Numerical Modeling of Groundwater Flow in the Navajo Sandstone Aquifer at the Tuba City, Arizona, Disposal Site – 15167

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ABSTRACT

A numerical model is being developed to describe groundwater flow in the Navajo Sandstone aquifer that underlies the US DOE Office of Legacy Management Tuba City disposal site that is located near Tuba City, Arizona. The site is a former uranium-ore processing mill that operated from 1956 until 1966. Resulting groundwater contamination extends approximately 457 meters (1,500 feet) off the site. The primary contaminants are nitrate, sulfate, and uranium. Onsite solid waste encapsulation was completed by 1990 and pump-and-treat groundwater remediation was implemented in 2002.

A site conceptual model, along with an approach to numerically simulate groundwater flow and advective transport of contaminants at the site, is being developed. Numerical model calibration will address transient periods of active and inactive groundwater withdrawal during the remedial action. The calibrated model will be applied to forecast contaminant capture under the current and hypothetical groundwater extraction scenarios.

INTRODUCTION

A numerical model is being developed to describe groundwater flow in the Navajo Sandstone aquifer that underlies the US DOE Office of Legacy Management (LM) Tuba City disposal site that is located near Tuba City, Arizona (Fig. 1). The site is a former uranium-ore processing mill that operated from 1956 until 1966. Resulting groundwater contamination extends approximately 457 meters (1,500 feet) off the site. Primary contaminants are nitrate, sulfate, and uranium. Cleanup goals are 44 milligrams per liter (mg/L) as NO_3, 250 mg/L, and 0.044 mg/L, respectively. Onsite solid waste encapsulation was completed by 1990 and extensive groundwater characterization efforts began by the early 1990s.

