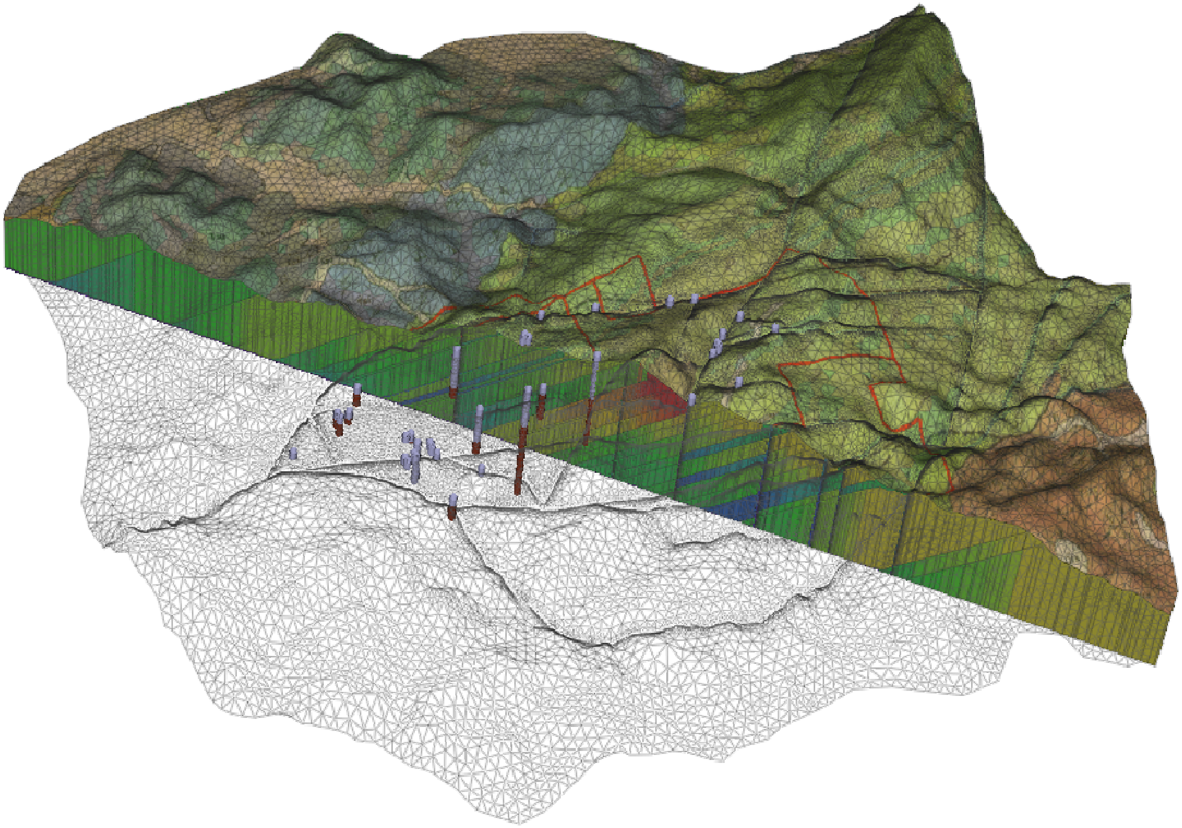
THREE-DIMENSIONAL GROUNDWATER FLOW MODEL REPORT

SANTA SUSANA FIELD LABORATORY
VENTURA COUNTY, CALIFORNIA.

November 2007



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October 31, 2007
In reply refer to SHEA-106507

Mr. Norman Riley
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RE: Three Dimensional Groundwater Flow Model Report
Santa Susana Field Laboratory, Ventura County, California

Dear Mr. Riley:

Pursuant to the Consent Order signed by DTSC, Boeing, NASA and DOE on August 16, 2007, we have prepared the subject report. The report will be distributed to DTSC under separate cover today directly from our contractor, MWH.

Please address any questions regarding this workplan to Mr. David Dassler at (661) 210-5673.

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

Signature: TD Gallacher
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Title: Director, Santa Susana Field Laboratory, Environment, Health & Safety
Date: October 29, 2007

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Three-Dimensional Groundwater Flow Model Report
Santa Susana Field Laboratory

This report has been prepared by a team of qualified professionals under the supervision of the senior staff whose seal and signature appears below. The findings, interpretations of data, specifications or professional opinions are presented within the limits of the available information at the time the report was prepared, in accordance with generally accepted professional engineering practice and within the requirements of the clients. There is no other warranty, either expressed or implied.

Information included in this report is based on available data obtained from public and private sources. Additional studies may or may not disclose information that may modify the findings of this report. In the event that there are appreciable changes in the nature and/or design of the project, or if additional subsurface data are obtained, the conclusions and recommendations contained in the report may require further evaluation by the qualified professionals who participated in its preparation.

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Executive Summary

This report documents the development and calibration of a three-dimensional groundwater flow model for the Santa Susana Field Laboratory (SSFL) and adjacent areas. The groundwater flow model has been developed as a tool to help understand the site-specific three-dimensional groundwater flow system as outlined in the *Work Plan for Additional Investigations, Chatsworth Formation Operable Unit (CFOU Work Plan)* (Montgomery Watson, 2000). The California Environmental Protection Agency, Department of Toxic Substances Control approved the work plan for implementation (DTSC, 2000). This work is being conducted as part of the Resource Conservation and Recovery Act (RCRA) corrective action process at the SSFL, which is currently in the RCRA facility investigation (RFI) stage.

A Mountain Scale Groundwater Flow Model (MSGFM) has been developed that can be used to understand site-specific groundwater flow. To sufficiently represent site-specific three-dimensional groundwater flow in the MSGFM, a preliminary regional scale model was developed to determine 1) the boundaries to the groundwater flow system originating at the SSFL, 2), the features that need to be represented in the model to provide a reasonable representation of site-specific groundwater flow, and 3) the field observations available to assess the reasonableness of the simulated groundwater system. Small scale box models were also utilized to determine how to best represent conditions at the SSFL, such as anisotropy of geologic units and the appropriate ways to represent seeps in the MSGFM.

The finite-element groundwater modeling code FEFLOW (WASY, 2007) was selected to prepare the MSGFM for the SSFL. Because the geologic setting at the facility, specifically the stratigraphy and structure, has a dominant influence on groundwater flow at the SSFL, FEFLOW's enhanced capabilities to incorporate these features were considered necessary to develop a representative modeling tool. The MSGFM domain encompasses the entire SSFL and extends to the surrounding alluvial valleys, an area of approximately 52 km^2 (20 sq. miles). The finite element mesh consists of 41 layers, more than 5.9 million elements and 3.1 million nodes. More than 500 distinct hydraulic conductivity zones are used to represent the complex geology and structure.

In its current form, the MSGFM represents the components of the current Mountain Scale Conceptual Model (MSCM) and provides a reasonable representation of three-dimensional groundwater flow as assessed by comparing simulated groundwater levels and groundwater discharge with field observations. The MSGFM is to be used at the SSFL to evaluate site-specific three-dimensional groundwater flow from key locations and to provide representative input conditions for additional FRACTRAN simulations of solute transport and fate. These two models will be used to provide insight into the migration of Chemicals of Potential Concern (COPCs) and to evaluate existing and possible locations for monitoring future contaminant transport.

Recognizing that groundwater models are simplifications of reality and that input parameters and boundary condition values are always based on incomplete data sets, model results always contain uncertainty. Understanding the uncertainty in simulating the groundwater flow system is addressed by conducting a sensitivity analysis, and by developing and calibrating alternative conceptual models of the hydrogeologic system. This work is underway and is being used to assess reasonable ranges in model predictions. In the state of calibration documented in this report, the three-dimensional groundwater flow modeling tools were developed to a stage that they are judged useful in providing insight into characterizing the groundwater flow system beneath the SSFL. Work continues to refine the model and evaluate alternative conceptual models, the results of which will be documented in a future report.

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Abbreviations

ASTM	American Society of Testing and Materials
Boeing	The Boeing Company
COPCs	chemicals of potential concern
DOE	Department of Energy
DTSC	Department of Toxic Substances Control (Calif. Env. Protection Agency)
EPM	Equivalent Porous Medium
ET	Evapotranspiration
FEFLOW	Three-dimensional Finite Element Groundwater Flow Model Software developed by WASY
FRACTRAN	Two-Dimensional Finite Element Discrete Fracture Flow, Fate and Transport Model Software developed by Sudicky and McLaren (1992)
gpm	gallons per minute
H & A	Haley and Aldrich
K	Hydraulic conductivity
m^3/d	cubic meters per day
MDEQ	Michigan Department of Environmental Quality
mm/yr	millimeters per year
MSCM	Mountain Scale Conceptual Model of Groundwater Flow
MSGFM	Mountain Scale Groundwater Flow Model
MWH	Montgomery Watson Harza
NASA	National Aeronautics and Space Administration
RFI	RCRA Facility Investigation
RCRA	Resource Conservation and Recovery Act
RSCM	Regional Scale Conceptual Model of Groundwater Flow
RSGFM	Regional Scale Groundwater Flow Model
SCM	Site Conceptual Model of TCE Movement at the SSFL
SSFL	Santa Susana Field Laboratory
UW	University of Waterloo
WASY	Institute for Water Resources Planning and Systems Research, - developers of FEFLOW
2D	Two-dimensional
3D	Three-dimensional

1.0 Modeling at the SSFL

1.1 INTRODUCTION

This report presents the development and calibration of a three-dimensional groundwater flow model for the Santa Susana Field Laboratory (SSFL) and adjacent areas (Figure 1). The SSFL is located in the southeast corner of Ventura County, 29 miles northwest of downtown Los Angeles, California. The location of the SSFL and adjacent areas is shown in Figure 1. The SSFL is jointly owned by the Boeing Company (Boeing) and the federal government (administered by the National Aeronautics and Space Administration (NASA)) and is operated by Boeing. A portion of the SSFL that is owned by Boeing was leased to the U.S. Department of Energy (DOE).

Previous subsurface environmental investigations have shown that groundwater underlying the SSFL has been impacted by historic releases of primarily volatile organic compounds (VOCs), with trichloroethylene (TCE) being the compound detected at the highest relative concentration and frequency. Other chemicals of potential concern (COPCs) that can be generally attributed to historical operations are present in the groundwater beneath the SSFL. However, these COPCs are present at lower relative concentrations and at fewer locations.

1.2 PURPOSE AND OBJECTIVES OF GROUNDWATER FLOW MODELING

This report was developed to partially fulfill the corrective action provisions of post-closure operating permits for Area I, II, and III (Figure 1), and hazardous waste operating permit for buildings 29 and 133 storage and treatment facilities at the SSFL. This work is being conducted as part of the Resource Conservation and Recovery Act (RCRA) corrective action process at the SSFL, which is currently in the RCRA facility investigation (RFI) stage. The overall goal of the SSFL RCRA corrective action process is to complete implementation of the corrective measures.

The purpose of groundwater modeling at the SSFL is to represent three-dimensional groundwater flow within the complex hydrogeologic setting of the SSFL and adjacent areas. The objectives for modeling include gaining insight into the:

1. Climatic, topographic, geologic and anthropogenic influences on groundwater flow at the SSFL and adjacent areas;
2. Groundwater flow volumes for the SSFL (water balance); and
3. Groundwater system's influence on the transport of dissolved COPCs, performance of groundwater monitoring networks, and performance of potential extraction systems.

This report documents the refinement and translation of a regional scale conceptual model and a mountain scale conceptual model to representative three-dimensional models. Model development work was framed in a regional context, however, the majority of the work centered on the area associated with the SSFL, at the mountain scale. Numerical models are one type of analysis being applied to answer decision questions related to site-specific three-dimensional groundwater flow. Insights gained through this work are considered in conjunction with other data sets and study results in the decision-making process.

Groundwater flow decision questions include those outlined in the *Work Plan for Additional Investigations, Chatsworth Formation Operable Unit (CFOU Work Plan)* (Montgomery Watson, 2000). The California Environmental Protection Agency, Department of Toxic Substances Control approved the work plan for implementation (DTSC, 2000). The modeling work described in this report is consistent with the applicable guidance and standards for groundwater flow modeling (e.g. CalEPA, 1995; ASTM Standard D 5447-93; Anderson and Woessner, 1992; USNRC, 2003).

1.3 BACKGROUND

At various times since the late 1940s, contaminants including TCE, petroleum hydrocarbons, perchlorate and tritium entered the subsurface environment beneath the SSFL (mid-1980s). Questions regarding the occurrence, migration and fate of these contaminants spawned field investigations beginning in the late 1980s with more intensive studies initiated in 1998. In 2000, a Site Conceptual Model (SCM) addressing the factors influencing the occurrence and movement of TCE beneath the SSFL (Montgomery Watson, 2000) was presented. This work described the groundwater flow, and the distribution and fate of TCE, in both dense non-aqueous liquid (DNAPL) and dissolved phase. It also described the general occurrence of TCE in the unsaturated and saturated portions of the subsurface. The SCM was recently updated by incorporating new data sets derived from field and laboratory investigations and preliminary results of this modeling effort (Cherry et. al., 2007).

The SSFL is located on a local topographic high (Simi Hills) 800-900 feet (240-275 meters) above the surrounding valleys Figure 2). The Chatsworth Formation is a fractured and faulted sandstone with interbeds of siltstones, mudstones and shales. It is the primary water-bearing geologic formation underlying the SSFL (Cherry et. al., 2007). The Chatsworth Formation has been uplifted and faulted such that geologic units dip to the northwest at an angle of 25-35^{o} and are offset across faults. A thin layer of alluvium, which at certain times and locations contains perched groundwater, is found at numerous locations and often overlies faults. At some locations within the SSFL the groundwater in the Chatsworth Formation rises into the overlying alluvium.

The groundwater system is recharged by precipitation. Recharge occurs throughout the Simi Hills and rates vary with the type of geologic material, slope and precipitation. In this setting the depth below the land surface to groundwater is relatively shallow (50-75 feet or 15 to 23 meters).The elevation of groundwater at the SSFL is up to 900 feet (275 meters) higher than the groundwater levels in the surrounding alluvial valleys (Simi and San Fernando Valleys). Consequently a simple comparison of area water levels would imply that general groundwater flow is from the higher elevations (Simi Hills) towards the topographically lower areas (alluvial valleys) (Figure 2).

The generalized description of regional groundwater flow directions presented above does not detail how the complex stratigraphy and structural features of the Chatsworth Formation influences site-specific three-dimensional groundwater flow. The complex physical features influence the local pathways and rate of movement of groundwater at the SSFL and adjacent areas. Groundwater flow directions are influenced by the storage and transmission properties of individual rock formations, complex interactions with multiple formations, and faults and shear zones. The higher groundwater elevations in the vicinity of the SSFL result in downward vertical head gradients. Groundwater recharged in the Simi Hills ultimately discharges through a number of pathways including; seeps and springs on the slopes of the Simi Hills, as lateral flow at depth towards and beneath the valleys, and pumping on and off-site. Thus groundwater flow directions are not easily interpreted using two-dimensional water level maps (plan or cross-section views). Therefore, a three-dimensional representation of hydrogeologic conditions was needed to assess site-specific groundwater flow directions.

