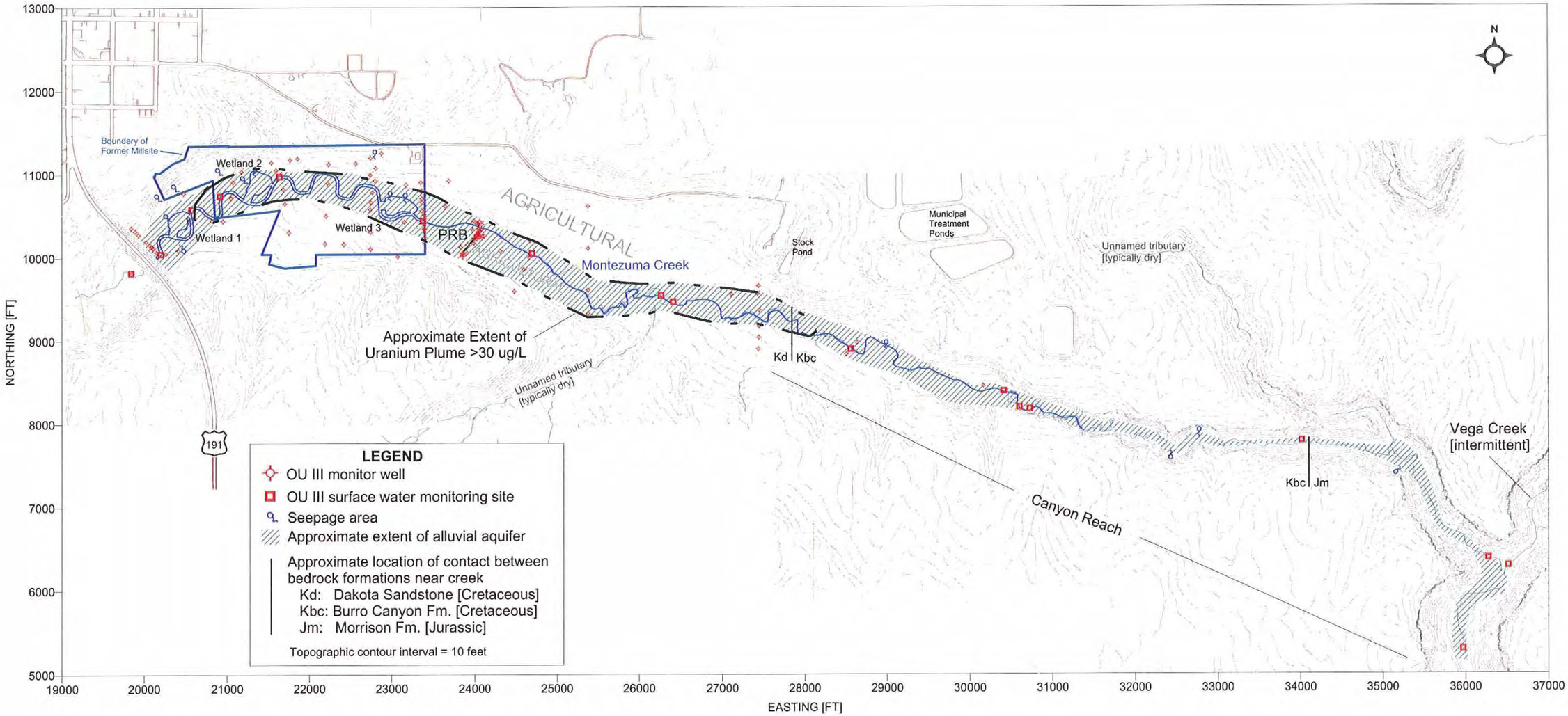


*Figure 3–3. Site Features Map*

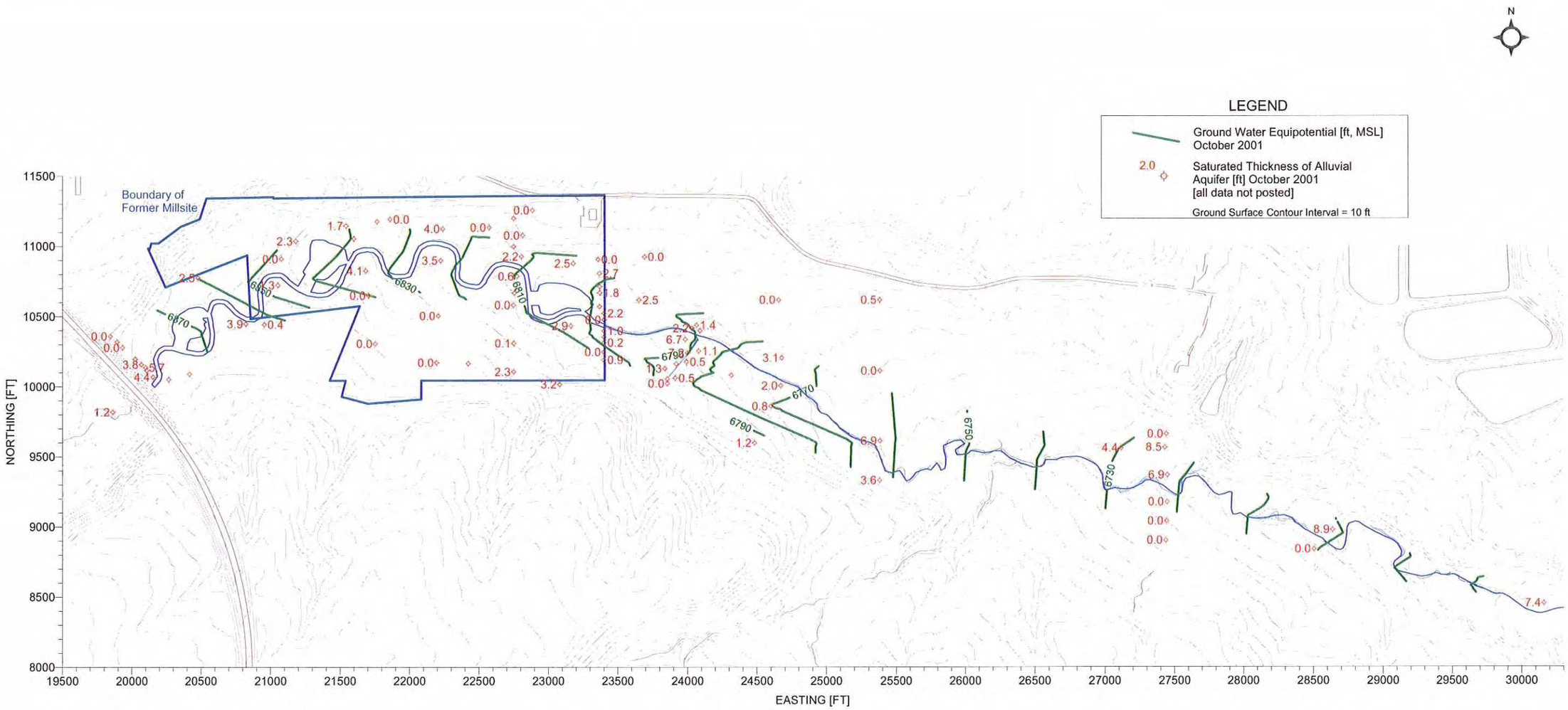


*Figure 3–4. Alluvial Aquifer Water Table and Saturated Thickness Map*

Since the completion of restoration, Montezuma Creek as it enters the Millsite has been dry or nearly dry (less than 10–20 gpm). Steady creek flow generally now occurs only below the outlet of Wetland 2. During 1999 through 2001, the net measured increase in creek flow at the east boundary of the Millsite, sustained wholly by ground water capture, was about 100 to150 gpm.

Directly east of the Millsite, the creek flows through irrigated cropland and pasture in a relatively broad valley (approximately 1,000 ft in width, north to south). This part of the creek has been characterized as typically a net losing-stream reach, on the basis of flow measurements and recent observations. For example, channel flow off the Millsite decreased to zero in this reach in summer and fall 2002. In wet years, water levels in wells adjacent to the creek are also below stream stage.

The head of the canyon reach, approximately 4,000 ft east of the Millsite, marks the return to a net gaining stream. This general area also coincides with the transition from the Dakota Fm. to the Burro Canyon Fm. (Figure 3–3, and Sections 3.2.2 and 3.2.3) as the upper bedrock unit in the valley center. Stream gain in this reach is attributed to full or near-full penetration of the alluvial aquifer to the Dakota Fm. by the creek at the head of the canyon, and to discharge from the Burro Canyon aquifer to the alluvial aquifer and subsequent discharge to the creek. In December 2002, when the reach upstream of the canyon was dry, creek flow through the canyon ranged from about 20 to 90 gpm, west to east.

In the lower third of the canyon, or downstream of Easting 34,000 (Figure 3–3), the upper bedrock is silt and claystone of the Morrison Fm. (Section 3.2.4). The valley floor broadens slightly, and measurement of creek flow and visual observation indicate stream loss in this reach. Surface water in this reach may be distributed more thinly into a wider aquifer, or alluvial ground water may be lost to evapotranspiration or infiltration into the Morrison Fm. Surface water discharge for December 2002 is illustrated in Figure 3–5. A summary of this and other recent stream flow measurements is included in Section E2.0 of Appendix E.

### 3.2.2 Dakota Formation Aquitard

Low-permeability, variably saturated mudstones, siltstones, and sandstones of the Dakota Fm. underlie the alluvial aquifer in the study area west of the canyon reach. Large areas of the Dakota Fm. were exposed during remediation on the Millsite. The base of the overlying Mancos Shale is topographically higher than the alluvial aquifer except west of the Millsite. The Dakota Fm. is about 80 ft thick in the west part of the study area. Approximately 1 mile east of the Millsite, near the head of the canyon, the Dakota Fm. has been entirely removed by erosion by Montezuma Creek (Figure 3–3). Where present, the Dakota Fm. restricts downward movement of alluvial ground water to the underlying Burro Canyon sandstone aquifer. Supporting documentation regarding the role of the Dakota Fm. as an aquitard is included in Section 3.6.4 of the RI (DOE 1998a).

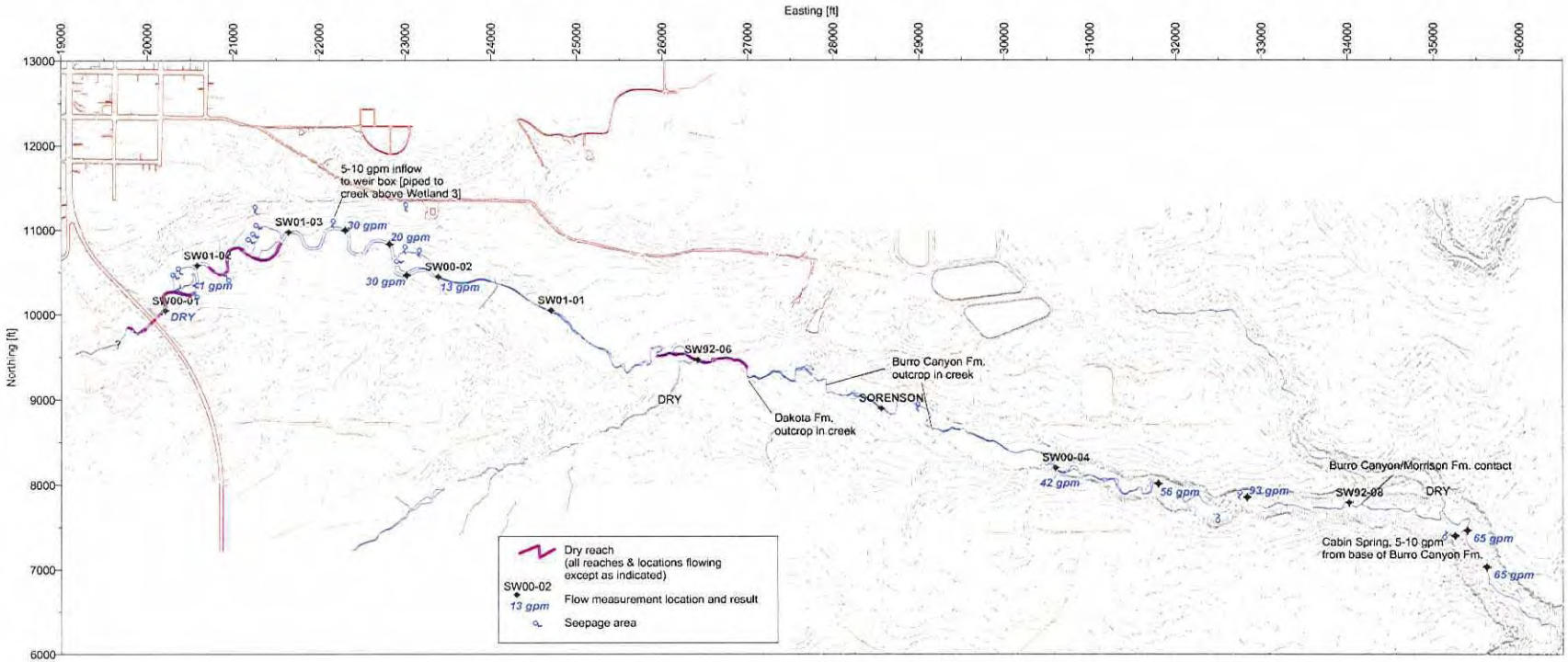


*Figure 3–5. Surface Water Flow Measurements—December 2002*

### 3.2.3 *Burro Canyon Formation Aquifer*

The Burro Canyon Fm. is about 115 ft thick locally and consists of fluvial sandstone and pebble conglomerate. Portions of the formation are saturated from precipitation recharge in outcrop areas in the foothills of the Abajo Mountains. The aquifer is unconfined at OU III monitor wells located about 1,000 and 2,500 ft west of the Millsite but becomes confined eastward by the Dakota Fm. due to the regional dip of the bedrock exceeding the slope of the potentiometric surface. Regional flow in the Burro Canyon aquifer is to the east but locally converges toward the creek in the canyon reach. The Burro Canyon Fm. is progressively incised through its entire thickness by the creek in the upper 1-mile of the canyon reach, resulting in ground water discharge to the alluvial aquifer and creek. Ground water monitoring of the Burro Canyon aquifer has been conducted at least since 1992. The Burro Canyon aquifer is not contaminated. The city of Monticello currently uses Burro Canyon ground water primarily for nondomestic purposes. Because of recent drought, Burro Canyon ground water is being used to augment the domestic water supply. The hydrogeologic effect of increased pumping from the Burro Canyon aquifer is addressed in Section 3.7.6.

### 3.2.4 Morrison Formation Aquitard

Underlying the Burro Canyon Fm. are variegated gray, pale-green, and maroon mudstones, with minor sandstone lenses, of the Brushy Basin Member of the Morrison Fm. The westernmost contact between the Burro Canyon and Morrison Fms. crops out in the creek bed about 1 mile into the canyon (at about Easting 34,000 in Figure 3–3). The mudstones form slopes in the lowest (easternmost) portions of the OU III study area. The fine-grained composition of Brushy Basin sediments implies that, in the absence of fracture flow, the permeability of this unit is relatively low.

### 3.2.5 Sources of Alluvial Ground Water

Sources of water potentially contributing to flow in the alluvial aquifer within the study area are underflow in the aquifer from the west, underflow from the north and south sides of the Millsite, discharge of ground water from the Burro Canyon aquifer in the canyon reach, and infiltration of precipitation and irrigation. Each of these possible inflow components is discussed under the following headings (see also Figure 3–7 in Section 3.4).

#### Underflow from West of the Millsite

The alluvial aquifer probably extends about 1 mile upstream of the Millsite. The aquifer in this area is recharged by inflow from North and South Creeks, which combine to form Montezuma Creek 0.5 mile west of the Millsite, inflow from Montezuma Creek, precipitation, and irrigation of the municipal golf course. The quantity of underflow entering the Millsite from the west is estimated in Section 3.4.

#### Underflow from Margins of the Millsite

Perennial seeps and springs on the north hillside and in the southwest corner of the Millsite (Figures 3–3 and 3–5) indicate general underflow to the aquifer from sources above the valley. The seeps and springs are commonly expressed as seepage faces near the contact with bedrock

and have been present throughout OU III remedial activities. Most of the water that enters the aquifer from these sources is captured by the creek and wetlands on the Millsite, as indicated, respectively, by stream gains and seepage to the wetlands from their north banks. Discharge from these sources in the summer and fall of 2002 was much less than measured previously, and the low flow is attributable to persistent drought conditions over the last several years.

**Burro Canyon Aquifer**

Discharge of Burro Canyon ground water to the alluvial aquifer is evident in the canyon reach of Montezuma Creek from numerous seeps near the base of the bedrock formation, upward flow potentials at paired wells in the valley floor, and geochemical distinctions (DOE 1998a). Much of this water ultimately discharges to Montezuma Creek (Section 3.2.1 and Section E2.0 of Appendix E) as indicated by gaining stream conditions. The estimated volume of Burro Canyon aquifer discharge is presented in Section 3.4.

**Surface Recharge**

Infiltration of precipitation may be a relatively unimportant source of recharge to the alluvial aquifer. Waugh (2002) describes a water balance model for fine-textured soils in semiarid regions such as the Monticello area. The rainfall pattern, high storage capacity of the soils, and high potential evapotranspiration in these regions combine to establish a yearly cycle of soil moisture storage in the vadose zone (November to March) followed by a period of depletion from storage by plant use and evaporation. The net effect is to prevent significant infiltration beyond the root zone. The water balance model is based in part on experiments conducted at the Monticello field lysimetry station in which annual infiltration through vegetated, fine-textured soil columns 150 centimeters (cm) in length was less than 1 mm from 1995 to 2001.

Pan evaporation and agricultural evapotranspiration rates in the Monticello area approach 40 inches/yr (Andrews 1994) and exceed the average annual precipitation of 15 inches/yr. Irrigation is locally applied at about 30 inches/yr (Andrews 1994).

### 3.2.6 Ground Water Sinks

Hydrologic sinks that remove water from the alluvial aquifer in the study area are Montezuma Creek, both at the Millsite and at the head of the canyon, discharge to Millsite wetlands, and evapotranspiration.