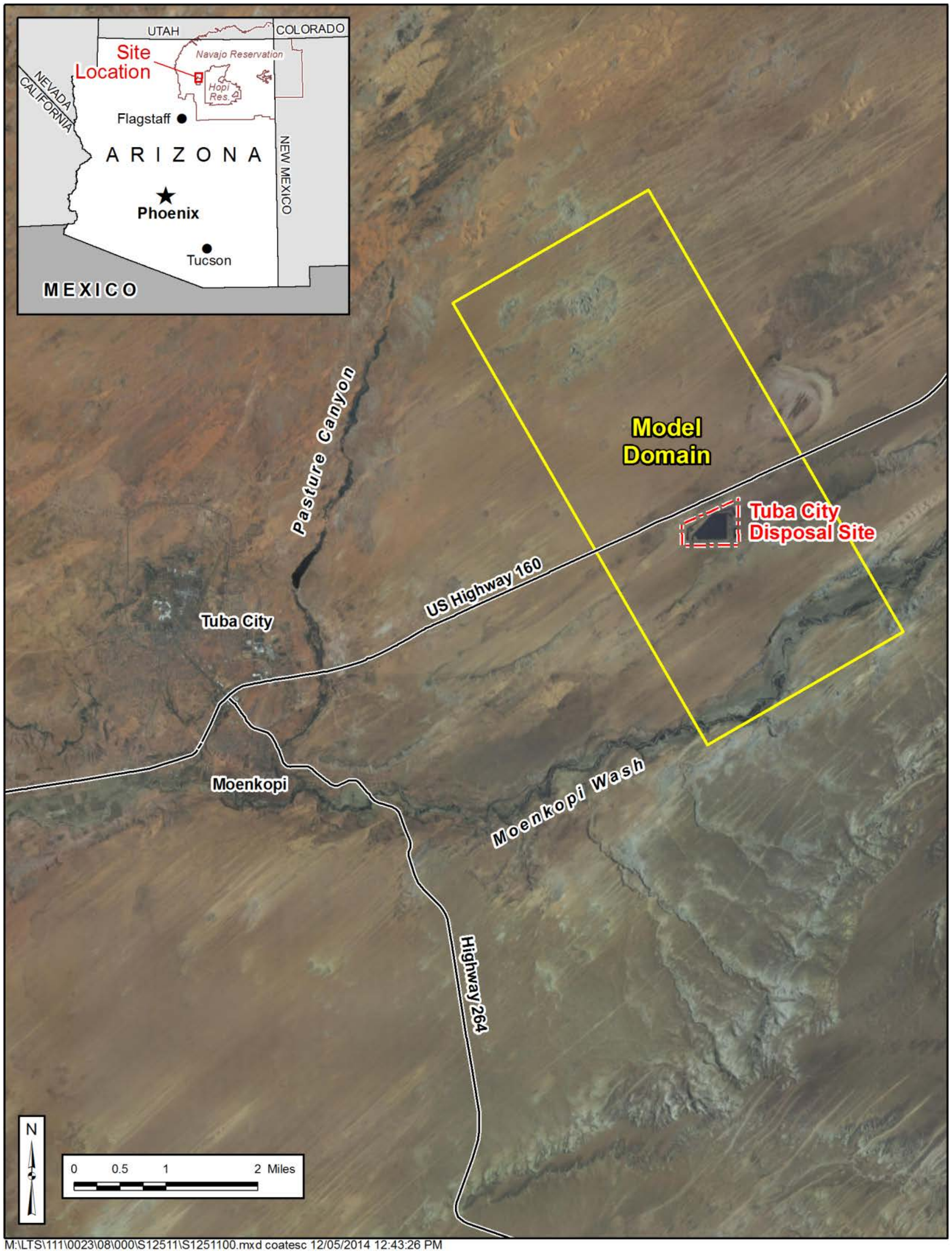

Fig. 1. The location of the Tuba City site and the outline of the groundwater model domain are shown in this figure.

Pump-and-treat groundwater remediation was implemented by US DOE LM in 2002 at an operating capacity of 454 liters per minute (lpm) (120 gallons per minute [gpm]). Thirty extraction wells are operated in an area of approximately 40.5 hectares (100 acres) to extract contaminated groundwater for treatment by mechanical distillation. Groundwater extraction declined from approximately 379 lpm (100 gpm) initially to approximately 303 to 322 lpm currently (80 to 85 gpm), presumably limited by aquifer yield. The system effectively captures and treats the bulk of the contaminant plume, resulting in significant mass removal from the aquifer, but corresponding reductions in contaminant concentrations are not evident. Recent estimates indicate that one-third of the plume volume has been withdrawn and treated.

DESCRIPTION

A site conceptual model, along with an approach to numerically simulate groundwater flow and advective transport of contaminants from the site, is being developed. Numerical model calibration will focus on transient periods of active and inactive groundwater withdrawal during the remedial action. The calibrated model will be used to analyze contaminant capture under the scenarios of current pump-and-treat remediation, reduced scope of remediation, and no active remediation.

Modeling objectives include time estimates of groundwater capture and estimates of solute travel time to potential exposure points under these scenarios. A phased approach is being implemented to focus on (1) data evaluation to refine the site conceptual model and provide estimates of parameter values, (2) model configuration (domain, grid, boundaries), and (3) model calibration to multiple head and flux targets using automated parameter estimation. A calibration goal is to match aquifer response to sustained, large-scale stresses during intermittent operation of the remediation system. Predictive contaminant transport by geochemical or matrix-controlled mass transfer processes is not a present focus of the modeling effort.

Conceptual Site Model

Groundwater beneath the site occurs in the regionally extensive Navajo Sandstone, which consists of massive, overlapping sand and silt cross-beds deposited as dunes in an ancient erg. Saturated thickness of the aquifer is approximately 100 meters (330 feet). Planar horizontal beds are common at the base of the cross-bed sets, as are thin (< 0.6 meter [2 feet]) beds of dense limestone. The horizontal extent of the limestone beds is uncertain but may be on the order of 0.8 kilometer (0.5 mile) or more in diameter. Depth to groundwater is approximately 15 to 18 meters (50 to 60 feet). Surficial aquifers are absent. The region is semiarid and annual precipitation is about 13 centimeters (5 inches).

Groundwater flow is generally from north to south beneath the site toward a prominent drainage (Moenkopi Wash). Figure 2 depicts the water table configuration during baseline (prepumping) conditions.

