**DRAFT**

# REPORT OF RESULTS
# FORMER SODIUM DISPOSAL FACILITY
# GROUNDWATER CHARACTERIZATION

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## SANTA SUSANA FIELD LABORATORY
## VENTURA COUNTY, CALIFORNIA

***VOLUME I OF II***

**February 2006**

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**The United States Department of Energy**

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**APPENDICES (Volume II)**

# 1.0 INTRODUCTION

This report presents groundwater characterization results of site- and activity-related chemical impacts to the groundwater within the area of the Former Sodium Disposal Facility (FSDF) in Area IV of the Santa Susana Field Laboratory (SSFL). 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 operated for the U.S. Department of Energy (DOE). 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 its surrounding vicinity is shown on Figure 1-1.

The work described in this report meets the objectives outlined in the *Work Plan for Additional Field Investigations, Former Sodium Disposal Facility, Chatsworth Formation Operable Unit* (CFOU Work Plan) (Montgomery Watson Harza, 2001) and the *Shallow Groundwater Investigation Work Plan*[1] (Ogden, 2000). The California Environmental Protection Agency, Department of Toxic Substances Control approved the work plans for implementation (DTSC, 2000 and 2002). Work performed on the near-surface groundwater at the FSDF and throughout the SSFL is provided in the *Near-Surface Groundwater Characterization Report* (MWH, 2003b).

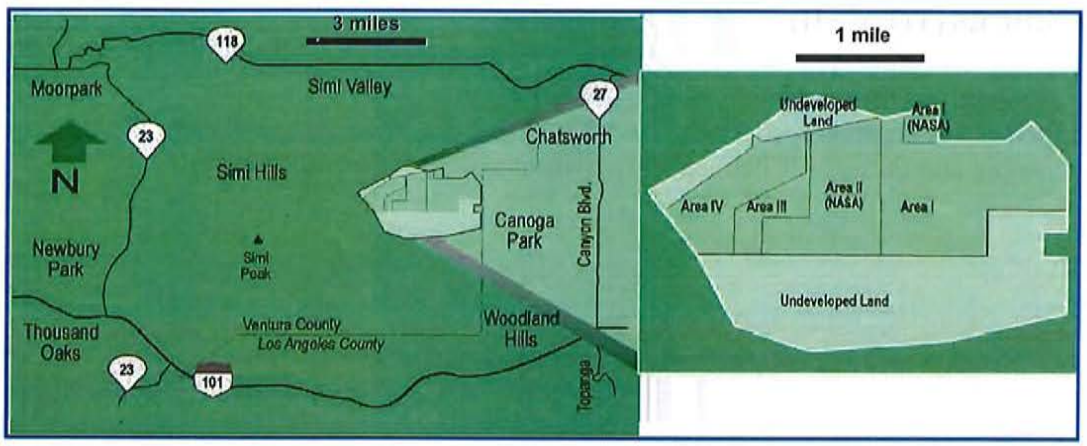



**Figure 1-1 SSFL Site Location Map**
The Santa Susana Field Laboratory is located in the Simi Hills. The city of Simi Valley lies about two miles to the north of the SSFL and the San Fernando Valley lies about two miles to the east-southeast. The SSFL is divided into four administrative areas (I through IV). Boeing owns the land in Areas I, III and IV. The federal government owns the land in Area II and a small parcel of land in Area I. Boeing operates all the facilities on Areas I through IV. Areas I through III have been used primarily for rocket engine and related component testing. Area IV has been used primarily for nuclear reactor research and is currently undergoing decommissioning and demolition.

[1] The near-surface groundwater underlying the SSFL has been defined as groundwater that occurs in alluvial or colluvial deposits and/or weathered bedrock. The near-surface groundwater system has been coupled with investigations of the unsaturated alluvial or colluvial deposits and/or weathered bedrock and these have collectively been defined as the Surficial Media Operable Unit (Surficial OU). The Surficial OU also contains other environmental media that include air, biota, surface water and pond sediments. Chatsworth formation groundwater has been defined as groundwater that occurs in unweathered bedrock beneath the SSFL. References to "groundwater" in this report will, by definition, include both the near-surface and Chatsworth formation groundwater.

The portion of the SSFL that is discussed in this characterization report is centered around the FSDF, which is located within Area IV in the northwest section of the SSFL, as shown on Figure 1-2. The FSDF investigation area is one of two areas where site-related impacts to groundwater are currently being characterized. The second area of the SSFL where such characterization efforts have been implemented is in the northeast portion, where a Report of Results has already been issued (MWH, 2004). The northeast investigation area is also shown on Figure 1-2.

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

## 1.1 Purpose

The FSDF CFOU work plan (Montgomery Watson Harza, 2001) provided a description of work to be performed to complete field investigations of Chatsworth formation groundwater at the SSFL. The purpose of this report is to present the results of data collected during the FSDF groundwater investigation.

This report is being prepared in partial fulfillment of the requirement to characterize environmental media that has been established in the corrective action provisions of the hazardous waste operating permit for the Buildings 29 and 133 storage and treatment facilities (permit number 93-3-TS-002/ CAD000629972). It should be noted that these facilities are no longer active and their closure is pending as of the date of this report.

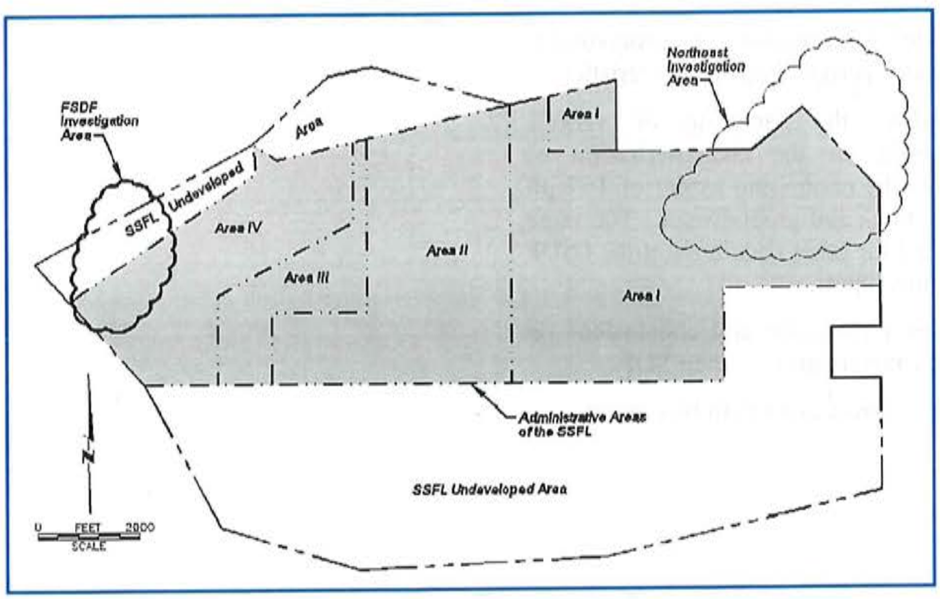



**Figure 1-2 SSFL Map Showing FSDF Investigation Area Study Boundary**
This report describes groundwater characterization work that has been performed at and near the FSDF in Area IV of the SSFL. This area is one of two areas throughout the SSFL where intensive groundwater characterization activities have been performed. The other area is within the northeast portion of the SSFL and its boundary is also shown above.

## 1.2 Report Organization

The first volume of this report is a summary overview of the work that has been performed to characterize groundwater at and near the FSDF. This report provides specific examples to illustrate the findings of this investigation. More complete data sets are provided in appendices contained in a subsequent volume. This report contains the following sections:

**Section 2** provides background information on operational usage and the historical development of groundwater characterization work at the FSDF and the approach taken in the work plan to characterize groundwater.

**Section 3** summarizes Chatsworth formation groundwater characterization activities that have been performed since 2002 and recaps near-surface groundwater characterization activities initiated in 2001.

**Section 4** provides data on the physical characteristics of the FSDF as related to groundwater characterization.

**Section 5** provides information on groundwater occurrence and other hydrogeologic characteristics.

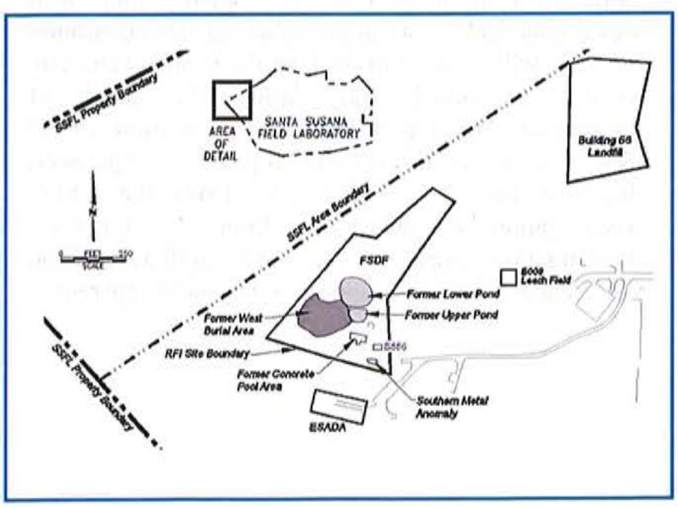
**Section 6** describes the sampling of various environmental media for the characterization of VOCs and presents the nature and extent of TCE in soil, soil vapor, bedrock and groundwater. The same material is presented for other chemicals at the FSDF in an appendix to this report.

**Section 7** provides a summary and conclusions on the groundwater characterization at the FSDF.

**Section 8** provides references cited in this report.

# 2.0 BACKGROUND INFORMATION

The FSDF site was used to clean metallic sodium and a mixture of sodium and potassium (NaK) from components such as pumps and valves that were used in support of liquid metal testing operations that were conducted in Area IV. The area was used to treat sodium and NaK by an exothermic reaction with water. Other materials, including terphenyl coolants, solvents, acids, and hydrocarbon compounds were also incidentally discarded in the former ponds within the FSDF (ICF, 1993). Historically, the FSDF included two water-filled unlined ponds (referred to as the Upper and Lower Ponds). A rectangular, concrete-lined pool filled with water was subsequently constructed and replaced the operational usage of the Upper and Lower Ponds. Other operational facilities at the FSDF included a small building (Building 886, now removed), and a steam lance. For the purposes of environmental characterization activities, these facilities have been grouped into a single Resource Conservation and Recovery Act (RCRA) facility investigation (RFI) site. The FSDF RFI site occupies about 4.6 acres and its boundary and facilities are shown on Figure 2-1. A detailed description of its operational usage was provided in previously submitted documents (ICF, 1993 and IT, 1999).




## 2.1 Chronological Development of Groundwater Characterization Work at and near the FSDF

The occurrence of TCE in groundwater beneath the SSFL was first discovered in early 1984 when water supply wells were sampled and analyzed for the presence of TCE and certain other VOCs. Conventional fractured-rock methods that included the installation of various types of groundwater monitoring wells were used to characterize the groundwater at the FSDF and throughout the SSFL from about 1985 through the current characterization program. New methods of groundwater characterization have been added since about late 1997 after Rocketdyne retained the groundwater advisory panel, which consists of Drs. John Cherry and Beth Parker from the University of Waterloo and Dr. David McWhorter, Professor Emeritus from Colorado State University (Panel). These new methods included crushing rock core and laboratory analysis of porewater, installation of multi-level monitoring systems, and advancements in borehole geophysics methods as performed by the United States Geological Survey.

**Figure 2-1 FSDF RFI Site.** The FSDF RFI site lies within Area IV in the northwest portion of the SSFL. The site was primarily used to clean metallic sodium and NaK from equipment used in testing operations. The facilities included an Upper and Lower Pond, a building, and a concrete lined pool, all of which have subsequently been removed. Three separate excavations have occurred since 1980 near the Upper and Lower Ponds and the soils beneath and adjacent to these ponds have been completely excavated to bedrock. Four other RFI sites lie near the FSDF investigation area and include Building 56 landfill, Building 9 leachfield and another site referred to as ESADA.

## 2.2 Overview of Groundwater Site Conceptual Model for SSFL

In April of 2000, a Technical Memorandum was prepared and submitted to the California Department of Toxic Substances Control (DTSC) that presented a site conceptual model (SCM) regarding the movement of TCE in the Chatsworth formation at the SSFL (Montgomery Watson, 2000). The site conceptual model was based on the Panel's understanding of solute transport in fractured sedimentary rock (e.g., Chatsworth formation) and the data collected using new methods during the late 1990's. The site conceptual model was also based on geologic characterization work provided by Dr. Ross Wagner of MWH and hydrogeologic analysis provided primarily by Dr. Wagner and Larry Smith of Haley & Aldrich.

The SCM provided the basis for the development of the CFOU work plan (Montgomery Watson, 2001) for the FSDF investigation area, the results of which are presented in this report. A summary of the primary elements of the site conceptual model is provided below, based on available data as of late 1999.

1. **The fractures at the SSFL are small, systematic and interconnected.**

2. **The small, systematic and interconnected fractures, coupled with the porous sandstone matrix, facilitates diffusion of TCE into the matrix.**

3. **TCE plume fronts are strongly retarded due to matrix diffusion and the presence of organic carbon, and advance at rates that are orders-of-magnitude slower than the average linear groundwater velocity.**

## 2.3 Overview of CFOU Work Plan Approach

The data quality objectives process (United States Environmental Protection Agency [EPA], 1994) was used to ensure that data of sufficient quantity and quality have been collected to characterize groundwater throughout the SSFL. The data quality objective (DQO) process consists of the following seven steps:

1. State the problem.
2. Identify the decision question(s).
3. Identify inputs into the decision question(s).
4. Define the study boundaries.
5. Develop a decision rule.
6. Specify limits on decision errors.
7. Optimize the design.

The problem statement is: Comply with regulatory requirements by developing an accurate site conceptual model that describes and predicts the transport and fate of chemicals of concern in the Chatsworth formation operable unit. Substantiate the site conceptual model and determine appropriate actions for the site.