The installation of monitoring wells, production wells and other instrumentation over the last 56 years in response to water supply and groundwater monitoring requirements at the SSFL allowed for the development of a well-supported hydrogeological model of the SSFL. However, a key concern following a review of the SCM in 2000 was that a representation of three-dimensional groundwater flow at the SSFL and the adjacent areas was needed. This need lead to the modeling effort described in this report.

1.4 PREVIOUS MODELING APPLICATIONS AT THE SSFL

Various two and three-dimensional numerical models have been applied at the SSFL since 1998 to aid in the characterization of groundwater flow, and contaminant transport and fate. The following is a brief chronology of groundwater model use at the SSFL:

1998 - 2007	FRACTRAN – 2D Contaminant Transport and Fate (Montgomery Watson, 2000)
2003	SEEP2D – 2D Groundwater Flow Simulation of the SSFL (MWH, 2003)
2004	MODFLOW – 3D Groundwater Flow Simulation - C1 Pumping Test (MWH, 2004)

Models have been used to analyze the results of field hydraulic conductivity tests and to generate input values for large scale numerical models. The reader is referred to the original documents for a detailed description of each application. None of the above modeling applications represented the full three-dimensional flow system at the site or mountain scale.

1.5 DOCUMENT ORGANIZATION

The remainder of the document is organized as follows:

Section 2: Modeling Approach, which provides an overview of the general approach followed in developing the model as well as considerations specific to the SSFL;

Section 3: Conceptual Groundwater Model Development, which describes the information and conceptualization steps required to develop the mountain scale groundwater flow model;

Section 4: Mountain Scale Modeling, which presents a detailed description of the mountain-scale groundwater flow model;

Section 5: Summary of Current Understanding of Groundwater Flow, which presents primary insights gained through the modeling to date; and

Section 6: Model Capabilities and Future Applications.

1.6 STUDY TEAM

Development of the three-dimensional groundwater flow model was primarily directed by the SSFL's Groundwater Advisory Panel that includes: Professors John Cherry (emeritus, University of Waterloo), David McWhorter (emeritus, Colorado State University) and Beth Parker (University of Guelph). The panel's modeling oversight and review was augmented by Professor William Woessner (University of Montana). Model development, construction and simulations were conducted primarily by Daron Abbey and Paul Martin at AquaResource Inc., with input into the geologic framework and its conceptualization provided by Dr. Ross Wagner. The work presented in this report was conducted under the supervision of Richard Andrachek of Montgomery Watson Harza (MWH), the flow model project's registered professional engineer.

2.0 Modeling Approach

Numerical groundwater models are structured tools developed to simulate groundwater flow, or flow and contaminant transport and fate by integrating a multitude of data (e.g. lithologies, water levels, groundwater/surface water features, pumping etc.) with a conceptualization of the natural geologic and hydrogeologic environment. Numerical models are used throughout the world to evaluate groundwater systems and have become increasingly popular with advances in computing technology since the 1970's. Model applications have evolved from simplified models, where geologic complexities were generalized into a two-dimensional system, to more detailed applications that utilize large amounts of three-dimensional data and interpretations to more fully represent the physical hydrogeologic system.

The approach to modeling at the SSFL has included the use of site-specific numerical models at multiple scales (regional, mountain and local) as well as box models (Appendix K). Site-specific models are used to understand the groundwater system specific to the SSFL, whereas box models are used to illustrate and document hydrogeologic and numerical processes and support the development of the site-specific numerical models. Examples of generic box model simulations can be found in Appendix K. Appendix L presents an example of a box model developed to help define reasonable hydrogeologic parameters based on field observations during the C1 pumping test.

2.1 SCALE OF SITE- SPECIFIC MODELING

A multi-scaled modeling approach was developed for the SSFL to address decision questions at various scales. The three major scales of assessment are outlined below and illustrated in Table 1 and Figure 3.

1. Regional scale representation of three-dimensional groundwater flow using an Equivalent Porous Media (EPM) approach (see section 2.3). The regional scale modeling is used to assess how the hydrogeologic setting of the SSFL fits into the regional groundwater flow system. As such, it is used to provide physically and hydrologically based boundary conditions for the Mountain Scale Groundwater Flow Model (MSGFM – described below). Using this telescoping approach, overall flow conditions within the area represented by the MSGFM are tempered by the larger hydrogeologic setting.

2. Mountain scale representation of three-dimensional groundwater flow using an EPM approach. The development and calibration of the model provides insight into how the complex hydrologic inputs and the geologic framework influence the occurrence and movement of groundwater in and adjacent to the SSFL. Once calibrated, the model is then used to explore both historical and future groundwater flow paths.

3. Local scale representation of contaminant transport and fate using a discrete fracture network (DFN) approach, with parameters tempered by mountain-scale flow simulations. Modeled flow paths and rates from the MSGFM are used to refine hydraulic conditions and formulate representative FRACTRAN networks. DFN simulations incorporate key transport and fate processes that are not practically simulated in the MSGFM.

The multi-scaled modeling approach used for the SSFL is a standard method, sometimes referred to as telescoping mesh refinement. The detail incorporated within smaller scale models is successively increased to create more representative illustrations of the key hydrologic processes at each scale and to address groundwater flow decision questions at these multiple scales (assumptions and limitations associated with each scale are presented in (Table 1). This multi-scale modeling approach was selected because there were not readily available model codes that would practically allow simulation of the complex fractured network and porous sandstone blocks at a scale sufficient to appropriately represent groundwater flow and dissolved contaminant transport processes over the entire mountain site.

The first two steps of this approach are documented in this report. The third step is ongoing and will be documented in a future report.

2.2 SITE-SPECIFIC MODEL DEVELOPMENT & APPLICATION

The approach to development of site-specific three-dimensional modeling tools for the SSFL follows a standard modeling approach (ASTM, 1993) and includes the following general steps:

- The development of a scale-dependent conceptual model (RSCM/MSCM);
- Translation of the RSCM and the MSCM into three-dimensional numerical groundwater flow models;
- Execution and calibration of the numerical models to observed field conditions; and
- Application of the MSGFM to better understand the likely three-dimensional behavior of the groundwater system.

The conceptual model for a site-specific region typically represents an assimilation and interpretation of data collected as part of a hydrogeologic investigation. Once the conceptual model is formulated, it is translated into a numerical groundwater model and then calibrated to observed and measured hydrogeologic data. The numerical model simulates the groundwater system within a computer and calculates groundwater flow directions and rates based on mathematical representations of physical processes. The numerical model is calibrated to reflect field observations. Commonly as a numerical model is being formulated and calibrated, the process provides insight into the reasonableness of the original conceptual model. As a result, the conceptual model may be revised to reflect a refinement of the original conceptualization. This process, which utilizes the numerical model as an interpretative tool, was applied at the SSFL.

Qualitative and quantitative comparisons of the field data and model simulations (calibration) provide confidence in the ability of the model to represent field conditions. A qualitative comparison applied in this study includes visual comparison of simulated water levels with observed water level map interpretations. Quantitative comparisons applied in this study include calculating differences between observed and modeled water levels at observation wells, and observed and modeled discharge at seep locations; statistical analysis of these differences (residuals) are used as a calibration measure.

Models are further calibrated or validated by comparing measured values associated with an independent data set of heads and flow (often of another time period not used for model calibration) with simulated results. The goal is to illustrate that the calibrated model is able to reasonably represent another time period or stress condition without modifying the model structure or properties. At the SSFL, simulated results were compared to water levels for the period from 1985 to present, and using recorded pumping rates from 1949 to present to check the calibration of the MSGFM.

Once a model is considered adequately calibrated to meet objectives, it can be used to estimate performance of remediation actions or other future conditions. As all models are a simplification of reality, the effect of the uncertainty in the conceptual model and the numerical parameters is evaluated to understand the variability in potential modeling results. This approach is being currently undertaken for the SSFL site.

2.3 GROUNDWATER FLOW MODEL SOFTWARE SELECTION

When selecting a numerical modeling code/software package for simulating three-dimensional groundwater flow at the SSFL the software needed to be able to efficiently incorporate the following features:

- Multiple formations, including the steep changes in topography;

- Folded geologic layers with variable dips and that are discontinuous in places;
- Directional hydraulic conductivity aligned with the dipping beds;
- Irregular distribution of faults with variable properties;
- Groundwater discharge zones (seeps) irregularly distributed along the slopes of the Simi Hills; and
- Irregular distribution of pumping and other anthropogenic influences.

Two commercial numerical models were considered for this project; the USGS MODFLOW (Harbaugh et. al, 2000) and FEFLOW (WASY, 2007). MODFLOW was considered because it is the most widely applied groundwater model in the world, and is commonly considered a standard. However, the steeply dipping beds, assumed hydraulic conductivity parallel to bed dip, the perceived limits of the generally horizontal assignment of model layers and the lack of readily available data, input and output management tools for complex three-dimensional models were considered major detractors for using MODFLOW to represent conditions at the SSFL. A detailed assessment of the finite element code FEFLOW was undertaken and it was determined that its advanced capabilities overcame most of the limitations of the MODFLOW model. FEFLOW's capabilities allow development of more representative models at the regional and mountain scale. The specific advantages of the FEFLOW application include:

- Ability for the mesh discretization to focus calculation points in the areas of interest to more precisely simulate observed physical features (faults, pumping wells, seepage locations, etc.) and naturally complex boundary conditions (Figure 4);

- Efficiency of localized mesh discretization, requiring far fewer calculation points to achieve the same level of precision as with finite difference grids which are forced to carry refinements to the model boundaries (allows simulation of shallow aquifer within the context of the Regional Scale Groundwater Flow Model (RSGFM));

- Ability of the elements to conform to the pronounced vertical variation of aquifer / aquitard layers;

- Ability to align principal directions of hydraulic conductivity with bedding planes which is believed to be an important control on groundwater flow at the SSFL; and

- Advanced boundary conditions (constrained seeps) to avoid potential impacts of non-physical boundary conditions on the simulation results.

In addition, the finite-element method uses more sophisticated numerical solution algorithms resulting in more stable and faster simulations, factors that often plague modeling efforts with large numbers of nodes and large contrasts in hydrogeologic properties (Martin and Frind, 1998; Anderson and Woessner, 1992; WASY, 2007; Wang and Anderson, 1995).

The FEFLOW code is becoming widely use to simulate complex groundwater systems worldwide. Over 200 leading research, consulting, and government organizations report use FEFLOW to address complex groundwater issues. Prominent FEFLOW users in California include researchers at Lawrence Livermore National Laboratory (LLNL) who use FEFLOW as a modeling tool to manage a complex site remediation project for the US Department of Energy, as well as the Sacramento Water Resources Control Board. Additionally, FEFLOW is applied by a number of consultants throughout California.

Though FEFLOW has capabilities to simulate both discrete fractures and porous sandstone block networks, simulation of flow and transport processes in a discrete fracture network requires far too many calculation points to be practical at the scale of the MSGFM and RSGFM. As a result, to formulate a representative three-dimensional groundwater flow system at the mountain scale, the hydrogeologic properties of both the fracture network and porous sandstone were combined into a representative value and the developed model represented hydrogeologic conditions using the standard equivalent porous media approach.

The regional and mountain scale models, and simple box models used to develop the current MSGFM described in this report all used an equivalent porous media (EPM) representation of the hydrogeologic setting. The EPM approach was selected because at methods needed to represent both discrete fractures and porous sandstone blocks at the Mountain scale are not practical using current simulation tools. Instead, the EPM representation treats a fractured porous rock system as an equivalent porous medium and assumes that the overall hydrologic properties of the fractured rock groundwater system can be simulated as a porous media with a set of properties that reflect average groundwater flow. This approach is consistent with approaches used at many fractured rock sites where general site conditions are represented (USNRC, 2003; Zyvoloski et al., 2004; Environ, 2000; Cook, 2003). This approach is supported by field and core observations (University of Waterloo 2003) which describe the SSFL aquifer system as having pervasive interconnected fracturing throughout all hydrostratigraphic units, and regular hydraulic responses to pumping that are observed throughout the site (MWH, 2003/2004).

In an attempt to represent the behavior of groundwater in a discrete fracture network observed at the site, FEFLOW results will be used to condition a smaller scale fractured rock model, FRACTRAN (Sudicky and McLaren, 1992). In this separate modeling effort the flow, transport and fate of dissolved TCE will be evaluated. While FEFLOW also has capabilities to simulate flow and transport processes in discrete fracture networks, the numerical approach applied in FRACTRAN (Laplace transform Galerkin approach) is much more efficient at performing such simulations. The results of FRACTRAN simulations will be reported under separate cover.

3.0 Conceptual Groundwater Model Development

Using the site-specific model development approach described above, the conceptual models developed for the SSFL site were transcribed into the numerical groundwater flow model and incorporated into the FEFLOW code. The following sections describe the available data and the steps undertaken to develop the conceptual model for the MSGFM. Section 4 describes the MSGFM in detail.

The SSFL SCM (MW, 2000) summarized the initial understanding of the movement of TCE in the Chatsworth Formation. This included a description of the topographic and geologic features that were considered to control groundwater flow as well as estimates of the hydraulic and hydrogeologic parameter values for conditions at the SSFL. As such, the SCM provided a starting point for developing and understanding three-dimensional groundwater flow at the SSFL.

However, prior to developing a numerical model to encompass the SSFL site, an understanding of how the SSFL fits within the regional groundwater flow system was required. As such, the first step in developing the MSGFM was to undertake a regional-scale analysis of hydrogeologic conditions using available data. The regional-scale analysis included the conceptualization of hydrogeologic conditions from regional recharge to discharge zones (the Regional Scale Conceptual Model (RSCM), see section 3.3), and the development of the numerical model at that scale (the RSGFM, see section 3.5). One of the key purposes of the RSGFM was to quantify reasonable boundary condition values for the MSGFM, such that simulations with the smaller scale model are “tied-into” the predicted regional groundwater flow system.

As outlined in section 2.2.1, the MSCM (section 3.5), which was developed to serve as the basis for the MSGFM, contains more detail than the RSCM.

3.1 AVAILABLE GEOLOGIC AND HYDROGEOLOGIC INFORMATION

The current conceptual understanding of the geologic and hydrogeologic setting at SSFL was developed through a review of both on and off-site information in the form of reports, maps, databases, and other numerical models (Appendix A). This information was compiled and reviewed as part of on-going RCRA corrective action activities from various on-site studies.

