Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington

MODFLOW Flow-Field Development: Technical Review Group Process and Results Report

November 2007

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List of Abbreviations and Acronyms

3-D	three-dimensional
BC	boundary condition
CEQ	Council on Environmental Quality
DOE	U.S. Department of Energy
Ecology	Washington State Department of Ecology
EIS	environmental impact statement
GHB	generalized head boundary
Hanford	Hanford Site
K_h	horizontal hydraulic conductivity
LUG	Local Users' Group
MFR	mountain-front recharge
MT3D	multispecies transport three-dimensional module
MT3DMS	multispecies transport three-dimensional module with multispecies delineation
MTRG	MODFLOW Technical Review Group
NEPA	National Environmental Policy Act
PCG	Preconditioned Conjugate-Gradient
PEST	parameter estimation module
RMS	root mean square
SIP	Strongly Implicit Procedure
STOMP	Subsurface Transport Over Multiple Phases
TC & WM EIS	*Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington*
Technical Guidance Document	*Technical Guidance Document for Tank Closure Environmental Impact Statement Vadose Zone and Groundwater Revised Analyses*
TOB	top of basalt
USGS	U.S. Geological Survey

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1.0 Introduction

The *Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington* (*TC & WM EIS*) will include an analysis of long-term impacts on groundwater for a variety of waste recovery, treatment, and disposal alternatives. Underlying this analysis is the development of a groundwater flow field for the Hanford Site (Hanford). A groundwater flow field is a time-dependent, spatially varying description of the direction and magnitude of groundwater flow. This document provides an overview of the development process, technical review, and main features of the flow model. A more-detailed description of the methodology and results will be provided in an appendix that will be published in the *TC & WM EIS*.

1.1 National Environmental Policy Act Considerations

The *TC & WM EIS* is being prepared in accordance with the National Environmental Policy Act (NEPA) of 1969, as amended (42 U.S.C. 4321 et seq.); U.S. Department of Energy (DOE) implementing procedures for NEPA (10 CFR 1021); and Council on Environmental Quality (CEQ) Regulations for Implementing the Procedural Provisions of NEPA (40 CFR 1500–1508). The purpose of an environmental impact statement (EIS) is to present a comparative evaluation of the impacts of the alternatives. An EIS should quantify impacts to the extent practicable, consistent with DOE's sliding-scale approach, and take into account available project information and design data. DOE's sliding-scale approach to NEPA analysis implements CEQ's instruction to "focus on significant environmental issues and alternatives" (40 CFR 1502.1) and discuss impacts "in proportion to their significance" (40 CFR 1502.2(b)). An EIS should acknowledge uncertainty and incompleteness in the data and, where the uncertainty is significant or a major factor in understanding the impacts, explain how the uncertainty affects the analysis.

Three key considerations for development of the groundwater flow field arise from the NEPA context.

- The flow field must provide a basis for unbiased evaluation of impacts under the alternatives.
- The flow field must provide a basis for understanding the alternatives in the context of cumulative impacts.
- The effects of uncertainties and gaps in input data, modeling assumptions, and numerical error on the predicted flow field must be evaluated and discussed.

1.2 *TC & WM EIS* Considerations

The *TC & WM EIS* groundwater impact analysis is designed to build on previous modeling efforts. In particular, the *TC & WM EIS* approach to developing the groundwater flow field is based in part on the Site-Wide Groundwater Model (Thorne et al. 2006), where the features of previous work were adequately documented, traceable, and could be independently verified. The flow calculation was implemented using the U.S. Geological Survey (USGS) MODFLOW 2000 Engine, Version 1.15.00 (USGS 2004).

The interface to this engine as implemented in the *TC & WM EIS* is Visual MODFLOW, Version 4.2 (WHI 2005).

Three key considerations in development of the MODFLOW flow field arise from the specific requirements of the *TC & WM EIS*.

- The flow-field development effort must rely on data sources that are documented, traceable, and independently verified.
- Reasonably foreseeable future conditions should be investigated.
- The flow field should be developed within the MODFLOW 2000 modeling framework.

1.3 Technical Guidance Considerations

The *Technical Guidance Document for Tank Closure Environmental Impact Statement Vadose Zone and Groundwater Revised Analyses* (*Technical Guidance Document*) (DOE 2005) provides guidance for technical assumptions, model input parameters, and methodologies for proceeding with *TC & WM EIS* vadose zone and groundwater analyses. The technical basis supporting many of the assumptions is a result of various multiyear field- and science-based activities consistent with the Hanford Federal Facility Agreement and Consent Order, also known as the Tri-Party Agreement (Ecology, EPA, and DOE 1989); the National Academy of Sciences review of the *Tank Waste Remediation System Draft EIS* (NRC 1996); and the *Tank Waste Remediation System EIS* Record of Decision (62 FR 8693).

Five key considerations in development of the MODFLOW flow field arise from specific *Technical Guidance Document* requirements.

- The flow field should be transient (i.e., change with time).
- The factor driving the transient behavior should be operational recharge to the aquifer rather than time-changing boundary conditions (BCs).
- Both a Base Case and an Alternate Case should be investigated; the difference between the two cases should take into account the uncertainty in the top of basalt (TOB) elevation in the Gable Mountain-Gable Butte Gap.
- MODFLOW flow-field development should be consistent with the framework for vadose zone modeling.
- The sitewide natural recharge rate should be 3.5 millimeters (0.14 inches) per year.