**Montezuma Creek and Wetland Areas**

Ground water that is captured by the creek and wetlands is conveyed out of the study area in quantities greater than the surface inflow to the area (typically zero); therefore, Montezuma Creek acts as a net ground water discharge zone through the study area. The losing reach of the creek directly downstream of the Millsite involves only local exchange of water and does not act as a zone of net ground water gain in the overall water budget. Similarly, leakage out of the downgradient edge of the wetlands returns some water locally to the aquifer; however, these infiltration losses probably return to the creek ultimately as surface water flow.

### Evapotranspiration

Willows line Montezuma Creek through most of the canyon reach, and thickets nearly span the width of the canyon at several locations. These thickets are sustained by a shallow water table in response to Burro Canyon Fm. aquifer discharge and to narrowing of the canyon. Evapotranspiration is likely a significant seasonal ground water sink; however, the quantity lost to plants is probably provided or offset by creek water and is reflected in decreased stream flows. Reestablishment of aquatic and riparian vegetation on the Millsite will increase evapotranspirative loss of ground water. The net effect may be slightly reduced seasonal stream flows.

## 3.3 Hydraulic Properties

The hydraulic conductivity of the alluvial aquifer has been estimated from 41 slug tests and 2 pumping tests conducted during the RI. Twelve additional slug tests were performed in association with PRB performance evaluation (DOE 2002a). Table 3–1 summarizes test results for the alluvial aquifer and ZVI that compose the PRB. Figure 3–6 illustrates the statistical distribution of hydraulic conductivities determined from the set of 41 slug tests conducted in 1994 (DOE 1998a). These tests were conducted in wells completed in the alluvial aquifer throughout the entire monitoring network at that time. A map view of the resulting conductivity values suggested a spatially random distribution. Application of the aquifer test results to the ground water model is discussed in Section 3.6.3.

The effective hydraulic conductivity of the PRB may be less than indicated slug test values for ZVI in Table 3–1 (DOE 2002a). Hydraulic conductivity of the PRB was assumed equal to that of the alluvial aquifer in the model.

Previous characterization of bedrock formations at the site concluded that the Dakota Fm. is generally less conductive than the alluvial aquifer by at least two orders of magnitude, thus limiting downward migration of alluvial ground water (DOE 1994, 1998b). The mean vertical hydraulic conductivity of the Burro Canyon Fm. (approximately $1 \times 10^{-4}$ centimeters per second [cm/s] [DOE 1998a]) was used to estimate upward leakage into the alluvial aquifer where the Dakota Fm. aquitard is absent (Section 3.4). Hydraulic conductivities of bedrock formations are not input parameters in the model because the bedrock surface is a no-flow boundary (see Section 3.6.2).

*Table 3–1. Summary of Hydraulic Conductivity*

| Formation | Hydraulic Conductivity (cm/s), slug test results | | | | |
|---|---|---|---|---|---|
| | Minimum | Maximum | Arithmetic Mean | Geometric Mean | n |
| Alluvium[a] | $2.5 \times 10^{-3}$ | $2.7 \times 10^{-2}$ | $1.3 \times 10^{-2}$ | $1.0 \times 10^{-2}$ | 9 |
| ZVI[a] | $6.0 \times 10^{-2}$ | $7.4 \times 10^{-2}$ | $6.9 \times 10^{-2}$ | $6.9 \times 10^{-2}$ | 3 |
| Alluvium[b] | $5.2 \times 10^{-5}$ | $1.5 \times 10^{-1}$ | $1.2 \times 10^{-2}$ | $1.7 \times 10^{-3}$ | 41 |
| | Hydraulic Conductivity (cm/s), pumping test results | | | | |
| Alluvium[b] | $1.5 \times 10^{-2}$ | | | | |
| Alluvium[b] | $1.9 \times 10^{-1}$ | | | | |

[a] DOE 2002a
[b] DOE 1998a
Note: cm/s = centimeters per second; n = number of wells tested

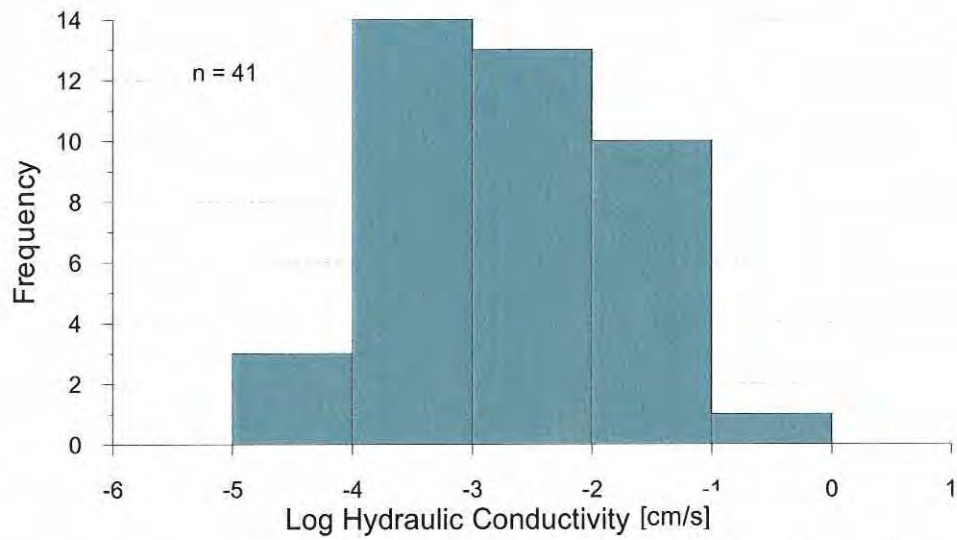


*Figure 3–6. Histogram of Hydraulic Conductivity Estimated From Slug Tests*

## 3.4 Water Balance

Estimated quantities of water for alluvial aquifer inflows and outflows as developed for the conceptual model are itemized in the water balance presented in Table 3–2. Figure 3–7 illustrates the distribution of these components in map view. Tabulated values are from analytical calculation or measured flow, as described below, and are assumed to represent nondrought conditions in general, rather than a specific water year. Comparison of the conceptual water balance with the numerical model water balance is presented in Section 3.6.4.

*Table 3–2. Conceptual Water Balance*

| Inflow[a] | $Q_{in}$ (gpm) | Outflow[a] | $Q_{out}$ (gpm) |
|---|---|---|---|
| Underflow through west boundary of model | 10 | Underflow through east boundary of model | 10 |
| Margins of Millsite | 125 | Montezuma Creek | 155 |
| Burro Canyon aquifer | 30 | Evapotranspiration[b] | 10 |
| Surface recharge | 10 | | |
| Total $Q_{in}$ | 175 | Total $Q_{out}$ | 175 |
| PRB[c] | 5–10 through-flow | PRB[c] | 5–10 through-flow |

[a] Creek flow measurement data are included in Section E2.0 of Appendix E. Section E3.0 of Appendix E includes calculations of the western boundary flow estimates and Burro Canyon discharge. Recharge is estimated as one-tenth of annual precipitation for the area of irrigated ranch land east of the Millsite. Recharge on nonirrigated land is assumed negligible.
[b] Evapotranspiration = Total $Q_{in}$ – ($Q_{out}$ creek + $Q_{out}$ east boundary outflow).
[c] Not a source or sink, flow through the PRB is presented for comparison to overall budget.
Note: Q = Volumetric flow rate

The water budget for the site is based partly on excavation dewatering rates measured during Millsite remediation. In March 1998, a ground water interception trench was excavated across the alluvial aquifer near the center of the Millsite. By October 1999, soil and alluvium had been removed to bedrock beneath most of the tailings pile areas. Seepage into the excavation occurred along its west and north faces. With the exception of the far southwest area of the Millsite, seepage from the south face of the excavation was absent. The open excavation captured all or most ground water flow through the Millsite.

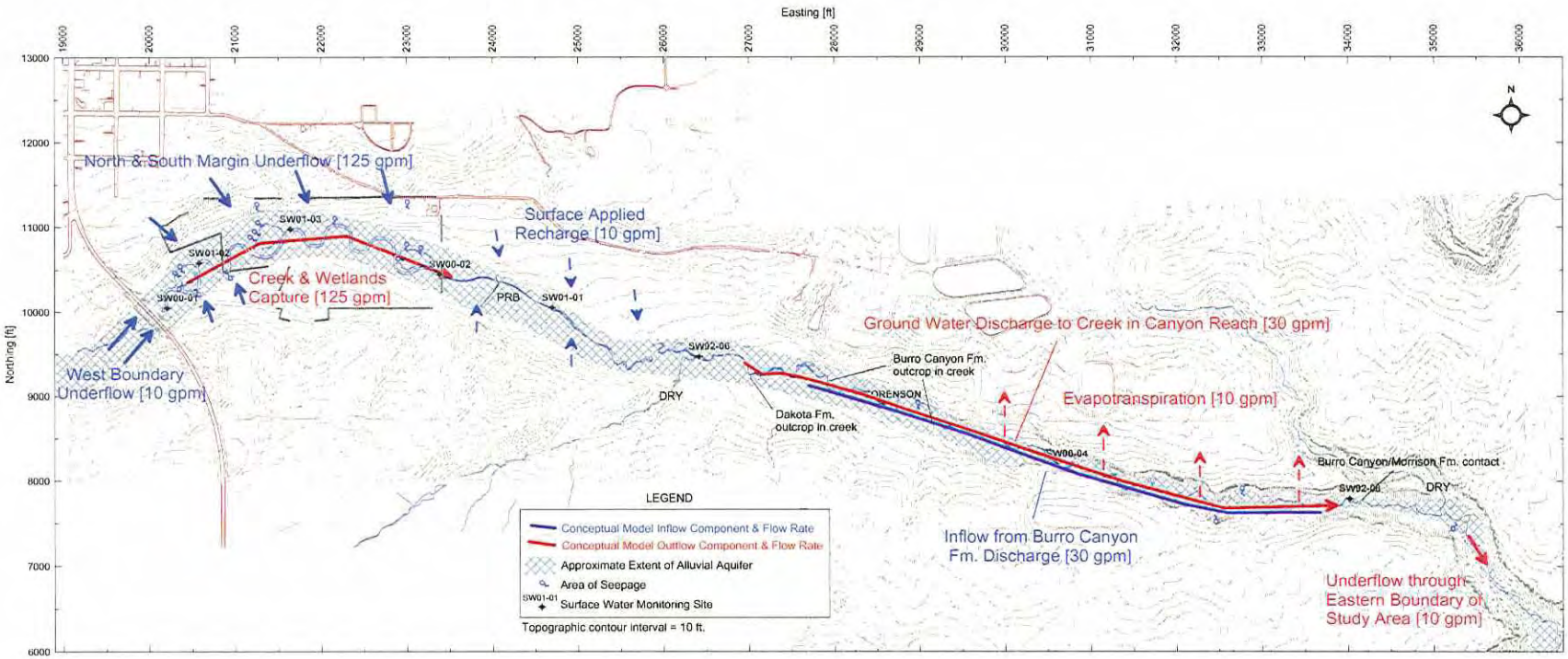


*Figure 3–7. Conceptual Model Water Balance*

Until August 2000, when final site and creek restoration began, impounded ground water was channeled out of the excavation and returned to the creek at the eastern edge of the Millsite. Periodic measurements consistently indicated ground water capture of about 90 to 100 gpm (Section E2.0 of Appendix E). Seepage that entered the excavation from the north on the east half of the Millsite was not channeled and so could not be accurately measured; however, this contribution was estimated to be about 25 gpm from flow measurements subsequent to creek restoration.

Investigations to evaluate performance of the PRB provided additional information on the quantity of ground water flowing in the alluvial aquifer. Analysis of a pumping test conducted in January 2001 indicated that ground water flow through the PRB was between 5 to 10 gpm (DOE 2002a). Flow rates determined from geochemical mass balance (Section 2.6.6) range from 2 to 20 gpm. The mean flow rate determined from that analysis, which is averaged over the entire period of PRB operation, is 5 gpm (DOE 2002a). These estimates, and the Millsite dewatering flow measurements, represent flow calibration targets for the ground water model (Section 3.6.4).

Section E3.0 of Appendix E provides a calculated range of underflow (less than 1 to about 70 gpm) from the west to the Millsite based on different values of hydraulic conductivity from the project database. A weighted-evidence approach based on the PRB flow determinations was used to develop the west and east boundary underflow components of the conceptual water budget presented in Table 3–2. Similarly, although analytical estimates of Burro Canyon aquifer discharge vary widely (about 20 to 1000 gpm [Section E3.0 of Appendix E, excluding the anomalous hydraulic conductivity value of $8.1 \times 10^{-10}$ cm/s]), it is the lower estimated values that are most consistent with results of recent creek flow measurements. Finally, the value of Burro Canyon aquifer discharge presented in Table 3–2 (30 gpm) is biased low among the flow measurement data (Section E2.0 of Appendix E) to avoid possible overstatement of the effect of this inflow on the transport model.

## 3.5 Computer Modeling Codes

Steady-state ground water flow at MMTS was numerically modeled using MODFLOW, a three-dimensional, finite difference, block-centered simulator of ground water flow in saturated porous media developed by the U.S. Geological Survey (USGS) (McDonald and Harbaugh 1988). Contaminant transport was modeled using the computer code MT3D96 (Zheng 1996), which was designed to simulate transport of a dissolved solute in ground water by advection, dispersion, and chemical reactions.

Data entry, execution of MODFLOW and MT3D, and analysis and presentation of model results was facilitated with Visual MODFLOW (version 2.8.3.52, Waterloo Hydrogeologic 2000). Visual Modflow is a Microsoft Windows-driven, graphical pre- and postprocessing software application designed for use with MODFLOW and MT3D. MODFLOW and MT3D96 are fully described in the references cited above. Each code has been verified and is approved by regulatory agencies and is used widely by ground water professionals.

## 3.6 Numerical Flow Model

This section describes individual elements of the current deterministic, single-layer, steady-state numerical flow model for OU III. Temporal variation of hydrologic stresses, such as seasonal or multiyear wet/dry cycles, is not simulated; however, some of these effects are evaluated separately in Sections 3.6.4 and 3.7.5. Use of a single-layer model assumes that the alluvial aquifer is vertically homogeneous, and that there is little or no vertical flow in the ground water within it. This is a valid simplification because the aquifer is very thin, and there is no indication that vertical concentration gradients in the ground water are significant. The flow model is deterministic in the context that it is developed using a specific set of input variables.

### 3.6.1 Domain and Grid

The domain encompasses the entire OU III study area. Dimensions of the domain are 2,600 ft south to north by 16,200 ft west to east, totaling 1.5 square miles. The model grid consists of 104 rows and 495 columns, resulting in 51,480 cells. Many grid cells are located outside the areal extent of the alluvial aquifer and are inactive for flow and transport.

The coordinate axes of the domain are rotated 12.5 degrees clockwise relative to the site coordinate system to align the principal direction of ground water flow (east-southeast) with the $x$-axis of the grid. True north is therefore 12.5 degrees west of page north in subsequent figures showing the model domain. The model domain and site features are illustrated in Figures 3–8 and 3–9. The area containing active cells is shown in white; inactive cell area is shown in dark gray. The grid is too dense to display in these figures.

Grid row height ($y$-dimension) is uniform at 25 ft. Grid column width ($x$-dimension) is variable. The minimum column width is 12.5 ft and is applied to 26 columns centered on the PRB. Progressing east and west from the PRB are columns that vary from 25 to 100 ft in width. Cells encompassing the main body of the uranium plume and continuing an additional 3,000 ft beyond the terminus of the plume are 25 ft by 25 ft in size. Columns 100 ft wide are generally out of the area of interest. Smooth transitions from one cell width to another were developed using a Visual Modflow utility program.

### 3.6.2 Model Boundaries

Model boundary conditions are assigned to define the physical limits of the flow system and the hydrologic sources and sinks identified in the site conceptual model. Figures 3–8 and 3–9 provide a map view of the boundaries applied in the OU III model. In those figures, red cells represent constant head boundaries at the wetlands and the inflow boundary at the west end of the model, green cells are general head boundaries used to simulate inflow from the margins of the Millsite, and light gray cells are drain cells that represent Montezuma Creek. Each boundary is described under the following headings.