Eight decision questions were identified by the team during development of the DQOs, each of which is shown on Table 2-1. The data that are needed to resolve the decisions were specified along with the locations where the decisions are to be resolved in the FSDF work plan (study boundaries, these are shown in Figure 1-2).

The groundwater characterization strategy at the SSFL includes focusing the initial characterization activities at the FSDF and northeast investigation areas. The hydrologic conditions encountered at these two areas are expected to define the end members of the range of hydrologic conditions at the SSFL (i.e., the FSDF as lower permeability and the northeast as higher permeability). Information collected from these two study areas, along with other data and information collected at and around the site, will be used to confirm the groundwater site conceptual model and define the level of investigation needed at the remaining portions of the SSFL. At times, this report will present comparisons between the data and results from the FSDF investigation against those from the northeast investigation area so that the similarities and differences in the site conditions are made apparent.

**Table 2-1 CFOU Decision Questions**

| No | Decision Question |
|---|---|
| 1 | Is the subsurface mass of chemicals present consistent with the estimated mass of TCE that may have been released and consistent with the conceptual site model (i.e., highest concentrations adjacent to the input locations)? |
| 2 | Has the maximum depth-of-penetration of chemicals been characterized? |
| 3 | Does the presence of chemicals in the unsaturated portions of the Chatsworth Formation contribute to the further migration of the plume front? |
| 4 | Has the three-dimensional flow of groundwater been defined such that the direction of chemical solute transport can be predicted? |
| 5 | Has the migration of chemical solute at the plume front become effectively stable relative to a concentration threshold? |
| 6 | Does the current groundwater monitoring program adequately characterize the temporal and spatial variability of chemical solute? |
| 7 | Have the attenuation effects of dispersion and biodegradation been considered and quantified? |
| 8 | Is restoration of the Chatsworth formation groundwater technically practicable? |

# 3.0 GROUNDWATER CHARACTERIZATION WORK PERFORMED SINCE 2001

Field programs have been performed since early 2001 to characterize groundwater at the FSDF consistent with the work plans submitted to DTSC. These field programs include work performed under the CFOU work plan (Montgomery Watson Harza, 2001) and the Shallow Groundwater Investigation work plan (Ogden 2000). The work performed on the near-surface groundwater characterization program was previously reported (MWH, 2003b). The work performed as described in the CFOU work plan is summarized in Table 3-1. The work included applying both conventional and new investigation methods. Activities included: borehole geophysical logging, retrofitting existing wells with multi-level monitoring systems, sampling and analysis of the multi-level monitoring systems, coring and analysis of rock core for select VOCs, and various methods of aquifer testing. The locations where this work was performed are shown on Figure-3-1.

Additionally, one well was installed (RD-91) in March 2004 to provide additional groundwater gradient control and to assess the possibility of impacts from operations at Building 100, which is located east of the FSDF (Haley & Aldrich, 2004a, b).

Work performed to characterize near-surface groundwater at the FSDF investigation area included the installation of piezometers at five locations, very frequent water level measurements (daily for a brief period), and groundwater sampling and analysis.

| Task | Description |
|---|---|
| 1 | Removed existing downhole groundwater sampling and/or pumping equipment from 17 wells to allow for well redevelopment, and retrofitting with multi-level monitoring equipment and transducers. |
| 2 | Completed borehole geophysical logging at 6 wells/coreholes within or near the study area to provide stratigraphic and formation property information (i.e., porosity, permeability and fracture characteristics). |
| 3 | Drilled and sampled rock core from one location within the former Lower Pond (C-8) to provide data for characterizing this source area and confirm the molecular diffusion of VOCs and other chemicals into the bedrock matrix. A multi-level monitoring system was subsequently designed and installed in this corehole. |
| 4 | Installed multi-level monitoring systems with transducers and data loggers in 10 existing monitoring wells. Slug tests were performed in select wells to obtain an estimate of the vertical distribution of hydraulic conductivity and to assess the extent of the vertical connectivity of the formation. Transducers and data loggers were also placed in 7 other existing wells to frequently record water levels. |
| 5 | Collected depth-discrete water quality samples from saturated intervals at each well where a multi-level monitoring system was installed. The water quality data were intended to characterize the concentration of VOCs and other chemicals in groundwater and to delineate patterns of groundwater flow and mixing. |
| 6 | Performed a pumping test using RD-54B as an extraction well to further evaluate the effects, if any, of geologic features (e.g., faults, fractures, and fine-grained stratigraphic members) and to evaluate the connectivity of the formation. The data were also used to calculate the formation transmissivity, hydraulic conductivity, and storage on a larger scale than the data obtained from the slug tests. |

**Table 3-1 Work Performed as Outlined in the CFOU Work Plan for the FSDF**

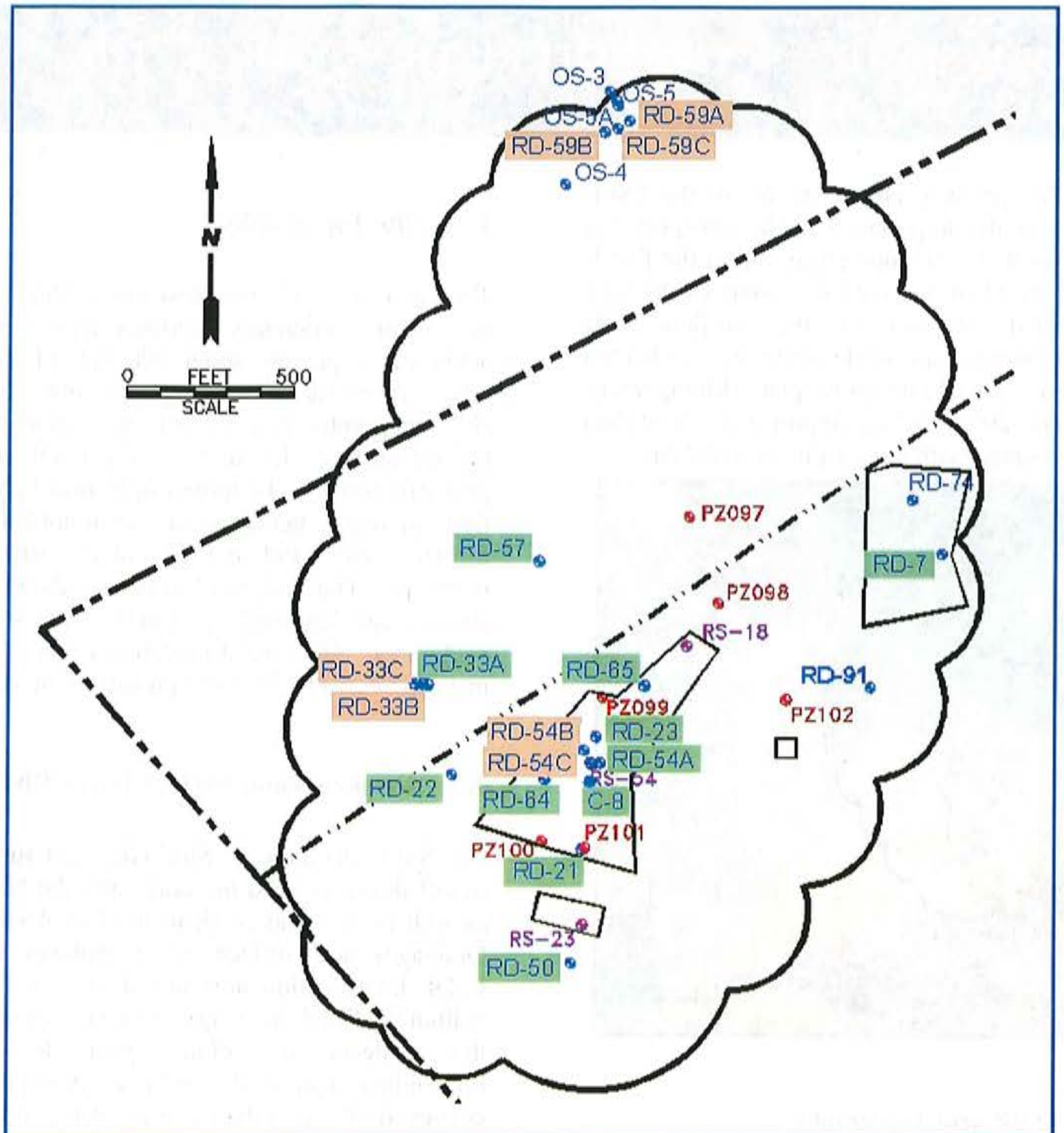



**Figure 3-1. FSDF Area Work Performed**

Groundwater characterization work at the FSDF included work on existing wells, installation of new wells and continuing implementation of new characterization methods developed by members of the groundwater advisory panel in the late 1990s. Work on existing wells included placement of pressure transducers for measuring water levels (highlighted above in orange) and retrofitting some of the wells with discrete-interval monitoring systems (highlighted above in green) that were used to collect vertical head profiles and for slug-testing. Five existing open-borehole wells (RD-7, RD-22, RD-23, RD-57, and RD-65) and one corehole (C-8) were also geophysically logged for stratigraphic, fractures, and rock property information.

The bedrock was cored at C-8 to a depth of 400 feet. Rock samples were collected at nearly one-foot intervals, crushed, preserved in methanol and then analyzed for select VOCs at this location. Nearly 300 samples of rock were analyzed in a laboratory for chemical constituents. A long-term pumping test (165 days of pumping) was also performed using RD-54B as the extraction well. New well installations consisted of 5 near-surface groundwater piezometers (identified above with a PZ prefix and shown in red) that were installed in 2001 and 2003 and one new well installed as part of characterizing groundwater near another potential source (RD-91 at the B100 RFI site). The three near-surface groundwater wells that existed prior to the work performed since 2001 are also shown above (RS-18, -23 and -54).

# 4.0 PHYSICAL CHARACTERISTICS OF THE FSDF INVESTIGATION AREA

Data regarding physical characteristics of the SSFL that have particular importance to the transport and fate of chemicals in the subsurface within the FSDF area are discussed in this section. Some of the data were collected as part of the Surficial OU characterization program, while others were collected as outlined in the CFOU work plan (Montgomery Watson Harza, 2001). Where appropriate, these data were supplemented with relevant historical data.

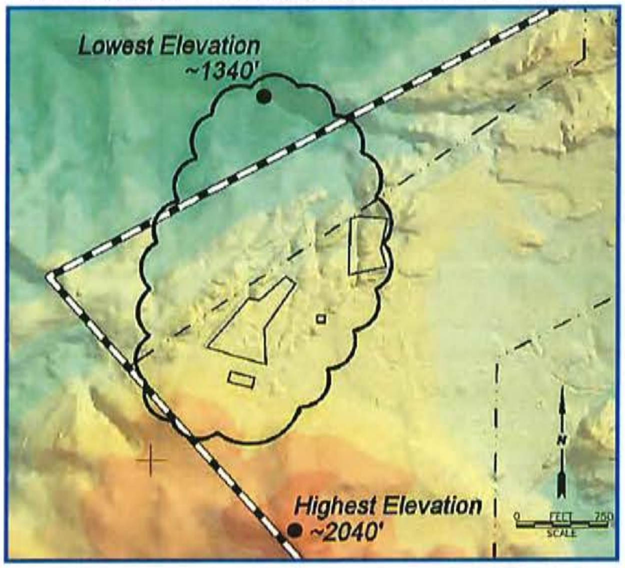



**Figure 4-1 FSDF Area Topography**
The topography within the FSDF investigation area varies by about 700 feet. The highest elevation (~2040 feet msl) lies south of the FSDF outside the study area boundary and the lowest elevation (~1340 feet msl) lies in the northern extent of the study area. RFI site boundaries are outlined in black.

## 4.1 Site Topography

The area of land encompassed within the FSDF investigation boundary occupies approximately 107 acres and expresses about 700 feet of topographic relief. A shaded-relief topographic map showing the site topography is provided on Figure 4-1. The highest surface elevations in the FSDF area occur primarily south of the former operational facilities. A ridge of rock outcrops exists north-northwest of the former ponds and extends along strike to the northeast. The highest elevation is about 2,040 feet above mean sea level (msl) and occurs south of the study area. The lowest elevation is about 1,340 feet msl and occurs in the northern part of the study area.

## 4.2 Drainages and Surface Water Divides

The SSFL sits atop the Simi Hills and surface water runoff drains both to the north into the Simi Valley, as well as east and south to the Los Angeles River. Drainages and surface water features within the FSDF investigation area are shown on Figure 4-2. Within the FSDF investigation area, the surface water that collects and drains from former active operational areas at the SSFL is intermittent and is conveyed offsite to the north in what is referred to as the northwestern drainage of the SSFL. The northwestern drainage connects to the Meier Canyon drainage offsite to the north and discharges into Arroyo Simi further to the north within Simi Valley. A small section of land in the northwest portion of the SSFL that has had no operational activities drains into Runkle Canyon.

Locally within the FSDF RFI site, surface water drains through two ephemeral channels, referred to as Channels A and B. Surface water discharges at these two channels are monitored at National Pollutant Discharge Elimination System (NPDES) permit outfall numbers 5 and 6, respectively. There are no surface water bodies within the FSDF investigation area.

