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JPL Groundwater Modeling Report

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Acronyms

1,2-DCA	1,2-dichloroethane
2-D	two dimensional
3-D	three dimensional
AL	action level
ASR	aquifer storage and recovery
bgs	below ground surface
DHS	California Department of Health Services
ClO_4^-	perchlorate
Caltech	California Institute of Technology
$CC1_4$	carbon tetrachloride
CDMG	California Department of Mines and Geology
DTSC	Department of Toxic Substances Control
DWR	California Department of Water Resources
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COI	chemical of interest
Cr	chromium
EE/CA	Engineering Evaluation and Cost Analysis
EPA	Environmental Protection Agency
FFA	Federal Facilities Agreement
FS	feasibility study
FWEC	Foster Wheeler Environmental Corporation
JPL	Jet Propulsion Laboratory
JPL/NASA	Jet Propulsion Laboratory/National Aeronautics and Space Administration
LACDPW	Los Angeles County Department of Public Works
MCL	maximum contaminant level
ME	mean residual
MET	Multimedia Environmental Technology

Metropolitan	Metropolitan Water District of Southern California
MLPU	Multi Layer Program Unsteady State (or in Dutch – *MeerLagen-Programma* Unsteady State)
msl	mean sea level
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
OU	operable unit
PCE	perchloroethylene
RBMB	Raymond Basin Management Board
RI	remedial investigation
RMS	root mean squared
RWQCB	Regional Water Quality Control Board
SVE	Soil Vapor Extraction
SVOC	semivolatile organic compound
TCE	trichloroethylene
USGS	United States Geological Survey
VOC	volatile organic compound

1. Introduction

This report documents the development and calibration of the Jet Propulsion Laboratory (JPL) groundwater flow model. The JPL groundwater flow model was developed based on the proposed technical approach described in the work plan for groundwater modeling for the JPL Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Site (CH2M HILL, 2001). This report primarily serves as a supporting document for the May 2003 Engineering Evaluation and Cost Analysis (EE/CA) for off-facility groundwater (Operable Unit [OU]-3) and should be referenced as such for more detailed documentation of the JPL groundwater flow model.

A work plan outlining the technical approach for the development of a three dimensional (3-D) groundwater flow and solute transport model for the JPL site was prepared in April 2001 (CH2M HILL, 2001). The work plan was developed in consultation with the Navy and the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (JPL/NASA). It focused on identifying and describing details of the proposed technical approach for constructing the groundwater model for the JPL site to meet Navy and NASA objectives.

This report primarily documents the JPL groundwater modeling effort in support of the JPL EE/CA. The steady-state model documented was calibrated, and model simulations were performed to evaluate the EE/CA alternatives. The JPL Groundwater Model used data from the Raymond Basin Management Board (RBMB) Watermaster reports for the calibration period 1996-2000. The report has been reviewed by the Environmental Protection Agency (EPA), Department of Toxic Substances Control (DTSC), Regional Water Quality Control Board (RWQCB) Los Angeles Region, and the City of Pasadena. In response to review comments , the groundwater budget has been updated to account for the Los Angeles County Department of Public Works (LACDPW) annual "general benefit" spreads for the Arroyo Seco Spreading Basins during the calibration period. The steady-state model was recalibrated, and new simulations were performed to evaluate the EE/CA alternatives. To update the transient calibration using the new groundwater budget, monthly data for the "general benefit" spreads for the Arroyo Seco Spreading Basins would be needed. Because the monthly data were incomplete at the time of issuing this report, it was not possible to update the transient calibration and document the results in this report.

The solute transport model development and calibration described in the work plan is not documented in this report at this time, because only the flow portion of the JPL groundwater model was used to evaluate the EE/CA alternatives. The solute transport portion of the JPL groundwater model has been developed for more detailed Feasibility Study (FS) and fate and transport application purposes.

1.1 Report Organization

The organization of this report is described below:

- Section 1 provides background information including the previous groundwater modeling work at the JPL site and groundwater modeling objectives.
- Section 2 describes the development of the conceptual model for the JPL groundwater model. In this section, the regional and local geology and hydrogeology are discussed, focusing on how this information is used to develop the conceptual model. The balance of the section discusses the development of the groundwater budget and documents the assumptions that are used for estimation of the different components of the groundwater budget. This section also describes addressing one of the major data gaps concerning the field measurement of the hydraulic conductivities needed for the calibration of the JPL groundwater model. A large-scale pumping test was performed based on the evaluation of the responses of the JPL groundwater monitoring wells to the City of Pasadena production wells. The calculated hydraulic conductivity values were used for the calibration of the JPL groundwater model.
- Section 3 describes the development of the numerical model for the JPL site, including review of the groundwater programs for code selection, model boundary and grid design, and boundary conditions and model stresses.
- Section 4 describes the steady-state calibration of the JPL groundwater model based on the average recharge conditions and water levels for the water years 1996-1997 through 1999-2000. The balance of the section focuses on data preparation including preprocessing and postprocessing, calibrated flow parameters, performance measurements, and evaluation of the flow field using particle tracking.
- Section 5 presents a list of the references for the groundwater modeling report.

1.2 Background

JPL is a government-owned, contractor-operated, national research and development center under the administrative responsibility of NASA. The facility is located in Pasadena, California (Figure 1-1). Although the federal government owns JPL, the California Institute of Technology (Caltech) operates JPL through a prime contract with NASA.

The testing of liquid propellant rockets in the Arroyo Seco began as early as 1936. Over time, various chemicals and materials have been used at JPL, including solvents, solid and liquid rocket propellants, cooling tower chemicals, and chemical laboratory wastes (Foster Wheeler Environmental Corporation [FWEC], 1999). In the early 1980s, analyses of groundwater from City of Pasadena (Pasadena) water supply wells located in the Arroyo Seco, near JPL, revealed the presence of volatile organic compounds (VOCs). VOCs were also detected in two Lincoln Avenue Water Company (Lincoln) water supply wells in the early 1980s. In 1990, NASA funded the installation of a water treatment plant in the Arroyo Seco (Behner Treatment Plant) so that the Pasadena wells could resume supplying water. By 1992, the Lincoln Avenue Water Company had installed a water treatment plant and had similarly restarted production.

From 1994 to 1998, groundwater from the areas beneath and adjacent to JPL has been sampled through a series of monitoring wells and analyzed for a comprehensive suite of analytes including VOCs, semivolatile organic compounds (SVOCs), metals, and ClO_4. Through this extensive investigation, only three VOCs (carbon tetrachloride [CCl_4], trichloroethylene [TCE], and 1,2,-dichloroethane [1,2-DCA]), one metal (chromium [Cr]), and perchlorate (ClO_4^-) were detected at levels exceeding state and federal Maximum Contaminant Levels (MCLs) or California Department of Health Services (DHS) Action Levels (ALs).

1.2.1 RI/FS Activities

In 1988, as part of the CERCLA process, a Preliminary Assessment/Site Inspection was completed at JPL; the results of these activities indicated that further site characterization work was warranted (Ebasco, 1988). In 1990, an Expanded Site Investigation was performed at JPL, during which several groundwater monitoring wells were installed onsite (Ebasco, 1990). VOCs were subsequently detected in onsite groundwater above drinking water standards, and the site was ranked using the CERCLA Hazard Ranking System. On October 14, 1992, the site was placed on the National Priorities List (NPL). EPA and NASA entered into a Federal Facilities Agreement (FFA) on December 10, 1993, pursuant to Section 120 of CERCLA.

In accordance with the FFA, NASA and Caltech have completed the Remedial Investigation (RI) for the groundwater OUs at JPL (onsite groundwater [OU 1] and offsite groundwater [OU 3]). During the OU-1/OU-3 RI, 13 additional wells were added to the existing JPL 10-well groundwater monitoring system. The locations of all JPL wells are shown in Figure 1 2.

A draft FS was completed in January 2000. Current RI/FS activities at the JPL site include the quarterly groundwater monitoring, Soil Vapor Extraction (SVE) pilot testing, the groundwater EE/CA, and perchlorate pilot testing of both ex-situ and in-situ technologies.

1.3 Previous Groundwater Modeling

As part of the groundwater modeling task, CH2M HILL reviewed previous regional groundwater modeling work for the Raymond Basin and the more site-specific groundwater modeling work undertaken at the JPL site. The primary objective of the review was to learn from previous modeling experiences prior to constructing the 3-D groundwater flow model described in this report.

1.3.1 Devil's Gate Multiuse Project

In the early 1990s, CH2M HILL developed a model of the Raymond Basin to evaluate conjunctive use alternatives for the City of Pasadena. Reports describing this work were reviewed, and included the following:

- *Technical Memorandum, Task 1: Describe Current Situation, Phase 1, Devil's Gate Multi-Use Project*, CH2M HILL, July 26, 1989.
- *Draft Phase 1 Report, Devil's Gate Multi-Use Project*, CH2M HILL, November 13, 1989.

- *Phase 2, First Technical Assessment, Devil's Gate Multi-Use Project*, CH2M HILL, 1992.

The Raymond Basin model was a basin scale model of the entire Raymond Basin and, as such, was not intended to accurately represent local scale groundwater movement in the JPL area. The model was composed of one to five layers, and was calibrated for the period 1955 through 1989. A brief overview of the model is given below.

Although the model was composed of from one to five layers, the model did not include vertical variations in hydrogeologic properties. Lateral variations in hydraulic conductivity were based on hydraulic conductivity estimates derived from the results of specific capacity tests that had been performed by well owners and drillers. These hydraulic conductivity values were then modified during calibration of the model. Hydraulic conductivity values in the JPL area ranged from 1 foot/day to 80 feet/day. Specific-yield values used near the JPL facility ranged from 0.09 to 0.12, and were based on contour maps of specific-yield estimates prepared by the California Department of Water Resources (DWR). The DWR estimates were based on assigning specific-yield values to the various sediment types observed in boring logs, and then vertically averaging the specific-yield values over the length of the boring logs.

Sources of recharge in the Raymond Basin included natural recharge from precipitation, recharge from applied water, artificial recharge from spreading grounds, and subsurface inflow from bedrock areas. Natural recharge values varied with land use in the basin, and were estimated based on precipitation/land use correlations developed by DWR. Recharge from applied waters is derived from return flow of applied irrigation water, and was estimated to be 12 percent of annual groundwater production. Estimates of recharge from spreading grounds were based on values reported by DWR for volumes of water captured and recharged in the Raymond Basin. Because initial attempts to calibrate the Raymond Basin model failed in the Monk Hill area, recharge estimates for the Arroyo Seco were modified for 3 years in the 1960s. The rationale for increasing Arroyo Seco recharge during this period was based on high precipitation during these years and observed flooding and standing water in the Devil's Gate area. It was necessary to add 10,000 acre feet infiltration events in the Arroyo Seco for each of the water years 1965, 1966, and 1968. Recharge from subsurface flow from bedrock areas was assumed to be 6,520 acre feet per year, based on DWR estimates. This volume of recharge was evenly distributed along model boundaries that represented contacts of the aquifers with bedrock.

Sources of discharge included in the Raymond Basin model were groundwater production and subsurface outflow across the Raymond Fault into the San Gabriel Basin. Groundwater production values were taken from DWR annual reports. A general head boundary was used to represent the Raymond Basin Fault that separates the Raymond Basin from the San Gabriel Basin to the east. Subsurface outflow from the Raymond Basin across this boundary ranged between approximately 7,900 acre-feet per year and 10,600 acre-feet per year over the calibration period.

1.3.2 Review of MET Groundwater Flow Model

Multimedia Environmental Technology (MET), Inc., contracted by Caltech through FWEC, initially developed a two-dimensional (2-D) groundwater flow model for the JPL site in 1996. The United States Geological Survey (USGS) groundwater code MODFLOW was used

for this purpose. The modeling effort at JPL benefited from the basinwide groundwater modeling work previously performed by CH2M HILL in the 1990s, referenced above.

The groundwater flow code MODFLOW was chosen to simulate groundwater flow at the JPL site because this code had the appropriate technical options, was widely used, was developed in the U.S., and was compatible with other programs that could be used to simulate contaminant transport (USGS, 1984). Initially, a 2-D groundwater flow model was developed and calibrated. After the calibration of the 2-D model, a 3-D groundwater flow model was developed so that vertical flow could be represented in the model. The model review below focuses on the most recent version of the 3-D groundwater flow model, as described in Appendix G of the Draft FS report. To supplement our understanding of the current model, it was necessary to review previous modeling reports because the model ultimately evolved from the initial 2-D model. The modeling-related reports reviewed included:

- *Groundwater Model Selection for NASA JPL Site*, Ebasco Environmental, July 1992.
- Review of Previous Data for Use in JPL Groundwater Modeling Study, Enserch Environmental, February 1995.
- *Development and Calibration of the Two Dimensional Groundwater Flow Model of the Jet Propulsion Laboratory*, Multimedia Environmental Technology, 1996.
- *Development and Calibration of the 3-D Groundwater Flow Model of the Jet Propulsion Laboratory*, Multimedia Environmental Technology, 1997a.
- *Calibration and Refinement of the 3-D Groundwater Flow Model of the Jet Propulsion Laboratory*, Multimedia Environmental Technology, 1997b.
- Report on the JPL Groundwater Model, Appendix G of the *Draft Feasibility Study Report for Operable Units 1 and 3: On-Site and Off-Site Groundwater*, Multimedia Environmental Technology, 1999.

To facilitate discussion, the model review has been divided into sections that provide summaries of the conceptual model (Hydrostratigraphic Units and Water Budget), Calibration Results, and Conclusions. In addition to providing an overview of the MET model, these sections describe significant assumptions and the basis for these assumptions, the difficulties encountered during the calibration process, modifications/refinements made to their initial conceptual model to improve the calibration, and whether these modifications are supported or are indicative of data gaps that may need to be addressed. Overall, the model review focused on assessing the extent to which the MET model could be utilized in the development of a combined groundwater flow and solute transport model, based on both technical and economical considerations.

1.3.2.1 Hydrostratigraphic Units of MET Groundwater Flow Model

The model domain was centered on the JPL site and covered a square area (rotated at 23 degrees to the east of north) with sides approximately 3 miles long. The extent of the model domain was chosen to encompass regional production wells as far to the northwest as the La Canada Irrigation District wells, and as far to the southeast as Rubio Canyon Land and Water Company and Las Flores Water Company wells.

The base of the model was taken as the surface of the underlying bedrock, based on the same data used to interpret the bedrock elevation in Figures 3-8 and 3-9 in the RI Report. The overlying alluvium was divided into six horizontal (flat-lying) conductive layers, based on the three major aquifer layers identified in the RI Report, with the three major aquifer layers subdivided so that modeling results could be more readily compared with the piezometric heads measured within the multiport wells. (Note: Although four "aquifer layers" were identified in the RI, one of these layers was present only at the deepest interval in the monitoring well located farthest from the JPL facility; this layer was not explicitly included in the model.) Aquitards, representing the silt layers in the eastern portion of the model, were represented by varying the leakage between adjacent aquifer layers.

Initial estimates of the hydraulic conductivity values were based on the regional Raymond Basin model (CH2M HILL, 1989), after modification to include the site-specific data from the slug and bail tests at the JPL monitoring wells. During the calibration of the 2-D model, hydraulic conductivity was adjusted, and storage coefficients were estimated by attempting to match the response of groundwater levels to pumping at the City of Pasadena wells (based on the period May through July 1993). As a result, a specific storage coefficient of 0.001 and specific-yield value of 0.003 were uniformly applied to the model.

To improve model calibration, MET found it necessary to include several significant aquitards in the model. Two of these aquitards extended over large areas south of the mouth of the Arroyo Seco and in the eastern half of the model between Layers 1 and 2, and between Layers 3 and 4. Another modification to the model was the addition of a hydraulic barrier below the mouth of the Arroyo Seco, which MET suggested might represent an unknown fault in this area. The barrier was added to represent the observed groundwater mounding in this area that is reflected in Monitoring Wells MW-1, MW-9, and MW-15.

1.3.2.2 Water Budget of MET Groundwater Flow Model

Factors affecting the water budget of the model included groundwater pumping, areal recharge in the area around the Arroyo Seco Spreading Grounds, and recharge and discharge through the model boundaries. Those factors that included significant assumptions are discussed in this section.

Because the production wells near JPL are screened through several model layers, it was necessary to make assumptions regarding the distribution of groundwater production to the various layers. To address this, MET opted to distribute all pumping from production wells to Layer 4 of the model and assign large vertical conductivity values to the aquitard layers in this area so that the effects of pumping could distribute vertically near the well. Although this may allow the effects of production to reach other layers near the model, this approach may also provide a conduit for vertical flow, especially during periods when the production wells are not active.

It was also necessary for MET to make several assumptions regarding the distribution and timing of recharge within the spreading basins because of the approximately 100 feet of unsaturated alluvium above the water table. Using a simple, 2-D modeling of the unsaturated zone, MET estimated that the spreading ground recharge may be applied to an area as large as four times the area of the spreading grounds. A derived correlation between precipitation records and surface recharge values determined during calibration of the 2-D

model was used to estimate a 1-month lag time for surface recharge to reach the water table. Details and assumptions for the 2-D modeling and derived correlation of recharge lag time were not included in any of the reports.

Several issues remain to be resolved regarding the manner in which natural and artificial recharges were applied in the model. Based on our review, recharge within the model domain (not including model boundaries) was limited to the area around the Arroyo Seco Spreading Grounds. At this location, variable recharge rates (monthly intervals) were assigned based on the correlation with precipitation records (discussed above). MET used this approach, rather than using the recorded volumes of water diverted to the Arroyo Seco Spreading Grounds (compiled by the RBMB), because, as MET described, all of the water diverted to the spreading grounds may not reach the water table as recharge. Natural recharge from precipitation was not applied to other areas within the model domain. Additionally, constant recharge rates were utilized at three other locations in this area. The basis for these locations and values is unclear. Based on a review of figures showing the distribution of recharge, it appears that recharge applied near the Arroyo Seco Spreading Grounds extended north to the boundary at the mouth of the Arroyo Seco. In all of these areas, recharge was applied to the upper layer of the model.

The other sources of recharge to the model were through the model boundaries. The upgradient boundary was handled as a no-flow boundary along the southwestern edge, with a flux boundary in the northwestern edge. It is not clear as to whether the applied flux was a constant value or varied based on fluctuations of regional groundwater levels. The volume of water, determined during model calibration, was applied to the upper model layer and was intended to represent a combination of both through-flow and recharge from irrigation and ponds in this area. The model did not receive through-flow from the other model layers at this boundary (a no-flow boundary was used for these layers). Other model boundaries contributing or removing water from the model domain included the variable flow boundary in the northeastern corner and the constant head boundary in the southeast corner of the model domain.

1.3.2.3 Calibration of MET Groundwater Flow Model

The 3-D flow model was calibrated to the 16-month period between August 1995 and December 1996. During the calibration process, several attempts were made to employ parameter optimization techniques to automate the calibration process. These attempts were unsuccessful because of significant fluctuations in model stresses (due to large temporal variations in recharge and groundwater pumping). Ultimately, the model was calibrated using a manual trial-and-error process, which required more than 200 additional simulations.

As discussed above, model parameters, recharge, and inflow through the upgradient boundary were adjusted during the calibration process. The success of the calibration was evaluated using hydrographs and linear regression coefficients to compare the simulated and observed heads at the monitoring wells. Although the calibration period for the 3-D model was from August 1995 to December 1996, only the simulation results from August 1, 1995, to April 1, 1996, are shown in the hydrographs and were used to calculate the linear regression coefficients. For the 40 observation points (10 shallow wells and 3 sampling intervals at 10 multiport wells), the linear regression coefficient (R^2) ranged

between 0.01 and 0.96, with a median value of 0.71. Approximately 35 percent of the observation points had regression coefficients below 0.50, which is indicative of a poor match. The overall correlation coefficient using all of the data combined into a single data set was 0.93. Flow directions and hydraulic gradients were not discussed as part of the calibration criteria.

Typical differences between simulated and observed groundwater levels are less than 35 feet, with most simulated groundwater levels differing between 5 to 15 feet of the measured values. For many of the wells, the differences between the simulated and observed values are as much as 50 percent of the overall fluctuation in groundwater levels observed at those wells. These differences in groundwater levels are fairly significant, particularly given the relatively short period of time shown in the calibration hydrographs (8 months). The worst match between groundwater levels and trends are found for wells near the mouth of the Arroyo Seco. The wells nearest the mouth of the Arroyo Seco (MW-1, MW-9, and MW-15) show a smooth increase of 5 feet in observed groundwater levels, whereas simulation results show a decrease in groundwater levels of approximately 15 feet.

No model verification simulations were performed for the MET model. However, an attempt was made to perform a comparison between the simulated groundwater levels from the calibration period (August 1995 to April 1996) and the measured groundwater levels from August 1997 to April 1998, without actually running the model to simulate the data from the latter period. The MET report refers to this exercise as a "model verification" effort, but this is not considered a traditional model verification. The model verification typically is performed by using data from a period outside the calibration period and actually running the model to compare the simulated heads with the observed ones for the same period.

The MET modeling effort was limited to the simulation of groundwater flow and did not include particle tracking simulations or solute transport modeling. However, during the RI, a simple model of solute transport (SOLUTE) was used to estimate the time when the concentrations of perchlorate, carbon tetrachloride, and TCE would exceed their respective MCL concentrations in the downgradient Monitoring Well MW-20.

1.3.2.4 Discussion of MET Groundwater Flow Model

The significant difficulty encountered during calibration of the model is evident from both the number of calibration simulations required and the failure of attempts to employ automatic calibration procedures. These difficulties were probably largely due to the complex and dynamic nature of the groundwater flow system in this area, which also is reflected in MET's conclusion that the model is sensitive to most parameters, including recharge, horizontal conductivity in all layers, and vertical conductivity of the aquitards. As discussed above, it was necessary to make several other modifications to improve the model calibration, including the addition of a hydraulic barrier below the mouth of the Arroyo Seco and revising the extent and properties of the aquitards.

To improve model calibration, MET found it necessary to include several significant aquitards in the model. Two of these aquitards extended over large areas south of the mouth of the Arroyo Seco and in the eastern half of the model between Layers 1 and 2, and between Layers 3 and 4. These aquitards had very low conductivity values—less than

0.0005-foot/day between Layers 1 and 2 and less than 0.003-foot/day between Layers 3 and 4—that are typically indicative of tight clays and silts, respectively. These types of materials were not noted in the boring logs for monitoring wells in this area.

Another modification to the model was the addition of a hydraulic barrier below the mouth of the Arroyo Seco, which MET suggested might represent an unknown fault in this area. The barrier was added to force the model to represent the observed groundwater mounding in this area that is reflected in Monitoring Wells MW-1, MW-9, and MW-15. In the RI Report, the groundwater mounding in this area is attributed to groundwater recharge through the mouth of the Arroyo Seco. Prieto Canyon, Milliard Canyon, and Arroyo Seco appear to be significant drainages in the San Gabriel Mountains north of the model boundary. Groundwater recharge may occur along these canyons or after they converge with the Arroyo Seco just north of the MET model boundary (located at the mouth of the Arroyo Seco), and result in groundwater recharge that would enter the model domain in this area. In the MET model, a no-flow boundary was used across this area.

During development of the JPL Groundwater Model, it was necessary to revisit many of the above assumptions, including the existence and extent of significant aquitards, the handling of the upgradient boundary, the handling of the boundary/addition of a hydraulic barrier near the mouth of the Arroyo Seco, the volume and distribution of natural and spreading grounds recharge, and the vertical distribution of production well pumping. Revisiting these assumptions focused on identifying alternative assumptions that reduce the degree of uncertainty and clearly describing the rationale behind the assumptions. Addressing an important data gap discussed in Section 2.6 also reduced model sensitivity and provided a stronger underlying basis for the hydraulic conductivities used in the JPL groundwater model.

In addition to identifying areas where model refinements may be needed, the MET modeling work also identified a numerical stability issue. This issue is caused by fluctuations in the water table elevation beneath JPL that cause the water table elevation to occasionally fall below the base elevation of the upper layer of model grid blocks. As noted by MET (and encountered by many other modelers), MODFLOW has significant problems converging under these circumstances. To address this issue, grid development or selection of a code that utilizes a more robust method for handling the movement of a free surface was implemented, as discussed in Section 3.1.

1.3.2.5 Conclusions on MET Groundwater Flow Model

In conclusion, the review of the MET model provided a number of invaluable lessons that are useful for the modeling effort described in this work plan. While the modeling information in the MET model was utilized to the maximum extent possible, the model described in this report is an improved and updated version of the MET model. The MET model has a number of conceptual assumptions that are not supported by the geologic and hydrogeologic data, as summarized above. To address these conceptual inconsistencies and to successfully meet NASA modeling objectives, fundamental modifications to the MET model were needed. Therefore, the new model was developed mainly to address the inconsistencies in the conceptual model, and focused on the following areas for modification and refinement:

- **Longer Groundwater Model Calibration Period**. Since the development and application of the MET model, more groundwater elevation and quality data have been collected and the modeling effort should benefit from the most recent data. The calibration period used by the MET model was only 16 months from August 1995 to December 1996. The new model uses the most recent data and a calibration period spanning at least from the mid 1990s to late 2000.
- **Utilizing More Recent Water Quality Data**. The MET model used the available data up to the 1997 timeframe; however, more current data are now available. In particular, perchlorate has been sampled from the onsite monitoring wells and City of Pasadena production wells from 1997 to the present time (February 2001). The new model described in this report was developed using the more recent data and was calibrated for a period of time that includes 1997 to the present time (February 2001) to simulate the fate and transport of perchlorate more closely.
- **Accurate and Extended Boundaries for the Model Domain**. The model boundaries should be defined based on known geologic and hydrogeologic features, and be supported by the existing data, as much as possible. The JPL Groundwater Model boundaries were placed far enough away from important features such as the production and injection wells within the new model area. This was done to minimize the hydraulic impacts of the model boundaries, and to simulate the performance of the wells more accurately without bias.
- **Finer Resolution**. A new grid was designed to cover the larger model domain; it provides adequate resolution to accommodate the important injection and production wells. The importance of the grid design is in minimizing the numerical errors inherent in the groundwater modeling codes. The finer grid requirement is particularly important for the solute transport simulations in minimizing numerical dispersion.
- **Modified Conceptual Model**. The conceptual model used in the MET model needed to be revisited to address the inconsistencies with the geologic and hydrogeologic data. Modifications were made to the conceptual model, as necessary.
- **New Model Inputs**. With a new calibration period, and an extended model domain and grid design, it was necessary to define and assemble almost all of necessary data required for the new model. This included, but was not limited to, model area geometry and elevations; model layer discretization; hydrogeologic properties for model layers; injection and production well information; and other groundwater-budget-related data, initial conditions, and boundary conditions.
- **Newer Groundwater Modeling Codes**. Finally, a new groundwater flow and solute transport code was selected as the most appropriate code to meet the objectives of the JPL site, based on the results of the code evaluation effort described in Section 3.

1.4 Groundwater Modeling Objectives

The objective of this report is to document the construction and validation of a comprehensive groundwater flow model that accurately represents the hydrogeologic conditions at the Site. The groundwater flow model will be used to satisfy the overall

groundwater modeling objectives, which are based on the needs of NASA/JPL to evaluate the potential fate and transport issues related to the chemicals in the groundwater and to develop site remediation strategies for both on-facility and off-facility groundwater.

The more specific groundwater modeling objectives are listed below.

1. Fate and Transport Evaluations

- Evaluate the fate and transport mechanisms in the groundwater at the JPL site (OU-1 and OU-3).
- Perform particle-tracking simulation runs focusing on the potential source area(s) and the immediate flow field downgradient of the suspected source location(s).
- Evaluate the impacts of potential offsite source(s) of perchlorate (i.e., injected Colorado River water) on treatment, as well as the potential impacts of the previously identified upgradient source(s) of perchlorate and perchloroethylene (PCE) on the JPL site (OU-1 and OU–3).
- The RBMB and Metropolitan Water District of Southern California (Metropolitan) proposed changes to the current spreading and conjunctive use approaches will be evaluated. The focus of the evaluation will be on the potential impact of these changes on groundwater conditions at the JPL site and ultimately on remedial activities at OU-1 and OU-3.

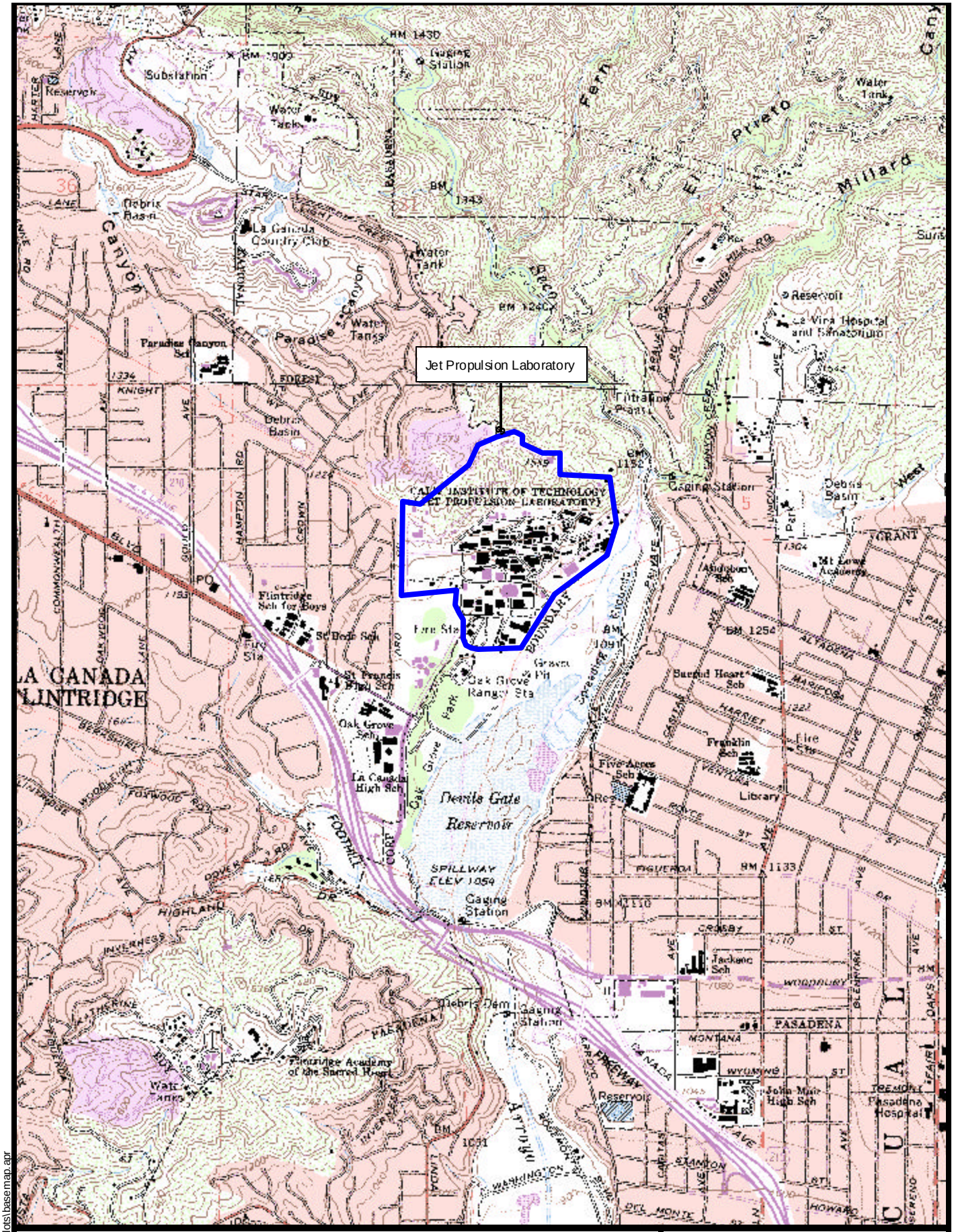
2. EE/CA and FS Support

- As future engineering analysis identifies potential remediation technologies, the model will be used as a tool to assist in evaluating the effectiveness of these technologies at the JPL site. Specifically, the model will be used to evaluate alternatives for groundwater extraction that are designed to prevent further migration of chemicals to local drinking water wells. This evaluation will include various disposal options for treated, extracted groundwater, including reinjection and land spreading.