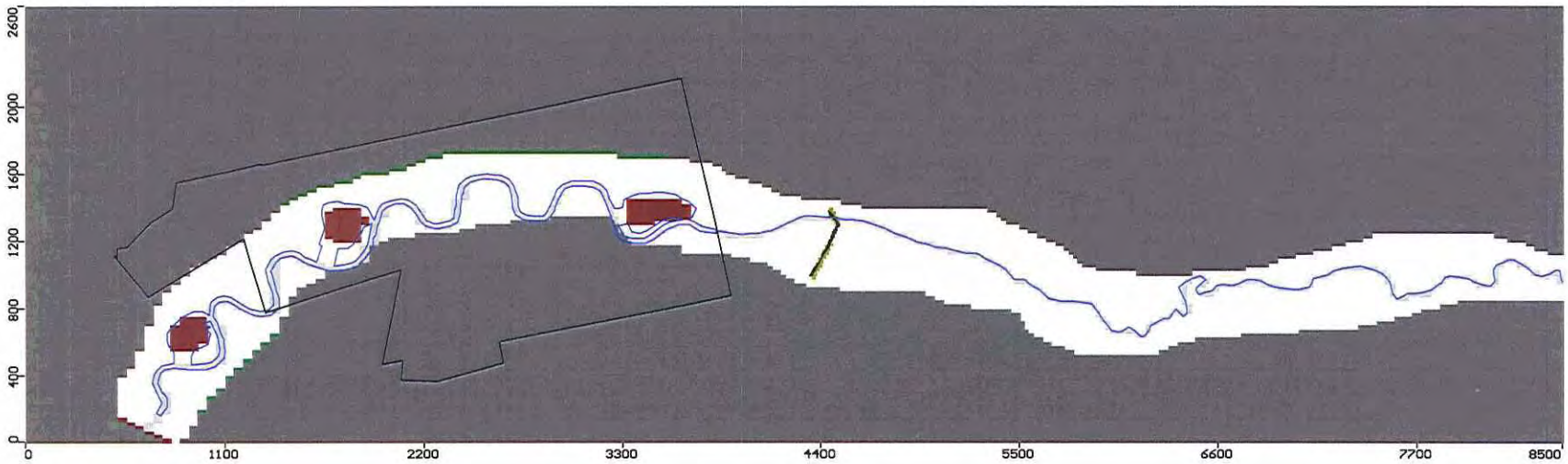


*Figure 3–8. Model Domain and Boundaries—West*

*(Red areas are constant head boundaries, green are general head, light gray are drains, dark grey area is inactive, white area is active. Millsite outline is blue polygon. Creek and Wetland traces are also in blue)*

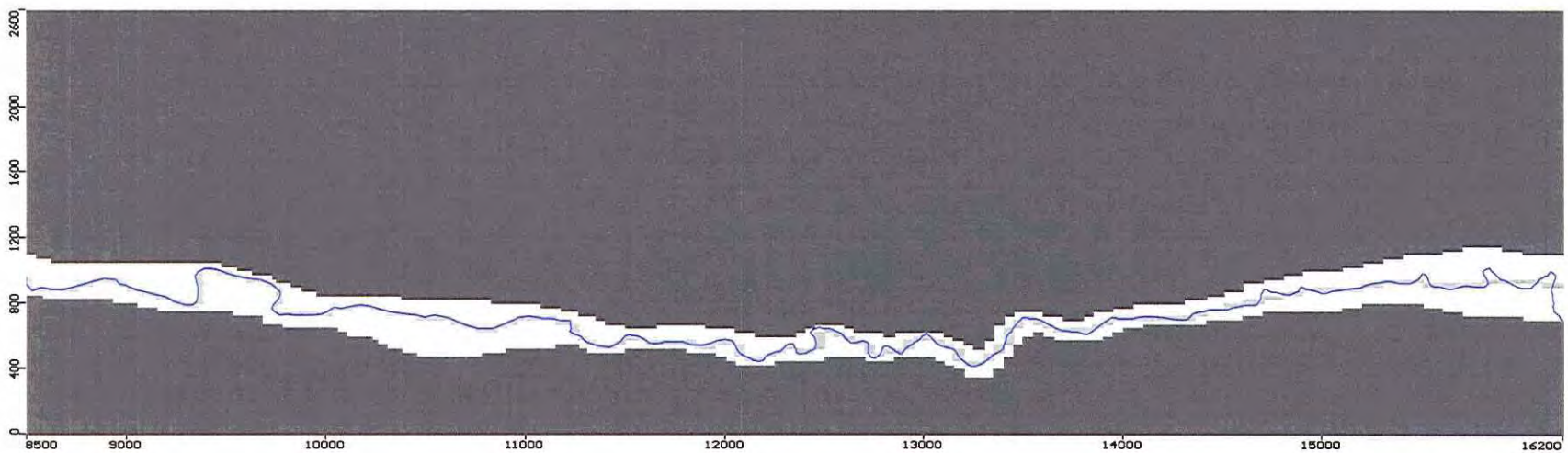


*Figure 3–9. Model Domain and Boundaries—East*

### Layer Top

The water table defines the upper boundary of the model, and its position is calculated by MODFLOW during program execution. The ground surface is not a boundary; however, it is included as input to the OU III model as the layer top as a convenience for presenting and interpreting model results. Data from the Monticello Projects engineering survey database were used to determine ground surface elevations composing the top of the model layer.

### Layer Bottom

The bottom of the model is treated everywhere as a no-flow boundary to represent the low-permeability, upper surface of the bedrock. Discharge of Burro Canyon Fm. ground water to the alluvial aquifer is represented as recharge in the model rather than upward leakage from bedrock to the alluvium. The upper bedrock surface was obtained using borehole information in the project database, engineering survey data for the areas excavated to bedrock on the Millsite, and field mapping. Bedrock elevation data were compiled and interpolated using SURFER, a grid-based graphics software application for three-dimensional surface mapping.

The elevation of the bedrock in the model required some manual modification to improve model stability. This was done mainly along the margins of the active domain where the aquifer was very thin (typically less than 1 ft) and the bedrock topography was irregular. In most instances, the bedrock was lowered slightly to prevent cells from becoming dry.

### Lateral and End Boundaries

Except for areas of the Millsite where lateral inflow occurs, the active domain is bounded north and south by no-flow cells to represent the low-permeability bedrock surface on the valley margins. No-flow conditions were initially assigned to all cells coinciding with bedrock outcrops and the mesas above the valley. Additional no-flow cells were adopted as modeling progressed to eliminate persistent dry cells where little or no water was anticipated. The cropland and pastures east of the Millsite and north of the creek were treated as no-flow zones because ground water there is very thin, seasonal, and discontinuous. Initial attempts to include these areas in the model created a very unstable result and produced numerous dry cells in the area. Maximum uranium concentration in ground water in that area is about 65 µg/L. The source of this contamination is believed to be related to former irrigation practices involving contaminated water.

The upgradient boundary of the model is assigned a specified head condition to account for inflow to the domain from the portion of the alluvial aquifer west of the Millsite. Specified ground water levels are applied across the alluvial valley at the west edge of the Millsite (westernmost red cells, Figure 3–8). Head elevations for this boundary were determined from October 2001 ground water levels in the north-south line of monitor wells located immediately downgradient of the boundary. No specific boundary condition is imposed across the downgradient end of the model, forcing all outflow from the model in this area to occur as discharge to Montezuma Creek.

### PRB

The slurry walls of the PRB system are represented using the horizontal flow barrier package in MODFLOW. The walls are assumed to be fully penetrating to bedrock, 4 ft wide perpendicular to flow, and of low hydraulic conductivity ($1 \times 10^{-5}$ cm/s).

### Montezuma Creek

Ground water discharge to Montezuma Creek is simulated using drain cells assigned to its trace. Drain cells permit water to be removed from the model but cannot act as ground water sources. Creek/aquifer interaction was initially simulated using the MODFLOW river package but was ultimately abandoned because it resulted in contaminant flushing that was much too rapid relative to historical monitoring data.

Creek stages used to estimate drain levels in the model were determined by automated gradient fill between intersections of the creek trace and known elevations from superimposed ground surface topography. The resulting elevations were within about 1 ft of the measured creek stage at six flow-monitoring stations surveyed during the RI. The elevation of the drain, equivalent to the base of the creek, was then assumed to be 0.5 ft below the estimated creek stage in each cell. The drain conductances were assigned manually.

### Lateral Inflow

Lateral inflow of ground water to the model is simulated through general head boundary (GHB) cells applied along the north margin of the Millsite and in the southwest corner of the active region of the model (Figure 3–8, green cells). The boundary head was assigned a value that was 1 ft above bedrock elevation in each cell. The GHB conductances were assigned manually.

### Wetlands

Constant head boundaries are used to represent wetland areas on the Millsite. Hydraulic heads at these locations are specified to match water level survey data and restoration design specifications for the wetlands. All cells within a given wetland are assigned the same head. In each wetland, the north, south, and west perimeter constant head cells capture ground water, and the east cells act as ground water sources.

### Surface Recharge

The surface recharge rate for the areas of irrigated ranch land east of the Millsite is specified as one-tenth of the mean annual precipitation in the Monticello area (15 inches/yr). Recharge on the Millsite is specified at 0.25 inch/yr. In anticipation of an established vegetation cover on the Millsite, this value is consistent with field lysimetry results discussed in Section 3.2.5. Site soils, particularly in areas formerly overlain by mill tailings north of the creek, are fine-textured and relatively thick (about 10 ft). The ground surface of the subpile area is also moderately sloped, which favors rapid runoff.

**Burro Canyon Fm. Discharge to the Alluvial Aquifer**

Specified recharge is used to represent discharge from the Burro Canyon Fm. to the alluvial aquifer where the former comprises the upper bedrock in the canyon. The amount of discharge is constrained to not exceed the measured stream gains in that part of the canyon, which vary between about 30 and 50 gpm.

**Evapotranspiration**

Evapotranspiration is not represented in the model. Instead, net surface recharge is specified as a percentage of annual precipitation. The areas of dense phreatophytes (willows) in the canyon (Section 3.2.6) are not represented as a ground water sink because ground water loss from evapotranspiration would be balanced by an equal amount of stream loss, with no net effect on hydraulic heads or overall water budget.

### 3.6.3 Hydraulic Properties

The alluvial aquifer is simulated as a homogeneous and isotropic system throughout the model area, including the constructed creek/aquifer corridor on the Millsite, with a hydraulic conductivity of 0.04 cm/s. This value is toward the high end of the measured range of hydraulic conductivities presented in Section 3.3 but provides the best fit to head and flow calibration targets (Section 3.6.4). Aquifer testing results (Section 3.3) were not used to discretize multiple zones of conductivity in the model. The data are instead interpreted to provide an approximate mean hydraulic conductivity that is representative of the aquifer as a whole. Hydraulic conductivity of the PRB reactive zone is set equal to that of the alluvial aquifer.
Total and effective porosity were assumed to be 0.30. Effective porosity is required by MODPATH (see Section 3.6.5) for ground water velocity calculation. Total porosity is required for MT3D advection and chemical reaction modules. Nonzero storage terms (specific storage and specific yield) must be entered to execute Visual Modflow. However, these parameters are not factors in a steady-state flow model, as is the OU III model, and are not required by MODPATH or MT3D.

### 3.6.4 Flow Model Calibration

The IRA Work Plan states that the model would be calibrated using October 2002 water levels. However, this approach was abandoned because the summer and fall of 2002 were abnormally dry. The model was instead calibrated to October 2001 measurements, which are assumed to better represent flow conditions in the aquifer.

Calibration criteria were not formally established for this project; however, a general goal during model construction was to predict hydraulic heads within 1 to 2 ft of observed values, with the error randomly distributed through the domain. Emphasis was also placed on matching estimates of ground water flow within OU III, as described later in this section.

Flow model calibration was achieved by trial-and-error modification of model variables. Initially, a working base model with satisfactory mass balance was developed. Parameters were then individually varied and the effects on head and flow calibration evaluated. The quantitative measure of calibration performance was the standard deviation of the difference between model-

computed and observed head at 66 active OU III monitor wells. Many alluvial wells near the PRB and all wells within the PRB were not used as calibration targets because of redundancy. All other active alluvial wells were included in the calibration assessment. No attempt was made to improve head calibration at individual control points by assigning small separate zones of hydraulic conductivity.

Calibration to flows focused on the measured flows in the creek and wetlands on the Millsite, flow through the PRB, and ground water discharge to the creek in the canyon reach of the study area. Variables modified during model calibration included hydraulic conductivity of the aquifer, inflow from the general head boundary on the north side of the Millsite, elevation of the constant head cells at Wetland 3, and the drain boundary used to represent the creek from the PRB east to the farthest downgradient monitor well (well 95–01).

**Results of Flow Model Calibration to Hydraulic Heads**

The similarity of the predicted and observed water-table contours as shown in Figures 3–10 and 3–11 demonstrates the model's capacity to reproduce the observed flow directions, hydraulic heads, and hydraulic gradient of the aquifer throughout the study area (model-predicted head contours in red, contours interpolated from observed heads in black). Head contours based on observed water levels extend only to the eastern extent of the monitoring network in Figure 3–11. The main departures between predicted and observed head occur between contours 6,790 ft and 6,770 ft, which are in the area of the PRB. Reasons for this include coarse model grid spacing and possible unreliable head data from monitor well MW00–07, which is located at the apex of the predicted head contour corresponding to 6,770 ft in Figure 3–10.

Figure 3–12 provides a scatter diagram of calculated and observed heads. Perfect calibration would result in all points falling on a line of unit slope. A point that plots above the idealized line indicates a model-computed head that is larger than the observed head at the corresponding monitor well. Points below the line correspond to model-predicted heads that are less than observed values.

The difference between model-predicted ground water elevation and the observed elevation at the corresponding monitor well is called the head residual. The standard deviation and mean absolute error of the head residuals for the calibrated model are 2.39 ft and 1.9 ft, respectively (Figure 3–12), indicating that the average model error is about ±2 ft. Head residuals range between –5 and +6 ft. The slope of the water table accounts for about 200 ft of vertical relief, west to east, within the existing monitor well network. In this context, the head residuals are small.

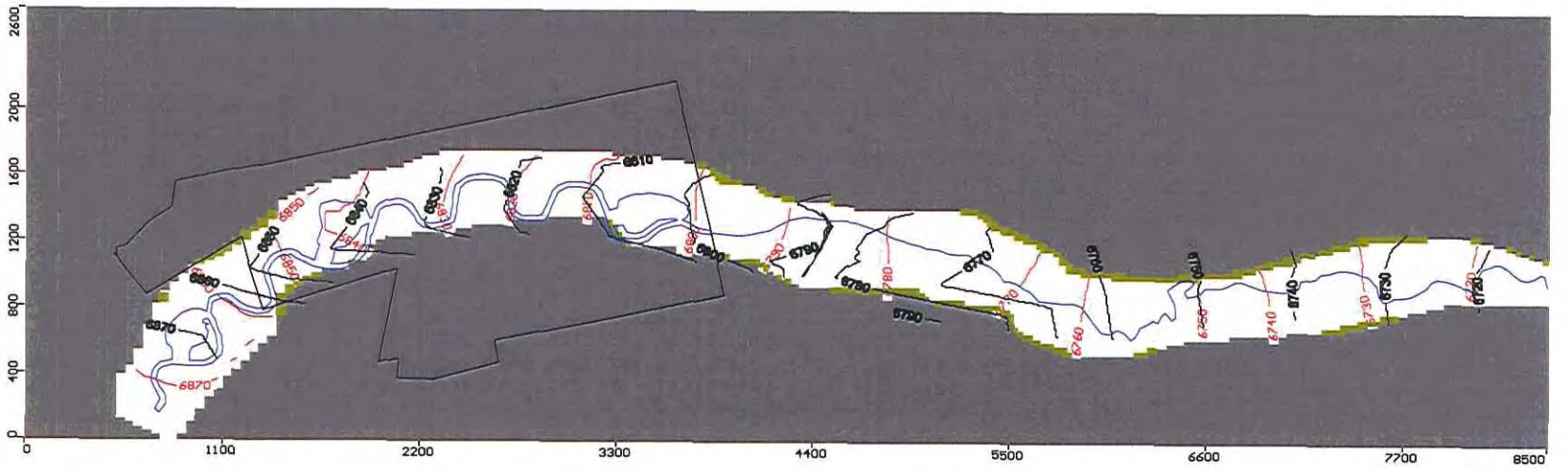


*Figure 3–10. Water Table Contours From Model Predicted Heads (red contours) and Observed Heads (black contours)—West Half of Model Domain*

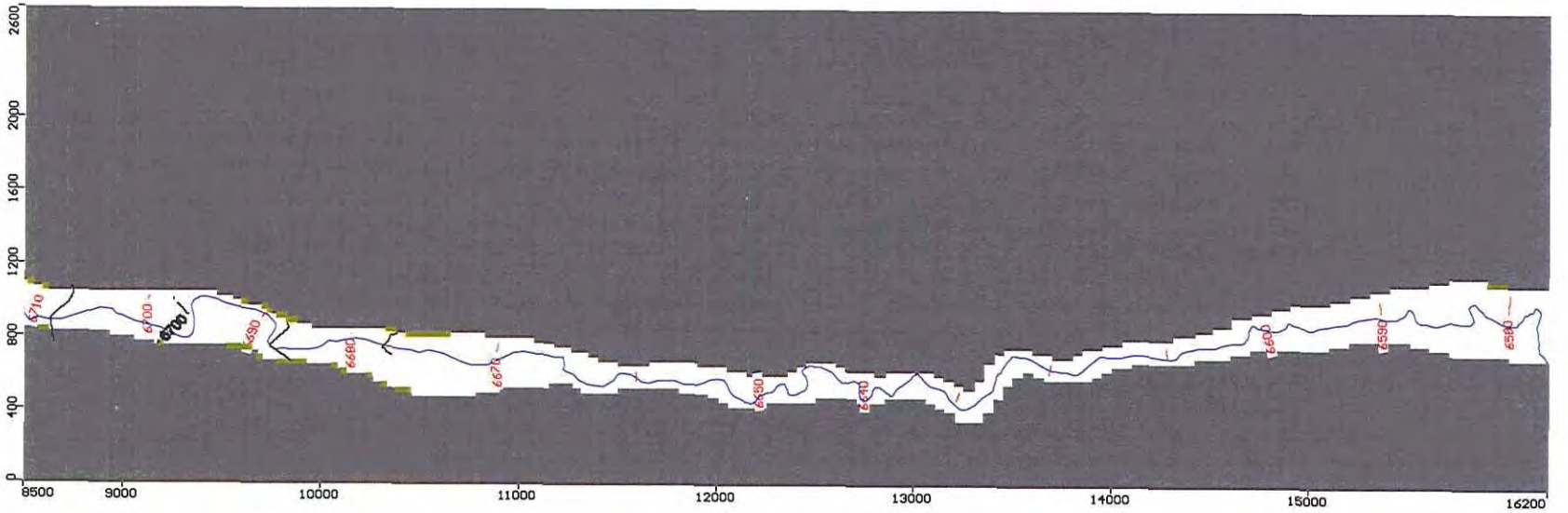


*Figure 3–11. Water Table Contours From Model Predicted Heads (red contours) and Observed Heads (black contours)—East Half of Model Domain*

