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Washington, DC 20585

April 22, 2014

U.S. Nuclear Regulatory Commission
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Decommissioning and Uranium Recovery Licensing Directorate
Division of Waste Management and Environmental Protection
Office of Federal and State Materials and Environmental Management Programs
U.S. Nuclear Regulatory Commission
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Washington, DC 20555-0001

Subject: Draft Groundwater Modeling Work Plan for the Tuba City, Arizona, Disposal Site March 2014

To Whom it May Concern:

Enclosed is the draft plan for a revised approach to the groundwater and geochemical modeling effort at the Tuba City, Arizona, Disposal Site. In brief, it is to support a previous effort to delineate the contaminant plume and any future migration away from the Tuba City mill site. Although the treatment system is effectively removing contaminants including uranium from the groundwater at the site, little change in groundwater concentrations have been observed after 9 years, primarily because groundwater extraction is problematic. The purpose of the revised modeling effort is to address the following issues: 1) plume locations; 2) plume movement; 3) potential risk to human health and the environment; 4) identify improvements for contaminant removal. A number of options to extraction will be examined, including the current approach to extraction, no extraction, and an intermediate level of groundwater extraction.

We welcome all comments, questions, criticisms, other possible scenarios or ideas offered in order to improve the work to be done. Our goal is to answer questions that may arise, and use this model information to propose a revision to the Groundwater Compliance Action Plan that better addresses actual site conditions.

Comments would be most helpful in making changes to the work plan if received by May 14, 2014. However, the plan and work will be an interactive process, and as we learn more from the modeling effort, there may need to be changes.

In addition, one or more presentations of this effort may be made at the next Navajo/Hopi Quarterly Meeting, planned for June 25, 2014. We encourage participation of all interested parties.

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FSME

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Sincerely,

Richard P. Bush
UMTRCA Program Manager

Enclosure

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Sites\Tuba City\4-16-14 Tuba City GW and Geochemical Modeling Plan (NRC)

LMS/TUB/S11469

Draft Groundwater Modeling Work Plan for the Tuba City, Arizona, Disposal Site

March 2014

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Draft
Groundwater Modeling Work Plan for the Tuba City, Arizona, Disposal Site

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Abbreviations

a	dispersivity
DOE	U.S. Department of Energy
ft	feet (foot)
gpm	gallons per minute
K_d	distribution coefficient
LM	Office of Legacy Management
mg/L	milligrams per liter

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1.0 Introduction

This plan describes the approach to numerically model groundwater flow in the Navajo Sandstone aquifer that underlies the U.S. Department of Energy (DOE) Office of Legacy Management (LM) Tuba City, Arizona, Disposal Site (Figure 1) located near Tuba City).

The primary objectives of groundwater modeling are to predict groundwater and contaminant capture under scenarios of (1) current pump-and-treat remediation scope, (2) reduced scope of pump-and-treat remediation, and (3) no pump-and-treat or other form of active remediation.

A phased approach will be implemented to include

- data evaluation to provide initial estimates of model input parameter values,
- construction and calibration of a groundwater flow model, and
- construction and calibration of a contaminant transport model.

This approach, using current advances in modeling methods, will allow (1) analysis of groundwater capture and plume control, (2) predicting aquifer restoration times, and (3) predicting uranium concentrations in groundwater over time, including at potential exposure points at Moenkopi Wash.

1.1 Modeling Schedule

The expected time to complete each phase is 1 to 2 months. LM will be apprised of the modeling progress throughout each phase through regular status meetings and periodic presentations upon completion of significant tasks.

1.2 Background Information

A uranium-ore processing mill was operated at the site from 1956 to 1966. Mill tailings were impounded at a single location (tailings pile) on the site. Process water was stored in unlined retention ponds along the south edge of the tailings pile during mill operation. Remedial actions to consolidate and encapsulate site-derived solid waste in an onsite disposal cell were completed by DOE between 1988 and 1990.

Groundwater in the underlying aquifer became contaminated as a result of waste disposal at the mill. Site-related contamination in groundwater extends approximately 1,500 feet (ft) south and southeast of the former mill. The affected groundwater occurs in the regionally extensive Navajo Sandstone aquifer. The history of mill operation and solid waste encapsulation accounts for about 30 years of plume development prior to waste isolation and about 12 years since waste isolation to the start of active remediation in 2002.

The primary contaminants in groundwater, applicable to the entire site, are nitrate, sulfate, and uranium. Remediation goals are 44 milligrams per liter (mg/L) for nitrate, 250 mg/L for sulfate, and 30 picocuries per liter for uranium (equivalent to approximately 0.044 mg/L).

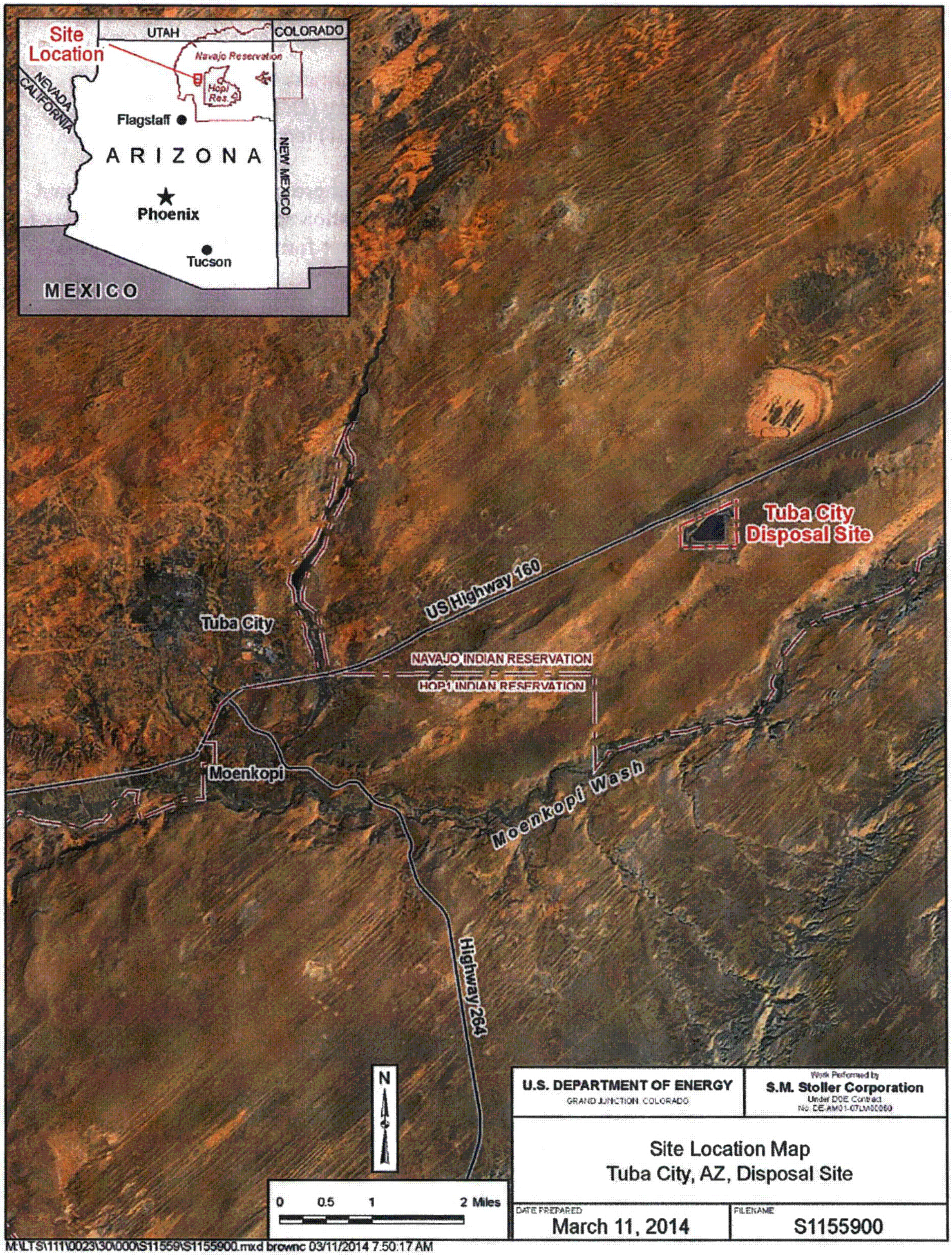

Figure 1. Tuba City Site Location Map

Figure 2 illustrates prominent site features, well locations, and the approximate lateral extent of groundwater contamination by uranium. The depth of groundwater contamination is limited to about the upper 100 ft of the aquifer. Plume geometries are similar for nitrate, sulfate, and uranium. The former evaporation ponds that stored mill process water were located within the southern boundary of the site boundary identified in the figure.

