GROUNDWATER MODEL INPUT AND CALIBRATION RESULTS

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List of Acronyms

amsl	Above mean sea level
CSC	Casmalia Resources Site Steering Committee
ERM	ERM-West, Inc.
GMS	Groundwater Modeling System
HELP	Hydrologic Evaluation of Landfill Performance
HFB	Horizontal Flow Barrier
HSU	Hydrostratigraphic Unit
LPF	Larger property flow
PCT	Perimeter Control Trench
PEST	Parameter Estimation
P/S	Pesticide/Solvent
PSCT	Perimeter Source Control Trench
RCF	Runoff containment facility
RI/FS	Remedial Investigation/Feasibility Study
RM	Residual mean
RMS	Root mean square
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

F3-1.0 Introduction

This Attachment to Appendix F of the Casmalia Resources Superfund Site (Site) Final Remedial Investigation Report describes the construction and results of a three-dimensional numerical groundwater flow model used to assist in characterization of groundwater flow at the Site. The model was developed and modified over the past three years consistent with approach specified in the *Remedial Investigation/Feasibility Study Work Plan* (RI/FS Work Plan) (Casmalia Resources Site Steering Committee [CSC], 2004) and in accordance with subsequent comments and requests made by the United States Environmental Protection Agency (USEPA).

The modeling objectives, approach and scope, including general descriptions of the model features, are summarized below and detailed in Section F3-2.0 of this Attachment. Section F3-3.0 presents the calibrated model results including calibration statistics, final simulated aquifer parameter values, and simulated flow rates and flow paths.

F3-1.1 Model Objectives

The objectives of the groundwater flow model are to: 1) aid in characterization and evaluation of groundwater flow conditions (sources, sinks, flow rates and directions) for Remedial Investigation purposes; and 2) to evaluate the potential effectiveness of final site remediation measures as a part of the Feasibility Study. As such, the site-wide model is capable of simulating:

- Three-dimensional groundwater flow within and between the Upper and Lower Hydrostratigraphic Units (HSUs);
- Flow in and out of the entire Zone 1 area;
- Flow from the North Ridge to the North Drainage and to Casmalia Creek;
- Groundwater-surface water interactions including flow to and from all ponds; and
- Horizontal and vertical flow around and into the extraction facilities.

The model also must be calibrated to observed site conditions, and provide a reasonable approximation of the Site groundwater flow system.

F3-1.2 Model Features and Scope

As specified in the RI/FS Work Plan, the CSC used the United States Geological Survey (USGS) finite-difference groundwater flow model code MODFLOW-2000 and the particle tracking code MODPATH to simulate three-dimensional groundwater flow at the Site. MODFLOW was selected for its usability, manageability, efficiency and transportability. In particular the transportability of the public domain MODFLOW program and site model input files are advantageous for future site modeling. The MODFLOW files can and have been provided to agency staff and other parties, and can be run without any proprietary software.

Most model construction and calibration work was performed using the Groundwater Modeling System (GMS) v6.0, which pre-processes and post-processes the MODFLOW and MODPATH files. Most of the input data were constructed and stored in GMS “map” and “scatter point” coverages. However, GMS software is not required to run the Casmalia MODFLOW model. The MODFLOW-2000 files created by GMS can be imported into other groundwater modeling applications, such as Visual MODFLOW or Groundwater Vistas, with minor modification, or run

using only executable MODFLOW and MODPATH codes. To evaluate some cell mass balance errors reported by the GMS version of MODPATH, the CSC also ran the models using the recently released USGS version (5.0) of MODPATH.

The flow model was developed using Site aquifer property and hydrologic data as calibrated through a process of trial and error adjustment of input parameters and parameter estimation using the Parameter Estimation (PEST) computer code.

To simulate flow in and adjacent to the critical Zone 1 area, the model domain was defined as the area extending from the North Ridge south to the A-, B-, and C-drainages, and from Casmalia Creek on the west to the North Drainage and A-Drainage to the east (Figure F3-1).

Seven model layers were constructed to simulate vertical and horizontal flow within and between the Upper and Lower HSUs (Figure F3-2). Table F3-1 lists the model layers and thicknesses used to simulate the Upper and Lower HSUs. The model layer geometries were developed on the basis of the Upper/Lower HSU contact surface (Figure F3-3). Model layers 1 through 3 were used to simulate the Upper HSU, with the base of model layer 3 corresponding to the HSU contact surface, and layers 4 through 7 simulate the Lower HSU. To simulate locally dry conditions in the Upper HSU, portions of the model grid in Layers 1, 2, and 3 were inactivated. A detailed topographic map of the model area is shown on Figure F3-4.

Specified head boundaries were defined along the creeks, where groundwater elevations are controlled by these natural boundaries and do not vary significantly over time (Section F3-2.4), and at the northwestern edge of the model, to allow underflow along the North Ridge. Specified head boundaries were also defined for the areas of the five onsite ponds, and a general head (head dependent flow) boundary was assigned to the base of layer 7 to allow limited inflow and outflow through the bottom of the model. No-flow boundaries were defined along other lateral edges of the model.

Pumping from the Site extraction wells and trenches was also simulated. The Gallery Well, Sump 9B, and Well C-5 extract water from the upper layers of the model. The Perimeter Source Control Trench (PSCT) and Perimeter Control Trench (PCT) trenches are simulated using high-permeability zones in the Upper HSU (model layers 1-3) to simulate the gravel backfill of the fully-penetrating trenches, while volumetric pumping at the actual PSCT and PCT Sump features (PSCT-1, PSCT-2, PSCT-4, RAP-1A, RAP-2A, RAP-3A, RAP-1B, and RAP-1C) is simulated from individual cells (well nodes) in layer 4.

Net groundwater recharge was initially simulated using calculated values from the USEPA “Hydrologic Evaluation of Landfill Performance” (HELP) rainfall-runoff model, and modified based on trial and error adjustment and PEST analysis during model calibration.

Heterogeneous horizontal and vertical permeabilities were used in model layers 1 through 4, while uniform horizontal and vertical permeabilities were used in each of model layers 5 through 7. Permeabilities were also adjusted during simulations performed with PEST.

During the initial model development process, both steady-state and historical transient model simulations were evaluated. Based on the preliminary results of the model simulations, the groundwater system was considered sufficiently stable such that only steady-state conditions were simulated, and calibration to steady-state “wet” and “dry” conditions was performed.

Using the calibrated steady-state flow models, forward and reverse flow paths were simulated using the USGS particle-tracking model MODPATH. Forward flow paths were simulated to evaluate three-dimensional groundwater flow directions from recharge areas, such as the North Ridge, to the extraction facilities and model boundaries, and reverse flow paths from the wells and sumps were simulated to identify capture zones of the existing extraction facilities.