2.0 The MODFLOW Flow-Field Development Process

The MODFLOW flow-field development process began with compilation of characterization data from documented, traceable, and verifiable sources. These data included:

- Borehole geologic and geophysical logs describing the sequence of materials present at locations across the study area
- Outcrop, geologic, borehole, and geophysical determinations of the TOB surface

- The location of the Columbia and Yakima River nearshores, and the long-term river stage along the nearshore

- Anthropogenic recharge and discharge as a function of time at sites across the study area (including non-DOE sites)

- Measurements of water table elevations as a function of time from wells across the study area

- Estimates of hydraulic properties from field studies, laboratory measurements, and previous modeling efforts

These data were encoded into the MODFLOW 2000 framework using the Visual MODFLOW interface. Encoding and quality assurance procedures were documented in accordance with *TC & WM EIS* practices.

The earliest version of the *TC & WM EIS* MODFLOW model was implemented as a steady-state solution (i.e., the flow field did not change with time, and anthropogenic recharge was ignored). The purposes of this version were to evaluate the extents of the model domain and lateral and vertical gridding, to explore numerical solution techniques, and to examine alternate ways of encoding BCs. After several iterations and reviews of this model, the development effort moved into a transient framework (in which the water table and flow directions and magnitudes change with time). Anthropogenic recharge and discharge were added, and time-stepping strategies were explored. Finally, measured water table elevations were encoded and the transient model was calibrated to these data. Calibration involved adjustments of model parameters to optimize the agreement of the model with observed conditions.

3.0 Technical Review Process

At key points during the MODFLOW flow-field development effort, technical reviews were performed to identify issues with important features of the model, provide suggestions for resolution of problem areas, and develop and understand alternate ways to conceptualize and encode model features. The technical review process had three major components.

- Review and comment by the Washington State Department of Ecology (Ecology) a cooperating agency on the *TC & WM EIS*

- Review and comment by a Local Users' Group (LUG), which consists of hydrogeologists and geologists from the Hanford community (modelers and field scientists)

- Review and comment by the MODFLOW Technical Review Group (MTRG), a group of four experts with commercial, governmental, and academic experience in groundwater modeling and/or environmental engineering

During each review cycle, the *TC & WM EIS* groundwater modeling team made presentations to Ecology and LUG. Written comments from these two groups were solicited and provided to MTRG for their consideration and to address as MTRG felt appropriate. The *TC & WM EIS* groundwater modeling team also presented the model development status to MTRG. These presentations were open to the public. The *TC & WM EIS* groundwater modeling team and MTRG then spent several days discussing details of the model development effort and considering comments from Ecology and LUG. Finally, a closeout meeting was held, which was open to the public, where MTRG provided their views, comments, and suggestions. The reports from these five meetings are summarized below.

December 4–6, 2006: Background Information on the Modeling Effort

- Review of model objectives
- Overview of Tank Closure and Waste Management alternatives
- Overview of the locations and sources for the cumulative impacts analysis
- Overview of the boring log retrieval process
- Overview of the TOB surface development process
- Discussion of the Subsurface Transport Over Multiple Phases (STOMP)/MODFLOW interaction
- Overview of available water-level monitoring records

The *TC & WM EIS* groundwater modeling team provided an overview of the Preliminary Steady-State Model to MTRG; the overview also outlined issues to be resolved before proceeding with further model development. MTRG reviewed comments on the Preliminary Steady-State Model submitted by Ecology and LUG.

The following comments and suggestions summarize MTRG's assessment of the issues discussed during the 3-day meeting.

- MTRG concurred with the approach of using STOMP to model vadose zone and saturated-zone transient flow and transport beneath the source areas, combined with MODFLOW/MT3DMS [multispecies transport three-dimensional module (MT3D) with multispecies delineation] models for transient flow and transport in the saturated zone in the far field.

- MTRG and the modeling team reached agreement on the sitewide conceptual hydrogeologic model.

- MTRG generally concurred with the model extents as specified. However, there was some concern that the Columbia River might not act as a hydraulic barrier to all flow beneath the river. MTRG recommended that consideration be given to expanding the active area of the model grid to the northern and eastern sides of the Columbia River to accommodate potential groundwater flow and transport beneath the river.

- MTRG reviewed the LUG and Ecology comments and discussed the model grid (lateral and vertical) at length. The consensus of MTRG was that a uniform lateral grid with 200- by 200-meter (656- by 656-foot) spacing would be adequate for the far-field model.

- With respect to vertical discretization (layering), MTRG recommended testing the fixed thickness versus the deformable-layers alternative by conducting test runs.

- Ecology and LUG comments suggested using an automatic gridding process, which is available with some MODFLOW preprocessors, to develop grid refinements. MTRG determined that automated grid refinement would not be necessary with a uniform 200- by 200-meter (656- by 656-foot) grid.

- MTRG concurred with the geostatistical approach for contouring the TOB surface using the data from available boring logs. Geostatistical techniques (such as kriging) are well-established and -documented approaches for estimating surface geometry from sparse observation points. Inferred data and geologic structures (such as faults) can also be incorporated with geostatistical techniques, thus utilizing a prior knowledge without unduly biasing the interpretation.

- MTRG recommended incorporating the inferred fault north of the Gable Mountain and Gable Butte area into the contour mapping of the basalt surface.

- The Columbia and Yakima Rivers were simulated as fixed-head BCs. This simulation was considered probably adequate given the relatively constant stage of the rivers. However, MTRG recommended utilizing the MODFLOW River package to simulate both rivers, so that potential river bottom resistances could be represented, if appropriate.