Groundwater remediation by pump-and-treat technology became fully operational by mid-2002. The remediation system was designed and implemented to capture the bulk of the contaminant plume; however, concentrations have leveled-off well above remediation goals and so a prolonged restoration period that exceeds initial expectations appears likely.

Comprehensive analysis of site characterization findings is documented in the *Final Site Observational Work Plan for the UMTRA Project Site Near Tuba City, Arizona* (DOE 1998). That document provides the technical rationale for selecting pump-and-treat remediation as the groundwater compliance strategy as documented in *Phase I Ground Water Compliance Action Plan for the Tuba City, Arizona, UMTRA, Site* (DOE 1999). Remediation progress is reported to LM and stakeholders annually.

1.2.1 Groundwater Remediation System

The groundwater remediation system comprises 37 extraction wells located in the contaminated region of the aquifer. Extracted water is conveyed to an onsite facility for treatment by distillation. Distillation products are distillate (uncontaminated water) and brine (the waste stream of concentrated water containing the contaminants). Approximately 90 percent of the extracted water is returned to the aquifer as distillate in an infiltration trench located upgradient of the contaminant plume. The brine (approximately 10 percent of the extracted water) is placed in a lined solar evaporation pond.

The operating capacity of the treatment system is about 120 gallons per minute (gpm). This capacity is generally limited to about 85 to 100 gpm by aquifer yield. Steady state drawdown in the aquifer is not yet achieved, indicating that water continues to be removed from storage in the extraction well capture zone and that yield may continue to decline.

Thorough description of the remediation system, including well completion information, is provided in annual groundwater reports (for example, DOE 2013a). The annual reports also provide detailed analysis of groundwater and contaminant capture, water level response to pumping, remedial action history, and contaminant concentration trend analysis.

1.2.1.1 Operational History of the Groundwater Remediation System

The remediation system became fully operational by mid-2002. Extraction rates of between about 85 and 100 gpm were sustained until October 2010, when the system was shut down for repairs through September 2011. The system has operated intermittently since that time.

1.2.2 Groundwater Restoration Progress

Analysis of concentration trending indicates a general absence of sitewide decreases toward achieving restoration goals within 100 years (a goal of the compliance strategy) under the current remedial action (see DOE 2013a for analysis of concentration trending). Examples of uranium concentrations observed over time at extraction wells located in the bulk of the uranium plume south and east of the disposal cell are provided in Figure 3 and Figure 4, respectively. These figures indicate concentrations are not decreasing at extraction wells located in the core of the plume (Figure 3) and in peripheral locations (Figure 4).

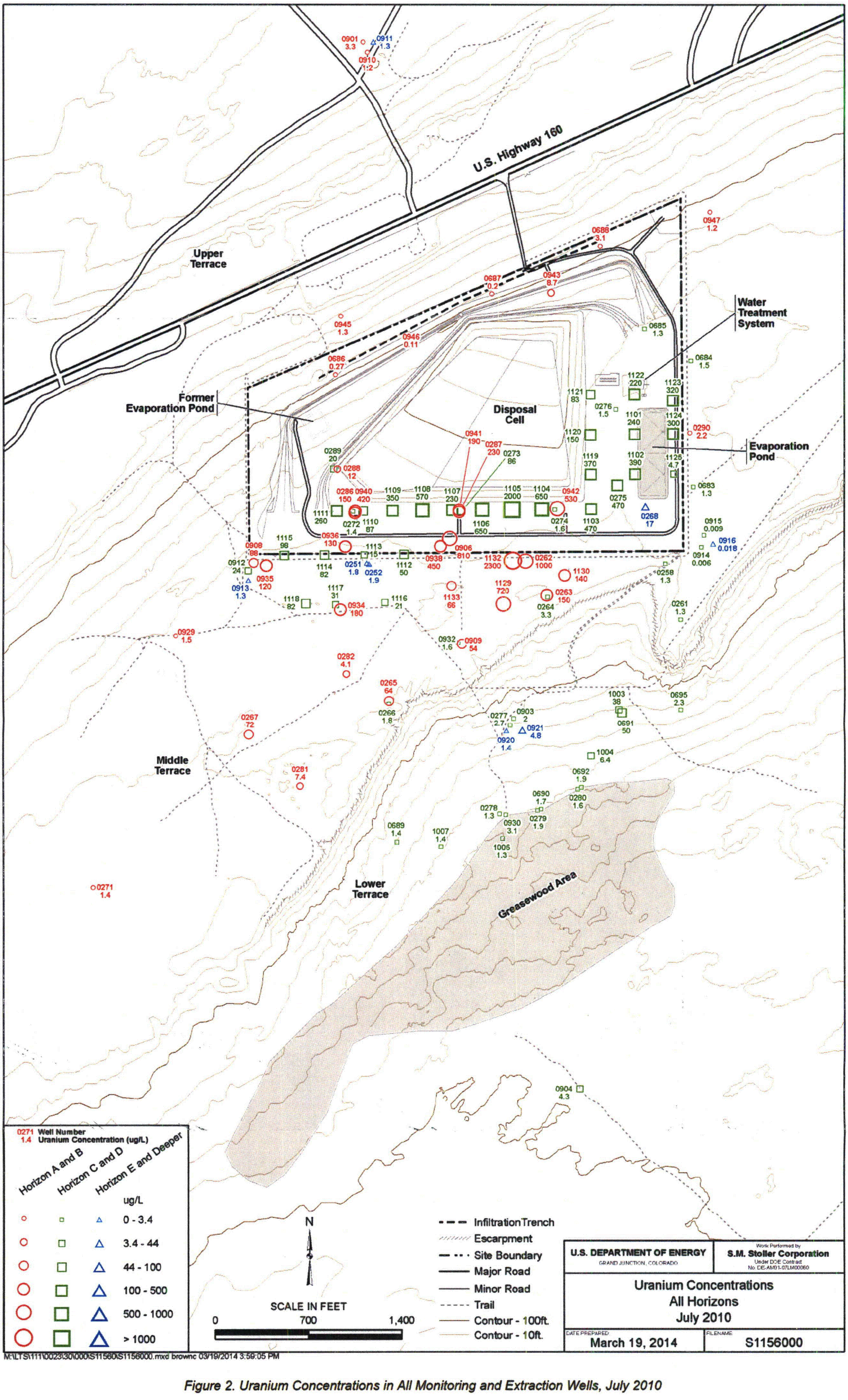

Figure 2. Uranium Concentrations in All Monitoring and Extraction Wells, July 2010