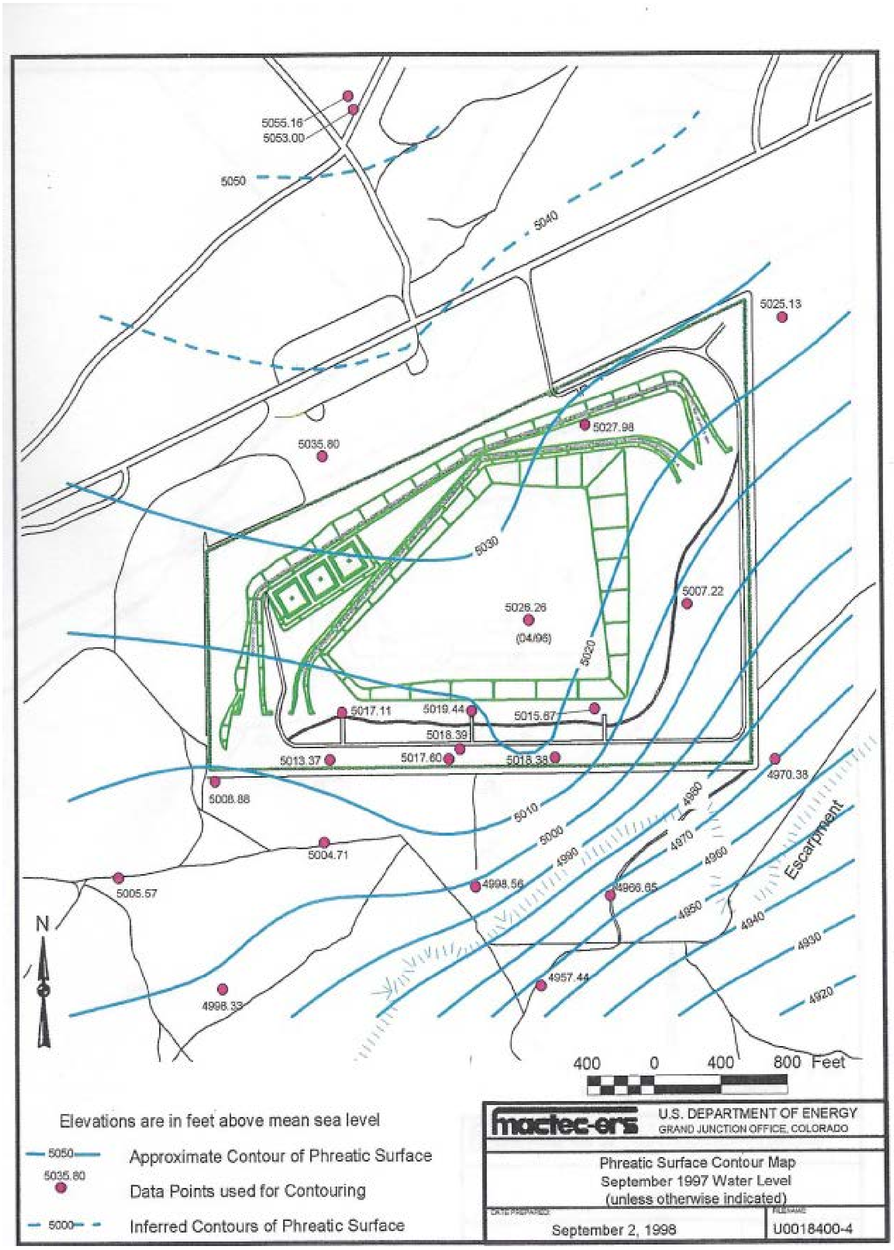

Fig. 2. The baseline (prepumping) water table indicates a south-to-southeast direction of groundwater flow beneath the site [1].

Baseflow in the wash is probably not more than 379 lpm (100 gpm) and underflow beneath the wash is not expected. Plant transpiration in the floodplain and riparian area of the wash (where shallow groundwater occurs) contributes significantly to groundwater discharge, as do seeps along discrete bedding planes in the bounding cliff faces. Prominent features of the wash, viewed to the northwest from within the model domain outlined in Figure 1, are shown in Figure 3.

Fig. 3. Moenkopi Wash is viewed to the northwest from within the model domain outlined in Figure 1. The wash is bounded by the prominent cliff in the background, along which a thin seep zone, where rock coloration changes from red-brown to light tan, is evident. The floodplain, riparian zone, and surface water flow in the wash are in the foreground. The flow channel is approximately 3 meters (9 feet) wide and 3 centimeters (1.2 inches) deep in this view. The current is slow moving.

