4.0 Groundwater Modeling

This section describes groundwater modeling activities being conducted at the Hanford Site that are relevant to the site-wide Hanford Groundwater Monitoring Project. Recent activities under the groundwater modeling task have focused on efforts to consolidate the site-wide groundwater models into a single model to eliminate redundancies and promote consistency in groundwater modeling analyses at the site. A discussion of this consolidation effort taken from a newly published U.S. Department of Energy (DOE) document (DOE-RL-2000-11, Rev. 1) is described in Section 4.1.

Section 4.1 also provides an overview of ongoing specific applications of the site-wide groundwater flow and transport model developed by the groundwater project.

Section 4.2 describes efforts by the environmental restoration contractor to apply other groundwater models at a local scale to design and evaluate pump-and-treat activities for the remediation of contaminated groundwater. These models were used to describe the capture and injection zones for extraction and injection wells, respectively, and to estimate the area affected by the pump-and-treat operations at different times.

Objectives of Hanford Site Groundwater Model

A computer model of Hanford Site groundwater must be able to

- assess performance of waste-disposal facilities
- predict movement of contaminants
- evaluate remediation strategies.

4.1 Site-Wide Groundwater Model Consolidation Process

P. D. Thorne, M. P. Bergeron, S. K. Wurstner

Until recently, the Hanford Site has maintained multiple versions of site-wide groundwater flow and contaminant transport models. These different groundwater models have developed among different contractors since the Hanford Site mission changed from producing special nuclear materials to environmental restoration. The Project Hanford Management Contractor, Fluor Hanford, Inc., maintained a vadose zone and groundwater modeling capability to support active and planned disposals in the 200 Areas and operational issues at the site. The environmental restoration contractor, Bechtel Hanford, Inc., implemented a site-wide groundwater model in support of past-practice operable unit investigations and cleanup activities. Pacific Northwest National Laboratory (PNNL) maintains groundwater modeling capabilities to support the site-wide groundwater project and vadose zone modeling capabilities for a variety of site and national programs.

In response to both internal and external recommendations, DOE initiated a site-wide groundwater model-consolidation process, which included the participation of all affected Hanford Site programs. The objective of this process is to eliminate redundancies and promote consistency in groundwater analyses produced for Hanford Site programs. On September 5, 1996, John Wagoner issued a Letter of Instruction to affected programs, and site contractors[(a)] that said "... with DOE and contractor customers, tribal and stakeholder participation, PNNL will develop and maintain a predictive Hanford standard groundwater model...."

(a) Letter from U.S. Department of Energy, Richland, Washington, to Pacific Northwest National Laboratory and Westinghouse Hanford Company, dated September 5, 1996, "Single Groundwater Project for the Hanford Site."

In a letter[b] to regulators and stakeholders dated July 28, 1997, DOE also made a commitment to initiate the model-consolidation process in fiscal year 1998.

The purpose of the model consolidation process is to

- foster consistency in assumptions and applications across programs
- provide model enhancements based on new data/information and improved technical capabilities
- provide model flexibility to meet and support new program needs and decisions.

4.1.1 Recommendations for a Site-Wide Groundwater Flow and Transport Model

As an initial step, DOE established the scope of the model consolidation. This included defining the needs and requirements of a Hanford site-wide groundwater model, an evaluation of current site-wide groundwater models and codes, and specific recommendations for a consolidated site-wide groundwater model. External review of the recommendations for the consolidated site-wide groundwater model was also initiated.

The specific needs and requirements of the site-wide groundwater model were developed based, in part, on a review of current and future groundwater modeling activities conducted for various Hanford Site programs. The needs and requirements also reflect input collected from external stakeholders.

Based on input received from Hanford Site contractors and stakeholders, the consolidated site-wide groundwater model needs to meet a variety of Hanford Site project objectives including

- site-specific performance assessments of proposed waste disposal facilities
- assessment of environmental impact involving the modeling of contaminant transport and exposure prediction
- evaluation of groundwater remediation strategies including natural attenuation, hydraulic control/containment, and contaminant removal/cleanup
- design and evaluation of groundwater-monitoring networks
- risk assessments.