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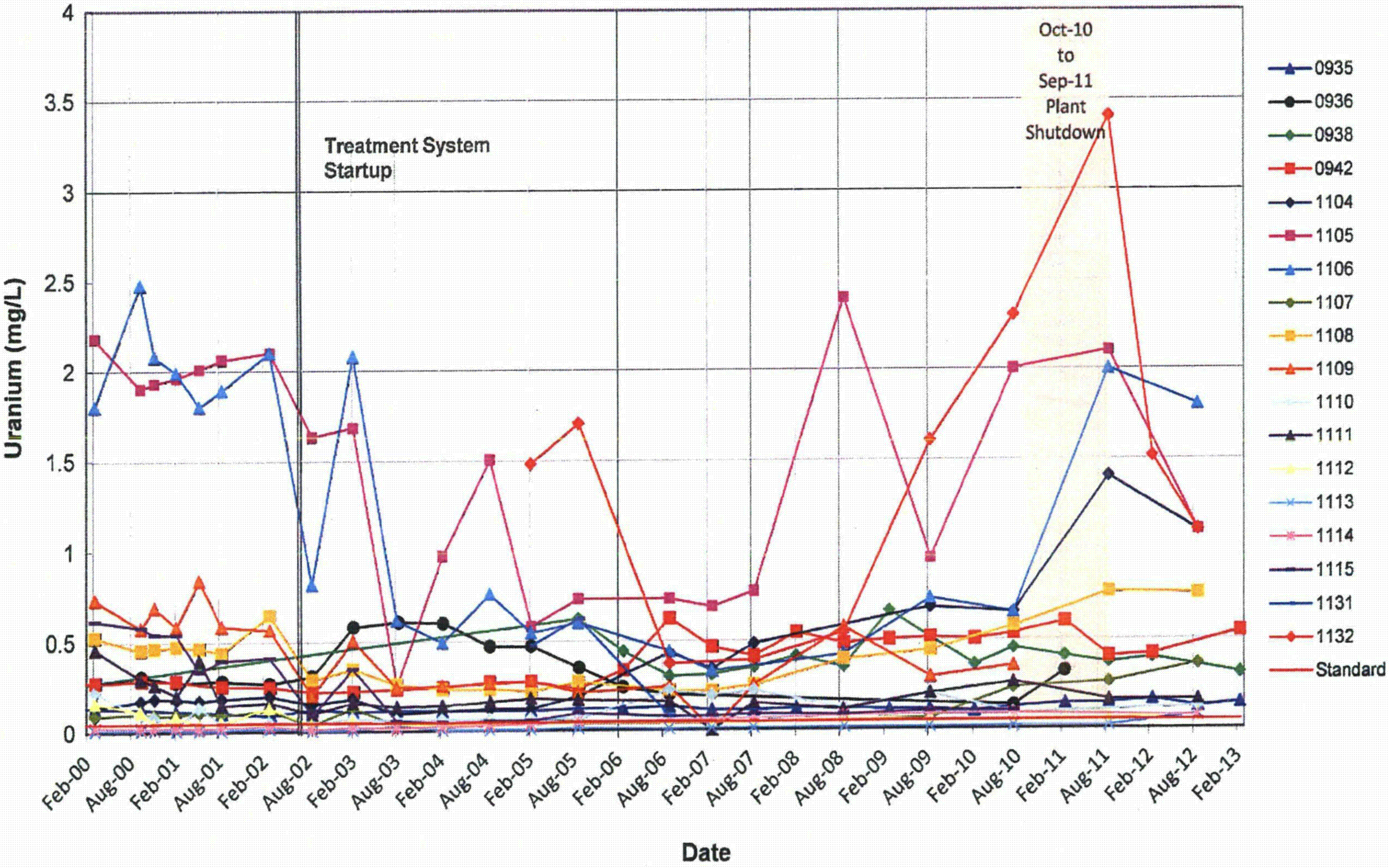

Figure 3. Uranium Concentration Trends at Extraction Wells 935–936, 938, 942, 1104–1115, 1131–1132 (South of Disposal Cell at or Within Site Boundary)

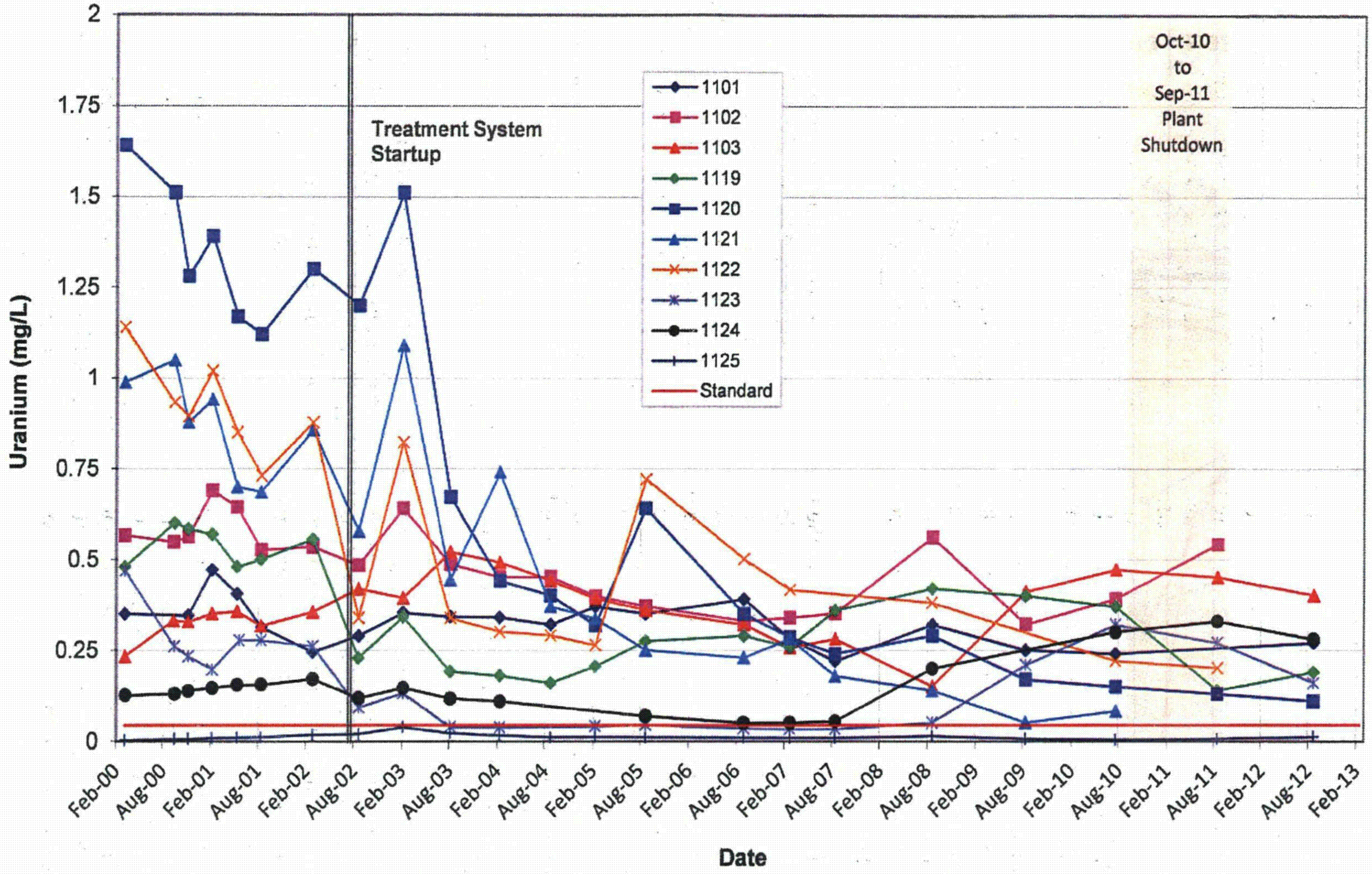

Figure 4. Uranium Concentration Trends at Extraction Wells 1101–1103, 1119–1125 (East of Disposal Cell)

2.0 Hydrogeologic Setting

2.1 Geology

The Tuba City site lies on the middle of three alluvial terraces formed during ancestral flow in Moenkopi Wash, which is located about 1.25 miles southeast of the site. The terraces, referred to as the upper, middle, and lower terraces, are capped by thin ($\leq$20 ft) deposits of coarse, indurated Quaternary alluvium (terrace gravels). Loose dune sand mantles the terraces at most locations. The terrace gravels and dune sands are unconformable over the regionally extensive Navajo Sandstone Formation, which is a massively cross-bedded, friable, fine-grained sandstone and siltstone of Jurassic age. Structurally, the site is located on the western limb of the northwest-trending Tuba City syncline. Regional dip of the bedrock is about 1 degree to the northeast. Prominent folding, faulting, jointing, and deformation is not evident.