F3-1.3 Model Development Chronology

The CSC has constructed and calibrated the model with USEPA input and oversight. The model approach and construction were originally proposed in the RI/FS Work Plan. After initiation of RI work in 2004, the model was developed by the CSC with USEPA input. Several meetings and workshops were conducted to provide USEPA with updates on model construction and results, and technical memoranda on modeling approach (depth, layering) and input data (recharge) were prepared by the CSC and submitted to USEPA for comment. The following summarizes the modeling communications and submittals during the RI:

Date	Modeling Activity
1-Sep-04	CSC-USEPA Meeting Model Kickoff
8-Apr-05	CSC-USEPA Meeting to Discuss Model Set-up (Workshop #1)
	CSC Prepares Model Based on Model Set-up Meeting
8-Jun-05	CSC-USEPA Meeting to Discuss Preliminary Calibration (Workshop #2)
23-Jun-05	USEPA Comments on Initial Model Set-up
	CSC-USEPA Discussion on 7-Layer versus 9-Layer Model
31-Oct-05	CSC Submits 7-Layer Model Technical Memo
7-Dec-05	CSC-USEPA Meeting to Discuss Model Layers
16-Dec-05	USEPA Letter Rejecting 7-Layer Model and Requesting Technical Memo on Quantifying Recharge
31-Jan-06	CSC Submits Recharge Technical Memo
	CSC-USEPA Discussion and Information Exchange regarding 7-Layer versus 9-Layer Model
5-Jun-06	CSC-USEPA Meeting to Discuss Model Status
9-Jun-06	USEPA Letter Approving 7-Layer Model and Recharge TM
21-Jul-06	CSC Submits Preliminary Uncalibrated Model Files per USEPA Request
31-Dec-06	CSC Submits Preliminary Model Calibration Package with Model (Rev 1)
30-Jan-07	USEPA Comments on Preliminary Model Calibration Package (Rev 1)
	CSC Responds to USEPA Comments on Preliminary Model
10-Apr-07	CSC Submits Updated Model Files (Rev 2)
26-Apr-07	Meeting to Discuss Calibration Results (Workshop #3)
3-May-07	USEPA Comments on Model Rev 2
6-Jun-07	CSC Submits revised Model (Rev 2B)
	USEPA Reviews Model (Rev 2B)
16-Aug-07	Meeting to Discuss Calibration Results of Model; USEPA States Steady-State Models Should be Used in lue of a Transient Model
29-Aug-07	USEPA Provides Written Summary of Their Comments Made at August 16th Meeting on Model (Rev 2)
20,27-Sept-07	CSC Submits revised Model (Rev 2C) addressing Unconfined/Inactive Upper HSU
1-Nov-07	Over the Shoulder Review by CH2M Hill

6-Nov-07	CSC Submits SuperPest Model (Rev 3) as Requested During "OTS" Meeting
28-Nov-07	USEPA Comments on Model (Rev 3)
8-Jan-08	CSC-USEPA Meeting to Discuss Parameter Adjustments and Particle Tracking
11-Jan-08	CSC Initiates Model Peer Review by ERM-West, Inc. (ERM)
22-Jan-08	Over the Shoulder Review by CH2M Hill
18-Feb-08	Livemeeting Review by CH2M Hill, additional teleconferences and file transfers pertaining to MODPATH Reported Mass Balance Errors
05-Mar-08	CSC Submits Model Files and USGS Model Executables very few mass-balance errors
30-Mar-08	CSC Submits Final Model Files and Documentation Package
17-Mar-09	Teleconference between CSC and CH2M Hill to review USEPA comments on groundwater model from Draft RI Report
30-Mar-09	Teleconference between CSC and CH2M Hill to review progress on addressing USEPA comments on groundwater model from Draft RI report
14-Apr-09	Teleconference and Information Exchange between CSC, CH2M Hill and USEPA on agency comments on C-Drainage Barrier construction, and potential impact of saturated wastes in the Pesticide/Solvent (P/S) Landfill on groundwater flow paths simulated by model
02-Jun-09	Teleconference and Information Exchange between CSC, CH2M Hill and USEPA on C-Drainage Barrier construction, flow path simulations in landfill area and other agency comments on groundwater model in Draft RI Report
02-Sep-09	Teleconference and Information Exchange between CSC, CH2M Hill and USEPA on remaining agency comments on groundwater model

The frequent communications and USEPA review throughout the development process have resulted in a correctly functioning and well-calibrated groundwater flow model.

The following sections document the model calibration process, input parameter values, and model results.

F3-2.0 Model Input and Calibration

This section presents the approach used to calibrate the model. The CSC and USEPA reviewed progress during modeling to ensure that the model was calibrated in such a way to generate meaningful flow predictions for current and future extraction scenarios.

Existing data were used to formulate the initial model input parameters. As described below, initial estimates of some input parameter values were modified during model calibration. Some input parameters, such as extraction well pumping rates and pond stage elevations, were defined on the basis of site measurements and were not varied for most of the model simulations, while other parameters including aquifer hydraulic conductivity and recharge rates were adjusted within defined ranges to achieve model calibration.

F3-2.1 Calibration Process and Criteria

Model calibration was accomplished by defining and achieving quantitative and semi-quantitative calibration goals or targets. Calibration was quantitatively assessed through evaluation of residuals (the difference between observed and simulated heads), gradient directions, and volumetric flow rates. For the steady-state models constructed to simulate 2001 (wet) and 2004 (dry) conditions, head residuals at each Site well or a subset of wells were calculated, and flux residuals at model boundaries and surface features were evaluated. The residual error at each point was evaluated using statistical parameters including mean error and root mean squared error.

The CSC and USEPA discussed acceptable calibration criteria as part of preparing the RI/FS Work Plan. The criteria proposed in the RI/FS Work Plan included a quantified maximum head error residual term, as well as an appropriate set of observation points used to assess the residuals. The CSC proposed a calibration assessment that focused on the Upper HSU in the critical Zone 1 area, while still assessing calibration of the Lower HSU. Two criteria proposed in the RI/FS Work Plan were a Root Mean Square (RMS) head residual error of less than ten percent of the model area groundwater elevation range and a mean residual of less than five percent. For the site-wide model, the proposed calibration criteria for the Upper HSU Zone 1 source areas and extraction facilities (i.e. from the North Ridge to the PCTs) was an RMS error of 30 feet and Residual Mean (RM) error of 15 feet. This corresponds to an elevation range of about 700 and 400 feet above mean sea level (amsl). The less rigorous calibration criteria proposed for the Lower HSU was an RMS error of 36 feet and a RM error of 18 feet. This corresponds to an elevation range of about 700 to 340 feet amsl.

During the course of reviewing the model development and calibration, USEPA also proposed more comprehensive calibration criteria, which including water balance, flow paths, and consistency between the results of the model simulations and observed hydrogeologic conditions. These additional calibration criteria were subsequently used by CSC to evaluate the model calibration and are discussed in Section F3.0.

Preliminary calibrations used general head boundaries, which USEPA determined allowed too much volumetric flow in and out of the model (greater flow than was applied as groundwater recharge). In subsequent simulations, the conductance of the general head boundaries was reduced, which limited the amount of subsurface flow through boundaries. After reducing the number of active model cells in the Upper HSU near the North Ridge, some MODPATH

forward-tracking particles started near the Ridge stopped after moving to inactive overlying cells. Adjustment of the inactive cell distributions corrected this problem.