Prior to the development of the RSCM, there was a limited understanding of the regional groundwater system beyond the SSFL site. A large portion of the off-site information was obtained during the RSCM development. Regional and off-site information was compiled from a variety of sources, including the Calleguas Water District (1998) and the Ventura Basin Study (Hopps, 2004). Information collected provided insight into the estimated depth of freshwater, geologic features affecting the groundwater system, estimates of groundwater recharge, and regional water quality.

Figure 5 and Table 2 show the types and location of regional and off-site information used to develop the flow model. The regional information provided general information on subsurface geology, water levels, and hydrogeologic conditions; the oil and gas wells provided detailed geologic and water salinity information.

The on-site characterization work undertaken at the SSFL is typically more complete and contains greater detail than the regional and off-site data. This is largely because on-site data are collected for specific RFI objectives that require a higher level of documentation and accuracy. Data sources and reports utilized in the development of the on-site characterization provide a substantial amount of hydrogeologic information for most areas and geologic conditions within the SSFL site boundaries (Table 3).

All of these datasets were utilized and formed the basis of MSCM (Table 3). During the development of the MSCM, additional data were collected to address data gaps within the mountain scale area. These data and associated analyses included additional geologic and structural mapping, seep, spring and phreatophyte mapping, as well as rock property investigations. These investigations are referenced throughout this document and some are included as appendices (e.g. Appendix B: Development of Geologic Data in Support of the Three-Dimensional Groundwater Model at the SSFL (MWH, 2007)). Appendix B lists key mountain scale datasets / information and how they are used in developing the MSGFM.

3.2 DATA MANAGEMENT AND MAPPING

Datasets for this project were managed within a Geographic Information System (GIS) allowing the presentation and manipulation of large data sets. The data were stored in relational databases; and mapping and modification of model input parameters were completed within a linked GIS. The FEFLOW modeling code uses standard database and GIS file formats for input of information and export of results. Such tools were essential in creating the SSFL models. However, the size and complexity of parameter distributions developed for the MSGFM also required that additional data management protocols be developed to automate the interface with the modeling database (see Appendix M for more details).

3.3 REGIONAL SCALE CONCEPTUAL MODEL

3.3.1 Regional Geologic History & Setting

An understanding of the geologic history and setting of the area provides the context for assessing the influence of geologic features on groundwater flow at the SSFL. The SSFL and regional study areas are located in the Western Transverse Ranges of Southern California. The geologic setting is a result of extensive tectonic activity, and the California Geologic Survey indicates that this geologic province is one of the most rapidly rising regions on Earth (CGS, 2003). The Transverse Ranges are in north-south compression, creating east-west trending geologic structures (faults and folds) within the Late Jurassic to Late Pliocene-aged sedimentary rock units that are found in the vicinity of the SSFL. Northeast-southwest trending faults are also located within the study area recording periods of variable stress fields (MW, 2000).

The stratigraphic column shown in Figure 6 provides an overview of the geologic environments and structural events that shaped the geology of the area over which the SSFL is situated.

3.3.2 Regional Geologic Setting

The regional study area encompasses the Simi, San Fernando, and Thousand Oaks Valleys, as well as the Simi Hills and parts of the Santa Susana and Santa Monica Mountains (Figure 1). The southern boundary of the regional study area coincides with the topographic high of the Santa Monica Mountains forming the south limb of a syncline. The north boundary of the study area coincides with the topographic high in the Santa Susana Mountains that separates the Santa Clara River Valley from the Simi Valley. Figure 2 shows a plan view map and cross-section of the regional geology for the study area (after Dibblee 1992). Additional regional cross-sections were developed for this study using available information and are contained in Appendix B.

The north-south cross-section shown in right panel of Figure 2 illustrates the stratigraphic and structural complexity of the study area to a depth of 1220 meters (4000 feet) below sea level. The stratigraphic system is characterized by the superposition of antiform and synform features across the entire geologic sequence. The bedrock is displaced across faults from multiple tectonic periods; including reactivation of old faults.

The mapped regional geologic units range from conglomerates and sandstones, to shales, mudstones and slates (Figure 6 and Figure 7). The Chatsworth Formation (Upper Cretaceous), which underlies SSFL, is interpreted to extend to a depth exceeding 1220 meters (4000 feet) below sea level throughout the study area. The Chatsworth Formation is a turbidite deposit that is predominately composed of sandstone with a number of finer-grained members. The overlying Tertiary units are the Simi, Santa Susana, Sespe, and Llajas Formations, which were deposited on top of and are younger than the Chatsworth Formation.

Figure 8 shows a three-dimensional representation of the regional geology developed from construction and interpretation of regional geologic cross-sections. Folding and faulting between the Early and Late Micoene geologic periods resulted in subsequent folding of the Chatsworth to Sespe Formations into a westward plunging syncline with an axis that is located beneath the Simi Valley (Figure 7). The Chatsworth and early Tertiary Formations dip northwestward into the trough of the syncline beneath the Simi Valley. Along the northwestern margin of the Simi Valley, the Chatsworth Formation is displaced by the Simi Fault. The Simi Fault is a northeast striking structure with an upward displacement to the north.

To the north of the Simi Valley, the Santa Susana Mountains have been uplifted by a combination of folding and faulting. The two most prominent faults to the north of the Simi Valley are the Simi Fault, a steeply dipping reverse fault located along the northwestern margin of the Simi Valley, and the Santa Susana Fault, a relatively gently northwestward dipping thrust fault that is located approximately 7 kilometers north of the Simi Valley.

The most extensive non-sedimentary unit in the regional study area is the Conjeo Volcanics. This unit is mapped at surface south and southwest of SSFL. Diabase dikes, likely associated with the Conjeo deposition, cross-cut sedimentary units in the regional study area and intrude fault systems that probably originated in the early Miocene period. The youngest geologic unit is the alluvium that infills current valleys. The alluvium consists of stratified but unconsolidated sands to silts and clays formed by the erosion and re-deposition of the adjacent rock units (Evensen, 1997).

3.3.3 Hydrostratigraphy and Hydrostructure

Variations in stratigraphy and lithology, including grain-size and primary porosity, are used to delineate hydrostratigraphic units. A hydrostratigraphic unit is the term used to describe the grouping of geologic units based on similar hydraulic properties. Grouping units in this manner allows for a simplification of the geologic setting into layers that suitably describe the components that are important for the analysis of groundwater flow. This approach also lends itself to development of groundwater flow model layers.

In fractured-rock environments, the occurrence of secondary porosity features such as fractures and joints is important to the hydrogeologic system. At the SSFL, the occurrence of fractures and joints are estimated to increase the bulk hydraulic conductivity of the Chatsworth Formation sandstone by an order-of-magnitude or more (MW, 2000). Hydrostructure refers to the nature of the secondary porosity or other features that may influence groundwater flow (e.g. fracture intensity, aperture, orientation, fault occurrence) within a particular geologic unit. A group of geologic units exhibiting similar hydrostructure belong to the same hydrostructural unit.

Hydrostructural units may exist as sub-domains of a single hydrostratigraphic unit or may crosscut multiple hydrostratigraphic units. For example, if fracture intensity is sufficiently greater in one section of a formation than another, such that groundwater flow characteristics would vary, then the single hydrostratigraphic unit (same lithology and primary porosity) could be divided into two hydrostructural units. Alternatively, a larger-scale structural feature may crosscut a number of hydrostratigraphic units, particularly where such features are perpendicular to strike, as in the case of some faults. If the hydraulic properties within such a feature are similar along the entire length of the structural feature, then it can be defined as a separate hydrostructural unit. Where fracture properties vary along the length of the structural features, regardless of whether single or multiple hydrostratigraphic units are crosscut, multiple hydrostructural units may be defined to describe a change in groundwater flow properties attributed to such features. Variation in fracturing is observed at SSFL, and it locally modifies permeability.

The SCM (MW, 2000) describes five groundwater units that are created by the presence of fine-grained units and faults at the SSFL (Table 4). These groundwater units may be composed of one or more hydrostratigraphic and hydrostructural units. Groundwater units are laterally bounded by a fault or shear zone hydrostructural units. The base of each groundwater unit is bounded by the underlying fine-grained member.

In developing RSCM, the specification of hydrostratigraphic and hydrostructural units throughout the study area allowed a model to be developed based on the hydraulic properties of each unit. This type of information is provided by the descriptions accompanying the geologic mapping (Dibblee, 1992; MW, 2000). Figure 6 summarizes the regional hydrostratigraphic units identified in the study area. Regionally, each formation has been assigned to a hydrostratigraphic unit based on its equivalent porous media properties.

Subsurface investigations by GWRC (2000), Haley and Aldrich (2000), Montgomery Watson (2000) and the University of Waterloo (2003) indicate that interconnected fracturing of the matrix is present within all units found beneath the SSFL. However fracture intensity, porosity and aperture sizes are variable. A literature review by MWH shows that existing interpretations suggest that there are three hydrologically significant zones within and adjacent to faults (Appendix E). At the regional scale it is assumed, based on large head differences across faults that regional faults generally act as low permeability features. A discussion of the three hydrologically significant zones is more appropriately addressed at the mountain scale.

3.3.4 Hydraulic Conductivity

Hydraulic conductivity is a property that can vary considerably between, and within, hydrostratigraphic and hydrostructural units. Values can be estimated from pumping tests and/or by using typical literature values and knowledge of the hydrogeologic environment. Table 5 presents the estimated bulk hydraulic conductivity values for each of the regional hydrostratigraphic and hydrostructural units. These values are derived from a number of reports that were reviewed as a part of this study. References used for each value are cited at the end of Table 5. In the RSGFM, a bulk conductivity value is assigned to each defined hydrostratigraphic unit based on the identified range and is adjusted during calibration to better reflect observed conditions. The available information was limited for fractured rock units to general literature ranges for each unit (Freeze and Cherry, 1979).

3.3.5 Precipitation and Recharge

Haley and Aldrich (2000) report that annual precipitation averages about 19 inches (482 mm) at the SSFL with the lowest rainfall being 6.2 inches (157 mm) in 2002. Within the entire study area average annual precipitation varies between 12 and 23 inches (305 and 584 mm) as illustrated in Figure 9 (CaSIL, 1997). This variation is largely due to orographic effects and the proximity of the study area to the Pacific Ocean. Local measurements of infiltration made using lysimeters in the northwest portion of the SSFL indicate even lower amounts of recharge, although the local area where the measurements are being collected has been modified through the engineered placement of lower permeability backfill (Shaw Environmental, 2006).

Groundwater recharge from precipitation provides the driving force for groundwater flow at the SSFL. The portion of precipitation that recharges the groundwater system depends on a number of factors including the infiltration capacity and permeability of the surficial material, land surface slope, and vegetation types and density. All of these factors including precipitation vary throughout the study area.

MWH (2003) provides a detailed analysis of groundwater recharge at the SSFL that uses multiple methods to provide estimates of recharge at the site. This report estimates 20-100% of precipitation is lost to evapotranspiration while actual recharge to groundwater accounts for 0.17 to 10% of the precipitation (using the chloride deposition method, MWH, 2004).

The chloride balance method indicates that recharge through the sandstone at the SSFL is approximately 6% of precipitation; a water balance estimate suggests that this value could be as high as 10% of precipitation. The recharge through the fine-grained units was estimated to be 0.4% (MWH, 2003), which is expected given the lower average hydraulic conductivity of the units. A 1:1,000,000 scale digital map of average long-term (30 year) precipitation was acquired from the California Spatial Information Library. This map was merged with the regional geologic maps to develop the recharge map shown in Figure 10. This figure illustrates the recharge distribution that results when the recharge is calculated as a percentage of precipitation based on the hydrostratigraphic units. The recharge distribution shown assumes 6% of precipitation is recharged through the sandstone units and 0.4% through finer grained units. Figure 10 does not distinguish recharge for hydrostructural units, except along mapped faults where recharge is prescribed to be zero. At the regional scale, modification of recharge using variations in vegetation and hence in evapotranspiration (ET) is not considered necessary as the number already considers ET based on MWH (2003).

3.3.6 Surface Drainages, Seeps and Springs

The available regional data shows that few surface water features are perennial within the regional study area. In less arid environments perennial stream flow is often sustained by groundwater discharge during dryer seasons (summer) and contributes to the total stream flow during wetter seasons. Perennial streams, where present, represent key boundaries to a local and possibly more regional groundwater flow system. At the SSFL perennial streams do not exist, but to the south of the site Malibu Creek appears to flow year round suggesting that a portion of the flow is derived from local groundwater discharge. Most drainages are dry for the majority of the year, with flow occurring during rainfall events composed primarily of runoff rather than groundwater discharge. However, a number of perennial seeps and springs have been mapped on the slopes of the Simi Hills (MWH, 2003) and the Santa Susana Mountains (Dibblee, 1992). Seeps and spring features are observed or mapped in areas where groundwater emerges at topographic lows in the ground surface, or due to the pinching-out of geologic units along bedding planes or at locations of faults.

The mapped locations of seeps and springs shown in Appendix C are considered incomplete for the regional study area (MWH, 2003). From the water balance perspective the discharge of groundwater to the seeps and springs can be correlated with recharge rates, and other water balance components (e.g. pumping) to evaluate the discharge location of groundwater recharged in the Simi Hills. The current seeps and springs observations highlight some of the potential groundwater discharge locations, but based on this information alone it is unclear what portion of recharge from SSFL discharges to seeps and springs.

3.3.7 Depth of the Active Groundwater Flow System

Regional data derived from oil and gas wells used in the Ventura Basin Study and reinterpreted for this study (Appendix D) show that the depth of fresh groundwater in the regional study area varies significantly from one location to another (Figure 11). The depth to the base of the fresh water zone is thought to be controlled by topography and local geologic structure. The presence connate water, brackish or saline groundwater incorporated into the formation at the time deposition in marine environments, at depth suggests that groundwater flow conditions at depth are relatively slow. Areas of relatively slow groundwater movement are not considered part of the near surface groundwater flow system, and such observations are typically used to identify the boundary of the freshwater flow system.

Interpretation of oil and gas well geologic and geophysical logs provided estimates of the depth to the bottom of fresh groundwater (freshwater) zone (defined as total dissolved solids TDS < 2500 mg/L); the bottom of brackish groundwater zone (defined as TDS from 2500 to 10,000 mg/L); and the top of the saline groundwater zone (defined as TDS >10,000 mg/L). These data indicate that elevated TDS values in groundwater are typically found at elevations above sea level within the valleys of the regional study area (Figure 11). Based on sampling of porewater beneath the SSFL groundwater salinity is considered low to depths greater than 900 feet or 275 m (SSFL is approximately 1800 ft asl). At greater depths salinity is expected to increase based on data from the surrounding areas (Cherry et. al., 2007).