Outcroppings of the Navajo Sandstone form escarpments that separate the three terraces. The terraces are capped by resistant beds of terrace alluvium or of thin limestone beds in the Navajo Sandstone. Figure 5 is a photograph that is viewed southwest to northeast showing the transition between the middle terrace (left on the horizon) and the lower terrace (right foreground). Vegetation profiles and field reconnaissance provide no evidence of shallow groundwater or groundwater seepage in this transition zone.

Figure 6 shows the prominent cliff face where the lower terrace is intersected by Moenkopi Wash. Also evident in this photograph is the scale of surface water flow in Moenkopi Wash (photograph taken on February 25, 2014). The width of the creek is about 15 to 20 ft, and the water depth is less than 1 ft. In this figure, groundwater discharge is apparent near the base of the cliff where sandstone coloration abruptly changes from red to white along a planar bedding feature. This discharge occurs at the upper surface of a thin (<3 ft thick) limestone layer that is observed in outcrop to extend along the wash for about 1 mile in this area of the site.

The limestone beds are remnants of inter-dune playa lakes, and are interspersed throughout both the classic and transition intervals. These beds are laterally continuous over 1 to 2 miles in outcrops along Moenkopi Wash, and are observed to pinch-out at some locations. These observations suggest that the limestone beds may extend laterally to the west beneath the plume and disposal cell.

One such limestone bed outcrops near the top of the transitional escarpment between the middle and lower terrace. This limestone bed (depicted stratigraphically in Figure 8) is much shallower than the limestone bed shown in Figure 6 at Moenkopi Wash and may be of particular relevance as a possible vertical barrier to groundwater flow and contaminant transport in the plume area. Core samples obtained during early site characterization activities will be re-examined to evaluate lateral continuity of this layer.

At about 200 ft below ground, the massive dune deposits typifying "classic" Navajo Sandstone become interbedded with fine-grained alluvium more typical of the deeper Kayenta Formation. This transition interval (also referred to as the intertonguing interval or the Kayenta-Navajo Transition Zone [KNTZ] by other authors) is approximately 400 ft thick. The true Kayenta Formation consists primarily of 100 ft or more of thin, horizontal-bedded red silt and fine sand and lacks the characteristic dune deposit cross-beds of the Navajo Sandstone.

Figure 5. Transition Between Middle Terrace and Lower Terrace

Figure 6. Moenkopi Wash, Viewed to the Northeast

2.2 Groundwater Occurrence

Groundwater occurs in the regionally extensive "N" multiple-aquifer (Cooley et al. 1969), which in the site area comprises the classic and transition (or KNTZ) intervals of the Navajo Sandstone. Because of its fine-grained composition, the Kayenta Formation is locally non-water bearing and considered to be the base of the N-aquifer in this area.

The local water table occurs within the Navajo Sandstone: the terrace and dune deposits in the site area are not saturated. Groundwater saturation extends from the water table, which is about 50 to 60 ft below ground surface on the middle terrace, to the contact with the Kayenta Formation, accounting for a saturated thickness on the order of 400 to 500 ft.

Except for local effects induced by groundwater withdrawal at the site, groundwater flow is to the south and south-southeast toward Moenkopi Wash, a prominent drainage that formed during humid times in the recent geologic past. Regional aquifer discharge is expressed at the wash as a laterally extensive (miles) spring zone at multiple intervals near the exposed base of the KNTZ interval. Groundwater is observed to discharge along distinct planar features at the base of major cross-bed sets and at the upper surface of limestone beds. Seepage is not evident from the broad cliff faces.

Groundwater discharge from higher in the formation likely occurs by way of plant transpiration by desert phreatophytes in the greasewood area noted in Figure 8. In this area, the depth to groundwater is about 20 ft below ground surface, which is the shallowest occurrence of groundwater at the site except possibly in the alluvium within Moenkopi Wash.

The types of vegetation comprising the greasewood area are unable to root into bedrock; therefore, the shallow groundwater probably occurs within decomposed bedrock or at the base of the loose dune sand. Core sample information indicates the presence of a shallow limestone bed in this area, which if present, could direct groundwater to flow laterally to support the desert phreatophytes comprising the greasewood area. The core samples, obtained during early site characterization activities, will be reexamined for the presence of a limestone bed in this area.

2.3 Climate

The site is at an elevation of approximately 5,100 ft above sea level. The elevation of Moenkopi Wash is about 4,750 ft. Precipitation in the Tuba City area is approximately 7 inches per year (Lopes 1997). June is the driest month and September is the wettest. Air temperature varies between average highs of 95 degrees Fahrenheit in July to about 47 degrees Fahrenheit in December. The regional area is considered as arid to semi-arid.

2.4 Vegetation

Vegetation varies between the disposal cell and Moenkopi Wash. Some of the variability is related to the depth to groundwater. Several plant species in this area, classified as desert phreatophytes, are capable of directly consuming groundwater. Other desert plants in this area cannot root close enough to the water table and so survive on precipitation. Although not directly consuming groundwater, these plants may affect the site water balance by limiting infiltration recharge to the aquifer.

Two desert phreatophytes, the black greasewood and the fourwing saltbush, grow in the 75-acre strip that comprises the greasewood area (Figure 8). Black greasewood is an obligate phreatophyte, meaning that roots usually tap into groundwater. Fourwing saltbush is a facultative species, meaning roots often tap into groundwater but the plants can survive without groundwater. Maximum rooting depths for these species are on the order of 40 ft.

Two riparian phreatophytes, tamarisk and cottonwood, grow in the seep zone and along the creek banks of Moenkopi Wash. Tamarisk is a small, invasive tree from Eurasia. Cottonwood is a large native tree. Vegetation on the middle terrace between the greasewood area and the lower terrace do not consume groundwater. The dominant plants in this area are snakeweed, Mormon tea, rabbitbrush, yucca, galleta grass, and Indian ricegrass.

Vegetation on the middle and lower terraces is in poor health because of a history of excessive livestock grazing and recent drought. Over-grazing could limit the amount of groundwater discharge by the desert phreatophytes but drought conditions may offset the available water from recharge precipitation.

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3.0 Conceptual Model of Groundwater Flow

The site conceptual model describes geologic and hydrologic features that affect the occurrence and movement of groundwater in the subsurface environment. These basic features are depicted in Figure 7 as a block diagram. Figure 8 is a cross-sectional depiction of the hydrogeologic system, parallel to the direction of groundwater flow (south to south-southeast), with added detail on groundwater inflow and outflow boundaries. In Figure 8, letter designations on the left side of the figure refer to a site-specific convention to identify depth intervals of the aquifer. This convention was adopted in previous site investigations as a vertical reference frame because continuous marker beds are absent. The following sections describe individual flow components depicted in these figures.

3.1 Groundwater Inflow

There are two possible natural recharge sources to the aquifer in the site area: (1) recharge from precipitation, and (2) through-flow in the aquifer from the north. There are no surface water features as recharge sources, nor are geographic highlands or humid settings present as recharge sources.

3.1.1 Recharge from Precipitation

The arid to semi-arid setting of the site suggests that precipitation recharge may be a small component of the water budget. However, it is necessary to represent this potential source of aquifer recharge in the groundwater flow model. The majority of recharge by precipitation is expected to occur in late fall when average annual temperatures decline, plant growth is less vigorous, and precipitation increases.

3.1.2 Groundwater Through-Flow

A primary component of groundwater flow beneath the site is through-flow in the aquifer from upgradient of the site. The Navajo Sandstone aquifer is not thought to be recharged from overlying or underlying water-bearing units. Darcy's Law (Q=KiA) will be applied to estimate a range of groundwater inflow for the site water budget. Inputs to Darcy's Law include site hydraulic conductivity (K), horizontal hydraulic gradient (i), and the width and saturated thickness of the aquifer (A).