3. Additional Modeling Support

- Support evaluation of additional fate and transport simulations, as requested by JPL/NASA.

In summary, the focus of this report is to describe the technical approach for the development of the 3-D flow model to address the objectives of JPL and NASA, particularly, to support the OU-3 EE/CA evaluations. Figure 1-3 illustrates the framework for the development and application of the JPL groundwater model as described in this report.



JPL Facility Boundary

Source: USGS
(Pasadena 7.5 Minute Quadrangle)

N

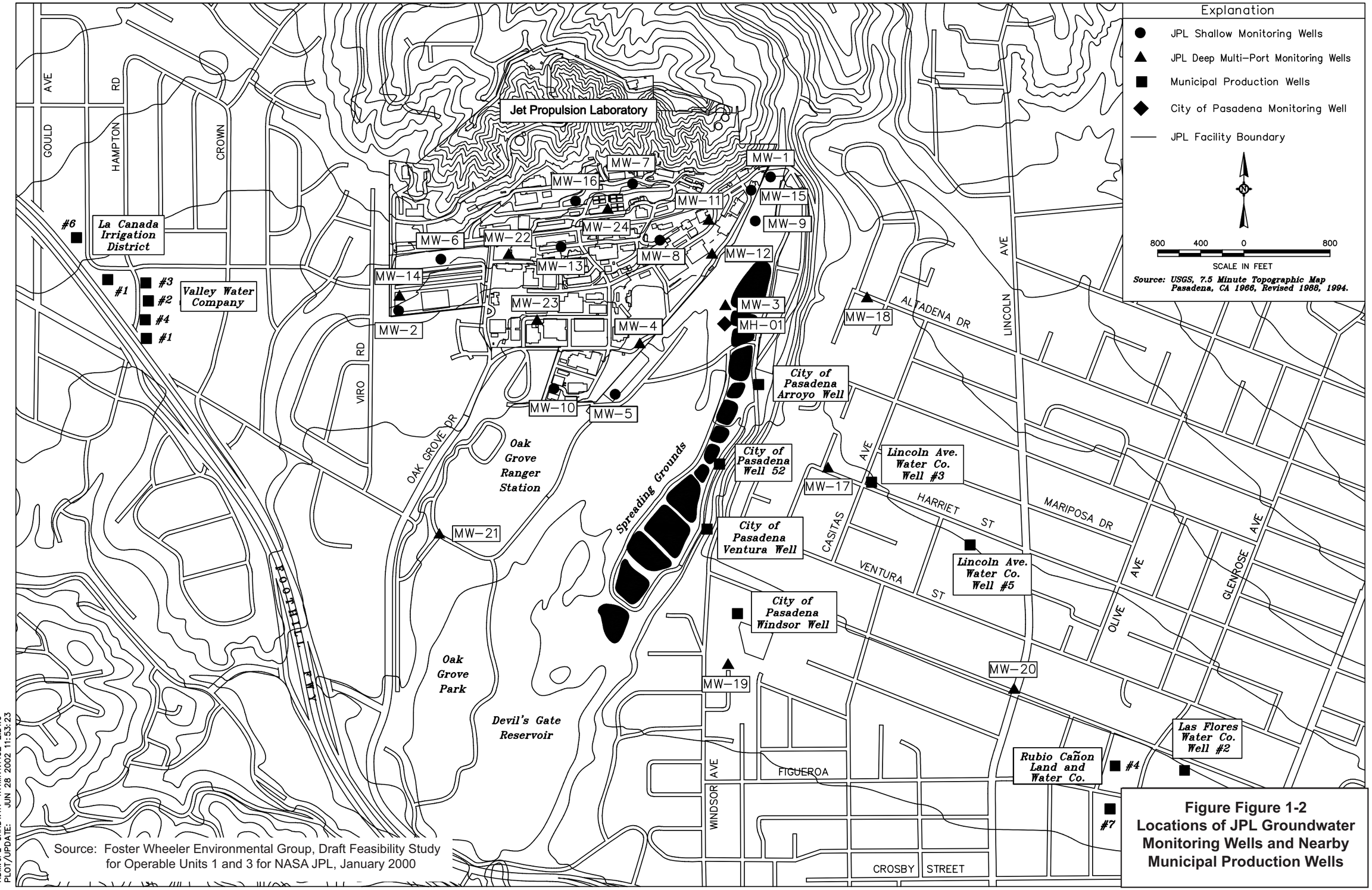
0.2 0 0.2 0.4 Miles

1:24000

Figure 1-1

Site Location Map
Jet Propulsion Laboratory

\\galtgis1\raymond\jplplots\basemap.apr



Source: Foster Wheeler Environmental Group, Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000

Figure Figure 1-2
Locations of JPL Groundwater Monitoring Wells and Nearby Municipal Production Wells

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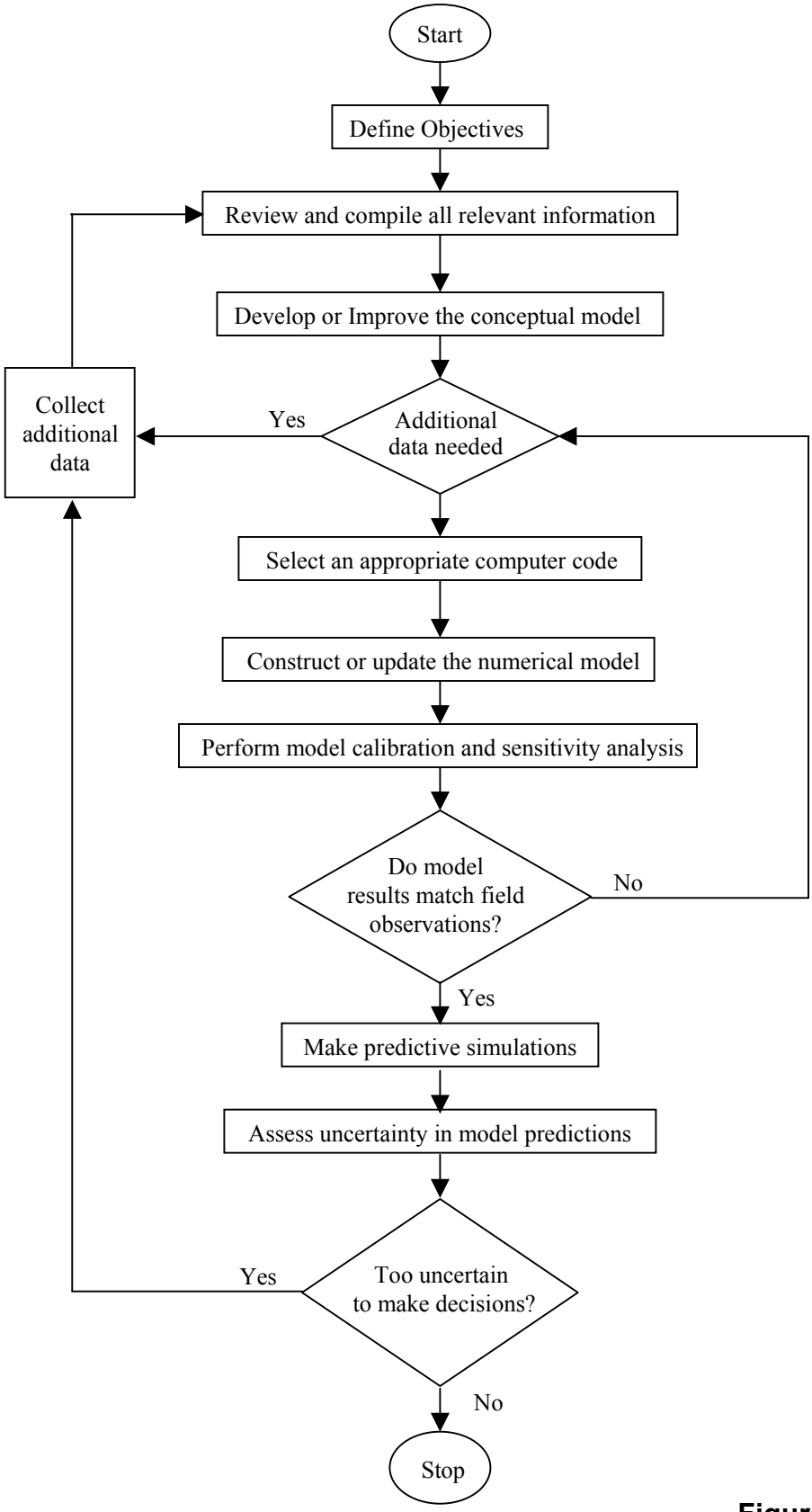


Figure 1-3
Framework for the
JPL Groundwater Model

2. Conceptual Model

A conceptual model identifies and characterizes the important factors that influence the groundwater system for the area of interest so that it may be implemented in a numerical model. As part of the conceptual model, available information was reviewed to identify hydrostratigraphic units, as well as sources of groundwater recharge and discharge (i.e., the water budget), and to provide initial estimates of hydrologic properties. Additionally, the conceptual model identifies simplifying assumptions necessary to develop the numerical model, such as identifying the extent of the numerical model domain and determining appropriate boundary conditions for the numerical model. Each of these factors is discussed within this section.

2.1 Regional Geology and Hydrogeology

The Raymond Basin lies in the northwestern part of the San Gabriel Valley, bounded by the San Gabriel Mountains to the north, the San Rafael Hills to the west, and ending to the south and east at the Raymond Fault. The San Gabriel Mountains, along with the San Bernardino Mountains to the east and the Santa Monica Mountains to the west, make up a major portion of the east-west trending Transverse Range geologic province of California. The San Gabriel Mountains are primarily composed of Cretaceous to Tertiary crystalline rocks, including diorites, granites, monzonites, and granodiorites, with a complex history of intrusion and metamorphism. The Sierra Madre fault system separates the San Gabriel Mountains to the north from the San Gabriel Valley to the south. Within the valley lies Quaternary alluvium, made up of sand, gravel, clay, or some mixture of each. Underlying the alluvium is the crystalline basement complex, comprised of the same general rock types that are exposed in the San Gabriel Mountains to the north (FWEC, 1999). The Raymond Basin covers approximately 40 square miles and slopes to the south, with elevations ranging from approximately 2,000 feet above mean sea level (msl) at the base of the mountains to approximately 600 feet above msl at the Raymond Fault. The alluvial deposits within the basin reach a maximum thickness of 1,100 feet (CH2M HILL, 1989).

As mentioned in previous reports, groundwater elevations in the basin can change significantly in response to pumping and natural recharge. Based on contours of groundwater elevation for fall 1998, groundwater in the upper portion of the basin ranges in elevation from 1,000 to 1,500 feet above msl and flows to the southeast (RBMB, 1999). The Raymond Basin is divided into three separate hydrologic sub-basins: the Pasadena Subarea, the Santa Anita Subarea, and the Monk Hill Sub-basin. The JPL site resides within the Monk Hill Sub-basin. Downgradient of the Monk Hill area, groundwater elevations range from 500 to 900 feet above msl and have a southern flow direction, which then curves to the southeast in the southern part of the basin. The direction of groundwater flow within the basin varies depending on the sub-basin. Estimates of regional hydraulic gradient range between 40 and 200 feet per mile (0.008- to 0.04-foot/foot) (RBMB, 1985).

2.2 Local Geology and Hydrogeology

The JPL site sits at the base of Gould Mesa, which is composed primarily of the Pacoima Formation. The JPL Thrust Fault runs east west across the middle of the site. North of the fault, depths to bedrock range from approximately 2 feet to more than 100 feet below ground surface (bgs) (Crandall et al., 1981). South of the fault, bedrock depths range from 550 feet bgs to more than 725 feet bgs. Overlying the crystalline bedrock are older Quaternary alluvial fan deposits, or fanglomerates. Generally, poorly sorted, poorly consolidated, coarse grained, brown sands with gravels, cobbles, and boulders characterize these sediments. Bedding is very poorly developed in the fanglomerates where the percentages of silt, clay, cobbles, and boulders fluctuate throughout the stratigraphic column. These fanglomerates reach a maximum thickness of approximately 750 feet near JPL and the mouth of the Arroyo Seco and gradually thin to the south, toward the South Pasadena area. This information is used in conjunction with hydrogeologic knowledge in the conceptualization of the hydrostratigraphic units, discussed later in this section.

The aquifer below the site has generally been considered to be an unconfined aquifer, with no discernible separate stratigraphic units. However, in the RI, the presence of vertical gradients in multiport wells located near municipal production wells during times of pumping was attributed to relatively thin, silt-rich layers that inhibit vertical flow (FWEC, 1999). Therefore, the aquifer was divided into four "hydrogeologic" layers (zones) based on how the silt-rich intervals influence the hydraulic heads in the aquifer during periods of pumping, as exhibited in well hydrographs. However, the aquifer seems to have a significant degree of differences in vertical hydraulic conductivities (anisotropy) on a scale larger than individual silt beds. Such vertical anisotropy can cause the vertical gradients and mounding beneath recharge areas that are observed at the monitoring wells.

The water table elevation varies significantly over the site, by as much as 130 feet. The groundwater elevation high point was measured in MW-1, located at the mouth of the Arroyo Seco. Groundwater mounding has been observed at this location throughout the RI monitoring period, and has been noted as one of the most significant features of the water table at JPL (FWEC, 1999). The RI Report indicates that the groundwater mounding in this area is the result of groundwater recharge from the mouth of the Arroyo Seco.

Figure 2-1 shows the significant change in average hydraulic head between the monitoring wells located near the mouth of the Arroyo Seco (MW-1, MW-9, and MW-15; see Figure 1-2 for well locations) and the monitoring wells to the southwest and west of the mouth of the Arroyo Seco. The change in flow regime across this area, significant difference in water levels over the relatively short distance, and lack of response of water levels near the mouth of the Arroyo Seco to pumping suggests the presence of either a very low conductivity area within the mouth of the Arroyo Seco or a hydraulic barrier that affects groundwater flow from this area. Based on a review of available information (boring logs, geotechnical logs, and slug test results) as well as the known faults observed near the area, the presence of a hydraulic barrier (such as a fault) was considered a more likely scenario. Although a hydraulic barrier was not initially included in the numerical model, it was necessary to add such a barrier during calibration to better reproduce hydraulic heads in this area. The calibrated horizontal and vertical conductivity values for the flow barrier were more than three orders of magnitude lower than those of the other areas.

2.3 Study Area

During development of the conceptual model, the extent of the study area for the water budget and modeling was determined based on review of water level contour maps, geologic maps, cross sections, well logs, and review of production well data for the Raymond Basin. When possible, natural boundaries such as the contact between the alluvium and the bedrock were utilized for the JPL model. The extent of the study area is shown in Figure 2-2.

The Monk Hill portion of the Raymond Basin is bounded by the San Gabriel Mountains along most of the northern boundary of the model, and by the San Raphael Hills along the northwest and western boundaries of the model. The furthest upgradient boundary for the model is the gap between the San Gabriel Mountains and San Raphael Hills in the northwest corner of the Raymond Basin. In this area, the underlying bedrock reaches its highest elevation locally, which results in a flow divide between the Raymond Basin and the adjacent Verdugo Basin. This boundary is located at a distance that allows potential upgradient source areas to be included in the model.

Based on review of Raymond Basin Watermaster water-level contour maps for the 1990s, the eastern boundary corresponds with the location of an approximately north-south flow line, and the southern boundary is selected as a location that has had relatively consistent water levels during the simulation periods. These model boundaries are located sufficiently downgradient to include all of the production wells that may influence groundwater flow within and downgradient of the JPL facility in the areas of interest.

2.4 Hydrostratigraphic Units

A hydrostratigraphic unit is a single unit or group of geologic units that have similar hydrogeologic properties, influences, and behavior. Information reviewed for delineating the hydrostratigraphic layers included hydrographs for shallow and multiport wells, boring logs, cross sections, electric logs of wells, and water quality data. Of particular importance were vertical head differences in multiport wells and notable changes in lithology within borings and cross sections. The amount of available information for delineating hydrostratigraphic layers significantly decreases with distance from the JPL facility and Arroyo Seco areas (where the monitoring wells are located). Outside these areas, the layering was assumed flat lying and was extended to the model boundaries.

The upper surface of the bedrock that underlies the alluvium represents the base of the modeled flow system (i.e., the bottom of the lowest hydrostratigraphic unit) because the underlying bedrock is considered significantly less conductive than the overlying alluvium. The elevation of the bedrock surface within the model domain was determined by integrating bedrock surface interpretations from several sources that are available at varying scales and levels of detail. These included the JPL RI Report (FWEC, 1999), top of bedrock contours for the Monk Hill portion of the Raymond Basin (California Division of Mines and Geology [CDMG], 1986), and top of bedrock contours for the entire Raymond Basin (DWR, 1969). The most detailed interpretation of the bedrock surface is provided within the RI Report and incorporates information from the JPL RI investigation. Outside this area, the base of bedrock contours was based on the contours for the Monk Hill area (CDMG, 1986),

except for a small area along the eastern boundary of the model based on combining the Monk Hill contours with the DWR contour map. Figure 2-3 shows the interpreted elevations for the base of alluvium for the JPL model. Figure 2-4 presents a 3-D visualization of the base of alluvium.

Four hydrostratigraphic units were identified for the JPL conceptual model. In the northwest portion of the model where the underlying bedrock elevation increases, the lower model layers are gradually pinched out and are not present at significant thicknesses. Figure 2-5 shows the location of the cross-sections, and Figure 2-6 presents the five geological cross-sections A-A' through E-E'.

2.5 Hydrogeologic Properties

Hydraulic parameters required for the modeling include the horizontal and vertical hydraulic conductivity, specific yield, and specific storage. The results of slug and bail tests conducted in the Westbay multiport monitoring wells and the regional model for the Devil's Gate project were reviewed to provide estimates of hydraulic properties. Because of the relatively high conductivity in the area, the slug and bail tests result in conductivity estimates that are representative of only small areas immediately surrounding the wells.

To provide estimates of hydraulic parameters closer to the scale for the groundwater modeling, a large-scale aquifer test was completed that utilized existing production and monitoring wells in the JPL facility area. The approach used for analyzing the pump test allows the inclusion of multiple production wells and multiple hydrostratigraphic units, and provides estimates of all properties of interest (horizontal and vertical conductivity and storativity). Hydraulic properties estimated from the large-scale pump test are based on integrating a significantly larger area and are more desirable given the scale of the numerical model. Properties from the Devil's Gate model were also reviewed to assist in modifying properties during model calibration. Ultimately, relatively few modifications to the estimates provided by the MLPU (an acronym of Multi Layer Program Unsteady State, or in Dutch: *MeerLagen-Programma* Unsteady State) were required during model calibration. An overview of the large-scale pump test is provided in the following section and additional details may be found in Appendix A.

2.6 Large-Scale Aquifer Test

A large-scale aquifer test was completed in May and June 2001 in Pasadena, California, to evaluate hydraulic properties of the hydrogeologic units in the vicinity of the JPL site. Analysis of the test data provided estimates of horizontal conductivity, vertical hydraulic conductivity, and storativity of the hydrogeologic layers included in the JPL numerical groundwater model. This aquifer test is unusual in that the test data were collected from a network of monitoring wells (including data at various depths in multiport monitoring wells) as a series of three large production wells was restarted after a period of shutdown.

The program MLPU was used to analyze the pump test results. MLPU is an analytical groundwater model that can be used to make estimates of hydraulic parameters for multiple layers in response to variable production rates from multiple production wells. Using an analytic element technique to represent the aquifer system and production well pumping,

MLPU's inverse modeling option estimates parameters by seeking to provide the closest match between simulated water levels and measured water levels. The optimization algorithm used is Levenberg-Marquard and can be used to make simultaneous estimates of up to 30 parameters in up to 7 independent groups using up to 500 independent head measurements.

MLPU requires knowledge or assumptions regarding the aquifer layering, the vertical distribution of pumping and monitoring well locations (both horizontal and vertical), and the time-dependent production rates and water-level measurements. The four hydrostratigraphic layers identified in the initial conceptual model (at their typical thicknesses in the vicinity of the production wells) were assumed for the MLPU analysis. The pump test analysis accounted for the production at three of the City of Pasadena's wells (Well 52, Ventura, and Windsor wells) and utilized the water-level responses at various depths at four multiport monitoring wells (MW-3, MW-4, MW-12, and MW-17) and at five shallow monitoring wells (MW-5, MW-8, MW-10, MW-13, and MH-01).

The results of MLPU runs are presented in Table 2-1. The model provided estimates of horizontal conductivity and storativity for each of the layers and an estimate of vertical conductivity between adjacent layers. Specific storage may be calculated from the resulting storativity value.

2.7 Water Budget for JPL Model Study Area

A groundwater budget was developed for the JPL area to identify sources of recharge and discharge sources and estimate quantities and the distribution of recharge and discharge within the model domain. The values presented here were developed for the conceptual model prior to calibration of the flow model and were used as starting points for calibration of the flow model. During calibration, it was not necessary to make changes to the methodology and approach developed for the conceptual model.

In this conceptual model, groundwater inflows to the model are as follows:

- Deep percolation of natural precipitation
- Spreading in the Arroyo Seco Spreading Grounds
- Return flow from applied waters
- Return flow from leaky distribution pipes
- Return flow from septic tanks
- Injection wells
- Mountain front recharge
- Leakage from streams and drainages
- Subsurface inflow

Outflow of groundwater from the model domain area is generally confined to the following:

- Groundwater pumping
- Subsurface outflow

2.7.1 Deep Percolation of Precipitation

Estimates for deep percolation in the basin were based on precipitation values for the Pasadena Station (obtained from the National Oceanic and Atmospheric Administration [NOAA]), and calculations to estimate the amount of precipitation available for deep percolation to groundwater and the area available for deep percolation to occur. The portion of precipitation that would be available as deep percolation was calculated based on the method proposed by Turner (1991) for a Mediterranean-type climate and is described by the equation:

$$R = P - 2.32 * P^{2/3} \quad \text{for } P >= 11.9 \text{ in.}$$

$$R = 0 \quad \text{for } P < 11.9 \text{ in.}$$

Where:

P = annual precipitation rate in inches per year

R = deep percolation rate in inches per year

The area available for deep percolation was estimated from land use classifications for the Raymond Basin. Each of the land use types and their associated pervious factors (percentage of the area available for deep percolation) are discussed below. Figure 2-7 presents the land use classification where deep percolation is assumed to occur.

- Residential: It is assumed that deep percolation from natural recharge occurs over 50 percent of all areas classified as residential.
- Industrial: It was assumed that industrial areas are impervious with the exception of open water storage facilities (within the model domain, limited to the area behind Devil's Gate Dam), water transfer facilities, and improved flood waterways and structures. For these areas, it is assumed that 100 percent of this area is available for deep percolation.
- Commercial: It is assumed that areas classified as commercial are generally impervious with the exception of educational facilities such as elementary schools and secondary schools. For these educational facilities, it is assumed that 75 percent of this area is available for deep percolation.
- Vacant: It is assumed that 100 percent of all areas classified as vacant are available for deep percolation.

The annual volume of recharge that occurs within each of the land use types is estimated by multiplying the deep percolation rate with the area available for recharge, as shown by:

$$V_{DP} = R * (F_P * A_{LUT})$$

Where:

V_{DP} = volume of deep percolation for a particular land use type
R = deep percolation rate
A_{LUT} = area of land use type
F_P = fraction of pervious area, land use type specific

2.7.2 Spreading in the Arroyo Seco Spreading Grounds

The Arroyo Seco Spreading Basins are located to the east of the JPL facility near the City of Pasadena production wells (Figure 2-8). When available, surface water in the Arroyo Seco is diverted to these basins and infiltrated to recharge groundwater. Additionally, the former sludge ponds associated with the former Behner Treatment Plant have been converted to infiltration basins and are currently operated in concert with the Arroyo Seco Spreading Basins for groundwater recharge.

The Raymond Basin Watermaster reports monthly volumes of water that are spread within the basins. Volumes for the former sludge ponds were reported separately from the City of Pasadena volumes beginning in the 1998-1999 water year. Prior to 1998-1999, the volumes spread in the former sludge ponds were reported as part of the City of Pasadena spread volume for the Arroyo Seco Spreading Grounds (personal communication, Ron Palmer, Executive Director of RBMB, March 2001). The annual spreads by LACDPW, referred to as the "general benefits," have been accounted for in the groundwater budget, reflected in the total recharge volumes for the Arroyo Seco Spreading Basins.

The Arroyo Seco channel is unlined above the Devil's Gate Dam and lined with concrete below the dam. According to the RBMB, the volume of water infiltrated along the river above the dam is included in the volume of water reported as spread in the spreading basins. The other major drainage channels within the study area are lined and, therefore, were not included as significant sources of recharge for the JPL groundwater model (personal communication, Ron Palmer, Executive Director of RBMB, March 2001).

2.7.3 Return Flow from Applied Waters

It is assumed that a portion of water delivered by water purveyors for use within the model domain results in return flows that recharge groundwater. The purveyor service areas are shown in Figure 2-9. The volume of recharge from return flows was based on the total water use volumes reported by the RBMB Watermaster Reports individual purveyors. The total water delivered is calculated from the sum of groundwater extractions, surface water diversions, and imported water, minus exported water. For purveyors with service areas that extend outside the model domain, the percentage of water delivered within the model domain was estimated based on the percentage of their service area that is within the model domain. Assuming that 20 percent of water delivered is utilized outdoors and 50 percent of that water results in groundwater recharge, the annual volume of recharge from return flows was estimated as 10 percent of the water delivered by each water purveyor.

2.7.4 Return Flow from Leaky Distribution Pipes

It was assumed that a small percentage of water delivered by purveyors is lost from the distribution system via leaky pipes. The basis for estimating the volume of water delivered by water purveyors within the model domain is provided in the previous section. It was assumed that 1 percent of the water delivered within the model domain (Figure 2-9) is lost from the delivery system and results in return flows that recharge groundwater.

2.7.5 Return Flow from Septic Tanks

Previous modeling for the Raymond Basin included a source of groundwater recharge from septic tank discharges for areas that are not connected to sewer systems (CH2M HILL, 1989). These unsewered areas are located in the northwest corner of the Raymond Basin and lie partially within the model domain (Figure 2-8). According to the RBMB (personal communication with Ron Palmer, June 2001), the extent of the unsewered areas has not changed substantially over the years. For the Devil's Gate model of the Raymond Basin (CH2M HILL, 1989), the estimated volume of return flow from septic tanks was based on DWR (1969) return flows for septic tanks and cesspools located in alluvial areas. Because of relatively few changes to the sewer system since that time, the Devil's Gate model assumed a constant value of return flow through 1988 based on the last DWR estimate (for 1962-1963). The JPL groundwater model assumed a septic tank return flow rate of 1,623 acre-feet per year based on adjusting the DWR value based on the percentage of the unsewered areas within the study area.

2.7.6 Mountain Front Recharge

DWR estimated that an average of 6,520 acre-feet per year of recharge from the surrounding bedrock enters the Raymond Basin alluvial groundwater system (DWR, 1969). For the JPL groundwater model area, the rate of recharge was reduced to 2,197 acre-feet per year based on the percentage of linear mountain front within the model study area (34 percent).

2.7.7 Production and Injection Wells

Within the JPL model study area, there are 16 production wells in service during the water budget period (1996-1997 through 1999-2000). Two of these wells located upgradient of the JPL facility (Valley No. 2 and No. 3) are aquifer storage and recovery (ASR) wells that are used for both extraction and injection of water. The RBMB compiles and reports the quantities (on a month-by-month basis) of water extracted and injected for each of these wells. These quantities were used in the groundwater budget for the study area.

2.7.8 Subsurface Inflow

It was assumed that in addition to surface water flow coming into the Raymond Basin via the Arroyo Seco, a component of underflow through the mouth of the Arroyo Seco contributes to groundwater recharge. Previous estimates of this value could not be identified; therefore, an initial estimate was needed for the steady-state water budget. Because the Millard Canyon spreading grounds are located north of the Raymond Basin boundary and upstream of the Arroyo Seco channel, the reported value for water spread in Millard Canyon was assumed as an initial estimate for the component of underflow through the mouth of the Arroyo Seco. Monthly volumes for water spread were obtained from the RBMB Watermaster Reports and ranged between 138 acre-feet per year and 1,855 acre-feet per year.

2.7.9 Subsurface Outflow

The volume of groundwater outflow along the southeastern edge was estimated based on cross-sectional area available for flow along the boundary, and an assumed hydraulic conductivity and average gradient at the boundary. The cross-sectional area

(3,609,738 square feet) available for flow was based on the layer thickness (distance between the water table and bottom of alluvium) and length of the boundary. Based on contour maps, an average value of the horizontal component of hydraulic gradient of 0.02 was assumed. A hydraulic conductivity value of 2 feet/day was estimated based on review of the range of conductivity values in this area used in the Raymond Basin Devil's Gate modeling.