F3-2.1.1 Historical Calibration Periods

To simulate the variability in hydrologic conditions at the Site, the CSC constructed steady-state models simulating two different historical periods, March 2001 and March 2004. The March 2001 model represents peak “wet” or “high groundwater” conditions, based on high rainfall and inferred recharge rates preceding this period, high extraction system pumping rates, and peak historical groundwater elevation conditions, based on water level hydrographs. The March 2004 model represents “dry” or “low groundwater” conditions after several below-average rainfall years between late 2001 and early 2004. The steady-state models were calibrated to both 2001 and 2004 conditions by adjusting recharge rates, pumping rates, and boundary conditions. Most of the model calibration runs were performed using the March 2004 data, because more water level data were available during this period than during March 2001. All of the PEST runs were performed using the March 2004 observations. Additional simulations of 2001 conditions were then performed using the final hydraulic properties from the 2004 model with adjusted recharge, pumping rates and boundary conditions (constant head boundary elevations for the ponds).

Initially both transient and steady-state models were constructed to simulate the variability in hydrologic conditions at the Site. The transient model included 90 monthly stress periods between January 1997 and June 2004. After reviewing the preliminary calibration results from the steady-state and transient models, CSC concluded that the steady-state models were adequate to meet the objectives of the RI and FS without the use of the transient model, and further development of the transient model was discontinued.

F3-2.1.2 Water Level Calibration Data

The CSC performed a review of well completion intervals and measured water levels, and defined a set of wells that was used to assess model calibration. Measured groundwater elevations for both 2001 and 2004 in the wells were used to assess calibration. Table F3-2 lists the wells used to assess model calibration along with information on well depth, model layer(s) assignments, and the measured elevations. Figure F3-5 shows the calibration well locations by layer. The observed water level calibration data set included most existing Site monitoring wells. Of the existing Site monitoring wells, the calibration well set only excluded a few Lower HSU wells with poor quality or anomalous water level data (non-equilibrium conditions in newly-installed and/or extremely low-yielding wells). Extraction wells and trench sumps also were excluded from the final calibration well data sets, due to inaccuracies in simulated drawdown to the model cells representing the wells/sumps from the finite difference cell area approximations and unknown well loss (friction) factors.

Figures F3-6 through F3-10 are contour maps of the measured March 2001 groundwater elevations and Figures 3-11 through 3-15 are contour maps of the measured 2004 groundwater elevations.. The maps show head equipotentials for wells corresponding to the separate model layers (layers 1-3 combined, layer 4, layer 5, layer 6, and layer 7) and were used for comparison with model-simulated heads to assess calibration.

F3-2.1.3 Calibration Approach

The CSC constructed and calibrated the model using both trial-and-error and PEST methods. Initial model construction and calibration runs were based on estimated input parameter values. Boundary conditions were developed based on observed groundwater and pond stage elevations and only minor modifications to the boundary locations and heads were made during calibration. For general head boundaries, some manual adjustments to conductance terms were made, and discretization for the layer 7 general head boundary was changed during calibration to provide a smoother head solution. Initial estimates of groundwater recharge were developed by constructing polygons of recharge zones based primarily on topographic slope. Initial estimates of net recharge for each polygon were developed using the HELP model and later adjusted based on PEST results. Similarly, initial hydraulic conductivity polygons for each layer were constructed based on geology and hydraulic testing results, and later modified based on initial calibration results and PEST simulations. Extraction well and trench pumping rates were not adjusted during calibration runs.

Several parameter estimation simulations were performed using PEST during calibration of the March 2004 model. The parameters selected for inversion included recharge, and horizontal and vertical hydraulic conductivity in each model layer. Later PEST simulations inverted all polygons for recharge and conductivity simultaneously. Minor manual adjustments of PEST-calculated recharge and conductivities were made for the final calibration. Results of the PEST simulations and final calibration are discussed in Section F3.0.

F3-2.2 Model Domain and Discretization

Figure F3-1 shows the model domain. The site-wide model domain includes the area bounded by:

- Casmalia Creek to the west;
- The North Drainage and North Ridge to the north;
- An eastern boundary between well RP-108 in the A-Drainage and well RP-110 in the North Drainage; and
- A southern boundary between well RP-108 in the A-Drainage and a point on Casmalia Creek around 2,000 feet south of well RP-72.

A uniform row and column grid spacing of approximately 20 feet was used. The model grid consists of 469 rows and 375 columns.

F3-2.3 Model Depth and Layering

During 2005 and 2006, the CSC and USEPA exchanged correspondence, and held meetings regarding the appropriate number and depths of the model layers. Because the depth/thickness of the low-permeability Lower HSU is up to several thousand feet, the depth of the model was limited to the upper portion of the Lower HSU because further deepening did not affect the model results. The CSC's analysis of the effects of model depth and bottom boundary conditions were presented to USEPA in a February 24, 2006 *Memorandum Providing Additional Technical Information Regarding Model Thickness, Layering, and Vertical Flow* (MACTEC, 2006). After additional correspondence and discussion, the CSC and USEPA agreed that

seven model layers should be simulated, with a general head boundary condition applied to the bottom of layer 7 to allow limited inflow and outflow through the base of the model.

The model grid was constructed using the MODFLOW Layer Property Flow (LPF) Package and a “true layer” approach, with defined grid top and bottom elevations. Figure F3-2 illustrates the geometries of the seven model layers, and Table F3-1 lists the model layers and thicknesses used to simulate the Upper and Lower HSUs. The model layer geometries reflect the structural geometry of the Upper/Lower HSU contact. To construct the model grid, elevations of the Upper/Lower HSU contact surface in borings wells and piezometers (Figure F3-3) were interpolated to the model cells. Model layers 1 through 3 were used to simulate the Upper HSU and model layers 4 through 7 simulate the Lower HSU. The bottom of model layer 3/top of model layer 4 corresponds to the Upper/Lower HSU contact surface.

While layer top and bottom elevations vary across the model grid, layer thicknesses are essentially uniform and telescope into the Upper/Lower HSU contact surface to more accurately simulate the effects of the Upper/Lower HSU permeability contrasts. Model layers 2 and 3 were each defined as 5 feet thick; e.g., the bottom elevation for each cell of model layer 3 is defined as the HSU contact and the top elevation for each cell of model layer 3 is five feet above the contact elevation. The base of model layer 1 was defined as 10 feet above the Upper/Lower HSU contact, and the top of model layer 1 was defined as the current ground surface (Figure F3-4). The top of model layer 4 corresponds to the Upper/Lower HSU contact surface, and model layers 4 through 7 were defined as 25, 50, 75, and 150 feet thick, respectively.

Due to its construction based on the Upper/Lower HSU contact surface, portions of the upper layers of the model grid extend above the water table or specified head boundary elevations. These areas occur along portions of the North Ridge, the hills between the A- and B-Drainages and B- and C-Drainages, and the northern portions of the ponds. The areas where this condition occurs change temporally; during “dry” periods the water table occurs at lower overall elevations and more of the grid is above the water table than during “wet” conditions. Simulation of these conditions with MODFLOW was performed by inactivating portions of the model grid using the IBOUND array, as described below.

F3-2.4 Boundary Conditions

Figures F3-16 through F3-20 show the locations of the model boundary conditions by layer, and Table F3-3 summarizes the head values assigned to each model boundary. During model development and construction, the USEPA requested several changes to boundary conditions (connection of the B- and C-Drainage head boundary arcs, addition of a head or flux boundary at the North Ridge, and model bottom boundary condition), and the CSC implemented the requested modifications.

