Section 6

San Fernando Basin Flow Model

The 1992 RI included development of a 3D groundwater flow model that was used to define regional flow fields, and later used in evaluating remedial alternatives as well as for evaluating long-term planning and basin management of the SFB. The objective of the groundwater flow and transport modeling effort in this RI Update Report is for evaluating flow and capture of COCs, and includes the setup of the model and development of capture zones at 2, 5, and 10-year time intervals assuming current pumping conditions. This model will also be utilized as part of the FS to provide a framework to preliminarily test the efficacy of the alternative treatment scenarios in terms of both the capture of contaminated groundwater and assisting in the determination of expected ranges of influent contaminant concentrations and masses into potential alternative treatment systems. The model will also be able to provide a framework to assess responses of the SFB hydrogeologic system including groundwater flow directions and velocities and contaminant mass distributions that result from potential future changes in production well pumping and recharge spreading.

Section 6.1 of the report includes the criteria used in model selection, specific model updates, and development of the capture zones based on the anticipated future pumping scenarios by LADWP and others. It should be noted that the evaluation of the models started with the previously-developed model and incorporated known hydrogeologic conditions to it to make it more robust. Because of time constraints, the update does not include all of the proposed layering and numerous specific details of the HCSM described in Section 3. These updates to the model are one of the recommended future actions as presented in Section 8 of this RI Update Report.

6.1 Flow Model

For this RI Update Report, a model evaluation was performed to determine the most appropriate model for evaluating groundwater flow and fate and transport of chemicals in the SFB. Since the development of the original flow model in the 1992 RI, numerous updates of the model have been performed by multiple entities in the SFB, including USEPA, various PRPs, and LADWP. With all of the models currently in circulation for the SFB, the first modeling task was selection of an appropriate model for evaluating flow and fate and transport of COCs in the SFB.

The previously-developed models were assessed in terms of their suitability to provide a framework to test the potential alternative treatment scenarios using particle tracking to evaluate groundwater capture and solute transport simulations to evaluate contaminant mass distributions. All of the models use a 3D finite-difference modeling method with a modular finite-difference flow model (MODFLOW) based computational code. MODFLOW is the industry-leading groundwater flow modeling code originally developed by USGS (Harbaugh and McDonald 1996; Harbaugh et al. 2000; Harbaugh 2005).

6.1.1 SFB Flow Model Evaluation

Each of the four individual groundwater flow models is described below. Following the descriptions, each model construct is assessed in terms of suitability to meet the model objectives presented in the beginning of Section 6.

6.1.1.1 LADWP Current Groundwater Flow Model

The model objective of the current LADWP groundwater flow model is to provide a framework for evaluation of proposed future production well pumping and recharge spreading over a future 5-year period for the ULARA Watermaster. It is based on the original 1992 RI Model, the most recent version of which is described in the ULARA (ULARA 2013b). The LADWP groundwater flow model consists of four vertical model layers and is divided laterally into a grid of 64 north-south rows and 86 east-west columns. The lateral grid cell size ranges from a minimum of 1,000 feet by 1,000 feet in the southeast portion of the model domain to a maximum of 3,000 feet by 3,000 feet in the northwest portion of the model domain. Production wells are simulated using the standard MODFLOW Well Package. Wells with screens that penetrate multiple model layers have pumping manually apportioned in the Well Package input file to allocate pumping to each layer by the relative transmissivity values of each layer. Spreading basin recharge is also represented using the MODFLOW Well Package to add the spreading recharge volumetric fluxes to model layer 1. Areal precipitation recharge is simulated using the standard MODFLOW Recharge Package.

6.1.1.2 USEPA 2007 Groundwater Flow Model

Since the early 1990s, USEPA and its contractors (including CH2M Hill) have developed and maintained a groundwater flow model to assist in assessing the hydraulic containment of contaminants and the design of treatment systems. The original 1992 RI groundwater flow model has undergone several USEPA modifications and updates over time. CH2M Hill (2013) provides a brief description of the history of the USEPA groundwater flow model versions, and the 2007 version is documented in CH2M Hill (2008). The 2007 USEPA groundwater flow model simulates 26 years over the time period from October 1981 through the end of September 2007.