The key uses of the site-wide model over the next 5 years include modeling support to

- the groundwater project
- future iterations of the composite analysis of waste sites located in the 200 Areas plateau
- assessments to support tank farm corrective actions, tank waste retrieval, and tank farm closure for the Office of River Protection
- assessment of the facilities being considered for disposal of immobilized low-activity tank waste and solid waste disposal
- the system assessment capability being developed as part of the Hanford Site Groundwater/Vadose Zone Integration Project

Groundwater modeling analysis may also be needed to support

- the Hanford Canyon Disposition Initiative
- the 200 Areas Soil Characterization and Remediation Project
- assessments of solid low-level waste burial grounds
- permitting for liquid discharge facilities
- updates of the Hanford Site-Wide Groundwater Remediation Strategy (DOE/RL-94-95, Rev. 1)
- the development of final records of decision for contamination being managed by interim remedial measures (e.g., pump-and-treat remediation) in the 100 and 200 areas.

A technical evaluation was conducted of site-wide conceptual and numerical models and preliminary

(b) Letter from U.S. Department of Energy, Richland, Washington, to U.S. Environmental Protection Agency and Washington State Department of Ecology, dated July 28, 1997, "Completion of the Columbia River Comprehensive Impact Assessment (CRCIA) Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) Interim Milestone M-15-80-8."

recommendations for the consolidated site-wide groundwater model were developed in a series of internal workshops attended by representatives of Hanford contractors involved in groundwater modeling. Two most recently used site-wide groundwater modeling efforts were considered. One was conducted for the groundwater project and the other for the development of the Hanford Site-Wide Groundwater Remediation Srategy (DOE/RL-94-95, Rev. 1).

In general, the evaluation showed that both are capable of meeting many of the needs and requirements for a consolidated site-wide groundwater model. However, DOE concluded that the model developed by the groundwater project has broader capabilities to meet the anticipated needs of the site. Therefore, this model was selected for the initial phase of the site-wide groundwater model consolidation process. Capabilities of the groundwater project model include

- model resolution - The model contains a higher level of resolution in its representation of the Ringold Formation than used in the groundwater remediation strategy model. This framework can be more easily used to evaluate and investigate the importance of three-dimensional hydrostratigraphic complexity in the Ringold Formation. This is expected to have an increasing influence on future flow and contaminant transport as the water table declines.
- extent of model - The areal extent of the model includes the area south of the Hanford Site between the Yakima and Columbia Rivers. Including this area in the model provides the capability to address the potential movement of contaminant plumes off the Hanford Site.
- natural recharge - The model incorporates the effect of natural recharge as an upper hydrologic boundary condition. The importance of natural recharge on future groundwater flow conditions and contaminant transport is increasing as the effect of artificial recharge on the water-table dissipates.

DOE also initiated an evaluation of computer codes to implement the consolidated site-wide groundwater model. Only two computer codes were reviewed in this initial phase of the model-consolidation process: (1) the VAM3D-CG code developed by Hydrogeologic, Inc., in Herndon, Virginia, and (2) the CFEST-96 code developed by the CFEST Co. in Irvine, California. The groundwater remediation strategy model is implemented based on the VAM3D-CG code. The groundwater project model is based on the CFEST-96 code. In a qualitative comparison of the two computer codes, both VAM3D-CG and CFEST-96 were found to be technically acceptable.

In the interest of minimizing the impact of initial cost and schedule, DOE selected the CFEST-96 code as an interim code for implementing the consolidated site-wide groundwater model. DOE deferred decisions on final selection of the code until the external peer review of the consolidated site-wide groundwater model and the resulting final refinements and modifications have been completed.

4.1.2 External Peer Review of the Recommended Site-Wide Groundwater Model

As a part of the model consolidation process, the selected site-wide model was reviewed by outside experts in the fall of 1998. The three member review panel consisted of Dr. Steven M. Gorelick of Stanford University, Panel Chair; Dr. Charles Andrews of S. S. Papadopulos and Associates, Inc.; and Dr. James W. Mercer of HSI-Geotrans, Inc. The review panel commented on three specific issues:

- adequacy of the conceptual model and its technical capabilities to meet the anticipated uses and needs
- possible improvements to the modeling framework/implementation
- immediate need for new data.

Computer Modeling Plans

Computer modeling experts reviewed the Hanford Site groundwater model and recommended some improvements. Responses to these recommendations included plans to

- re-evaluate calibration of the model
- develop alternative conceptual models
- analyze uncertainties associated with the model.