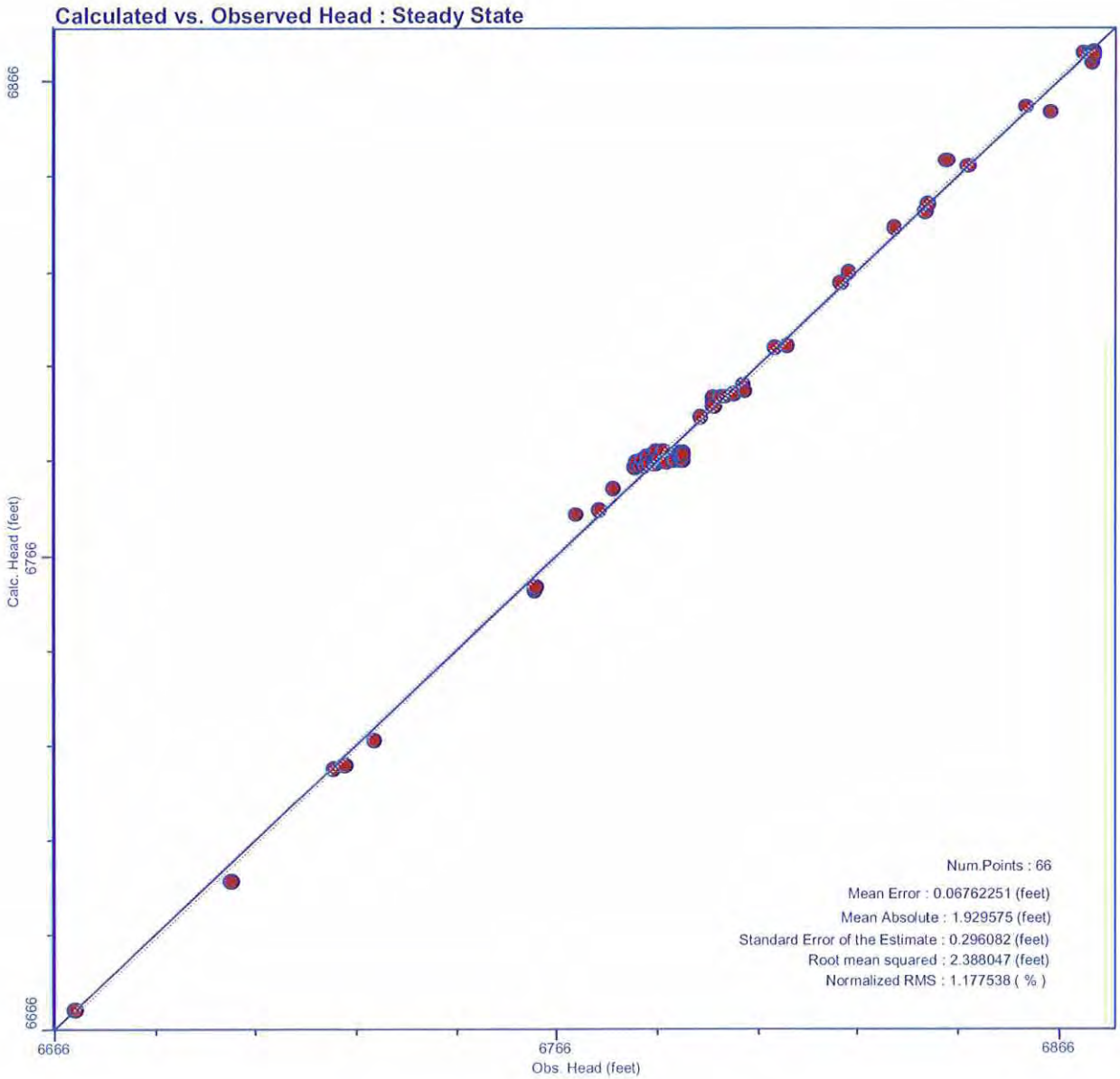


*Figure 3–12. Predicted vs. Observed Head*

Many of the largest head residuals are associated with wells near the PRB. These correspond to the widely scattered points near the center of Figure 3–13. This scatter occurs because the model grid is too coarse in this area to resolve the steep hydraulic gradients across the PRB and slurry walls. In general, predicted heads in the PRB area are lower than observed on the west side of the barrier system and higher on the east side.

Farther upgradient of the PRB, head residuals appear to be randomly distributed, suggesting no systematic error in that region. The maximum head residuals upgradient of the PRB occur at wells T01–27 (–5 ft) and T01–25 (+6 ft). Some of this error probably results from uncertain or irregular bedrock topography such as ledges and troughs in the excavated area, or inaccurately represented inflow from seeps and springs in the southwest corner of the Millsite.

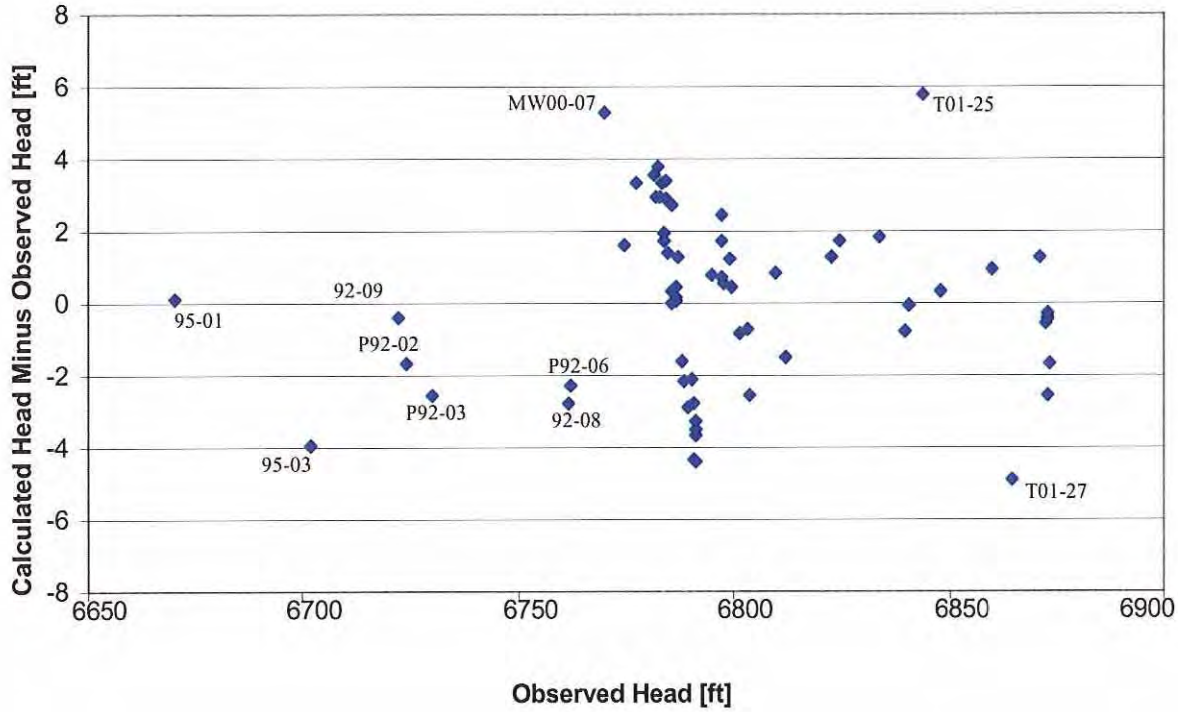


*Figure 3–13. Residual Head vs. Observed Head*

The large head residual at well MW00–07, located just downgradient of the PRB, is possibly attributable to faulty construction of the well. East of MW00–07, the computed heads are less than observed (negative head residual) at six of the seven well locations. These negative residuals are not caused by excessive drain capture because model elevations closely match surveyed elevations of the creek. Head calibration for the wells in this reach improved only slightly when the entire drain boundary in the reach was deleted.

Omission of potential inflows may instead account for the negative residuals. Flow measurements and recent observations indicate creek loss through much of that reach. Deactivating the drain boundary and applying 20 gpm of recharge over the reach eliminated the negative residuals at the six wells, but improvement in model performance as a whole was minor. Addition of this water produced some plume dilution during transport simulations but did not ultimately affect the flushing period. Rather than impose an additional boundary condition, the final calibrated model retains the drain configuration shown in Figures 3–8 and 3–9.

## Results of Flow Model Calibration to Measured Flows

Table 3–3 compares model-predicted to measured flows at several locations in the study area. The flow calibration target at the midsection of the Millsite refers to a qualitative average of measured ground water inflow to the dewatering trench/excavation during tailings removal. The difference between measured creek flow to and from the Millsite represents the total amount of ground water captured by the creek and wetlands in that reach. The measurement data for the

Millsite locations served primarily for determining inflows to the alluvial aquifer from sources to the north and south.

*Table 3–3. Comparison of Measured and Model-Computed Flows*

| Flow Calibration Target | Measured Flow (gpm) | Model-Computed Flow (gpm) |
|---|---|---|
| Underflow at midsection of Millsite | 100 | 94 |
| Net ground water capture on Millsite | 125 | 124 |
| Flow through PRB | 5–10 | 6 |
| Montezuma Creek gain in canyon reach | 30 (estimated minimum) | 22 |

In Table 3–3, the estimated flow for Montezuma Creek in the canyon reach refers to the net gain in stream flow in that reach from discharge of ground water. The gaining condition begins near the head of the canyon and is attributed primarily to discharge from the Burro Canyon aquifer to the alluvial aquifer and subsequent discharge to the creek. Flow measurements (Section E2.0 of Appendix E) indicate the creek may gain up to 100 gpm from ground water discharge in the canyon reach. The value presented in Table 3–3 (30 gpm) is biased low among the measurement data to avoid possible overstatement of the effect of this inflow on the transport model.

Some of the observed gain at the head of the canyon probably also results from discharge of alluvial ground water upstream of the Burro Canyon discharge zone. Alluvial ground water discharges to the creek at the head of the canyon because, as indicated by outcrops of Dakota Sandstone Fm. in the creek bed, the aquifer locally is nearly to fully penetrated by the creek. The model accounts for about 10 gpm of alluvial ground water discharge to the creek in the reach upstream of the Burro Canyon discharge zone.

### 3.6.5 Flow Model Particle Tracking and Advective Transport

USGS developed the computer program MODPATH (Pollock 1989) to calculate three-dimensional ground water flow lines from the output of steady-state MODFLOW simulations. MODPATH flow lines for the OU III model are shown in Figures 3–14 and 3–15. Each line originates at a hypothetical particle placed at a user-specified location. Particle travel in these figures terminates at cells that capture at least 50 percent of the inflow to the cell. Travel distance between 1-yr time increments, indicated by tick marks on the flow lines, corresponds to an average linear ground water velocity of about 6 ft/day in the region occupied by the main body of the uranium plume east of the Millsite. Important features of the model illustrated in Figures 3–14 and 3–15 are ground water capture at the wetlands, leakage from the east side of Wetland 3, through-flow and bypass of the PRB, and the ability of the creek to become a strong sink at the head of the canyon (between about $x$ = 8,500 and 9,000 ft in Figure 3–15).

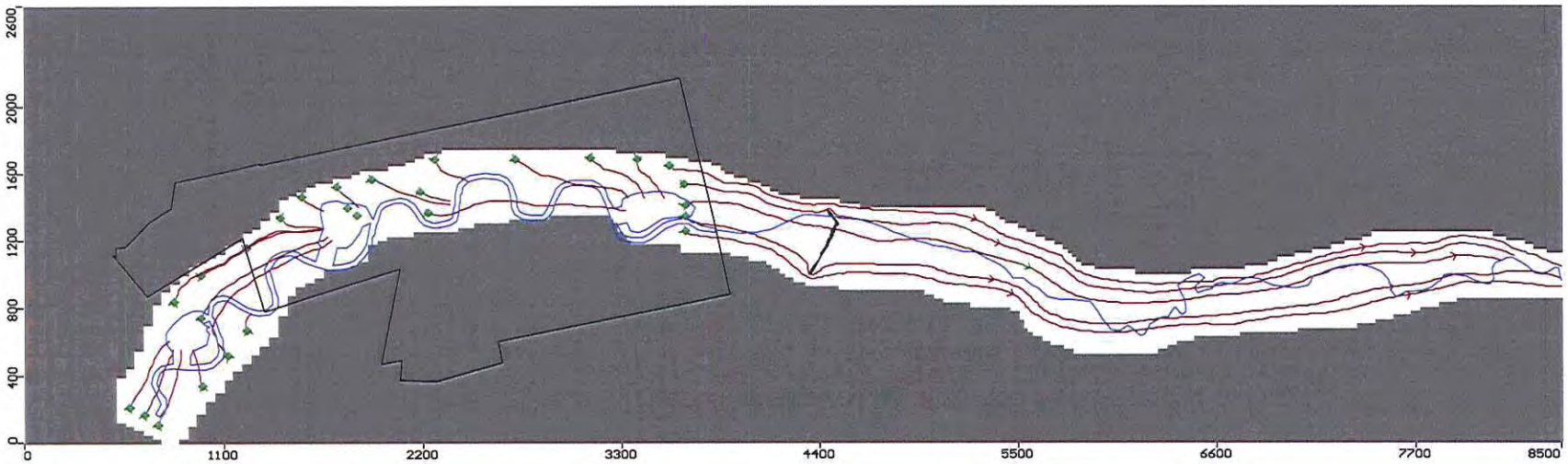


*Figure 3–14. Predicted Flow Paths—West*

*(Predicted steady state flow paths [red lines] for hypothetical particles [green symbols]. Distance between tick marks represents 1-yr of particle travel by advection.)*

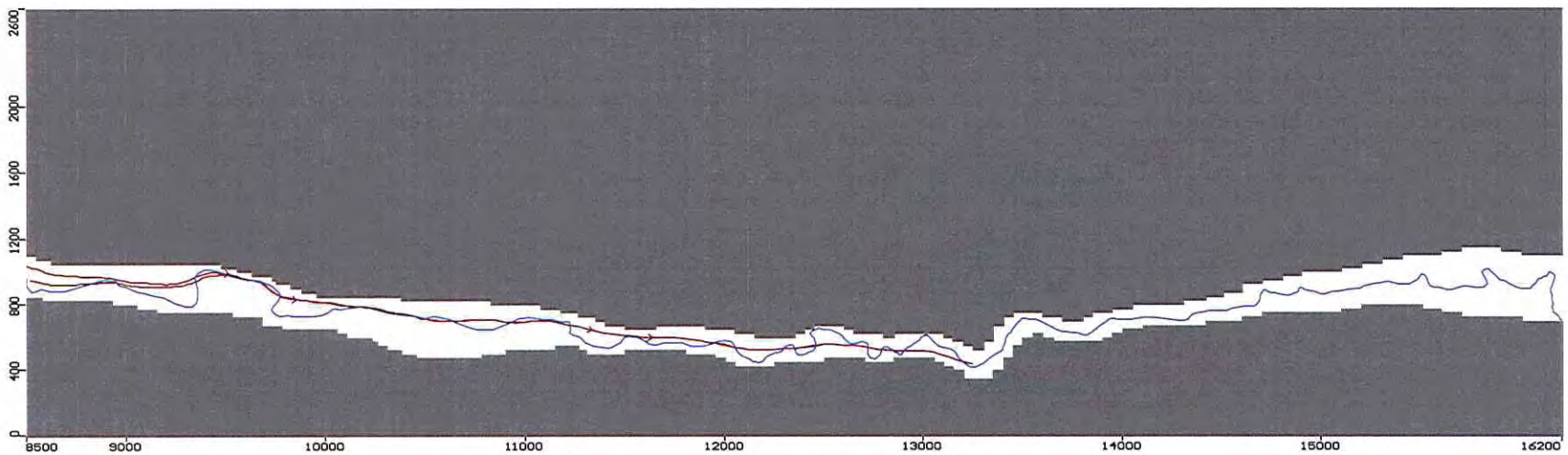


*Figure 3–15. Predicted Flow Paths—East*

### 3.6.6 Flow Model Sensitivity

The sensitivity of the flow model to model inputs was evaluated with simulations in which a single variable or boundary condition was changed from the calibrated value. The primary flow parameters that were varied were hydraulic conductivity, GHB inflow, and the prescribed head of Wetland 3 (see Table 3–4). The general sensitivity of the flow model to the drain boundary representing Montezuma Creek is described in Section 3.6.4.

*Table 3–4. Flow Model Sensitivity Analysis Parameters and Values*

| Parameter | Baseline Model Value | Sensitivity Analysis Value |
|---|---|---|
| Hydraulic Conductivity | $4 \times 10^{-2}$ cm/s | $3 \times 10^{-1}$ to $3 \times 10^{-3}$ cm/s |
| GHB Inflow | 35 gpm | 25 and 47.5 gpm |
| Wetland 3 Elevation | 6,801.5 ft | 6,800 and 6,803 ft |

### Hydraulic Conductivity

Model sensitivity to hydraulic conductivity variations is illustrated in Figures 3–16, 3–17, and 3–18. The first figure shows the effect of hydraulic conductivity on the root mean squared error (RMSE or standard deviation) of head residuals in the model. The RMSE was generally insensitive to hydraulic conductivity variations between $3 \times 10^{-1}$ and $3 \times 10^{-2}$ cm/s. Error increased significantly at lower values. Although reasonable head calibration is achieved using hydraulic conductivity of $3 \times 10^{-1}$ cm/s, this value is generally not consistent with sitewide conductivity measurements (Table 3–1). Flow targets are best matched using a hydraulic conductivity of $4 \times 10^{-2}$ cm/s (Figures 3–17 and 3–18), assuming bypass around the PRB is not disproportionate to PRB through-flow. In the calibrated flow model, ground water flow through the PRB is 6 gpm, whereas only 1.8 gpm of flow through the PRB is predicted when the hydraulic conductivity of the aquifer is $1 \times 10^{-2}$ cm/s.