3.2 Groundwater Outflow

3.2.1 Discharge at Moenkopi Wash

Moenkopi Wash is a regional boundary for discharge of the N-aquifer because it fully or nearly fully penetrates the aquifer. This implies that all water in the aquifer discharges at the wash and that no water flows beneath the wash. Field observations indicate that groundwater discharge is from discrete, planar beds that underlie large cross-bed sets rather than from expansive areas of the cliff faces. Seepage along the wash also occurs immediately above a limestone bed that outcrops in the cliff along much of the downgradient limit of the model domain.

The U.S. Geological Survey maintains a flow gaging station at Moenkopi Wash near the Village of Moenkopi about 5 miles downstream of the site. Flow measurement data from that station, in conjunction with estimated plant transpiration in the wash will be included in the site water budget.

3.2.2 Plant Transpiration

Uptake of groundwater by desert phreatophytes that comprise the greasewood area may locally induce upward groundwater flow. This effect is not thought to be of regional significance or to extend deep into the aquifer. Groundwater uptake by plants may have a potential future effect on plume movement; however, contamination has not yet reached the greasewood area and contaminant concentrations on the lower terrace upgradient of the greasewood area are declining (note that in Figures 2, 7, and 8, the greasewood area is on the lower terrace). In other areas of the site, groundwater is too deep to support desert phreatophytes except at Moenkopi Wash.

Estimated plant transpiration of groundwater at the site was first documented in the *Final Site Observational Work Plan for the UMTRA Project Site near Tuba City, Arizona* (DOE 1998). Ongoing investigations by LM will contribute to improved knowledge of plant transpiration and precipitation recharge at the site based on (1) characterizing current vegetation overlying the plume flow path and (2) applying recent LM advancements in estimating groundwater transpiration at the former Monument Valley, Arizona, Processing Site (DOE 2013b).

Groundwater discharge and recharge along the groundwater flow path between the former processing site and Moenkopi Wash will be estimated for the current vegetation and for possible future conditions that will incorporate plausible changes in grazing management and climate.

The conceptual approach to evaluate plant transpiration has four steps:

1. Characterize and map vegetation along the groundwater plume flow path between the disposal site and Moenkopi Wash.
2. Estimate the current fractional cover of desert phreatophyte populations potentially rooted in groundwater along the plume flow path.
3. Use the relationship between fractional cover and transpiration flux, as established by LM for the same plant species at the Monument Valley site, to estimate groundwater transpiration (discharge) for the current and potential future health of phreatophyte populations.
4. Use existing remote sensing tools to interpret and map groundwater discharge and recharge zones on a broader landscape scale in the vicinity of the Tuba City site.

3.2.3 Phreatic Evaporation

Evaporation from the phreatic surface is assumed to be insignificant. This is because the water table is too deep (greater than 30 ft within bedrock, except as noted in the greasewood area). Phreatic evaporation, and subsequent vapor transport to the atmosphere, is therefore not likely to represent significant groundwater outflow.