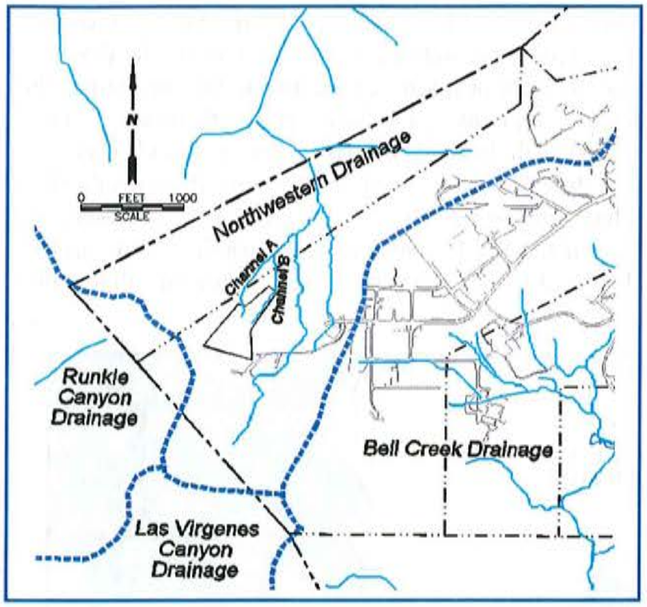



**Figure 4-2. Northwest Area Surface Water Divides**
The topography to the south of the FSDF investigation area creates a number of surface water divides that are the headwaters to four different drainages. Operational activities at the FSDF were conducted within one of the four drainages (i.e., the Northwestern drainage). All drainages are ephemeral in nature. When flowing, the Northwestern drainage flows into the Simi Valley as does the Runkle Canyon drainage. The Bell Creek drainage flows into the San Fernando Valley, while the Las Virgenes Canyon drainage flows through the Santa Monica Mountains to the south.

## 4.3 Precipitation

Precipitation at the SSFL has averaged approximately 18.8 inches per year between 1960 and 2004. The annual precipitation has ranged from a low of 5.7 inches in 2002 to a high of 41.2 inches in 1998. Figure 4-3 shows annual precipitation between 1960 and 2004. The majority of the precipitation at the SSFL occurs between the months of November and March of each year, consistent with the regional precipitation pattern of southern California. Precipitation has been measured daily at the SSFL during rainstorms at two on-site measuring stations. One station is located in the northeast portion of Area I within the IEL RFI site and the other station was located near the FSDF. These gauges are referred to as Stations I and IV, respectively. The measuring station near the FSDF is no longer active.

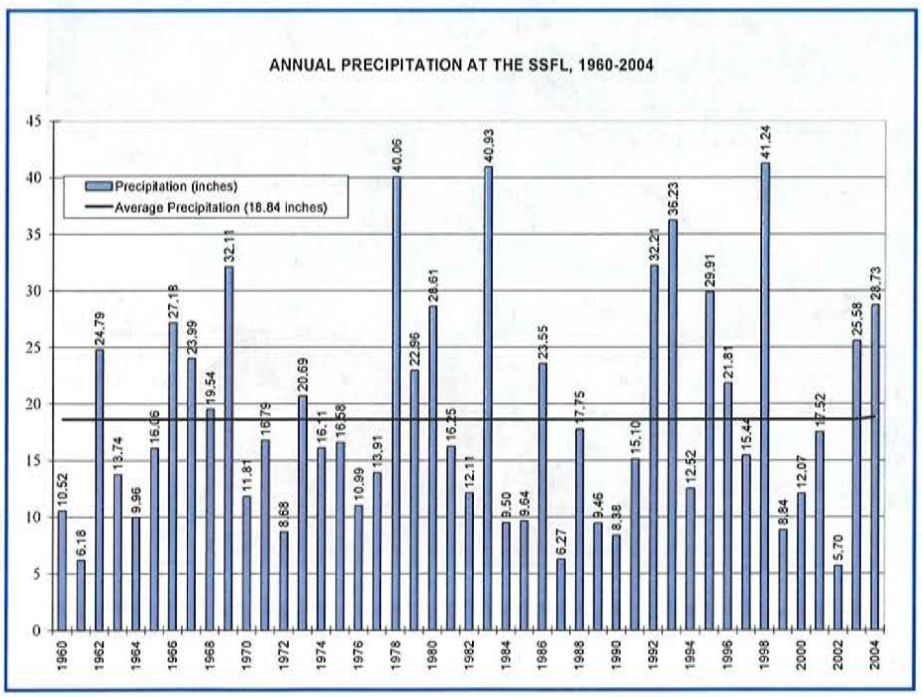



**Figure 4-3 Annual Precipitation Diagram**
Annual precipitation at the SSFL over the last 45 years has averaged about 18.8 inches. The maximum amount of annual precipitation recorded occurred in 1998 and was more than 41 inches. The minimum amount of annual precipitation recorded occurred in 2002 and was 5.7 inches.

## 4.4 Regional Geology

The SSFL is located in the Transverse Ranges of southern California, a geologic province that is in north-south compression. Geologic structures, such as faults and folds, strike in an approximately east-west direction. The regional geology is shown on Figure 4-4.

Most of the SSFL is underlain by the late Cretaceous Chatsworth formation, a deep-sea turbidite deposit that consists primarily of sandstone interbedded with lesser amounts of shale and siltstone. The Chatsworth formation strikes approximately N70°E and dips 25° to 35° to the northwest. As a result, the Chatsworth formation is younger in the northwestern part of the SSFL than it is in the southeastern part of the SSFL. Previous work showed that the

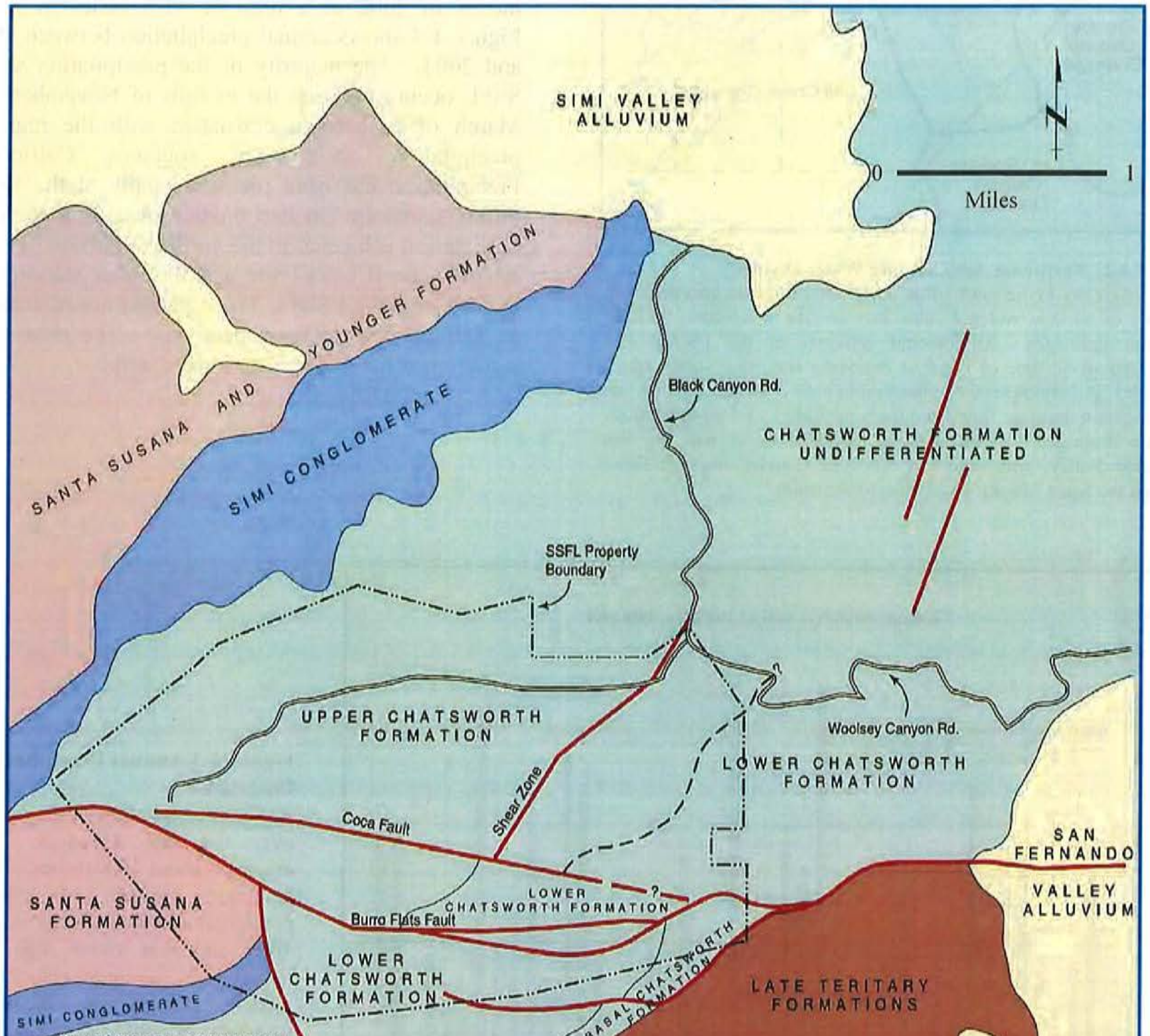



**Figure 4-4 Regional Geology**
The Chatsworth formation lies beneath the SSFL, with the Simi Conglomerate, Santa Susana and younger formations lying stratigraphically above the Chatsworth formation northwest of the SSFL. To the south of the SSFL, the late Tertiary formations lie uncomformably atop the Chatsworth formation.

Chatsworth formation can be subdivided into several stratigraphic units based on variable amounts of finer-grained sediment (Montgomery Watson 2000).

The Chatsworth formation is conformably or disconformably overlain by the Simi Conglomerate Member of the Paleocene Santa Susana formation in the northern part of the site, and is faulted against the Santa Susana formation in the western part of the site. To the south, the Chatsworth is unconformably overlain by southward dipping late Tertiary formations. Structurally, the facility is located on the south flank of an east-west striking and westward plunging syncline which passes through the central part of the Simi Valley.

## 4.5 Site-Specific Geology

The primary geologic units present at the SSFL are the Quaternary alluvium and the Cretaceous Chatsworth formation. However, local to the FSDF investigation area, the Santa Susana formation is present both to the north and south. Alluvial soils are generally thin at the SSFL and are typically 5 to 15 feet thick. The alluvium usually occurs at the base of hill slopes, in topographic lows, and along stream drainages. Fill soils have been placed within the FSDF investigation area subsequent to implementing interim measures that included the excavation of soil to the top of bedrock. Native and fill soils are

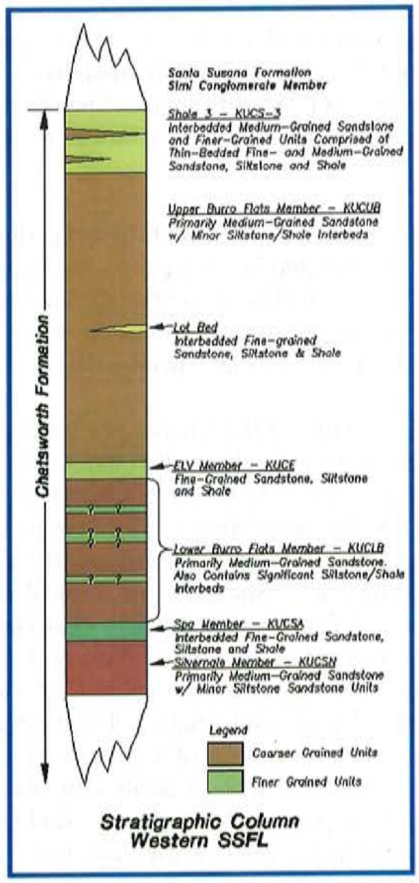



**Figure 4-6 FSDF Area Stratigraphic Column**
The coarser-grained Upper Burro Flats member primarily lies beneath the FSDF investigation area. A sequence of finer and coarser-grained members underlie the Upper Burro Flats member as shown on the stratigraphic column. The finer-grained Shale 3 lies stratigraphically above the Upper Burro Flats member. Individual beds within these members were also identified and mapped when appropriate.

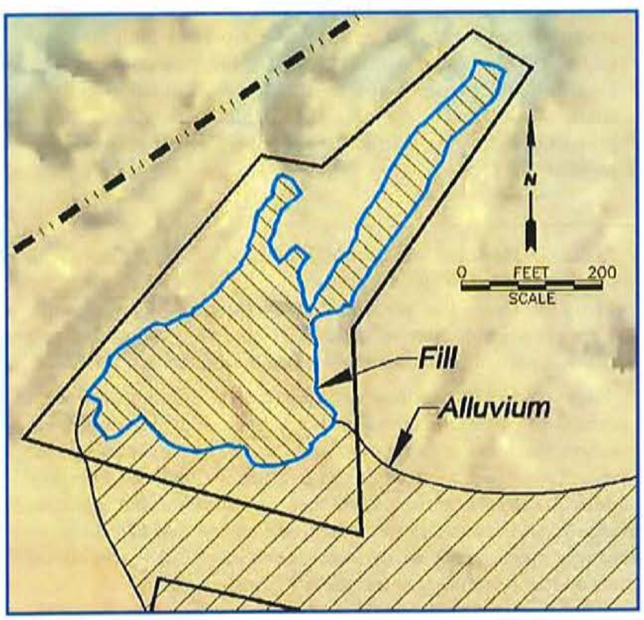



**Figure 4-5 Alluvium/Fill Areas**
Both alluvium and fill are present at the FSDF at thicknesses ranging from about 2 to 12 feet. Alluvium is present primarily south of the FSDF and is derived from weathering of the Santa Susana and Chatsworth formations. Fill soils have been placed over the excavated portions of the FSDF and were obtained from an on-site source located to the south/southeast of the FSDF.

generally comprised of the weathered Chatsworth and Santa Susana formation materials, and are typically fine-grained silty sands. The distribution of alluvium/colluvium and/or fill soils is shown on Figure 4-5.

Stratigraphy beneath the FSDF investigation area of the SSFL is depicted in Figure 4-6. Stratigraphically, the FSDF lies within a coarser-grained sandstone member of the Upper Chatsworth formation referred to as the Upper Burro Flats member (KUCUB).