- MTRG reviewed Ecology and LUG comments concerning recharge through upstream springs and subsurface influxes into the model domain, which may also be called mountain-front recharge (MFR). While the nature of these potential recharge sources may not have been well understood in December 2006, the net effect appeared to be a relatively consistent source of water inflow to the model domain, as indicated by available water-level data. MTRG recommended that the MFR initially be estimated using field evidence (springs, seeps, etc.), then modified on a reach-by-reach basis as necessary during the calibration process.

- MTRG reviewed Ecology and LUG comments concerning the estimation of material properties using literature values, laboratory measurements, and data from aquifer pumping tests and slug tests. Given that these data have various levels of certainty and applicability to a regional-scale model, MTRG advised that these preliminary estimates be used with caution. MTRG recommended using the available data initially to constrain the material properties, modifying them as necessary during the calibration process.

- MTRG also recommended using hydrograph data from as many wells as possible to visualize the three-dimensional (3-D) flow field over the period from 1940 to 2005, at approximately 5- to 10-year intervals.

- In developing a calibration strategy, MTRG encouraged the use of all relevant information to the fullest extent possible, including head and flow measurements, core sample analysis, slug tests, aquifer pumping tests, and solute concentrations.

- MTRG suggested that the calibration process be constrained by the use of site-specific representative property values. MTRG believed that the results of core sample examination, slug tests, and aquifer tests that had already been conducted should provide some estimate of the properties of each geologic formation (i.e., Hanford, Ringold), and recommended that these estimates be used as initial guessed values for the calibration exercise and possible upper and lower acceptable limits.

February 5–9, 2007: Status of the Modeling Effort

Emphasis was on the STOMP/MODFLOW interface; MODFLOW model representation of sitewide hydrostratigraphy; material property delineation and encoding into the MODFLOW model; nature and extent of the model BCs (MRF and the river); and transient simulation approach (number of stress periods, time steps per stress period, time-step multiplier, etc.). MTRG also reviewed and discussed comments submitted by Ecology and LUG.

Following is a list of comments and recommendations resulting from discussions on modeling strategies and procedures.

- To assist the process of model development and evaluation, MTRG strongly recommended documentation of the hydrogeologic conceptual model of the site, using appropriate graphics and summary tables. MTRG specified that the hydrogeologic conceptual model should, at a minimum, discuss the model domain and boundaries, hydrostratigraphy, water budget, and groundwater flow system.

- MTRG recommended that the hydrogeologic conceptual model be presented as a 3-D block diagram and/or a series of cross sections showing the topography of the major hydrogeologic strata beneath the site.

- MTRG recommended preparing an outline of the proposed calibration strategy and procedures (hydraulic properties, BCs, generalized head boundaries [GHBs], treatment of the rivers, etc.) for flow and transport models and a discussion of the transient events to be included in the calibration scenarios.

- MTRG recommended further evaluation of the possibility of flow beneath the Columbia River by examining the hydrographs (heads) on either side of the river and consideration of groundwater utilization for municipal, industrial, or irrigation sources on the far side of the river.

- MTRG recommended preparing a series of one-dimensional figures or cross sections to show distribution of contaminants in boreholes and preparing time-series figures for boreholes with multiple observations (animated if possible); these data could be utilized to further evaluate vadose zone transport and lag times.

- MTRG recommended preparing a 3-D well screen location map to evaluate screen intervals of observation wells to facilitate the selection and placement of head calibration targets in the model.

- MTRG recommended preparing hydrographs of potential observation wells for calibration. MTRG instructions were to prepare a summary of historical annual water table maps or 3-D piezometric surface maps (animated if possible) to facilitate the selection and placement of calibration targets in the model and help evaluate flow paths, potentially unveiling upward leakage from the underlying basalt as well as other potential fluxes that might have been omitted.

- MTRG recommended preparing a 3-D well screen location map to evaluate screen intervals of tritium observation wells to facilitate the selection and placement of transport calibration targets in the model.

- MTRG recommended preparing time-concentration plots of potential observation wells for calibration to facilitate the selection and placement of transport calibration targets in the model.

- MTRG recommended preparing a summary of 3-D, or at least 2-D, historical annual tritium distribution maps, animated if possible, to facilitate the selection and placement of calibration targets in the model and help evaluate flow paths and flow velocities.

- Consistency between STOMP saturated hydraulic parameters and MODFLOW hydraulic parameters for the same material type beneath each STOMP model is a desirable goal. However, due to the different data set utilized to estimate hydraulic properties and the differences in model scales, it is possible that some of the material properties will be different. Consistency within a reasonable and defensible range should be considered adequate.

- Restarting a transient model from a steady-state model often is not a smooth transition. BCs for a steady-state model may not be the same for a transient simulation due to the added effects of storage and delayed yields. Suggestions to overcome this problem included:

  - Run a long-term transient solution (e.g., 100 years) of initial conditions (i.e., 1940) using multiple time steps (i.e., 100 time steps) to allow the model to converge on a stabilized head solution for the initial BCs. Use the resulting head distribution as the initial heads for the transient model.

  - MODFLOW 2000 allows mixing steady-state and transient stress periods in a single run. Run the model as steady state for the first stress period; use transient stress periods thereafter. Note that there may be issues using MT3D with this method.

The flow model was run using the Strongly Implicit Procedure (SIP) solver with 10 to 20 time steps and a time-step multiplier of 1.2. These settings appeared to lead to some numerical instability during later time steps.

- MTRG recommended using the USGS Preconditioned Conjugate-Gradient (PCG) solver instead of SIP; PCG is more robust and often converges faster.

- MTRG suggested using a smaller time-step multiplier of 1.0 to 1.1 so the range in duration of time steps would be smaller and more consistent during stress periods.