Both constant and general head boundaries were used to constrain the model. The North Drainage, A-Drainage, B-Drainage, Casmalia Creek, North Ridge, and onsite ponds were assigned constant head boundaries. Ambient vertical flow conditions were simulated using appropriate boundary conditions in each model layer. For the creek boundaries, vertical gradients were simulated by assigning different head values to the different model layers, based on water level observations in each HSU along the creeks. At the North Ridge, a general head boundary was assigned to allow underflow into the model domain. The bottom layer (layer 7) was assigned a general head boundary to allow limited inflow and outflow through the model base. The following sections describe the lateral and vertical boundary conditions.

F3-2.4.1 Creek Head Boundaries

Figure F3-16 shows the locations of constant head boundary nodes and arcs used along the North Drainage, A-Drainage, B-Drainage, and Casmalia Creek, and Table F3-3 summarizes the head values used at each boundary arc/node. During 2005, the USEPA reviewed the initial model boundary conditions and requested adjusting (combining) the Casmalia Creek and B-Drainage head boundaries, which the CSC modified accordingly. Boundary heads were assigned to nodes at the endpoints of general head arcs constructed along the current creek alignments, and at least one additional node was defined at intermediate points along the arcs for head control. Continuous constant head boundaries were then defined along the arcs by interpolating the nodal head values. Head values in each layer were developed based on groundwater elevations measured in Upper and Lower HSU wells and piezometers at or adjacent to the creeks, and at some locations different heads were assigned to the Upper and Lower HSU model layers creating small local vertical gradient conditions.

Along Casmalia Creek and the B-Drainage, constant heads ranged from 575 feet amsl at the northern nodes to between 338 and 340 feet amsl at the B-Drainage nodes. At the A-Drainage, constant heads ranged from 348-350 feet amsl. Along the North Drainage, constant heads ranged from 724 feet amsl at the northern nodes to 430 feet amsl at the southeastern nodes.

F3-2.4.2 North Ridge Head Boundary

The model includes a local general head boundary along the northwestern portion of the North Ridge to allow groundwater inflow to the model domain. Boundary heads along the North Ridge ranged from 780 to 830 feet amsl in layers 1 through 3 to 770 to 810 feet amsl in the Lower HSU. Some of the general heads on the Upper HSU model layers were not actually used in the simulations because a large portion of the Upper HSU at the North Ridge is dry and most of the cells in model layers 1 through 3 in the middle of this area were inactivated (see Section F3-2.3.5). Conductance values for the North Ridge general head boundaries were uniformly set to 0.0000004 square feet per day per foot.

F3-2.4.3 Pond Head Boundaries

Constant head boundaries in model layers 1 through 4 were defined over the wetted areas of the five onsite ponds. Figure F3-16 shows the pond locations and Table F3-3 lists the pond areas and head elevations. For the different calibration periods, different wetted areas and head elevations were used. For the March 2004 “dry” simulation, model cells in the upper three layers corresponding to portions of the ponds were inactivated using the MODFLOW IBOUND array, because the pond stage elevations in these areas were below some of the corresponding upper layer cell bottom elevations.

F3-2.4.4 Layer 7 General Head Boundary

All cells at the bottom of the model (layer 7) were assigned general head boundaries to allow limited inflow and outflow through the base of the model. Figure F3-20 shows the general head polygons used to construct the bottom boundary condition. For all of the layer 7 general head boundaries, uniform conductance values of 0.000001 square feet per day per square foot were defined to allow limited in and outflow. Other conductance values used for the bottom general head boundary resulted in too little or too much in/outflow and resulted in poor calibration.

F3-2.4.5 Inactive IBOUND Zones

Portions of the Upper HSU along the North Ridge and the tops of the hills between the A- and B-Drainages, and B- and C-Drainages are unsaturated, and the water table occurs below the Upper/Lower HSU contact. Because the model grid is constructed based on the Upper/Lower HSU contact surface, portions of model layers 1 through 3 of the model grid extend above the water table or specified boundary heads. These areas occur along portions of the North Ridge, and at the tops of the hills between the A- and B-Drainages, and B- and C-Drainages. In addition, constant heads representing the northern portions of the ponds are in some cases below the bottoms of the model cells in layers 1, 2, and 3, especially for "dry" pond conditions. The areas where this condition occurs change temporally; during "dry" periods the water table and ponds are at lower overall elevations and more of the grid is above the water table/ponds than during "wet" conditions.

Simulation of these conditions with MODFLOW was performed by inactivating portions of the model grid using the IBOUND array. Local model cells in model layers 1 through 3, which were determined to be above the water table or pond stages, were inactivated in the IBOUND array. Different inactive areas were constructed for 2004 and 2001 using the estimated saturated thickness of the Upper HSU during these periods (Figures F3-21 and F3-22).

Initially, different areas were inactivated for each model layer, with more inactive cells in layer 1 than the underlying two layers. However, this resulted in some problems with forward particle tracking. For the initial models with inactivated Upper HSU model cells near the top of the North Ridge, forward particles were stopping where a particle entered an active cell with a simulated head above the top of that cell (i.e., confined conditions) and with an inactive cell directly overlying the particle. In these cases, the vector path calculated for that confined cell included an upward component which transported the particle to the top of the active cell where it "bumped" into the overlying inactive cell and stopped. MODPATH interprets a particle moving to an inactive cell as an exit point and stops further particle migration even in cases where the stopping point is not a true internal sink. The CSC subsequently revised the distribution of inactive cells to allow forward particles to continue moving through the flow field. This was accomplished by merging the inactive cells in layers 1, 2, and 3 into a single inactive area (the area previously used for layer 3), as opposed to different inactive zones for each layer. By making this change, forward particles starting along the North Ridge remain in active model cells and do not stop.

F3-2.5 Extraction Wells and Trenches

All existing extraction facilities (wells and extraction trenches) were simulated using the MODFLOW Well Package. Figure F3-23 shows the locations of the extraction wells and trenches. Pumping rates are tabulated and plotted in Attachment F-2 (Water Budget) and vary significantly over time. Extraction wells and trench sumps/collection points are operated as to specified drawdown or "action" levels. Time-varying pumping rates generally correspond with rainfall and associated net recharge, and during "wet" years higher flow rates are required to maintain the action levels. For the steady-state simulations, representative flow rates corresponding to the average rate over the 6 month period prior to and after the calibration period were used (Table F3-4).

Design and construction of the extraction trenches is described in Section 2.0 of the RI Report. The extraction trenches were constructed as gravel-backfill slit trenches excavated to the

Upper/Lower HSU contact, with sump facilities overdrilled into the Lower HSU. Action levels for the extraction trench sumps are currently below the Upper/Lower HSU contact. Because head levels in the trench sumps are below the trench backfill depths, the MODFLOW Drain Package could not accurately simulate the construction and operation of the trenches. Instead, pumping of the extraction trenches was simulated using the MODFLOW Well Package, with "high permeability" hydraulic conductivity zones constructed in model layers 1 through 3 along the trench alignments (see below). Operating sumps associated with the PSCT (PSCT-4, PSCT-2, and PSCT-1), PCT-A (RAP-1A, RAP-2A, RAP-3A), PCT-B (RAP-1B), and PCT-C (RAP-1C) were simulated as pumping from layer 4. The Gallery Well, Sump 9B, and C-5, which are conventional vertical extraction wells pumping from the Upper HSU, were simulated as pumping from layer 3.