The 2007 version of the USEPA groundwater flow model uses MODFLOW-SURFACT (HydroGeoLogic 2007), a proprietary version of the USGS MODFLOW code with enhanced features. MODFLOW-SURFACT incorporates methodologies for allowing the model to be variably saturated with model cells drying and re-wetting as simulated groundwater levels fall and rise. Previous USGS versions of MODFLOW included the ability to allow model cells to re-wet, but the methodologies incorporated in MODFLOW-SURFACT are both more robust and numerically stable. MODFLOW-SURFACT also includes a Fracture Well Package, in which pumping wells may penetrate multiple model layers with the code automatically dynamically apportioning pumping between layers based on the relative transmissivities of the model layers including the effects of groundwater drawdown because of pumping. Further, if the upper layers penetrated by a well are simulated to de-saturate the pumping from those layers is subsequently shifted to lower layers (in the standard MODFLOW Well Package, the pumping specified is simply inactivated for model cells that become unsaturated during simulation). MODFLOW-SURFACT also includes robust solute transport simulation capabilities using the Total Variation Diminishing (TVD) method (Zheng and Bennett 2002).

The 2007 USEPA groundwater flow model consists of four vertical model layers and is divided laterally into a grid of 73 north-south rows and 89 east-west columns with a telescopic mesh refinement approximately centered on the RT well field pumping well RT-15. This refined area consists primarily of only four model rows and two model columns and the minimum model cell size in this refined area is 181 feet by 250 feet. Away from this area of refinement the maximum row spacing is 2,000 feet, and the maximum column spacing is 3,250 feet. Production wells are simulated using the Fracture Well Package with pumping dynamically allocated between the appropriate model layers. Spreading basin recharge is also represented using the Fracture Well Package to add the spreading recharge volumetric fluxes to model layer 1. Areal precipitation recharge is simulated using the standard MODFLOW Recharge Package.

6.1.1.3 USEPA 2009 Focused Feasibility Study Model and 2012 Groundwater Management Plan Models

CH2M Hill constructed future predictive versions of the USEPA 2007 groundwater flow model to assess the potential impacts of remedial alternatives in the NHOU FFS (CH2M Hill 2009) and proposed pumping and spreading in the draft Groundwater Management Plan submitted by LADWP to USEPA in early 2012 as described in a technical memorandum (CH2M Hill 2012). Both of these versions of the model have four vertical layers divided laterally into 243 north-south rows and 272 east-west columns. A telescopic mesh refinement was performed in the NHOU area in which the minimum grid spacing is 50 feet by 50 feet. Both versions of the model continued to use MODFLOW-SURFACT.

6.1.1.4 USEPA 2013 Groundwater Flow Model

CH2M Hill made subsequent additional updates to the groundwater flow model in 2013 (CH2M Hill 2013). The flow modeling code was switched to the updated USGS software MODFLOW-NWT (Niswonger et al. 2011) from MODFLOW-SURFACT. MODFLOW-NWT was chosen as the modeling code because it is freely available/public domain and includes the same capabilities related to simulation of variably saturated conditions and multi-layer wells as MODFLOW-SURFACT. The use of MODFLOW-NWT allows interested parties to operate the model without purchasing the proprietary MODFLOW-SURFACT software.

The 2013 model update included several modifications:

- The modeled time period was extended to the end of September 2011 for a total simulation period of 30 years.
- The grid spacing in the north and west portions of the model domain was reduced to have a more uniform grid density.
- Spreading basin recharge is applied using the Recharge Package instead of being applied through a well-type package in case of the condition that model layer 1 becomes unsaturated beneath spreading grounds because MODFLOW-NWT inactivates injection wells in dry cells; this condition has been simulated in previous forecasting simulations.
- No-flow boundaries along the Verdugo Mountain front were adjusted to better reflect the geometry of the mountain front.
- The Verdugo Fault in the northern portion was explicitly incorporated in the model using the Horizontal Flow Barrier (HFB) Package (Hsieh and Freckleton 1993) to simulate the restriction to groundwater flow observed across the fault as well as to simulate suspected fluvial breaches in the Verdugo Fault that are less restrictive to groundwater flow.
- Additional model calibration of hydraulic conductivity, specific yield, and areal precipitation recharge was performed for the extended simulation period (i.e., 2008 through 2011) as well as to match the results of the 2010 Burbank OU aquifer test.
- In addition to these modifications to the USEPA groundwater flow model, two issues were introduced during the 2013 model update effort:
  - The General Head Boundary (GHB) Package model cells at the Los Angeles River Narrows were not included in the extended modeling period, thus not allowing water to flow out of the model domain for that period of the model simulation.
  - The River Package model cells representing the Los Angeles River had undocumented changes to the specified input values of river stage elevation and river bottom elevation that were inconsistent.

6.2 Selection of RI Update Groundwater Flow Model Construct

Based on the previous descriptions of the available groundwater flow model constructs, these constructs were evaluated for their suitability to achieve the modeling objectives of assessing groundwater capture using particle tracking methods and contaminant mass distribution and capture using solute transport methods. Effective particle tracking and solute transport modeling generally requires that:

- The model grid spacing needs to be fine enough to appropriately resolve groundwater flow directions and velocities
- The selected model construct should be free of known issues with boundary conditions or other obvious inconsistencies
- The selected groundwater flow modeling code needs to either include an integrated companion transport modeling code or have a compatible transport code that is tested and generally accepted by the modeling community

The current LADWP model, described in Section 6.1.1.1, is well calibrated to observed groundwater levels, but the 1,000-foot grid spacing through the areas of interest is too coarse to effectively resolve groundwater flow directions and velocities critical to the particle tracking and solute transport methodologies. The USEPA 2007 and 2013 groundwater flow models have somewhat finer grid spacing in the areas of interest for particle tracking and solute transport, but these areas of grid refinement are relatively limited. The USEPA 2009 FFS and 2012 Groundwater Management Plan groundwater flow models have much finer grid spacing (50 feet by 50 feet) over much larger portions of the areas of interest for particle tracking and solute transport, although the area of grid refinement is focused primarily on the NHOU. The model grid used in the USEPA 2009 FFS and 2012 Groundwater Management Plan groundwater flow models is the most suitable for performing particle tracking and solute transport modeling to achieve the model objectives (Figure 6-1).

The USEPA 2013 groundwater flow model included several improvements in the model's representation of the hydrogeology and groundwater flow system, most notably the corrections to the no-flow boundaries along the Verdugo Mountain front and the addition of an explicit representation of the Verdugo Fault. However, a review of the USEPA 2013 model revealed issues with modifications to both the GHB Package and River Package boundary conditions described above. A review of the USEPA 2007 model revealed no obvious errors in boundary condition package inputs other than minor issues related to Fracture Well layer assignments based on well screened intervals at a few wells.

Though solute transport is not included in this RI Update Report, the ability to model solute transport was one consideration in model selection. MODFLOW-SURFACT includes a robust solute transport model code fully integrated into the flow modeling code. The most recent versions of USGS MODFLOW (MODFLOW-2005 and MODFLOW-NWT) do not include integrated solute transport capabilities. The industry standard solute transport code used with USGS MODFLOW is Modular 3D Multi-Species Transport Model (MT3DMS) (Zheng and Wang 1999). However, some inconsistencies between MODFLOW-NWT and MT3DMS have been discovered (Morway et al. 2014). The USGS is currently working on an updated version of MT3DMS that will be consistent with MODFLOW-NWT that has not yet been released (Morway 2014).

Given all of the considerations outlined above, the model construct selected for this modeling effort is the USEPA 2009 FFS and 2012 GMP model layering and grid, and MODFLOW-SURFACT as the modeling code. Recharge spreading has been applied using the Fracture Well Package as in the USEPA 2007 model. However, the selection of these items for the model construct does not preclude inclusion of appropriate modifications and updates from the USEPA 2013 groundwater flow model, RI Update Report, or other pertinent information at a later date. Maps of recharge and pumping used in the model are included in Appendix K.