Stratigraphic units of the Chatsworth formation at the SSFL are not defined on the basis of a unique lithology associated with each of the members, but on the basis of the proportion of finer-grained material in the member. The finer-grained members (e.g., the ELV member and Shale 3) are typically at least 50 percent siltstone and shale. Coarser-grained members (e.g., Upper Burro Flats and Silvernale Members) are typically composed of less than 5 percent siltstone and shale. Lithologically, the finer-grained units consist of a mixture of sandstone, siltstone, and shale, with siltstone and shale making up at least 50 percent of the rock. Bedding in the finer-grained units is typically less than three feet thick, and commonly is less than one foot thick. The finer-grained stratigraphic units locally contain sandstone beds that are up to 10 to 20 feet thick. These sandstone beds can be persistent laterally, and they are lithologically indistinguishable from sandstones that comprise the coarser-grained units. The coarser-grained stratigraphic units are composed of medium to fine-grained sandstone. The sandstone beds are typically three to six feet thick and are amalgamated. Siltstone and shale interbeds are relatively rare or absent. As a result, stratigraphic intervals that are as much as tens of feet thick are composed exclusively of sandstone.

A number of geologic structures are present within the FSDF investigation area. The locations of these features are shown on Figure 4-7. The Burro Flats fault lies in the southern portion of the study area and strikes approximately east-west at this location. There are two features that strike approximately north-south in the eastern portion of the study area that have been defined as the Western and Eastern FSDF structures. These features have been defined as structures because outcrop data are insufficient to establish if the structure is a fault zone or consists solely of deformation bands. A series of deformation bands are also present within the RFI site that generally strike northeast-southwest and have currently been defined to comprise the western extent of the North Fault zone. Deformation bands[1] exhibit small displacements (i.e., less than six inches) of the stratigraphy that are distributed across a narrow cataclastic[2] zone (typically 0.1 inches wide or less). Alternately, faults typically show stratigraphic displacements that exceed five feet. A detailed geologic map local to the FSDF was developed during the interim measure implemented in 2000 and is included within Appendix A.

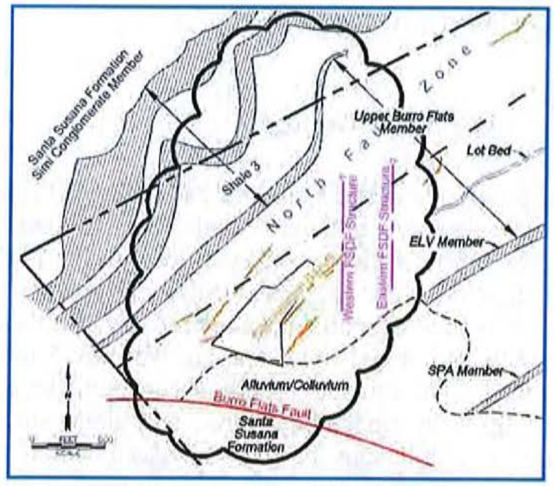



**Figure 4-7 Geology of the FSDF Investigation Area**
The geologic map of the northeast portion of the SSFL shows the locations of the Burro Flats fault, the FSDF structures and a series of deformation bands that comprise the western extent of the North fault zone. The Burro Flats fault strikes east-west and interrupts the stratigraphic sequence as is evident by the presence of the Santa Susana formation to the south of the fault. Stratigraphically, the study area lies primarily within the Burro Flats member, which is overlain by Shale 3

[1] Aydin (1978) describes deformation bands as "small faults with displacements of a few millimeters or centimeters that are primary structures that precede the development of large faults. Deformation bands have much smaller grain size, poorer sorting and lower porosity than the original parent sandstone."

[2] Engelder (1974) defines cataclasis as a "friction-dependent mechanism of deformation involving fracturing and rigid-body rotation that occurs during faulting in sandstone in the upper crust. Two stages of cataclasis of a sandstone include (1) mildly deformed cataclastic sandstone that is shattered but contains many original grains that have not fragmented and (2) gouge so severely deformed that the few surviving grains are almost surrounded by a fine-grained matrix of crushed grains."

## 4.6 Bedrock Properties

The bedrock matrix underlying the SSFL has a controlling influence on groundwater flow and contaminant transport and fate. As such, measurements of various physical properties of the bedrock were made. Values for bedrock properties were estimated based on laboratory measurements performed on selected samples of the bedrock, and from borehole geophysical logs that were collected from select wells and boreholes in the FSDF investigation area. It should be noted that the direct physical measurements from the bedrock samples represent discrete values for discrete vertical intervals. Alternately, the geophysical logs infer the bedrock properties by using various instruments to make measurements nearly continuously over the full length of the borehole. Laboratory measurements taken from coreholes throughout the SSFL and geophysical measurements from wells located within the FSDF investigation area are discussed below.

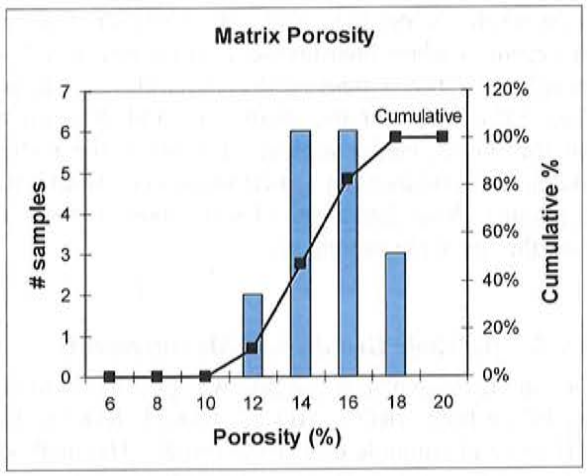
### 4.6.1 Laboratory Measurements

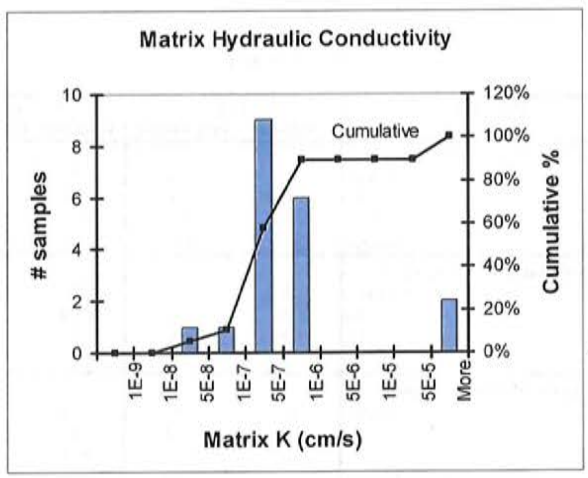
Tests were performed on samples of bedrock collected from corehole C-8 at the FSDF and from other coreholes and wells located throughout the SSFL. These tests measured bedrock properties, including hydraulic conductivity, air permeability, organic carbon content, wet and dry bulk density, porosity, and calcium carbonate content.

Bedrock samples were collected from corehole C-8 at various depths. Sampling and analytical methods have been previously reported [Sterling (1999), Golder (1997) and the University of Waterloo (2003)]. The physical property measurements made on the samples from C-8 are summarized as follows:

- Hydraulic conductivity (19 samples) – 2.6 x $10^{-7}$ centimeters per second [cm/s (geometric mean)]
- Geometric mean organic carbon content (percent by weight):
  - All sandstones (12 samples) - 0.014
  - Interbedded (3 samples) - 0.302
- Average wet bulk density (17 samples) - 2.45 grams per cubic centimeter (g/cc)
- Average dry bulk density (17 samples, sandstones) - 2.31 g/cc
- Average total porosity (17 samples) - 14.2 percent

Histograms of the rock matrix porosity and hydraulic conductivity from the sample measurements from C-8 are shown on Figures 4-8 and 4-9, respectively.




**Figures 4-8 and 4-9 Histograms of Matrix Porosity and Matrix Hydraulic Conductivity.** Laboratory measurements have been made of the physical properties of the bedrock matrix underlying the FSDF from samples collected at corehole C-8. These measurements show that the geometric mean of the matrix hydraulic conductivity is about 2.6 x $10^{-7}$ centimeters per second. The measurements also show that the average porosity is about 14 percent.

The samples on which laboratory measurements were made were grouped into two lithologies, sandstones and interbedded for both corehole C-8 and for all other coreholes located throughout the site for which measurements have been made. This comparison is shown on Table 4-1. Additional details on the site-wide measurements are described in the Source Zone Characterization Report (University of Waterloo, 2003). Inspection of the tabulated results indicates that the measurements from corehole C-8 samples are similar for porosity and wet and dry bulk density (i.e., the relative difference between the C-8 and site-wide results is less than 5%). However, the fraction of organic carbon measurements from corehole C-8 samples are lower than in the site-wide sample set (i.e., 33% lower for the sandstones and 26% lower for the interbedded samples). Likewise, the matrix hydraulic conductivity measurements from the corehole C-8 sandstone samples are about 36% lower than the site-wide sample set.

### 4.6.2 Borehole Geophysical Measurements

Downhole geophysical logging was performed in six wells/boreholes (RD-7, RD-22, RD-23, RD-57, and RD-65) and corehole C-8 at the FSDF. The methods and results of the logging, including geophysical montages for each well and borehole, are reported in *Technical Memorandum – Collection of Various Bedrock Properties Using Borehole Geophysical Logging Methods in the FSDF Area* (MWH, 2002b).

The borehole geophysical measurements were used to evaluate the stratigraphy at depth and for inter-well correlations to characterize the three-dimensional geometry of the geology. The borehole geophysical tools also provided porosity and permeability estimates of the rock matrix and information on the frequency and orientation of bedding planes and fractures. A section of the geophysical log from RD-23 depicting the rock matrix porosity and permeability measurements is shown on Figure 4-10.

**Table 4-1**
Laboratory Measurement of Rock Matrix
Physical Properties

| Parameter | C-8 Sandstone | C-8 Interbedded | All Coreholes Sandstone | All Coreholes Interbedded |
|---|---|---|---|---|
| **Porosity (%)** | | | | |
| # samples | 17 | NA | 105 | 13 |
| Min | 10.9 | NA | 3.70 | 2.30 |
| Max | 17.3 | NA | 19.3 | 13.8 |
| Average | 14.2 | NA | 13.6 | 6.70 |
| **Wet Bulk Density (g/cm$^3$)** | | | | |
| # samples | 17 | NA | 92 | 10 |
| Min | 2.07 | NA | 2.19 | 2.42 |
| Max | 2.78 | NA | 2.58 | 2.53 |
| Average | 2.45 | NA | 2.42 | 2.47 |
| **Dry Bulk Density (g/cm$^3$)** | | | | |
| # samples | 17 | 5 | 100 | 16 |
| Min | 1.96 | 2.34 | 2.07 | 2.31 |
| Max | 2.62 | 2.44 | 2.54 | 2.54 |
| Average | 2.31 | 2.40 | 2.29 | 2.43 |
| **$f_{oc}$ (%)** | | | | |
| # samples | 12 | 3 | 134 | 20 |
| Min | 0.008 | 0.274 | 0.006 | 0.025 |
| Max | 0.017 | 0.354 | 0.264 | 1.382 |
| Geomean | 0.014 | 0.302 | 0.021 | 0.410 |
| **Matrix K (cm/s)** | | | | |
| # samples | 19 | NA | 110 | NA |
| Min | 4.96E-08 | NA | 3.68E-09 | NA |
| Max | 9.65E-02 | NA | 9.65E-02 | NA |
| Geometric Mean | 1.01E-06 | NA | 7.94E-07 | NA |
| Geometric Mean (excluding outliers) | 2.61E-07 | NA | 4.06E-07 | NA |

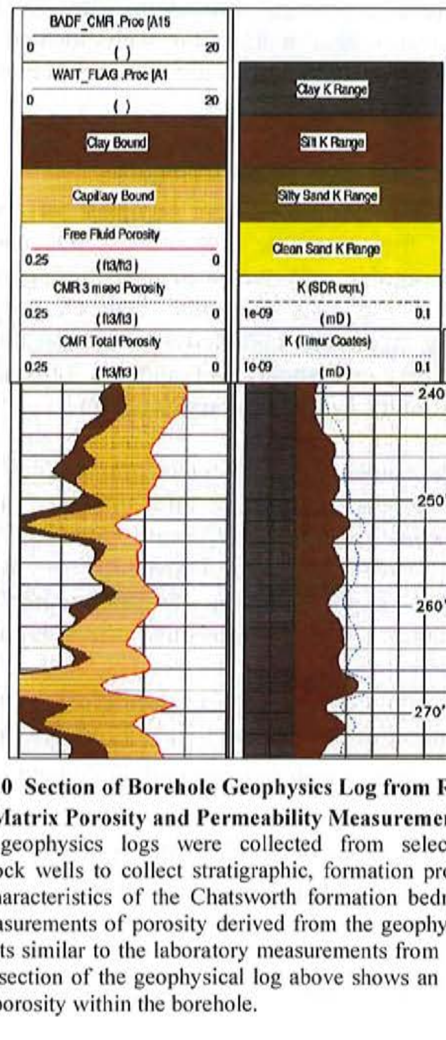



**Figure 4-10 Section of Borehole Geophysics Log from RD-23 Showing Matrix Porosity and Permeability Measurements**
Borehole geophysics logs were collected from select existing open-bedrock wells to collect stratigraphic, formation property and fracture characteristics of the Chatsworth formation bedrock. The in-situ measurements of porosity derived from the geophysical tools show results similar to the laboratory measurements from samples at C-8. The section of the geophysical log above shows an interval of increased porosity within the borehole.

# 5.0 GROUNDWATER

This section of the report describes the hydrogeologic conditions of the groundwater system germane to the site conceptual model, including:

- Groundwater occurrence
- Temporal changes in water levels
- Recharge and discharge
- Formation connectivity, and
- Hydraulic conductivity.

Tables and figures that provide supporting information to this section are provided in Appendix A.

## 5.1 Groundwater Occurrence

As previously discussed, groundwater at the SSFL occurs in alluvium/colluvium, weathered bedrock, and unweathered bedrock.