F3-2.6 Recharge

An analysis of net groundwater recharge rates was performed to accurately simulate recharge rates and distribution. Net recharge is one of the most critical input parameters and initial recharge rates for different site areas were estimated using an independent rainfall-runoff model, the HELP model. Net recharge rates for different site subareas from the HELP model simulations were used as initial estimates, and subsequently changed during PEST model calibration simulations and final model calibration.

Input parameters for the HELP model included weather data, soil design data. The model also uses solution techniques that account for the effects of surface storage, snowmelt, surface slopes and runoff, infiltration, evapotranspiration, vegetative growth, and soil moisture storage. The HELP model simulations were performed for 35 polygon areas within the model domain (Figure F3-24). Common parameters such as rainfall rate, temperature, wind speed, etc., were used for each polygonal area, while topographic slope, depth to groundwater and soil permeability were varied for each polygon. The input parameters and results of the HELP model simulations are described in detail in Attachment F-2. Net recharge estimated using the HELP model ranged from around three to 50 percent of annual rainfall. The net recharge rates generated from the HELP model were input into the MODFLOW model for the initial calibration simulations.

Subsequently, net recharge was estimated using PEST calibrated to March 2004 conditions. For the PEST recharge inversions, the range of allowable net recharge was set from three to 50 percent of average rainfall, except over the capped landfill areas, where recharge was set to zero. Minor adjustments to the recharge rates estimated by PEST were made to the final calibrated model. Tables F3-5 and F3-6 list the recharge rates used in the final models calibrated to 2004 and 2001 conditions, respectively. Comparison of the net recharge rates estimated using the HELP model and PEST reveals some differences but overall agreement with higher rates simulated on the ridges and in the flatter areas of the Site, and less recharge on the steeper slopes. For the 2001 "wet conditions simulation" around 36 percent more recharge was simulated than for the 2004 "dry conditions simulation". Additional discussion of final simulated recharge and water budget components is presented in Section F3-3.3, below.

F3-2.7 Aquifer Hydraulic Properties

The model grid and aquifer hydraulic properties were simulated using the MODFLOW LPF Package. Heterogeneous hydraulic conductivities were assigned within each HSU, with more detail in model layers 1 through 4 around the most important local-area features. Clay barriers

adjacent to the Gallery Well, PCB Landfill, PCT-B and PCT-C were simulated using the MODFLOW Horizontal Flow Barrier (HFB) Package.

Initial values for horizontal and vertical hydraulic conductivity were developed based on the mapped distribution of geologic materials and results of pre-RI hydraulic testing (slug, packer, and pumping tests) and adjusted during model calibration. Table F3-7 lists the results of the hydraulic tests (as hydraulic conductivities) by model layer, and a comparison of the hydraulic conductivity test results and the conductivity values used in the calibrated models is shown in Figure 3-25. Figures F3-26 through F3-30 show the point hydraulic conductivity test values and hydraulic conductivity polygons used in the individual model layers. Based on evaluation of the hydraulic testing results and geologic mapping of alluvium, fill, and weathered claystone, the Upper HSU permeability distribution is controlled by the extent of relatively higher permeability alluvium and emplaced fill, which occurs primarily in paleo and active stream valleys. Permeability zones for the Upper HSU (model layers 1 through 3) were developed using polygons constructed for the alluvial and weathered claystone areas (Figure F3-26). Permeabilities in the Lower HSU are controlled by fractures, which do not show definitive trends in planar orientation or lateral distribution, but do tend to decrease with depth (Appendix E).

During model calibration, trial-and–error and PEST simulations were performed and both horizontal and vertical permeabilities for the Upper and Lower HSUs were adjusted relative to the initial estimated values. These adjustments were limited to the range of permeabilties measured in the Upper and Lower HSU by hydraulic tests (Figure 3-25) and to reasonable values for the subsurface materials that are present at the Site. The following sections discuss the initial and final simulated horizontal and vertical hydraulic properties for the Upper and Lower HSUs, and for the clay barriers.

F3-2.7.1 Upper HSU Hydraulic Properties

Figure F3-26 shows the hydraulic property polygons constructed to simulate permeabilities of the Upper HSU. Due to the relatively small thicknesses of model layers 1 through 3, the same polygons and permeability values were used for all Upper HSU layers. Forty-nine permeability polygons were ultimately used to simulate the Upper HSU. The polygons were constructed on the basis of the mapped distribution of alluvium and fill, which exhibit the highest permeabilities, and additional polygons were constructed to provide detail and flexibility to increase calibration quality. For the initial model setup and runs, relatively higher permeabilities of 2.0 feet per day were assigned to alluvium areas and lower permeabilities of 0.02 foot per day were assigned to weathered claystone areas. For the extraction trenches, high permeability zones of 50 feet per day horizontal hydraulic conductivity with a horizontal to vertical anisotropy of one were defined along the trench alignments. For the trench segments, row-to-row or column-to-column connectivity was maintained to allow proper simulation of the extraction trenches.

During model calibration, both horizontal and vertical permeabilities (anisotropy ratio) for the Upper and Lower HSUs were adjusted relative to the initial estimated values. Table F3-8 lists the final horizontal hydraulic conductivities and anisotropy ratios used in the calibrated models. Both horizontal and vertical permeabilities for each permeability polygon in each layer, along with recharge, were inverted during the PEST simulations. For the Upper HSU, the range of allowable horizontal hydraulic conductivity was set to 0.01 to 10 feet per day, and anisotropy was allowed to vary from 1 to 50. In general, the PEST results for both horizontal and vertical permeabilities are consistent with the site conceptual model of higher permeability in alluvium and fill areas, and lower permeability in weathered claystone areas. The highest permeabilities

were simulated in the creek drainages, where PEST calculated hydraulic conductivities of between 1 and 10 feet per day. Lower hydraulic conductivities were calculated for weathered claystone areas. PEST-estimated anisotropies tended to be highest in the creek and alluvial areas, where ratios of up to 50 were calculated, with lower values calculated for some weathered claystone areas. These values are consistent with the site conceptual model of higher horizontal permeability and anisotropy ratios in the stratified alluvial materials and with the range of measured permeabilities from the hydraulic tests (Table F3-8 and Figure F3-25).

F3-2.7.2 Lower HSU Hydraulic Properties

Figures F3-27 through F3-30 show the hydraulic property polygons constructed to simulate permeabilities of the Lower HSU (layers 4, 5, 6, and 7). Table F3-8 lists the final horizontal hydraulic conductivities and anisotropy ratios used in the calibrated models.

For layer 4, ten polygons were constructed to provide flexibility in permeability distribution and allow improved calibration. Individual cells representing the extraction trench sumps in layer 4 were assigned high permeabilities of 50 feet per day horizontal hydraulic conductivity with a horizontal to vertical anisotropy of one. Horizontal hydraulic conductivities for the other layer 4 polygons calculated by PEST ranged from 0.0031 to 0.24 foot per day, and anisotropy ratios ranged from 5 to 20.

For layers 5 through 7, homogeneous horizontal hydraulic conductivities and anisotropies were used within each layer. Horizontal hydraulic conductivities for layers 5, 6, and 7 calculated by PEST were 0.0005, 0.0003, and 0.0001 foot per day, respectively. Anisotropies for layers 5, 6, and 7 calculated by PEST were 7.2, 8.0, and 1.0, respectively.