2.7.10 Water Budget Summary

The water budget was prepared for the period of July 1996 through June 2000. Table 2-2 provides an annual summary for each of these sources of recharge and discharge within the model domain. Over this period, the conceptual water budget estimated a decrease in storage of 252 acre-feet, which is an average decrease in water levels of less than 0.1-foot for the model domain. The steady-state model calibration was based on utilizing the average recharge and water levels for the water budget period.

Figure 2-10 shows the percentages of the inflow groundwater budget components. These percentages were calculated based on the average values over the budget period.

TABLE 2-1 Results Of MLPU Aquifer Test Analysis

Layer	Thickness [ft]	Horizontal Conductivity [ft/d]	Vertical Conductivity [ft/d]	Storativity [–]
1	213	14.4		1.7×10^{-5}
Between Layers 1 and 2	—	—	9.2×10^{-3}	—
2	164	28.2	—	2.7×10^{-4}
Between Layers 2 and 3	—	—	6.2×10^{-3}	—
3	131	27.9	—	2.2×10^{-4}
Between Layers 3 and 4	—	—	1.1×10^{-2}	—
4	328	3.9	—	1.3×10^{-4}

TABLE 2-2 Summary of Groundwater Budget (units are acre-feet per year)

Inflows	1996-1997	1997-1998	1998-1999	1999-2000	Average
Deep percolation of precipitation	517	3,606	0	641	1,191
Arroyo Seco Spreading Basins	6,390.1	4,384	3,670.1	2,096.6	4,135.1
Return flow from applied water	1,184	1,020	1,132.8	1,291.6	1,157.2
Return flow from leaky distribution pipes	119	102	113	129	116
Return flow from septic tanks	1,623	1,623	1,623	1,623	1,623
Injection wells	626	625	486	520	564
Mountain front recharge	2,197	2,197	2,197	2,197	2,197
Subsurface inflow	1,064	1,855	171	138	807
Total Inflow	**13,720**	**15,412**	**9,393**	**8,636**	**11,790.3**
Outflows:					
Groundwater extraction	11,962	9,194	9,473	10,681	10,327
Subsurface outflow	1,210	1,210	1,210	1,213	1,211
Total Outflow	**13,172**	**10,404**	**10,683**	**11,896**	**11,538**

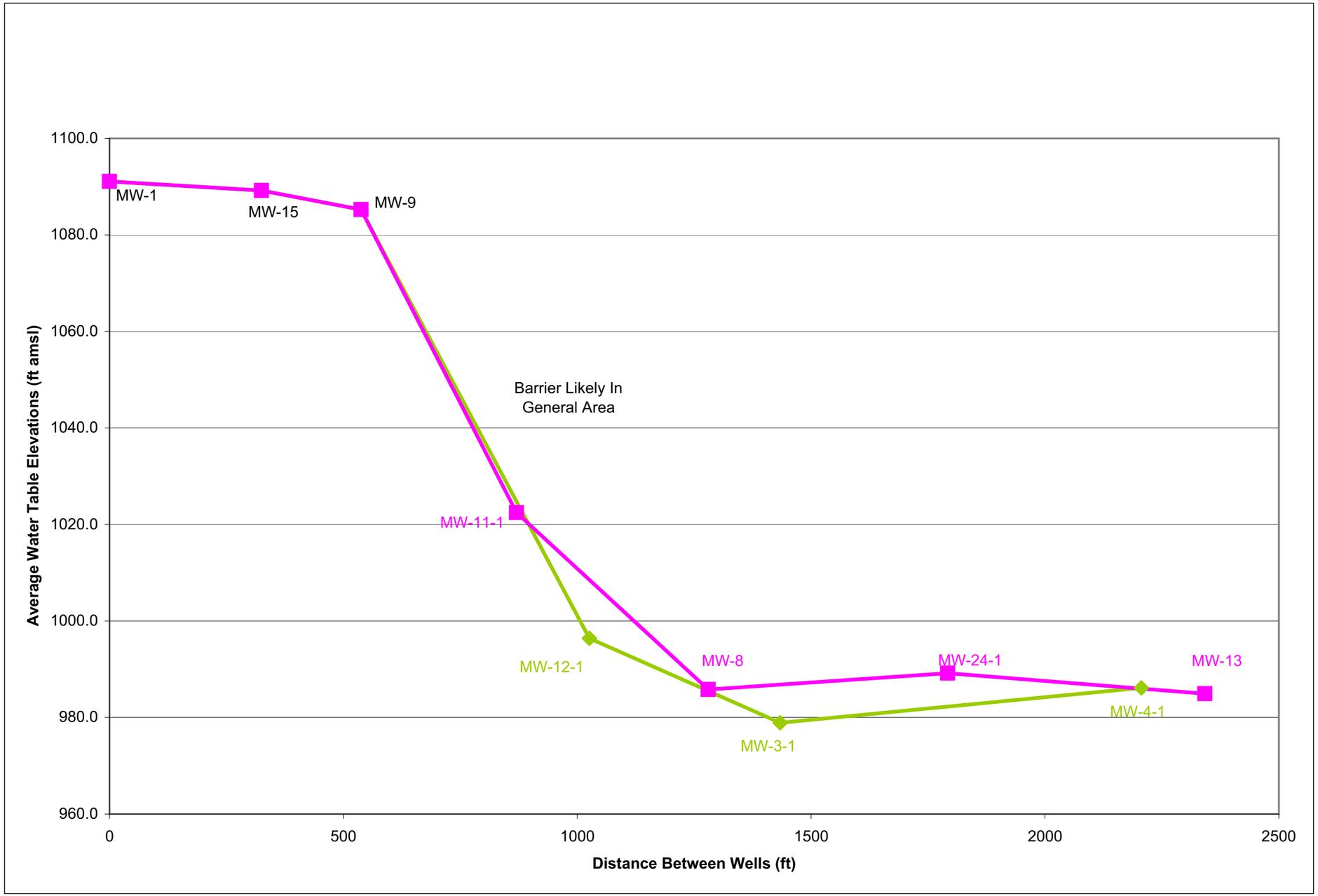


Figure 2-1
Water Head Difference Across
Potential Hydraulic Barrier
JPL Groundwater Model

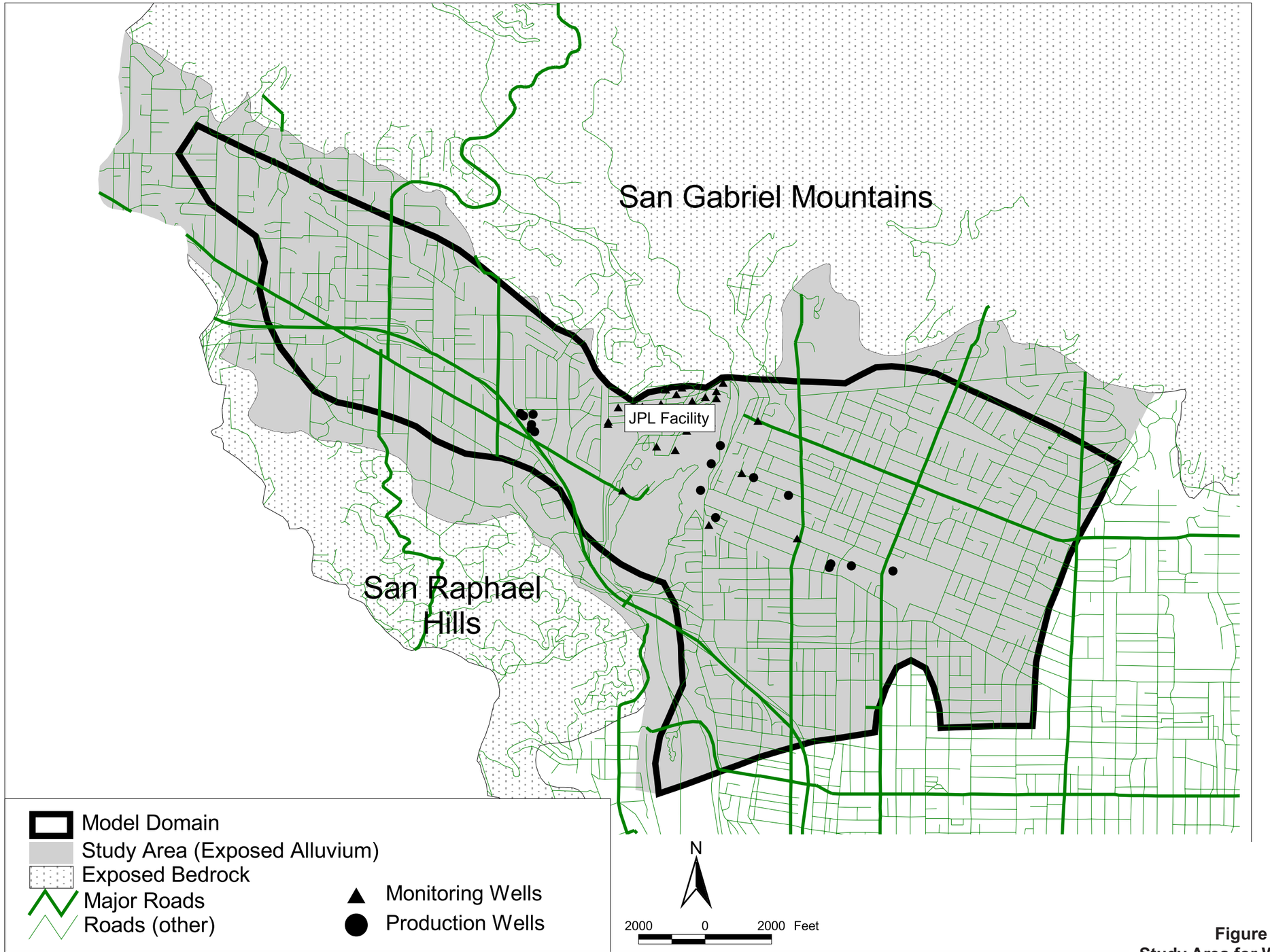


Figure 2-2
Study Area for Water Budget
JPL Groundwater Model

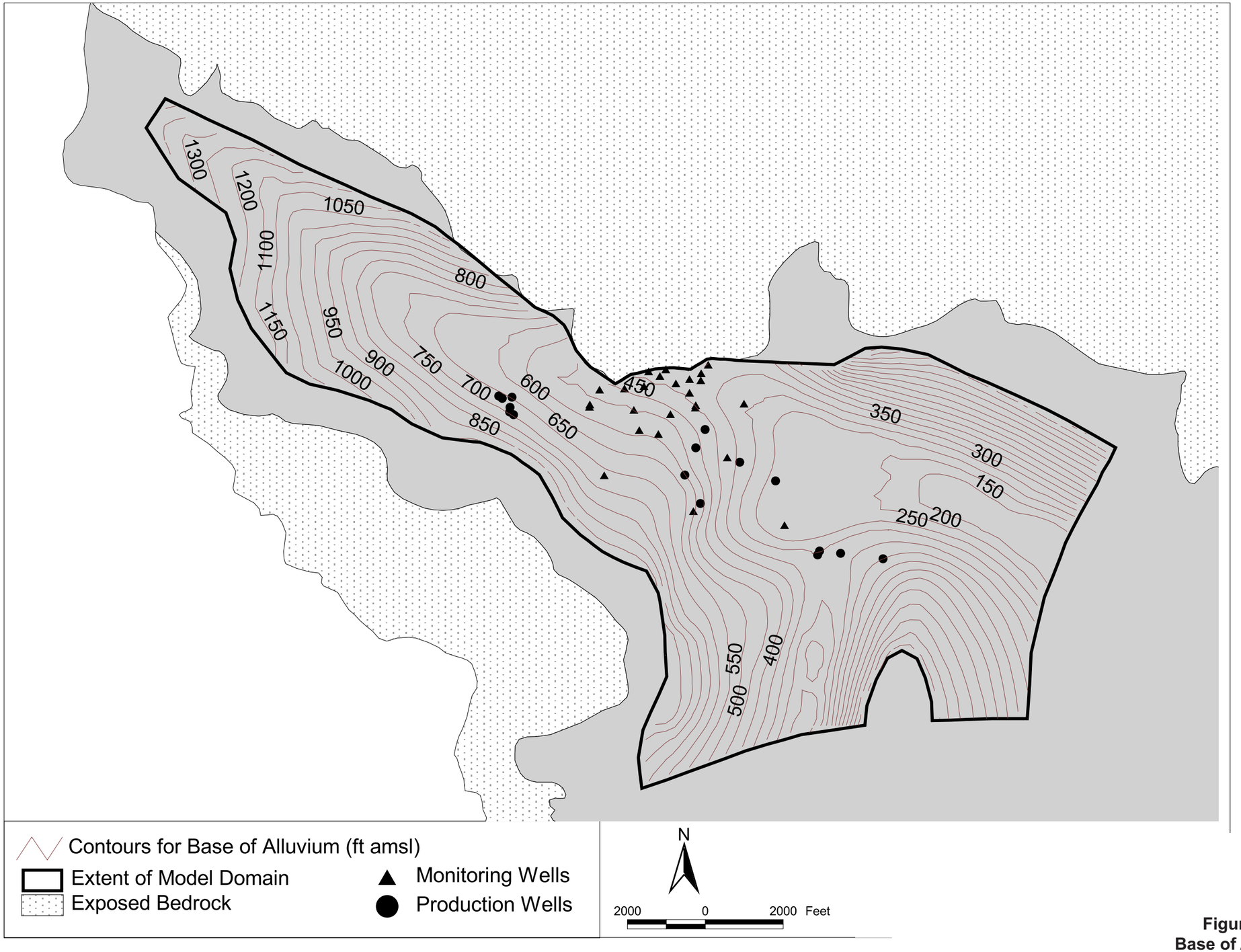
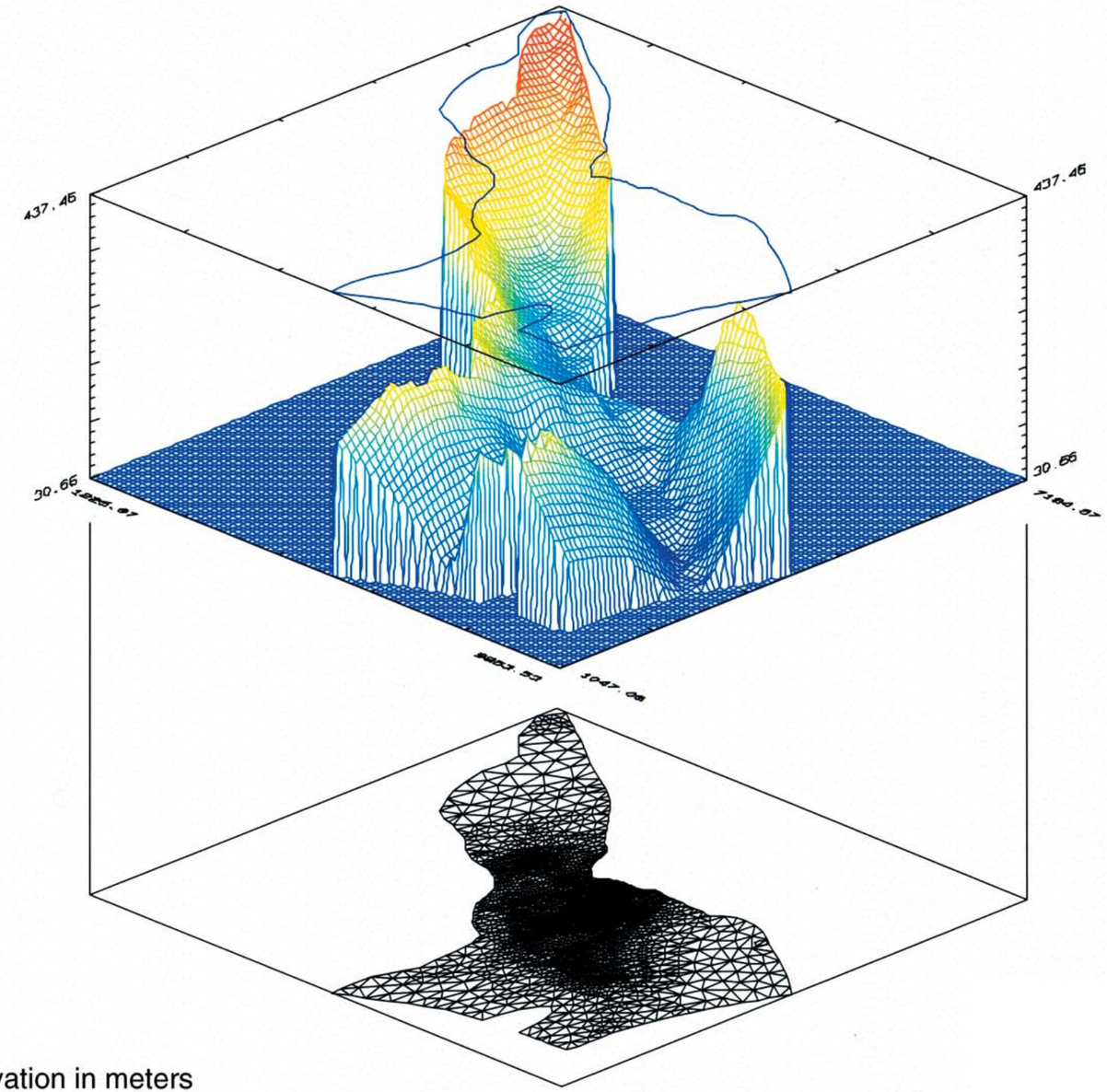


Figure 2-3
Base of Alluvium
JPL Groundwater Model



Note: elevation in meters

Figure 2-4
3-D Visualization of the
Base of Alluvium
JPL Groundwater Model

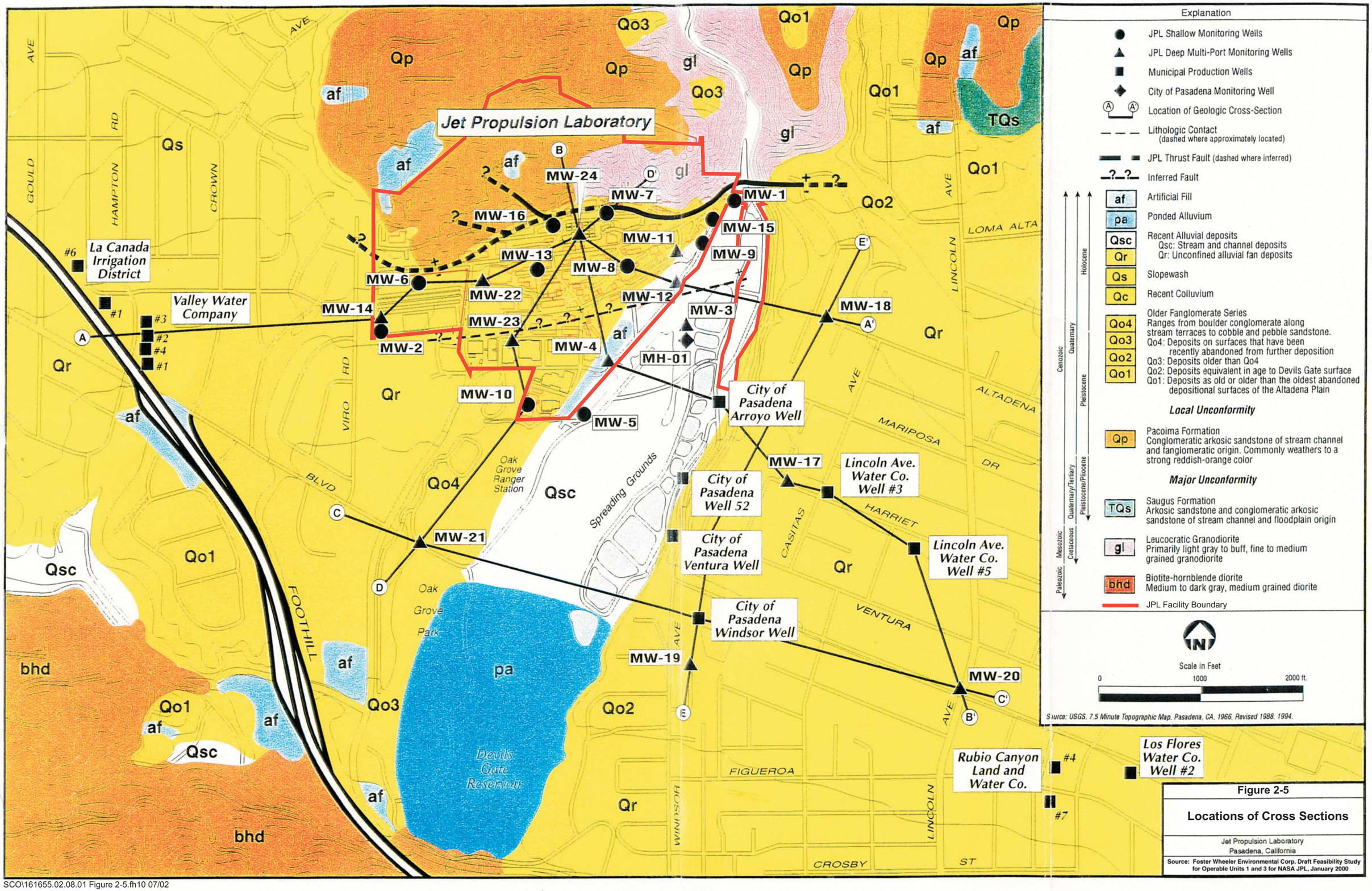


Figure 2-5

Locations of Cross Sections

Jet Propulsion Laboratory
Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000

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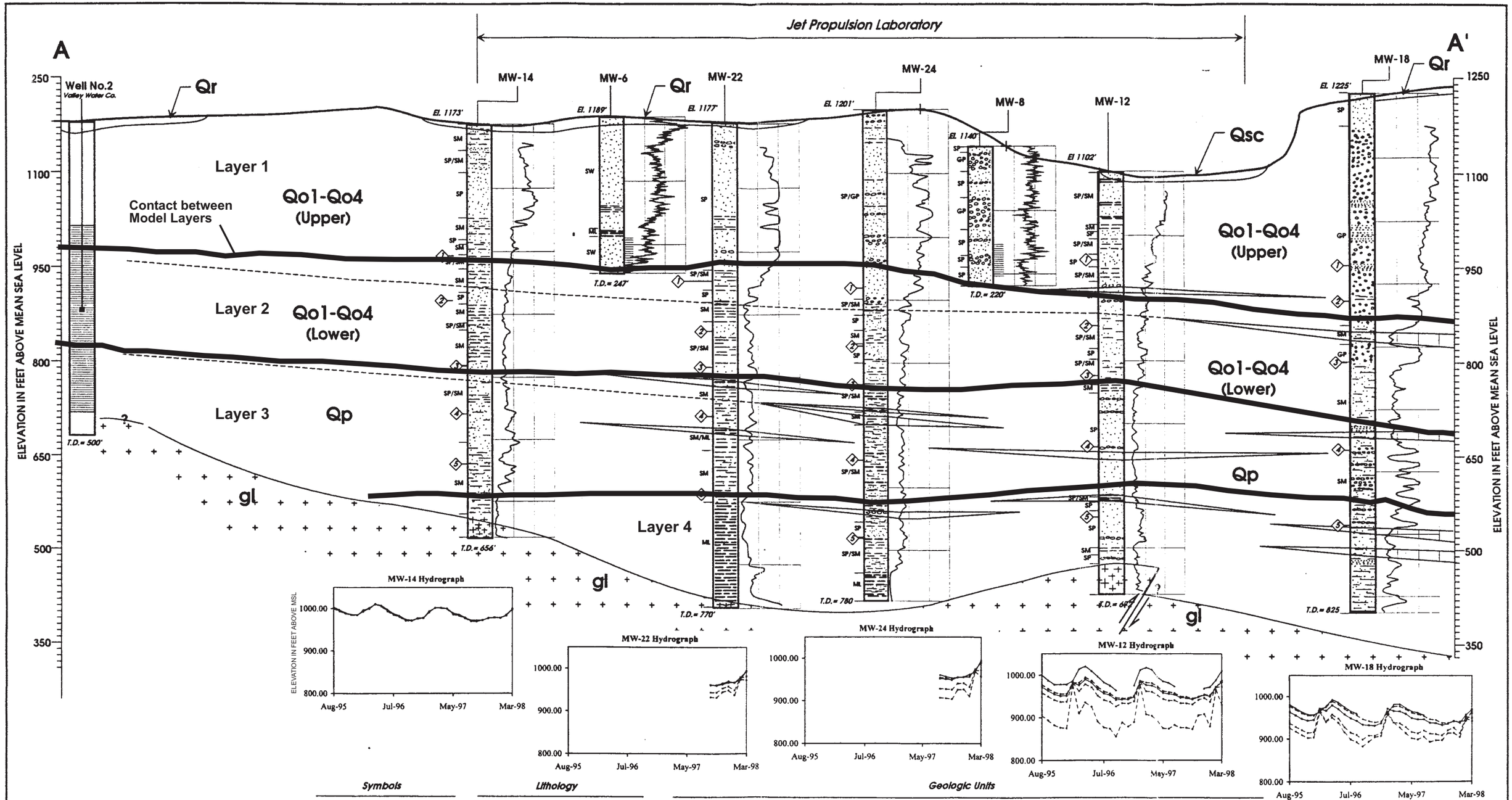


Revised June 17, 1998

Figure 2-6, Page 1 of 5

Geologic Cross Section A-A'

Jet Propulsion Laboratory, Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000

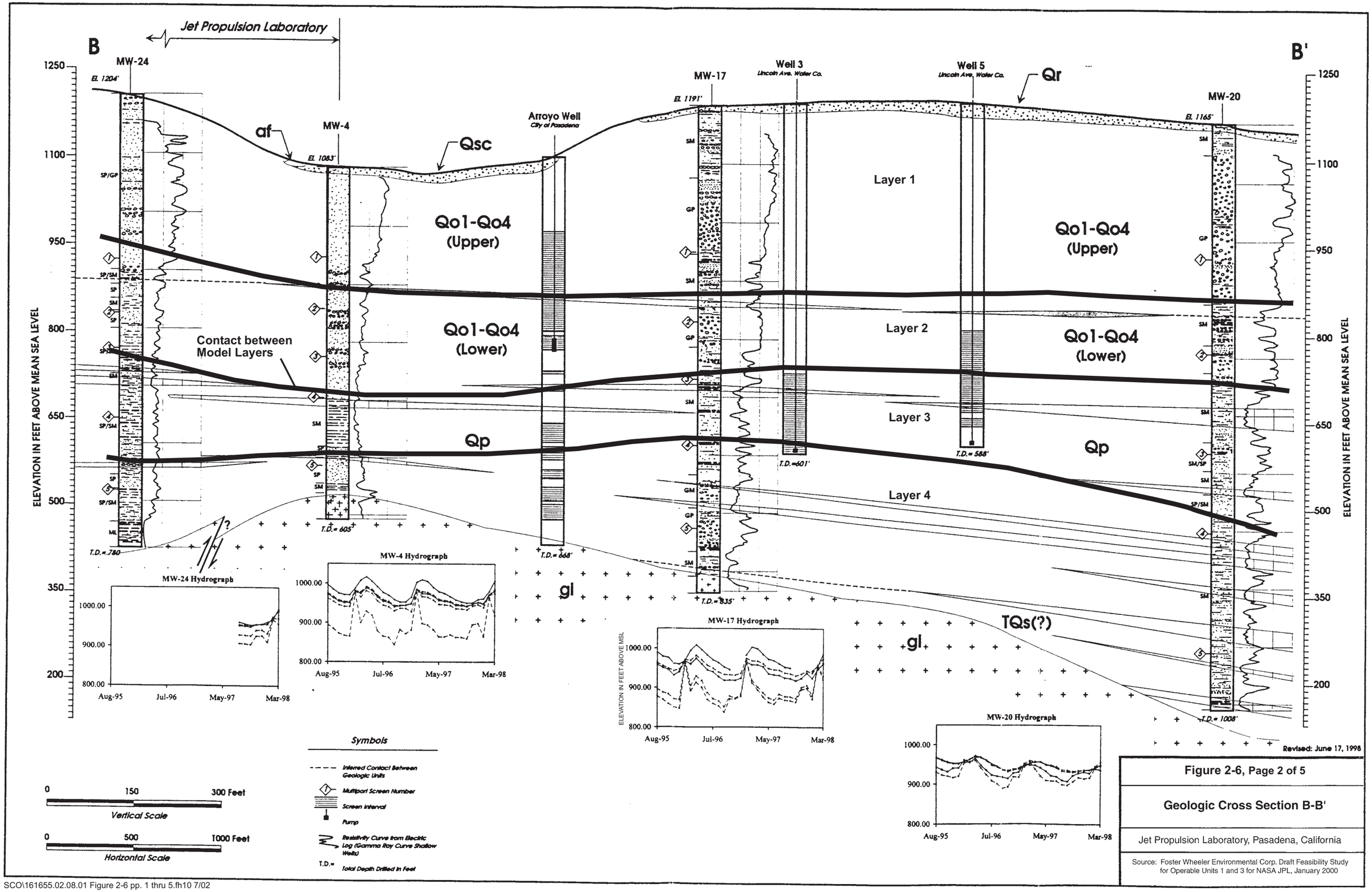


Figure 2-6, Page 2 of 5

Geologic Cross Section B-B'

Jet Propulsion Laboratory, Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000