MTRG conjectured that simulation of contaminant transport might reveal issues with the flow-field calibration and recommended that a transport simulation of a conservative tracer be evaluated as soon as possible:

- Run transport for tritium or some other conservative tracer from the 1940s to the present. Compare the resulting tritium plume evolution to observed data (isopleth maps). Discrepancies in the migration path of the center of the plume over the simulation period may require recalibration of the flow model.

In February 2007, the MODFLOW model consisted of 31 horizontal, uniform-thickness model layers ranging from 1 to 40 meters (3.3 to 131.2 feet) in thickness. The TOB surface was encoded by specifying model cells as no-flow cells. Hydraulic properties were encoded from lithologic interpolation of boreholes on a row-by-row basis. MTRG felt that the use of horizontal, uniform-thickness model layers might have several drawbacks.

MTRG expressed concern that the practice of encoding material properties in the model introduced heterogeneities that appeared artificial. Also, the interpretation of material properties from the boring logs appeared inconsistent. Furthermore, the range in model layer thickness (1 to 40 meters [3.3 to 131.2 feet]) might introduce some numerical inaccuracy, especially for transport.

- MTRG strongly recommended establishing procedures to ensure consistent interpretation of boring log data and encoding of the data into the model. To enhance the stratigraphic interpretation from boring logs, MTRG recommended that geophysical logs of selected boreholes also be used.

- MTRG reiterated its December 2006 statement that use of the deformable grid layers is a superior approach to fixed-layer discretization in large, regional-scale flow and transport models. Deformable grid layers may be easier to implement in MODFLOW, may simplify encoding of material properties, and possibly reduce model run times. Although there is nothing inherently wrong with the current approach of horizontal, uniform-thickness model layers, MTRG recommended completing evaluation of the alternate, deformable-layer approach as soon as possible and implementing this approach if it appears to be better.

The topic of contouring the TOB surface was discussed in detail during the December 2006 meeting, and MTRG expressed its views on this subject in its first report dated December 13, 2006. Additional discussions on this topic were held during the February 5–9, 2007, meetings.

- MTRG concurred with the addition of a few control points to smooth geostatistical interpretation and more closely honor surface outcrops, observed subsurface faults, and inferred geologic structure.

MTRG understood that the model would be calibrated to the observed hydraulic head distribution and possibly the tritium transport data from 1940 through 2006. MTRG understood that approximately 20 monitoring wells with long-term histories had been selected as preliminary targets for calibration.

- MTRG recommended that model calibration criteria be established and documented prior to model calibration. MTRG recommended utilizing calibration criteria similar to that utilized by Thorne et al. (2006).

- MTRG recommended utilizing additional monitoring wells as observation targets for model calibration.

Model verification (also called validation) is a test of whether the model can be used as a predictive tool by demonstrating that the calibrated model is an adequate representation of the aquifer system(s). The common test for verification is to run the calibrated model in predictive mode to check whether the prediction reasonably matches the responses of the system(s) induced by known, new stresses, deliberately excluded from consideration during model calibration.

- MTRG discussed the merits of calibrating the model for a subset of the model period, then using the model in predictive mode to simulate the remainder of the simulation period to the present. MTRG did not recommend this procedure, as it would exclude valuable later-time data from the calibration process. In addition, the stresses (BCs or fluxes) of the recent period were generally unknown or poorly constrained, and, as such, they might be treated as parameters to be calibrated.

- MTRG recommended conducting model verification by excluding several sets (approximately 10 percent) of long-term monitoring well data from the calibration process. These wells should be randomly selected from the available well database.

- Following model calibration, compare the calibrated model heads to the excluded monitoring well data set. Confidence in the predictive capabilities of the model will be enhanced if the residual statistics and simulated hydrographs for the verification data set meet the pre-defined model calibration criteria.

The Columbia and Yakima Rivers have been encoded in the model using the MODFLOW river package. The rivers have been subdivided into a number of smaller reaches, with a constant gradient within each reach. River stage for each reach is held constant based on the annual average river stage throughout the simulation period. River bottom conductance was calculated based on the river width, model cell length, and assumed river bottom hydraulic conductivity equivalent to Hanford gravel (approximately 1,000 meters [3,281 feet] per day). The conductance will be adjusted as necessary through calibration.

- MTRG concurred with the use of the river package to represent rivers in the model domain. The encoding utilized appeared to be an appropriate representation of the rivers.

- Evidence has been presented that there is some surface and/or subsurface inflow into the model domain from the mountains bordering the western edge of the unconfined aquifer system. The exact mechanism (stream flow, springs, fracture flow, etc.) and the quantity of this inflow have not been quantified. The inflow, designated MFR, has been represented in the model utilizing the GHB package of MODFLOW at four locations.

- – MTRG concurred with the general approach to represent MFR in the model.
- – MTRG recommended conducting a water-balance evaluation for the watershed(s) feeding the MFR to further quantify the volume of water entering the unconfined aquifer.

- MTRG recommended further evaluation of the spatial distribution of MFR.
  - – MTRG recommended evaluation of reported deep inflow from fractured basalts. Fracture flow should be considered if the water balance cannot account for sufficient water entering the basin via MFR.

April 23–27, 2007: Transient Flow Model Calibration Assessment

The opening presentation briefly described the status of the transient flow model calibration to date; MODFLOW model representation of sitewide hydrostratigraphy; material property delineation and encoding into the MODFLOW model; nature and extent of the model BCs (MFR and the river); and transient simulation approach (number of stress periods, time steps per stress period, time-step multiplier, etc.). The *TC & WM EIS* groundwater modeling team provided MTRG with a set of groundwater elevation maps from 1948 through 2006 to review historical changes in groundwater levels beneath the site. These data provide a basis for assessing the transient flow model calibration.