The panel's comments and recommendations for each issue summarized from Gorelick et al. (1999a) are described below.

(1) The panel recommended that the highest priority is to adopt a broader modeling framework that accepts conceptual model uncertainty. Within this new framework, the site-wide model would serve as an important tool to help guide new data collection efforts. First, the degree of potential impact of the various sources of uncertainty can be assessed through analysis of all uncertainties including those introduced by alternate conceptual models. Second, the worth of new data for reducing model uncertainty can be evaluated. The integration of the site-wide model with a geographic information system is an excellent means to preserve the Hanford Site data for applications at a variety of spatial scales. The panel recommended that databases (original field measurements) and information bases (interpretations or interpolations) both be maintained. For example, this would enable details in well logs found in the database to be used to develop a geostatistical model for scales smaller than those found in the interpreted hydrogeologic facies information base. The panel also recommended that the site-wide groundwater model be thought of as a flexible and evolving platform for analyzing groundwater flow and contaminant transport. The model itself must not be stagnant because, as more data are collected, it is likely that the conceptual model of the groundwater system will change. In addition, new predictive capabilities will be desired. The model framework must be one in which new concepts can be tested and enhancements readily included. The framework must have the capability of being modified to test alternative conceptual models, reflect the most recent consensus conceptual model, and address concerns regarding water resources and water quality.

(2) The panel recommended that a new modeling framework be established that accepts the inherent uncertainty in model conceptual representations, inputs, and outputs. Given such a framework, the expected values of hydraulic heads and contaminant concentrations, as well as the range (distribution) of predictions, would be products of the site-wide groundwater model. A priority item is to construct a list of alternate conceptual model components and assess each of their potential impact on predictive uncertainty. The panel recommended a series of important improvements to the current site-wide modeling effort:

- The model should be recalibrated using a three-dimensional, transient inverse calibration.
- The existing representation of chemical reactions is limited to first-order decay and linear sorption. Although potentially adequate for some of the prevalent contaminants found in Hanford Site groundwater, for most of the contaminants of concern found in the vadose zone, reactive transport needs to be represented.
- Boundary conditions and boundary fluxes should be re-inspected because of some inconsistencies with existing information and because there is an insufficient conceptual basis for use of these conditions for applications of the site-wide model at both large and small scales.

- The spatial representation of recharge should be represented as a parameter having an expected value and estimated uncertainty.

(3) The panel commended the modeling team for their efforts in dealing with voluminous data, complex field conditions, and integrated/interdisciplinary approach to model building. With regard to the issue of model adequacy, the spectrum of anticipated uses and needs is so broad (ranging from time scales of less than 1 day to thousands of years and spatial scales of meters to kilometers) that this or any general, site-wide model cannot be expected to be adequate for all potential uses. It was suggested that an initial task should be to specify a narrower, and perhaps more pragmatic, list of model uses.

4.1.3 Response to Peer Review

This section presents an overview of the project plan that will be followed to address technical issues and concerns raised by external stakeholders and the external peer review panel on the site-wide groundwater model.

Based on specific advice provided by the external peer review panel (Gorelick et al. 1999b), the consolidated groundwater model project will focus on high-priority tasks that represent the key model improvements and modifications recommended by the panel:

- re-evaluation of the calibration of the site-wide model using a transient inverse calibration of Hanford Site historical operations, which will provide valuable information on parameter uncertainty and sensitivity coefficients
- development of realistic alternative conceptual models that will assist in bounding the uncertainty in flow and transport simulation results. Each of the alternative conceptual models will be individually calibrated to Hanford Site historical operations
- development and implementation of an uncertainty analysis framework that can receive a range of uncertain inputs taken primarily from the results of the development and calibration of the several alternative conceptual models and generate a range of related model results.

In the latter half of fiscal year 1999 and in fiscal year 2000, the consolidated site-wide groundwater modeling task has been performing some work in all three areas outlined above. However, the primary focus of the first effort is on calibration of the site-wide model to observations of hydraulic head, hydraulic testing results, and contaminant concentration data. This is a significant departure from previous approaches to site-wide model calibration that were limited to conditions observed in 1979. The 1979 period was assumed to represent a short period of unchanging hydraulic conditions that was suitable for a steady-state calibration of the site-wide model.