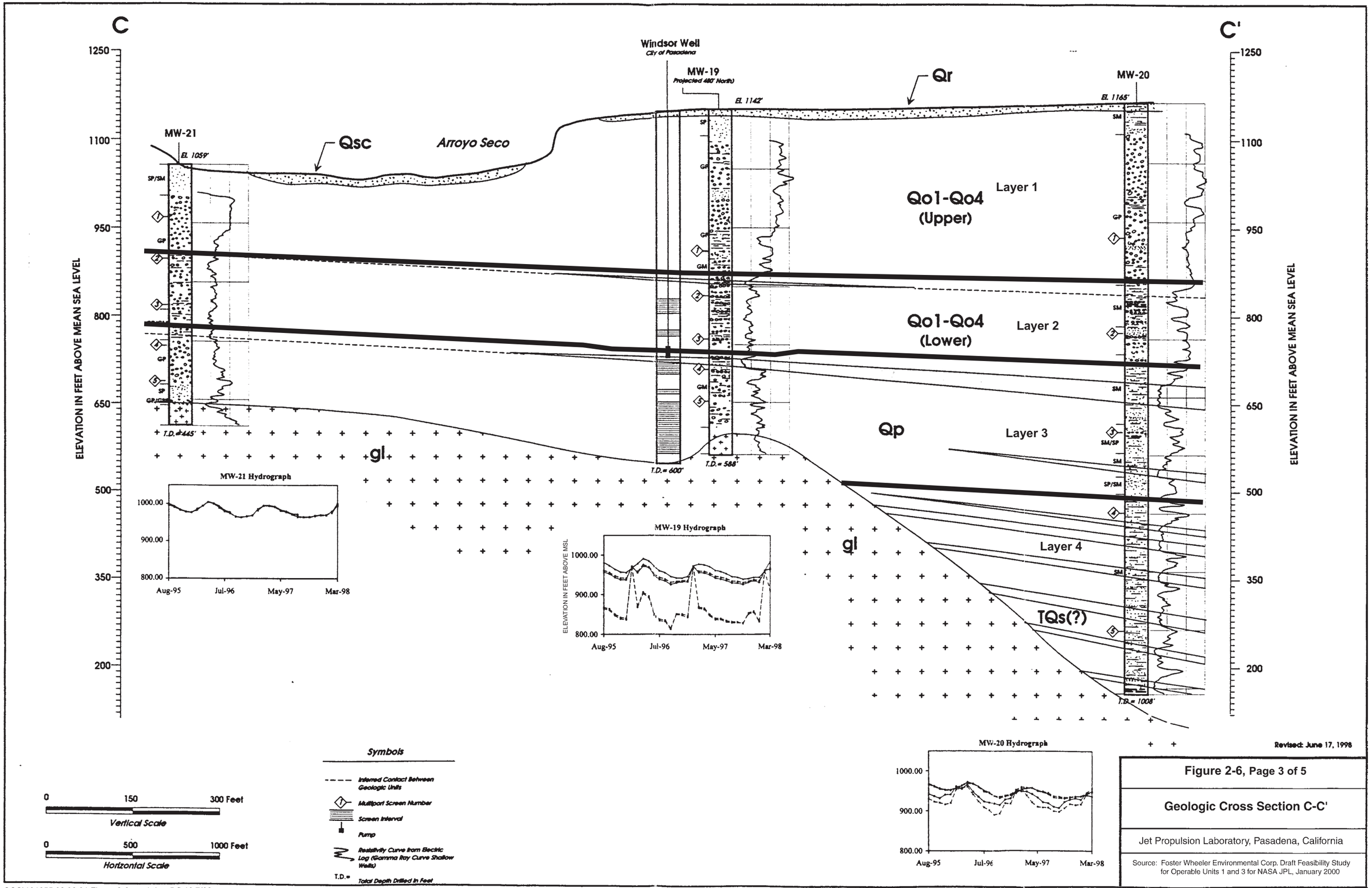
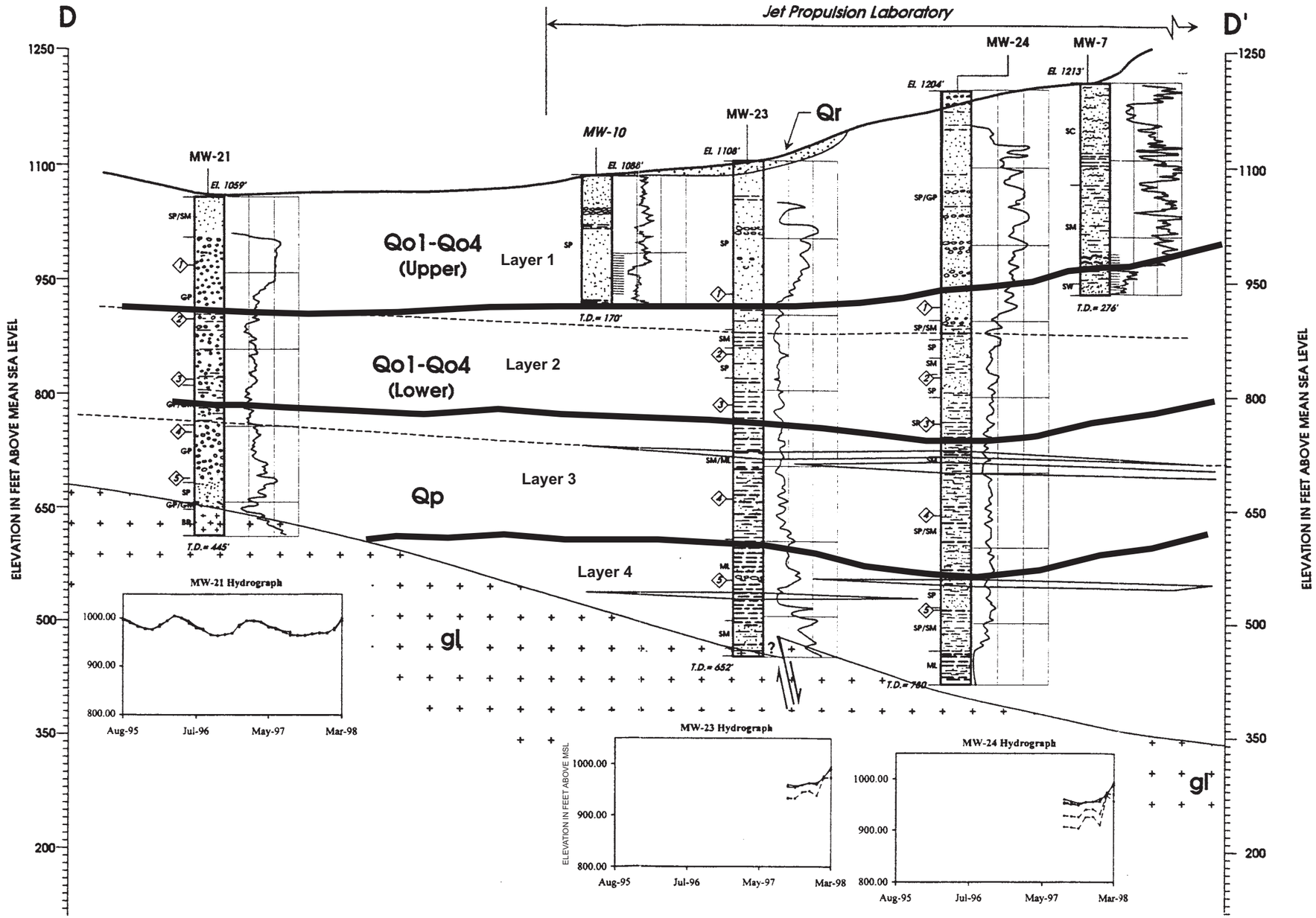


Figure 2-6, Page 3 of 5

Geologic Cross Section C-C'

Jet Propulsion Laboratory, Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000



Symbols

- Inferred Contact Between Geologic Units
- Multiport Screen Number
- Screen Interval
- Pump
- Resistivity Curve from Electric Log (Gamma Ray Curve Shallow Wells)
- T.D.= Total Depth Drilled in Feet

0 150 300 Feet
Vertical Scale

0 500 1000 Feet
Horizontal Scale

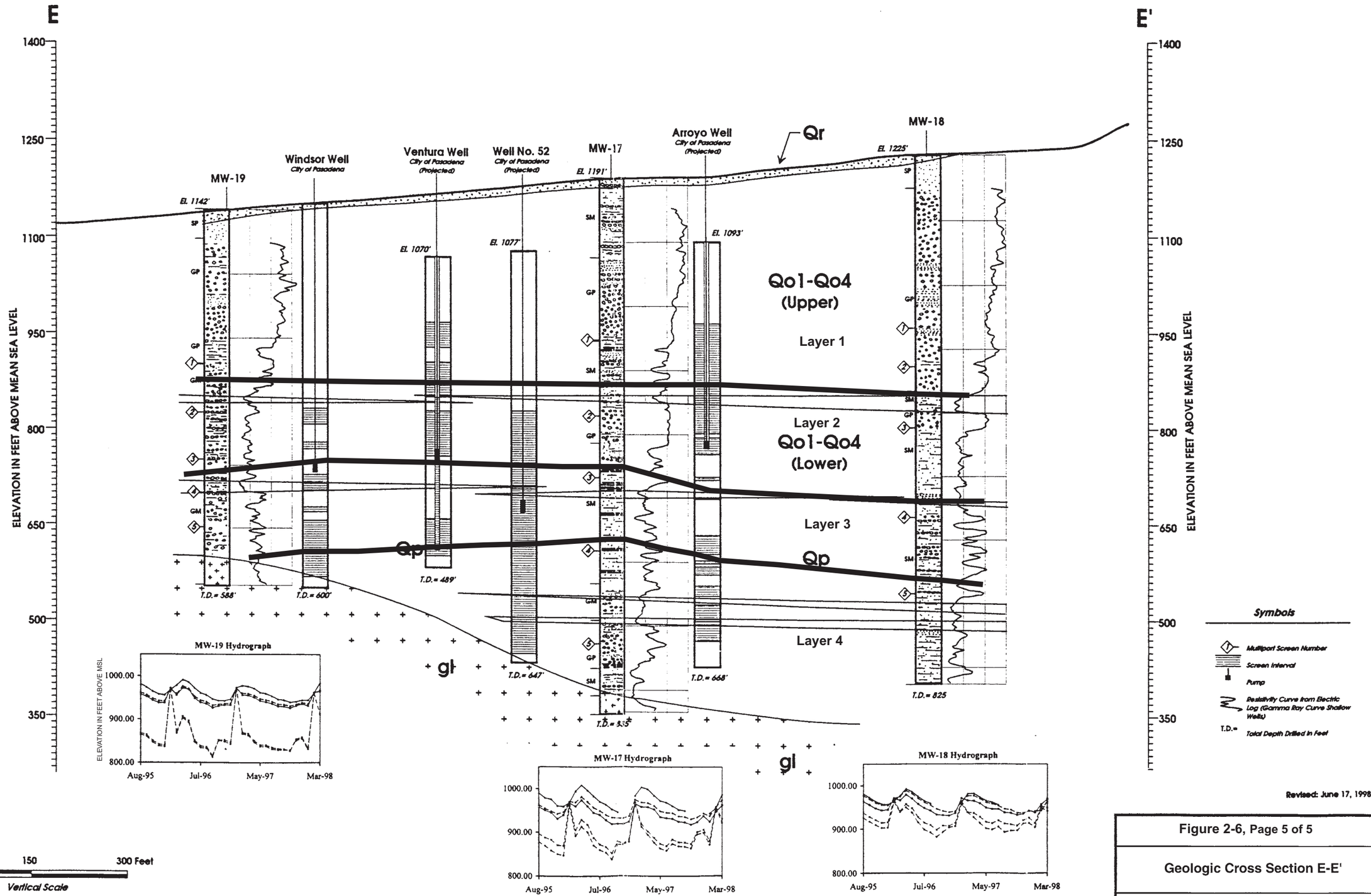
Revised: June 17, 1998

Figure 2-6, Page 4 of 5

Geologic Cross Section D-D'

Jet Propulsion Laboratory, Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000



Revised: June 17, 1998

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Geologic Cross Section E-E'

Jet Propulsion Laboratory, Pasadena, California

Source: Foster Wheeler Environmental Corp. Draft Feasibility Study for Operable Units 1 and 3 for NASA JPL, January 2000

Figure 2-7
Land Use Classification
JPL Groundwater Model

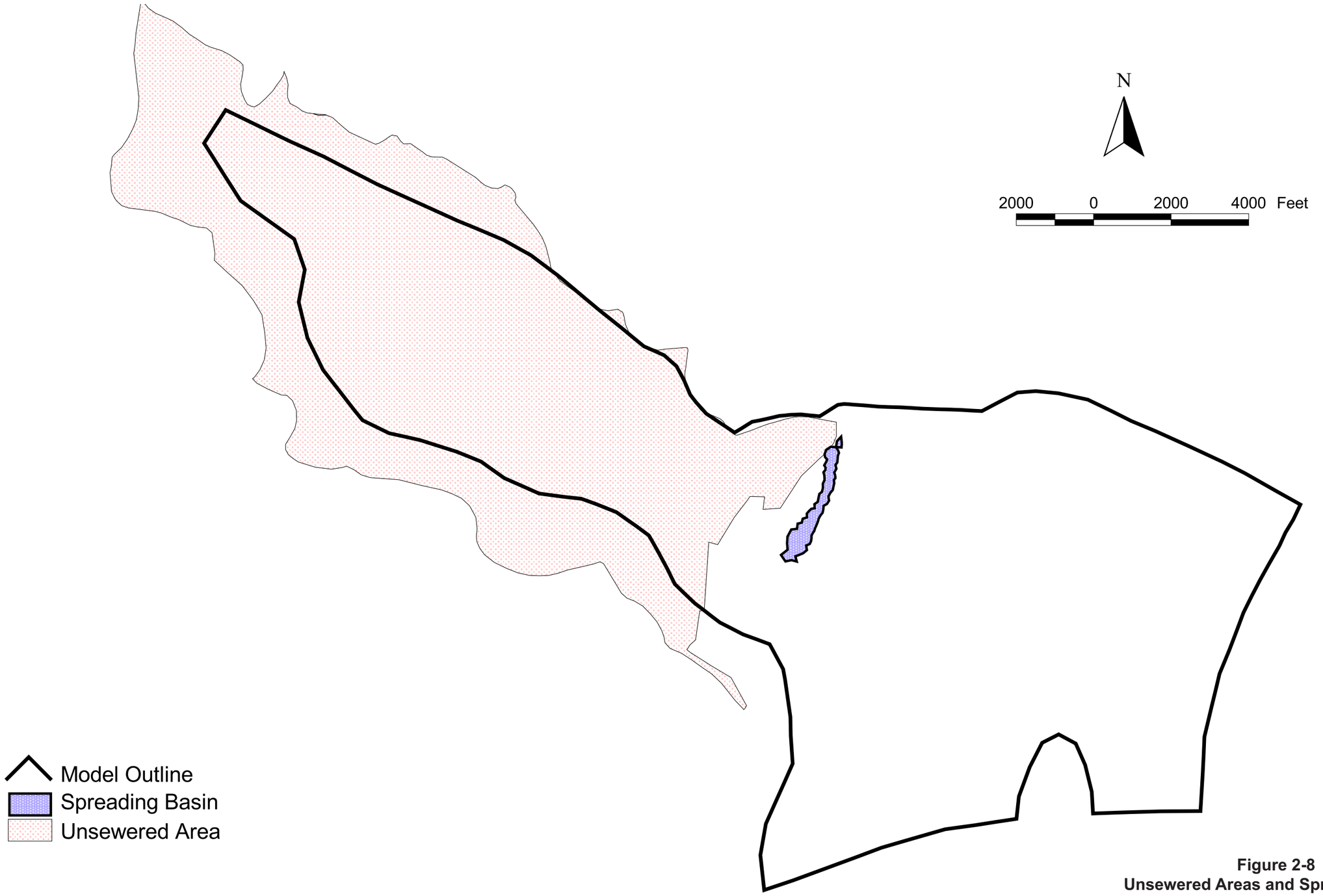

Figure 2-8
Unsewered Areas and Spreading Basin
JPL Groundwater Model

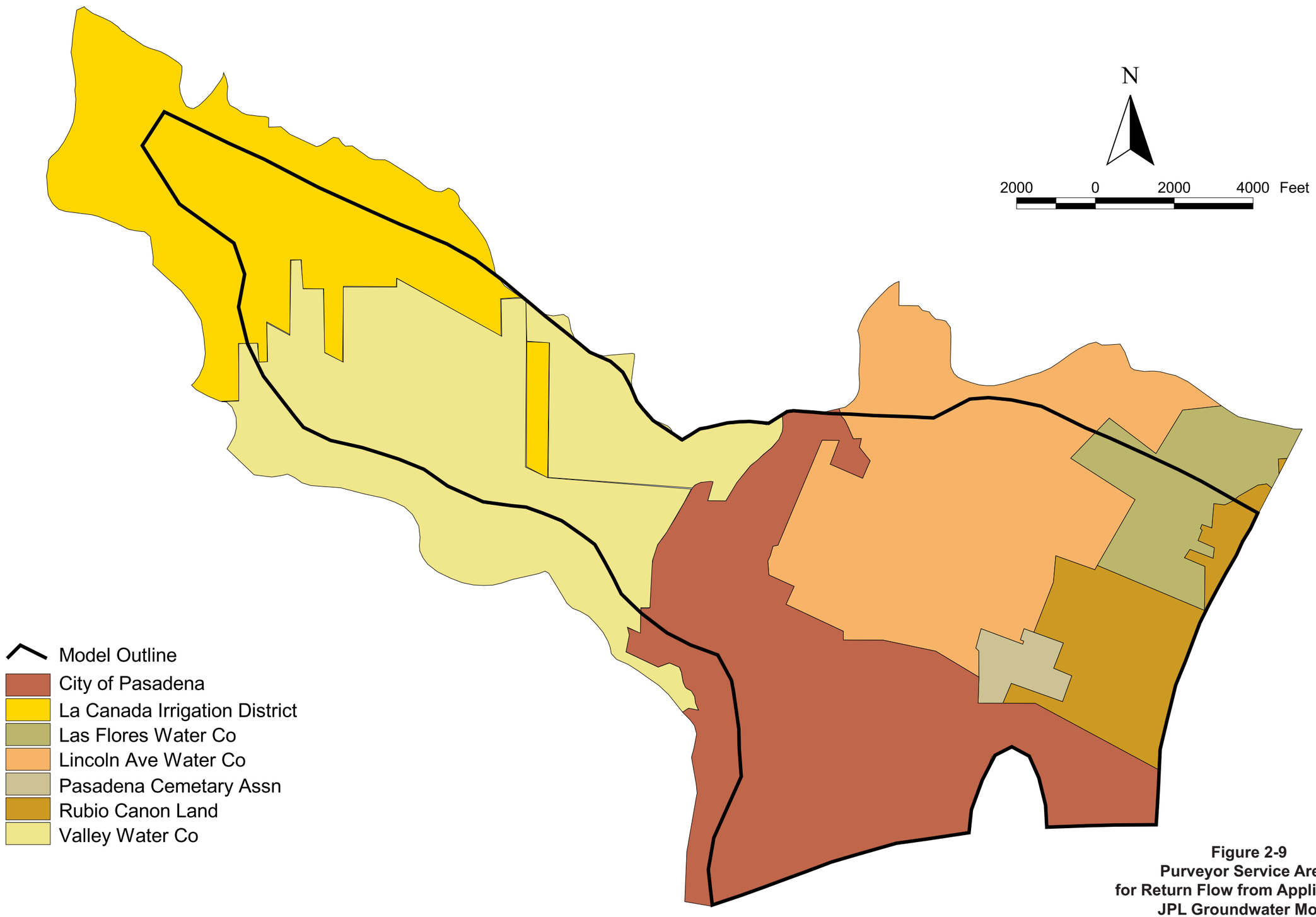

Figure 2-9
Purveyor Service Areas
for Return Flow from Applied Water
JPL Groundwater Model

3. Numerical Model

3.1 Groundwater Program Selection

Prior to beginning the JPL groundwater modeling, groundwater flow programs were reviewed and evaluated to determine the most appropriate groundwater flow program for the JPL groundwater model. This selection was based on (1) identifying a number of candidate programs, (2) an initial screening to identify those programs with the desired options for the JPL model, (3) a detailed evaluation based on selection criteria, and (4) a comparative evaluation focused on JPL site-specific conditions. Details regarding the model selection process are available in the JPL Groundwater Model Work Plan (CH2M HILL, 2001). An overview and results of the review are provided below.

Selection criteria for evaluating the programs were based on requirements for the JPL modeling, the ability to efficiently handle site-specific conditions, options for implementing a robust numerical model, and user features that allow for efficiently setting up, using, and evaluating model results. The selection criteria can be summarized as follows:

- Capable of simulating transient, 3-D flow and transport
- Particle tracking capability
- Established history of successful use
- Availability of technical support
- Handling of free surface
- Versatility of boundary conditions
- Finite difference or finite elements
- Pre- and postprocessing capabilities

Table 3-1 includes a list of the candidate programs and summarizes the results of the initial phases of the model selection process. Based on this review and experience with these programs, the list of potential candidates for simulating groundwater flow and transport beneath the JPL site was narrowed to two options: MODFLOW and FEFLOW. Based on our evaluation, MODFLOW and FEFLOW were the most appropriate finite difference and finite element program options, respectively, for use at the JPL site. As discussed in the Work Plan, finite element programs (such as FEFLOW) offer several inherent advantages over finite difference programs (such as MODFLOW) for the JPL site. FEFLOW also offers robust methods for handling a fluctuating free surface and dynamically allocating pumping, whereas MODFLOW has historically experienced convergence issues with fluctuating free surface problems. Because MODFLOW does have a longer history of use in the U.S. (although both MODFLOW and FEFLOW have received regulatory acceptance at Superfund Sites in California) and has historically been recognized as the user-friendliest program available, MODFLOW was also retained for further evaluation.

Additional evaluation of these programs was focused on assessing the relative level of effort required for developing the JPL model using FEFLOW or MODFLOW, and confirming whether the FEFLOW approach for handling a fluctuating water table was superior to the

MODFLOW approach for the JPL site. To evaluate these two codes, test problems were designed, implemented, and solved using both MODFLOW and FEFLOW. To facilitate a fair comparison of model results with analytical solutions, similar numbers of cells/elements and grid spacing were utilized for MODFLOW and FEFLOW simulations. For both problems, the choice of problem parameters was based on the observed or expected range of conditions at the JPL site.

For these problems, the level of effort associated with implementing the problems and reviewing the model results in MODFLOW and FEFLOW were very similar. Based on this, the estimated preparation times for the JPL model were expected to be relatively similar for both programs. Both programs offered similar functionality for the pre- and postprocessing required for these problems, although FEFLOW does offer more flexible options that were expected to be useful for the JPL model. For the evaluation problems, MODFLOW experienced convergence difficulty related to the fluctuating surface issue and FEFLOW was able to more efficiently and accurately solve these problems. Therefore, based on technical considerations and practical constraints, FEFLOW was selected as the most appropriate choice for modeling the groundwater flow and transport at the JPL site.

FEFLOW is the most thoroughly developed finite element program available. The development of FEFLOW began in East Germany in 1979, although it was not available in the U.S. until the 1990s. FEFLOW offers the ability to simulate saturated and/or variably saturated flow and solute transport and also has options for simulating density-dependant flow and heat transport. FEFLOW is more widely utilized in Europe than in the U.S., although it has been used in the U.S. on major projects, including use by Lawrence Livermore National Laboratory at the Livermore Superfund Site in California. FEFLOW offers significant flexibility in entering data through visual methods, as well as importing information from ASCII files, CAD coverages, and GIS coverages. FEFLOW also offers robust approaches to handling fluctuating free surfaces, the ability to dynamically allocate pumping, and robust visualization capabilities.

3.2 Model Domain/Grid Design

The JPL groundwater model encompasses a 4,560-acre area that includes the Monk Hill portion of the Raymond Basin. Figure 3-1 shows the JPL model area in relation to the Raymond Basin and in comparison with the previous MET model area. Vertically, the JPL model has four model layers corresponding to the four hydrostratigraphic units (zones) as identified in the initial conceptual model. Figure 2-6 presents the four hydrogeologic units delineated on the five cross sections as model layers. Figure 3-2 shows the extent to which each model layer is present and the elevations of the base of each model layer. In the northwest portion of the model where the underlying bedrock elevation increases, the lower model layers are gradually pinched out and are not present at significant thicknesses. In actual implementation of the numerical model in FEFLOW, each model layer is bounded by two “slices,” representing the top and bottom of the model layer, respectively. Therefore, the JPL model is comprised of five slices.

In some areas, the JPL model does not extend to the contact (as observed at ground surface) of the alluvium and the bedrock that indicates the extent of the alluvial basin. This is because, based on the water levels and the interpreted elevation of the top of bedrock, the

underlying bedrock (which forms the surrounding mountains) is steeply rising along the basin margins in these areas and would intersect the water table near the locations shown as the model boundaries. Recharge received within these alluvium areas at the basin margins is assumed to recharge the groundwater system, and is included in the numerical model (discussed in Section 3.3). A similar situation occurs along the southern boundary of the model where bedrock rises to form Monk Hill.

Figure 3-3 shows the finite element meshes for the JPL groundwater model. Element sizes within the mesh were varied to provide greater detail in the area near and downgradient of the JPL facility, while maintaining a reasonable number of elements. Much finer detail was used around high stress areas such as production wells, and element sizes were transitioned gradually away from these areas. The model domain was composed of 3,630 nodes and 5,851 elements per model slice, corresponding to a total of 18,150 nodes and 29,255 elements for the entire model.

3.3 Boundary Conditions/Model Stresses

Boundary conditions and recharge for the JPL groundwater model were derived from the sources of inflow and outflow identified in the water budget development. Figure 3-4 shows the boundary conditions of the JPL groundwater model.

The area represented by the JPL groundwater model is bounded to the north by the San Gabriel Mountains and to the west and southwest by the San Raphael Mountains. The base of the alluvium (the interpreted elevation of bedrock) represents the bottom of the flow system and was represented by a no flow boundary.

Recharge that occurs within the alluvium between the surrounding mountains and the model boundaries was applied along the model boundaries in these areas as horizontal fluxes. Similarly, mountain front recharge and groundwater inflow at the mouth of the Arroyo Seco were also applied to the model boundaries as lateral fluxes for the appropriate stretches of the model boundary. In actual calculation, the flux boundary was divided into 10 different stretches based on the flux rates that resulted from the combination of mountain front recharge, groundwater inflow at the mouth of the Arroyo Seco, and recharge that occurs within the alluvium outside the model domain. An average lateral flux rate over the entire simulation period was calculated for each stretch, and these values were used in the steady-state model.

Recharge from deep percolation of natural recharge was distributed over the model area consistent with the land use types and associated recharge factors discussed in Section 2.7. Likewise, recharge derived from return flows of applied waters, leaky distribution pipes, septic tanks, and the Arroyo Seco Spreading Basins was also distributed over the areas associated with these various sources. The entire model domain was divided into 40 different subareas based on the recharge rates resulting from the combination of these areal recharge sources. For the steady-state simulations, an average recharge rate over the entire modeling period was calculated for each of the 40 subareas, and these values were applied as areal recharges from the top of the aquifer in the model.

There are 14 production wells and 2 ASR wells that are used for both extraction and injection of groundwater within the modeling area. These wells were represented as point

sources and/or sinks in the JPL model. The extraction/injection of these production wells was distributed vertically to each slice based on the screened intervals of the wells and local material properties. Figure 3-5 shows the screened intervals of the extraction/injection wells in relation to model slice elevations. No well screen information was available for production wells (LCID No. 6 and Park 2-3); therefore, only the slice elevations are shown for these two wells. Table 3-2 gives the resulting distribution factors for the five model slices for these wells. In the steady-state model, the extraction and injection rates were the average extraction and injection rate over the entire simulation periods. Because the model does not extend over the entire area of the Raymond Basin, it was necessary to develop appropriate boundaries to the south and east of the JPL site. The eastern and southern boundaries were selected based on groundwater elevation contours in the Raymond Basin for the 1990s. The eastern model boundary was selected to represent an approximate groundwater flowline and is represented in the model as a no-flow boundary. The southern boundary corresponds with the relatively consistent location of a groundwater elevation contour line and is represented by a constant-head boundary.