The persistence of saline water at depth is related to the sluggish rate of flow of fresh groundwater by recharge. The salt and brackish groundwater found at depth reflects the conditions at the time of deposition of the Chatsworth Formation (65 million years ago) and other formations in a saline sea environment. Subsequent uplift (approximately one to five million years ago) of these units and the commencement of recharge of fresh water via precipitation has flushed the sea water from the shallower zones. The contrast in density due to the higher salinity of water at depth, and the mapped location of the regional depth (or elevation) of saline water, suggests that the freshwater flow system is active to a depth near sea level (100 meters (300 ft) below sea level to 275 meters (900 feet) above sea level). Below this depth little mixing with fresh groundwater occurs such that groundwater recharge is not expected to penetrate much deeper than sea level at or in the areas adjacent to the SSFL. Therefore, sea level represents a reasonable bottom boundary to the groundwater flow system. This generalized depth is being evaluated further in on-site studies of water quality (Cherry et. al., 2007).

3.3.8 Groundwater Use

Within the regional study area the most common use for groundwater is for domestic supply for the few homes that exist outside the alluvial valleys. Historically groundwater pumping occurred in the Simi Valley for irrigation that significantly lowered groundwater levels in the alluvium in the 1950s and 1960s (Evensen, 1997). When irrigation use was reduced groundwater levels in the alluvium recovered and some dewatering was necessary in the west end of the valley where artesian conditions developed.

Groundwater was pumped at the SSFL as early as 1949 for use for use in operations. Groundwater pumping on-site was greatest in the 1950s and 1960s, and pumping ceased in the early 1960s when water started to be imported to the site. In the 1980s pumping recommenced at a number of locations (Table 8). At date of this report on-site pumping occurs at the well labeled as WS-9A.

From a water balance perspective, on-site groundwater extraction removes a large portion of the local groundwater recharge. In the late 1990s it was estimated to be up to 30% of the average recharge (section 3.5.5). The domestic use of groundwater off-site is considered non-consumptive (returned back through septic systems) and is likely to be on the order of 400 gallons/day/household for those locations using groundwater outside of the alluvial valleys. The rate of groundwater pumping from the dewatering wells in Simi Valley is on the order of 1290 gpm (Evensen, 1997).

3.4 REGIONAL GROUNDWATER FLOW MODEL

A Regional Scale Conceptual Model (RSCM) of groundwater flow was developed from the various sources of information that included the topography, geology, precipitation, water level measurements and withdrawals. The preceding sections provide a summary of the general occurrence of groundwater and the hydraulic properties of the subsurface and provide insight into the general regional water balance. However, the available information is not sufficient to constrain the understanding of the groundwater flow system and water balance such that boundaries can be defined for the Mountain Scale Groundwater Model (MSGFM). Therefore a Regional Scale Groundwater Flow Model (RSGFM) was developed to be used interpretatively and to evaluate the following:

1. Physical boundaries to the mountain scale groundwater flow system;
2. The influence of formation-level geologic conditions, and regional faults on water levels; and

3. Refinement of the regional groundwater balance.

Development of the RSGFM began in 2003 and was developed based on the available regional off-site information, which was sparse, as well as cross-sectional projections of stratigraphy and structural features. As a result, detailed interpretation of the regional and local flow systems was not possible and the development of the RSGFM served to guide additional data requirements for the MSCM. For example during the RSGFM development questions arose regarding the role of seeps and springs in groundwater discharge as well as the effective depth of the freshwater flow system (Appendix D and Appendix B).

The following sections summarize the formulation, input, results and interpretations of the regional groundwater flow modeling. Additional representations of the systems were achieved that may also reasonably represent the system using different combinations of freshwater system depths, hydraulic conductivities and variations in recharge. However, the simulation summarized below provides the best general representation of the RSCM and provides appropriate physical boundaries for the MSGFM. A more detailed summary of the RSGFM, input parameters and calibration is contained in Appendix C: Summary Presentation of Regional Groundwater Flow Model.

3.4.1 RSGFM Structure and Properties

The RSGFM domain area is show in Figure 1. The model is subdivided into 22 layers (23 slices) and consists of 3,168,946 elements and 1,662,509 nodes (Figure 12). The variable elevations of each of the slices that define the top and bottom of each layer follow the interpreted elevations of the top and bottom contacts of each formation mapped in the model domain (Figure 7 and Appendix C). The elevation of slice 1 varies according to the topography mapped using a 10 meter digital elevation model (USGS, 2001). A constant hydraulic conductivity was assigned to each model layer representing the properties of the formation as listed in Table 5. The model input was assigned based on the available field information and adjusted within physically reasonable bounds and literature values (e.g., range of hydraulic conductivity).

3.4.2 RSGFM Boundary Conditions

Boundary conditions applied in the RSGFM included recharge to the groundwater system and specified head boundary conditions along selected edge and surface nodes to allow flow interchange with the surrounding environment. On-site and off-site pumping were also incorporated. The recharge distribution shown in Figure 10 was mapped onto the top slice of the model representing the recharge flux at the water table. Specified-head boundary conditions were assigned at nodes in the mesh with an elevation equal to the ground surface elevation at the location of original mapped seep and spring locations (MWH, 2003) (Appendix C).The groundwater elevation was also specified along sections of Malibu Creek in the southern portion of the model domain in locations of mapped perennial stream flow. On the borders of the model domain groundwater elevation was specified based on the general depth to groundwater where the model domain intersected the alluvial valleys (Appendix C) (Evensen, 1997). At depth groundwater elevations were specified along the east and west borders of the model reflecting estimated depth to groundwater from available wells and through model simulations (Appendix C).

On-site pumping and dewatering in Simi Valley were simulated in the RSGFM. Pumping rates for the 13 well locations thought to be dewatering wells in Simi Valley were each prescribed a rate of 150 to 200 m^3/d (~28 to 37 gpm), a total of up to 2600 gpm. Other wells thought to be potentially active pumping wells were prescribed at a rate of 150 m^3/d (~28 gpm). These pumping rates were estimated from previous model runs based on the ability of the system to reduce the artesian heads in the Simi Valley; actual pumping rates were not available at the time. Subsequent information from Evensen (1997) indicated that the total average pumping rate in 1994-95 is approximately 1290 gpm from six wells dewatering wells. The effect of the increased simulated extraction rates relative to that reported in the literature is expected to have minimal affect on the MSGFM. This expectation is based on the fact that the lateral boundary of the MSGFM domain is distant from the majority of the Simi Valley dewatering wells and that the total simulated pumped volume can be derived from direct recharge to Simi Valley.

On-site pumping was simulated by specifying the pumped water level at each pumping well based on average monitoring data from the 1990s.

3.4.3 RSGFM Simulation Approach

The RSGFM was designed to simulate average annual (steady-state) groundwater flow. It is not considered to represent a given year however it is intended to represent long-term flow conditions.

The model was considered representative when a regional model was developed that could reproduce the observed shallow water table in the Simi Hills, appropriately represent effects of estimated pumping, predict seepage discharge at most known locations, and be based on input parameters considered representative of the data and literature values. This generalized approach provided one representation of the regional groundwater flow system.

3.4.4 RSGFM Simulation Results

Figure 13 shows a plan view and fence diagrams of groundwater levels simulated in the RSGFM. In general water levels are highest in the Santa Susana and Santa Monica Mountains. Water levels at the SSFL are at a higher elevation (~500 m asl) than the surrounding valleys (~200 m asl – Simi Valley). Regional faults that were simulated in the model show significant head differences across the faults from the upgradient to downgradient sides in both plan and fence views. Horizontal gradients (plan view) and vertical gradients (fence view) are greatest across fine-grained units (i.e. those with lower permeability) such as the Llajas Formation.

In both the 2D plan view and 2D fence projections of the three-dimensional water levels, groundwater equipotentials indicate flow is from the highland areas to the valleys (Figure 13). While three-dimensional path of groundwater originating at a given location cannot be traced using these diagrams (they only show slices through the system that are not necessarily aligned along flow paths) they do provide insight into the flow system. Groundwater equipotentials viewed in plan view indicate groundwater flows out of the model domain through the west end of the Simi Valley alluvium, and flows east through the San Fernando alluvial valley. In addition, groundwater appears to leave the model domain through Malibu Canyon in the south.

Figure 14 presents a summary of the regional water balance simulated using the RSGFM. The groundwater flow quantities are presented as a percentage of the total recharge to the regional model domain which is estimated to be 45,000 m^3/d (8255 gpm) or on average 18.7 mm/year (1.04 inches per year) or 5-6% of average regional precipitation. The following lists the key water balance quantities:

- ~10% of the groundwater recharge discharges by groundwater pumping
- ~6% of groundwater recharge discharges through the west end of the Simi Valley Alluvium
- ~22% of groundwater recharge discharges through the east end of San Fernando Valley Alluvium
- 0% of groundwater recharge flows out the west side of the model through the bedrock
- ~11% of groundwater recharge flows out of the east side of the model through bedrock
- ~30% of groundwater recharge flows out through Malibu Creek
- ~21% of groundwater recharge discharges to the simulated seeps and springs

Note: All water budget quantities are referenced as a percentage of the volume of recharge to the entire modeled area.

The regional water balance presented above is considered reasonable as the model uses physically based input parameters and provides a three-dimensional representation of the hydrogeologic system, including key features expected to control groundwater from (the variation in hydraulic conductivity and thickness of formations, the influence of dipping beds and low permeability faults).

3.4.5 Groundwater Flow System Boundary for the SSFL

The RSGFM output was used to help define the MSGFM domain and establish physically-based boundary condition values for the edges of that domain. The simulated water levels from the RSGFM provided physically realistic groundwater elevations for boundary condition values along the border of the MSGFM (see Figure 1 for location). Recognizing that seeps and springs are important groundwater discharge locations, the MSGFM model domain was designed to incorporate those features. To accommodate the seeps, the more detailed mountain scale study area was extended to the edge of the alluvial valleys and major drainages surrounding the site (Figure 1). The design of the MSGFM area facilitates more-detailed simulation of flow to the valleys and discharge to seeps and springs. Additional descriptions of how the boundaries for the MSGFM were selected are found in section 4.2.3.

Fluxes across the boundaries of the MSGFM are summarized in Figure 14 and are later used for general comparison at the same location in the MSGFM. The water balance for the mountain scale area computed using the RSGFM indicates that 60% of the recharge within the MSGFM area flows to surrounding valleys (see Figure 14 for details). The remaining 40% is discharged to seeps, springs and pumping wells on-site. It is also noted that 28% of the simulated recharge within the MSGFM domain is computed to originate in the on-site area, which is less than the 40% computed to discharge at seeps, springs and on-site pumping wells.

3.5 MOUNTAIN SCALE CONCEPTUAL MODEL

The following section summarizes the current Mountain Scale Conceptual Model (MSCM) that has evolved through the characterization and modeling work at SSFL to date as it relates to groundwater flow. Maps, tables, and descriptions are used to summarize the current interpretations of each component developed by the Study Team. Details of each of the components of the MSCM are referenced and can be found in other documents for the SSFL and in appendices to this report.

3.5.1 Mountain Scale Geologic Setting

The mountain scale study area occupies the central portion of the regional study area (see Figure 1). The area encompasses the Simi Hills, extending from the site to San Fernando Valley/Box Canyon in the east, Simi Valley in the north, Runkle/Las Virgenes Canyon in the west and Bell Canyon in the south.

The SSFL, located in the approximate center of the mountain scale study area, occupies approximately 2,850 acres of hilly terrain that expresses approximately 335 meters (1,100 feet) of topographic relief near the crest of the Simi Hills. The highest surface elevation at the SSFL occurs near the center of the site at an approximate elevation of 684 meters (2,245 feet) above mean sea level (msl). The highest surface elevations at the SSFL occur along two general ridges that trend northeast-southwest, consistent with the geology of the Chatsworth formation that is described in this section.

The lowest elevation within the SSFL occurs at the eastern property boundary in Dayton Canyon and has an elevation of approximately 358 meters (1,175 feet) above msl. The lower elevations at the SSFL occur primarily along the eastern, southern and north-central to northwestern perimeters of the property. A broad, relatively flat area of topography exists within the northwestern portion of the SSFL and is referred to as the Burro Flats area. Most of the operational areas used at the SSFL were positioned in lower topographic areas, below the ridges formed by certain stratigraphic units of the Chatsworth formation.

A Mountain Scale Conceptual Model (MSCM) was developed to represent groundwater flow at the mountain scale. This model was framed within the previously developed RSCM and the results of the RSGFM. In contrast to the RSGFM the MSCM documents more geologic and hydrogeologic complexities present within the SSFL and adjacent area. As with the RSGFM, the complex discrete fractures and porous blocks of rock are represented as equivalent porous media. The flow data and analyses developed in the Site Conceptual Model (SCM) for the SSFL (MW,2000; and Cherry et. al., 2007) provided much of the flow characterization understanding that was incorporated into the MSCM.

The geologic setting of the mountain scale model area is indicated in Figure 15 (after Dibblee,1992). Additional site geologic data were derived as part of the development of the SCM (MW, 2000). The geologic mapping completed to refine the conceptual models is most detailed within and adjacent to the boundaries of the SSFL. Detailed mapping was extended off-site to provide a continuous interpretation of the system to physical geologic boundaries (MWH, 2007a). The extent of this detailed mapping helps complete interpretations of on-site conditions, and to reconcile regional mapping by Dibblee (1992) with on-site interpretations. The areas of specific focus outside the site boundary include the Eastern Simi Hills, east of Black Canyon and Woolsey Canyon Roads, as well as the area directly north of the site into the Brandeis-Bardin property (MWH, 2007a). This additional mapping indicated that all of the operational areas of the SSFL are underlain by the Late Cretaceous marine turbidites of the Chatsworth Formation.

As described by MWH (2007a), the sandstone is interbedded with finer-grained units composed of thin-bedded sandstone, siltstone and shale. The finer-grained units comprise only a small percentage of the total thickness of the Chatsworth Formation. Individual turbidite sandstone beds are lenticular, typically less than 2 meters (6.5 feet) thick and have a lateral extent of as much as 1000 meters (3,280 feet). Although individual sandstone beds are less than 2 meters (6.5 feet) thick, in most areas the sandstone beds are not separated by finer-grained units. This commonly results in sandstone units that are tens of meters thick, with little or no finer-grained interbeds.

At the SSFL, the Chatsworth Formation was divided into stratigraphically upper and lower units by MW (2000). The Lower Chatsworth Formation is located in the eastern and southern portions of the site (Figure 16) and is differentiated from the Upper Chatsworth Formation by an increase in the proportion of fine-grained units in the stratigraphically highest parts of the Lower Chatsworth. Although variable in thickness, many of these finer-grained units can be traced along strike throughout the Chatsworth Formation outcrop in the Simi Hills. The recognition of these laterally continuous, finer-grained units permits the Upper Chatsworth Formation to be subdivided into several members as shown in Figure 15. The members have been mapped across the site and are observed to vary in thickness and are often offset vertically across faults.