Efforts that will lead to the transient calibration of the current site-wide groundwater model and the alternative conceptual models involve four broad tasks related to

- gathering and analysis of historical data on hydraulic head, hydraulic testing information, artificial recharge, natural recharge, Columbia River and Yakima River stage changes, and other related information that will be needed to simulate the historical period of Hanford Site operations
- acquisition and testing of a universal inverse code, called UCODE (Poeter and Hill 1998)
- linking the UCODE to the current site-wide groundwater model code, CFEST-96, to allow efficient and effective execution of the UCODE/CFEST-96 package in the transient inverse calibration
- preparing historic observation data and information into required model data input files for use in the transient inverse calibration.

The consolidated groundwater modeling project plans to complete the transient inverse calibration of the current site-wide groundwater model using the UCODE/CFEST-96 computational framework in fiscal year 2000. Results of this work will be published in September 2000.

The consolidated groundwater model team will also work to define alternative conceptual models. It is anticipated that three to five alternative conceptual models will emerge that will reflect different credible combinations of boundary conditions and interpretations of the hydrogeologic framework.

In fiscal year 2000, a strategy for an uncertainty analysis framework will be developed. Uncertainties associated with prescribed processes, physical features, initial and boundary conditions, system stresses, field data, and model parameter values will be addressed. This analysis framework will ultimately be used to assess uncertainty in results produced by the range of alternative conceptual models.

Communication with the external peer review panel, regulators, Tribal Nations, stakeholders, and model users is being facilitated by means of an internet-based forum. A web page (available at http://etd.pnl.gov:2080/gwmodeling/) has been dedicated to the purpose of tracking technical issues and concerns and posting of other related information. This approach will provide for instant, widely available communication on technical issues and provide concern resolution with all parties, as well as enhancing feedback from concerned parties. The process of regulator and stakeholder interaction has already been initiated in the consolidation process and will continue through the web-based approach.

4.1.4 Model Applications

During fiscal year 1999, PNNL used the site-wide groundwater flow and transport model to predict water quality impact. This work continued into fiscal year 2000, and results will be presented in the Solid Wastes Environmental Impact Statement when it is completed. The purpose of this analysis is to calculate concentrations of contaminants in groundwater from source areas defined in each of the environmental impact alternatives. The analysis also assesses the impact to accessible surface water resources from contaminated groundwater. Calculated concentrations of key contaminants are compared with drinking water standards and provide the basis for estimates of potential human health risk and ecological risk for comparison between the alternatives.

The site-wide model was applied to an environmental impact statement for solid waste in fiscal year 1999. Results will be available after the work is completed in 2000.

The potential sources of groundwater contamination are solid radioactive and hazardous waste contained in burial grounds located in 200 East and West areas. This waste include past low-level waste buried since 1970, newly generated Category I and III low-level radioactive waste, mixed low-level radioactive waste, and transuranic waste retrievably stored in trenches and caissons located in several of the existing burial grounds.

4.2 Modeling to Support Pump-and-Treat Operations

W. J. McMahon, L. C. Swanson

Groundwater models were used at a local scale in operable units in the 100 and 200 areas to assess the performance of groundwater pump-and-treat systems to remediate contamination within the unconfined aquifer system. These models evaluated system performance and overall progress toward remediation objectives and goals, including evaluating different extraction and injection well configurations, predicting effects of different operational and pumping schedules, assessing extent of hydraulic influence, and evaluating groundwater travel times and extent of the capture zone.

Modeling was conducted using Micro-FEM©, a two-dimensional finite-element code. The MicroFEM© model was used to evaluate the following remedial action sites and contaminants of concern in the 100 K, 100 N, 100 D, 100 H, and 200 West areas:

- 100-KR-4 Operable Unit (100 K Area) - hexavalent chromium

- 100-NR-2 Operable Unit (100 N Area) - strontium-90
- 100-HR-3 Operable Unit (includes both 100 D and 100 H areas) - hexavalent chromium
- 200-UP-1 Operable Unit (200 West Area) - technetium-99 and uranium
- 200-ZP-1 Operable Unit (200 West Area) - carbon tetrachloride.