Table 3-1
Code Selection Summary

CODE / PROGRAM	Description	Solute Transport	3-D Particle Tracking	Pre- and Post-Processing Capabilities	Supports Mesh Generation	Interfaces with GIS/CAD	Handling of Free-Surface / Dynamic Allocation of Pumping	Widespread Use	Technical Support	cost
FEFLOW	Finite Element, 3D, saturated and/or unsaturated flow and transport. Options to include density-dependant flow and heat transport.	Yes	yes, forward and reverse	very good	good capabilities for refinement and incorporation of ASCII / GIS data	GIS and CAD import and export	Free surface handled by BASD method. Has option to dynamically allocate pumping.	medium, used at Livermore Site, more widely utilized in Europe	If purchased from Waterloo, free support for 6 monthes (phone, fax, email). Developer requires maintance contract ($1995 for 1 yr)	3-D flow, transport, and particle tracking - $4995
CFEST	Full 3-D flow and transport finite element program, options for heat transport and density dependant flow	Yes	yes, forward and reverse	limited, utilizes Argus and Arcview	Yes, through Argus	Yes, Argus options for DXF and ESRI Shape files	Allows drying/rewetting of cells by using an iterative approach. Has option for dynamically allocating pumping.	medium, used for San Gabriel Basin EPA modeling	available in-house	Free
Mike-She *	Finite Difference, saturated/unsaturated flow and contaminant transport	yes, module MIKE SHE AD	yes, module MIKE SHE PT	uses Arcview	Yes	GIS and CAD	--	very limited in North America	4 hours free per module, $100 / hr after that, typically less than 1 day turnaround	MIKE SHE - $5,500 Pre-Processor - $1,500 AD module - $3,125 PT module - $875
MODFLOW	Finite Difference, (quasi-)3D saturated flow and transport	uses MT3D	yes, forward and reverse	NA	NA	NA	Allows drying/rewetting of cells by using an iterative approach. No dynamic allocation of pumping.	high	NA	NA
Visual Pro and Explorer	NA	NA	NA	good	Yes	imports CAD, exports CAD and ESRI Shape files	NA	NA	6 months free from Waterloo Hydrologic	MODFLOW Pro package (includes Explorer and WinPEST) -$1900
GMS	NA	NA	NA	good	Yes	imports/exports shape files/CAD	NA	NA	lifetime support provided free, some users note 1-2 day delays in response time	MODFLOW package - $2600
Groundwater Vistas	NA	NA	NA	good	Yes	exports DXF files	NA	NA	lifetime support provided free by developer	MODFLOW package - $850
FEMWATER - GMS	Finite Element, 3D sat/unsat flow, variable density flow and transport	uses LEWASTE	No	good	Yes	GIS and CAD	Free surface not an issue since the variably saturated flow equation is solved. Model does not dynamically allocate pumping.	medium	FEMWATER is not supported, GMS pre- / post-processor has free lifetime support (some users note 1-2 day delays in response time)	FEMWATER package - $1350
AQUA3D	Finite Element, saturated flow, solute and heat transport	Yes	No	limited	Yes	Imports DXF files, exports as Data Points	Allows drying/rewetting of cells by using an iterative approach. No dynamic allocation of pumping.	limited	availability unclear, provided by developer (Vatnaskil Consulting Engineers, Iceland)	AQUA3D - $900
3DFEMFAT *	Finite Element, saturated and/or unsaturated flow and transport	Yes	No	Uses GMS FEMWATER	Yes	GIS and CAD	--	limited	availability unclear, provided by developer	3DFEMFAT - $1000
PTC	Finite Element, 3D saturated flow and transport	Yes	No	limited, uses Argus PIE	Yes	Yes, (Argus does)	Allows drying of nodes, but not rewetting. No dynamic allocation of pumping.	medium, was used at Woburn Mass. Site	availability unclear, provided by developer	No Cost

Table 3-1
Code Selection Summary

CODE / PROGRAM	Description	Solute Transport	3-D Particle Tracking	Pre- and Post-Processing Capabilities	Supports Mesh Generation	Interfaces with GIS/CAD	Handling of Free-Surface / Dynamic Allocation of Pumping	Widespread Use	Technical Support	cost
HST3D *	Finite Difference, variable or constant density flow, solute and heat transport.	Yes	No	Argus PIE, very limited	Yes	Yes, (Argus does)	Yes, has deformable upper surface and drying/rewetting of cells	--	free email support for 1 year from developer	code - free, code documentation - $80 ArgusONE - $900 Argus PIE - $900
TOUGH2 - ALLTOUGH *	Finite Difference, 3D, variably saturated, multi-phase flow and transport.	yes	no	limited, utilizes SATURN for postprocessing	limited, uses spreadsheets to design model	no	--	used predominantly for unsaturated flow and transport	Telephone and email - $95 / hour, response time variable	ALLTOUGH - $999 TOUGH2 - $999 Spyglass for postprocessing - $999
SWIFT *	Finite Difference, 3D, transient, flow, solute and heat transport	Yes	Yes, Surfer displays results (2-D)	limited, SURFER used for post-processing	--	No	has moveable free surface	low	Requires sub-contract from Geotrans, Inc.	SWIFT - $395 SURFER - $575
FEMWATER - Argus PIE	Finite Element, 3D sat/unsat flow, variable density flow	No	No	very limited, uses Argus PIE	Yes	Yes	--	limited	none	ArgusONE GUI is free
AQUIFEM-N *	Finite Element, (quasi-) 3D, saturated flow and transport	only 2-dimensional	no	limited	Yes	imports DXF as pictures,save picyures as DXF files	--	limited	--	AUIFEM-N - $975 Pre-/Post-Processors - $975
MicroFEM	Finite Element, 3D flow	No	Yes	good	Yes	yes, DXF and ESRI Shape files	--	medium	--	MicroFEM - $725

Notes:

* indicates full version or demo is not available or was not obtained
-- unclear, or not further researched because other criteria indicated the model was not appropriate for ased on results of other criteria.
NA not applicable, description either applies to model or support software.
No current descriptions or purchasing information was located for DYNEFLOW, PLASM3D, IGSM, PORFLO-3

Table 3-2
Vertical Distributing Factors for the Model Slices
for the Extraction/Injection Wells

	Average Extraction/Injection Rate		Vertical Distributing factors				
Well ID	m^3/day	gpm	Slice 1	Slice 2	Slice 3	Slice 4	Slice 5
Arroyo	2348	431	0.15	0.3	0.1	0.3	0.15
Well 52	6950	1275	0	0.15	0.35	0.35	0.15
Ventura	7269	1334	0.1	0.3	0.3	0.3	0
Windsor	4044	742	0	0	0.3	0.5	0.2
Lincoln #3	2440	448	0	0	0.5	0.5	0
Lincoln #5	1327	243	0	0.1	0.8	0.1	0
Valley #1	1227	225	0.1	0.2	0.5	0.2	0
Valley #2	-672	-123	0.1	0.2	0.5	0.2	0
Valley #3	430	79	0	0.2	0.5	0.3	0
Valley #4	1453	267	0	0.2	0.6	0.2	0
LCID #1	220	40	0	0.3	0.5	0.2	0
LCID #6	42	8	0	0.35	0.35	0.3	0
Rubio #4	1432	263	0.2	0.5	0.3	0	0
Rubio #7	3120	572	0	0.3	0.5	0.2	0
Park 2-3	207	38	0.2	0.2	0.2	0.2	0.2
Las Flores #2	1155	212	0.2	0.45	0.25	0.1	0

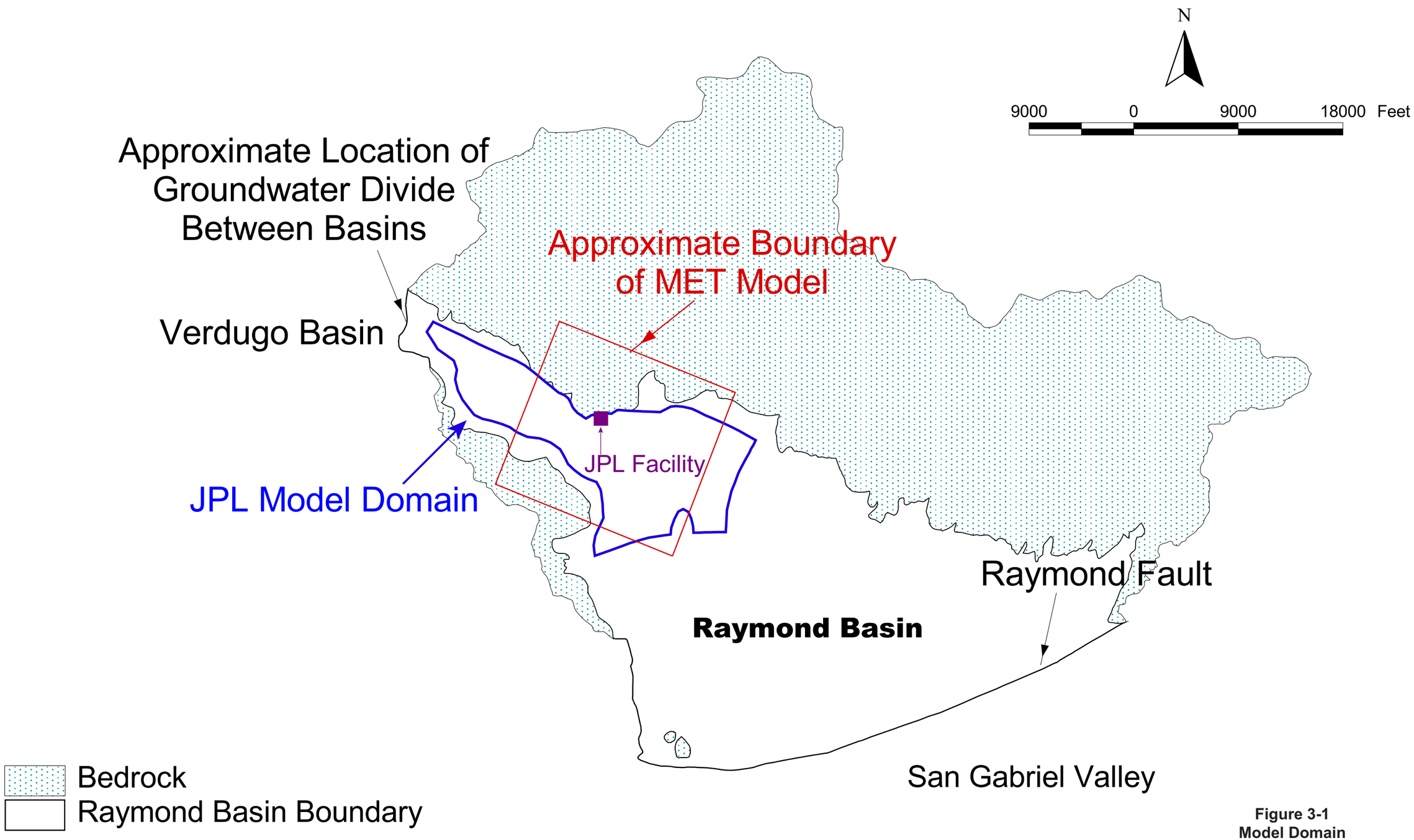

Figure 3-1
Model Domain
JPL Groundwater Model

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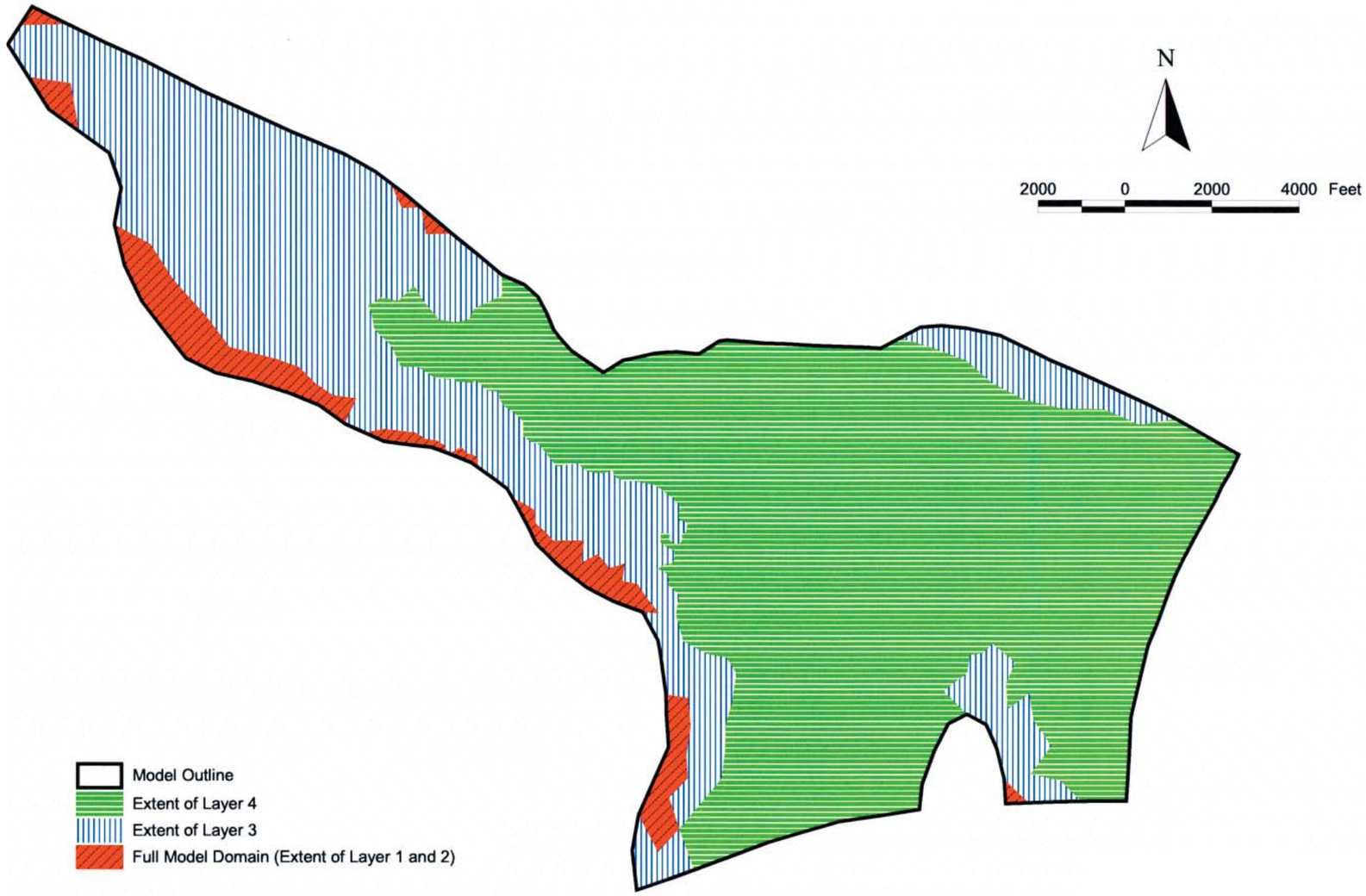

Figure 3-2
Extent of Model Layers
JPL Groundwater Model

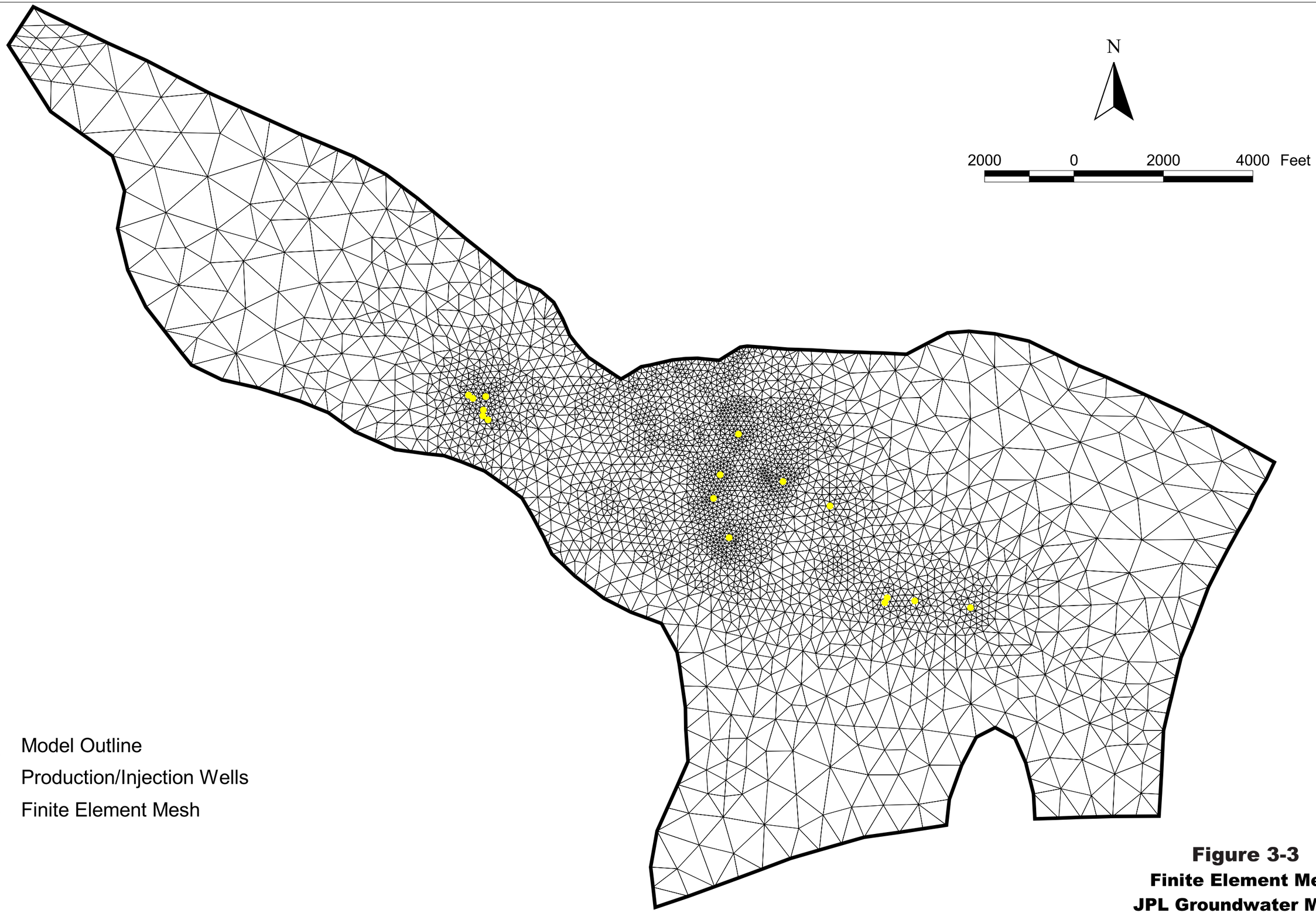

Figure 3-3
Finite Element Mesh
JPL Groundwater Model

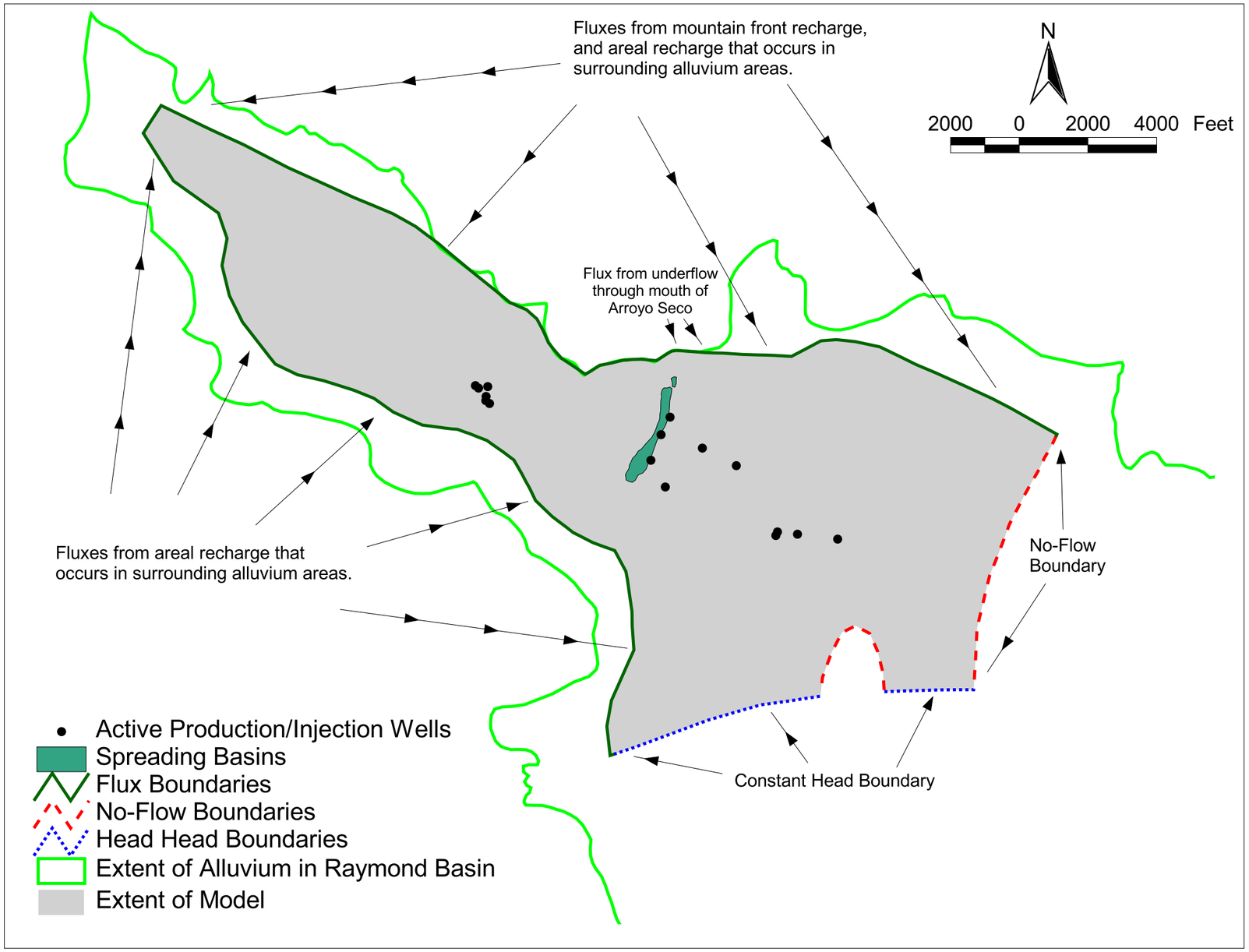

Figure 3-4
Boundary Conditions
JPL Groundwater Model

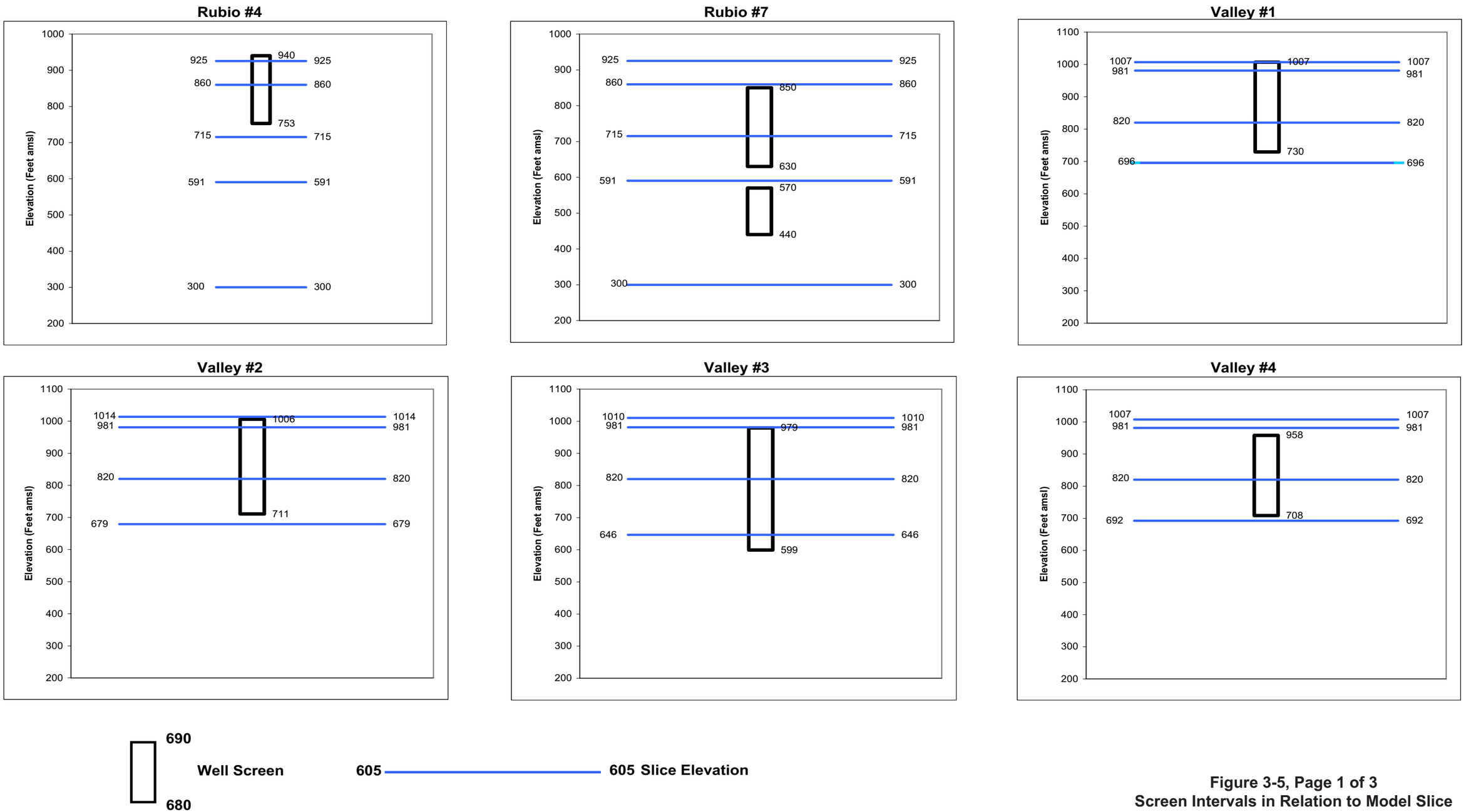

Figure 3-5, Page 1 of 3
Screen Intervals in Relation to Model Slice Elevations for the Production/Injection Wells
JPL Groundwater Model

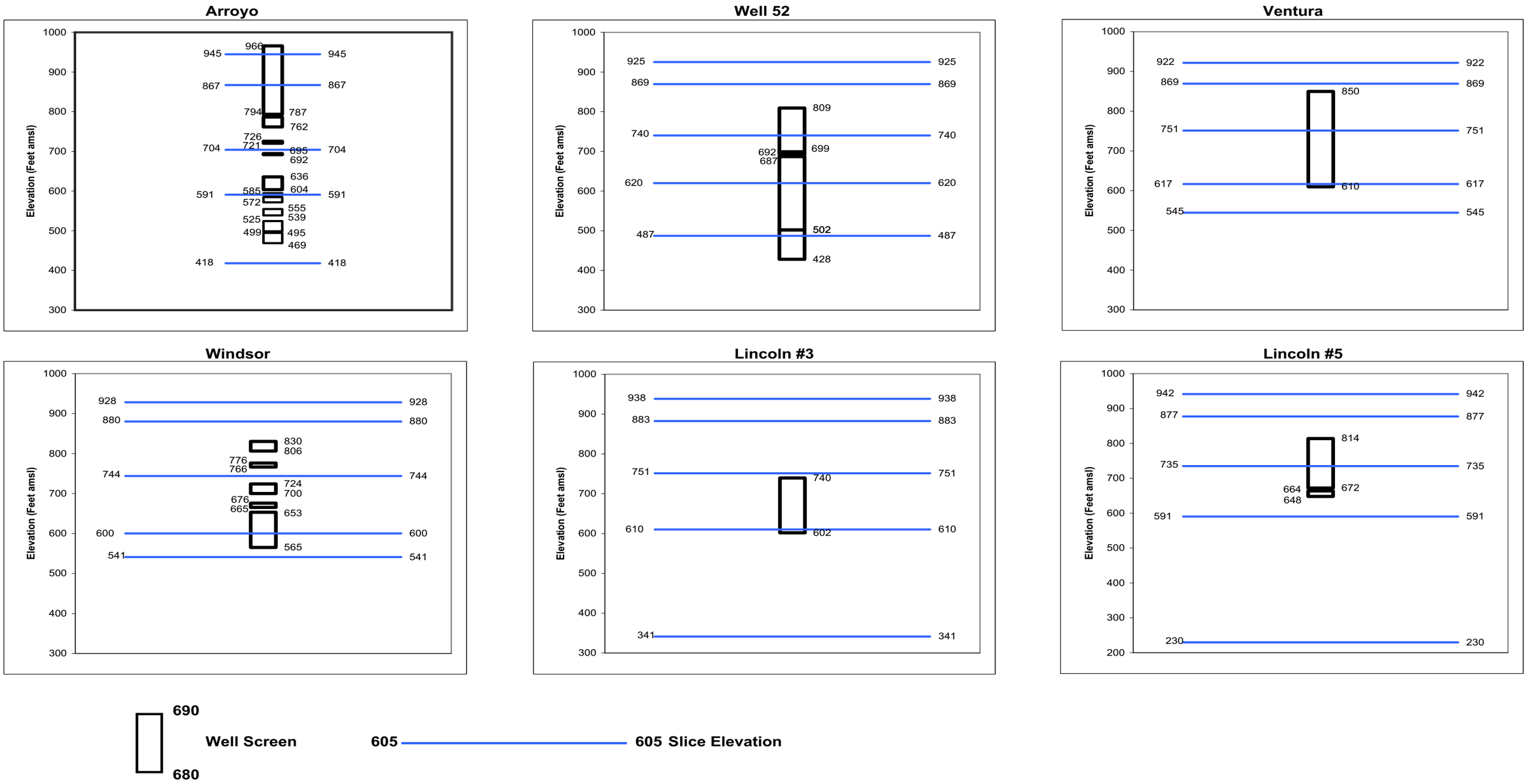

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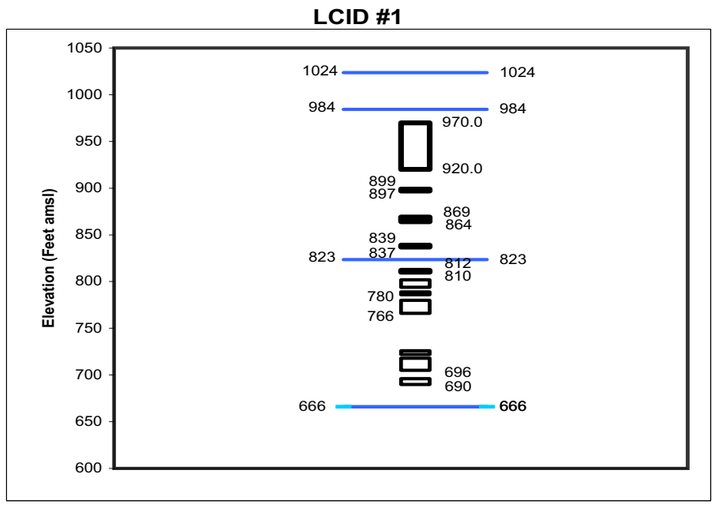
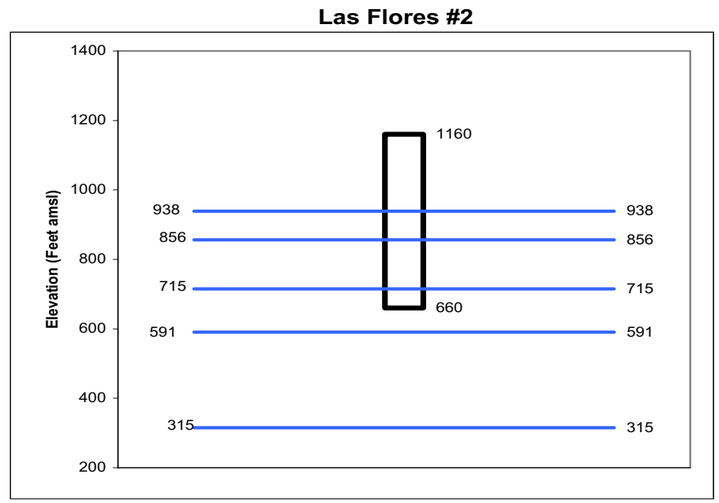
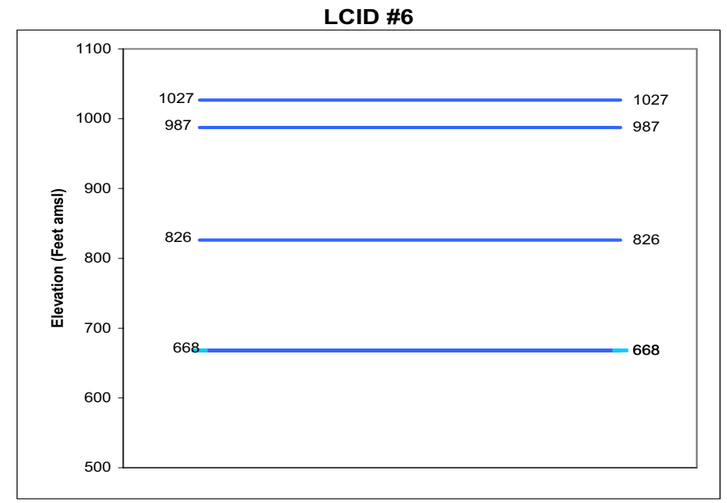
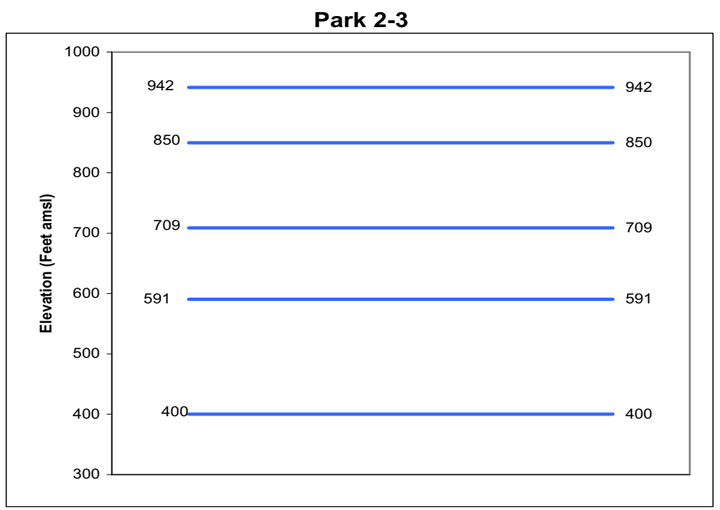
Figure 3-5, Page 2 of 3
Screen Intervals in Relation to Model Slice Elevations for the Production/Injection Wells
JPL Groundwater Model









690

Well Screen

680

605 605 Slice Elevation

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Figure 3-5, Page 3 of 3
Screen Intervals in Relation to Model Slice Elevations for the Production/Injection Wells
JPL Groundwater Model

4. Model Calibration

The model calibration was based on average groundwater flow conditions for the JPL area; it was used to refine the hydraulic conductivity distribution and assess the conceptual water budget components and areal distribution. Hydraulic storage parameters were addressed by the calibration of the transient flow model. The steady-state calibration of the JPL groundwater model was based on the average recharge conditions and water levels for the water years 1996-1997 through 1999-2000. This period was selected because overall water levels are similar at the beginning and end of this period, indicating a relatively small change in the overall groundwater storage in the area. Furthermore, the conceptual water budget suggested a very small change in storage for this period (an average of less than 0.1-foot for the model domain). The conceptual water budget for this period is discussed in Section 2 and summarized in Table 2-2. All components of the water budget were assigned consistent with the conceptual water budget, with the exception of the outflow through the downgradient constant-head boundary, which was calculated by the model.