A topographical divide north (upgradient) of the site is thought to represent both a local groundwater divide and a surface water divide. The groundwater divide may result from prolific aquifer discharge to Pasture Canyon northwest of the site (Fig. 1). In the presence of the groundwater divide, underflow to the site would be minimal or none; as a result, groundwater flow beneath the site is assumed to be from recharge of precipitation within the local watershed. Prominent site features are shown in Figure 4.

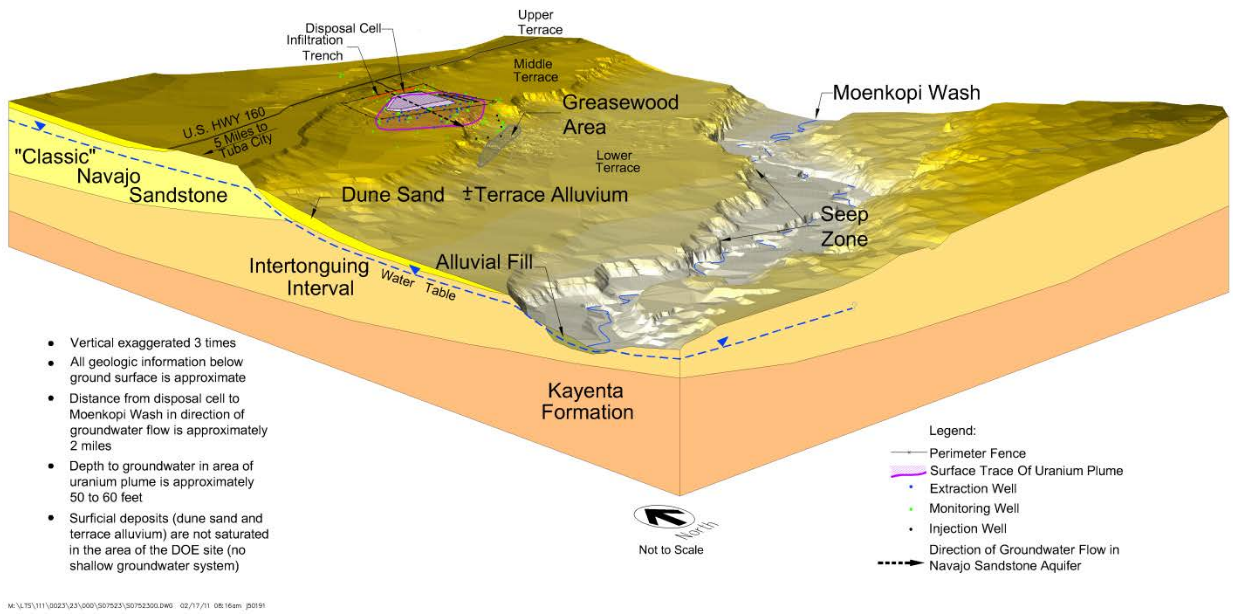

Fig. 4. This figure presents a block diagram of the hydrogeologic setting at the Tuba City site [2].

The base of the aquifer occurs at the top of the locally non-water-bearing Kayenta Formation. Complex interbedding of dune-type deposits and fine-grained fluvial deposits characteristic of the Kayenta Formation forms a transition zone or “intertonguing interval” between the two primary formations.

Flow conditions are characterized by prominent downward vertical hydraulic gradients. These gradients and the hydrogeologic setting suggest a local flow pattern that is dominated by precipitation recharge and subsequent discharge to a local drainage. Intervening low permeability layers within the aquifer may also contribute to the development of vertical flow potentials.

The position of the surface water and groundwater flow divide coincides approximately with the northern extent of the block model depicted in Figure 4. In the local setting, groundwater recharge by precipitation occurs on the upper, middle, and lower alluvial terraces depicted in Figure 4. Groundwater discharge in the site area occurs mainly by plant transpiration along Moenkopi Wash and as upflow to surface water.