These results are generally consistent with measured permeabilities from the packer tests and pumping tests (Table F3-7 and Figure F3-25), and the site conceptual model, which indicate decreases in permeability with depth in the Lower HSU. The measured permeabilities from the slug tests are somewhat higher than values from the packer and pumping tests, and the values used in the model for layers 5 and 6. However, the slug tests, which only sample the region immediately adjacent to the well borings, may be more representative of the disturbance of well installation or development than the in situ conductivity of the Lower HSU.

F3-2.7.3 Horizontal Flow Barriers

Clay barriers present in Zone 1 were simulated using the MODFLOW HFB Package. Clay barriers adjacent to the Gallery Well, PCB Landfill, PCT-B and PCT-C were simulated using a hydraulic conductivity of 0.00001 ft/day. The clay barrier near the PCB Landfill was assigned to model layer 1 only, while the other clay barriers were simulated as extending from layer 1 through layer 3.

F3-2.7.4 Landfill Wastes

The wastes and other materials in the landfills, with the exception of a portion of the wastes in the P/S Landfill, are unsaturated and were not simulated in the model, which is a saturated flow model. In response to USEPA comments on the draft model, CSC evaluated the potential impact of the saturated wastes in the P/S Landfill on groundwater flow paths simulated by the model. In this evaluation, the saturated wastes were represented as a high permeability zone in model layer 1. The evaluation indicated that the saturated wastes in the P/S Landfill had no

significant impact on the flow paths simulated by the model and the hydraulic conductivity zonation in layer 1 of the final model was not modified to simulate the saturated wastes.

F3-2.8 Flow Path Modeling

Using the calibrated MODFLOW solution, forward and reverse flow paths were simulated using the USGS particle track code MODPATH. MODPATH uses flow budget files generated by MODFLOW and calculates three-dimensional flow paths and travel times for particles in the groundwater flow system. MODPATH was used to determine ultimate discharge points for particles entering the groundwater system as recharge, and the capture zones of the extraction wells and trenches at the Site. To determine the fate of water recharging the groundwater system, numerous particles were started near the water table in model layers 1, 2, 3, and 4 in critical site areas including the North Ridge and allowed to move forward through the flow field to their ultimate discharge points (extraction facility or model boundary). Capture zones of the extraction wells were determined by reverse-tracking numerous particles started adjacent to extraction wells and allowed to flow backwards through the flow field.

Additional model testing and validation related to particle tracking and mass balance errors reported by MODPATH was performed after most calibration runs were completed. Results of the model calibration and flow path simulations are discussed below.

F3-3.0 Model Results

This section presents the model results, including simulated three-dimensional hydraulic heads, calibration quality, volumetric mass budgets for the model inflow and outflow components, and flow path results. The results presented in this section focus on the March 2004 simulation, although the March 2001 simulation results are also documented and discussed.

The final model was developed after preliminary and intermediate calibration runs, based on the initial results and modified based on observed model response to input parameter changes. After construction and specification of model layering, boundaries, extraction system flows, and construction and modification of polygonal zones for recharge and permeability, the PEST program was utilized to adjust net groundwater recharge, and horizontal and vertical hydraulic conductivities. For the March 2004 PEST run, all recharge and permeability polygons were inverted simultaneously. Initial estimates for the input parameters and allowable ranges were provided, and 20 PEST iterations were performed with good results. Table F3-9 summarizes the PEST process including error and parameter values for each PEST iteration. Final "manual adjustments" were then performed to some of the input parameters including certain hydraulic conductivity and recharge zones.

F3-3.1 Simulated Heads

Model-simulated groundwater elevations were tabulated and mapped in areal and cross-sectional views. Tables F3-10 and F3-11 list the simulated heads at each observation well location for the March 2004 and March 2001 simulations, respectively. For the March 2004 calibration, simulated steady-state water levels within the entire model domain range from 338 to 927 feet amsl. Simulated March 2004 heads at the Site observation wells range from 352 to 700 feet amsl. For the March 2001 calibration, simulated steady-state water levels within the entire model domain were on average around 8 feet higher than groundwater elevations simulated for March 2004.

Figures F3-31 through F3-37 present contours of simulated equipotentials in map view for each model layer for the March 2004 simulation. For the March 2004 calibration, simulated heads in each of Upper HSU model layers 1, 2, and 3 are similar (Figures F3-31 through F3-33), with only a few feet of head difference simulated between the Layers at most locations. Accordingly, overall horizontal hydraulic gradients in each of layers 1, 2, and 3 are similar. The equipotential contour patterns in the Upper HSU reflect the boundary conditions, sources and sinks, and permeability zones, which cause changes in gradient magnitudes and directions.

The final calibrated steady-state models simulate flow conditions which are consistent with the site conceptual model. Divergent flow from the North Ridge results from simulated recharge and the three dimensional hydraulic conductivity field, which is based on the HSU structure and distribution of geologic materials. Simulated heads indicate divergent flow from the North Ridge north to the North Drainage and South through Zone 1. The inactivated cells in model layers 1, 2, and 3 along the North Ridge are also illustrated on Figures F3-31 through F3-33.

At and downgradient (south) of the waste landfills, convergent flow occurs into the relatively high permeability aquifer materials in the central drainage. Flow to the PSCT is also indicated by the heads and equipotentials, which "V" and converge into the trench alignment. Upper HSU flow also converges into the northern edges of the pond boundaries. Flow to the North

Drainage, A-Drainage and B- and C-Drainages and Casmalia Creek is also indicated by the simulated heads.

In the Lower HSU (model layers 4, 5, 6, and 7 - Figures F3-34 through F3-37), simulated March 2004 heads are also consistent with observed flow conditions. Inflow from the general head boundary at the western edge of the North Ridge moves along and away from the ridge to the North Drainage and Casmalia Creek and into Zone 1. In Layer 4 (Figure F3-34) convergence of flow to the PSCT and to a lesser degree to the PCT is inferred from the simulated heads and contours, as is flow to the head boundaries along the creeks. With increasing depth, the head field in each Layer is smoother, reflecting the homogenous permeabilities assigned to lower layers 5, 6, and 7.

Figures F3-38 through F3-44 present contours of simulated equipotentials for each model layer for the March 2001 simulation. In accordance with increased recharge and boundary heads and with observed groundwater elevations, slightly higher groundwater elevations were simulated for March 2001 than for March 2004. However, overall flow directions and rates for this period are similar to the March 2004 simulation.

Figure F3-45 shows the location of four model row and column cross sections, and Figures F3-46 through F3-453 show contours of simulated equipotentials in cross-section view for the March 2004 and March 2001 simulations. Figures F3-46 through F3-53 are oriented along model columns (north-south) or rows (east-west) and are quickly generated from the model. At USEPA's request, four additional "bending" cross-sections of simulated heads approximately aligned along and perpendicular to presumed flow paths were constructed (Figure F3-45). These cross-sections have been used previously to present and interpret measured groundwater elevations as documented in the main section of this Appendix and in the RI/FS Work Plan and Semiannual Groundwater Monitoring Reports. Simulated hydraulic heads along the bending cross-sections were extracted from the MODFLOW head solution file using the PEST utility program SECTION.