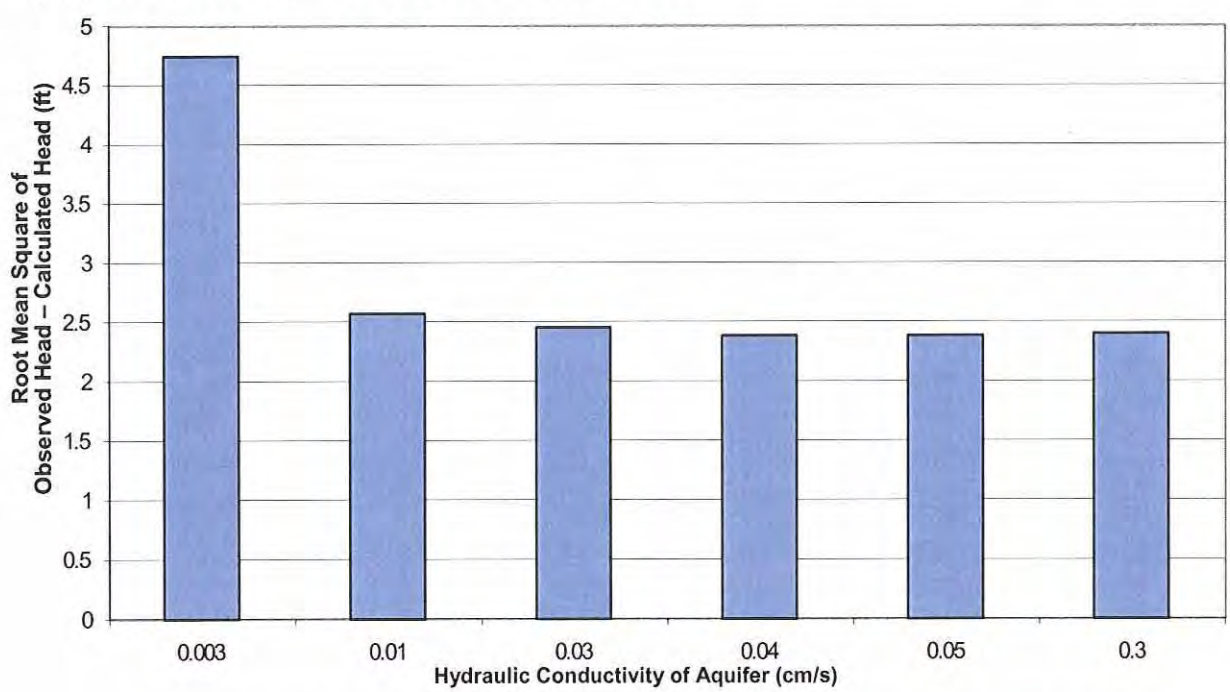


*Figure 3–16. Standard Deviation of Residual Head vs. Hydraulic Conductivity*

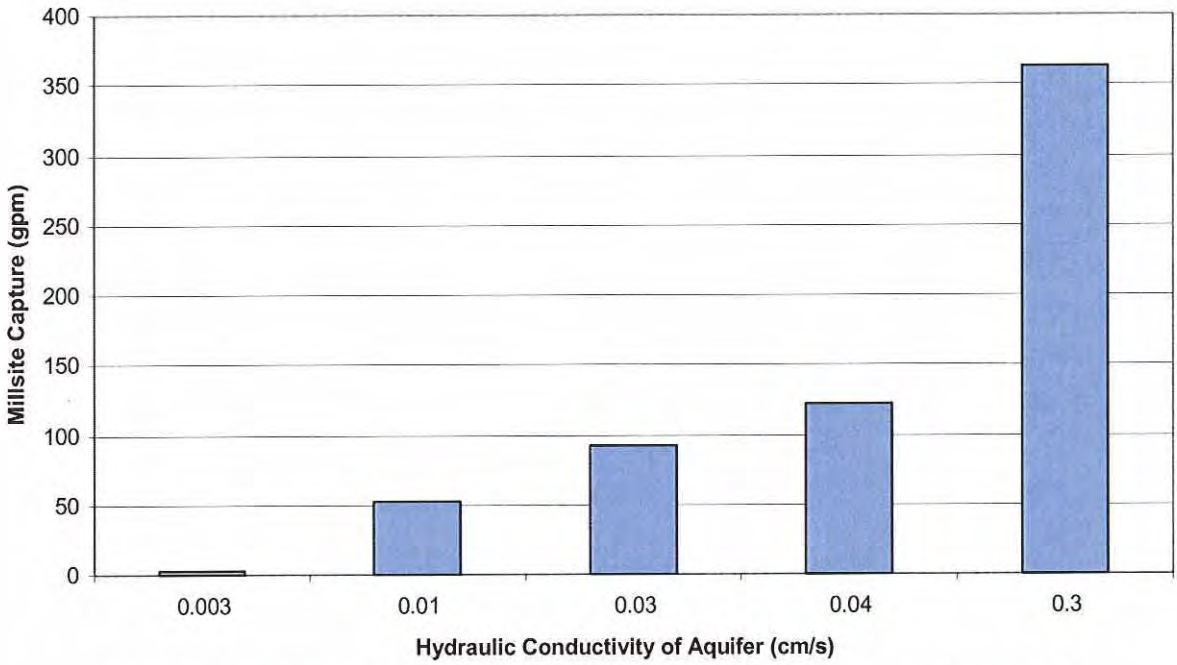


*Figure 3–17. Predicted Ground Water Flow on the Millsite vs. Hydraulic Conductivity*

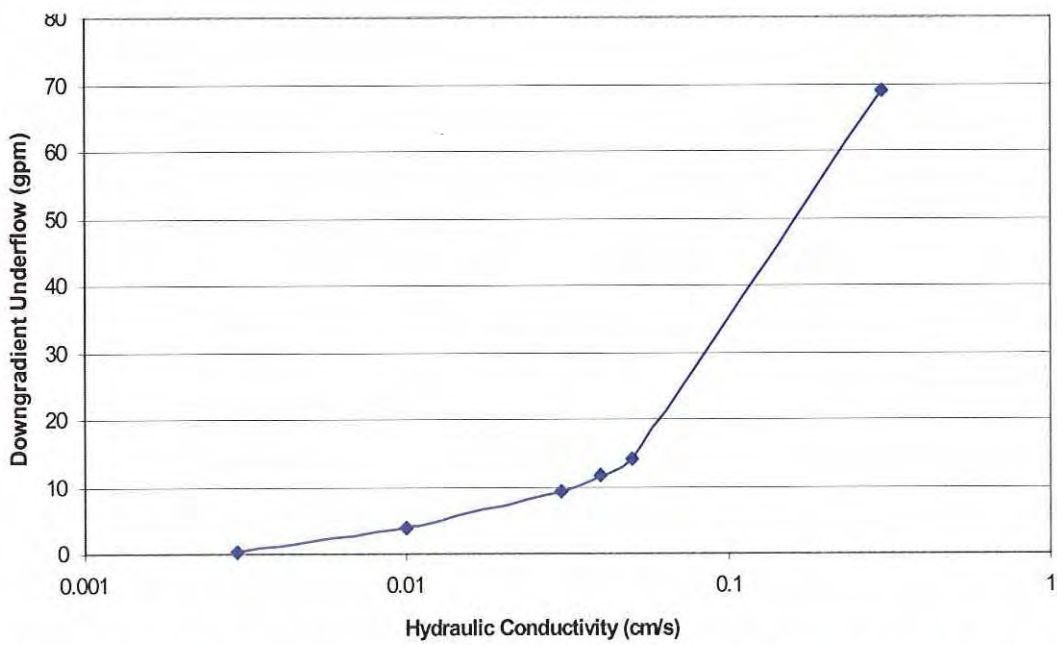


*Figure 3–18. Predicted Ground Water Flow From the Millsite vs. Hydraulic Conductivity*

## North General Head Boundary

Model sensitivity to the northern GHB is limited to the Millsite, as indicated in Figure 3–19 by the slight change in off-site flow relative to variations of the inflow. About 20 percent of the water from the GHB flows off the Millsite as underflow. The remainder is captured by the creek and wetlands on the Millsite.

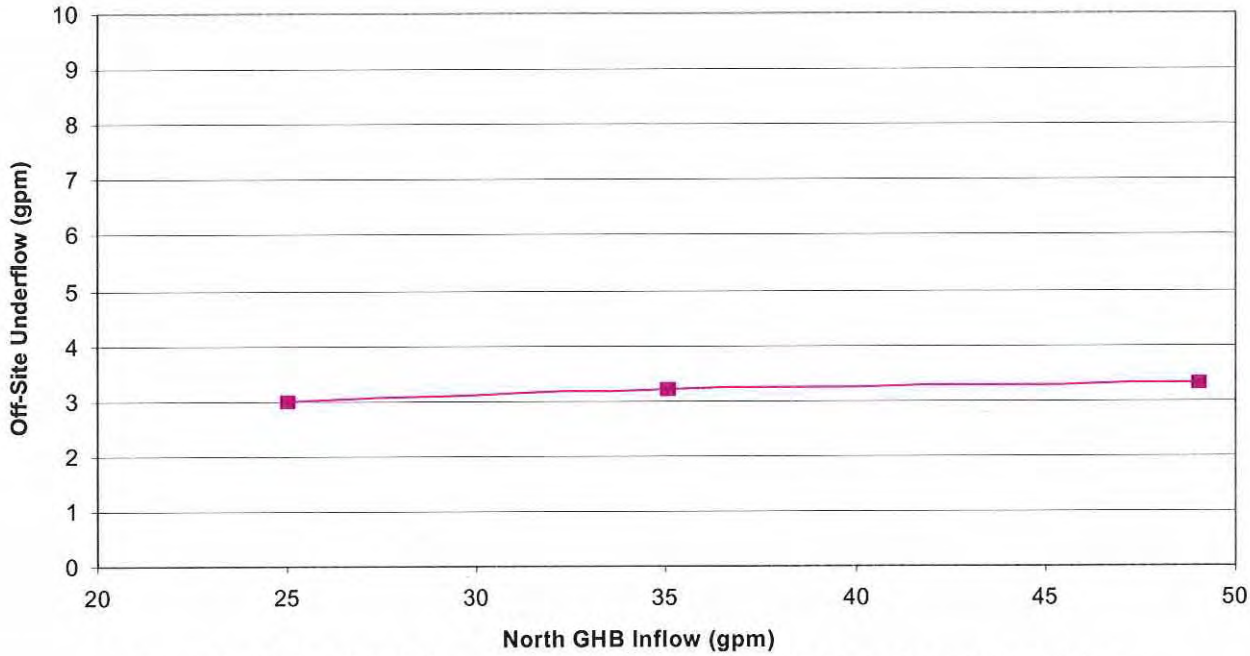


*Figure 3–19. Predicted Ground Water Flow From the Millsite vs. General Head Flow*

## Wetland 3 Elevations

Leakage from Wetland 3 contributes about 80 percent, or 8 gpm, of the total off-site flow in the calibrated model. Figure 3–20 illustrates that the amount of off-site flow changed by about 40 percent when the wetland elevation is either increased or decreased by 1.5 ft from its relative position in the calibrated model. Figure 3–21 shows the effect of Wetland 3 elevation on the model RMSE. It is noted that the elevation of the wetland (6,801.5 ft) in the calibrated flow model is 0.3 ft higher than the waterline measured during low-flow conditions in September and December 2002.

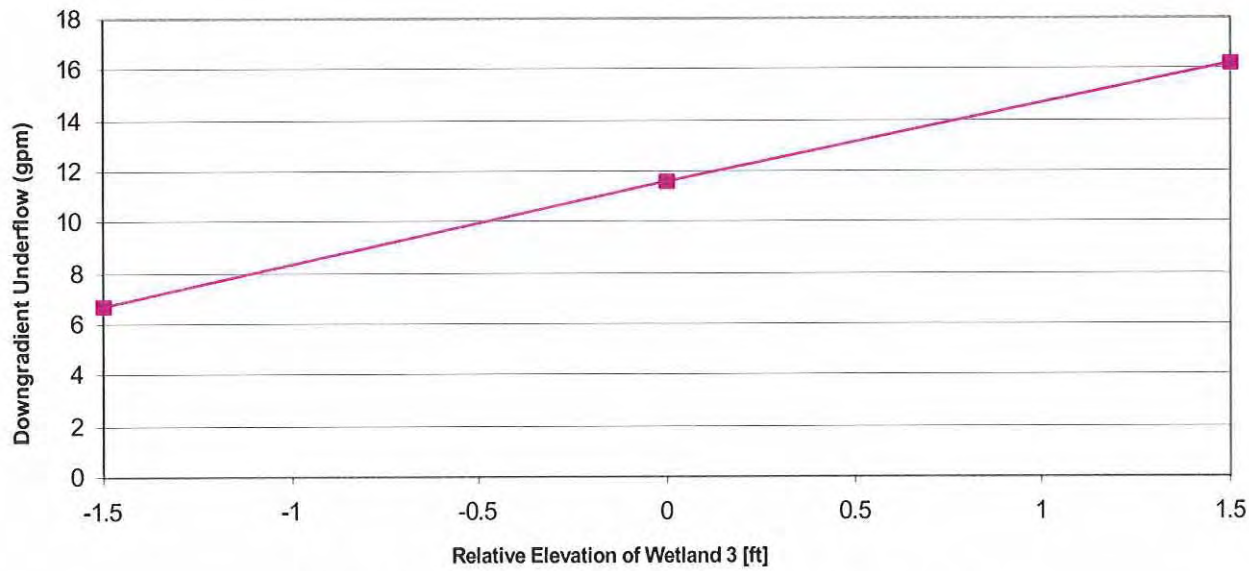


*Figure 3–20. Wetland Leakage vs. Wetland 3 Elevation*

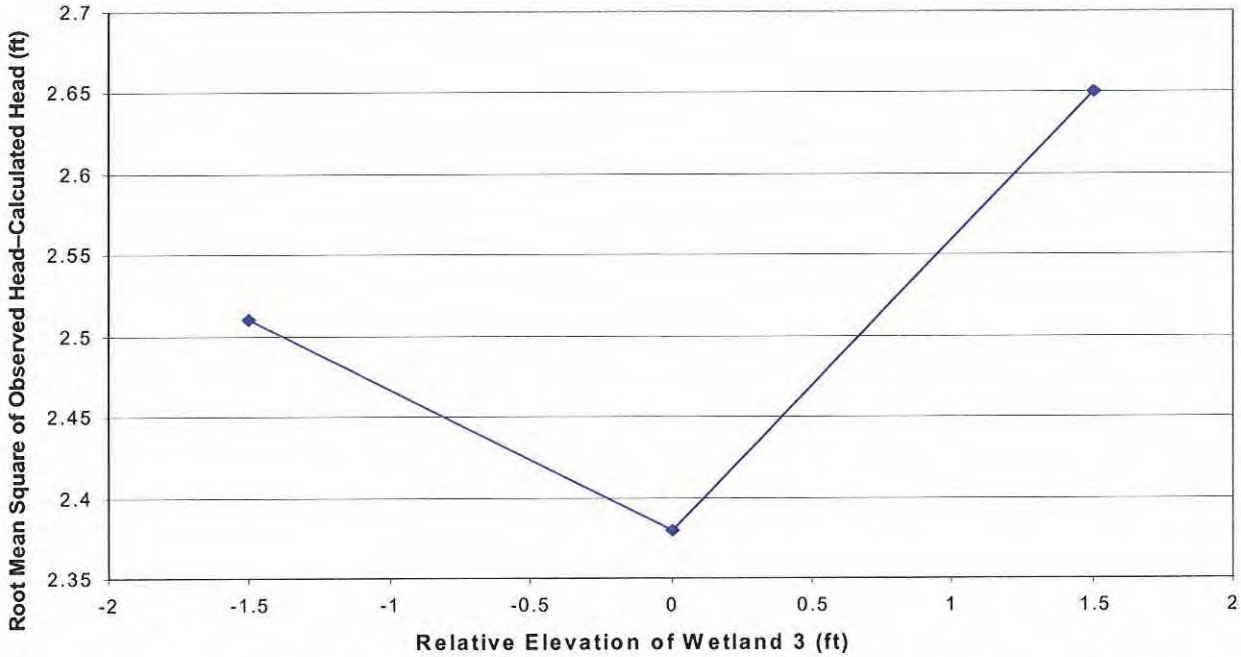


*Figure 3–21. Residual Head vs. Wetland 3 Elevation*

### 3.6.7 Flow Model Mass Balance

The flow model solution was computed using the strongly implicit procedure described in McDonald and Harbaugh (1988). Mass balance error in the calibrated model was minor. Total inflow was balanced by total outflow within minus 0.02 percent. Mass balance error within individual user-defined water budget zones did not exceed 0.1 percent. Section E4.0 of Appendix E contains Visual Modflow mass balance output for the calibrated model.

## 3.7 Solute Transport Model

The transport model for OU III simulates movement of dissolved uranium in the alluvial aquifer using initial concentration conditions observed in October 2002. Processes simulated in the transport model are advection, dispersion, and chemical adsorption. Predicted concentrations are also affected by inflows and outflows through flow model hydrologic boundaries and by prescribed solute source boundaries.

This section first presents the baseline transport model in which uranium transport is simulated for 50 yr. Variations of the baseline model, with simulations up to 150 yr, are then addressed.

### 3.7.1 Uranium Sources and Sinks

Sources of uranium in the model are (1) the initial dissolved plume, (2) the vadose zone beneath former tailings piles, and (3) Wetland 3. Uranium is removed from the model at hydrologic sinks, which are the wetlands and Montezuma Creek.

### Initial Concentrations

The initial distribution of uranium as shown in Figure 3–22 was interpreted from the results of 49 wells sampled in October 2002. This distribution was developed using SURFER with a 50-ft × 50-ft grid, the natural neighbor method, a grid anisotropy ratio of 5, and an anisotropy angle of minus 10 degrees. Wells within the PRB were not included in the analysis. In many cases, the uranium concentrations produced by this methodology are slightly less than the corresponding measured concentrations; however, a given isopleth encompasses a broader area than would result from an exact interpolation. Contours in Figure 3–22 correspond to 30, 100, 200, 500, and 800 μg/L; the color spectrum corresponds to increasing concentrations from purple and blue, through green to yellow at the maximum concentrations. Areas in white signify concentrations less than 30 μg/L.

### Subpile Vadose Zone

Vadose zone soil beneath portions of the former tailings areas is a potential source of contamination to ground water (DOE 2000e, 2001a). This source is represented in the model by recharge concentration cells (fuchsia-colored cells, Figure 3–23) coincident with the former tailings areas north of the creek.

Mass loading from the subpile zone is determined as the product of the flow model recharge rate (0.25 inch/yr) and a uranium concentration equal to the average of the peak effluent concentration (1,110 μg/L) from eight of twelve column-leach tests (DOE 2001c). Two tests were excluded from the calculation of the mean effluent concentration because peak values (22 and 17 μg/L) were too low. The results of two other tests were excluded because the samples used in those tests were collected from beneath the former Acid Pile. The source potential there is considered low because very little vadose zone remains, and the flow path from this area to the aquifer is incomplete. Any seepage from this area will either surface at the bedrock ledge that separates the former Acid Pile from the newly constructed creek/aquifer corridor or will enter the constructed drain that traverses the area and leads to Montezuma Creek.