The Chatsworth Formation strikes approximately N70E and dips approximately 25 to 30o to the northwest as part of an anticlinal limb. The southeast limb of the anticline has been eroded. The Chatsworth Formation is bounded on the northwest by sediments of the Simi Formation, and to the west and south by the Burro Flats Fault. To the south of the SSFL, late Tertiary stratigraphic units lie unconformably on the Chatsworth Formation. These late Tertiary units dip southward (Figure 7, Figure 15 and Figure 16) and infill a younger basin that formed following erosion of the southeast dipping limb of the older anticline.

Alluvium has been mapped on-site (Figure 17) and is generally 0.5 to 5 meters of silty sand. In some developed areas on-site, the fill thickness is up to 10 meters thick. Off-site, alluvium is found along drainage pathways and topographic lows (MWH, 2007a), the extent of which is not well mapped, but is represented in Figure 15.

Fracturing of the deposits is observed in both rock cores and outcrops. The fractures are ubiquitous and commonly oriented parallel to bedding or they are steeply dipping joints some of which cross-cut bedding planes (Cherry et al., 2007). Observations of the fracture network in core, downhole geophysical logs, outcrop, and on aerial photographs indicate an interconnected fracture network at multiple scales (MW, 2000). Measurements of fracture frequency, orientation, and spacing have been undertaken at multiple scales using aerial photographs, outcrop mapping, and core analysis. Two dominant fracture orientations were observed in outcrop; bedding parallel and bedding perpendicular (MWH, 2007a).

The pattern of regional faulting has also been mapped at the mountain scale. The near-vertical faults generally strike in a northeasterly direction. A number of fault structures cross-cut and offset members of the Chatsworth Formation (Figure 2). At SSFL, geologic features are classified into three types:

- Fault/fault zones – narrow zones long-enough to be mapped, usually main failure planes
- Deformation bands – wider zone (100 + feet) composed of multiple small offset failure planes
- Structures – antiform and synforms, ridges and valleys on-site

Each of the above classifications exhibits some degree of vertical displacement. A full description of each type of structure can be found in MWH (2007a). All three types of structures are identified and mapped either through aerial photograph interpretation and field mapping or both. The majority of faults in the study area are near vertical (>70^o) and are approximated as being vertical in the numerical model. The vertical offset of geologic members is evident on Figure 15. In zones of deformation bands (widths up to 800 feet), the total measured vertical offset is equivalent to the displacement on a fault that is less than 1-2 feet wide. The vertical offset in the deformation bands is translated via smaller displacements of individual fractures in the zone rather than a single trace.

Gouge is commonly present in fault zones, and in some cases increased fracturing is present adjacent to the gouge. The Shear Zone is a structure that exhibits significant fracturing. It extends from near the southern boundary of the site, northeastward to the Santa Susana Pass Fault Zone (see Appendix E). It has a width of 5 to 15 meters, and shows significant gouge and fracturing. Diabase dikes locally intrude the Shear Zone (MWH, 2007).

The geologic model depicted in Figure 17 represents the three-dimensional spatial relationship of each of the units within the mountain scale area. The three-dimensional geologic framework was developed from available literature, field mapping, drilling and interpretation primarily supported by Cherry et. al., 2007, and MWH, 2007a. Figure 18 shows selected cross-sections through the three-dimensional hydraulic conductivity distribution of the MSGFM; the difference in color reflects the sandstone and siltstone/shale units incorporated in the model. Appendix F presents the detailed methodology used to construct and calibrate the three-dimensional geologic framework model of the mountain scale study area which is reflected in Figure 17 and Figure 18.

3.5.2 Hydrostratigraphy and Hydrostructure

Three types of hydrostratigraphic units have been identified for the MSCM based on grain size and the estimated ability to transmit groundwater flow:

- Alluvium - aquifer
- Sandstone/Conglomerate Fractured Rock Members -aquifer
- Shale/Siltstone Fractured Rock Members – aquitard

Subsurface investigations by GWRC (2000), Haley and Aldrich (2000), Montgomery Watson (2000) and the University of Waterloo (2003) suggest that interconnected fracturing is present within all units found beneath the SSFL (MW, 2000); however fracture intensity, porosity and aperture are variable. Three hydrostructural units have been defined and mapped at SSFL (Figure 15) based on this variability as follows:

- Fault/fault zones - disturbed zone surrounding a fault, where fractures are often in-filled with fault gouge;
- Deformation bands - with minor offsets, within a thin cataclastic zone, in zones up to 800 feet wide,
- Protolith - areas outside of the above units that exhibit an interconnected fracture network but no vertical offset or characteristics associated with faulting.

A hydrostructural unit may cross-cut more than one hydrostratigraphic unit. Within fault and deformation band units, the fracturing is thought to be in-filled with gouge that results in similar hydrogeologic properties within sandstone and shale units. Variations in fracture characteristics appear to depend more on the spatial location, local geologic history and local tectonic forces (e.g. fracture spacing is greater stratigraphically above Shale 2) (MWH, 2007a).

Fracture apertures within each of the hydrostructural units are also interpreted to close with depth due to increased pressure with depth from the weight of the overlying rock, resulting in a reduction in fracture porosity and fracture hydraulic conductivity. A relationship describing fracture closure with depth was developed using data from core samples at the SSFL. The results of this analysis are provided in Appendix G. Figure 19 shows an estimated relationship between fracture closure and depth for both sandstone and shale at SSFL. Due to the lower compressive strength and joint strength in shale, fractures are expected to close more quickly than for sandstone.

3.5.3 Hydraulic Conductivity, Porosity and Storage

Hydraulic conductivity and storativity measurements of both the matrix and bulk rock units (matrix and fractures) have been made at various locations at the SSFL (MWH, 2007; Appendix H). These values reflect estimates of fracture hydraulic conductivity and bulk hydraulic conductivity values. Additional bulk conductivity and storage estimates of units outside the site (e.g. Simi Conglomerate) are derived from literature values (see RSCM).

Hydraulic conductivity and storage at the SSFL varies with the type of rock matrix (sandstone vs. shale) and the nature of the secondary porosity (fracturing). Hydraulic properties of geologic members can be measured in the field or lab using core tests or downhole geophysics to estimate matrix properties and pumping tests to estimate bulk properties. Appendix H summarizes the results of hydraulic conductivity testing at SSFL where all of the above mentioned methods were applied at locations across the site. Saturated storage values were also computed for a variety of pumping tests (MW, 2000).

In a layered sedimentary system, the bedding-perpendicular hydraulic conductivity is generally lower than the bedding-parallel conductivity due to stratification that occurred during deposition. This feature is referred to as anisotropy. Although it has not been well quantified at SSFL and additional testing is unlikely to reduce the uncertainty in site-specific values, anisotropy is thought to exist because of the layering of sandstone and siltstone/shale beds that is typically observed in core holes (also typical for a turbidite deposit). The anisotropy value could not be uniquely quantified with the available pumping test information, but is conceptualized to be in the range of 50:1 to 100:1 for sandstone units (due to the high frequency of shale interbeds within the sandstone members) and 10:1 for shale units (see Appendix L).

Most faults at SSFL are assumed to have conductivities less than or equal to those of the shale units. Head differences of up to 100 meters are observed across the shear zone, thus indicating low conductivity for fault features. Hydraulic properties of faults are not measured directly, as they are of limited thickness compared to the geologic members. Indirect evidence is used to infer the range of properties for faults and deformation bands. Within faults, hydraulic conductivity depends on the fracturing and whether or not the fractures are in-filled by gouge. MWH identified two hydraulically significant zones that may exist within and adjacent to faults (MWH, 2003). There is commonly a zone of fine-grained gouge in the middle part of a fault. This gouge is finer-grained than adjacent rocks, and typically creates a relatively low permeability zone. One fault area where gouge has not been observed occurs along the east-west trending section of the North Fault which is simulated with a moderate hydraulic conductivity. Adjacent to the gouge a damaged zone may exist that is characterized by increased fracturing and the absence of gouge. Both of these characteristics can increase the permeability of the damaged zone when compared to that of the gouge-filled fault, and perhaps undamaged rock adjacent to the fault. To date this damaged zone has only been observed in relation to the IEL fault through field observations and interpretation of pumping test responses. In Table 6, the range of conductivity and storage presented for the faults is estimated based on observed hydraulic responses and the hydrostratigraphic and hydrostructural characteristics of each.

In a fractured-rock environment, porosity is a reflection of both the spacing between matrix grains and fracturing. At the SSFL, matrix porosity is on average 13%; sandstone porosity ranges from 11 to 16% and shales from 6 to 11%. Fracture porosity is estimated to range from 0.0005 to 0.01% based on fracture spacing and a hydraulic aperture of 50 microns (MW, 2000). The matrix porosity (and therefore storativity) is three to four orders of magnitude greater than the corresponding fracture porosity. The hydraulic conductivity is expected to decrease with depth due to a reduction in fracture apertures with depth as a result of an increase in the lithostatic load of the rock mass.

Figure 20 and Table 6 summarize the bulk hydraulic conductivity values for each geologic member and fault zones at the SSFL compiled from field measurements and literature values. The values are presented as ranges reflecting the complexity of the system and variation in rock parameters locally. The range of properties for a given member or fault are generalized from available on-site data. Where measurements were not available, values have been inferred based on the geologic description of the unit and comparison with a similar unit within the same hydrostratigraphic or hydrostructural grouping. In the MSGFM, bulk hydraulic conductivity values are assigned to each member based on the range of values and any location-specific data. The hydraulic conductivity of a member may vary from location to location (e.g. in different fault blocks) and this will be reflected by assigning different bulk hydraulic conductivity values in each area.

3.5.4 Precipitation and Groundwater Recharge

In the MSGFM, the distribution and magnitude of recharge is refined from the RSCM. Recharge is known to vary spatially due to variations in precipitation, hydrostratigraphy, hydrostructure and slope. Figure 9 shows the average annual precipitation within the regional scale area. Regional precipitation is shown to vary from 15 to 18 inches annually (30 year mean) (CalSLib, 1997) due to topographic effects. On-site the precipitation ranges from 18 to 22 inches annually (MWH, 2003) and water content of the unsaturated zone is estimated at 70-80% (MW, 2000). The average on-site recharge to the Chatsworth Formation was estimated to be about 6% of precipitation using the chloride mass balance method (MWH, 2003), but could vary from 2% to 12% when uncertainties are considered.

The MSCM refines the recharge representation by considering lithological variations in surface outcrops, land surface slope and the distribution of precipitation as controls on the distribution of recharge. Based on these conditions a set of rules were developed for estimating the spatial distribution of recharge in the mountain scale area. The rules are presented in Table 7 and were developed using basic hydrologic principles that apportion a higher recharge rate to more permeable units where the ground surface is flatter. Lower values were applied in regions with higher slopes and less permeable units. The rules were validated by computing the on-site average annual recharge rate and adjusting the rules to match the range determined by MWH (2003). The resulting recharge map for the mountain scale area is shown in Figure 21. The mapped average on-site recharge is 7% of precipitation using the rules based approach. The recharge distribution shown in Figure 21 was adjusted during model calibration as local variations in recharge and slope were evaluated in the context of the hydrogeologic properties, including hydraulic conductivity. The recharge map presented in the model calibration section (Figure 28) reflects the modifications following calibration of the MSGFM. The rules of recharge were modified in local areas where additional information exists.

3.5.5 Water Levels, Groundwater Flow and Discharge

Contour maps of the water table are created as part of the monitoring program at SSFL. Water table maps of observed data are shown in Figure 22 and Figure 23 for the spring sampling periods in 1998 and 2004. These water table maps were created by contouring point water levels for the Chatsworth Formation wells from which depth to water measurements were made as part of the monitoring program at the SSFL (Haley & Aldrich, 1998; 2004).

These maps highlight a number of features of the groundwater flow system:

- The shallow depth to the water table in the Simi Hills despite the low recharge;
- The existence of larger horizontal gradients across faults;
- Large horizontal gradients are also observed across shale units;
- Smallest horizontal gradients are associated with the most transmissive units (sandstone and alluvium);
- Pumping depresses groundwater levels, with the most obvious areas within the central portion of Sandstone 1; and

- Water level contours change depending on the rate and location of pumping (as can be seen by comparing 1998 and 2004 maps of water levels).

Due to the complexity of the geology and groundwater flow system it is difficult to contour potentiometric maps for each hydrostratigraphic unit. Thus, the standard two-dimensional water table contour maps do not provide sufficient information to understand the following:

- groundwater levels/flow directions outside of the observation points;
- groundwater velocities and travel times;
- the three-dimensional groundwater flow paths from any recharge location; and
- flow directions beyond the site.

The current understanding of groundwater flow off-site is derived from water level information from off-site wells, the RSGFM, and mapping of groundwater discharge locations (seeps, springs and phreatophytes) (MWH, 2003). The mapping of seeps has been expanded since the development of the RSGFM (reflected in Figure 24) within the mountain scale model area and are interpreted to represent potential discharge locations for groundwater. *Appendix I: Technical Memo: Consumption of Groundwater Around the Santa Susana Field Laboratory by Phreatophyte Vegetation* represents an additional refinement to the understanding of groundwater discharge by assessing the influence of phreatophytes on groundwater discharge. Figure 24 shows a current map of the seep and phreatophyte locations. Shallow groundwater is associated with this plant type and the vegetation directly uses groundwater in its growth process (transpiration of water). Estimates indicate that groundwater discharged by phreatophytes mapped in the mountain scale area is on the same order as seep discharge. MWH (2004) estimated that the total discharge through seeps and phreatophytes is about 817 m^3/d (150 gpm).

Groundwater also leaves the mountain scale area through groundwater pumping on-site which has been estimated to have had an annual rate as high as 1580 m^3/d (290gpm) in the past. Pumping has the effect of depressing water levels and modifying groundwater contours. Modifications of groundwater flow directions due to pumping can be observed by comparing Figure 22 and Figure 23 in the Sandstone 1 area where local water level contours have changed due to the pumping conditions. A summary of the extraction well locations and the average pumping rates are listed in Table 8.

The base of the active freshwater groundwater flow system has been conceptualized to coincide with the depth at which salinity and density of groundwater elevated (see RSCM section 0). The elevation of this boundary is expected to vary and is estimated to be at approximately sea level. This limit to fresh groundwater circulation is based on the interpretation of groundwater salinity data from oil and gas wells in the region (Appendix D).

The following section describes how the MSCM is represented in a numerical model to provide a means for evaluating site-specific three-dimensional groundwater flow.