Based on review of groundwater contour maps and hydrographs, groundwater conditions for the JPL facility have a seasonal variation in groundwater levels (largely related to seasonal variations in pumping), but are generally consistent on an annual basis. Although the direction of migration of dissolved solutes will have some seasonal fluctuation, the net long-term solute transport is expected to relate to the average flow conditions in the area. This was later verified by particle tracking for the steady-state model that yielded flow patterns similar to the observed overall plume movement, as described in Section 4.4.

4.1 Data Preparation: Preprocessing and Postprocessing

As described in Section 3.3, the flux boundary of the JPL model was divided into 10 different stretches. Flux rates for these stretches were calculated as the sum of the mountain front recharge, groundwater inflow at the mouth of the Arroyo Seco, and recharge that occurs within the alluvium between the mountains and the areas surrounding the model domain. Similarly, the entire model domain is divided into 40 different subareas. The recharge rate for each subarea was the combination of areal recharge rates from deep percolation of precipitation, recharge derived from return flows from applied waters, leaky distribution pipes, septic tanks, and the Arroyo Seco Spreading Basins. Extraction and/or injection of the production wells was vertically distributed to the model slices as described in Section 3.3.

The FEFLOW code outputs simulated hydraulic heads at model slices. Recall that each model layer is represented by two slices, one at the top and another at the bottom of the model layer. The multiport wells are screened at different depths, and these ports do not necessarily coincide with the model slices. Therefore, the simulated water levels/heads at these slices cannot be directly compared with the measured water levels. Additional processing of the simulated water levels is needed. The water level for a specific port of a multiport well was calculated as the weighted-average of the simulated heads at the slice above and below the well screen, based on the relative depth of the well screen to the depth

of the corresponding model slice. Table 4-1 summarizes the elevations of the center of the screen for all the monitoring wells in relation to model slice elevations.

4.2 Calibrated Flow Parameters

During the steady-state flow calibration, it was not necessary to modify the water budget for the model or the areal distribution of recharge, and only minor modifications to hydraulic conductivity values and the vertical distribution of pumping were necessary to improve the model calibration. Each of the simulated water budget components was almost identical to the conceptual model values, with the exception of the constant-head boundary, which was determined by the model. The mass balance error for the model was approximately 0.2 percent, indicating that the model solution had properly converged for the steady-state simulation.

Hydraulic conductivity estimates from the JPL pump test (Section 2.6) were used for assigning initial material properties (horizontal and vertical hydraulic conductivity) to the model layers. The few changes made to the material properties during the model calibration included increasing the vertical conductivity values and adding a flow barrier in the area south of Monitoring Wells MW-1, MW-9, and MW-15. The flow barrier was implemented by substantially reducing the hydraulic conductivity value in the model grid cells that represent the barrier. Figure 4-1 presents the calibrated horizontal conductivity values for the steady-state flow calibration. Figure 4-2 presents the calibrated horizontal hydraulic conductivity values for the steady-state calibration. An overview of the calibration criteria results is presented below.

4.3 Performance Measurements

Criteria evaluated for calibration of the groundwater model included scatter plots of the measured versus simulated hydraulic heads, model-simulated vertical profiles of hydraulic head at multiport wells in comparison with the observed ones, and comparison of model-predicted path lines of particles released from potential source areas with the observed chemicals of interest (COIs) plumes at the JPL site. Additionally, three statistical measures, the mean residual error (ME), root mean squared error (RMSE), and the correlation (r) between simulated and the observed water head were used to quantitatively assess the quality of model calibration. The RMSE is based on the differences between simulated and average measured head values, and is defined as:

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (h_m - h_s)_i^2}$$

Where:

n = number of monitoring (observation) wells

h_m = measured heads at the monitoring wells

h_s = simulated heads in the latest calibration run

In addition to calculating the statistical measures for the entire aquifer using all the calibration wells, a separate set of the statistical measures was also calculated for each model layer using only the calibration wells screened within that specific layer.

Scatter plots presenting the measured versus simulated hydraulic heads are shown in Figure 4-3. The vertical profile of hydraulic heads at the multiport wells is presented in Figure 4-4. The statistical measures are summarized in Table 4-2. The overall ME is 2.2 feet, RMSE is 9.6 feet, and correlation is 0.97 (r^2= 0.94).

Statistically, r^2 values more than 0.5 and closer to 1 are indicative of a "good" fit. Based on the overall r^2 of 0.94, the steady-state calibration is considered a "good" calibration and adequate for meeting the objectives of the groundwater modeling. More discussion of the calibration results is provided below.

In general, the steady-state flow model did a good job of matching heads throughout the model domain. The most significant difference in hydraulic heads occurred in the deepest model layer (Layer 4) and in Layer 3 near MW-19. During the steady-state flow calibration, it was necessary to increase the vertical conductivity values for several of the model layers. A hydraulic barrier south of Monitoring Wells MW-1, MW-15, and MW-9 was also added during the model calibration by substantially reducing the hydraulic conductivity values in the model grid cells that represent the barrier. The hydraulic barrier may represent a fault across this area, and was necessary to represent the pattern of water levels in this area. Water levels for the three wells north of the barrier are much higher than water levels south of the barrier, and the hydraulic gradient in each area appears to be substantially different. This suggests that a significant barrier to flow is present in the area. Figure 2-1 (Section 2.2) shows the average water levels for the water budget period across the area where a hydraulic barrier is apparently present.

The simulated flow field for the JPL model is shown in Figure 4-5. The flow field shows similar flow patterns in comparison to the contour maps based on quarterly monitoring data. In particular, the simulation results capture the general flow directions, and reproduce the observed features such as the local water table mounding beneath the spreading basins (top of Layer 1 in Figure 4-5) and the flow reversal downgradient of the City production wells in the deeper portion of the aquifer (top and bottom of Layer 3 in Figure 4-5).

4.4 Evaluation of the Flow Field Using Particle Tracking

Particle tracking was used to confirm the appropriateness of the simulation results with regard to the flow directions and gradients in the JPL facility area. Particles were released in the northern portion of the JPL facility near where the highest concentrations of chemicals have been measured and forward tracked until they were either captured by a pumping well or migrated to the model boundary. As shown in Figure 4-6, particles started at the water table (solid lines) and particles started at the bottom of Layer 1 (dashed lines) result in flow paths that are very similar to the pattern of perchlorate observed in the aquifer. All of the particles that were released were captured by the City of Pasadena production wells (Arroyo Well or Well 52). Assuming a uniform porosity of 0.3, it is estimated that particles released at the water table will reach Well 52 under advective flow conditions in 20-25 years

and particles released at the base of Layer 1 will reach Well 52 under advective flow conditions in 25-30 years. It should be noted that not all the particle tracking results that were conducted are included in this report.

Table 4-1
Screen Depth in Relation to Model Slice Elevations for Monitoring Wells

Well ID	Port Number	Center of Screen (Feet)	Slice Elevations (Feet)					Bounding Slices		Model Layer
			Slice 1	Slice 2	Slice 3	Slice 4	Slice 5	Above	Below	
MW-1	1	1026.6	1154.5	929.1	770.0	590.0	400.1	1	2	1
MW-10	1	957.7	1105.1	913.9	779.7	610.0	536.3	1	2	1
MW-11	1	994.3	1160.6	915.6	767.1	590.0	400.0	1	2	1
	2	884.3						2	3	2
	3	714.3						3	4	3
	4	619.3						3	4	3
	5	504.3						4	5	4
MW-12	1	962.1	1120.3	892.6	752.3	589.2	400.0	1	2	1
	2	857.1						2	3	2
	3	782.1						2	3	2
	4	667.1						3	4	3
	5	551.1						4	5	4
MW-13	1	978.4	1190.4	941.6	743.4	570.7	403.1	1	2	1
MW-14	1	963.4	1181.8	949.4	778.5	580.3	508.7	1	2	1
	2	893.4						2	3	2
	3	788.4						2	3	2
	4	715.4						3	4	3
	5	630.4						3	4	3
MW-15	1	1076.6	1148.8	921.9	769.9	590.0	401.4	1	2	1
MW-16	1	981.7	1250.3	950.7	756.8	572.7	400.1	1	2	1
MW-17	1	939.9	1188.5	878.7	702.3	619.4	374.5	1	2	1
	2	819.9						2	3	2
	3	719.9						2	3	2
	4	608.0						4	5	4
	5	463.0						4	5	4
MW-18	1	954.3	1211.1	860.5	700.1	570.0	300.0	1	2	1
	2	894.3						1	2	1
	3	799.3						2	3	2
	4	659.3						3	4	3
	5	539.3						4	5	4
MW-19	1	898.2	1142.9	879.6	740.4	600.3	559.4	1	2	1
	2	828.1						2	3	2
	3	748.2						2	3	2
	4	696.2						3	4	3
	5	646.2						3	4	3
MW-20	1	931.9	1165.0	870.0	718.8	590.0	200.0	1	2	1
	2	771.9						2	3	2
	3	601.9						3	4	3
	4	461.9						4	5	4
	5	261.9						4	5	4
MW-21	1	967.9	1085.7	911.6	786.5	665.9	665.6	1	2	1
	2	897.9						2	3	2
	3	817.9						2	3	2
	4	748.0						3	4	3
	5	688.0						3	4	3

Table 4-1
Screen Depth in Relation to Model Slice Elevations for Monitoring Wells

Well ID	Port Number	Center of Screen (Feet)	Slice Elevations (Feet)					Bounding Slices		Model Layer
			Slice 1	Slice 2	Slice 3	Slice 4	Slice 5	Above	Below	
MW-22	1	932.8	1213.2	941.4	758.4	578.9	440.2	2	3	2
	2	847.8						2	3	2
	3	787.8						2	3	2
	4	707.8						3	4	3
	5	587.8						3	4	3
MW-23	1	933.3	1117.9	920.1	770.1	607.4	500.0	1	2	1
	2	853.3						2	3	2
	3	788.3						2	3	2
	4	663.3						3	4	3
	5	563.3						4	5	4
MW-24	1	920.9	1218.7	945.4	750.1	571.6	400.0	2	3	2
	2	825.9						2	3	2
	3	765.9						2	3	2
	4	645.9						3	4	3
	5	529.9						4	5	4
MW-3	1	924.8	1120.0	862.5	731.3	580.0	400.0	1	2	1
	2	844.8						2	3	2
	3	750.8						2	3	2
	4	539.8						4	5	4
	5	444.8						4	5	4
MW-4	1	930.7	1119.1	870.7	696.0	588.6	500.7	1	2	1
	2	840.7						2	3	2
	3	759.7						2	3	2
	4	688.7						3	4	3
	5	568.7						4	5	4
MW-5	1	961.5	1093.0	887.7	738.0	610.0	538.1	1	2	1
MW-6	1	968.5	1208.8	939.1	769.8	580.0	484.9	1	2	1
MW-7	1	963.4	1241.3	951.5	767.0	587.6	400.0	1	2	1
MW-8	1	959.5	1164.9	912.1	750.3	581.0	400.0	1	2	1
MW-9	1	1063.0	1124.9	906.5	762.4	590.0	401.6	1	2	1

TABLE 4-2 Summary Statistics for Model Calibration

Model Layer	Number of Wells	ME (feet)	RMS (feet)	r	r^2
Layer 1	20	1.28	6.27	0.99	0.98
Layer 2	25	-1.51	6.49	0.94	0.89
Layer 3	16	-2.64	10.28	0.97	0.94
Layer 4	12	4.05	16.08	0.78	0.60
All	73	-0.08	9.53	0.97	0.94

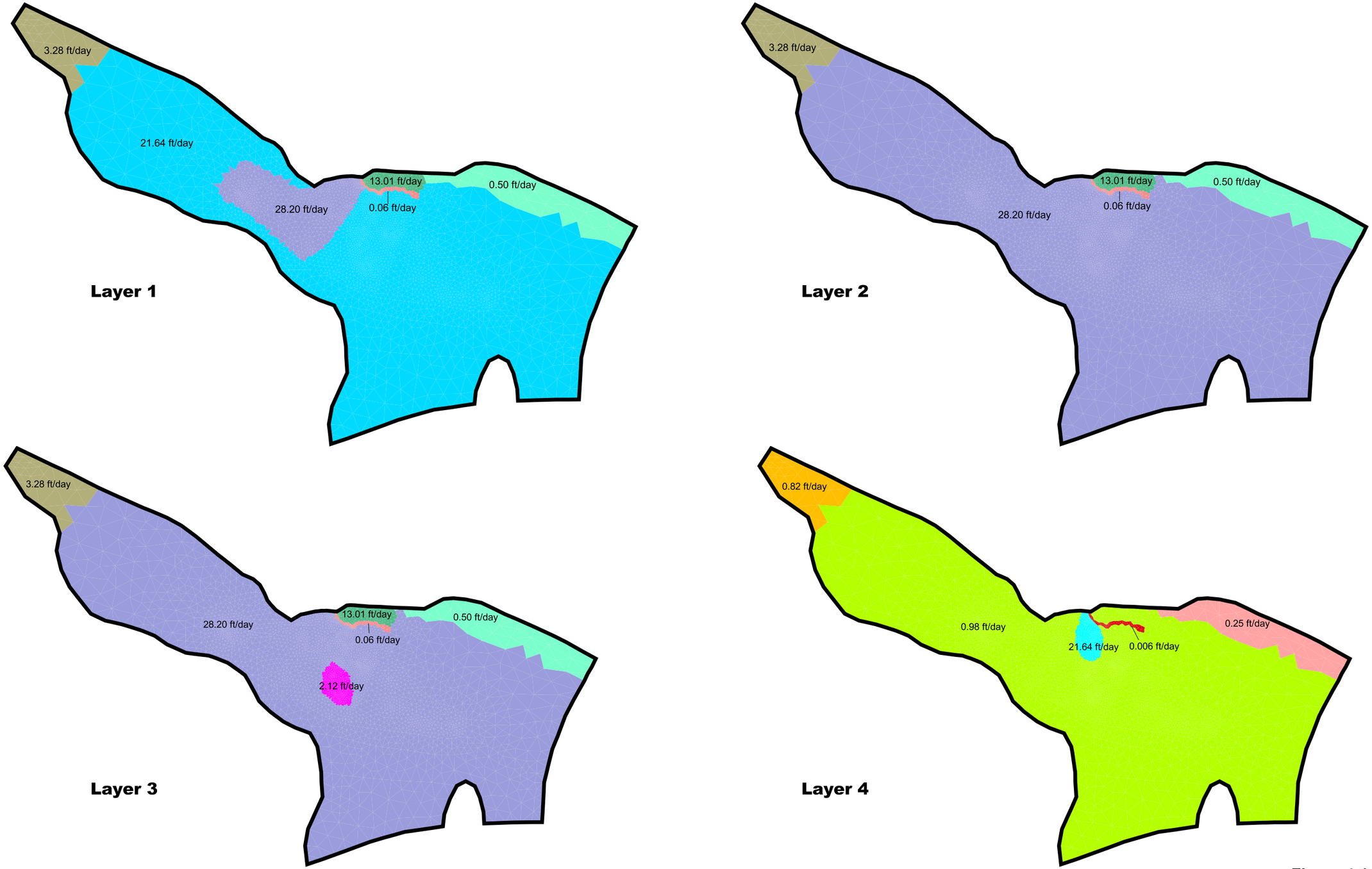


Figure 4-1
Horizontal Hydraulic Conductivity
JPL Groundwater Model

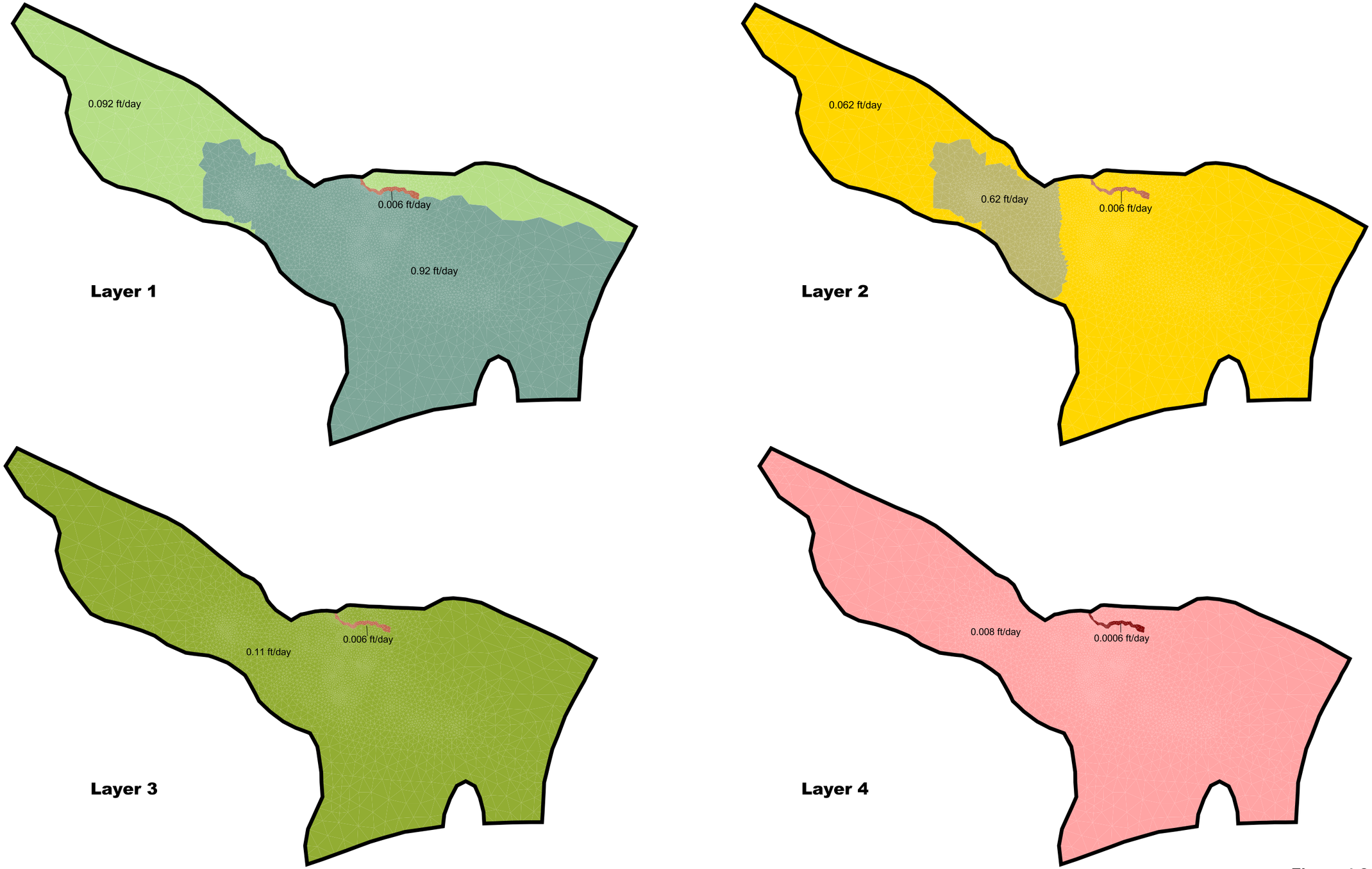
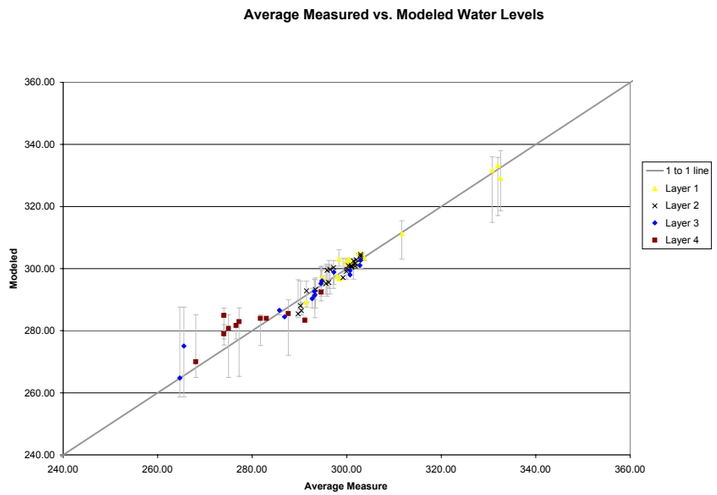
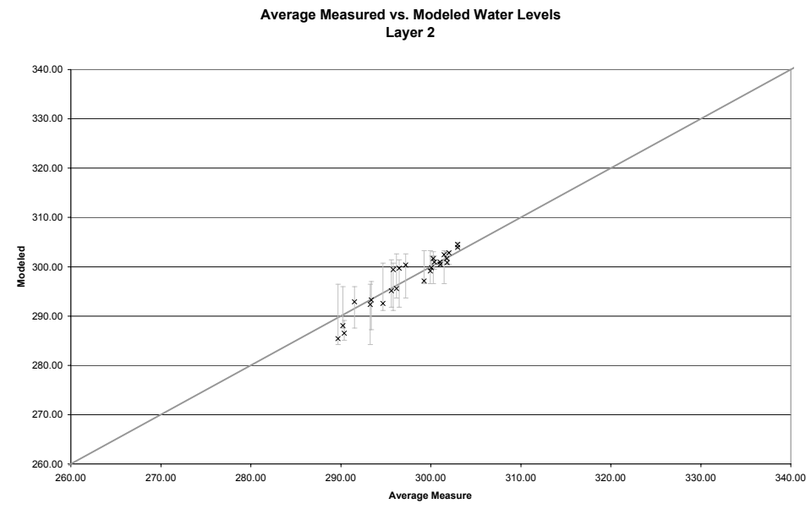
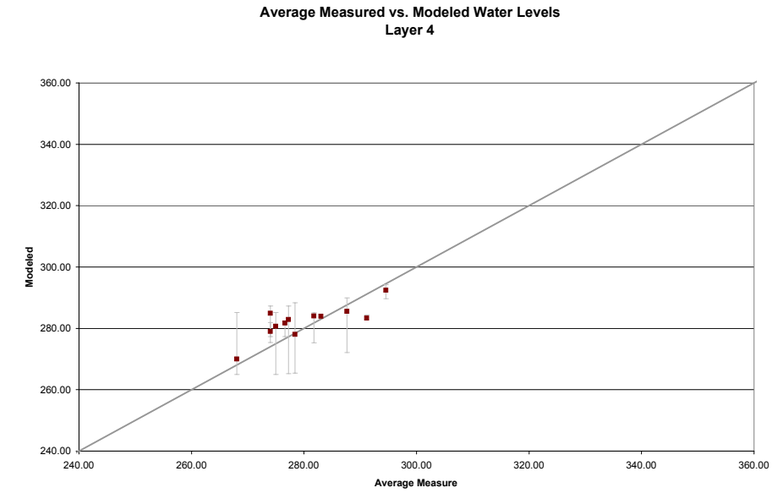
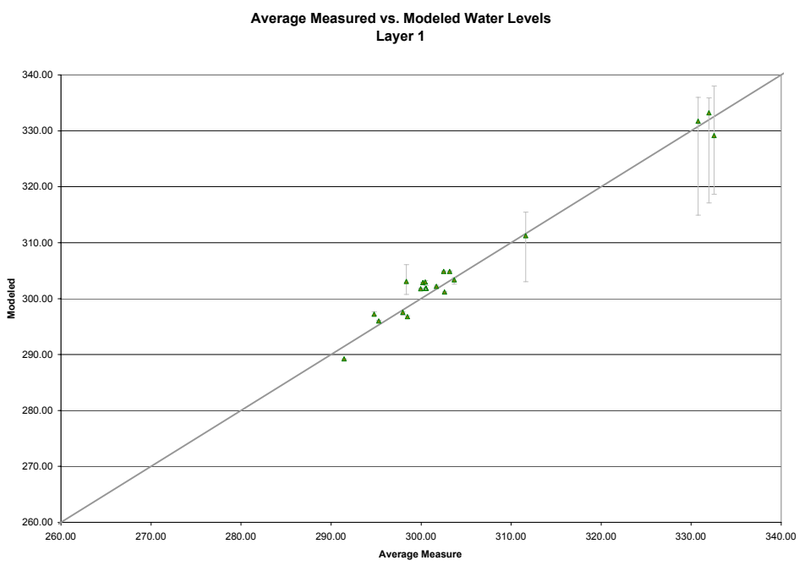


Figure 4-2
Vertical Hydraulic Conductivity
JPL Groundwater Model









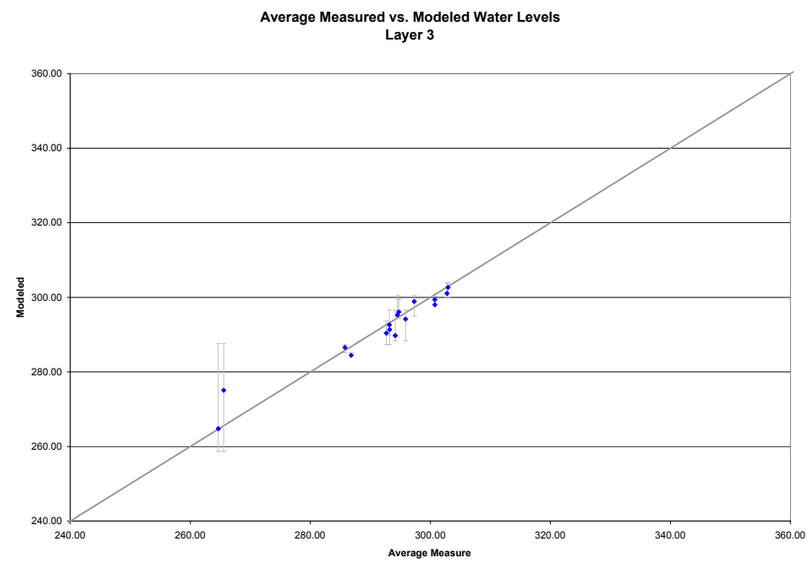
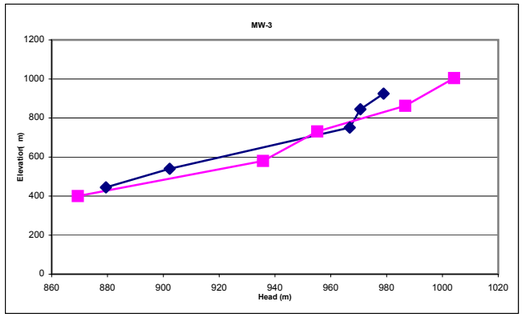
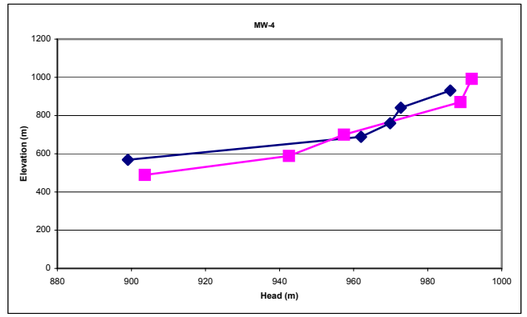
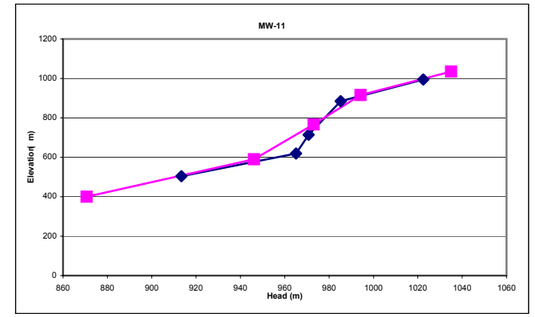
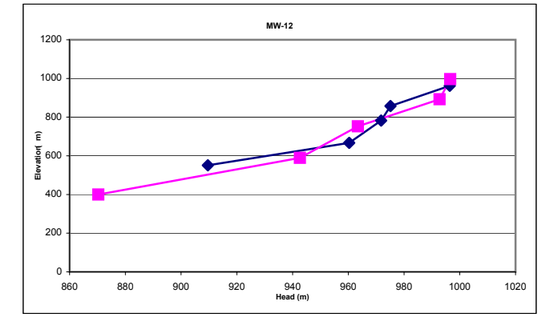