During the column tests, peak uranium concentrations, ranging from about 500 to 1,500 μg/L, were eluted within the first several pore volumes passed through the columns. Concentrations were then generally reduced by half with the passage of 4 or 5 additional pore volumes. In the transport model, because the residence time of pore water in the vadose zone probably exceeds 50 yr, the average of the early peak values was held constant.

Also shown in the figure is the outline (in red) of the areas excavated to bedrock. In general, subpile areas excavated to bedrock are not represented as sources of uranium contamination to ground water. This is because the subpile soil has been removed, and the bedrock surface is not regarded as a potential source. Small areas of residual source material within the bedrock excavation outline (Figure 3–23) represent subpile soil that was moved into the excavation as fill to reconstruct the Millsite.

### Wetland 3

Some ground water captured at Wetland 3 leaks back into the aquifer at its eastern edge. The ground water that seeps into the wetland from its north bank is contaminated with COCs, including uranium. Sampling results also confirm uranium contamination of surface water in Wetland 3. Wetland 3 is therefore represented as a solute source in the transport model. It

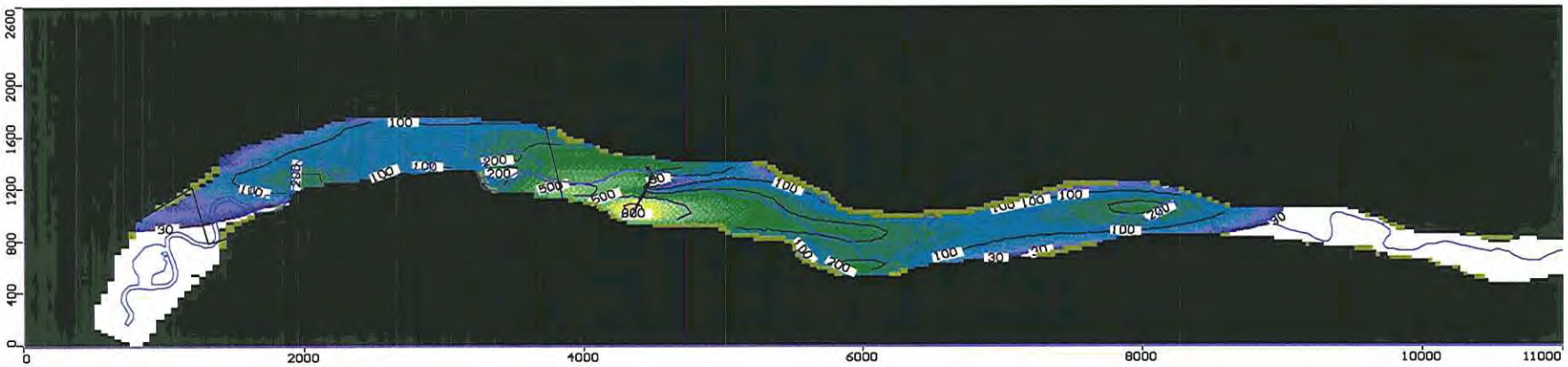


*Figure 3–22. Initial Uranium Concentrations in micrograms/liter*

*(Concentration color shading described in text.)*

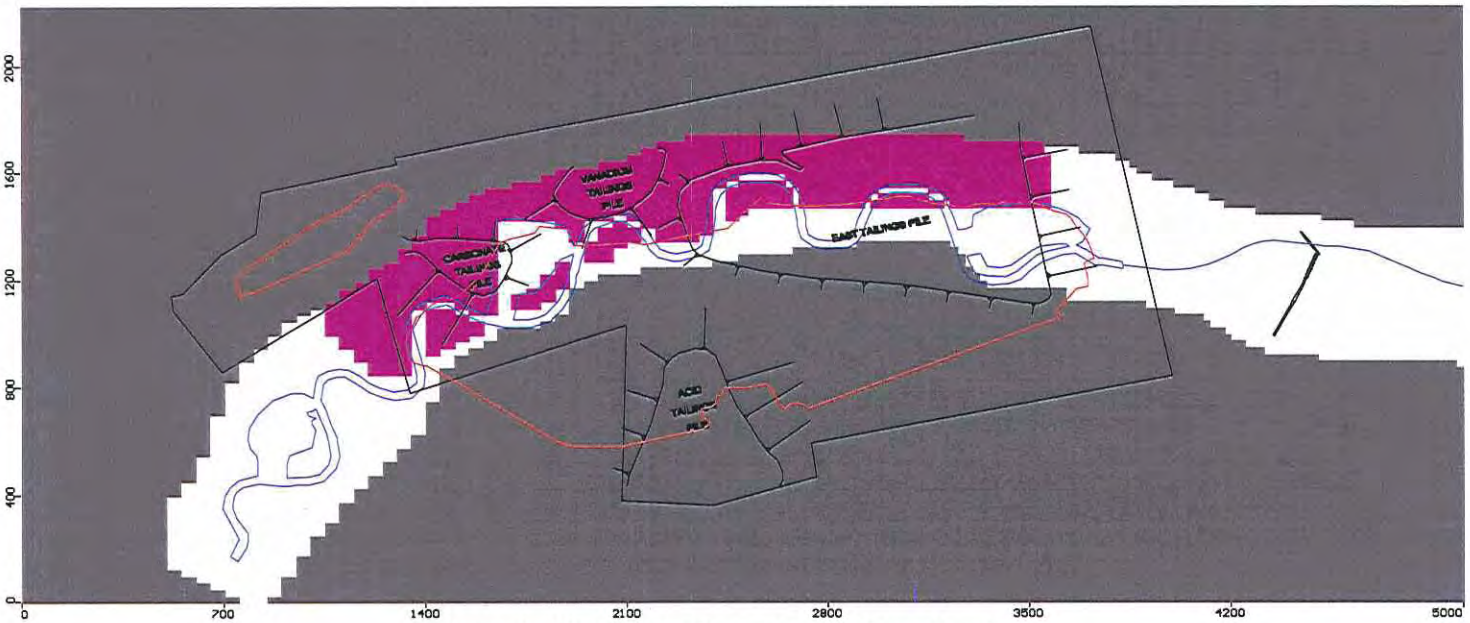


*Figure 3–23. Subpile Concentration Boundary Cells*

*(Red outline signifies areas of the Millsite that were excavated to bedrock during remedial actions. Fuschia-colored area represents uranium source area from subpile vadose zone.)*

remains a solute source until the uranium plume moves off the Millsite. At that time, seepage into the wetland is not contaminated with uranium.

To determine the source concentration of Wetland 3, transport was first simulated assuming no solute source at the Wetland 3 constant head boundary. The resulting predicted concentrations that entered the wetland along its north edge decreased linearly from 200 µg/L during the first year to about 8 µg/L during the 14th year. These concentration values were then assigned as the uranium source concentrations at Wetland 3 for the subsequent transport simulation. The values were assigned in 1-yr increments through the initial 14 yr. Thereafter, the inflow concentration to the wetland became constant at about 7 µg/L. Without the Wetland 3 concentration boundary, leakage of uncontaminated water from the wetland results in local dilution that is too rapid in comparison to observed trends at nearby wells.

**Permeable Reactive Barrier**

The PRB is represented in the baseline transport model as having zero effect on uranium concentration. Uranium removal by the PRB is addressed in Section 5.0 of this report, in which treatment periods that are effective for 3, 8, and 13 yr from October 2002 are assumed in 50-yr transport simulations. Section 5.0 also includes ground water modeling to evaluate possible enhancements to reduce the quantity of ground water flow that is not captured and treated by the current system.

**Other Contaminant Sources**

Contaminated ground water beneath cropland and pastures east of the Millsite and north of the alluvial aquifer is not represented in the transport model. Concentrations there vary between approximately 40 and 65 µg/L uranium. The quantity of this water entering the aquifer is assumed to be insufficient to maintain uranium concentrations greater than 30 µg/L upon mixing.

Another area of contaminated ground water not represented in the model is the southeast corner of the Millsite. Ground water occurrence there is seasonal, thin, and discontinuous. The uranium at this location resides in soil previously in contact with impounded wastewater from the mill (see Section 2.8.5), or from formerly impounded brine from the water treatment plant that operated during remediation of the Millsite. This residual uranium is probably remobilized to the ground water during wet years when these soils become saturated. The recently installed riprap-filled drain extending south from the terminus of Deer Draw may intercept the flow of this contaminated ground water.

In areas remediated to supplemental standards, contaminated soil and sediment in the streambanks and floodplain are potential sources of ground water contamination. The contribution of these sources to ground water contamination is not known. These secondary sources of uranium are not represented in the model.

### 3.7.2 Transport Parameters

Uranium dissolved in ground water is assumed in the model to be affected by linear equilibrium adsorption. This refers to the process of rapid, reversible partitioning between dissolved uranium and uranium that is chemically attached to surfaces of the aquifer mineral grains. The proportionality constant used to describe the concentration ratio of adsorbed and dissolved solute

in a solution at equilibrium with the mineral grains is the $K_d$. This parameter was measured in experiments conducted during the IRA using samples of alluvium from uncontaminated regions of the aquifer and an aqueous solution prepared in the laboratory to simulate the ionic composition of background ground water (DOE 2001d). Results of those experiments are summarized in Table 3–5. The $K_d$ used in the OU III baseline model is 2 milliliters per gram (mL/g).

*Table 3–5. Laboratory-Determined Distribution Coefficients for Uranium at OU III*

| Laboratory Sample No. | Mean $K_d$ (mL/g), <2 mm size fraction only[a] | Mean $K_d$ (mL/g), adjusted for >2 mm size fractions[a] |
|---|---|---|
| NEF 351 | 3.28 | 2.1 |
| NEF 352 | 3.8 | 0.5 |
| NEF 354 | 2.81 | 0.79 |
| Representative Value[b] | | 0.65 |

[a] Mean of six variable mass sorption tests per substrate sample.
[b] Recommended value (DOE 2001d).

Longitudinal dispersivity in the transport model is assigned a value of 15 ft. This term describes the degree of solute spreading, owing to variable flow velocities through porous media on a microscopic scale, in the direction parallel to ground water flow. This is a mechanical process that spreads dissolved solute into increasingly greater volumes of the aquifer during transport, and thus dilutes the solute concentration. Transverse dispersivity (solute spreading perpendicular to the ground water flow direction) is set at 1.5 ft. The model is generally not sensitive to this latter parameter because the aquifer is very narrow. Vertical dispersion is not relevant because the model comprises a single layer. The value used for longitudinal dispersivity is based on the monitored progress of a pulse of nitrate transported in ground water between the Millsite and PRB. The nitrate release resulted from application of fertilizer during revegetation efforts in 1999 and 2000. Ground water velocity was approximated using observations of the plume, and the Ogata-Banks equation in Domenico and Schwartz (1998) was subsequently applied to estimate longitudinal dispersivity.

The adsorptive capacity of the materials composing the aquifer matrix, and thus chemical retardation, is proportional to bulk density of those materials. Bulk density was specified at 100 pounds per cubic foot in the model, which is consistent with measured values from previous MMTS engineering studies (Dames & Moore 1992).

### 3.7.3 Transport Model Calibration

The transport model was not calibrated to a period of recorded plume movement. Instead, to provide a measure of model accuracy, predicted uranium concentrations in response to different parameter values were compared to recent, observed trends at several OU III monitor wells. The flow and transport parameters varied for this analysis were hydraulic conductivity and the uranium $K_d$. Figures 3–24 through 3–27 illustrate observed uranium concentrations over the past several years at four wells located in the central portion of the plume.

The final observed point corresponds to concentrations measured in October 2002. Following this point, the results of three separate model runs are projected into future years at the respective well locations. The three runs consisted of (1) the baseline model, (2) the baseline model with a larger $K_d$, and (3) the baseline model with a lower hydraulic conductivity. As shown in the figures, continuation of the observed trend is best predicted by the baseline model.