4.0 Mountain Scale Modeling

The intended uses of the calibrated MSGFM are to evaluate site-specific groundwater flow at the SSFL as well as to evaluate the various geologic / hydrogeologic conceptualizations (such as recharge rates and distributions and the high or low transmissive properties of faults at the site). These simulations will enhance the understanding of groundwater flow and potential flow paths from SSFL, as well as assist in identifying and ranking knowledge and data gaps.

The Mountain Scale Groundwater Flow Model (MSGFM) described herein is a three-dimensional numerical model that represents the "state-of-the-practice" in groundwater model development. The model was initiated in December 2005 following development of the RSGFM. The development of the model included significant effort to translate the complicated three-dimensional multi-layered faulted and fractured MSCM model into an EPM numerical model. Recognizing that uncertainty is inherent in the characterization of the subsurface a number of representations of the system were tested through the calibration process. A preliminary discussion of the key uncertainties in the understanding of site-specific groundwater flow is presented in Section 6. A formal sensitivity and uncertainty analysis is currently underway that will document model sensitivity and uncertainty in identified site-specific groundwater flow, the results of which will be communicated in a separate report.

In constructing the detailed MSGFM, data were utilized (such as measured water level, stratigraphic, topographic, and rock properties) as described in the Mountain Scale Conceptual Model (MSCM). Additional detail (member level) was incorporated at this scale as compared to the regional scale representation (Figure 25)

Once constructed, a model must be "calibrated" to observed field conditions to provide confidence that the model predictions are representative of natural conditions to the greatest extent possible. The process of model development and calibration of the MSGFM is more rigorous than the approach taken in developing the RSGFM. During this model calibration process, physical parameters (e.g. hydraulic conductivities) are adjusted within accepted field and literature derived ranges until the model's output closely simulated the observed field conditions. Once calibrated, a model can then be applied to simulate groundwater flow, including water levels and three-dimensional flow paths under various scenarios.

4.1 MOUNTAIN SCALE MODEL APPROACH

The approach to representing the MSCM in the MSGFM using FEFLOW is based on standard modeling approaches as described in the following selected references:

- ASTM, Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem. ASTM Standard D 5447-93, 6 p.
- California Environmental Protection Agency (CalEPA). 1995 Ground Water Modeling for Hydrogeologic Characterization. Guidance Manual for Ground Water Investigations 24 p.
- Anderson, M.P. and W.W. Woessner, 1992, Applied Groundwater Modeling. Academic Press, Inc., San Diego, CA, 381 p.
- Michigan Department of Environmental Quality (MDEQ). 2002. Groundwater Modeling Guidance. Richard J. Mandle Groundwater Modeling Program. 55 p.
- United States Nuclear Regulatory Commission (USNRC). 2003. A Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear Facilities. Prepared by S.P. Neuman and P.J. Wierenga. University of Arizona. NUREG/CR-6805. 309 p.

Figure 25 summarizes the iterative approach to model development and calibration. The process involves representing the components of the conceptual model in the numerical model using parameters and boundary conditions. Simulation results are compared against field observations to evaluate how well the model represents field conditions. Model parameters and boundary conditions are then modified and refined to improve the model representation of the system. Once a reasonable representation is achieved, a sensitivity analysis is completed to evaluate the uncertainty in the model results with respect to key decisions being made using the model.

In refining and summarizing the conceptual models for groundwater flow, a number of digital datasets were updated or created from field information. Table 9 summarizes the key features of the conceptual model, the datasets that describe the features, and how they are represented in the FEFLOW model. The following sections discuss all of the components of model development and describes how each of the key features is represented in both the steady-state and transient models.

4.2 MODEL DESIGN:

4.2.1 Model Domain Mesh and Layers

The three-dimensional model domain encompasses the entire mountain scale study area and is approximately 7 km by 8 km (4 x 5 miles) having an area of 52 km^2 (20 sq. miles). The model mesh consists of 39 layers, 40 slices and 5,988,528 elements and 3,087,200 nodes. The model mesh was designed to efficiently discretize the model domain, by using smaller elements around features where large gradients are expected and larger elements outside these areas to minimize run times (Figure 26). Mesh refinements were designed to follow the mapped location of all faults and the mapped geologic member outcrops. The smallest elements are three meters on a side and are located along the faults. The largest elements are 100 meters on a side and are located in areas away from faults and the pumping wells. The nodal spacing of the mesh was sufficient for representing the location of pumping wells, seeps, phreatophytes and the on-site drainage features.

The stratigraphic layering of the geologic members (hydrostratigraphic units) is represented in the FEFLOW mesh using slices (Figure 27). Slices are surfaces that define the top and bottom contacts of each model layer and vertically subdivide or discretize the model domain. The slices are continuous surfaces that slope and conform to the geologic member contacts, where present, and ground surface beyond an outcrop location. The SSFL model uses 40 slices to represent 24 geologic units. The additional slices are used to accommodate the vertical offsets across faults and to better represent vertical gradients in thick geologic members.

Inset 2 in Figure 27 shows the model layer/slice system and illustrates how four slices are used to represent the offset of a geologic unit across a fault. The continuous model slices are shown to conform to the geologic contacts dipping at 25° where the unit exists in the subsurface. Where the units do not exist they are shown to pinch-out to minimum layer thickness (contact outcrops or at the intersection with the bottom of the model). The bottom of the model is fixed at an elevation equal to sea level. This is interpreted in the conceptual models to correspond to the bottom of the freshwater flow system. This interpretation also facilitates evaluation of the potential for discharge to the sediments filling the adjacent alluvial valleys. The approximate elevation of the bottom of the alluvial sediments in the Simi Valley is 170 meters above sea level and 100 meters above sea level for the San Fernando Valley (Evensen, 1997; DWR, 2003).

4.2.2 Hydrogeologic Properties

Saturated groundwater flow properties include hydraulic conductivity, porosity, and storage. Hydraulic conductivity is used in steady-state and transient simulations to calculate the head distribution. Effective porosity (as opposed to total porosity) can be used in both types of simulations to estimate average computed groundwater velocities. Storage is only applicable in transient simulations where the storage is allowed to vary with time. In FEFLOW, specific storage is referred to as storage/compressibility.

In the MSGFM, a variably saturated simulation mode is used to represent the groundwater system. This mode requires the specification of unsaturated zone parameters that describe the pressure head-saturation and conductivity-saturation relationships. The Van Genuchten Modified Model (VG model) (Schaap and Leii, 2000) is used to represent these relationships. Saturation, residual saturation, and constants describing the variation in conductivity and saturation with pressure head are assigned to all elements in the model. Bulk, equivalent porous media parameters are used to represent the combined contribution from the matrix and fractures. These relationships are used in the simulation of storage release due to drainage of pores in the unsaturated zone (specific yield) during transient conditions. Unsaturated zone parameters are also required to obtain an accurate representation of shallow zone transmissivity and thus an accurate water table representation. In the Mountain Scale model, two sets of unsaturated parameters are applied; one for all bedrock formations and another for all alluvial sediments. This approach is considered appropriate for the scale of the model. Parameter values for the rock formations were determined through a transient calibration of the C1 pumping test (Appendix L). WASY (2007) provides further justification for this approach.

Initial hydraulic conductivity, porosity and storage values were assigned in the model based on the values presented in Table 6. The conductivities were applied using FEFLOW’s layer parallel conductivity setting. This aligns the principle axes of the conductivity field parallel to the dipping beds as represented in the geologic model. Layer-parallel hydraulic conductivity reflects the expected alignment due to stratification of geologic members along the dipping beds. The simulation database and custom FEFLOW routines were used to assign hydraulic conductivity parameters to appropriate elements and modify those parameters through various calibration scenarios. When assigning hydraulic conductivities, a custom FEFLOW IFM routine also scaled the hydraulic conductivity values to account for fracture closure with depth. The hydraulic conductivity reduction was based on the average elevation of each element and the depth factors shown in Table 10.

Storage is assigned using a separate but similar IFM module and the storage look-up table. Storage is not scaled with depth. In this fractured rock environment, it is expected that residual soil moisture conditions persist throughout the year and that the vast majority of water within the unsaturated zone is held within the rock matrix (total water content 70 to 80%). However, when recharge occurs, fracture zones are expected to fill rapidly, transmitting water to the water table within a short time period. Similarly, when the underlying saturated zone is pumped, drainage of fractures within the unsaturated zone is expected to happen rapidly. A slow release of water initially held within the matrix also contributes to storage release and it likely travels to the water table through the fractures over a long period of time. The volume of water contributed by release of storage within the unsaturated zone is expected to be more than the fracture porosity (10^{-5}) and less than the total porosity (0.11 to 0.17). This volume is expected to be a relatively small proportion of the overall water released from storage; the majority of water is expected to be generated by depressurization within the saturated zone.

To represent the unsaturated zone under transient conditions, the MSGFM contains porosity values of 1% applied to fractured rock and 25% applied to the alluvium. The appropriate value for the fractured rock was derived based on the representation of specific yield in the C1 pumping test model (Appendix L). This porosity value may be adjusted for each of the hydrostratigraphic or hydrostructural units as necessary.

During calibration, hydraulic conductivity and storage values for individual units were modified by updating the values in the appropriate table within the simulation database. The values were adjusted within the ranges derived in Table 6. The values used for the current model calibration are shown in Table 11.

4.2.3 Boundary Conditions

Boundary conditions are used to represent locations where groundwater enters or leaves the model domain. Groundwater is conceptualized to enter the MSGFM domain through recharge and leakage from on-site drainage features. Groundwater leaves the domain through pumping wells, seeps, phreatophytes and flow out of sections along the perimeter of the model to the surrounding area. The bottom of the model is treated as a no-flow (impermeable) boundary.

4.2.3.1 Recharge

The initial spatial distribution of recharge is shown in Figure 21. This distribution was based on the rules for recharge shown in Table 7. Recharge is assigned to each element on the top slice of the model as a flux. The value is assigned by linking to the recharge map in Figure 21 within FEFLOW, and intersecting the recharge polygons with each element.

The recharge rules were initially applied throughout the model domain. However, adjustments were made during calibration to improve local water levels. These adjustments were made in the areas of on-site alluvium and non-Chatsworth formations to reflect local water levels. In these areas, the direct recharge through alluvium differed from recharge in areas with a perched alluvium/weathered-zone water table. Recharge was also increased in the Llajas, Santa Susana and Simi Formations to the north and west of the SSFL above the values suggested by the initial distribution rules to better represent groundwater levels and seep discharge locations.

Recharge adjustments were made based on the chloride water balance estimated recharge for the area of between 2 and 12% of average annual precipitation (MWH, 2003). In addition, recharge on individual units conforms to a physically constrained hierarchy (e.g. recharge in sandstone was assumed to be greater than shale, and the greater the land surface slope the lower the recharge). Figure 28 shows the calibrated recharge distribution map for the MSGFM model. Recharge values range from 0 inches/year on faults to 3.59 inches/year on alluvium in low slope areas.

4.2.3.2 Interior Boundary Conditions

Groundwater discharges within the mountain scale area through seeps, phreatophytes, pumping wells and through lateral boundaries. These features are represented using nodal boundary conditions. Nodal boundary conditions are also used to simulate the leakage from on-site drainages during periods of pumping. The location of each of the interior boundary conditions is shown on Figure 29.

Pumping wells are typically simulated using a pumping well boundary condition (Type 4). Nodes are assigned to the appropriate slices to represent the open, screened or packer-isolated pumping interval. The boundary condition uses a one-dimensional line element to connect nodes on adjacent slices over the open interval. This approach allows the total pumping rate to be apportioned over the layers intersected by the open section based on the transmissivity of each layer. In transient mode, a Type 4 boundary condition is used and a power function is assigned at the deepest node that defines the time varying pumping over the duration of the simulation.

In steady-state simulations, an alternative representation of pumping wells was used to simplify the calibration process. Type 1 boundary conditions (specified head) were applied along the open interval of the pumping well with a specified head value equal to the observed water level in the well. This fixes the water level at these locations and flow out of the boundary conditions is computed using the FEFLOW Budget Analyzer. With this approach, the well’s pumping rate becomes a calibration parameter.

Seeps and phreatophytes mapped in the mountain scale area (Figure 24) are represented as head-dependent flux boundaries (Type 3-Cauchy) (Figure 29). Type 3 boundary conditions are assigned at the nodes closest to the mapped seeps and phreatophytes on slice 1. A head value is assigned to the boundary condition equal to the ground surface elevation and a conductance value (transfer coefficient) is assigned to represent any resistance to discharge at the boundary. The boundary condition is constrained such that discharge occurs only when the water table is greater than or equal to the ground surface. Specification of the ground surface elevation at phreatophytes likely underestimates the discharge amount as the phreatophytes withdraw water from below the ground surface. The updated seep mapping (Figure 24) combined with the representation of phreatophytes has increased the number of potential discharge locations with respect to the RSGFM. This increases the likelihood that a larger proportion of water can discharge to seeps in the MSGFM than in the RSGFM.

A constraint is added to the boundary conditions for seeps and phreatophytes, so they are only able to remove water from the system when the water table elevation is equal to ground surface. If the water table is below ground surface the boundary conditions automatically turn off so as not to provide water to the subsurface and artificially fix the water table elevation. A large transfer rate (conductance) is assigned to the elements connected to the Type 3 boundary conditions; this infers that the seeps and springs are directly connected to the groundwater system (there is no resistance to water exiting at these locations).

4.2.3.3 Model Perimeter Boundary Conditions

On the perimeter model boundary, groundwater is expected to discharge to areas outside the domain. This interpretation is based on a limited set of hydraulic head measurements off-site and flow directions simulated in the RSGFM. Groundwater is interpreted to the leave the mountain scale area across the entire thickness of the freshwater system in the Simi and San Fernando Valleys as well as in Box, Bell, and Runkle Canyons (Figure 14 and Figure 29). Groundwater flow is also interpreted to the leave the model domain along Las Virgenes Canyon through seeps and shallow groundwater flow.

Perimeter boundary conditions were only assigned to nodes along sections of the model perimeter where groundwater was interpreted to leave the domain. A specified head boundary condition (Type 1-Dirichlet) was used to specify the groundwater elevation at these locations (Figure 29); the values applied were established based on simulation from the RSGFM. The perimeter boundary conditions were not simulated as varying with depth. The heads specified at the Type 1 boundaries were based on simulated water levels in the RSGFM but were adjusted during calibration through a local evaluation of simulated water levels. This included consideration of newly mapped seeps on the borders which provided constraints on the depth to groundwater. The uncertainty in these boundary elevations will be considered in the sensitivity and uncertainty analysis that is currently in progress.

4.3 STEADY-STATE CALIBRATION

Model calibration refers to the process by which model parameters are adjusted within the range of possible values defined in the MSCM to achieve the best representation of the groundwater flow system. The ability of the model to represent the groundwater flow system is evaluated by comparing simulated water levels and discharge with values measured in the field.