The distribution of vertical hydraulic gradients is illustrated on the cross-sections. Model cross-section N-S 1 (Figure F3-46), along model column 194, extends from the North Drainage Boundary south up the North Ridge to the groundwater divide, and topographically downhill through the P/S Landfill Gallery Well, PSCT 2, and Runoff Containment Facility (RCF) Pond area. Section N-S 2 (Figure F3-47), along model column 161, extends from the North Drainage Boundary south up the North Ridge to the groundwater divide, and topographically downhill through the PSCT 4 and PCT-B area. From the recharge areas along the North Ridge, simulated heads indicate downward vertical gradients beneath the ridge and divergent flow to the north and south. Model cross-section E-W 1 (Figure F3-48), oriented along model row 172, extends along the North Ridge and indicates downward flow along the ridge. Within Zone 1, the hydraulic effects of the extraction wells and PSCT are indicated by the equipotential patterns indicating convergent flow to the wells and trench in model layers 3 and 4 (Figures F3-46 and F3-47). Cross-section E-W 2 (Figure F3-49), which is oriented along model row 317 and intersects the PCT-C and PCT-A, also indicates convergent and upward flow to the trench. Head equipotentials indicate predominantly horizontal flow through the Zone 1 area between the PSCT and PCT. Vertical gradients beneath the ponds indicate groundwater discharge to the ponds in the upgradient/northern portions and groundwater recharge from the ponds to the aquifer in the downgradient/southern areas. Gradients near the PCTs are generally upward. Gradients at the bottom of the model are generally horizontal, indicating limited inflow and outflow to and from the bottom general head boundary.

The bending cross sections (Figures F3-54 Figure F3-61) show similar head patterns. Downward gradients are present beneath the North Ridge, as illustrated on sitewide sections A-A', C-C', and D-D' (Figures F3-54 through F3-56 and Figures F3-58 through 3F-60). Convergent flow to the Gallery Well and PSCT is indicated on Sections C-C', D-D', and F-F' (Figures F3-55 through F3-57 and Figures F3-59 through F3-61). Upward flow to the PCT-A and PCT-B is indicated on Sections C-C' and D-D' (Figures F3-55, F3-56, F3-59, and F3-60).

F3-3.2 Calibration Results

Over the course of model development, numerous modifications of the input parameter values and distribution were made in attempts to improve model calibration. Due to uncertainties in the actual distribution of recharge, hydraulic conductivity in three-dimensions, and the inherent limitations of model approximations in some areas of the Site, excellent calibration proved difficult to achieve. In some areas of the model domain, adjacent observation wells within a particular model layer exhibited significantly different groundwater elevations over relatively small lateral distances; in these areas perfect calibration to these multiple observations was impossible. In other areas, such as between PSCT-1 and the RCF Pond only very small head differences were observed over relatively large lateral distances, which also prevented excellent calibration. In addition, final manual adjustment modifications to model construction and input parameters relative to those generated by PEST in order to "balance" values for different parameter polygons, and the IBOUND array modifications necessary to eliminate apparent MODPATH errors (see below) resulted in poorer calibration quality in some areas.

To assess model accuracy, simulated heads were compared with observed heads. Model calibration also focused on simulating three-dimensional flow from and to the critical site hydrologic features in accordance with the site conceptual model. As described above, the final calibrated steady-state models simulate flow conditions which are consistent with the site conceptual model.

Tables F3-10 and F3-11 present the observed versus simulated head results for March 2004 and March 2001 models, respectively. Observed versus simulated calibration charts by model layer are presented in Figures F3-62 through F-68 for the 2004 model and in Figures F3-69 through F3-74 for the 2001 model. The tables include the groundwater elevations and differences (error) in simulation results at each calibration well point, and calibration quality summary statistics. Observed and simulated heads in each model layer were compared and overall calibration was assessed through head residuals.

Overall calibration of the steady-state models meets the calibration criteria defined in the RI/FS Work Plan. As illustrated on the regression charts and residual tables, correlation between observed and simulated heads for each model layer is good. For the site-wide model, the CSC proposed a mean head residual of less than five percent of the model area groundwater elevation range and a RMS error of less than ten percent of the model area groundwater elevation range, which corresponds to an RMS of 30 (Upper HSU) to 36 (Lower HSU) feet and mean error of 15 to 18 feet. As listed in Table F3-10, the RMS and mean error results for the March 2004 model are significantly lower than the maximum criteria. In model layers 1 through 3, the mean error residuals are 1.26, 6.23, and 2.80 feet, respectively. In model layers 4 through 7, the mean error residuals are -0.04, 6.26, 0.86, and 2.21 feet, respectively. The composite mean error for all layers for the March 2004 model is approximately 3.5 feet, significantly lower than the calibration criteria of 15 to 18 feet. The root mean squared errors for

each of model layers 1 through 7 of (7.93 to 22.94 feet) and for the entire model are also lower than the calibration criteria of 30 to 36 feet.

F3-3.3 Water Balance and Volumetric Fluxes

Volumetric flow data generated by MODFLOW and stored in the cell-by-cell flow budget file (.ccf) were mapped and evaluated to determine the relative and absolute magnitudes of inflow and outflow components and vertical flux conditions within the model domain. Tables F3-12 and F3-13 present the water budget results for the March 2004 and March 2001 simulations, respectively. The overall water budgets for these simulations had very low net errors, and the relative magnitudes of inflows (through recharge and boundary conditions) and outflows (though boundaries and wells) are consistent with the rates assigned as input and the site conceptual model. For the March 2004 and March 2001 simulations, similar volumetric flow rates were calculated for the head boundaries. Constant head boundaries (creeks and ponds) had much higher volumetric flow rates than the general head boundaries (North Ridge and Layer 7). The largest flux differences between the 2004 and 2001 simulations were calculated for pumping wells and recharge; for 2001, extraction pumping was around 220 percent of 2004 pumping, and recharge was around 136 percent of 2004 recharge.

In response to USEPA comments on the draft model, CSC calculated the volumetric mass balance for the constant head boundary representing Casmalia Creek in the 2004 model (Figures F3-16 through F3-20). The volumetric mass balance for the western constant head boundary was calculated using the USGS MODFLOW utility program ZONEBUDGET and is summarized in Table F3-14. There is a net outflow along the boundary in the Upper HSU (layers 1, 2 and 3) representing discharge of shallow groundwater to the creek. The groundwater flux along the boundary in the Lower HSU (layers 4, 5, 6 and 7) is negligible indicating that there is no significant groundwater flow across the boundary in the Lower HSU.

For the March 2004 and March 2001 simulations, Figures F3-76 through F3-83 show the recharge rate from precipitation, pond recharge and discharge flux, and the vertical components of groundwater flux between the Upper and Lower HSUs (layers 3 and 4), and through layer 7. Based on the .ccf data, local upward and downward vertical components of groundwater flux occur in most model layers. For example, the vertical flux component between model layers 3 and 4 (FiguresF3-78 and F3-82) is downward beneath the North Ridge, and upward near the creek boundaries. An upward vertical flux component between layers 3 and 4 also occurs near the northern portions on the onsite ponds (Figures F3-77 and F3-81) and beneath some of the extraction facilities, indicating groundwater discharge from the Lower HSU into the ponds and pumping wells/trenches, while a downward vertical flux component occurs along the southern portions of the ponds, indicating groundwater recharge from the ponds to the aquifer and downgradient PCT extraction systems. Both upward and downward vertical components of groundwater flux also occur through the base of the model (layer 7), but at relatively low rates (Figures F3-79 and F3-83). Although vertical components of groundwater flux occur in most model layers, particle tracking shows that the horizontal components of groundwater flux simulated by the models are greater than the vertical components (Section F3-4).