MTRG identified the following concerns related to the status of the calibration effort.

- The sitewide hydrostratigraphy and material property delineation appeared to have a significant artificial east-west bias in assigned transmissivities, which is inconsistent with the reported geologic depositional environment and maps of transmissivity presented by others (Thorne et al. 2006).

- The spatial distribution of simulated heads and hydraulic gradients was inconsistent with observed heads and gradients in most model runs. Simulated groundwater elevations in the west were too flat, while heads in the 200-East Area and the Gap were too steep, suggesting that the horizontal hydraulic conductivity (K_h) of the west area of the transient flow model was too high and the K_h of the 200-East Area and the Gap were too low.

- The transient flow model did not sufficiently capture an inferred hydrogeologic boundary (probable spatial variation in transmissivity) as represented by the persistent 125-meter (410.1-foot) above-mean-sea-level contour line observed in the historical water-level maps.

- The transient flow model had a problem with "dead zones," where dry cells isolated individual cells or small areas at the TOB surface, a situation that is physically unrealistic. This problem accentuated the uncertainty of groundwater flow through the Gap. Various basalt/alluvium conceptualization alternatives to address this issue were discussed.

MTRG's recommendations included:

- Reexamination of the boring log data to see if improvements could be made to the hydrogeologic interpretations, focusing less on formation identification and more on material properties. Allow for material properties to vary from location to location within a reasonable range that is justifiable by the available data. The inclusion of material property zonation will account for heterogeneity and facies changes within formations.

- Experimental utilization of a numerical approach to interpolate stratigraphy between borings on a layer-by-layer basis to remove the east-west bias introduced by the cross sections. If the results appear physically more realistic, consider using these results instead of the cross-sectional discretization.

- Elimination of the dead zones either by assigning low conductivity values to the underlying basalt or by modifying the "rewetting" parameters for selected groups of cells.

- Increase of the hydraulic conductivity of the Gap area to facilitate groundwater flow through the Gap and help prevent unrealistic dewatering in the Gap and mounding of water south of the Gap.

MTRG reviewed a table comparing estimated saturated horizontal hydraulic conductivities (K_{hSat}) for specific units for the STOMP and MODFLOW models. STOMP was used to estimate vertical hydraulic conductivities (K_{vSat}) based on visual comparison of the observed and simulated moisture contents with depth. Saturated horizontal hydraulic conductivities were estimated assuming a constant K_{hSat}/K_{vSat} ratio of 10. The estimated K_{hSat} values from STOMP were one to two orders of magnitude less than K_{hSa} measurements from pumping tests, core samples, and estimates from the rough MODFLOW model calibration.

MTRG reviewed a summary of issues with STOMP/MODFLOW interfacing. The composite STOMP models for multiple waste management units appeared to contain too many nodes (i.e., $>10^5$) to simulate with the available computers. However, using individual STOMP models for each management unit does not allow for interaction between waste management units in the vadose zone, possibly underestimating the arrival time and peak concentration of waste at the water table. MTRG and the *TC & WM EIS* groundwater modeling team discussed the following possible solutions.

- Use smaller-scale "STOMPlet" models with no interaction between separate waste management units modeled. The lack of interaction may require a correction factor to achieve satisfactory STOMP model calibration to observed moisture content. This process will also expand the number of STOMP models from 200 to about 2,000, resulting in significant data management issues for both STOMP and MODFLOW.

- Decouple STOMP/MODFLOW, losing the transient water table response and mixing at and below the water table beneath each waste management unit. This solution is likely to underestimate impacts on groundwater.

- Accept and explain less precision in the STOMP/MODLFOW interaction. Discuss the results of 10^5 node model runs qualitatively in the model text.

- Run a parallel version of STOMP (under development) for the larger-scale composite models. The software may not be available for use.

MTRG discussed the STOMP/MODFLOW interaction issues presented and recommended the following tasks:

- Further evaluate the discrepancy between STOMP K_{hSat} estimates and rough calibrated values for MODFLOW in an effort to make the STOMP values more consistent with field data.
- Rather than explicitly simulating the interaction between multiple waste management units using large STOMP models, use smaller STOMP models and "planes of symmetry" based on the principal of image wells to simulate interactions between adjacent waste management units. This strategy assumes that the flows and concentrations in each waste management unit are similar in time and space in the overlapping areas.
- Run STOMP models for each submodel area and calculate flows and concentration terms along the boundaries between adjacent submodels. Represent these in the adjacent submodel as prescribed flux boundaries. This will require running each STOMP model twice, once to estimate the prescribed flux terms, and a second run to include the prescribed flux terms from adjacent STOMP models.
- Run a multiple waste management unit model for a specific set of waste management units, allowing for explicit interaction. Run planes-of-symmetry STOMP models for the same set of waste management units, allowing for simulated interaction. Run prescribed flux STOMP models for the same set of waste management units, allowing for simulated interaction. Compare the results among the three methods. If the results are acceptably close, use the most computationally efficient approach for the STOMP/MODFLOW interactions.

MTRG reviewed the results of the study (suggested by MTRG in February 2007) of river stage versus groundwater elevation data. The study reviewed groundwater levels in approximately 500 wells and identified 18 pairs of wells in reasonable proximity to each other (one well on each side of the Columbia River per pair). A review of the hydrographs showed that groundwater levels were typically more than 5 meters (16.4 feet) above the river stage at most locations, with the wells in the east and north sides of the river typically showing higher levels than the west and south sides of the river (Hanford). These observations support the proposition that the Columbia River acts as a regional sink and, as such, is an appropriate boundary for the numerical model. MTRG agreed with this assessment based on the available data.