To provide confidence that the model representation of three-dimensional flow is representative of site conditions at SSFL, a steady-state calibration to average field observations was completed for the period of 1995 to 1998. This time period was chosen as an extensive water level monitoring data set and pumping rates were available for a number of wells covering the entire site. Steady-state simulations assume that the change in storage is negligible over the simulation time period and calibration efforts are focused on representing the distribution of recharge and three-dimensional hydraulic conductivity.

MSGFM calibration was facilitated using the simulation database, where a record of the hydraulic conductivities assigned to various zones in the model was maintained along with statistical calibration metrics for each simulation. Recharge for individual polygons was adjusted within the range defined in SCM using the rule based map of recharge (Figure 21) to provide the best match to field conditions.

4.3.1 Calibration Datasets

Steady-state calibration targets for the MSGFM are the observed average water levels at wells during the simulation time period and estimated flow from seeps and phreatophytes. Figure 31 shows the location of the wells with water levels used as calibration targets. Table 12 lists the well names and the computed average water level for the 1995 to1998 time period.

Seeps and phreatophyte locations are shown in Figure 29. The total flow estimated for seeps and phreatophytes for each drainage is summarized in Table 13. Seep flow rates were estimated in the field (2001-2006) and phreatophyte groundwater use rates were estimated based on the type of phreatophyte mapped at each location (MWH, 2003g). In some locations seep discharge was not estimated and is therefore only identified as a location of a seep. These were represented in the model as potential discharge locations (water was allowed to discharge).

Average pumping rates were also computed for each well pumping during the 1995 to 1998 period. During steady-state calibration, these pumping rates were used as a secondary calibration target. Using the Type 1 representation for pumping wells described above, the average pumped water level was assigned to each pumping well. The amount of water removed from each group of Type 1 well boundary conditions was compared to average pumping rate.

4.3.2 Steady-State Calibration Results

More than 180 steady-state model simulations were completed to achieve the current model calibration. The details of these runs are contained in the simulation database. Figure 30 shows a calibration scatter plot of the calculated water levels at each well versus the observed water levels for run 184 (a one to one fit would have all dots aligned along the diagonal). Additional plots of observed and calculated water levels are show in Figure 31 and Figure 32. Figure 30 shows good agreement between the calculated and observed values. Statistical measures of the difference are provided as follows:

- Normalized root mean squared (NRMS) error = 7.16%. This percentage value allows the goodness-of-fit in one model to be compared to another, regardless of the scale of the model. Typically a model is considered representative with a 10% NRMS, and a good calibration is considered to be 5% NRMS or less; (reference).
- Root mean squared (RMS) error = 12.73 m. The RMS is similar to a standard deviation, providing a measure of the degree of scatter about the 1:1 best-fit line. The measure indicates that the majority of the statistical population of predicted water levels would fall within 12.4 m of the observed value. An error of this magnitude is reasonable given that during 1995 to 1998 pumping was occurring on site causing large fluctuations in water levels.
- Mean Error = -1.77 m. The mean error is a measure of whether average predicted water levels are higher or lower than those observed (ideally it should be close to 0). This statistic indicates that on average, the simulated water levels are low by 1.77 m.
- Mean Absolute Error = 5.89m. The mean absolute error is a measure of the average deviation between observed and simulated water levels. The value of 5.89m is less than the population statistic (RMS) and within the range of the expected level of error when using water levels from averaged monitoring data in the vicinity of pumping wells.

The graphical plots (unless otherwise noted) plot the average observed water level at a well and the head simulated at the slice that is closest to the depth where the well is completed. Selection of this representative slice is difficult for wells with long screens that span more than one geologic unit (Table 12). To assess the effect of long open wells on the observed water levels a blended head value was calculated from all of the slices that are intersected by the open section of the well. The blended head was calculated for the well by weighting the head at each slice based on the transmissivity of the intersected geologic unit. However, in the end the simulated head at the representative slice was used to assess calibration and for computation of the statistics as it was more consistent with the observed water levels.

A weighting factor was used in calculating the calibration statistics whereby wells that showed a variation in field measured water levels over the 1995 to 1998 of greater than 10 m were assigned a weight of 0.5, all other wells were assigned a weight of 1.0. Therefore the calibration was weighted less towards wells with less representative average water levels for that time period.

A map showing the spatial distribution of water level residuals (difference between calculated and observed) for the steady-state simulation is presented in Figure 31. The map shows that there are no site wide trends in the residuals. Locally water level residuals have been minimized, but water levels are under predicted (observed value is greater than calculated) below the ELV member in the Burro Flats area and in the Canyon member in the northeast. Water levels are slightly over predicted along the North Fault.

Figure 33 shows the simulated and observed vertical gradients at selected multi-level wells in Burro Flats (RD-54AB), west of the Shear Zone in Sandstone 2 (RD-45ABC) and east of the Shear Zone (RD-36ABCD). These plots illustrate the downward groundwater gradient observed in the Chatsworth Formation for many on-site areas. These wells indicate that the downward gradient is slightly over predicted at the site as deeper water levels are predicted to be lower than observed.

Table 13 shows the difference in total simulated discharge to seeps and phreatophytes (Figure 29) and the estimated observed values. The total discharge to seeps and phreatophytes in the MSGFM is 150% of the observed values. This is considered reasonable as flows were not reported or measured for each seep. Further, measured flows are only considered to be accurate to within one order of magnitude. Some drainages where seep flow or phreatophytes were observed are simulated as having zero discharge. This may be due to the fact that the seeps are from local groundwater flow systems or interflow and are not connected with the deeper water table. It may also indicate that the model is not representing the local water table accurately at those locations. The drainages exhibiting the most seep/phreatophyte discharge are Bell and Meier Canyons.

4.3.3 Steady-State Groundwater Flow Discussion

Figure 34 shows a plan view map of the simulated water table and Figure 35 shows the three-dimensional water levels illustrating the large vertical gradients observed in the domain. The calibrated water levels reflect the average pumping conditions that existed in 1995 to 1998 when the water levels in Sandstone 1 were up to 100 meters lower than water levels east of the shear zone. In the Northeast, Burro Flats, and areas south of the Burro Flats Fault, groundwater is simulated to flow offsite toward lower elevations. Bedding dip and simulated anisotropy strongly influence groundwater flow directions. The simulated conductivity decrease with depth promotes flow perpendicular to bedding at depth as groundwater flows down dip and the conductivity contrast is reduced between sandstone and shale layers.

Vertical gradients are predominantly downwards within the SSFL site boundaries. Upward gradients are observed off-site, near drainage features and across fine grained units on hill slopes. On the north side of the site, beds dip in the same direction as topography. South of the site Chatsworth Formation beds dip in the opposite direction of topographic slope. On the south side of the site strong horizontal gradients are observed in the shallow system as topography forces flow perpendicular to bedding in areas where it overcomes the dip. A weak regional groundwater divide between dominantly northwest groundwater flow and southwest flow is observed approximately along the east-west alignment of the Burro Flats Fault (Figure 34). East of the shear zone, particularly in the northeast, vertical gradients are simulated across fine-grained members (e.g. Happy Valley). Dominant groundwater flow directions align with strike as the topography slopes to the east. In the west, topography rises above the elevation of the site. Groundwater flow in this area aligns with the northeast and southwest flow directions.

Seeps are observed at a number of locations on the slopes of the Simi Hills. Seeps form where water table intersects the ground surface. Phreatophytes can also exist in areas where the water table is at or near the ground surface. The model simulation shows that the greatest seep and phreatophyte discharge occurs in the North Drainage (East) and South Drainage areas. These seeps exist on the south side of the site where topography slopes in the opposite direction of bedding, resulting in a shallower water table and greater seep discharge where fine grained units outcrop. On the north side seep discharge is greatest where Shale 3 outcrops, which is also coincident with a change in slope of the topography.

Table 13 and Figure 36 summarizes the simulated water budget for the mountain scale area. The total recharge in the model domain is 4374 m^3/d (802 gpm), 31 mm/yr (1.2 inches/year), or 7% of precipitation. Within the SSFL site boundary the average recharge is 37 mm/year (1.5 in/yr) or 8% of precipitation. Under steady-state conditions 653 m^3/d (120 gpm) or 55% of pumped groundwater leaks back to the water table from on-site drainages. Pumping wells extract 1178 m^3/d (216 gpm) or 23% of total mountain-scale recharge.

These simulated values are within 4% and 6% of the estimated average leakage and pumping in the field (Table 13). Pumping wells are represented as Type 1 (specified) head boundaries by fixing the average head at the location of the well. This elevation may not correspond exactly with the average pumping rate; slight adjustments in the specified elevation would change the pumping discharge rate. However, the simulated rate is within the range of pumping that occurred during 1995 to 1998 and provides a good fit to water levels, and seep discharge. Discharge to seeps is 1336 m^3/d (235 gpm) or 27% of the recharge to the entire model domain. These values are consistent with the total estimated discharge to seeps and phreatophytes (Table 13). The remaining groundwater (2513 m^3/d or 461 gpm) leaves the MSGFM domain through the perimeter boundary conditions. This represents 50% of the total groundwater recharge to the model.

A comparison of the flow out of the MSGFM domain using the MSGFM and the RSGFM can be made by comparing Figure 14 and Figure 36. This comparison provides a check of the consistency of the mountain scale outflow with the regional flow system and therefore a check of how representative the boundary conditions are in the MSGFM. The comparison of the figures indicates that similar percentages of outflows occur at the west and east boundaries of the MSGFM (Los Virgenes/Runkle Canyons and San Fernando Valley) in both models. However, the percentage flow out to Simi Valley and Bell Canyons has changed whereby the percentage discharge to Simi Valley is reduced by 20% while the percentage discharge to Bell Canyon doubles. The reduction in discharge to Simi Valley can be explained by the increased discharge to seeps. The increase in discharge is likely due to the identification of additional spring/seep and phreatophyte locations primarily updip of the Simi Valley in the MSGFM compared to the RSGFM. The increase in percentage outflow to Bell Canyon reflects the fact the few additional spring/seep and phreatophyte locations other than those near the model border were identified. Thus, the volumetric discharge in this area is similar, but is a larger proportion of the total outflow in the MSGFM. This comparison indicates that the mountain scale border boundary conditions appear to reasonably represent the connection with the regional flow system. However, these boundary conditions will be further explored in the sensitivity analysis.

4.4 TRANSIENT CALIBRATION

The steady-state calibration is non-unique, meaning that there may be multiple sets of hydraulic conductivities and flow through the model that yield the same hydraulic head distribution. Calibration using average or steady-state datasets requires a best fit approach to matching calibration targets and results in some inherent uncertainty in the actual water level or flows at a given location. Transient calibration provides a higher level of testing of aquifer properties and structure to reproduce well responses (timing and drawdown) to the operation of multiple time-varying pumping wells. Further, calibration to site-scale conditions or stresses such as pumping tests enhances the model's ability to represent flow at that scale and reduces some of the uncertainty inherent in the use of averaged datasets in the steady-state calibration.

One time period selected for transient simulation in the MSGFM was 1949 to 2006. This represents the time period covering the first pumping on-site to near present day. Average annual pumping rates are available for each of the pumping wells (for most years) and site-wide water level observation data are available beginning in the late 1980s. A limited set of observation data are available from 1949 to 1990.

Transient calibration was completed in two steps; the first was to adjust storage parameters to provide the best overall representation of pumping well drawdown and observation well responses. The model representation was evaluated by comparing the simulated and observed hydrographs for each well. The second step was a more detailed calibration exercise focusing on the time period from 1998 to 2006, a period during which extensive monitoring was completed while large pumping wells were shutdown. This includes the cessation of extraction from former water supply wells WS-5 and WS-6. Cessation of pumping at these wells produced water level responses at a number of wells. This data set provides a good test of the model's ability to simulate hydraulic connections.

The transient version of the MSGFM was setup to represent pumping wells as Type 4 boundaries, each with their own with time varying pumping schedule (Table 8). Storage parameters were assigned to each hydrostratigraphic and hydrostructural unit as defined in the SCM using the calibration database and IFM module to facilitate data input. The on-site drainages, which provide recirculation water to wells during pumping, were simulated as being active for the periods that pumping was occurring. Similarly, a constant head boundary was specified above well WS-9A to represent the direct flux of re-circulated water to this well. All other boundary conditions, including recharge, were simulated as constant values for the duration of the transient simulations. Further adjustments were made to hydraulic conductivity during transient simulation. The updated values were incorporated into the steady-state simulations and are reflected in the steady-state calibration presented in section 4.3.

4.4.1 Transient Calibration Datasets

Transient water level information is available for 209 observation points at SSFL. Figure 37 shows the location of the pumping and observation wells simulated in the 1949 to 2006 simulation and the 1998 to 2006 simulation. Much of the data are for the time period after 1990. The transient hydrographs for each observation point are the primary calibration dataset. A custom FEFLOW routine (IFM module) was developed to efficiently record the simulated water levels at the corresponding observation points during the simulation. After the simulation, predicted water levels are imported into the database and the simulated and observed hydrographs are compared graphically. The hydrographs can be used to assess how changes in model input parameters affect a well response to a change in pumping (drawdown or recovery). The assessment can guide changes in input parameter values and geologic unit distributions.

Figure 38 and Figure 39 show two additional data sources used to evaluate the transient calibration. Figure 38 is a historical conceptual figure showing the observed response to pumping at SSFL from 1949 to 1960. The figure indicates an initial period of fast drawdown, followed by stabilization and then increased drawdown. This description is used to evaluate the transient responses during this time period. Figure 39 developed by MWH (2006) shows wells that responded to the shutdown of WS-5 and WS-6. Simulated well responses during the period of this test are compared to these figures.

Transient seep and phreatophyte observation datasets do not exist. It is expected that these features would have existed through the duration of the simulations, although the locations and volumes may have changed. Given that recharge is simulated as being constant throughout the duration of the transient simulations, the seep and phreatophyte discharge can be monitored to assess whether the predicted range of discharge is reasonable. If pumping is increased a reduction in seep and phreatophyte discharge could reasonably be expected to occur, if pumping is reduced it is expected that more groundwater will discharge to these features.

4.4.2 Initial Conditions

Initial conditions for hydraulic head distribution and saturation must be specified in a transient model. For the 1949 to 2006 simulation initial conditions were developed by running a version of the steady-state model with all pumping wells and drainage re-circulation turned off. The resulting three-dimensional head distribution was used to represent the pre-pumping conditions in the mountain scale area.

Initial conditions for the 1998 to 2006 simulation were derived from the calibrated steady-state model. The head and saturation values from the steady-state simulation provided the best representation of three-dimensional conditions.