In response to USEPA comments on the draft model, CSC investigated the upward vertical component of groundwater flux in layer 7 in the landfills area (Figures F3-79 and F3-83), which is inconsistent with the original site conceptual model. The results of this investigation indicated that the upward vertical component of groundwater flow simulated in the model in this area was due to the zero recharge rate used for the landfills, which are capped. The landfill caps do not

allow recharge into the groundwater flow systems; therefore, there is no downward flow under the landfills area. CSC considers the upward component of vertical groundwater flow in layer 7 simulated by the model to be consistent with measured upward vertical gradients near the landfills after capping (Section 6.1.2) and to represent a real-world refinement of the site conceptual model.

F3-3.4 Flow Path Results

Forward and reverse flow paths calculated by MODPATH were used to evaluate flow conditions and capture zones of the extraction facilities. MODPATH uses the cell-by-cell budget file generated by MODFLOW to calculate forward and reverse flow vectors through an interpolation algorithm. Forward flow paths were simulated by generating single particles in selected individual model cells along the North Ridge, which were allowed to move advectively through the flow field. Reverse flow paths were simulated by generating a series of particles in an arc around each extraction facility, which were allowed to move advectively backward through the flow field to the sources of inflow contributing to the extraction point.

For the initial flow path results provided in 2007, USEPA expressed concerns about some forward particles “stopping” within the flow field prior to reaching a true sink. The CSC subsequently researched the problem and determined that in previous models with IBOUND-inactivated Upper HSU model cells near the top of the North Ridge, forward particles were stopping where a particle entered an active cell with a simulated head above the top of that cell (i.e., confined conditions) and with an inactive cell directly overlying the particle. In these cases the vector path calculated for that confined cell included an upward component which transported the particle to the top of the active cell where it “bumped” into the overlying inactive cell and stopped. MODPATH interprets a particle moving to an inactive cell as an exit point and stops further particle migration even in cases where the stopping point is not a true internal sink.

The CSC subsequently revised the distribution of inactive cells in the model to allow forward particles to continue moving through the flow field. This was accomplished by merging the inactive cells in layers 1, 2, and 3 into a single inactive area (the area previously used for layer 3), as opposed to different inactive zones for each layer. By making this change, forward particles starting along the North Ridge remain in active model cells and do not stop.

The USEPA also expressed concern on some mass balance errors for individual model grid cells reported by MODPATH. A new version of MODPATH was released by the USGS in November of 2008. This version corrected errors in the earlier versions of MODPATH that incorrectly reported the volumetric mass budgets for individual cells under certain conditions. The particle tracking simulations were subsequently rerun by CSC for the Final RI Report using this latest version of MODPATH and the results of the revised simulations included in this section.

Figures F3-84 through F3-87 show simulated forward flow paths for particles generated just south of the North Ridge groundwater divide in the Upper and Lower HSUs, respectively. Forward particles generated in the Upper HSU, just south of the inactivated cells on the North Ridge (Figures F3-84 and F3-86), flow south through the flow field and ultimately discharge to the extraction wells, trenches, ponds, and creek boundaries. Forward particles generated in the Lower HSU, just south layer 4 groundwater divide at the North Ridge (Figures F3-85 and F3-87), also flow to the extraction wells and boundaries, although fewer particles originating in the Lower HSU discharge to the wells and ponds than those originating in the Upper HSU.

Figures F3-88 and F3-89 show reverse track flow paths or “capture zones” of the extraction wells and trenches. Based on the reverse flow paths, groundwater extracted from the Gallery Well originates from areas to the northwest, near the PCB Landfill just south of the North Ridge. The capture zone of Sump 9B extends to the North Ridge, north of the P/S Landfill. PSCT-4 captures groundwater originating from areas due north including the western portion of the PCB Landfill area and North Ridge. PSCT-2 extracts water entering the PSCT north and west of PSCT-2. PSCT-1 extracts water recharging in the central drainage between the P/S and Metals Landfills and from the North Ridge.

The reverse flow paths indicate groundwater extracted from the PCT-A sumps originates from both the RCF Pond and hills north and east of RAP-1A. PCT-B captures water originating from the RCF and Pond 13. PCT-C and C-5 capture water originating from the A-Series Ponds and from upgradient areas as far north as the North Ridge.

Figures F3-90 through F3-93 show simulated forward flow paths for particles generated within the boundaries of the total volatile organic compound (VOC) plumes identified in the Upper and Lower HSUs. The flow paths show that all the particles in the Upper HSU and Lower HSU are captured by the extraction systems, except for two small areas near Pond 18 and the RCF Pond in the March 2004 Upper HSU model simulation (Figures F3-90), and one area near the Casmalia Neutralization System in the March 2001 Upper HSU simulation (Figure F3-92). Although the model simulations indicate that the groundwater in these three areas in the Upper HSU is not captured by the existing extraction systems, the VOC concentrations in the groundwater are low and would be expected to undergo significant dilution and attenuation before it migrates off-site.

During the review of the draft model, USEPA requested that additional particle tracking simulations be run to evaluate deeper groundwater flow simulated by the model and to determine potential flow paths from several areas in the Lower HSU that might have been impacted by primary source areas. The March 2004 model was used for these simulations. Particles were placed in layer 6 of the model along the North Ridge, between the landfills and the PSCT, between the PCB Landfill and extraction sump PSCT-4, and near monitoring wells RPGZ-6C/D and RPGZ-7C/D. Forward particle tracking simulations were then run to determine the groundwater flow paths simulated by the model. The results of these simulations are shown in Figures F3-94 through F3-97. The simulations show that groundwater flow paths simulated by the model in layer 6 from these areas of the Site are to the south or southwest.

In response to USEPA comments on the draft model, CSC also evaluated the deeper groundwater flow simulated by the model in the lower HSU in the landfills area where an upward vertical component of groundwater flux was present (Section F3-3). For these simulations, particles were placed in layer 7 of the March 2004 and March 2001 models within the areas of upward vertical flux near the North Ridge. Forward particle tracking simulations were then run to determine the groundwater flow paths simulated by the models. The results of these simulations are shown in Figures F3-98 and F3-99. The particle tracking simulations indicate that the groundwater flow paths simulated by the models in the areas of upward vertical flux in layer 7 are predominantly lateral, not vertical. Groundwater flows laterally from near the North Ridge and then moves gradually upward as it moves away from the ridge. These flow paths are consistent with the flow paths simulated by the model in the shallower model layers as shown in Figures F3-84 through F3-87.

F3-4.0 References

Casmalia Resources Site Steering Committee (CSC), 2004. *Remedial Investigation/Feasibility Study Work Plan,* June.

MACTEC, 2006. *Memorandum Providing Additional Technical Information Regarding Model Thickness, Layering, and Vertical Flow*. February 24.