The occurrence of groundwater at the SSFL is depicted diagramatically in Figure 5-1.

Groundwater that is present in either alluvium/colluvium and/or weathered bedrock has been referred to as near-surface groundwater for the purposes of human health and ecological risk assessments. Depending upon location at the SSFL, the near-surface groundwater can either be perched above or vertically continuous with the Chatsworth formation groundwater.

Near-surface groundwater is perched above Chatsworth formation groundwater in the FSDF investigation area. A cross-sectional diagram of near-surface and Chatsworth formation groundwater occurrence is shown on Figure 5-2. Near-surface groundwater is encountered at an average depth as shallow as 7.6 feet bgs at RS-18 to 22.7 feet bgs at RS-54. The near-surface groundwater in the FSDF area is laterally discontinuous and has limited areal extent. The occurrence of near-surface groundwater in the FSDF is shown in plan view of Figure 5-3.

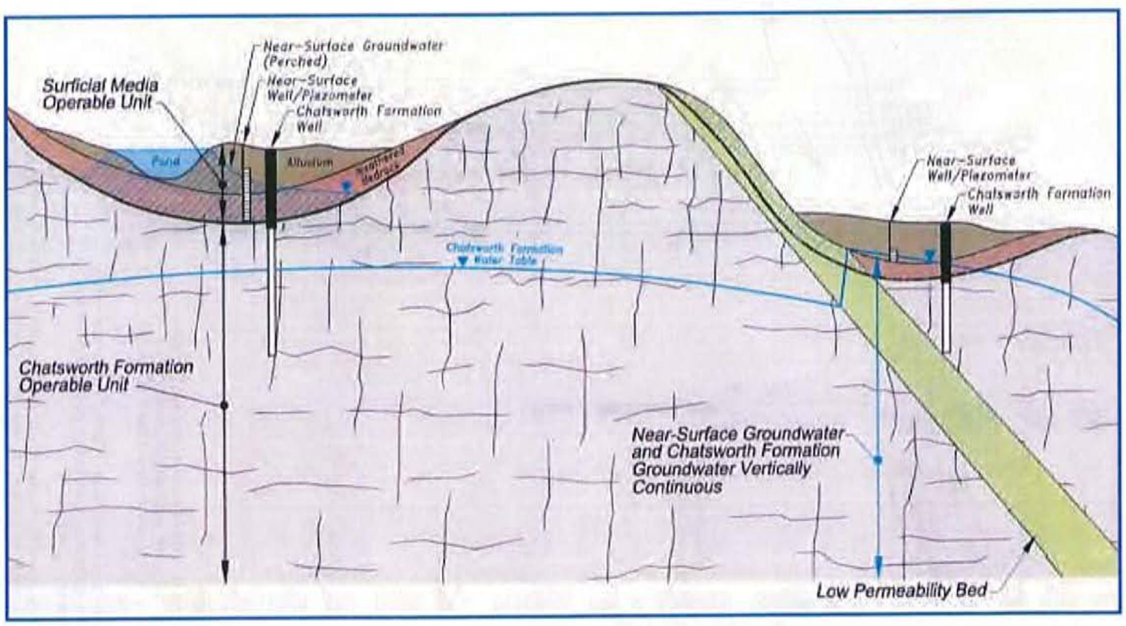
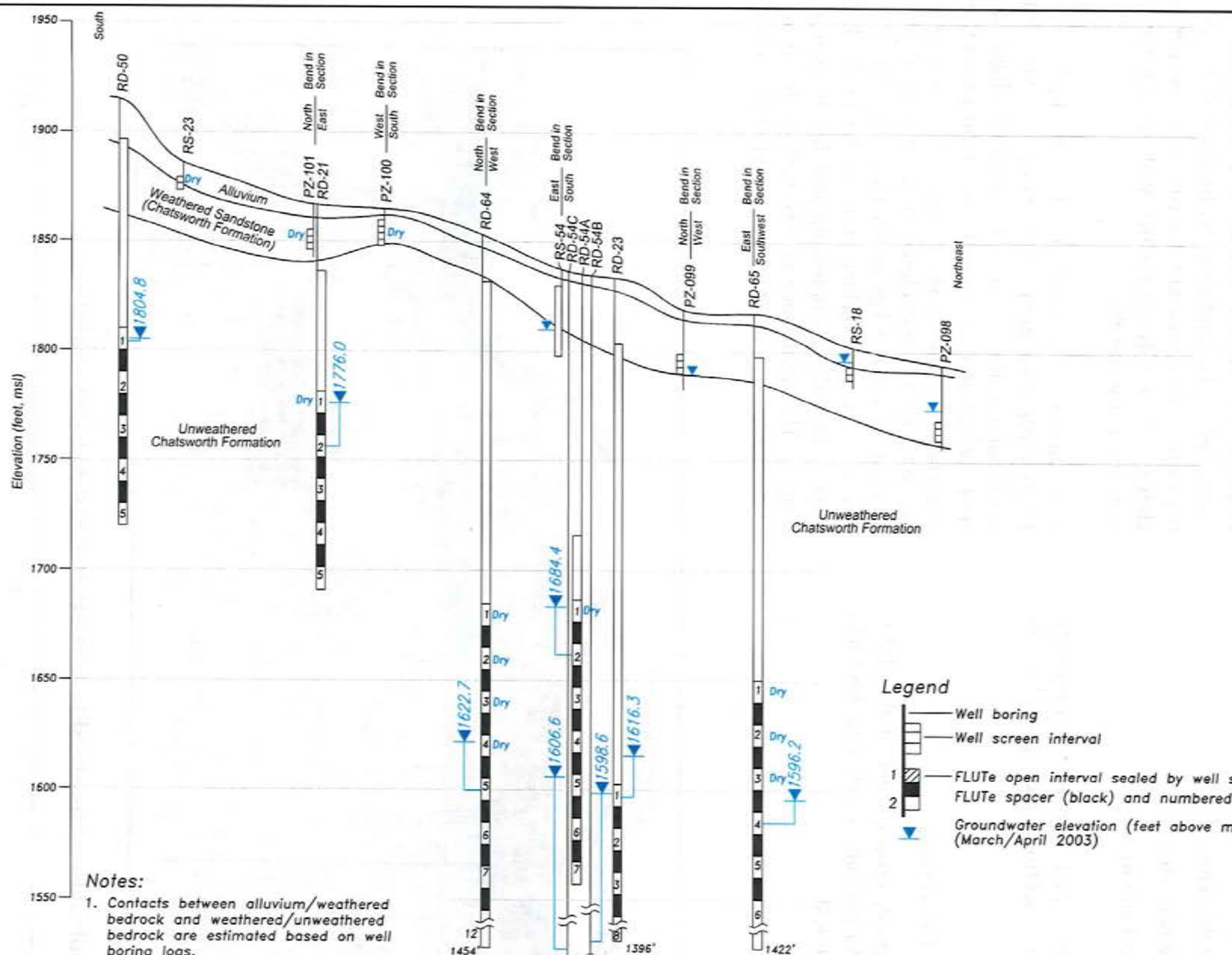
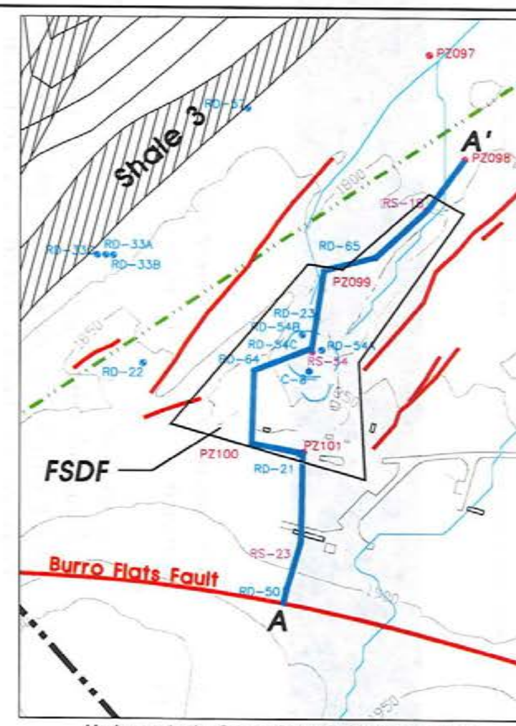



**Figure 5-1 Conceptual Diagram of SSFL Groundwater System (cross-section)**




Notes:

1. Contacts between alluvium/weathered bedrock and weathered/unweathered bedrock are estimated based on well boring logs.
2. Multi-Level well liner (FLUTe) with alternating open (discrete monitoring port) and closed (spacer) intervals.
3. For wells with FLUTe multi-level systems installed, water level data is shown for the first saturated port only. Liner in RD-64 ruptured during or shortly after installation.
4. Stratigraphy and structure of Chatsworth Formation not show.




Hydrogeologic Cross Section A-A' Location

0 FEET 200
SCALE

MWH

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FEBRUARY 2006

HYDROGEOLOGIC CROSS SECTION A-A'

FIGURE 5-2



INDSVR\INDUSTRIAL\CAD MLUEBKE\BOEING\SANTA SUSANA\FSDF\XSEC AA 2 06

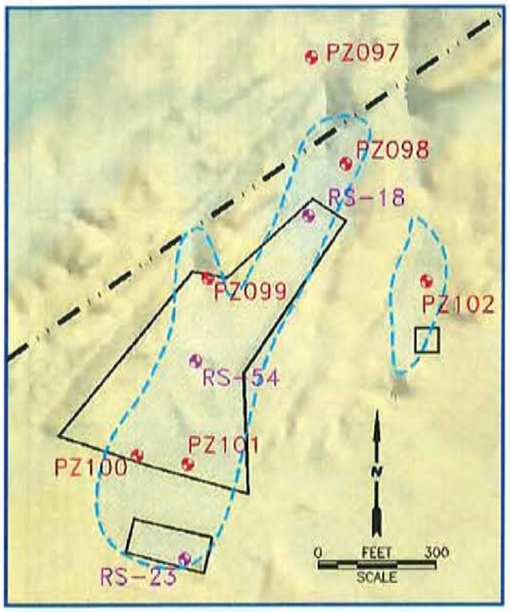



**Figure 5-3 Plan View of Near-Surface Groundwater Occurrence**

The near-surface groundwater within the FSDF area of the SSFL occurs within the weathered bedrock and is perched above the Chatsworth formation groundwater. Chatsworth formation groundwater does not rise into the weathered bedrock within the FSDF area. The occurrence of near-surface groundwater is shown in blue on this figure and is based on water level measurements collected in March 2005.

Depth to Chatsworth formation groundwater in the FSDF area is quite variable. This variability is the result of one or more of the following physical conditions at the FSDF investigation area:

- Large vertical changes in surface topography over short lateral distances (i.e., steep slopes) that may cause groundwater to perch atop lower permeability units,
- Small-scale geologic features in the form of finer-grained beds and deformation bands that may produce large local changes in the potentiometric surface across these features (see Figure A-1 in Appendix A for surface geology local to the 2000 FSDF excavation), and
- A reduced bulk hydraulic conductivity of the formation (discussed further in Section 5.6).

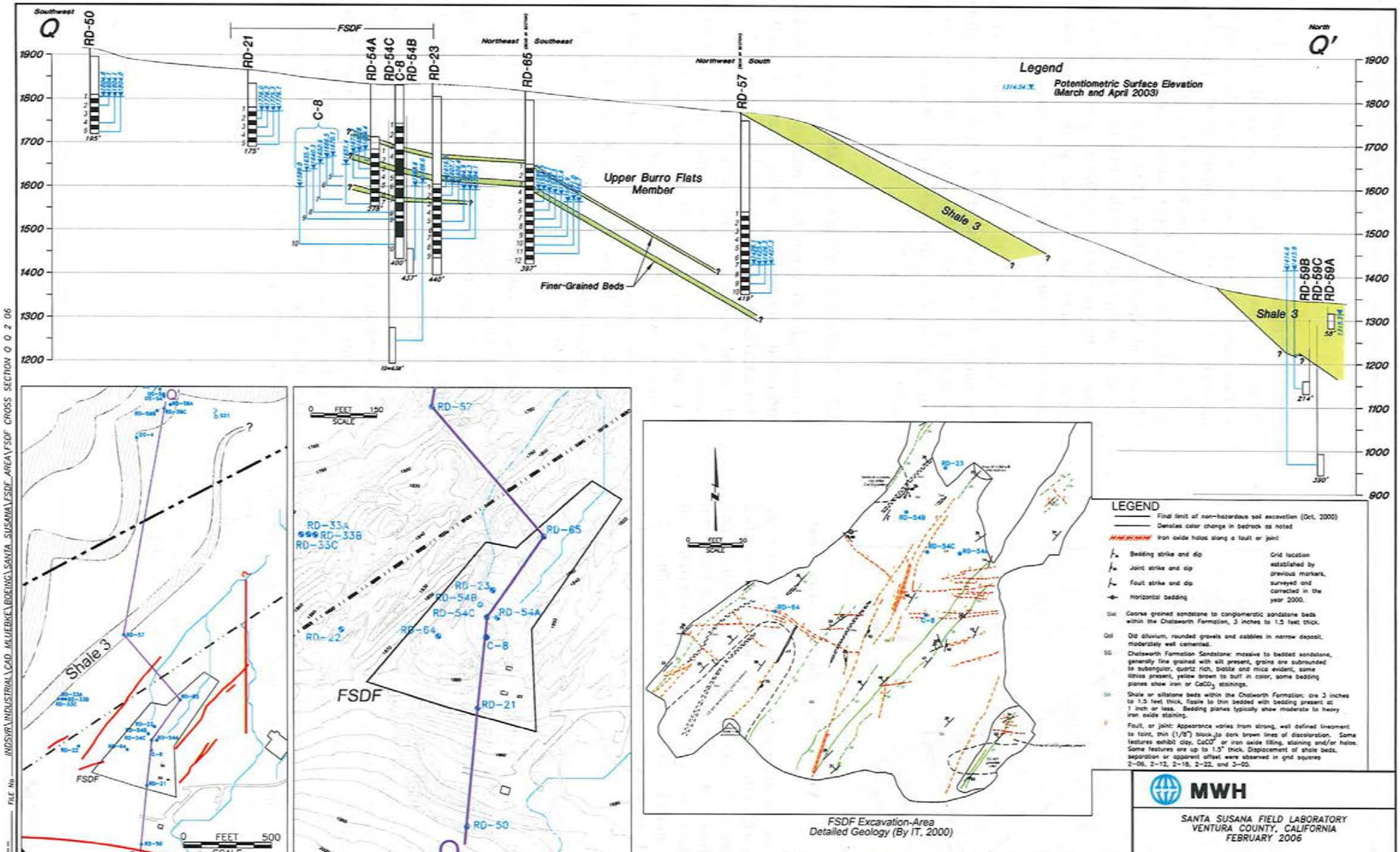
Figure 5-4 depicts various information related to the discussions above. The cross-section shows the surface topography, well construction and completion intervals (including the multi-level monitoring systems) and the head measurements collected from the wells and multi-level monitoring systems in March and April of 2003. Plan view inserts are also included on this cross-section that depict the various scales of the geology [investigation area and FSDF excavation area (created during the 2000 interim measure)], and the topography of the area.