6.2.1 Flow Model Review and Modifications

The groundwater model for the RI Update Report was updated through a step-wise process. The general water level history matching of the model was checked at various stages of the process to ensure that the model remained suitably calibrated. Groundwater Vistas™ (Rumbaugh and Rumbaugh 2011) was used as the graphical pre- and post-processing software, the same groundwater modeling graphical user interface as has been used by CH2M Hill. The step-wise process to updating the model was as follows:

1. Using the 2012 Groundwater Management Plan model Groundwater Vistas file as an initial starting point, changed the model stress period and time-stepping setup to match the USEPA 2007 groundwater flow model.
2. Imported Fracture Well Package pumping and spreading recharge information from the USEPA 2007 groundwater flow model.
3. Imported water level observation information at 88 well locations from the USEPA 2007 groundwater flow model.
4. Add water level observation information from USEPA's SFV database at 317 additional well locations distributed more widely across the SFB than the original 88 well locations, for a total of 405 well locations.
5. Evaluate the consistency of the Fracture Well Package well screen elevation and model layer assignments and correct inconsistencies for five wells in the Fracture Well Package.
6. Update the no-flow boundaries in each model layer along the Verdugo Mountain front to match the USEPA 2013 groundwater flow model as closely as possible, given that the lateral model grid spacing differ.
7. Add HFB Package input to explicitly represent the Verdugo Fault, matching the HFB geometry and distribution of HFB hydraulic input parameters to the USEPA 2013 groundwater flow model as closely as possible given that the lateral model grid spacing differ.
8. Extend the simulation period to match the USEPA 2013 groundwater flow model by adding the period October 2007 through September 2011.
9. Add October 2007 through September 2011 stress period and time-stepping setup information.
10. Add October 2007 through September 2011 well pumping rates from USEPA 2013 groundwater flow model.
11. Add October 2007 through September 2011 spreading basin recharge rates from the USEPA 2013 groundwater flow model by extracting out the areal recharge from the model cells with spreading basins, multiplying by the model cell areas to get volumetric rates, and summing the volumetric rates to distribute to the appropriate Fracture Well Package locations. By finding specific stress periods with zero spreading recharge at each spreading basin, the background areal precipitation volumetric fluxes for those spreading basin cells were calculated and removed the additional areal precipitation recharge included in those spreading basin cells. This methodology of calculating the total 2013 model spreading basin cell recharge fluxes and removing the areal precipitation recharge fluxes was checked against the 1981 through 2007 period spreading basin fluxes in the 2007 model, and the maximum difference was 0.3 percent.
12. Add water level observation information from October 2007 onward from the USEPA's SFV database for the 405 well locations.

After completing these model modifications, the water level history matching calibration was reviewed through a comparison of observed and simulated water levels at the observation wells. A “residual” is defined as the observed (or field-measured) water level minus the simulated water level at the same location. Positive residuals represent a model-calculated head value that is lower than the observed head value, and negative residuals represent a model-calculated head value that is higher than the observed value. A residual value of zero represents a perfect fit between the model-calculated and observed values. Calibration statistics based on the residual are used as a quantitative measure of the overall ability of the model to match water level calibration targets. Calibration statistics that are calculated to quantify the average error include:

- Residual mean (RM), the average of the residuals
- Absolute residual mean (ARM), the average of the absolute value of the residuals
- Residual standard deviation (RSD), the standard deviation of the residuals
- Root mean squared error (RMSE), the square root of the mean of the squared residuals

A residual mean near zero indicates that the model is simulating groundwater levels neither too high nor too low. The ARM provides an indication of the average difference between observed and simulated water levels regardless of whether the residual is positive or negative. When the ratio of the RSD (or RMSE) to the range of observed head values in the system is small, discrepancies between simulated and observed values constitute a relatively small part of the overall model response (Anderson and Woessner 1992). As such, the RSD (or RMSE) divided by the range of observed heads is a measure of how well the model simulates the overall hydraulic gradient within the model domain. A scaled RSD (or RMSE) value of less than 10 percent is generally considered acceptable for a calibrated model.