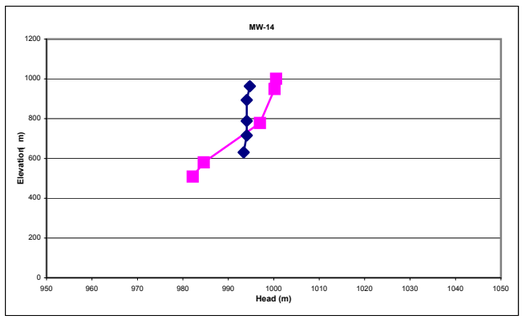
Figure 4-3
Simulated vs. Observed Hydraulic Heads
Steady-State Flow Calibration

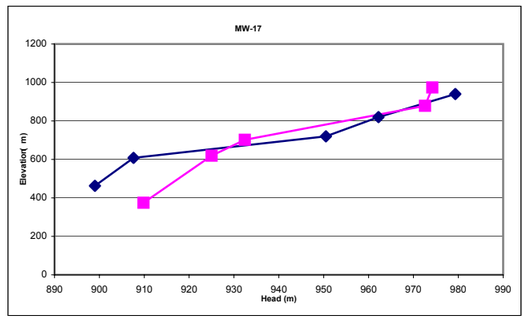


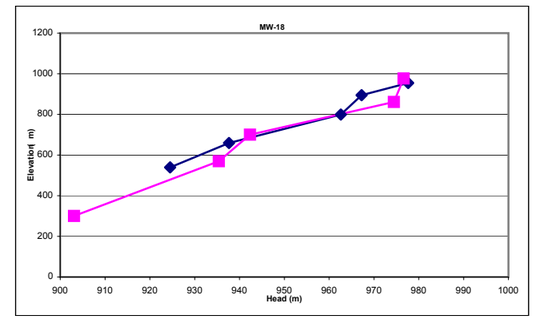


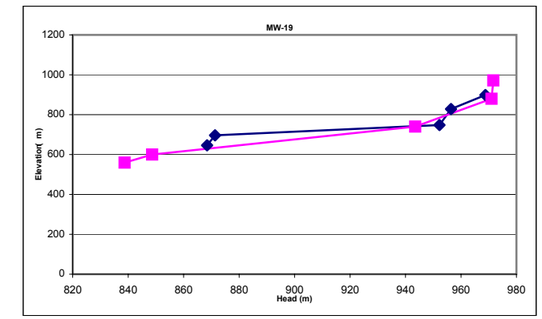


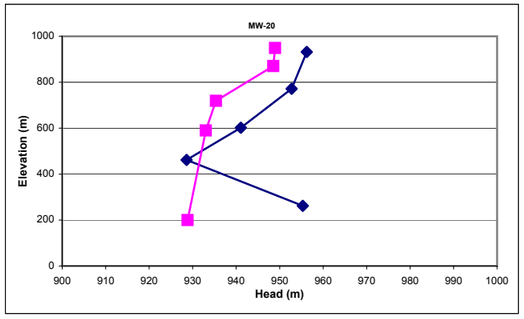


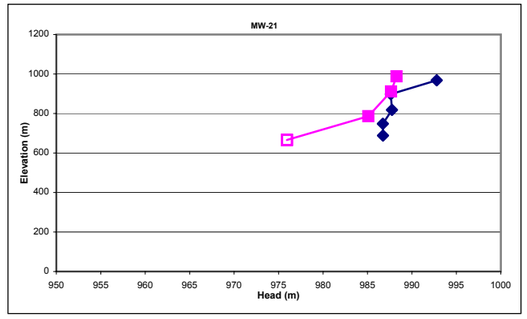


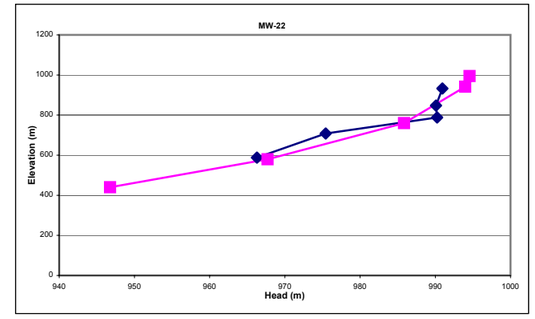


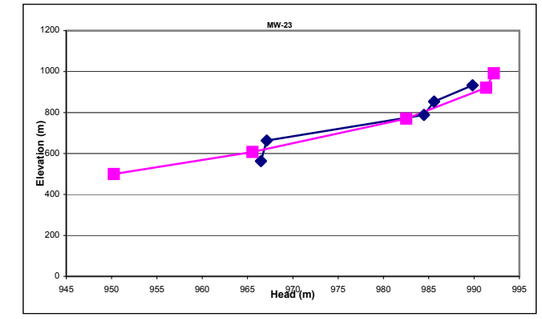


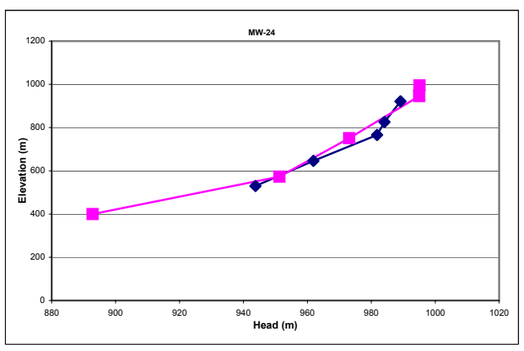












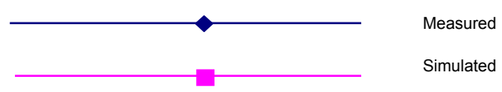


Figure 4-4
Simulated vs. Observed Vertical Profiles
at Multiport Monitoring Wells

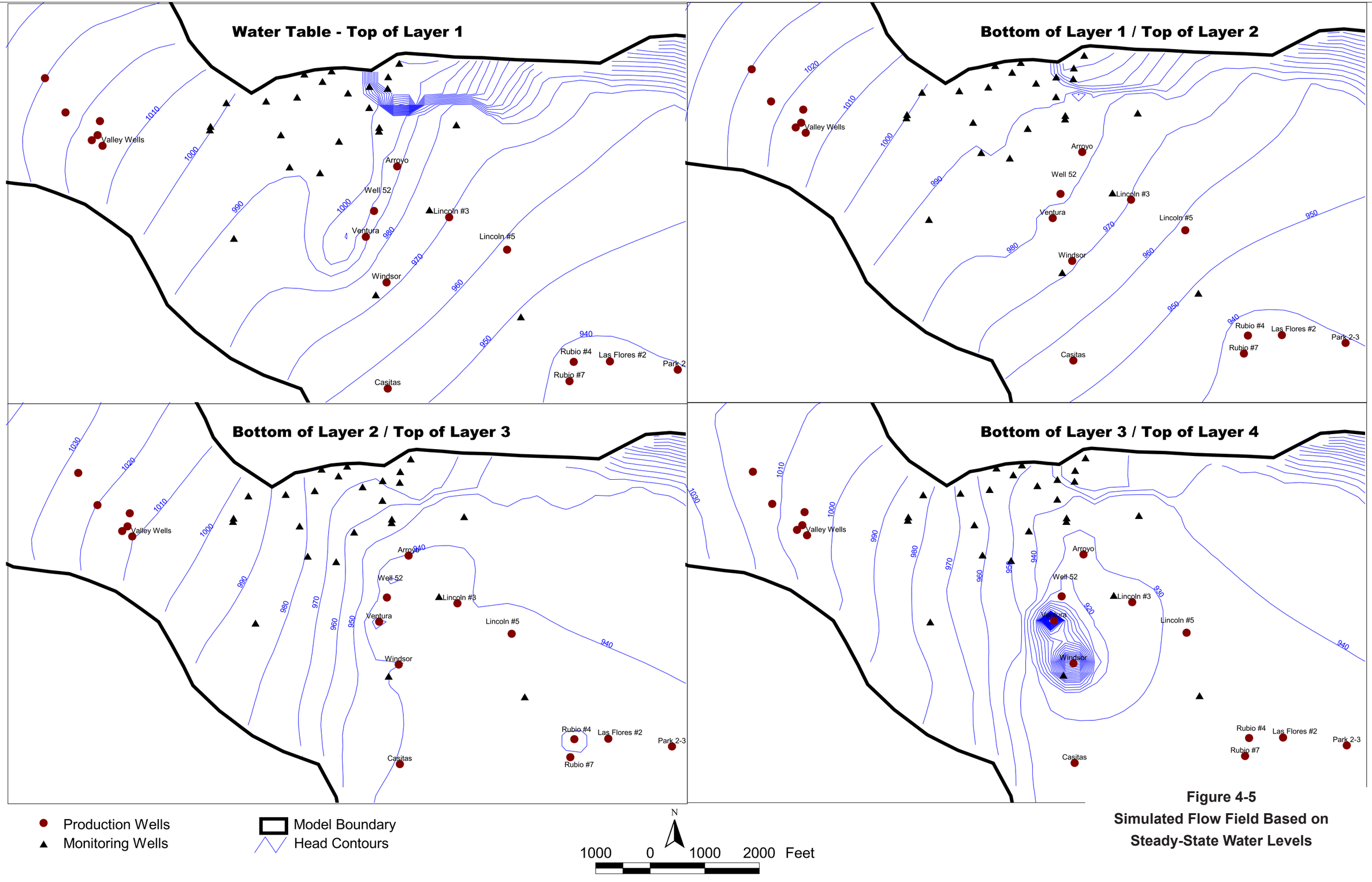


Figure 4-5
Simulated Flow Field Based on Steady-State Water Levels

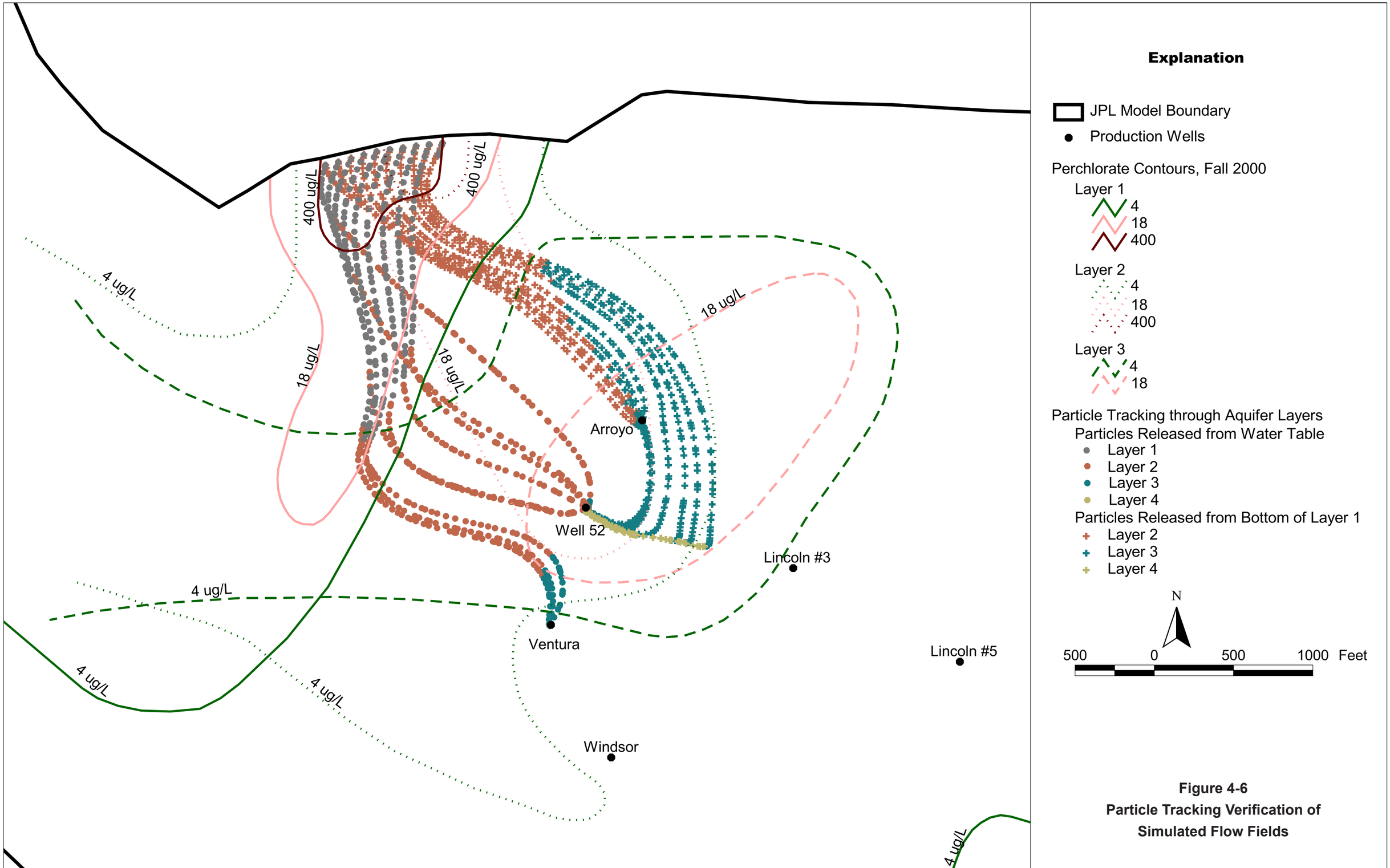


Figure 4-6
Particle Tracking Verification of Simulated Flow Fields

5. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the sensitivity of the JPL groundwater flow model to the key model input parameters, and thereby address the uncertainties associated with the calibrated flow model parameters. Each model parameter (either a flow parameter or a water budget component) was varied, and an additional simulation run was conducted. Changes of simulated average groundwater levels that resulted from the variation of the model parameters were calculated for each sensitivity run. A sensitivity coefficient was calculated for each model layer based on the calculated changes in average water levels within that model layer. The sensitivity of the calibrated model to each parameter or water budget component was evaluated based on the calculated sensitivity coefficient.

In general, for the flow parameters, the model is most sensitive to the vertical hydraulic conductivities, moderately sensitive to horizontal hydraulic conductivities, and least sensitive to storage parameters. Additional field measurements of the vertical hydraulic conductivities for the different aquifer layers using pumping tests that are designed for this purpose would certainly enhance the calibration results. For the groundwater budget components, the model is most sensitive to the volume of surface water applied to the Arroyo Seco spreading basins and the groundwater inflow at the mouth of the Arroyo Seco. A future increase in the volume of applied surface water by the expansion of the Arroyo Seco spreading basins would significantly impact the groundwater flow conditions in the Monk Hill basin. The next recharge component that the model is most sensitive to is the return flow from applied water. Among all the recharge components, deep percolation from precipitation is the inflow component to which the model is least sensitive.

The model also is sensitive to variations in the constant-head boundary conditions. However, the sensitivity coefficient for the constant-head boundary was calculated differently than those for the other water budget components. Consequently, the sensitivity of the model to the constant-head boundary cannot be directly compared to the sensitivity of the model to other flow components.

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Appendix A – Technical Memorandum
Results of Aquifer Test Analysis using MLUP

ATTACHMENT 1 -TECHNICAL MEMORANDUM

Results of Aquifer Test Analysis using MLPU, in Support of the Jet Propulsion Laboratory Superfund Site at Pasadena, California

DATE: December 18, 2001

The purpose of this technical memorandum is to describe the results of an aquifer test performed in May and June 2001 in Pasadena, California. The aquifer test was completed to evaluate hydraulic properties of the hydrogeologic units in the vicinity of the Jet Propulsion Laboratory (JPL) Site. Analysis of the test data provided estimates of horizontal and vertical hydraulic conductivity, transmissivity, and storativity of the hydrogeologic units included in the JPL numerical groundwater model that has been constructed using the FEFLOW code. This aquifer test is unusual in that the test data were collected from a network of monitoring wells as a series of three large production wells were restarted after a period of shutdown.

MLPU Description

MLPU (an acronym of Multi Layer Program Unsteady state, or in Dutch: MeerLagen-Programma Unsteady State) is an analytical groundwater model meant for analysis of steady-state flow in (un)confined and leaky single and multiple aquifer systems of at most nine aquifers. In addition, unsteady-state flow due to "transient" wells can be modeled. Aquifers are assumed to be isotropic, homogeneous, and of infinite extent. Implemented analytic elements comprise steady-state and transient wells; linesinks (drains) in the upper aquifer; infiltration ponds; parallel or uniform flow; and some global infiltration solutions, depending on the situation.

MLPU allows inverse modeling (termed optimization in MLPU) of aquifers where parameter values can be estimated from a series of head measurements in multiple wells with multiple transient pumping wells. The optimization algorithm used is Levenberg-Marquard; implementation in MLPU followed roughly the methods outlined by Bus et al (1975), Hemker (1985) and Olsthoorn (1995). MLPU allows simultaneous computation of up to 30 parameters in up to 7 independent groups using up to 500 independent head measurements.

Implementation of MLPU for the Pasadena Aquifer Test

Using MLPU requires knowledge or assumptions on the following:

- Aquifer layering
- Location and layer assignment of monitoring wells
- Schedule of pumping
- Layer assignment of pumping wells

Each of these is discussed in the following sections.

Aquifer Layering

It is assumed that there are four aquifer layers underlying the area. The assumed thickness of each of the layers is shown in Table 1.

TABLE 1
Assumed Layer Thickness

Layer	Thickness (m)
1	65
2	50
3	40
4	30

Location and Layer Assignment of Monitoring Wells

The location of the monitoring wells is shown in Figure 1. The layer assignments for the wells are presented in Table 2.

TABLE 2
Layer and Port Assignments for Monitoring Wells

Well ID	Port ID	Model Layer
MW-3	1	1
	2	2
	3	2
	4	4
	5	4
MW-4	1	1
	2	2
	3	2
	4	3
	5	4
MW-5	shallow	1
MW-8	shallow	1
MW-9	shallow	1
MW-10	shallow	1
MW-12	1	1
	2	2
	3	2
	4	3
	5	4
MW-13	shallow	1
MW-17	1	1
	2	2
	3	3
	4	4
	5	4

Schedule of Pumping

Table 3 shows the pumping history of the three wells that caused the drawdown observed in the monitoring wells

TABLE 3
Data used in MLPU Analysis.

Well Name	Stress Period	Stress Begin	Stress End *	Pumping Rate (cfs)
Ventura	*1*	*01/24/2001 13:30*	*05/16/2001 12:20*	*0*
	2	*05/16/2001 12:20*	*05/16/2001 15:47*	*3.3*
	3	*05/16/2001 15:47*	*05/18/2001 14:00*	*0*
	4	**05/18/2001 14:00**	**05/19/2001 11:30**	**3**
	5 (1)	**05/19/2001 11:30**	**05/19/2001 23:30**	**2.5**
	6	**05/19/2001 23:30**	**05/20/2001 10:25**	**2**
	7	**05/20/2001 10:25**	**05/22/2001 8:22**	**1.7**
	8	**05/22/2001 8:22**	**05/24/2001 19:00**	**3.1**
Windsor	*1*	*03/20/2001 8:20*	*04/10/2001 9:55*	*2.3*
	2	*04/10/2001 9:55*	*04/11/2001 15:03*	*0*
	3	*04/11/2001 15:03*	*05/15/2001 7:30*	*2.5*
	4	*05/15/2001 7:30*	*05/18/2001 14:15*	*0*
	5	**05/18/2001 14:15**	**05/24/2001 19:00**	**2.3**
Well 52	*1*	*03/20/2001 8:10*	*04/05/2001 15:25*	*3.1*
	2	*04/05/2001 15:25*	*04/10/2001 10:00*	*0*
	3	*04/10/2001 10:00*	*04/10/2001 10:40*	*3.6*
	4	*04/10/2001 10:40*	*05/16/2001 13:52*	*0*
	5	*05/16/2001 13:52*	*05/16/2001 15:32*	*2.8*
	6	*05/16/2001 15:32*	*05/18/2001 14:30*	*0*
	7	**05/18/2001 14:30**	**05/24/2001 19:00**	**2.3**

Note: Bold type denoted data used in MLPU analysis; grayed areas not used in analysis.

Layer Assignment of Pumping Wells

The MLPU program requires that the amount of pumping from a well be assigned to individual layers. Based on consideration of the well construction and screened interval, assignments of the pumping at the various layers were made. The assignments are presented below in Table 4.

TABLE 4
Percent of Total Pumping Assigned to Layers

Well	Layer 1	Layer 2	Layer 3	Layer 4
Well 52	7.5%	25%	35%	32.5%
Ventura	25%	30%	30%	15%
Windsor	0%	15%	40%	45%

Results

The results of MLPU runs are presented below in Table 5. Comparisons of the observed and simulated drawdowns at the monitoring wells are presented graphically in Figures 2 through 10.

TABLE 5
Results of MLPU Aquifer Test Analysis

Layer	Thickness (ft)	Transmissivity (ft^2/d)	Covering Resistance (d)	Horizontal Hydraulic Conductivity (ft/d)	Vertical Hydraulic Conductivity (ft/d)	Storativity
1	213	3095		14.4		1.7×10^{-5}
Between layers 1 and 2			21361		9.2×10^{-3}	
2	164	4597		28.2		2.7×10^{-4}
Between layers 2 and 3			23302		6.2×10^{-3}	
3	131	3677		27.9		2.2×10^{-4}
Between layers 3 and 4			20764		1.1×10^{-2}	
4	328	1315		3.9		1.3×10^{-4}

Notes :

1. Aquifer test results are based on optimized MLPU results using data from the test starting from 5/18/2001: 2:00 p.m. and continuing for about 5 days.
2. Reference: Neinhuis, Philip 2000.

References

Bus, J.C.P., B. van Domselaar en J. Kok. *ALGOL Routines for Least Squares Solution of an Overdetermined System of Nonlinear Equations.* In: Hemker, P.W. et al. *NUMAL Library.* CWI, Amsterdam. 1975.

Hemker, C.J. "Steady Groundwater Flow in Multiple Leaky Aquifer Systems." *Journal of Hydrology.* Volume 72. 1984. Pp. 355-374.

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Hemker, C.J. and C. Maas. "Unsteady Flow to Wells in Layered and Fissured Aquifer Systems." *Journal of Hydrology.* Volume 90. 1987. Pp. 231-249.

Hunt, B. "Solutions for Steady State Groundwater Flow in Multi-layer Aquifer Systems." *Tr. Por. Med.* Volume 1. 1985. Pp. 419-429.

Neinhuis, Philip. *MLPU, an Analytical Groundwater Model for the Analysis of Steady and Transient Flow in a Multiple Aquifer System.* Amsterdam. 2000.

Olsthoorn, T.N. "Effective Parameter Optimization for Ground-water Model Calibration." *Groundwater*. Volume 33, Number 1. 1995. Pp. 42-48.

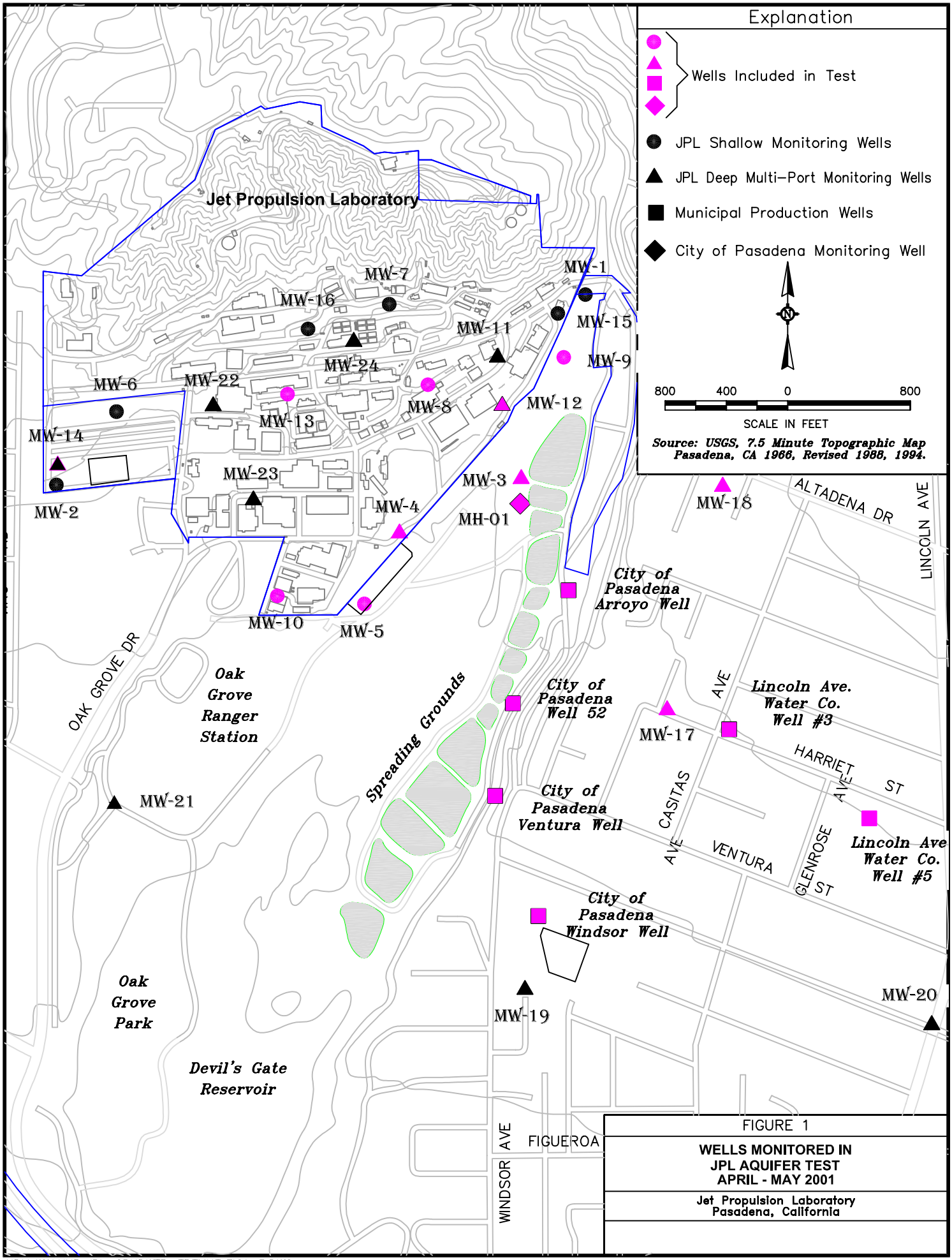

FIGURE 1

WELLS MONITORED IN JPL AQUIFER TEST APRIL - MAY 2001

Jet Propulsion Laboratory
Pasadena, California

NDM: WALKUP: JPL-GRNDWTR-TRTMNT: FIG1-3.DWG
PLOT/UPDATE: JUNE 28 2002 11:53:23

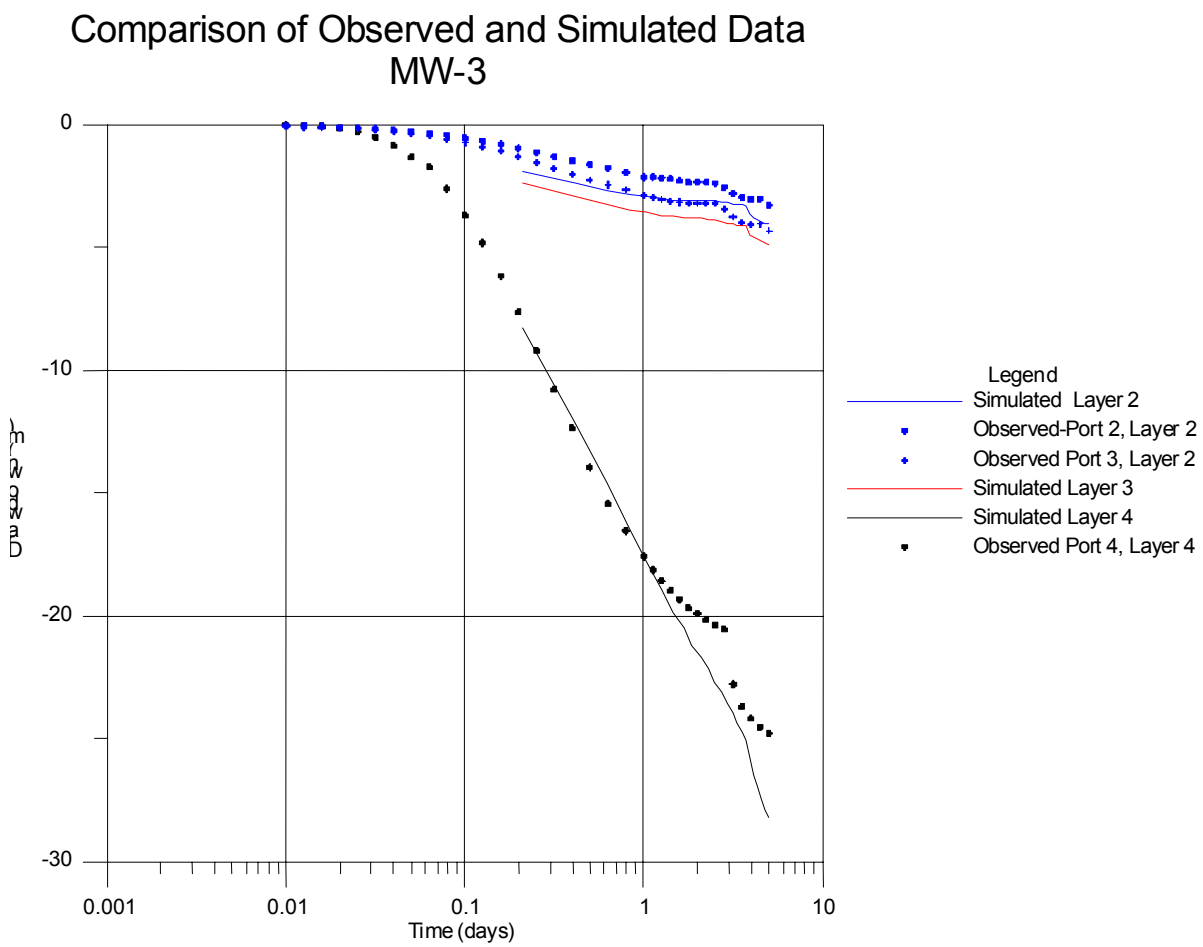
Comparison of Observed and Simulated Data
MW-3
0
-10
-20
-30
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 2
Observed-Port 2, Layer 2
Observed Port 3, Layer 2
Simulated Layer 3
Simulated Layer 4
Observed Port 4, Layer 4