MTRG recommended in February preparing an outline of the proposed calibration strategy and procedures (hydraulic properties, BCs, GHBs, treatment of the rivers, etc.) for flow and transport models. MTRG reviewed the proposed calibration strategy and procedures, and the proposed calibration target data sets for the groundwater flow model. MTRG agreed with the proposed calibration strategy and criteria.

June 11–14, 2007: Transient Flow Model Calibration Assessment

Discussion continued on a number of topics that were partially addressed during the April session. The opening presentation briefly described the status of the transient flow model calibration to date; revised implementation of sitewide hydrostratigraphy; material property delineation and encoding into the MODFLOW model; revisions to the nature and extent of the model BCs (MFR); and the results of transient predictive simulations using particle tracks in the post-Hanford flow field. The discussion focused on the potential impacts of two simplifying assumptions: (1) no vadose zone attenuation of anthropogenic recharge, particularly in the 200-West Area; and (2) the assumption of a uniform hydraulic conductivity for each material type. These simplifying assumptions appeared to be the largest source of error in the June model. Additional LUG concerns included large predicted Darcy velocities along

Rattlesnake Mountain; possibly anomalous northerly flow in the Cold Creek unit; the presence or absence of Ringold mud in the Yakima Ridge Gap; and the potential lack of definition of the anticlinal structure southeast of Gable Mountain.

During the week-long meeting, MTRG general discussion centered around three questions: (1) Can the model be improved? (2) Does the model need to be improved to meet the needs of the EIS? and (3) Is the level of model complexity appropriate or “in balance” to facilitate the presentation of the model in the EIS?

MTRG reviewed the current model status and determined that significant progress had been made in calibrating the model during the preceding weeks. Evaluations of the TOB surface, reasonable GHBs along mountain fronts, and preliminary manual calibration to heads were achieved. Automated calibrations using the parameter estimation module (PEST) were completed, and work was ongoing to refine the selection of calibration parameters and data weighting.

Additional, specific improvements to better address the needs of the EIS were discussed and are listed below.

Geology

Discussions examined several interrelated issues, including:

- Was there sufficient flow from the 200-East Area to the southeast?
- Was there sufficient flow from the 200-East Area to the north?
- Was the expression of the anticline structure southeast of Gable Mountain adequate?
- Were the Rattlesnake Mountain GHBs in connection with Hanford gravel reasonable?
- Was the presence of Ringold mud in the Yakima Gap outlet reasonable?
- Was additional zonation necessary, particularly in the Hanford gravel?

A review of available groundwater-level data and historical tritium plume data indicated a relatively significant flow to the southeast from the 200-East Area. The model-simulated flow field also indicated a flow to the southeast (via particle tracking); however, the flow field appeared to arrive at the Columbia River north of the observed tritium plume. The model flow field also indicated a portion of simulated flow from the 200-East Area toward the north through Gable Mountain Gap. MTRG discussed several changes to the model that could be investigated by simulating historical observations of tritium and technetium-99, including:

- A review of the TOB surface indicated that the northwest-southeast trending anticlinal structure east of Gable Mountain had been adequately encoded in the model. Although the TOB surface in the model was in general agreement with field measurements, there was some uncertainty associated with the TOB surface and the anticlinal structure in this area. Alternate models of the TOB surface in the anticlinal area were recommended to be considered as part of the calibration process.

- The GHBs along the Rattlesnake Mountain front in contact with Ringold gravel appeared reasonable. Four GHB cells in contact with Hanford gravel appeared to contribute an excessive amount of MFR in this area. Elimination (or modification) of these four GHB cells appeared appropriate.

- The presence of Ringold mud in the Yakima Gap outlet appeared to be an artifact of vertical interpolation in this area where there were few data control points. Removal of the Ringold mud in this area was appropriate, based on prevailing hydrogeologic data.

- In the June model, the material properties of the various sediments beneath the site were assumed to be homogeneous. However, available aquifer pumping test field data indicated that the Hanford and Ringold gravels exhibited significant lateral variation in hydraulic properties across the site. The hydraulic data suggested a zone of relatively high hydraulic conductivity in a northwest-southeast trending zone from Gable Mountain Gap through the 200-East Area. The incorporation of such a zone was suggested to reduce hydraulic gradients in this area and make the simulated water table closer to observations.

- There appeared to be a zone of low hydraulic conductivity in the Hanford gravel in the vicinity of the Columbia River southeast of the 200-East Area. Creation of such a zone in the model was thought to have the effect of increasing the flow toward the southeast, which would be in line with the observed tritium plume.

<u>Artificial Recharge</u>

MTRG extensively discussed the assumption of "no lag" in the vadose zone between surface application of water and its arrival at the water table. The MTRG consensus was that this assumption was too simplistic and not supported by field observations in the 200-West Area, which showed a significant lag (on the order of years) between surface disposal and its impact at the water table. MTRG discussed various methods to improve the encoding of artificial recharge, ranging from explicit representation with STOMP models to simple empirical methods based on observations of head. MTRG strongly recommended that the encoding of artificial recharge be modified to more closely reflect the observed changes in the water table over time. This change was recommended to be implemented prior to additional manual or PEST calibration of hydraulic parameters. MTRG noted that the project team was exploring alternate methods to more accurately encode artificial recharge.