Additional information on pump-and-treat operations and figures showing the modeled capture zones are presented in Section 2.

4.2.1 Model Results for 100-KR-4, 100-NR-2, and 100-HR-3 Operable Units

Numerical modeling for these pump-and-treat operations provides a quantitative method to evaluate the hydraulic capture and optimize the pumping rates of the pump-and-treat system wells. Results of the modeling indicated that pump-and-treat extraction wells intercepted ~70% of the groundwater flow through the targeted area in the 100-KR-4 Operable Unit (DOE/RL-99-13). The capture zone is shown in Figure 2.3-18. Optimizing the pumping rates increased the capture to ~84%. Much of the uncaptured groundwater passing through the targeted plume area occurs in a culturally sensitive area. The decision to add wells to the network must balance the benefits of improved capture with the consequences of disturbing the sensitive area.

Computer modeling of pump-and-treat systems in the 100 Areas estimate that most of the contaminated groundwater in the target plumes is intercepted before it reaches the Columbia River. In fiscal year 1999, model results were used to optimize pumping rates and recommend locations for new wells to increase the effectiveness of the systems.

At the 100-NR-2 Operable Unit during the same time, the model results indicated that the pump-and-treat system was reducing the net groundwater flow to the Columbia River through the targeted plume area by ~96% (DOE/RL-99-02). The capture zone is shown in Figure 2.4-6.

The 100-HR-3 Operable Unit includes both 100 D and 100 H areas. At 100 D Area, the model results indicated that the extraction wells intercepted over 90% of the groundwater passing through the targeted plume area. At 100 H Area, the model results indicated that the extraction wells intercepted ~82% of the groundwater passing through the targeted plume area (DOE/RL-99-13). The capture zone is shown in Figure 2.6-16.

The analyses were run for the November/December time frame, which corresponds to the low flow time of year in the Columbia River when groundwater discharge to the river is greatest. During other times of the year, when the river stage is higher, the extraction wells intercept a higher percentage of the flow. For additional discussion on the 100-KR-4 and 100-HR-3 models, refer to DOE/RL-99-13. For additional discussion on the 100-NR-2 model, refer to DOE/RL-99-02.

4.2.2 Model Results for 200-UP-1 Operable Unit

Numerical modeling for this pump-and-treat operation was performed to evaluate effectiveness in containing the targeted area of the technetium-99 and uranium plumes and to track the progress of remediation. On the basis of the modeling results, the steady state capture flow lines extend outside and contain the entire targeted area of the plume (see Figure 2.8-40). Thus, the one extraction well (299-W19-39) appears capable of capturing and containing the entire high concentration area of the technetium-99 and uranium plumes. By the end of September 1999, the extraction well had removed at least one pore volume from the entire targeted plume area. The plume capture

efficiency was ~71%, which is the ratio of the amount of water removed from the target area of the plume to the total amount of water removed from the aquifer. For additional discussion on the 200-UP-1 model, refer to DOE/RL-99-02 and DOE/RL-99-79.

Computer models of two pump-and-treat systems in the 200 West Area estimate the capture zone of pumping wells.

4.2.3 Model Results for 200-ZP-1 Operable Unit

Numerical modeling was also performed to evaluate the remedial action at this pump-and-treat operation. The modeling results show the capture flow lines of the extraction wells extending outside the targeted carbon tetrachloride plume area and converging in the areas between the wells (DOE/RL-99-79). Thus, modeling indicates that the pump-and-treat extraction wells contain the entire high concentration area of the plume, and provide a continuous hydraulic barrier to plume movement. The capture zone is shown in Figure 2.8-17.

The three northernmost extraction wells have operated since 1996, and the areas of capture for individual wells have merged. The numerical modeling predictions indicate that pump-and-treat operations have removed 1 pore volume of water from the upper 15 meters of the aquifer from an area of 332,000 square meters around the northernmost extraction wells. The three southernmost extraction wells began operating in 1997, and the areas of capture for individual wells have not merged. The modeling predictions indicate that wells 299-W15-32, -36, and -37 have removed 1 pore volume of water from an area of 12,000, 24,000, and 31,000 square meters, respectively, around those wells. For a more detailed description of 200-ZP-1 modeling, refer to DOE/RL-99-02 and DOE/RL-99-79.