4.4.3 Transient Calibration Results

Figures 40-45 show the calculated and observed hydrographs for a number of wells in the MSGFM model. The wells selected illustrate the site-wide responses in both simulations and/ or represent key observation wells for the WS-5/WS-6 shutdown test. A complete set of well hydrographs are contained in the transient simulation database.

In order to calibrate the transient model, the following parameters were updated as follows:

- Increased the hydraulic conductivity of Sandstone 1 compared to the original steady-state estimate.
- The North fault along its east-west trending section was represented as having the conductivity of a sandstone rather than lower conductivity. Both representations resulted in a head match in steady-state but the higher permeability representation provides a better match to observed well responses.
- Saturated storage (specific storage) was represented and calibrated with values of 1E-5 and 5E-5 for the low and high conductivity features, respectively.
- The hydraulic conductivity of the Sage members were increased west of Shear Zone to sustain pumping rates.
- The hydraulic conductivity of the Upper and Lower Burro Flats and the Silvernale members were reduced by half an order of magnitude to simulated well responses.

In general, the plots (Figures 40-42) show the simulated water levels represent the water level changes suggested in Figure 38 for the time period of 1949 to 1960. Pumping on site shows an initially rapid drawdown with drawdown temporarily stabilizing in 1955 and increasing again between 1958 and 1963, after which time pumping was reduced and water levels recovered. The simulated water levels are not however at the base of wells WS-6 or WS-13 as predicted in Figure 38.

The simulated hydrographs also show that the model represents the change in water levels at most locations across the site after 1963 to present day. Recovery data also shows that simulated recovery matches the observed recovery quite well. Pumping responses at WS-9A are muted by specifying the direct recirculation water, which is a local phenomena historically observed in the field. This boundary condition can be refined to better represent the flux over time.

Figures 43-45 focus on the transient water levels for 1998 to 2006. This includes the period of time when WS-5 and WS-6 were shutdown, among other wells. The shutdown of these wells resulted in water level changes in Sandstone 1 and Sandstone 2. The simulated hydrographs provide a good match to the observed hydrographs for wells in 1998 to 2006. In general wells that were observed to respond to the WS-5 and WS-6 shutdown were simulated to respond, but the magnitude of the response was muted. Key observed well responses are illustrated in Figure 39. Figure 43-45 show that key simulated wells such as WS-14 and WS-12, and RD-51C match the observed responses closely while wells more distant to WS-5 and WS-6 along the North Fault, such as RD-56 and RD-70 show less simulated response than observed in the field.

A number of the shallow ES and RS series wells that are screened in the alluvium southwest of Silvernale Pond show excessive drawdown to the point where wells initially go dry in the 1998 to 2006 scenario when WS-9A is simulated as pumping. This is likely due to the initial condition under-representing the level of saturation. Additional work is required in this area to represent the shallow water level yields.

4.4.4 Transient Groundwater Flow Discussion

The hydrographs in Figures 40-42 show a good match for observed and simulated water levels between 1949 and 2006. The exception is at RD-01 which is located between the two traces of the Happy Valley Fault. In the vicinity of this well, it is expected that enhanced fracturing and hydraulic conductivity exist; the excessive drawdown simulated is likely due to the application of average EPM parameter locally at the well. The good match in recovery at RD-01 and the other pumping wells and review of water levels adjacent to the wells suggest this is a local condition.

The transient calibration helped to refine local parameter distributions that were non-unique in the steady state model (e.g. North Fault) by assessing well responses. The multitude of details regarding the transient simulations is difficult to present graphically in a report. However, the hydrographs provide an idea of how water levels change over time at selected points in the system. The variation in location and rate of pumping results in a highly transient system with varying flow directions through the 1949 to 2006 time period.

The following observations were made from the transient simulations:

- Initial conditions (non-pumping 1949) show downward gradients on-site;
- Groundwater that recharges at SSFL flows off-site to discharge at seeps or perimeter boundary conditions;
- Pumping on-site increases the magnitude of downward vertical gradients and reduces water levels on-site;
- Pumping captures water that otherwise would eventually flow off-site;
- Local flow directions near pumping wells were variable depending on the rate of pumping at any given time;
- Faults generally bound pumping responses such that pumping in Sandstone 1 is not reflected as a drawdown response in wells east of the Shear Zone, the exception is the North and IEL Faults, which seem to transmit pumping responses;
- Drawdown is rapid in the early stages of pumping between 1949 and1955 followed by a period of stabilization in 1955-1960, when water levels decline rapidly prior to a large reduction in pumping;
- From 1963 to the mid-1980s water levels slowly recover to almost the original water level, illustrating generally low recharge to the system;

- The resumption of pumping on-site in 1980s reduced water levels, especially in Sandstone 1, where water levels were drawdown by as much as 100 m;

- Large reductions in pumping since 2000 have seen recovery of water levels but levels are still depressed by as much as 20-50 meters (WS-5 and WS-6) since the early 1980s; and

- Additional refinement to the simulated shallow pumping from alluvium southwest of Silvernale pond and direct recirculation to WS-9A will improve the understanding of groundwater flow in this local area.

5.0 Insight to Three-Dimensional Groundwater Flow

The calibrated steady-state and transient Mountain Scale Groundwater Flow Model (MSGFM) is a tool that can be used for characterizing the flow of groundwater such that the flow of COPC solute transport due to advection can be reasonably understood. The MSGFM has been shown to provide a supportable representation of three-dimensional groundwater levels, flow conditions, water budget estimates and responses at wells due to hydraulic stresses. The model integrates the key components of the MSCM. The current understanding of groundwater flow at the SSFL, as derived from the SCM, RSCM, and MSCM and refined through the groundwater flow model, can be summarized as follows:

Geologic Setting:

- The turbidite deposits of the Chatsworth Formation and younger units can be grouped into three hydrostratigraphic units for the purposes of understanding groundwater flow at SSFL:
    - Alluvium - aquifer
    - Sandstone/Conglomerate -aquifer
    - Shale/Siltstone – aquitard
- The Chatsworth Formation and younger units have been fractured and faulted such that an interconnected fracture network is observed at all scales and within all units. The fracture spacing is observed to vary but three distinct hydrostructural units are defined:
    - Fault/fault zones – usually indicated by offset of stratigraphic units on either side of the feature;
    - Deformation bands – broad zones of gouge filled fractures with small offsets on each fracture;
    - Protolith - areas outside of the above units that exhibit an interconnected fracture network but no vertical offset or characteristics associated with faulting.

Hydraulic Properties:

- At most locations within the SSFL, the fractures and joints are estimated to increase the bulk hydraulic conductivity of the Chatsworth Formation sandstone by at least an order-of-magnitude or more above the hydraulic conductivity of the rock matrix (MW, 2000).
- Matrix hydraulic conductivity is generally an order of magnitude lower than bulk conductivity.
- Sandstone 2 has lower bulk hydraulic conductivity than Sandstone 1.
- At certain locations with the SSFL, faults bound pumping responses; For example, pumping in Sandstone 1 in the central portion of the SSFL does not induce appreciable drawdown in wells east of the Shear Zone.
- At other locations such as the North fault and IEL fault, observed hydraulic responses in wells screened on either side of the fault are similar.

Recharge:

- Precipitation is on average 18 inches per year and average recharge on-site is estimated to be between 2-12% of precipitation. Model calibration indicates this value to be 8% on-site and 7% for the entire mountain scale area.

Groundwater Flow: Historical and Average 1995 to 1998:

- The largest horizontal gradients are observed across some faults and fine grained units.
- Downward gradients are simulated to have existed at most locations on-site when pumping was not occurring (i.e., prior to 1949).
- Groundwater that recharged at SSFL will move off-site to discharge at seeps or distant surface water features.
- With the commencement of pumping on-site, the magnitude of downward vertical gradients increased locally and water levels were reduced on-site.
- Pumping captures water that otherwise would flow off-site.
- Local flow directions near pumping wells have changed over time depending on the rate of pumping at any given time.
- Drawdown was most rapid in the early stages of pumping between 1949 and 1955 followed by a period of stabilization between 1955 and 1960, after which water levels decline rapidly prior to a large reduction in pumping.
- From 1963 to the mid-1980s water levels slowly recovered to almost the original water level, indicating generally low recharge of water to the system.
- The resumption of pumping on-site in the 1980s reduced water levels, especially in the central portion of the SSFL (i.e. within Sandstone 1), where water levels were drawn-down by as much as 100 m.
- Water levels have recovered as groundwater extraction was reduced starting in late 2000 to allow for the characterization of the Chatsworth Formation at the SSFL. However, water levels are still depressed by as much as 20 to 50 meters (WS-5 and WS-6) compared with the early 1980s.

Water Budget:

- Average groundwater pumping during 1995 through 1998 was estimated to be 23% of the total recharge and leakage from drainages on-site within the mountain scale model domain.
- Seeps or springs that exist beyond the winter rainy season are fed by groundwater. On average between 1995 and 1998 discharge to the seeps and phreatophytes was estimated to be 27% of total recharge or 67% of on-site recharge.
- Between 1995 and 1998 the average flow out of the model into adjacent areas through perimeter boundary conditions was estimated at 50% of total recharge or 137% of on-site recharge.

The three-dimensional MSGFM embodies the necessary features to be able to replicate observed site conditions. This model is a useful tool for understanding the groundwater flow system at SSFL.

6.0 Model Capabilities & Future Applications

The current calibrated transient and steady-state models have been shown to reasonably represent the field conditions. The model tool provides a three-dimensional representation of the flow system that can be used to:

- Gain insight into the site-specific three-dimensional groundwater flow system
- Evaluate hydraulic connections (e.g. well responses to pumping)
- Evaluate volumetric fluxes
- Evaluate the effect of uncertainty in the MSCM and model parameters with respect to key decisions about the flow system

Specifically, the model facilitates an assessment of:

- groundwater levels/flow throughout the mountain scale area
- three-dimensional groundwater flow from any recharge location
- vertical gradients and the vertical component of flow
- flow directions beyond the site
- range of flow directions given uncertainty

The model is an essential tool for integrating multiple datasets in a complex environment and facilitates further understanding and assessment of site conditions, as part of the RCRA corrective action process.

6.1.1 Key Uncertainties

As part of the application of the model it is important to evaluate the uncertainty associated with model predictions. To accomplish this, sources of uncertainty must be identified and a process developed to evaluate uncertainty.

In the process of qualitative and quantitative calibration, decisions are made as to the appropriate parameters and boundary conditions. Field observations that have been incorporated into the MSCM provide an estimated range of appropriate values but they are not absolute. It is recognized that more than one representation of a parameter or boundary condition, or their combination, may adequately represent field conditions. Two representations that are equally well calibrated may result in different flow conditions at key locations within the model.

Uncertainty in flow conditions results from uncertainty in the characteristics of features in the MSCM and values assigned for key input parameters. One method of addressing uncertainty is to use the model to evaluate how flow directions may change when a feature is represented using an alternative conceptual model or by varying the value of an input parameter. This approach to uncertainty analysis using groundwater models is well documented by ASTM (5611-94), Anderson and Woessner (1992), MDEQ (2002), USNRC, (2003) and CalEPA (1995). Although approaches vary in the details and focus they explore uncertainty and model sensitivity from two perspectives:

- Calibration – how is the quantitative calibration affected with a change in the parameter or boundary?

- Prediction – how does groundwater flow change with a change in parameter or boundary condition?

By varying single parameter values or multiple values within the range measured in the field it is possible to find other combinations of parameters that calibrate the model (sensitivity analysis). It is also possible to rule out other parameter values or combinations. This analysis can identify key parameters for which additional measurements are needed to refine the range of possible parameter combinations. This can be a complex undertaking involving a large number of model parameters.

The uncertainty associated with features in the MSCM including the three-dimensional structure of the geology, have recently been addressed in approaches to uncertainty analysis (USNRC, 2003; Bredehoeft, 2002; Wellman and Poeter, 2006). Beyond the parameter value assigned to a feature (e.g. hydraulic conductivity) it may be that the flow changes if a feature is represented using an alternative conceptual model. Alternative conceptual models may for example represent a shale bed as pinching out rather than being laterally continuous. The key to addressing uncertainty in the SCM features is to identify which features are poorly constrained and to develop alternative conceptual models. In developing and calibrating the SSFL MSGFM, the key features and parameters to be considered in addressing uncertainty are:

- Anisotropy
- Conductivity change with depth
- Water level at perimeter boundary conditions
- Local geologic structures and hydraulic properties
- Local recharge
- Elevation of the bottom boundary of the model
- Connection of seeps to Chatsworth flow system

Additional data collection and data analysis were completed in an attempt to address each of these features (see Appendix A; Appendix G; Appendix H; Appendix J;Appendix L). These data sets were used to further constrain the model framework and parameter values. However, a sensitivity analysis has not yet been completed.

6.1.2 Application of Model

In its current form, the MSGFM represents the components of the current MSCM and provides a supportable representation of three-dimensional groundwater flow as assessed by comparing simulated groundwater levels and groundwater discharge with observed data. The model is to be used at SSFL to evaluate site-specific three-dimensional groundwater flow and to provide representative input conditions for additional FRACTRAN simulations of solute transport and fate. These two models will provide insight into flow directions for COPCs and evaluate existing and possible locations for monitoring future contaminant transport. Two key FEFLOW model tools can be used in these evaluations.

Groundwater flow conditions can be evaluated using three-dimensional particle tracking routines in FEFLOW with the steady-state and transient simulated flow fields. Particle tracking uses the velocity field derived from the head distribution and assigned aquifer properties to simulate the movement of a particle along the flow path from a point of origin that can be anywhere in the three-dimensional volume of the model (e.g. water table or bottom of a well). Particle tracking is easily accomplished but in a fractured rock groundwater flow system the selection of an appropriate porosity can be challenging. Particle pathlines are best viewed in two and three dimensions using GIS and three-dimensional visualization tools.

FEFLOW Explorer and TecPlot are two tools that can be used to evaluate flow paths relative to geologic structure and water levels.

The second set of modeling tools are used for water balance analysis (Water Budget Analyzer and Flux Analyzer). These tools provide information on the volume or rate of flow into or out of the model domain through boundary conditions or flow from one area in the model to another. This can be particularly useful for understanding groundwater flux across a fault or other feature. The flows also help to understand the role of the seeps as discharge points and the potential for deeper flow out through perimeter boundaries.

Together these tools provide a means of understanding and quantifying three-dimensional groundwater flow at SSFL. The model should be viewed as a living tool such that it is updated and kept current as new data and interpretations arise.

6.1.3 Future Work

Additional worked planned to complete the MSGFM includes two primary thrusts. First, a sensitivity analysis will be completed to assist in identifying key model parameters that most significantly affect the model. Second, an alternate conceptual model(s) will be considered to evaluate other ideas about the groundwater flow system and to assess if calibration can be achieved within the measured parameters of the site.

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