<u>Calibration to Plume Data</u>

MTRG discussed the calibration metrics for the project as summarized in the June groundwater model status report. Although the procedures and metrics for hydraulic head appeared reasonable and feasible within the project schedule, it was difficult to define and evaluate similar concentration-based metrics. However, a qualitative assessment of predicted plume behavior was an important aspect of flow model performance evaluation. A number of alternate strategies were discussed, including comparisons between model predictions and observations for (1) calculated first and second spatial moments of the plumes, (2) selected point concentration data, and (3) locations of specific concentration contours. Prior to completing the flow model calibration process, MTRG recommended that the groundwater model status report be updated to include relevant plume-based objectives and procedures (e.g., graphical comparisons) for evaluating them.

Summary

A sitewide groundwater flow model of Hanford was successfully created using MODFLOW 2000. This model was calibrated to historical water-level elevation data using the calibration criteria specified in the *Technical Guidance Document*. Additional refinements of the model to better simulate historical contaminant plume evolution were ongoing, using manual and automatic (PEST) calibration procedures.

October 24–26, 2007: *TC & WM EIS* Objectives

MTRG reviewed the objectives of the EIS goals, including:

- Evaluate the EIS alternatives without bias.
- Understand and document model uncertainties and the potential effects on the alternatives analysis.
- Prepare and reasonably calibrate a Base Case model (with long-term flow to the east) to the operational period head data.
- Prepare and reasonably calibrate an Alternate Case model (with long-term flow to the north through Gable Gap) to the operational period head data.
- Evaluate potential impacts of reasonably foreseeable events (e.g., Black Rock Reservoir).

MTRG then reviewed the status of the transient flow model calibration; revised implementation of the sitewide hydrostratigraphy; material property delineation and encoding into the MODFLOW model; revisions to the nature and extent of the model BCs, including MFR; and results of transient calibrations using three separate target data sets. The PEST software was utilized to evaluate the sensitivity of model hydraulic parameters (K_h, K_v, Sy, Ss) to the three target data sets. All three PEST runs indicated that the same five model parameters were particularly sensitive: K_h4 Hanford gravel; K_h5 Ringold sand; K_h6 Ringold gravel; K_h12 Cold Creek gravel; and K_h13 Super Hanford gravel. The three PEST runs yielded model parameter estimates that were fairly close in value; however, the PEST runs were all started using the same initial parameter estimates and generated small confidence intervals that were regarded by MTRG as possibly unrealistic.

Two types of Monte Carlo simulations were presented that examined a larger range of parameter values and determined if optimum values had been estimated. Using a manual Monte Carlo generator, 340 sensitivity simulations were compared with target data set No. 1 to identify improved values for the 13 model parameters. These simulations evaluated a broader range of parameter space than the PEST runs, yielding some improvement in the root mean square (RMS) error statistic used to evaluate model calibration.

A second set of 5,000 Monte Carlo simulations was generated by varying the 13 model hydraulic conductivity parameters and parameters Sy and Ss (a total of 15 parameters), assuming each hydraulic conductivity parameter had a lognormal distribution with a log standard deviation of 0.5. The Monte Carlo simulations were compared with random selections of target data sets Nos. 1 through 3 to identify improved values for the 15 model parameters. The 5,000 Monte Carlo simulations also evaluated a broader range of parameter space than the PEST runs, yielding some improvement in RMS values. Evaluation of additional parameter sets will continue using some form of Monte Carlo simulation.

MTRG also reviewed the Base Case model flow field and particle tracks, comparing them to observed hydrographs and tritium plumes, respectively. Most hydrographs showed reasonable fit to observations, although some simulated hydrographs in the 200-West Area showed differences relative to the observed recharge. Particle tracking using the calibrated Base Case model yielded relatively good agreement with the shape of the observed tritium plume. The tritium plume particle tracks for each of the "10 best" hydraulic parameter sets showed some local variation, but were generally in agreement with each other. Thus, it appears that improvement in the head calibration RMS is associated with improvement in tritium plume particle tracking.

The Alternate Case model was discussed. The primary difference between the Base Case and Alternate Case is an approximately 3-meter (9.8-foot) lower elevation of the TOB surface in the Gable Gap area. The resulting flow field shows only a small change in heads (expressed as RMS), with slightly more flow and a higher groundwater velocity through the Gap. MTRG discussed the efficacy of using the 10 best Base Case parameter sets as input to the Alternate Case. It was concluded that if there was no significant difference (less than 10 percent) in the RMS between the Base and Alternate Cases, then the parameterization may be considered adequate. However, MTRG believed that a more-rigorous evaluation of parameter selection for the Alternate Case was warranted, perhaps using PEST. That is, the Base and Alternate Cases should be independently calibrated, if feasible.

MTRG also reviewed the results of a particle tracking simulation using the Alternate Case. The simulation results showed particle tracks generally similar to the Base Case, with some additional spreading of particles through Gable Gap (as expected). The simulated heads in the center of the model domain also showed some variations relative to the Base Case as a result of the increased flow through the Gap.

MTRG reviewed the current project status and believes that significant progress has been made in calibrating the model during the past few months. Careful evaluations of the TOB surface, reasonably assigned GHBs along mountain fronts, and successful preliminary manual calibration to heads have been achieved. Automated calibrations using PEST and Monte Carlo simulations are ongoing to refine the selection of optimum calibration parameters. Additional combined optimization of GHBs and hydraulic parameters may yield further improvement.

Summary

A sitewide groundwater flow model of Hanford has been successfully created using MODFLOW 2000. This model was calibrated to historical water-level elevation data using the standard calibration procedures. Additional refinements of the model to better simulate historical contaminant plume evolution continue.

4.0 The MODFLOW Groundwater Flow Model for Hanford

This section provides a brief overview of the main features of the flow model. A more-detailed description of the methodology and results will be provided in an appendix that will be published in the *Draft TC & WM EIS*, which will undergo a public review and comment process.