Depths to Chatsworth formation groundwater are encountered as shallow as 25 feet below ground surface (e.g., in RD-59A, offsite to the north of the property boundary) to nearly 345 feet below ground surface (e.g., in RD-57).

## 5.2 Temporal Changes in Water Levels

Hydrographs of water level changes in Chatsworth formation monitoring wells were created to characterize the temporal variability over the period of record, which for some wells is nearly 17 years. Figure 5-5 shows two hydrographs typical of temporal water level fluctuations in Chatsworth formation wells in the FSDF area. Hydrographs for all Chatsworth formation wells are provided in Appendix A. Hydrographs for RD-50 and RD-54A are representative of hydrographs for most of the wells in the FSDF area.

As can be seen on the hydrograph of RD-54A, water levels fluctuate slightly over multiple seasons and years. Between 1996 and 2002, water levels remain within a range of about 10 feet. Seasonal water level fluctuations are generally less than a few feet and occur gradually. Groundwater fluctuations corresponding to the wettest and driest seasons during this period are not evident in the hydrograph (see Figure 4-3 for annual rainfall amounts). A similar pattern of water level fluctuation is evident in RD-23, RD-33A, and RD-59A.




Please Note: The original version of this figure includes colorized features and shading. A black and white copy of this figure should not be used because it may not accurately represent the information presented.

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FEBRUARY 2006

**CROSS SECTION Q-Q'**

FIGURE 5-4

JOB No. — FILE No. — INDSVR\INDUSTRIAL\CAD MLUEBKE\BOEING\SANTA SUSANA\FSDF AREA\FSDF CROSS SECTION Q Q 2 06

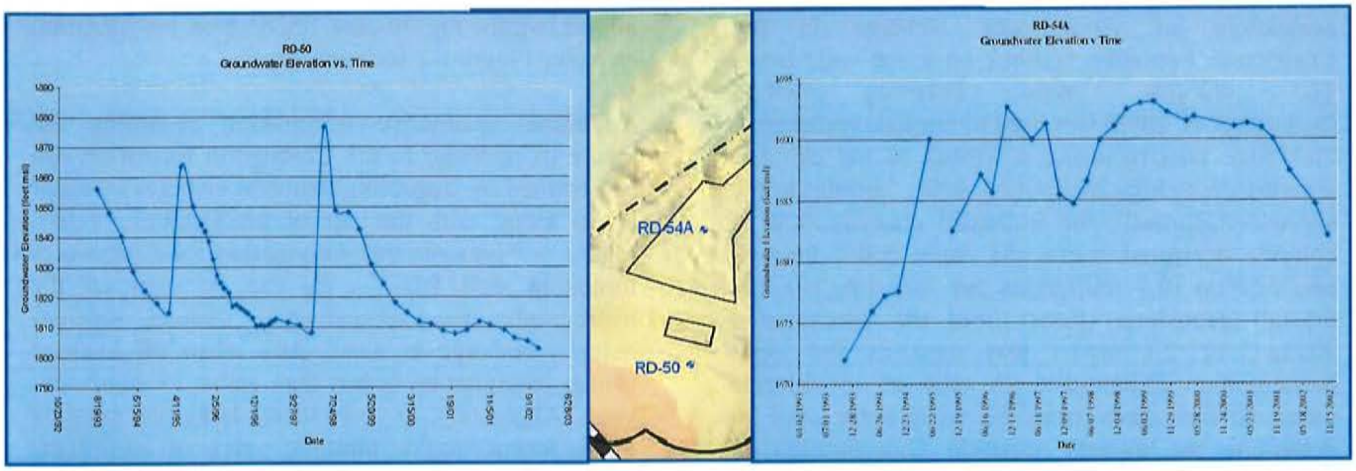



**Figure 5-5 Hydrograph of RD-50 and of RD-54A with Site Location Map.** The lesser fluctuations that occur in RD-54A likely reflect either (1) high storage capacity for the screened interval of bedrock, which would act to "buffer" the impacts of infiltrating precipitation and surface water, or (2) the presence of low permeability sediments between the well screen and ground surface. If present, the low-permeability sediments prevent or minimize infiltration of precipitation and surface water to the monitored horizon.

The larger fluctuations and rapid response to precipitation events observed in RD-50 reflect the small storage capacity of the bedrock. The hydrograph for RD-50 has one of the largest hydraulic responses to recharge (68 feet of rise) of the wells in the FSDF area in winter 1997-1998. This large increase occurred after heavy rains (41 inches) in that winter. Water elevations then decline gradually through winter 2001, a period of about three years. The average rate of decline is about -2.4 feet per month during this period, or about 12 times more gradual than the rate of water level rise in the winter of 1997-1998.

The hydrograph for RD-50 shows relatively large water level fluctuations between 1993 and 2002. The three wettest years within the period of examination (1993, 1995 and 1998) are marked by significant increases in water levels. The water level increased by about 68 feet over a short period during the 1997-1998 winter. The water level did not drop back to the original level until April of 2000, about 24 months later. The calculated rate of decline is 2.4 feet per month or more than 12 times slower than the rate of water level increase. A similar phenomenon occurred in winter of 1995-1996. Other wells exhibiting a similar pattern of fluctuation include RD-7, RD-22, RD-59B and RD-59C.

The lesser fluctuations that occur in the first group of wells likely reflect either: (1) higher storage capacity for the screened interval of bedrock, which would act to "buffer" the impacts of infiltrating precipitation and surface water, or (2) the presence of low-permeability sediments between the well screen and ground surface, which would minimize infiltration of precipitation and surface water to the monitored horizon.

The larger fluctuations, and rapid response to precipitation events observed in the deeper wells, reflect the small storage capacity of the bedrock. The years 1993, 1995, and 1998 were the three wettest years since 1978 (see Figure 4-3). Precipitation amounts in each year exceeded 35 inches. Each period of increased water levels in the deeper wells listed above is followed by a prolonged gradual decline, (unless the well is located along an ephemeral stream, which appears to augment recharge). The gradual decline reflects the low to moderate bulk permeability of the bedrock. Once recharge ceases after significant precipitation events, water levels gradually decline as water slowly drains from the rock.

### 5.3 Recharge

The *Technical Memorandum – Analysis of Groundwater Recharge* (MWH, 2003c) provided both quantitative estimates and qualitative evaluations of groundwater recharge in the Chatsworth formation bedrock on a site-wide basis. The chloride mass balance method (Scanlon et al, 2002) was used to estimate recharge in the FSDF area by using a sub-set of the chloride measurements from monitoring wells. Similar to the site-wide approach, the estimated concentration of chloride deposited across the entire SSFL through precipitation (0.7 milligrams per liter [mg/L]) and dry-fall deposition (three times the precipitation amount, or 2.1 mg/L) was used as the input concentration (2.8 mg/L). A total of 38 chloride measurements taken from 17 wells were used to determine the average chloride concentration in Chatsworth formation groundwater within the FSDF area. The average measured concentrations from each well are shown on a histogram on Figure 5-6.

The average chloride concentration in Chatsworth formation groundwater in the FSDF area is 53 mg/L. This value is 10 percent lower than the SSFL-wide estimated value of 59 mg/L. Dividing the input concentration of 2.8 mg/L by the average groundwater concentration yields a recharge value of 5.3 percent of the average annual rainfall of 18.8 inches per year or about 1 inch of rain per year. This rate of recharge converts to about 1.5 gallons per

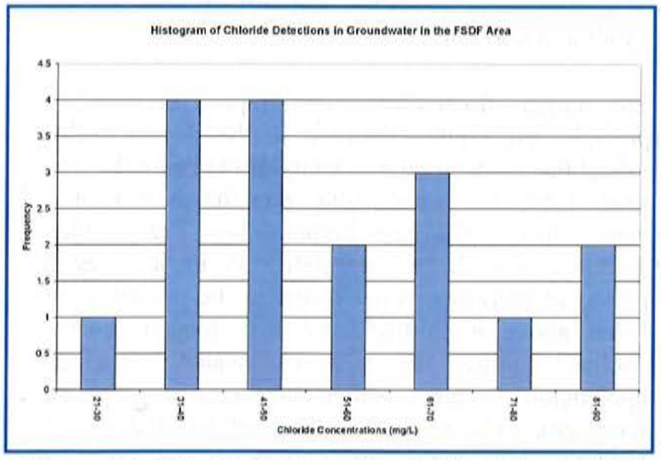



**Figure 5-6 Chloride in Groundwater Histogram**
This histogram shows the distribution of the average chloride concentration in Chatsworth formation monitoring wells located in the FSDF area. Concentrations range from a low of 26 mg/L at RD-57 to a high of about 89 mg/L in RD-22. The average concentration is 53 mg/L. Values from two wells, RD-33A and RD-33B, were discarded as outlier concentrations that were not representative of Chatsworth formation groundwater.

minute within the 30-acre FSDF area investigation area (see Figure 1-2 for boundary).

Additional qualitative information regarding the nature of recharge to the Chatsworth formation can be obtained by inspecting temporal changes in water levels along with the annual precipitation record. Figure 5-7 presents this information for Chatsworth formation well RD-7. As can be seen on the hydrograph, the groundwater system receives reduced recharge in most years when the average annual precipitation is less than about 15 inches per year. Alternately, in years where large precipitation events occur and/or multiple years of significant precipitation, large changes in the water levels are measured. Furthermore, the rate of declining water levels is as little as 15 percent of the rate of rise.

## 5.4 Groundwater Discharge and Emergences

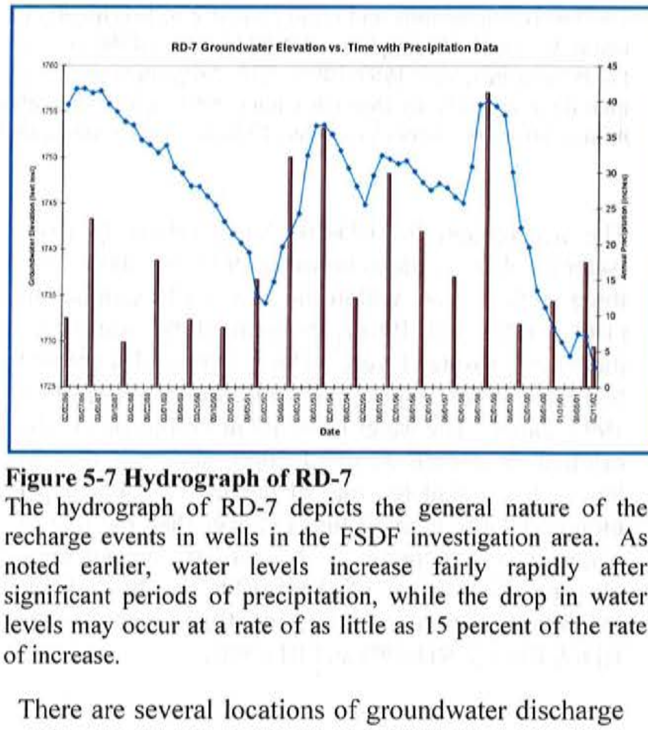
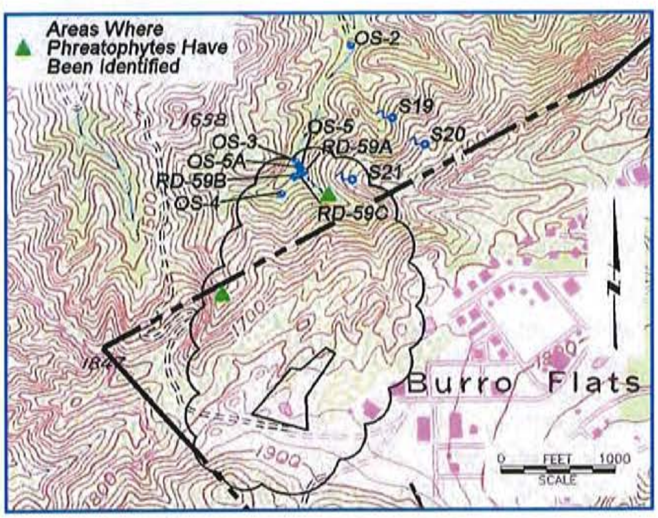



**Figure 5-7 Hydrograph of RD-7**
The hydrograph of RD-7 depicts the general nature of the recharge events in wells in the FSDF investigation area. As noted earlier, water levels increase fairly rapidly after significant periods of precipitation, while the drop in water levels may occur at a rate of as little as 15 percent of the rate of increase.