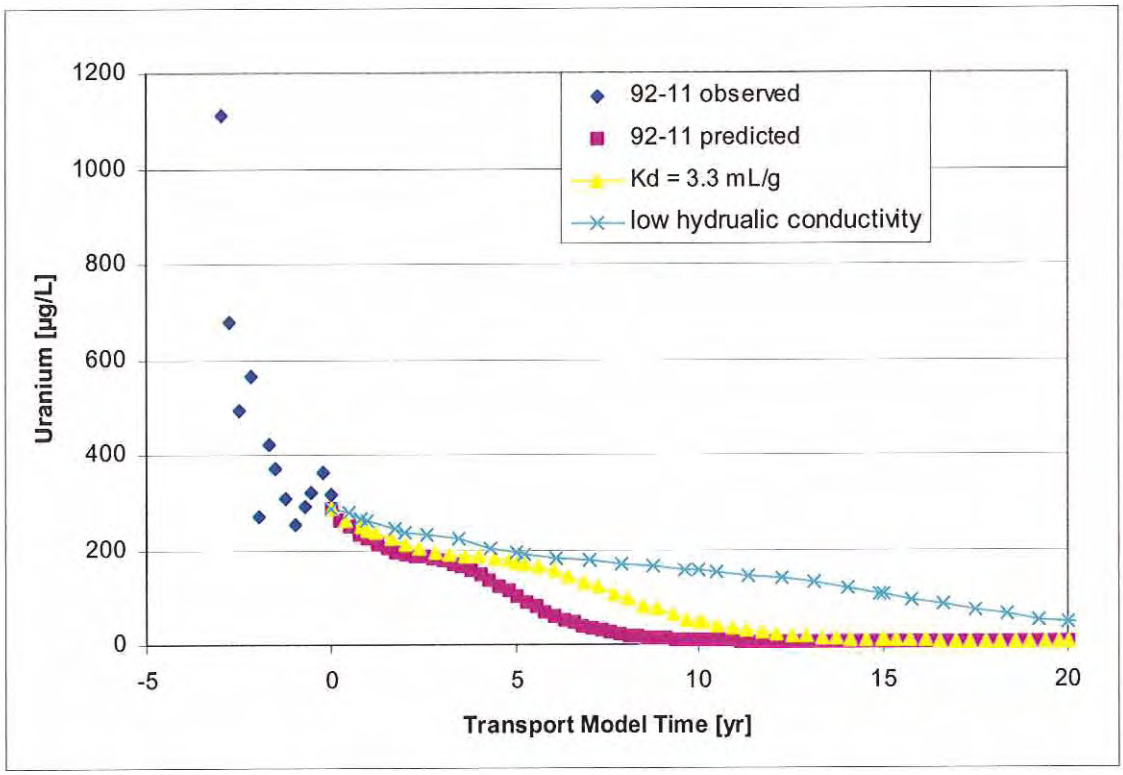


*Figure 3–24. Observed and Predicted Concentrations at Well 92–11*

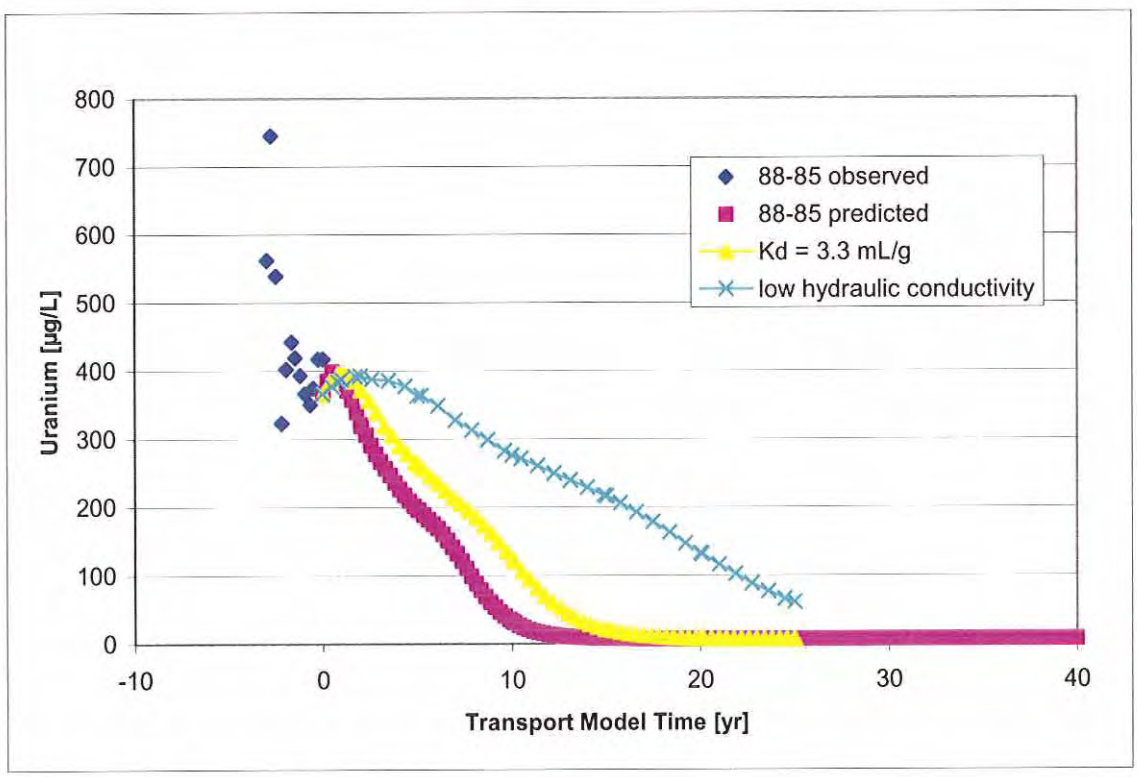


*Figure 3–25. Observed and Predicted Concentrations at Well 88–85*

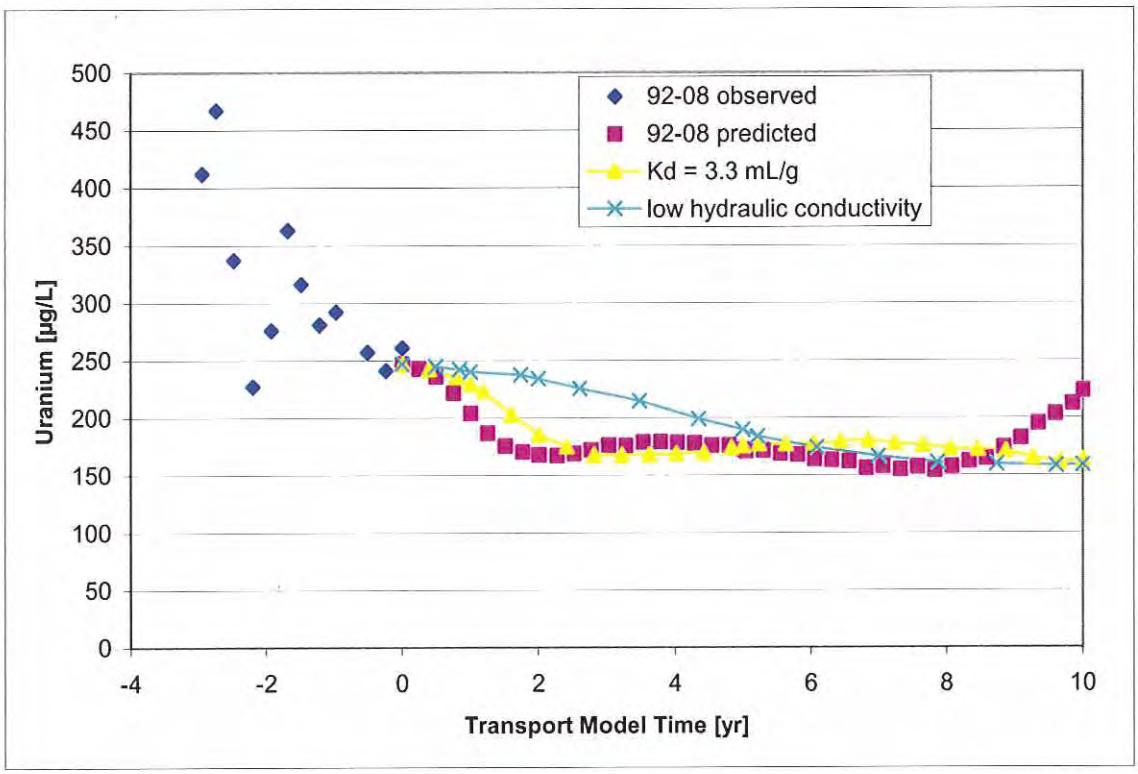


*Figure 3–26. Observed and Predicted Concentrations at Well 92–08*

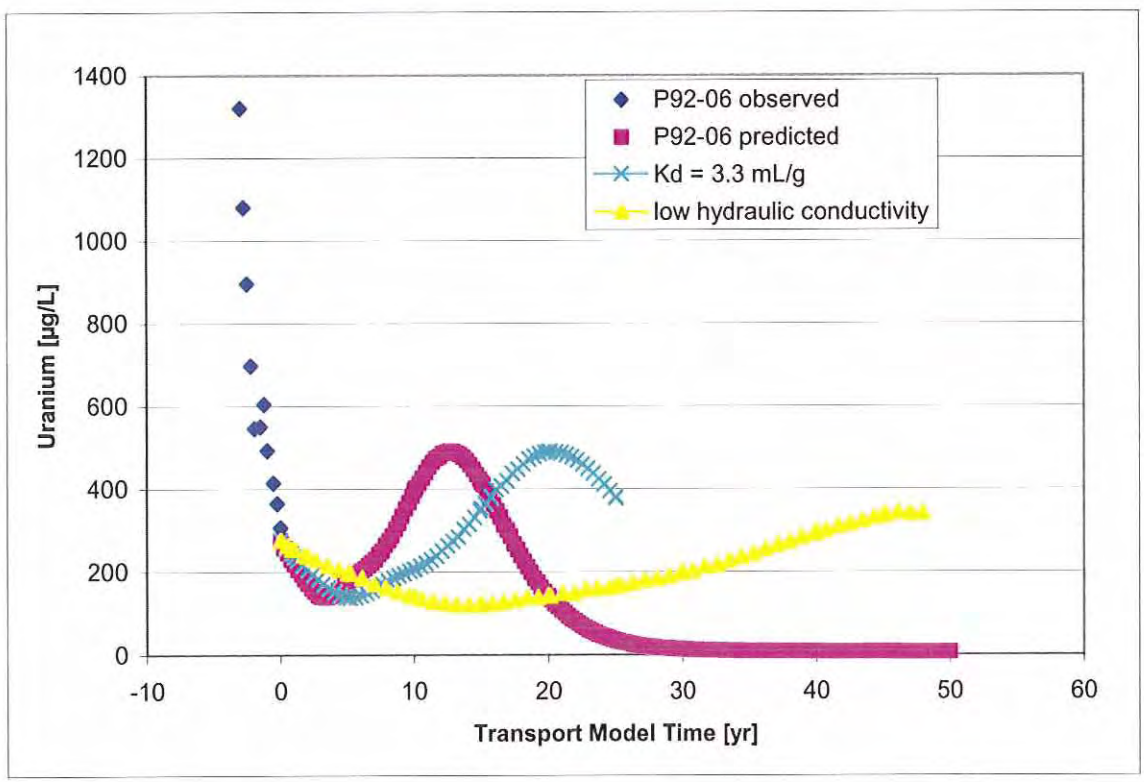


*Figure 3–27. Observed and Predicted Concentrations at Well P92–06*

### 3.7.4 Transport Model Results

Uranium concentrations predicted by the model are shown in Figures 3–28 to 3–31 for simulation times of 5, 10, 25, and 40 yr relative to the starting time of October 2002. Contours in the figures correspond to 30, 100, 200, and 500 μg/L; the color spectrum corresponds to increasing concentration from purple and blue, through green to yellow at the maximum concentrations. Areas in white signify concentrations less than 30 μg/L.

The model predicts that uranium concentrations at all locations in the alluvial aquifer decrease to less than 30 μg/L in 42 yr. This conclusion ignores a small stagnant area south of the creek at Wetland 3 where concentrations ≤40 μg/L persist through the full 50 yr of simulation. Contamination indicated at Wetland 2 (center wetland area on the Millsite) is relict uranium captured early in the simulation. Excluding those areas, uranium flushing on the Millsite, and from the Millsite to the PRB, is predicted to be complete in about 14 yr. At the downgradient end of the plume, the model predicts no significant advancement of uranium beyond its initial extent because of dilution by Burro Canyon Fm. inflow and capture by the creek in that area. Time series of predicted uranium concentrations at several OU III monitor wells are shown in Figure 3–32. The prominent peaks observed in this figure correspond to the arrival and passage of the high-concentration uranium "slug" that is presently at the south end of the PRB slurry wall (Figure 3–22).

Concentrations were predicted in MT3D using the Hybrid Method of Characteristics. This is a particle-tracking scheme that uses the velocity field of the flow model to calculate advective transport. Zheng (1996) provides a detailed discussion of transport algorithms used with this technique. Numerical dispersion was not a source of transport error in the model, and transport mass balance error decreased to less than one percent at 0.5 yr of simulation.

### 3.7.5 Transport Model Sensitivity Analysis

The variables that most affect uranium transport in the model are hydraulic conductivity and the uranium $K_d$. Dispersivity also affects solute distribution during transport but typically to a lesser degree. The hydraulic conductivity and $K_d$ were each varied separately from the value used in the baseline model to evaluate their effect on uranium transport. Of particular interest was the predicted time for uranium concentrations to decrease to less than 30 μg/L everywhere in the model (flushing period). The sensitivity runs, parameter values, and summary results are listed in Table 3–6. The first sensitivity run involved reducing the hydraulic conductivity of the aquifer from $4 \times 10^{-2}$ cm/s to $1 \times 10^{-2}$ cm/s. Though the lower value is within the range of conductivity measurements made at the site, the baseline value provided the best match to both head and flow calibration targets and also provided a better match to recent uranium concentration trends (Section 3.7.3). Decreasing the hydraulic conductivity by a factor of 4 increased the time for uranium concentrations to decrease to less than 30 μg/L from 42 yr to about 140 yr, which represents a 3.3-fold increase in the flushing period.

*Figure 3–28. Predicted Uranium Plume at Time = 5 Years*

*(Concentrations in micrograms/liter)*

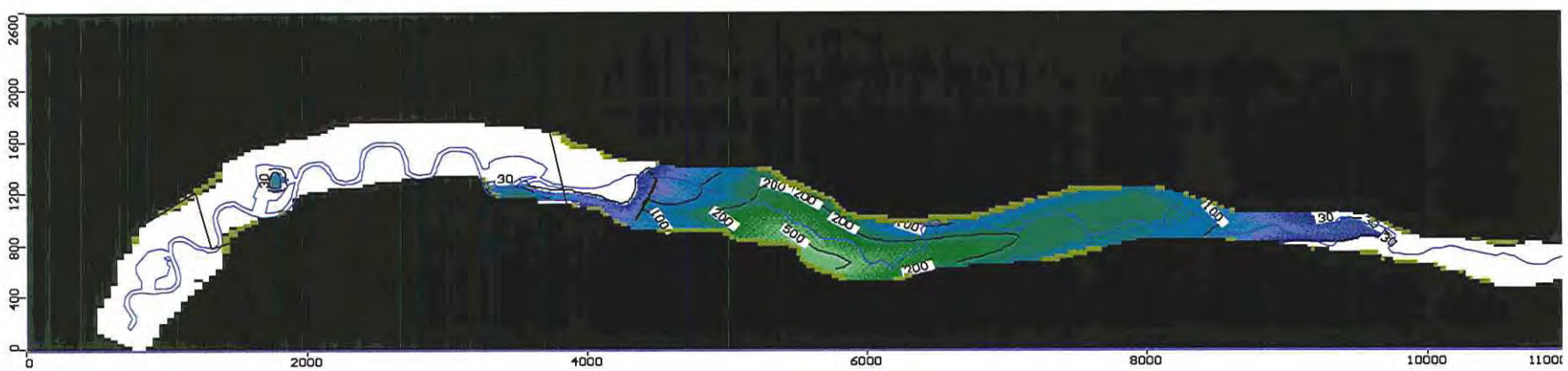


*Figure 3–29. Predicted Uranium Plume at Time = 10 Years*

*(Concentrations in micrograms/liter)*

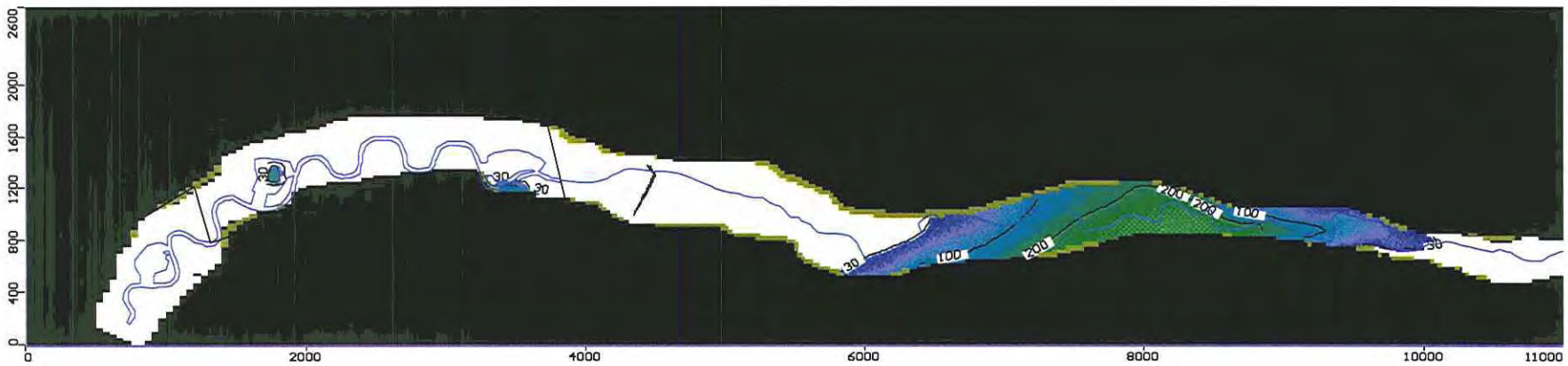


*Figure 3–30. Predicted Uranium Plume at Time = 25 Years*

*(Concentrations in micrograms/liter)*

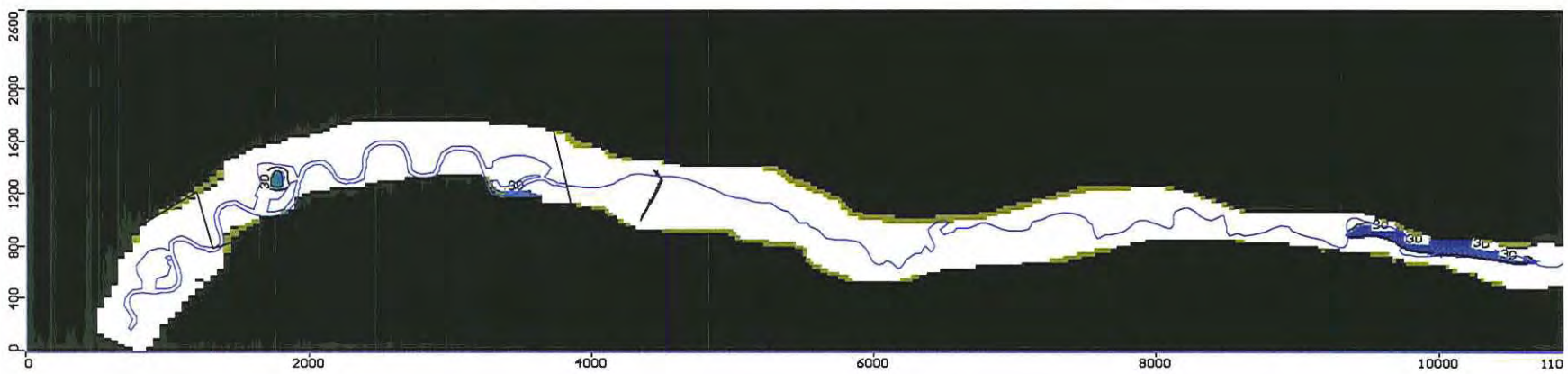


*Figure 3–31. Predicted Uranium Plume at Time = 40 Years*

*(Concentrations in micrograms/liter)*

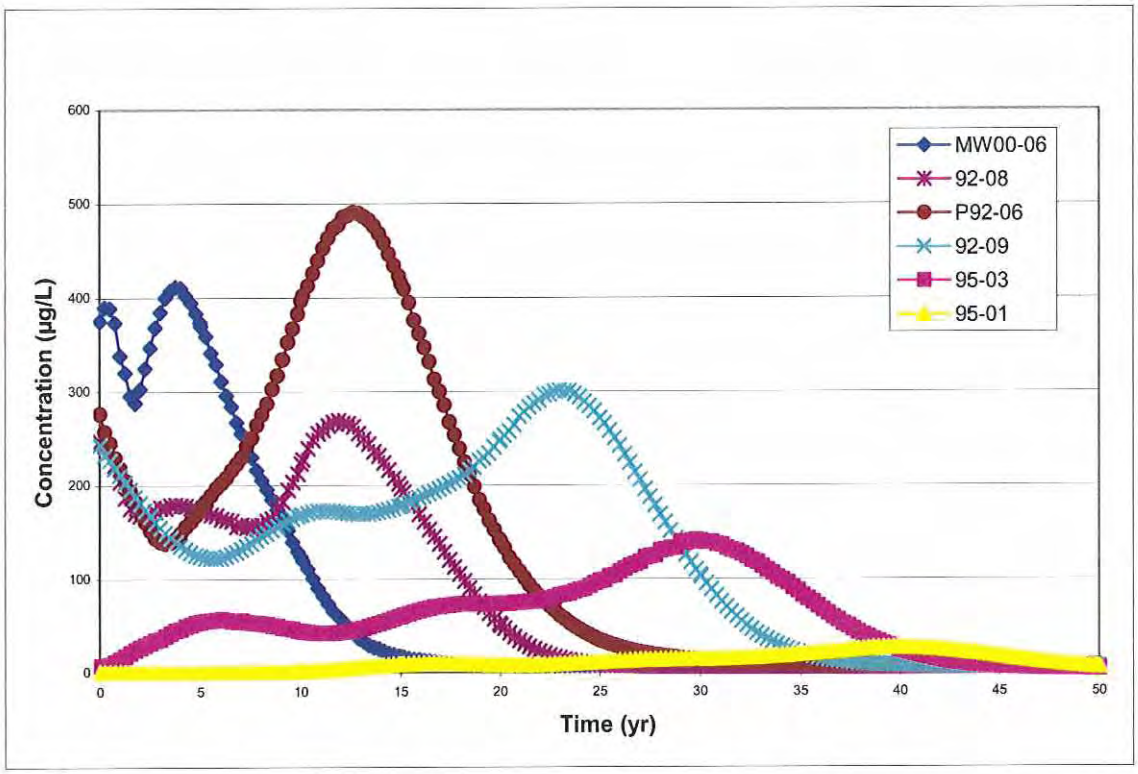


*Figure 3–32. Predicted Concentration vs. Time at OU III Monitor Wells*

*Table 3–6. Transport Model Sensitivity*

| Model Scenario | Years for Aquifer to Flush | Ground Water Capture on Millsite (gpm) | Ground Water Flux from Millsite (gpm) |
|---|---|---|---|
| Baseline model | 42 | 124 | 11 |
| Lower hydraulic conductivity to 0.01 cm/s | 140 | 50 | 3 |
| Decrease distribution coefficient to 1 mL/g | 22.5 | 124 | 11 |
| Increase distribution coefficient to 3 mL/g | 60 | 124 | 11 |
| Increase longitudinal dispersivity to 150 ft | 42 | 124 | 11 |
| Decrease longitudinal dispersivity to 1.5 ft | 45 | 124 | 11 |
| Wet-year model | 42 | 157 | 20.5 |
| Dry-year model | 45 | 25 | 10 |
| Lower Wetland 3 constant head elevation by 0.8 ft | 42 | 125 | 8 |
| No-wetlands model | 42 | 89 | 11.5 |

Reducing the $K_d$ from 2 mL/g to 1 mL/g decreased the flushing period to 22.5 yr (Table 3–6). Increasing the $K_d$ from 2 mL/g to 3 mL/g increased the flushing time to 60 yr. Laboratory-determined $K_d$ values from IRA batch tests, including a correction for percent gravel, ranged from 0.5 to 2.1 mL/g. The baseline model is therefore conservative with respect to this parameter. The mean of the uncorrected $K_d$ measurement was 3.1 mL/g.