Model Domain

- The model domain is bounded to the north and east by the Columbia River, to the southwest by the Yakima River, and to the northwest by a basalt subcrop above the water table.

Gridding

- The horizontal gridding of the model is based on a uniform 200- by 200-meter (656- by 656-foot) mesh covering the model domain.

- The vertical gridding includes 31 layers, each with top and bottom surfaces parallel to each other and roughly parallel to the ground surface, and with variable thicknesses ranging from 1 meter (3.3 feet) (in areas where the TOB surface is near the water table) to 40 meters (131 feet) deep (in the aquifer where less resolution is required).

Top of Basalt Surface

- A geostatistical analysis of over 850 observations of the TOB surface defined the TOB surface Base Case.

- In addition to the Base Case surface defined by the observed TOB surface, a value was assigned to each observation representing interpretational, positional, and measurement uncertainties. A series of Monte Carlo realizations was run, and the lower 95th percent confidence interval was chosen to represent the TOB surface in the Gable Gap area for the Alternate Case.

Hydrostratigraphic Units

- Thirteen material types were encoded into the model based on interpretations of over 4,500 boring logs.

The Columbia and Yakima Rivers

- The positions of the nearshores of the Columbia and Yakima Rivers were measured by differential Global Positioning System and encoded into the model.

- The long-term stages of the Columbia and Yakima Rivers were taken from Thorne et al. (2006).

Natural Recharge

- Natural recharge across the site was set to 3.5 millimeters (0.14 inches) per year, based on the value provided in the *Technical Guidance Document*.

- Following calibration, the model is not strongly sensitive to this parameter.

Anthropogenic Recharge

- Values for over 200 sources (or sinks) of water were taken from the Cumulative Impacts Inventory Database and encoded into the model.

Solver Settings

- The PCG solver was used to solve the flow equations.
- The head-closure criterion was set to 0.1 meters (0.3 feet).
- The groundwater mass balance closure was within 5 percent throughout the simulation.

The Pre-Hanford Solution (Initial Condition)

- The Pre-Hanford water table was calculated by draining an arbitrarily high water table in a transient simulation for a period of 500 years while holding the pre-Hanford BCs constant.

- This procedure eliminated unnatural dry cells in the final model.

- Calibration results show that the model is relatively insensitive to perturbations in the initial condition.

Calibration

- Initial calibration efforts using gradient-based methods (i.e., PEST) provided reasonable estimates of hydraulic conductivities for three independent calibration data sets.

- Evaluation of the topology of the objective function surface showed fine-scale structure, suggesting that the gradient-based estimates were probably affected by local minima, and that the uncertainty in the parameter estimates was probably poorly described by the assumption of local linearity.

- Monte Carlo optimization experiments were run to examine a wide range of parameter space without resorting to the assumption of local linearity. A series of over 7,000 realizations defined the best 2 percent of the solutions (with respect to differences between observed and predicted heads). These results provide a group of best estimates of the hydraulic parameters, as well as their uncertainties.

- In total during the development process, over 15,000 variants of the model were run to evaluate model parameter uncertainty and estimate the best model parameter data set.

- The model is strongly sensitive to the hydraulic conductivities of the Hanford, Ringold, and Cold Creek gravels. The final estimated conductivities are within the set of values inferred from field tests at the site.

Conclusion

- A groundwater flow field has been developed to analyze long-term impacts on groundwater beneath Hanford for the *TC & WM EIS*. The development effort was designed to address NEPA, DOE, Ecology, and U.S. Environmental Protection Agency considerations. Technical issues arising from the development, including comments from the public, were presented to a Technical Review Group at key points during the development effort. The *TC & WM EIS* groundwater modeling team and MTRG view the resulting groundwater flow field to be appropriate for use in the *TC & WM EIS*.

5.0 References

DOE (U.S. Department of Energy), 2005, *Technical Guidance Document for Tank Closure Environmental Impact Statement Vadose Zone and Groundwater Revised Analyses*, Final Rev. 0, Office of River Protection, Richland, Washington, March 25.

Ecology, EPA, and DOE (Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy), 1989, Hanford Federal Facility Agreement and Consent Order, Document No. 89-10, as amended, accessed through http://www.hanford.gov/tpa/tpahome.htm.

NRC (National Research Council), 1996, *The Hanford Tanks: Environmental Impacts and Policy Choices*, Committee on Remediation of Buried and Tank Wastes.

Thorne, P.D., M.P. Bergeron, M.D. Williams, and V.L. Freeman, 2006, *Groundwater Data Package for Hanford Assessments*, PNNL-14753, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington, January.

USGS (U.S. Geological Survey), 2004, *MODFLOW 2000 Engine, Version 1.15.00*, August 6.

WHI (Waterloo Hydrogeologic, Inc.), 2005, *Visual MODFLOW v.4.1 User's Manual – For Professional Applications in Three-Dimensional Groundwater Flow and Contaminant Transport Modeling*, Waterloo, Ontario, Canada, August.

Code of Federal Regulations

10 CFR 1021, U.S. Department of Energy, "National Environmental Policy Act Implementing Procedures."

40 CFR 1500–1508, Council on Environmental Quality, "Council on Environmental Quality Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act."

40 CFR 1502, Council on Environmental Quality, "Environmental Impact Statement."

Federal Register

62 FR 8693, U.S. Department of Energy, 1997, "Record of Decision for the Tank Waste Remediation System, Hanford Site, Richland, Washington," February 26.

United States Code

42 U.S.C. 4321 et seq., The National Environmental Policy Act of 1969.