The model calibration statistics are presented in Table 6-1. The statistics in Table 6-1 show the model is well-calibrated.

Table 6-1. Modified Model Bulk Calibration Statistics

Calibration Statistics	2013 Hydraulic Conductivity, Specific Yield, Recharge
Residual mean (RM)	1.41
Absolute residual mean (ARM)	9.85
Residual standard deviation (RSD)	16.75
Root mean squared error (RMSE)	16.81
Range in observations	989.21
Scaled RSD	1.69%
Scaled RMSE	1.70%

The RM is 1.52 feet, indicating that the model is not biased toward simulating water levels too high or too low. The ARM is 9.25 feet, which is reasonable for a basin-scale groundwater model, and especially for the SFB’s relatively high degree of observed transient water level fluctuations. The scaled RSD and RMSE values of less than 1.5 percent indicates that the model is well-calibrated. Visual inspections of a calibration scatterplot of the observed versus simulated water levels (Figure 6-2) and calibration hydrographs (a map of calibration points and hydrographs are included in Appendix K) also indicate that the model is well calibrated.

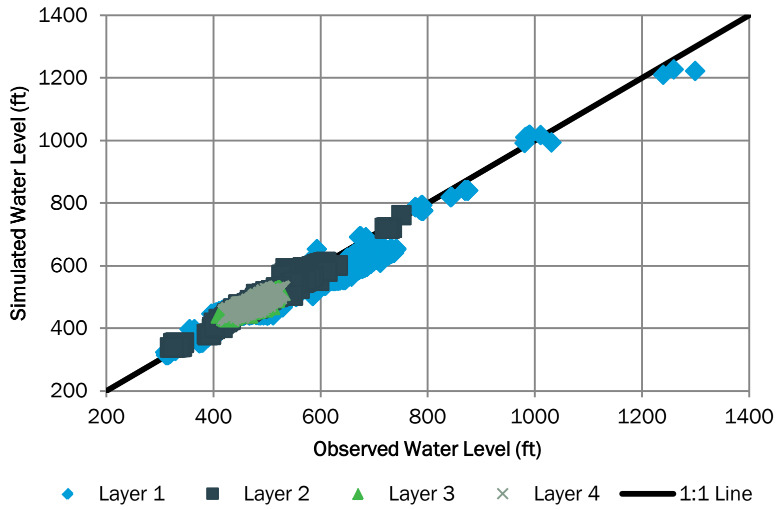

Figure 6-2. Scatter Plot of Observed versus Simulated Water Levels

6.3 Predictive Flow Model and Capture Zones

Particle tracking was used to delineate simulated zones of capture for each target pumping well. Particle tracking methodology involves tracing the advective movement of imaginary particles through the flow field of a numerical groundwater flow model (Anderson and Woessner 1992). Particle tracking codes compute the model's velocity fields at each model time-step from the simulated water level solution for the time-step and use that velocity field to track the movement of the input imaginary particles for the length of the time-step. Delineating zones of capture for pumping wells is generally performed using reverse tracking, in which initial particle locations are placed at the pumping wells and tracked in the reverse (i.e., upgradient) direction. Further, appropriate delineation of capture zones under transient aquifer or pumping conditions requires the initial release of particles at wells at multiple times to track particles as the simulated flow velocity field changes transiently (Rayne et al. 2014).

Capture zone delineation for each alternative scenario was performed using the USGS particle tracking code MODPATH (Pollock 1989), which is the industry-standard companion tracking code for MODFLOW models. Initial particles were placed around each pumping well in a circle with particle release times coinciding with the beginning of each time-step of the alternative scenario simulations. Particle tracking is a form of advective transport modeling and thus requires model inputs of aquifer effective porosity. Effective porosity was set to 0.23 based on the average results of geotechnical samples collected in the SFB as described in Section 5.3.1 and presented in Table 2-4. After tracking the particles for a 10-year period, capture zone maps were developed for 2, 5, and 10-year periods. Maps of these capture zones as compared to the TCE, PCE, and 1,4-dioxane plumes are included on Figures 6-3 through 6-5, respectively.