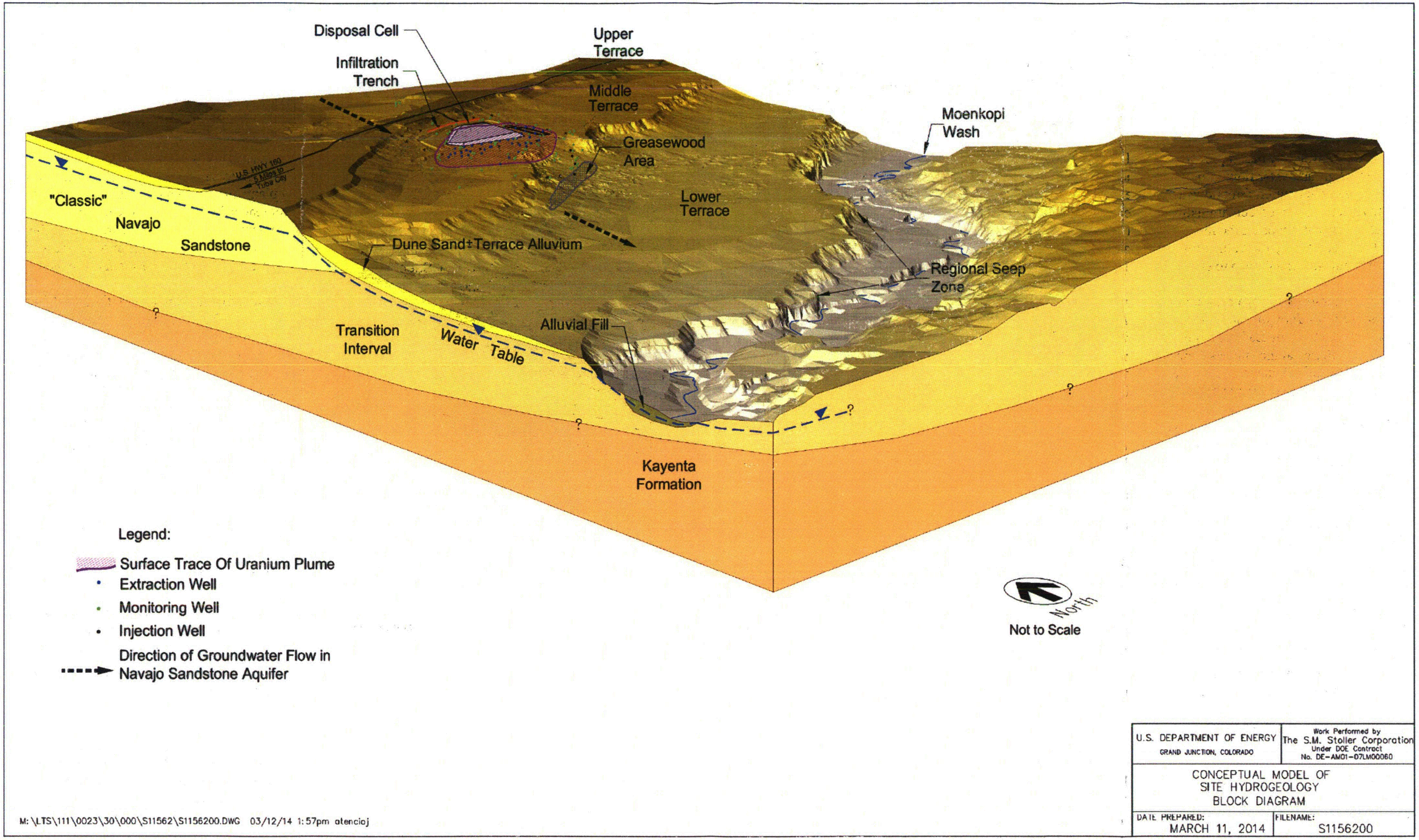

Figure 7. Conceptual Model of Groundwater Flow – Block Diagram

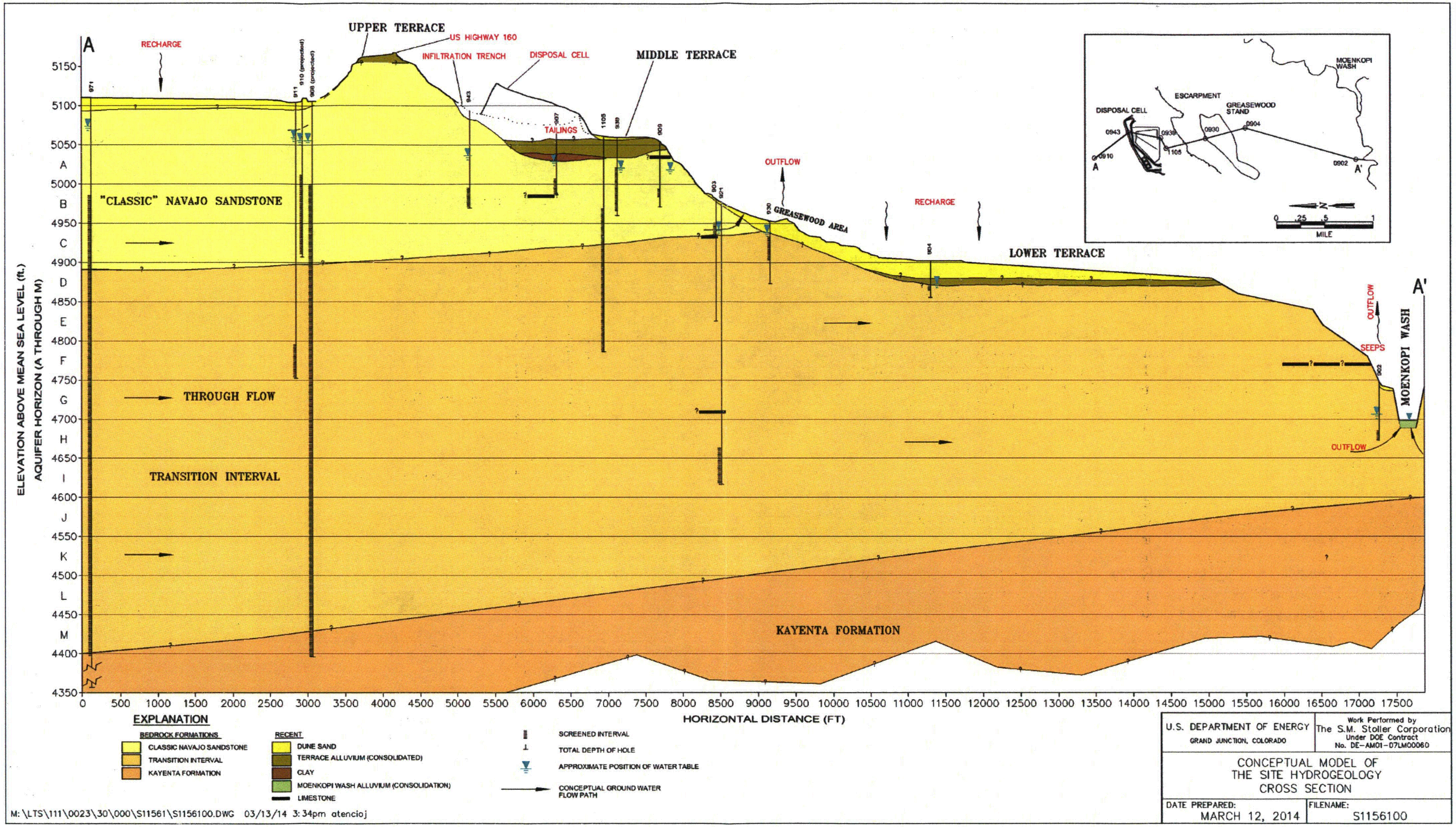

Figure 8. Conceptual Model of Groundwater Flow – Cross Section

3.2.4 Extraction and Infiltration by the Remediation System

Groundwater extraction by the remediation system represents a local hydrologic sink at a sustained rate of approximately 85 to 100 gpm. Approximately 90 percent of the treated water is returned to the aquifer at the infiltration trench; the balance (brine) is placed in the evaporation pond, where it is isolated from the groundwater system. Extraction (outflow) and infiltration of the distillate (inflow) by the remediation system therefore represents a net outflow condition.

3.2.5 Vertical Hydraulic Gradients

Site characterization activities identified the presence of significant vertical flow gradients during pre-pumping baseline conditions. These gradients were predominantly downward through the monitored thickness of the aquifer, and may be influenced by (1) greater horizontal hydraulic conductivity at depth in the sandstone deposits, (2) low-permeability limestone beds interspersed in the sandstone deposits, or (3) a low-permeability resulting from the plume-derived mineral precipitation.

Drill log and outcrop observation does not identify lithologic contrasts in the sandstone that would identify more conductive zones at depth. The presence of locally continuous and dense limestone beds may be a more plausible explanation for the observed vertical flow gradients. Available core samples will be re-examined to evaluate bedrock lithology. The presence of plume-derived mineral precipitates has not been investigated.

3.3 Water Budget

Model development will include an estimate of the water budget for the model domain. The water budget will provide estimated ranges of inflow and outflow quantities at the recognized hydrologic boundaries. A site water budget ensures that all inflow and outflow boundaries are accounted for and that a reasonable balance of inflows and outflows is achieved in the conceptual and numerical models. The water budget provided in *Final Site Observational Work Plan for the UMTRA Project Site near Tuba City, Arizona* (DOE 1998) will provide a basis for water balance estimates for the groundwater model.

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4.0 Groundwater Flow Modeling

This section describes the methodology to develop a numerical model of groundwater flow based on the conditions of the conceptual model. Groundwater flow modeling will use MODFLOW 2005 (Harbaugh 2005), a public domain code for simulating groundwater flow in porous media. MODFLOW can accommodate the various boundary conditions, aquifer properties, and transient stresses recognized at the site.

4.1 Model Domain and Grid

The domain of the groundwater model will be approximately 12,000 ft wide (east to west) by 23,000 ft long and centered on the disposal cell. The domain is oriented orthogonally north to south to approximately parallel the direction of groundwater flow. Figure 9 shows the model domain in map view in relation to site location.

The upgradient limit of the domain (an inflow boundary) should be beyond the influence of site remediation activities. The downgradient extent of the domain encompasses the aquifer discharge boundary along Moenkopi Wash. Lateral boundaries of the model domain (no-flow boundaries) should be of sufficient distance from the site to ensure that the no-flow condition is not influenced by site activities. Boundary distances will be adjusted to ensure that there are no influences from pumping or injection at the prescribed boundaries.

4.1.1 Horizontal Discretization

Grid spacing is expected to be 25 ft × 25 ft or 50 ft × 50 ft in the area of the present uranium plume where concentration and water level gradients are steepest. Extraction and monitoring wells in this area are separated by at least 50 to 100 ft. Coarser grid spacing may be assigned to more distal areas of the domain where less resolution is required; however, refining the horizontal grid spacing may be required if excessive numerical dispersion is apparent in the contaminant transport simulations.

4.1.2 Vertical Discretization

The model will be discretized vertically into multiple layers through the entire saturated thickness of the Navajo Sandstone aquifer. The base of the model is assumed to coincide with the top of the Kayenta Formation. Vertical discretization will initially specify a layer thickness of 25 ft for the upper 200 ft of the aquifer. Consideration will be given to implicitly represent the thin, low permeability limestone beds as individual model layers if these layers show to be continuous beneath the site.

The remaining model layers will be 50 ft thick as an initial specification. Grid spacing is designed such that vertical flow gradients and the vertical extent of contamination can be accurately resolved. Refining the vertical grid spacing may be required if excessive numerical dispersion is apparent in the contaminant transport simulations.

4.2 Inflow Boundaries

4.2.1 Groundwater Through-Flow

The northern boundary of the model (inflow, or through-flow boundary) will be specified in MODFLOW as either a constant head or a general head condition. Use of a general head condition allows not only an elevation specification of the inflow boundary but also the ability to adjust the rate of groundwater inflow to the model through the conductance term.

4.2.2 Precipitation Recharge

Recharge by precipitation will be assigned using the recharge package in MODFLOW. Precipitation recharge is assumed to be temporally and spatially homogeneous throughout the model domain. Separate zones of zero recharge may be assigned to the disposal cell and the evaporation pond. Model calibration may require a separate recharge zone to represent precipitation runoff from the disposal cell. Runoff may have a local recharge effect along the southern edge of the disposal cell.

4.2.3 Infiltration Trench

The infiltration trench can be represented in MODFLOW as a recharge boundary. This boundary condition can simulate recharge to the aquifer from the trench using trench dimensions with temporal variations from process data. Current process information indicates that approximately 90 percent of the extracted water is placed in the infiltration trench to recharge the aquifer.

4.2.4 Surface Water Sources

Surface water bodies (streams, rivers, lakes) that could affect groundwater flow in the model domain are absent. Therefore, no boundary specifications are applicable for surface water features. In addition, the site area is not irrigated, so surface-applied recharge by this source is not applicable.