There are several locations of groundwater discharge and emergences (springs) within the FSDF study area. These locations are found off-site from the SSFL, north of the FSDF facility and near the RD-59 well cluster (Figure 5-8). The spring locations were previously reported in the *Spring and Seep Sampling and Analysis Report, Santa Susan Field Laboratory, Ventura County, California* (MWH 2003a). One spring location (S20) is found stratigraphically in the upper Burro Flats member of the Chatsworth formation, below the contact with Shale 3. Another (S19) emerges from Shale 3 and one (S21) emerges from colluvium deposits at the base of a steep slope.

There are several wells in the vicinity of these discharge points, which have been completed within these stratigraphic units. Two of these wells (OS-3 and OS-4) flow and discharge to the ground surface. On October 11, 2000, flow from these two wells was measured at a rate of 20.5 liters per minute. On October 11, 2000, the flow rate from well OS-2 (located just north of the study area) was estimated to be approximately 1.7 liters per minute. The minimum flow from springs in the vicinity of the RD-59 well cluster was estimated to be greater than 2.7 liters per minute in September and October of 2000. Two wells within the RD-59 cluster (RD-59B and RD-59C), have static heads above the ground surface when they are not shut-in. These wells are shut-in except for periodic groundwater gauging and sampling and do not discharge onto the surface.

Phreatophyte vegetation (sycamores and willows) has also been identified in the area near spring/seep S-21 and at another location on-site. Locations are shown on Figure 5-8.

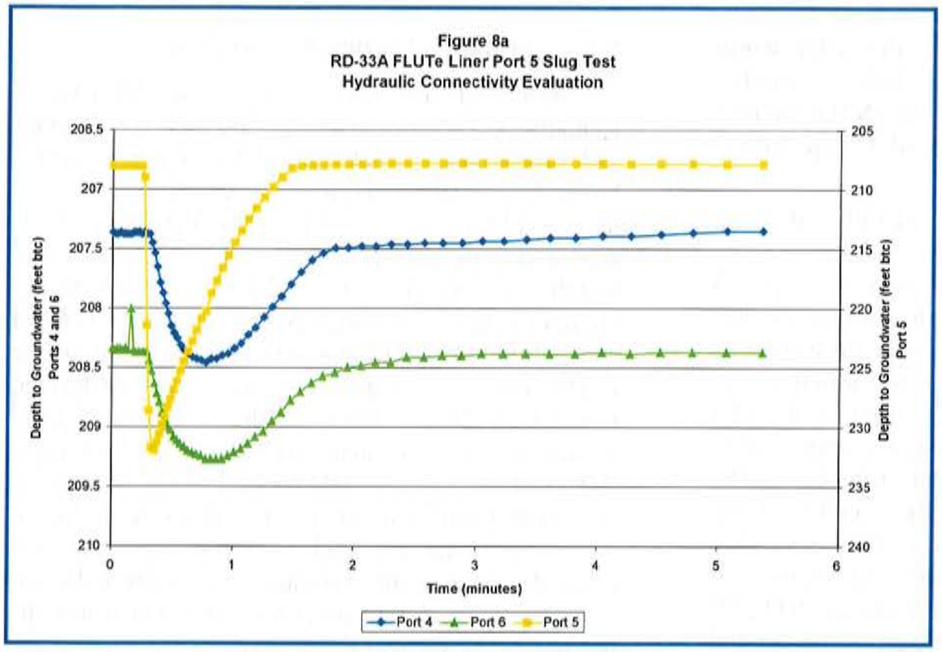


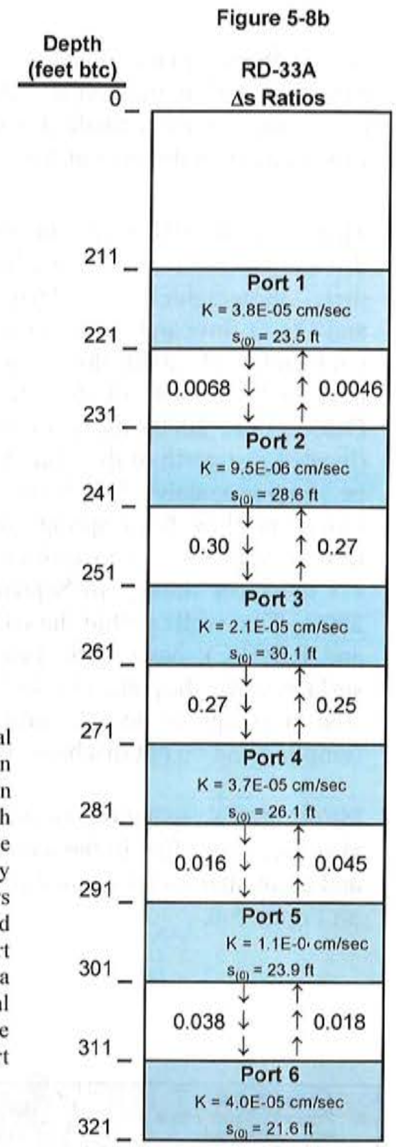

## 5.5 Formation Vertical Connectivity

As described in Section 4.5, the Chatsworth formation consists of fractured sandstones, siltstones and mudstones. Rock core VOC data, outcrops, borehole logs and borehole geophysical logs of wells in the FSDF area confirm that the bedrock is fractured, although the fractures appear to be more widely spaced than other parts of the SSFL. Hydraulic data were collected to evaluate the vertical connectivity of the Chatsworth formation within the FSDF investigation area. A study was performed between April and June of 2003 using multi-level monitoring systems that had been placed in wells RD-21, RD-33A, and RD-65 and in corehole C-8. Pressurized nitrogen was used to displace a slug of water from the selected test port (i.e., discrete interval) and pressure measurements were collected at the test port and at the ports above and below the test port. The vertical connectivity of the Chatsworth formation was qualitatively demonstrated using these single-pulse test data. Single slug pulses were induced in 26 discrete intervals (5 in RD-21, 6 in RD-33A, 9 in RD-65 and 6 in C-8) and a total of 65 measurements were collected (i.e., pressure measurements were collected in the interval pulsed and/or the intervals above and below the pulsed interval).

Vertical formation connectivity was observed between the pulsed interval and adjacent intervals at all except one (between ports 1 and 2 of RD-21) of the intervals tested. An example graph depicting the connectivity tests and a summary depiction of the responses at each port is shown in Figures 5-9a and 5-9b for well RD-33A. Complete diagrams for each well are provided in Appendix A.

**Figure 5-8 Plan View Showing Locations of Groundwater Discharge and Emergences in the FSDF Investigation Area.** Groundwater discharge and emergences in and near the FSDF investigation area include springs, seeps, and flowing artesian wells. These are located offsite, to the north of the SSFL property boundary.




**Figures 5-9a and 5-9b Vertical Connectivity Graph and Ratio Evaluation for RD-33A**
This graph depicts changes in hydraulic head in various monitoring intervals of a discrete-interval monitoring system that was placed into an existing well (e.g., ports 5, 6, and 7 of RD-33A) from an induced disturbance in one of the discrete intervals (e.g., port 5). In this example, a slug was induced in port 5 that displaced about 24 feet of water and pressure responses were seen in ports 4 and 6, which were located above and below port 5, respectively. These pressure responses demonstrate that the fracture network is vertically interconnected. Figure 5-9b is a summary diagram of the connectivity test results for all of the discrete-intervals in the RD-33A multi-level monitoring system. The arrows depict the responses in adjacent ports to an induced disturbance at a single port. The value posed adjacent to the arrow is the relative magnitude of the measured response in the adjacent port to the port in which disturbance was introduced. As an example, for port 4, a response was measured when a disturbance was introduced in port 3 and the magnitude of the response was 27 percent of the initial displacement of 30.1 feet in port 3. When a disturbance was introduced in port 5, responses were measured in both port 4 (magnitude of 4.5 percent) and port 6 (3.8 percent) of the displacement in port 5 (23.9 feet). The hydraulic conductivity estimate for each port is also depicted on the figure.

The pumping test that was conducted RD-54B (described in the following section) also provides hydraulic data demonstrating the connectivity of the Chatsworth formation. The pumping test is fully described in Appendix B. Clear responses to pumping were measured and confirmed in 6 observation wells located at distances of up to 400 feet away from the extraction well. The magnitude of the measured responses in wells is shown on Figure 5-10.

## 5.6 Hydraulic Conductivity Estimates

Two different methods were used to obtain hydraulic conductivity estimates of the Chatsworth formation in the FSDF investigation area. First, slug tests were performed on discrete-intervals of the multi-level monitoring systems that were placed into the existing wells. Second, a long-term pumping test was performed at well RD-54B.

It is important to recognize that the analytical solutions available for analyzing hydraulic data are not directly applicable to the physical conditions in the FSDF area in which the slug or pumping tests were performed. The physical system consists of wells that partially penetrate a fractured, dual permeability, heterogeneous bedrock system under both water table (unconfined) and confined conditions. The following quantitative analysis should be considered within this context.

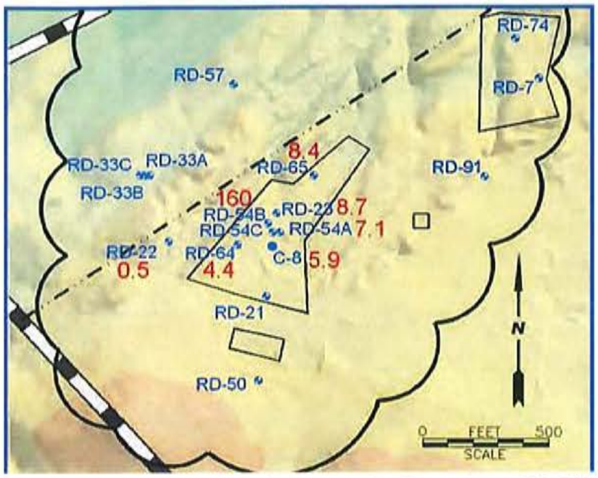



**Figure 5-10 Values of Induced Drawdown-RD-54B Pumping Test**
This figure depicts the values of the induced drawdowns (in feet) in monitoring wells during the RD-54B pumping test after 165 days of pumping. Drawdowns resulting from pumping were measured in monitoring wells located more than 400 feet away from the pumping well. The pumping test demonstrated that the formation is interconnected horizontally in wells screened within the Upper Burro Flats member and, with some local variation, within 400 feet or so of the pumping well.

### 5.6.1 Slug Tests

Slug tests, including slug-in and slug-out tests, were performed in five existing open-hole wells. Each well was equipped with a discrete-interval monitoring system. Separate tests were performed for selected ports in each well, resulting in a total of 26 tests.

The conditions and/or assumptions used to derive the analytical solutions for estimating hydraulic conductivity include:

- The aquifer has infinite areal extent, is homogeneous, isotropic, and of uniform thickness.
- The aquifer potentiometric surface is initially horizontal.

It should be noted that these conditions are not met for the wells at the FSDF and throughout most of the SSFL due to the nature of the Chatsworth formation.

Hydraulic conductivity results from the slug tests using the multi-level monitoring systems are shown in a histogram on Figure 5-11. A modification to the analytical method derived by Hvorslev (1951) was needed to account for pressure losses in the plumbing of the multi-level monitoring systems. The methodology was provided in a previous report (MWH, 2004). The geometric mean value from the multi-level monitoring system tests was 5.4 x $10^{-6}$ cm/s and the variability in the measurements spanned three orders of magnitude. Variations measured in individual ports from a single well were small, generally less than a factor of ten.

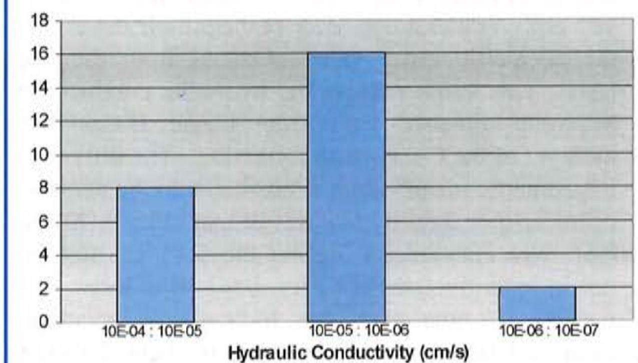



**Figure 5-11 Histogram of Hydraulic Conductivity Estimates From Multi-Level Monitoring System Slug Tests.**
Twenty-six slug tests were performed using the discrete-interval monitoring systems that were placed into four existing wells in the FSDF investigation area. The histogram of the values of hydraulic conductivity that were derived from the slug tests shows that about 90 percent of the tests had values in the $10^{-5}$ to $10^{-6}$ cm/s range. The values spanned a range of three orders of magnitude, with the geometric mean value being about 5.4 x $10^{-6}$ cm/s. This value is about two orders of magnitude lower than the geometric mean value of 6.5x$10^{-4}$ cm/s obtained from slug tests performed in the northeast investigation area.

### 5.6.2 RD-54B Pumping Test

A pumping test was conducted at the FSDF using RD-54B as the extraction well. The pumping test, data and resultant analyses are provided in Appendix B. Groundwater was extracted at a rate of about 173 gallons per day for 165 days, inducing a drawdown of about 160 feet, and 16 adjacent wells were fitted with pressure transducers to monitor potential hydraulic responses. Clear responses to pumping were measured and confirmed in 6 of the 16 observation wells, and were measured at distances of up to 400 feet away from the extraction well.

Data collected from the RD-54B pumping test were then used to obtain estimates of hydraulic conductivity. An analytical solution provided by Moench (1984) was used to obtain hydraulic conductivity estimates of the pumping well and the monitoring wells in which clear responses were measured. The method developed by Moench (dual-porosity for fractured rock) most closely represents the physical system at the SSFL. The geometric mean hydraulic conductivity using the analytical solution derived by Moench was about 6 x $10^{-7}$ cm/s, or about one order of magnitude lower than the geometric mean value obtained from the slug tests. This value reflects the hydraulic conductivity of wells screened within the Upper Burro Flats member of the Chatsworth formation. The difference in geometric mean values is attributed to the presence of lower-permeability features beneath the FSDF area that were encountered during the pumping test but not in individualized (i.e., localized) slug tests. It is worthy to note that the hydraulic conductivity estimated from the pumping tests is about 2.3 times greater than the bedrock matrix ($2.6 \times 10^{-7}$ cm/s, see Section 4.6.1). These data indicate that the fracture network within the FSDF area does not appreciably enhance the bulk hydraulic conductivity of the Chatsworth formation.