Numerical Methods

Groundwater flow in the Navajo Sandstone aquifer will be simulated using the computer code MODFLOW 2000 [3]. Model calibration will focus on matching hydraulic heads to baseline conditions that preceded active remediation (presumed to be steady-state flow) and to transient flow conditions during active remediation. The transient head targets correspond to measured water levels over several years of sustained treatment operation, as well as during an approximately 1-year recovery period in 2010 and 2011 while the system was not in operation.

Flow model calibration will employ automated parameter optimization using the computer code PEST [4]. PEST is model-independent and, similar to trial-and-error calibration, solves the reverse problem by which parameter values are optimized to provide the "best fit" to measured calibration targets (e.g., hydraulic heads). PEST also automatically ranks parameter sensitivity so that calibration can focus on varying only the most important or sensitive parameters to achieve calibration success. Automated parameter estimation is more thorough and less time-consuming than a conventional trial-and-error approach.

MODFLOW 2000 supports model calibration and parameter optimization by PEST using any combination of steady-state and transient stress periods and targets. Parameter optimization is constrained by initial user-specified ranges of input values. As with trial-and-error calibration, the results of automated parameter estimation must conform to the site conceptual model. Numerous simulations based on user-specified adjustments to initial parameter values or boundary conditions may therefore be necessary to attain an acceptable calibration.

Model Configuration

The domain of the model centers on the disposal site and was designed to encompass the upgradient watershed boundary and the downgradient discharge boundary represented by Moenkopi Wash and the floodplain and riparian zones (see Figure 1 for model domain orientation). The length of the domain, oriented parallel to groundwater flow, is approximately 8,839 meters (29,000 feet) and the width is 3,962 meters (13,000 feet). Grid cells measure 7.6 meters by 7.6 meters (25 feet by 25 feet) in the area of groundwater contamination and increase to 152 meters by 152 meters (500 feet by 500 feet) along the upgradient boundary of the domain and 61 meters by 61 meters (200 feet by 200 feet) along the remaining margins. The vertical dimension is discretized into 32 layers with thicknesses varying from 0.9 to 4.6 meters (3 to 15 feet). Model layers are horizontal, conforming to the general attitude of bedding features where measurement is possible (e.g., surface exposures of limestone layers).

The upgradient boundary of the model is prescribed as no-flow, corresponding to the topographical watershed divide. No-flow boundaries are also prescribed to the lateral margins of the model (perpendicular to groundwater flow). Groundwater discharge at Moenkopi Wash is represented by drain cells to simulate upflow to the creek and plant transpiration in the adjacent floodplain and riparian zones. The water budget is balanced by estimated recharge based on an innovative approach implemented by US DOE LM that correlates remote sensing imagery to measured ground-based evapotranspiration. This effort resulted in the identification of nine evapotranspiration zones based on plant community analysis (see Figure 5). Zones 1 through 7 (with the minor exception of Zone 3) were indicated as net recharge zones, while Zones 8 and 9—dominated by evapotranspiration along Moenkopi Wash—were indicated as areas of net groundwater discharge.