4.2.4.1 Evaporation Pond

Water contained in the evaporation pond is assumed to be isolated from and unavailable as groundwater recharge. Although the area of the evaporation pond is small relative to the model domain, it may be represented as a zone of zero recharge.

4.3 Outflow Boundaries

4.3.1 Groundwater Extraction Wells

Groundwater extraction from the aquifer by the groundwater extraction wells will be simulated using the MODFLOW well package. This allows groundwater extraction to occur from discrete depth intervals of the wells and at prescribed extraction rates that can vary over time.

Figure 9. Model Domain

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4.3.2 Aquifer Discharge at Moenkopi Wash

Groundwater discharge at Moenkopi Wash and the cliff-face seepage along the wash will be assigned using the MODFLOW drain package. Drain cells only allow water to exit the model domain. The quantity of water that is discharged from a drain cell is a function of the elevation of the drain cell and the conductance term, which regulates the resistance to flow into the cell. The drain conductance will be adjusted during model calibration to match the expected groundwater discharge to the wash.

4.3.3 Plant Transpiration

Removal of groundwater by plant transpiration will be specific to the greasewood area and to the riparian zone in Moenkopi Wash. Water removal by plant transpiration will be simulated either by (1) a zone of negative recharge or (2) applying the evapotranspiration package in MODFLOW. Use of the evapotranspiration package may be advantageous because it allows temporal variability in removing groundwater as a function of the water table position whereas the recharge option is independent of water table position.

4.4 Aquifer Properties

4.4.1 Hydraulic Conductivity

Results of aquifer pumping tests completed during site characterization indicate a range in hydraulic conductivity of between less than 1 ft/day to about 10 ft/day (DOE 1998). Weiss (1987) reports values between about 1 and 2 ft/day. Chandler et al. (1989) reports values ranging over four orders of magnitude (0.002 ft/day to 30 ft/day) based on field permeameter tests conducted under unsaturated conditions across and along cross-bed sets. A similar range may be expected for saturated sediments.

Cooley et al. (1969) reports regional values of hydraulic conductivity that are generally not more than about 1 ft/day. Laboratory permeameter tests of the Navajo Sandstone (DOE 1998) reported an average value of vertical conductivity of about 0.3 ft/day. Vertical hydraulic conductivity measured by Heilweil and Watt (2010) were on the order of 1.5 ft/day. Results of hydraulic testing are reported in AMEC 2013 for a study area that is situated over the Navajo Sandstone aquifer approximately 5 miles south of the LM site. Those data will be reviewed for relevance to the Tuba City site model.

4.4.1.1 Vertical Anisotropy

Vertical anisotropy is an aquifer property whereby the hydraulic conductivity varies with the vertical direction of measurement compared to the horizontal direction of measurement at a given point. This property is commonly related to the horizontal alignment of platy minerals parallel to a sedimentary bedding plane. Horizontal and vertical hydraulic conductivity values described above suggest an equality that precludes significant vertical anisotropy.

4.4.2 Storage

Aquifer storage is suspected to be low based on results of aquifer pumping tests (DOE 1998) and observation of pronounced drawdown over large distance in monitoring wells during groundwater remediation. Aquifer storage will be treated as a calibration parameter.

4.4.3 Effective Porosity

Effective porosity of the Navajo Sandstone was estimated between about 20 and 30 percent in laboratory tests on core samples in 1998 (DOE 1998).

4.5 Groundwater Flow Model Calibration

Groundwater flow model calibration will use PEST as the parameter-estimation technique (Doherty 2004). PEST is a computer code that determines best-fit values for sensitive input parameters such as hydraulic conductivity and recharge to match specified calibration targets (e.g., groundwater elevations and boundary flux). Parameter estimation is constrained by user-specified ranges of input values. Current versions of MODFLOW support model calibration by PEST using any combination of steady-state and transient stress periods.

PEST also allows the use of pilot points, which can be assigned to constrain parameter values within areas of a model where specific parameter data are absent but they can be reasonably estimated based on available calibration data. The use of pilot points is particularly useful in computing a spatially continuous hydraulic conductivity field.

4.5.1 Calibration to Hydraulic Head

The groundwater flow model will be calibrated to hydraulic head elevations recorded in monitoring wells during (1) steady-state flow that preceded active remediation (baseline conditions), (2) transient water level drawdowns during the period of active remediation until suspended in October 2010, and (3) between October 2010 and September 2011, a period of water-level recovery when the remediation was suspended. Water level drawdown and recovery during these periods provides the opportunity to calibrate the model to transient stresses on a large temporal and spatial scale. An additional calibration target that may be used to ensure that observed vertical flow gradients are preserved in the calibrated model are head differences between adjacent wells screened at different elevations in the aquifer.

4.5.2 Calibration to Discharge at Moenkopi Wash

Rates of groundwater discharge to Moenkopi Wash (estimated and measured) will be used as calibration targets for the groundwater flow model. Calibration to flux targets will complement calibration to hydraulic heads to constrain the volumetric rate of groundwater flow in the model and thus minimize non-uniqueness of the calibrated model. Flux calibration targets will include groundwater discharge in seeps along the cliff-face that bounds the wash and measured surface water flow in Moenkopi Wash using the USGS gaging station near the village of Moenkopi.

4.5.3 Parameter Sensitivity Analysis

In addition to estimating parameter values, PEST calculates composite parameter sensitivities prior to and at the conclusion of parameter estimation. This analysis ensures that the calibration process focuses only on the most important, or sensitive, input parameters. Current guidance suggests that any parameter having sensitivity within two orders of magnitude of the most sensitive parameter can be estimated uniquely (Hill 1988). Parameters having sensitivities between two and three orders of magnitude less than the most sensitive parameter may or may not be able to be estimated uniquely. Parameters having sensitivities more than three orders of magnitude less than the most sensitive parameter cannot be estimated uniquely, so confidence in these estimated parameter values is highly uncertain and the uncertain parameters should be assigned representative values and excluded from the calibration process.

4.6 Groundwater Mass Balance

The volumetric rate of water entering and exiting the model domain will be summarized to develop a better understanding of groundwater flow volumes in the vicinity of the Tuba City site under ambient and remedial system pumping flow conditions. Recharge features to be evaluated include precipitation recharge and groundwater through-flow from upgradient sources. Discharge evaluation will include quantifying discharge rates to pumping wells, evapotranspiration volumes to the greasewood stand, discharge rates to the springs and seepage zones, and discharge rates to Moenkopi Wash. In addition, the discharge rates across the confining limestone beds (assuming lateral continuity) will also be summarized.

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5.0 Contaminant Transport Modeling

This section describes the methods for developing a calibrated contaminant transport model for the site. The calibrated transport model will be used in conjunction with the calibrated groundwater flow model to predict future uranium concentrations under various scenarios of groundwater extraction and treatment. Transport modeling will be performed using MT3DMS (Zheng 1999), a contaminant transport code that interfaces with MODFLOW.

As presented in Section 1.0, uranium concentrations in groundwater are not decreasing significantly on a site-wide basis and remain relatively constant over time, greatly above the remediation goal, at a given location. This apparent stabilization of contaminant concentration in groundwater is referred to as the 'tailing effect' and is not unique to the Tuba City site. Transport modeling will evaluate dual-domain mass transfer or rate-limited desorption in MT3DMS as a bulk transport parameter without identifying specific uranium transport mechanisms.

5.1 Transport Model Calibration

Transport modeling will focus on history-matching to plume behavior since waste encapsulation was completed in 1990. Contaminant mass and volume loading during mill operation will be estimated as a mass balance check; however, transport model calibration will not address plume development during that time because the estimates are likely to be highly uncertain. The primary parameters that will be evaluated during transport model calibration are matrix diffusion, the uranium distribution coefficient (K_d), and matrix dispersion.