FIGURE 2

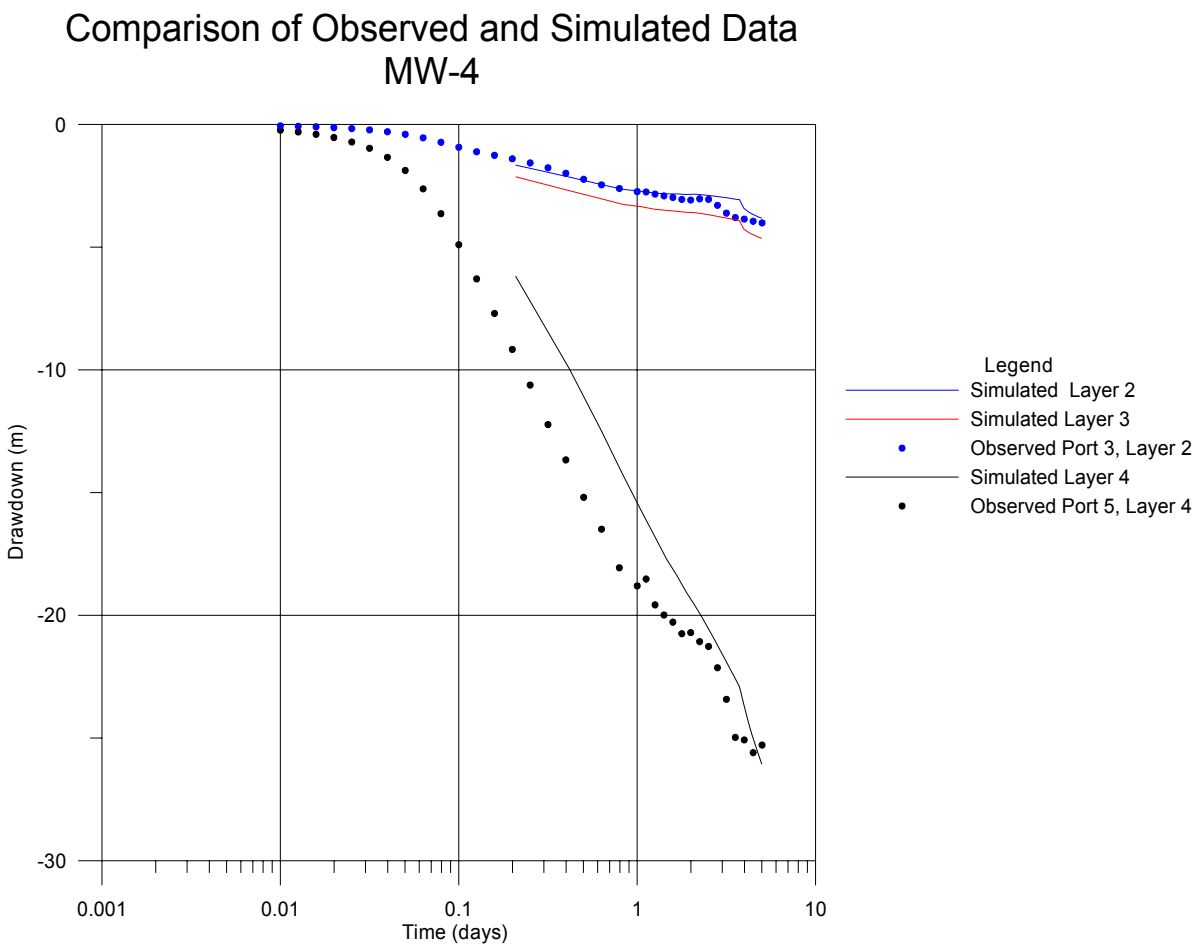
Comparison of Observed and Simulated Data
MW-4
0
-10
-20
-30
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 2
Simulated Layer 3
Observed Port 3, Layer 2
Simulated Layer 4
Observed Port 5, Layer 4

FIGURE 3

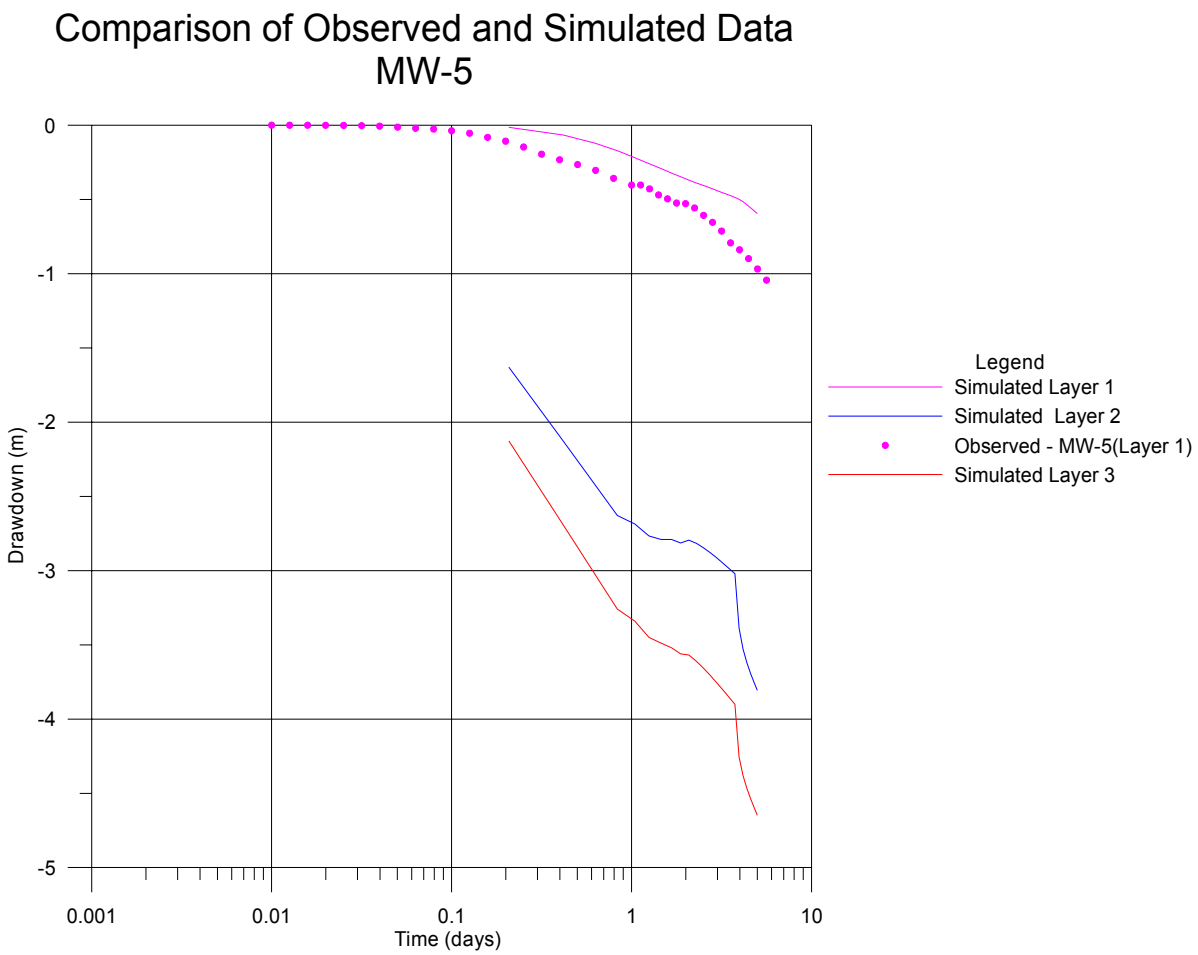
Comparison of Observed and Simulated Data
MW-5
0
-1
-2
-3
-4
-5
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 1
Simulated Layer 2
Observed - MW-5(Layer 1)
Simulated Layer 3

FIGURE 4

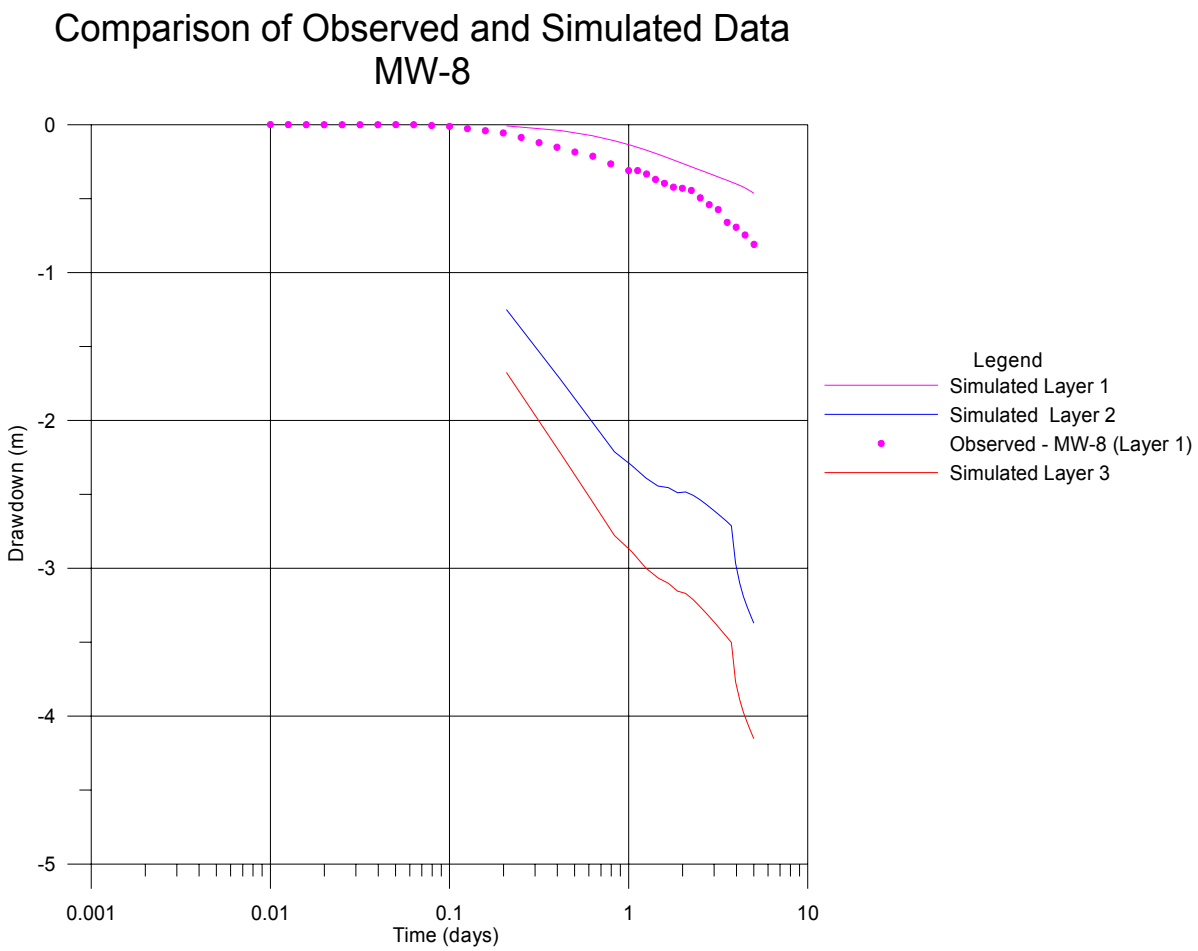
Comparison of Observed and Simulated Data
MW-8
0
-1
-2
-3
-4
-5
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 1
Simulated Layer 2
Observed - MW-8 (Layer 1)
Simulated Layer 3

FIGURE 5

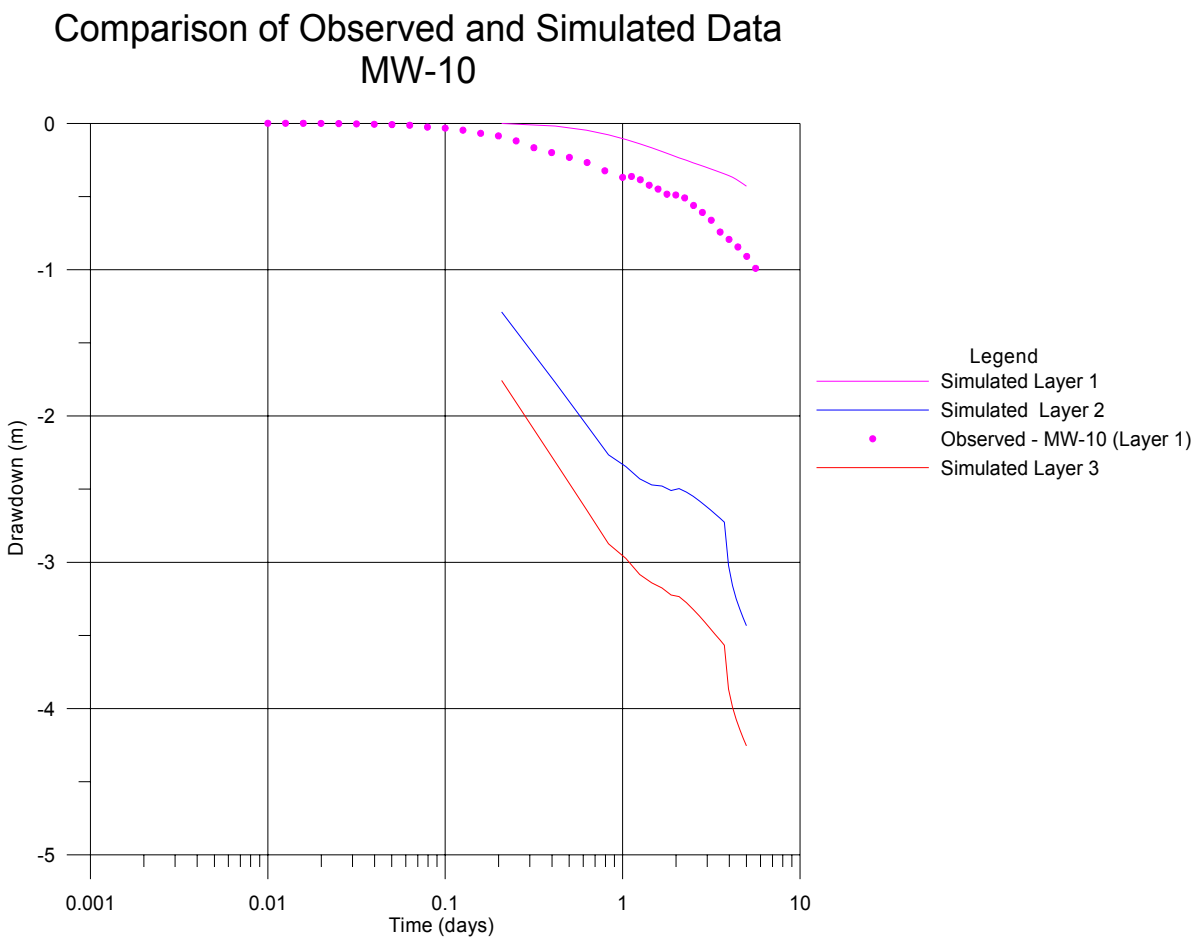
Comparison of Observed and Simulated Data
MW-10
0
-1
-2
-3
-4
-5
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 1
Simulated Layer 2
Observed - MW-10 (Layer 1)
Simulated Layer 3

FIGURE 6

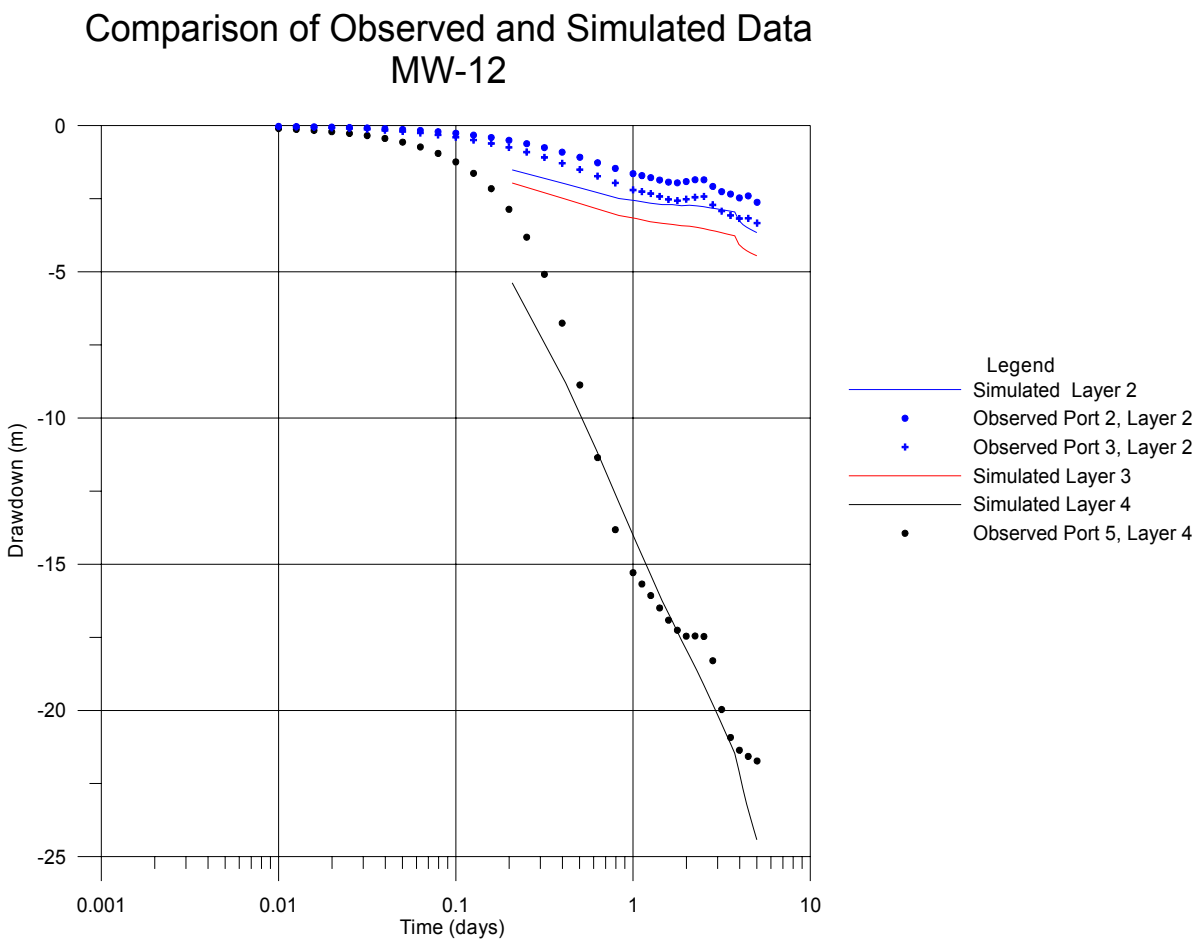
Comparison of Observed and Simulated Data
MW-12
0
-5
-10
-15
-20
-25
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 2
Observed Port 2, Layer 2
Observed Port 3, Layer 2
Simulated Layer 3
Simulated Layer 4
Observed Port 5, Layer 4

FIGURE 7

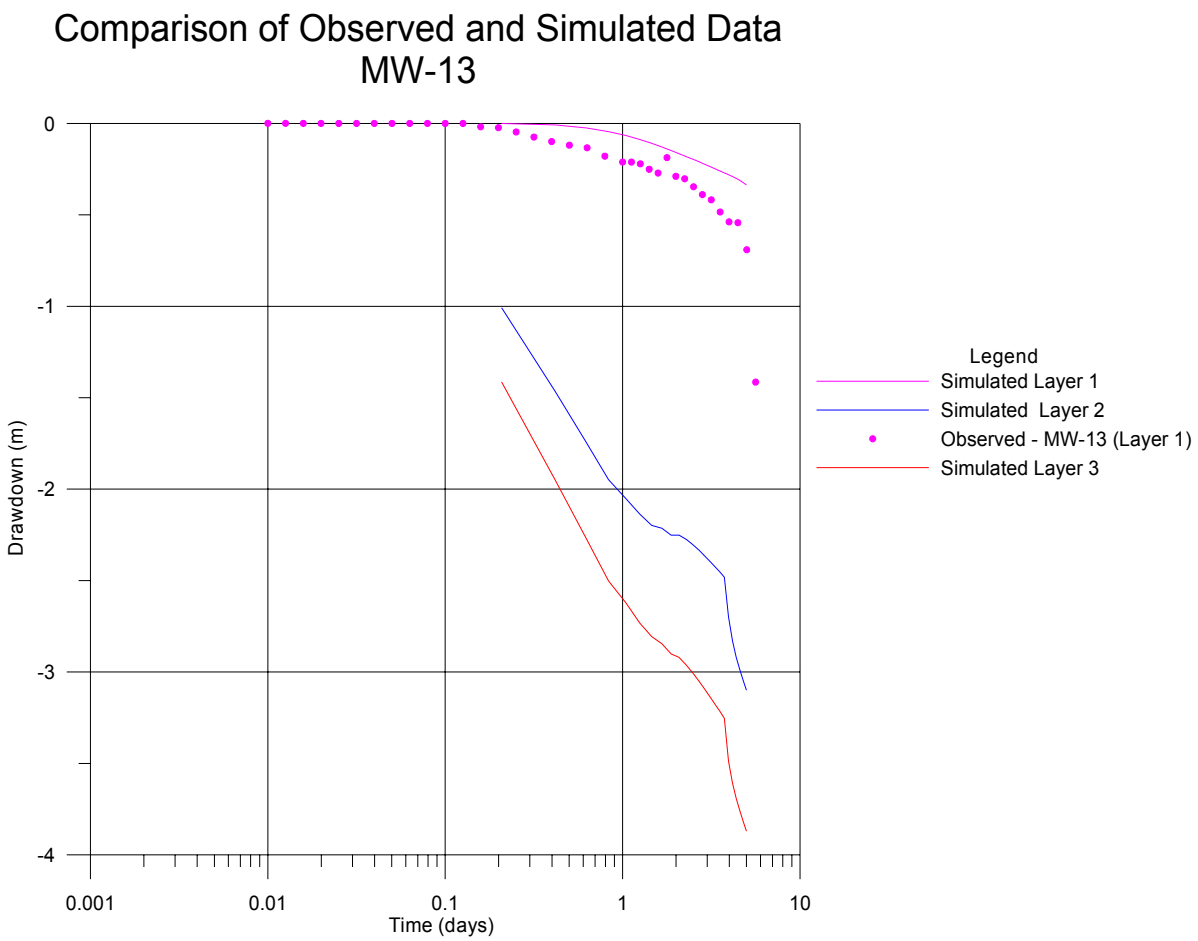
Comparison of Observed and Simulated Data
MW-13
0
-1
-2
-3
-4
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 1
Simulated Layer 2
Observed - MW-13 (Layer 1)
Simulated Layer 3

FIGURE 8

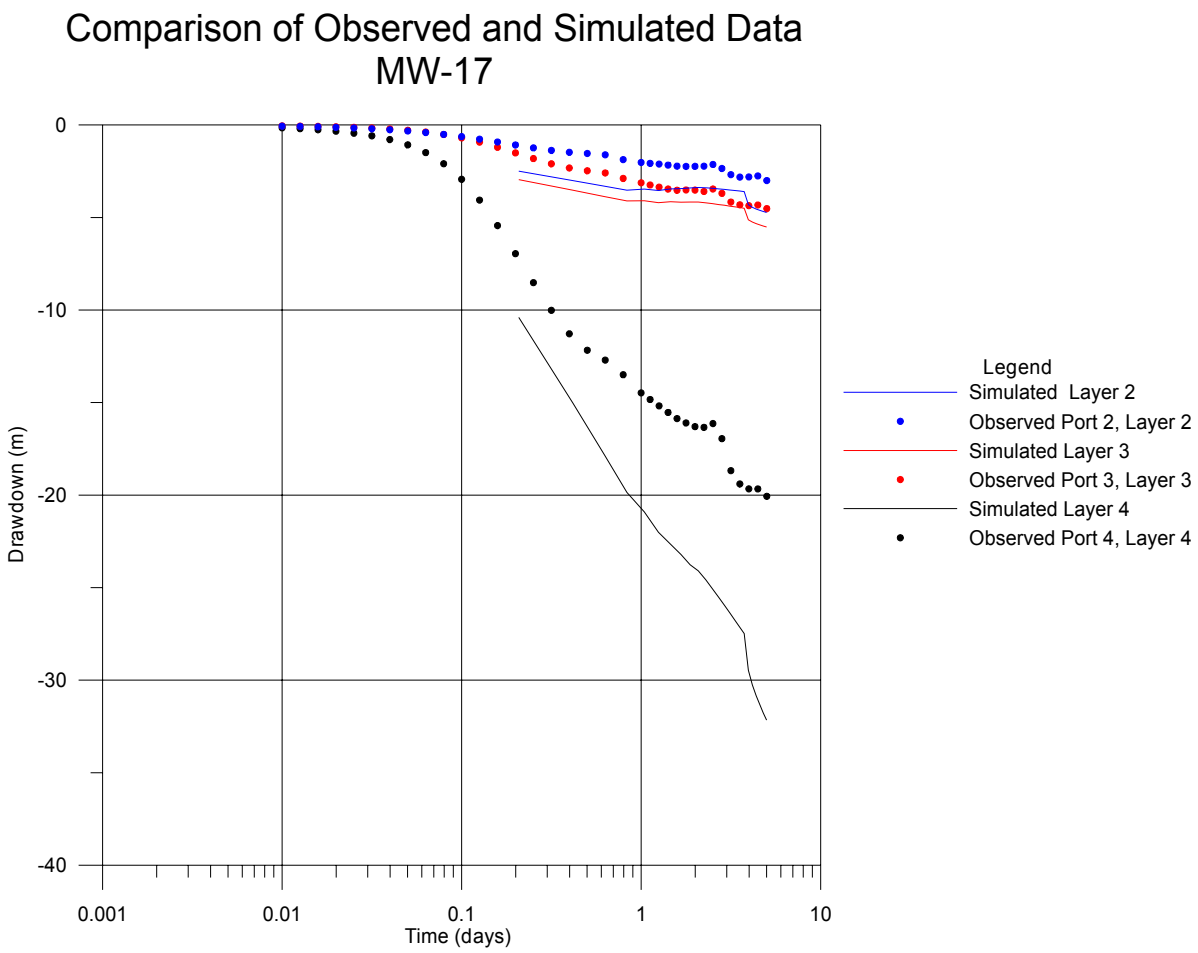
Comparison of Observed and Simulated Data
MW-17
0
-10
-20
-30
-40
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 2
Observed Port 2, Layer 2
Simulated Layer 3
Observed Port 3, Layer 3
Simulated Layer 4
Observed Port 4, Layer 4

FIGURE 9

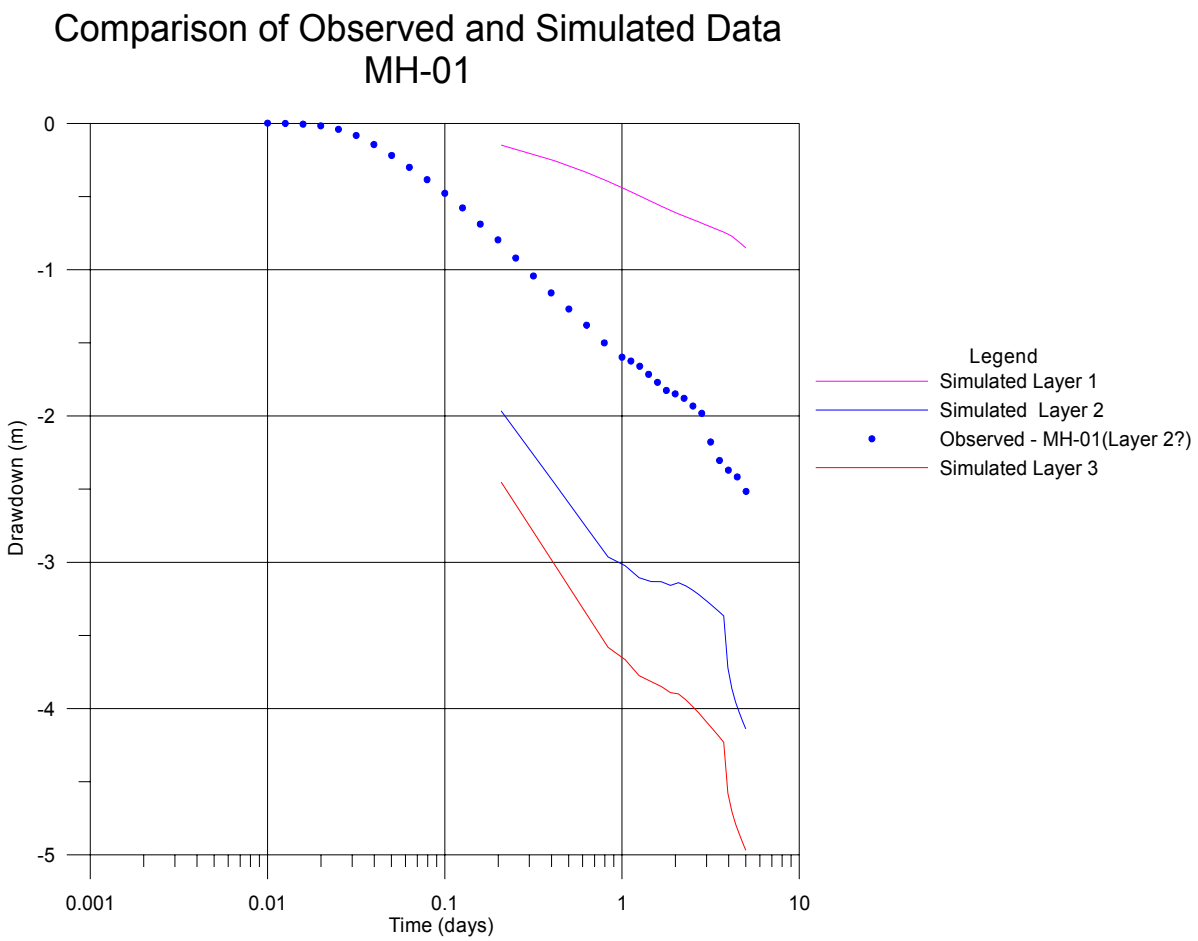
Comparison of Observed and Simulated Data
MH-01
0
-1
-2
-3
-4
-5
Drawdown (m)
0.001
0.01
0.1
1
10
Time (days)
Legend
Simulated Layer 1
Simulated Layer 2
Observed - MH-01(Layer 2?)
Simulated Layer 3

FIGURE 10