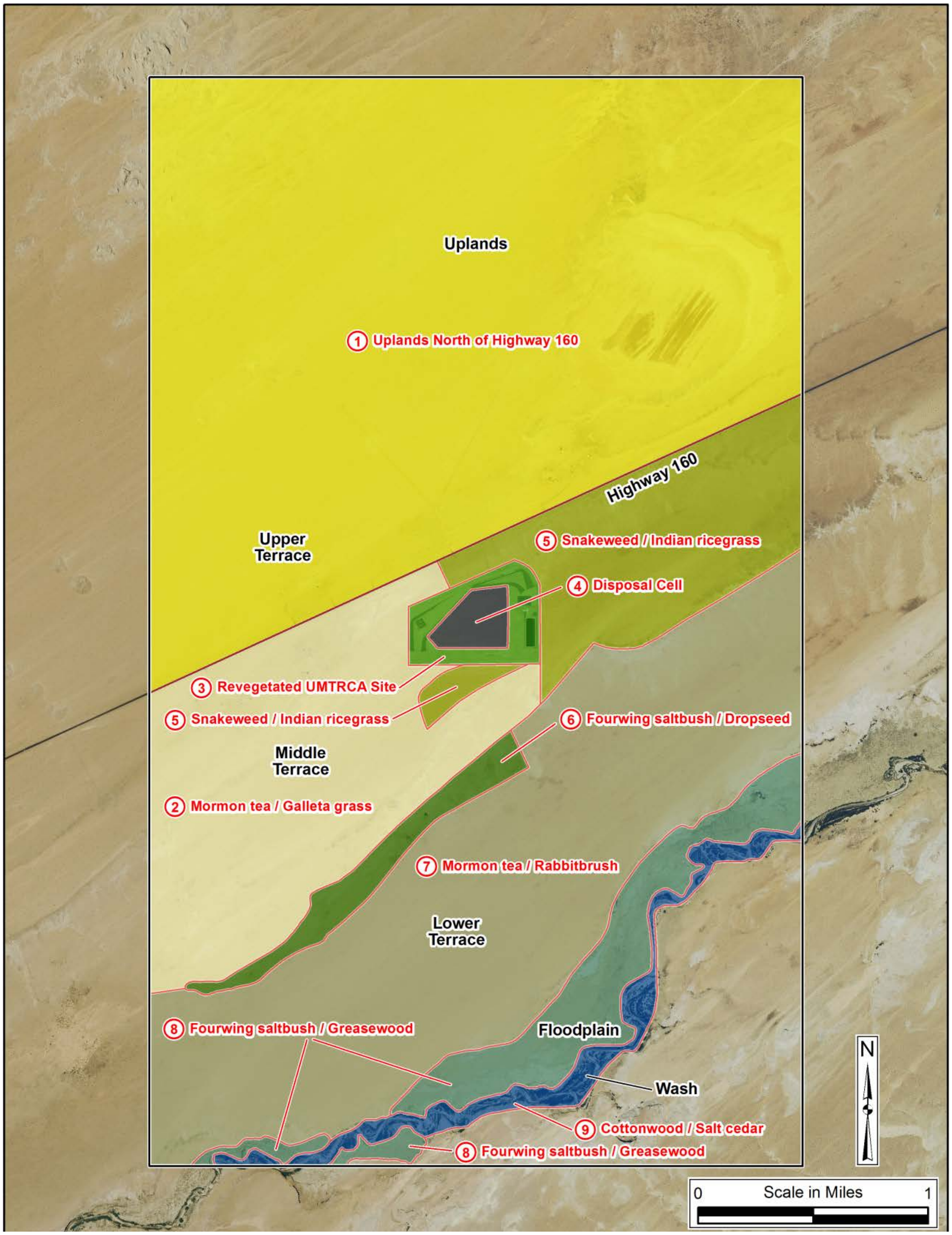

Fig. 5. Field mapping and remote sensing identified nine zones of evapotranspiration. Net aquifer recharge is estimated for Zones 1 through 7 (Zone 3 is a minor exception) and significant net discharge by evapotranspiration is indicated in Zones 8 and 9.

DISCUSSION

Application of the calibrated groundwater model will focus on predicting groundwater flow and capture by three remediation strategies: (1) active remediation under the current scope, (2) active remediation at a reduced scope of extraction and treatment (e.g., by evaporative treatment using existing infrastructure), and (3) no active remediation. Under each of these scenarios, groundwater capture analysis will be conducted using a particle tracking scheme, such as MODPATH, that is supported by MODFLOW 2000. Particle tracking is used to show the flow path and travel times of individual, strategically placed user-assigned particles in the aquifer. Particle tracking can also be used to estimate contaminant mass captured (independent of a solute transport model) by concentration-based weighting of particles within known boundaries of a contaminant plume. Particle tracking relies solely on the groundwater advection and does not address dispersion or other transport-related processes.

CONCLUSIONS

The current focus of groundwater modeling is to develop a model of groundwater flow using advanced numerical techniques and based on a sound conceptual model. Prediction of contaminant concentration over time is not a focus of the present modeling effort. Groundwater modeling will provide technical support for risk managers in determining the future scope of groundwater remediation at the Tuba City US DOE LM site. There are no current or projected receptors of the contaminated groundwater and, because progress to date indicates that the success of active remediation is uncertain, US DOE LM may consider revising the current groundwater compliance strategy to one of less intensive active remediation or to an administrative solution.

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