5.1.1 Matrix Diffusion

The potential for a contaminant to diffuse into less permeable zones of an aquifer and then to back-diffuse into the preferred flow paths forms the basis of the dual-domain mass transfer concept. In the forward direction, plume stagnation can occur if the storage capacity of the block matrix is significantly greater than the volume of water in an adjacent preferred flow path. In the reverse direction, back-diffusion (solute movement from the block matrix to the zone of preferential flow) can account for the tailing effect because concentrations are greater in the block matrix than in an adjacent preferred flow path.

5.1.2 Distribution Coefficient

MT3DMS can simulate both equilibrium and nonequilibrium sorption of a solute. The sorption behavior of uranium will be evaluated as a transport parameter to determine if nonequilibrium desorption contributes to the apparent tailing effect. An initial estimate of the distribution coefficient (K_d) will be assigned based on site-specific laboratory sorption testing (unpublished file report by Rio Algom, October 1997). These tests indicated a range of K_d between about 0.1 and 0.8 milliliter per gram, and investigators concluded a relatively low adsorption capacity of the aquifer matrix. Uranium sorption tests on Navajo Sandstone samples were reported in AMEC 2013 for a study area located approximately 5 miles south of the LM site. These data will be reviewed for relevance to the Tuba City site model.

5.1.3 Dispersivity and Dispersion

Dispersivity is an aquifer matrix property that reduces solute concentrations during advective transport as a mechanical mixing process. Dispersivity is represented in a transport model as a coefficient in the equation of hydrodynamic dispersion (dispersion), which incorporates the variables of groundwater flow velocity and molecular diffusion. Dispersivity/dispersion is characterized by the degree of concentration change along the plumes margins. If concentrations gradually change toward the plume margins, dispersion is potentially significant. If the concentration front is abrupt, dispersion is likely insignificant.

Dispersion can occur in the direction of plume migration (longitudinal dispersion), horizontally perpendicular to plume migration direction (transverse dispersion) and vertically perpendicular to plume migration direction (vertical dispersion). Appropriate values for the dispersivity coefficients will be determined during transport model calibration.

5.1.4 Disposal Cell Leakage

As an initial condition, contaminant transport modeling will assume that the disposal cell does not contribute significant water or contamination to the aquifer Estimates of transient drainage from mill tailings in the cell should not be significant at this time (DOE 1998). The integrity of the disposal cell cover is assumed to prevent significant infiltration recharge to the aquifer.

6.0 Groundwater Flow Model Predictions

The calibrated groundwater flow model will be used to predict groundwater flow direction and velocity from hydrologic sources and to hydrologic sinks under current and reduced groundwater extraction scenarios. Using MODFLOW output, particle tracking will be applied to analyze and compare plume capture efficiency under various extraction scenarios using only the existing extraction wells.

6.1 Groundwater Flow Path Evaluation

Particle tracking will be performed using MODPATH as a tool to interpret and display the groundwater flow paths and velocity within the flow field computed by MODFLOW. Particle tracking is initiated by placing particles at strategic locations (for example, at the tailings pile or at groundwater inflow or outflow boundaries) and allowing them to migrate forward (or in reverse) in the flow field. In this way, model-predicted flow paths and flow velocity can be compared to the site conceptual model and field observations. MODPATH can be particularly useful in depicting the capture zone of hydrologic sinks (for example, groundwater extraction wells). MODPATH addresses only groundwater advection as a contaminant transport process.

6.2 Well Field Optimization

To evaluate optimal well-field operation at reduced rates from the current scope, a separate computer program will be utilized. This program (Brute Force) is a particle-tracking optimization code that works with MODFLOW-based groundwater flow models. Brute Force identifies and ranks the most productive wells in removing contaminant mass and plume capture. Particles are weighted on a relative scale of contaminant concentration instead of assigning actual concentration values. Optimal solutions for plume capture can be computed for specified mass, volumetric extraction rates (cumulative and per well basis), and temporal capture constraints. The program can also account for contaminant retardation in developing an optimal capture solution.

Evaluating well field optimization will be initiated by simulating pumping of existing extraction wells at prescribed individual pumping rates. The well location that captures the greatest number of mass-weighted particles is chosen for further optimization by incrementally increasing pumping until all mass-weighted particles are captured within the specified capture time, or the prescribed drawdown (prevents a well from being over-pumped) or maximum pumping rate constraint is exceeded.

If a single well cannot capture all particles without exceeding the specified constraints, those particles that are captured by the well within the specified time criteria are omitted from further consideration. The process is then repeated with the first well pumping at the optimized rate, to identify the well location that captures the most remaining mass-weighted particles. Wells are iteratively added in this way until a specified mass-capture percentage is achieved within the specified capture time or until the maximum allowable number of wells is exceeded.

After each well evaluation and selection iteration, the program outputs potentiometric head, drawdown, and plots showing which portions of the plume are being captured within the specified capture time. Program output also includes a mass capture plot for all iterations. These plots are useful in showing the point where operation of specific wells attain the greatest mass capture and where operation of additional wells provides only a marginal benefit.

6.3 Groundwater Flow Model Sensitivity Evaluation

Sensitivity evaluation consisting of manual, systematic adjustment of the calibrated flow model parameters will be performed to evaluate how parameter uncertainty influences flow model predictions such as groundwater flow paths, capture zones, and recharge/discharge volumes.

7.0 Transport Model Predictions

Forward (future) contaminant transport simulations will be performed using the calibrated transport parameters for various remedial pumping options and cessation of pumping. Initial uranium plume concentrations at simulation initiation will be based on recent (2014) groundwater sampling data. The only other presence of uranium in the aquifer will be that represented as sorbed phase through the assigned distribution coefficient. Uranium uptake to vegetation will not be simulated as a potential contaminant sink.

Predictive transport simulations will extend 250 years into the future. Transport simulations will predict future uranium temporal concentrations within the Navajo Sandstone aquifer and at Moenkopi Wash where groundwater discharge is expressed as springs and seeps. Transport simulations will also provide estimated time to restore the aquifer to the uranium remediation goal. Simulating uranium transport over 250 years compares to approximately 30 years of plume development followed by an additional 220 years of simulated flow and transport after waste isolation.

7.1 Sensitivity Evaluation

To bound uncertainty associated with the forward transport model predictions, sensitivity evaluation will be manually performed by systematically increasing and decreasing individual transport parameter values within expected ranges. The results will show how the perturbations influence transport model predictions relative to those of the calibrated transport model.

7.2 Transport Prediction Uncertainty

Uranium concentrations predicted by the transport model will be viewed as approximations that are subject to much uncertainty. Despite this limitation, the predictions will be used to compare remedial strategies in relative terms, and to identify order-of-magnitude approximations of restoration time and exposure point concentrations at Moenkopi Wash.

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8.0 Summary of Modeling Objectives and Approach

The objectives of numerical groundwater modeling proposed in this plan are to

- Evaluate groundwater contaminant plume capture under multiple remediation scenarios including current, reduced, and no active remediation.
- Predict future concentrations of uranium in groundwater and at seeps and springs where groundwater discharges at Moenkopi Wash (a potential exposure point for groundwater ingestion).
- Predict the time to meet the uranium restoration goal under multiple remediation scenarios.

Numerical groundwater modeling will be conducted in several phases that will address

- Re-evaluating site data and other sources relevant to groundwater flow and contaminant transport at the site.
- Groundwater flow model calibration using automated methods. Calibration will focus on an extensive record of transient hydraulic stresses.
- Transport model calibration to observed concentration trending of uranium following waste isolation/source removal. Calibration will focus on extensive record of temporal and spatial uranium concentration data.
- Capture zone analysis under current and hypothetical pumping scenarios.
- Plume capture optimization analysis.
- Transport simulations to predict future concentration of uranium and to estimate aquifer restoration times.

The proposed modeling effort may reveal the need for additional data collection to confirm the conceptual and numerical models. Possible areas of further investigation may include but are not limited to

- Core study of possible plume-derived mineral precipitates.
- Core study of the extent of limestone beds.
- Reactive transport/geochemical modeling.

These possible areas of further study are not perceived as representing significant data gaps that would invalidate the numerical modeling approach proposed in this work plan.

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