Increasing the baseline model value of longitudinal dispersivity by an order of magnitude to 150 ft resulted in no change to the predicted time for uranium concentrations to decrease below 30 µg/L. This model did, however, predict more rapid flushing of the Millsite (8 yr) than was observed with the baseline model. The uranium plume was also predicted to migrate

downgradient of the PRB within 14 to 15 yr. Increasing the dispersivity caused greater spreading of solute along ground water flow paths; as a result, peak concentrations at the locations shown in Figure 3–32 were lower, and the leading and trailing concentrations were greater. Decreasing the dispersivity to a value of 1.5 ft marginally increased the flushing period to 45 yr.

Table 3–6 also includes flushing times for four other steady-state flow scenarios that are described below. These hypothetical scenarios address extended periods of dry and wet years, lowering the elevation of Wetland 3 by 0.8 ft and eliminating wetland head specifications from the model.

**Wet Year Model**

In the wet year model, the amount of ground water entering the Millsite through the north and west model boundaries was initially increased by 40 percent relative to the baseline model. Consistent with flow model sensitivity results discussed in Section 3.6.4, nearly all the added water was captured by the creek and wetlands on the Millsite. Uranium flushing was more rapid on the Millsite than in the baseline model, but no downgradient effect was produced. The simulated elevation of Wetland 3 was then raised 3.5 ft, increasing the flow from the Millsite to about 21 gpm. This latter change also did not cause a net decrease in the flushing period, because all the added water was captured by the creek in the first 1,500 ft east of the Millsite. Consequently, the portion of the plume farther downgradient was unaffected.

**Dry Year Model**

The dry year model was developed by eliminating the GHB on the south side of the Millsite, eliminating the wetland specified head boundaries, lowering the specified head boundary at the western edge of the model by 0.5 ft, and restricting inflow from the northern GHB to 22 gpm as compared to 65 gpm in the baseline flow model. In response to these changes, ground water capture on the Millsite by the drain boundary representing the creek is 25 gpm, and eastward ground water flow from the Millsite is 10 gpm. (Table 3–6). The predicted rate of creek capture is consistent with recent dry-season flow measurements. Removing the wetland head boundaries eliminated the need to specify a concentration boundary at Wetland 3. This did not affect the overall hydrologic and solute mass budgets.

The value of surface recharge on the Millsite was also varied in the dry year model from the value in the baseline model (0.25 inch/yr) to 0.083 inch/yr. This specification is based on the assumption that during drought, surface recharge is, at a minimum, reduced in proportion to other ground water recharge sources. The concentration boundary specification used to represent uranium input from the subpile vadose zone was not changed from the baseline model (1,100 µg/L through the 50-yr simulation).

The dry year flow model was calibrated to ground water levels measured in October 2002. Head residuals were generally less than those of the baseline flow model that was calibrated to October 2001 water levels. As indicated above, the dry year model was also successfully calibrated to measured dry year flows. The predicted water budget for the model region east of the Millsite remained unchanged from the baseline condition.

Results of the dry year model predict that uranium concentrations will decrease to less than 30 µg/L in 45 yr. Inflows from the GHBs on the Millsite are sufficient, at one-third of the inflows from the same boundaries in the baseline model, to dilute uranium from the subpile source to negligible concentrations in ground water and to flush the ambient plume from the Millsite within about 15 yr. Discharge of contaminated ground water to the creek on the Millsite was an important process in this model.

In a variation of the dry year model, the subpile source remained insignificant when GHB inflows were further reduced to 10 gpm. Surface recharge on the Millsite was applied at the same rate as in the baseline model (0.25 inch/yr). Predicted ground water discharge to the creek on the Millsite was 14 gpm, and off-site underflow was 9 gpm. The flushing period for this model was 45 yr.

**Lower Wetland 3 Model**

The baseline model was modified to evaluate the effect of removing a temporary dam of riprap at the east edge of the Millsite that may maintain an artificially high water level in Wetland 3. Removing the dam could possibly lower the creek stage at the outlet of Wetland 3 by 1.5 ft. Fieldwork performed in December 2002 confirmed that a ledge of bedrock forms a broad-crested weir across the outlet of Wetland 3. The elevation of the top of this feature is about 6,800.7 ft, which was approximately 0.5 ft below the surveyed waterline at the time of the fieldwork. Assuming sufficient inflow occurs from the seeps and gallery, removing the dam will lower the water level in Wetland 3 no more than 0.5 ft below its present level and no more than 0.8 ft below the specified Wetland 3 head.

Lowering the surface of Wetland 3 by 0.8 ft in the calibrated flow model had no effect in reducing the predicted flushing period for the uranium plume. Although flow off the Millsite was reduced, with a corresponding reduction in saturated thickness, the flux per unit area of aquifer perpendicular to eastward flow in the aquifer did not change.

**No-Wetlands Model**

The final variation of the baseline model took into account elimination of the head specifications for the wetlands on the Millsite. This was done to determine if ground water exchange at the wetlands (sink and source processes) biased the transport predictions. Inflow through the west underflow boundary (approximately 14 gpm in the baseline model) and GHB were not significantly affected by the removal of the specified heads at the wetlands. Also, predicted capture by the creek on the Millsite remained consistent with the target range for this process, and predicted off-site flow did not change significantly in this model (Table 3–6). The concentration boundary at Wetland 3 was omitted from the transport simulation. The no-wetlands simulation produced results that were similar to those from the baseline model; that is, the aquifer was predicted to attain concentrations less than 30 µg/L at all locations within 42 yr. And, unlike in the baseline model, the remnant area greater than 30 µg/L south of Wetland 3 was predicted to flush. The time required for the plume to move off the Millsite and beyond the PRB was extended slightly to about 16 to 17 yr.

### 3.7.6 Effects of Ground Water Extraction from the Burro Canyon

Recent drought has increased reliance on ground water from the Burro Canyon aquifer for secondary use in Monticello. Pumping rates for 2002 totaled about 270 gpm from nine municipal wells located within or near city limits (Monticello 2003). Continued pumping will lower the potentiometric surface of the Burro Canyon aquifer. At present, the potentiometric surface of the Burro Canyon aquifer is approximately 0.5 and 4 ft above the water table of the alluvial aquifer at monitor wells 95–01 and 95–03, respectively, located in the canyon reach of Montezuma Creek. If drawdown greater than those amounts extends into the canyon reach, ground water discharge from the Burro Canyon aquifer in that region may decrease, thereby possibly reducing dilution of the uranium plume and allowing it to extend farther into the canyon. However, significant discharge of alluvial aquifer ground water to the creek occurs in the reach directly above the Burro Canyon aquifer discharge zone and therefore drawdown in the Burro Canyon aquifer may not totally eliminate the hydrologic boundary effect that prevents further migration of the uranium plume.

A numerical ground water flow model, independent of the OU III baseline alluvial aquifer ground water model, was developed using MODFLOW to estimate transient drawdown in the Burro Canyon aquifer resulting from ground water extraction at the Monticello well field. Results of that model, as shown in Figure 3–33, indicate that drawdown will exceed 2 ft in the canyon between wells 95–01 and 95–03 after about 12.5 yr of constant pumping. Drawdown increases to about 4 ft at 22.5 yr and 7.25 ft at 50 yr. There are insufficient data to calibrate the Burro Canyon aquifer model. Details of the Burro Canyon aquifer ground water model are included in Section E5.0 of Appendix E.

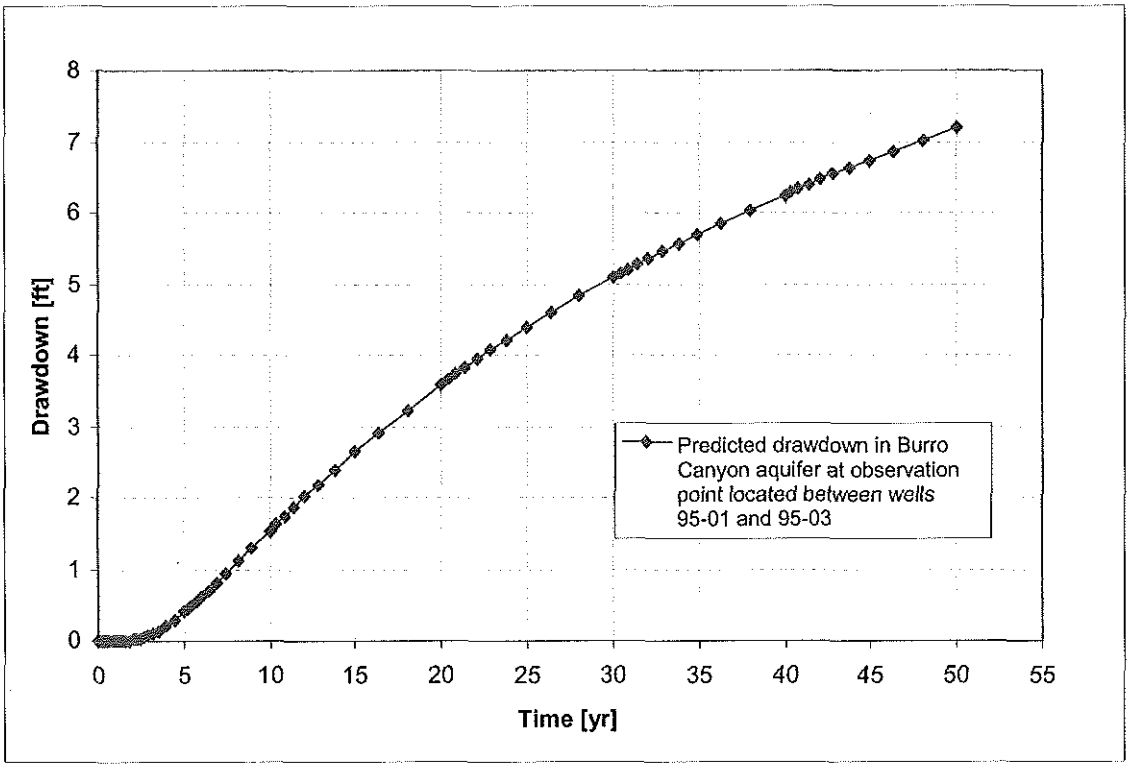


*Figure 3–33. Predicted Drawdown in the Burro Canyon Aquifer at an Observation Point Located Between Wells 95–01 and 95–03*

In the model, a specified head boundary was applied to represent ground water extraction and pumping levels in the Monticello well field. Rates of extraction from this boundary were predicted to decrease logarithmically from the initial rate of 360 gpm to about 75 gpm at 10 yr, and 50 gpm at 40 yr, as the available ground water in storage is depleted. If actual extraction declines at a similar rate, recovery may become inefficient in the near future and the practice discontinued. The initial high rate of simulated extraction (360 gpm) decreased rapidly within 1 yr of pumping in the model as a result of depletion of storage near the well field (see Section E5.0 of Appendix E, Figure A3–5.10).

In this model, ground water flow in the Burro Canyon aquifer under nonpumping conditions is 26 gpm. The specified head boundary on the west side of the model, from which this flow originates, was not intercepted by the well field cone of depression in 50 yr of simulation, and therefore, the boundary condition did not bias the predicted drawdowns. Assumptions in the model that minimized the estimated drawdown include (1) the specified head representing the pumping level in the production wells was about 20 ft above the maximum available drawdown, and (2) a relatively high value for the storage coefficient (0.015) was used in the model.

### 3.7.7 Summary of Transport Model Results

In Section 3.0, the stated objectives of the ground water model for OU III were to predict the time required for uranium concentrations to decrease to less than 30 μg/L in the alluvial aquifer, to predict uranium concentrations in ground water for calculation of risk to human health, and to provide a calibrated model for evaluating remedial alternatives for ground water. Each objective has been achieved as follows:

- The model predicts that uranium concentrations in ground water will decrease to less than 30 μg/L in 42.5 yr from October 2002 (Table 3–6 and Figures 3–28 through 3–31).
- Section 4.1 of this report provides calculation of future risk to human health posed by uranium in ground water. The predicted uranium concentrations that support the risk calculations are shown in Figure 3–32.
- Section 5.0 of this report includes analysis of remedial alternatives for ground water using the calibrated model.

## 3.8 Summary of Ground Water Modeling

This section summarizes the main features and results of the OU III ground water flow model and uranium transport model.

### 3.8.1 Ground Water Flow Model

- The site conceptual model describes west to east ground water flow in the unconsolidated water-table aquifer composed of stream-deposited sand and gravel (alluvial aquifer). The alluvial aquifer occupies the central portion of the valley of Montezuma Creek. The saturated zone is thin (≤8 ft); the aquifer is very narrow in aspect (approximately 15,000 ft in length to about 100 to 500 ft in width). Depth to ground water ranges from about 3 to 30 ft depending on location, but is generally within 15 ft of ground surface.

- Distant sources potentially of cultural origin contribute significant recharge (approximately 100 gpm) to the alluvial aquifer. This water enters the aquifer along its north and southwest boundaries on the former Millsite. Almost all of this water is discharged to Montezuma Creek on the Millsite. Ground water flow from the Millsite and eastward in the most significant area of ground water contamination is about 10 gpm. A similar quantity is thought to enter the Millsite area from the western extension of the alluvial aquifer.

- Beginning about 1 mile east of the Millsite, and occurring over a distance of about 1 mile in the canyon of Montezuma Creek, the alluvial aquifer receives significant recharge (>25 gpm) in the form of upward leakage from the underlying Burro Canyon Fm. sandstone aquifer. The resulting ground water mixture is displaced upward and discharges to Montezuma Creek. Discharge of alluvial ground water to the creek is also promoted at this location by full to near-full penetration to bedrock of the aquifer by Montezuma Creek and because the canyon becomes much narrower, thereby forcing alluvial ground water toward ground surface and ultimate capture by the creek. These boundary conditions prevent contaminant migration beyond this region.

- A numerical model of steady-state ground water flow was constructed using MODFLOW, in which the alluvial aquifer comprised an isotropic and homogeneous single layer. The lateral margins (north and south) and the base of the model were no-flow boundaries to represent low-permeability bedrock that bounds the alluvial aquifer. Model inflow boundaries were assigned to represent the underflow component from the west (constant head boundary) and the recharge received along the north and south margins of the aquifer on the Millsite (general head boundary). Montezuma Creek was represented as a ground water outflow boundary, using drain cells, to simulate the predominant gaining-stream condition observed at the site. Recharge received from the Burro Canyon aquifer was represented as a specified flux boundary in the appropriate reach of Montezuma Creek. No other hydrologic boundaries were specified in the flow model.

- The flow model was calibrated to ground water levels measured at 66 monitor wells in October 2001 and to measured flows of ground water discharge. The flow calibration targets were determined from periodic measurement of steady-state ground water discharge from the alluvial aquifer to dewatering excavations on the Millsite during remedial actions, from pumping test analysis and geochemical mass balance analysis of ground water flux through the PRB, and from measurements of the flow in Montezuma Creek through the narrow canyon reach during times when the reach immediately upstream was dry.

- A single zone of hydraulic conductivity represented the alluvial aquifer in the model. The value resulting in the best calibration to head and flow targets was close to the mean value determined from more than 50 single-well alluvial aquifer slug tests distributed throughout the OU III monitoring network, and was also very consistent with results of the 2 pumping tests conducted in the alluvial aquifer at the site. Flow rates in the calibrated model are as indicated above for the respective boundary. The calibrated flow rate through the PRB was 5 gpm. Ground water underflow at the downgradient (east) limit of the model (no boundary specification) was about 8 gpm.

- Flow model calibration was also evaluated by comparing recent trends in uranium concentrations in ground water at selected monitor wells to transport model predicted trends.

### 3.8.2 Uranium Transport Model

- Transport of uranium in the alluvial aquifer was simulated using the computer program MT3D96. This program is designed for use in conjunction with the output of a MODFLOW ground water model. Uranium was selected for transport modeling because its contribution to potential future risk to human health far exceeds that of the remaining site COCs. The geochemical behavior of uranium is relatively well understood, and much of the IRA data collection activity was directed at further evaluating and characterizing uranium distribution and mobility in the vadose zone and aquifer at the site.

- Initial concentrations of uranium in ground water were specified in the model as measured in October 2002. Transport was simulated for 50 yr following October 2002. The PRB was assumed to have no effect in immobilizing uranium in the model.

- Remnant subpile soil was represented in the model as a source of uranium contamination to ground water. A single value of uranium concentration, determined as the average among peak concentrations eluted from subpile soils in column leach tests, represented this source contribution to ground water. The rate at which the subpile source water entered the aquifer was specified on the basis of infiltration research conducted at the Monticello field lysimetry station.

- The geochemical behavior of uranium during transport was represented by linear, equilibrium-controlled (rapid and reversible) sorption. The $K_d$, was quantified for uranium in the alluvial aquifer in a series of laboratory batch tests. The value specified in the model (2 mL/g) was the highest among the test results, accounting for the nonsorbing gravel fraction of the substrate. For reversible sorption, higher $K_d$ values imply greater aquifer restoration periods by natural attenuation because proportionally greater quantities of the contaminant are available to desorb from the substrate into the ground water, thus maintaining elevated concentrations.

- Transport model calibration by history matching was not possible because of the recent, major changes to the ground water system and distribution of contaminants in soil and ground water at the site. Model calibration was instead qualitatively evaluated by comparing the relative success in predicting the continuation of observed trends at strategic monitoring wells since completion of Millsite remediation.

- The transport model predicts that uranium concentrations will decrease to less than 30 µg/L throughout the study area in 42 yr, beginning October 2002. The uranium plume of concentrations greater than 30 µg/L is not predicted to extend beyond its present extent because of dilution caused by simulated discharge of the Burro Canyon Fm. aquifer, and by solute capture at the drain boundary representing Montezuma Creek, in the canyon reach of Montezuma Creek.

- The transport model predicts that uranium concentrations will decrease to less than 30 µg/L in ground water west of the PRB in about 13 yr.

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