## 5.7 Groundwater Extraction Interim Measure

In 1997, an interim measure was initiated at the FSDF by extracting and treating groundwater from well RD-21. This interim measure remained operational until the CFOU investigations at the FSDF were initiated in 2002, when groundwater extraction was ceased to allow for the hydraulic studies that are described in this report. Typical extraction rates averaged about 173 gallons per day.

# 6.0 NATURE AND EXTENT OF VOCS IN THE FSDF AREA

This section describes surficial media and Chatsworth formation volatile organic compound (VOC) sampling results in the FSDF investigation area of the SSFL. As mentioned in section 2.0, the FSDF site was historically used to clean metallic sodium and NaK (a mixture of sodium and potassium) from testing components such as pumps and valves. Other materials including terphenyl coolants, solvents, acids, and hydrocarbon compounds (ICF 1993) were also used in the FSDF area.

TCE will be used as the study chemical for groundwater impacts in this section because it is the most prevalent chemical contaminant present in both the near-surface and Chatsworth formation groundwater in the FSDF area, and occurs at the highest relative concentrations. Other VOCs that were detected frequently and at relatively elevated concentrations include 1,1-DCE, cis-1,2-DCE, and 1,1-DCA. A description of the nature and extent of other chemical impacts is provided in Appendix C.

## 6.1 Samples Collected

TCE and VOC characterization of soils at the FSDF has relied on the laboratory analysis of soil matrix samples. Soil matrix samples were collected in 1987 and 1996 and two soil vapor samples were collected in 1999. Unsaturated and saturated bedrock samples were collected in 2001 and were analyzed for TCE and select other VOCs. Starting in about 1988, samples of near-surface and Chatsworth formation groundwater have been collected from piezometers and monitoring wells. Most of the samples have been collected as part of the quarterly groundwater monitoring program. A summary of the samples of various media that have been analyzed for TCE is provided in Table 6-1.

**Table 6-1. Summary of TCE Sampling Results at FSDF**

| Media Sampled | Frequency of Detection | Range of Concentrations Detected (parts per billion) | Location of Maximum Detection |
|---|---|---|---|
| Soil Vapor | 0 of 2 | ND | None |
| Soil Matrix (1987) | 4 of 8 | 300 – 740,000 | BPL-2 (near former Lower Pond) |
| Soil Matrix (1996) | 0 of 76 | ND | None |
| Unsaturated & Saturated Bedrock | 44 of 296 rock samples | 5 to 53,000 | Below top of bedrock in former Lower Pond |
| Near-Surface Groundwater | 5 of 8 wells | < 5 – 4,500 | RS-54 |
| Chatsworth Groundwater | 9 of 23 wells | < 2 – 2,900 | RD-21 |

## 6.2 Extent of VOCs in Surficial Media and the Chatsworth Formation

A systematic approach was used to evaluate the occurrence and distribution of TCE and other VOC impacts by depth at the FSDF - first to soil matrix and then to unsaturated and saturated bedrock and groundwater. As discussed earlier, the occurrence and distribution of TCE is used below as a general indicator for the presence of VOCs. Additional evaluations of the frequency and distribution of other VOC compounds is presented in Appendix C.

TCE occurrence and distribution were analyzed by combining information on the site history and potential chemical use, the temporal and spatial sampling coverage, and the analytical results to ensure that:

- Potential releases at areas where solvents were either used or were likely to have been used were sampled, and
- The temporal and spatial coverage of sampling was adequate to characterize the extent of potential TCE impacts. The extent of TCE impacts to groundwater was determined by screening the detected concentrations against the

primary maximum contaminant level for drinking water of 5 micrograms per liter (ug/L). This is referred to in this report as "screening level.[1]"

Where applicable, isoconcentration contours are used to delineate spatial trends in TCE concentrations in groundwater (i.e., 'plumes').

### 6.2.1 Surficial Media

The nature and extent of VOCs in soils at the FSDF is considerably different than that presented in the Phase 1 Report of Results for the northeast portion of the SSFL (MWH, 2004). This is due to the fact that there have been a number of interim measures conducted at the FSDF starting in about 1980 that have resulted in the near-complete removal of soils to the bedrock interface where the potential source areas were located. A brief chronology of sampling results of VOCs in soil and the timing of interim measures excavations is provided below:

1980 – Approximately 20 cubic yards of soil were excavated from the Lower Pond, primarily to remove a radioactive isotope of cesium.

1987 – Eight soil matrix samples were collected and analyzed for various constituents, including VOCs, from five locations at depths to 6 feet below the ground surface. These results are the only ones available that give an indication as to locations of elevated concentrations of VOCs in soil. VOC sample results and locations are shown on Figure 6-1.

1992 – The Lower Pond and a significant portion of the Upper Pond were excavated to bedrock as part of closure plan under the Toxic Pits Clean-up Act (administered at the time by the Los Angeles Regional Water Quality Control Board). Approximately 10,000 cubic yards of soil were excavated and disposed of off-site during this work.

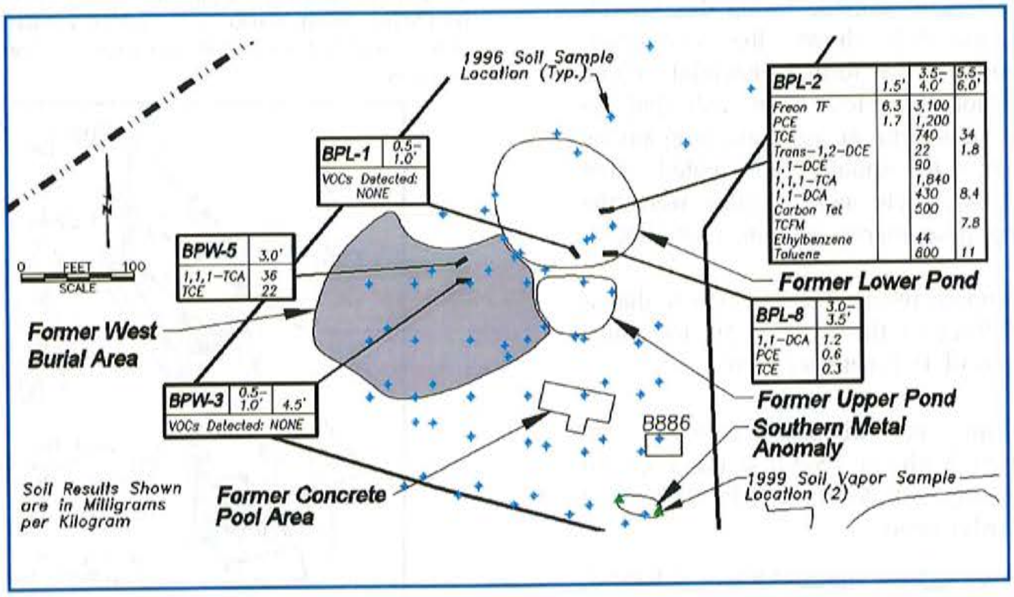



**Figure 6-1 FSDF VOC Soil Sample Locations**
This figure shows sample locations at the FSDF that have been analyzed for VOCs. The results from the analysis of soil matrix samples collected in April 1987 are depicted on the figure. VOC results from soil matrix samples collected in 1996 and from soil vapor samples collected in 1999 did not contain appreciable concentrations of VOCs.

[1] Chemical-specific screening levels were selected to serve as a basis for discussing analytical results within some regulatory context. Screening levels for groundwater consisted of federal or state maximum contaminant levels for drinking water, notification levels established by the California Department of Health Services, public health goals established by the California EPA's Office of Environmental Health Hazard Assessment or to groundwater comparison values as presented in the Site-Wide Risk Assessment Methodology Work Plan (MWH, 2005).

1995 – Seventy-six soil samples were collected on a sampling grid from 38 locations over and above the potential sources at the FSDF (Concrete Pool Area, Western Burial Area, Upper and Lower Ponds, and Building 886). Samples were collected at depths of about 0.5 feet to 1.0 feet bgs and at about 5 feet bgs or refusal. There were no VOCs detected in any of the 76 sample locations. Sample locations are also shown on Figure 6-1.

1999 – Two soil vapor samples were collected within and near the Southern Metal Anomaly and were analyzed for VOCs. Sample depths were at 10 and 15 feet bgs. PCE was the only VOC detected and the concentrations were 1.8 and 3.4 micrograms per liter vapor. Sample locations are shown on Figure 6-1.

2000 – Additional interim measures excavations were conducted within the FSDF area that resulted in the removal of about 10,000 cubic yards of soil. The soil beneath all of the potential source areas was excavated to the top of bedrock during this interim measure. Figure 6-2 shows the excavation boundaries relative to the former potential source areas. Confirmation samples were collected to demonstrate that the interim measure clean-up targets had been met. It should be noted that poly-chlorinated biphenyls and mercury were the chemicals driving these interim measures, not VOCs.

The 1987 soil sample results for TCE show that it was detected at three of the five sample locations. The concentrations of TCE detected were:

- 740 milligrams per kilogram (mg/kg) and 34 mg/kg from depths of 3.5-4.0 feet and 5.5-6.0 feet respectively, at location BPL-2 located within the Lower Pond,
- 0.3 mg/kg from a depth of 3.0-3.5 feet at BPL-8, also located within the Lower Pond, and
- 22 mg/kg from a depth of 3.0 feet at BPW-5 in the Western Burial Area.

### 6.2.2 TCE in Near-Surface Groundwater

TCE has been detected at the highest concentrations in near-surface groundwater monitoring well RS-54. TCE has also been consistently detected at near-surface groundwater monitoring well RS-18 and was detected above the drinking water maximum contaminant level (MCL) of 5 micrograms per liter (µg/L) in samples collected on one occurrence from piezometers PZ-098, PZ-099 and PZ-101. TCE has

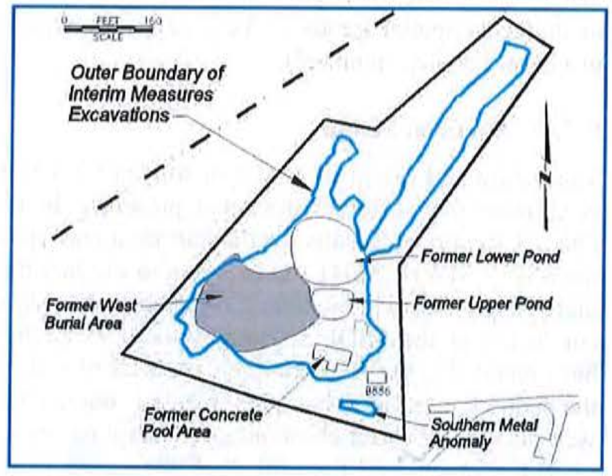



**Figure 6-2 Interim Measures Excavation Boundaries.** Interim measures excavations conducted in 1992 and 2000 have resulted in the near complete removal of most of the potential source areas at the FSDF. About 20,000 cubic yards of soil have been excavated to the top of bedrock and interim measures clean-up targets have been met.

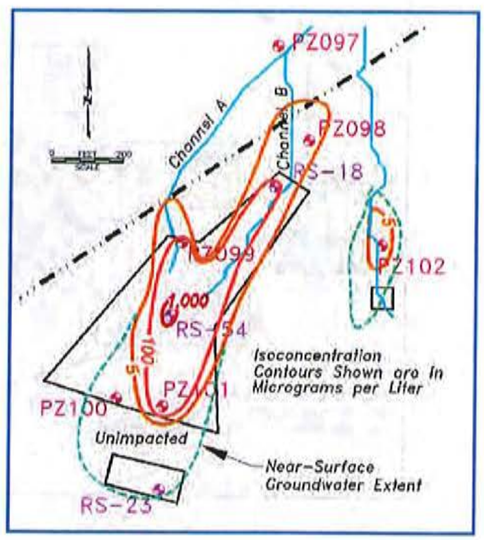



**Figure 6-3 Near-Surface Groundwater TCE Isococentration Contours.** TCE isoconcentration contours for near-surface groundwater are shown above along with wells, piezometers and drainages. The two downgradient plume "fingers" associated with the FSDF plume are based on the presence of a rock outcrop that divides these two drainages. It is expected that near-surface groundwater is not present beneath the outcrop. Additionally, the low concentration of TCE detected in PZ-102 is separated from the FSDF plume because of the presence of additional rock outcrops, below which near-surface groundwater is expected to be absent.

not been detected in PZ-100 or in RS-23. Plan view TCE isoconcentration contours in near-surface groundwater are shown on Figure 6-3. The area of the TCE plume depicted on the figure covers approximately four acres and the plume length from the upgradient extent near PZ-101 to the downgradient extent north of PZ-98 is about 990 feet.

### 6.2.3 TCE in Bedrock Samples

Data are available from one corehole (C-8, shown on Figure 3-1) that has been drilled in the FSDF to characterize select VOCs, including TCE, in both unsaturated (vadose zone) and saturated bedrock. Collecting and crushing rock samples and extracting porewater for laboratory analysis provides the primary means of confirming that matrix diffusion occurs in the Chatsworth formation and that it has a controlling influence on contaminant transport.

The porewater profile for TCE (and other chlorinated ethenes) at corehole C-8 is shown on Figure 6-4. The rock core data show that C-8 contains TCE mass within the vadose zone, which is about 180 feet thick. More than 99 percent of the mass is located in the vadose zone as can be seen in the cumulative equivalent TCE mass profile shown on Figure 6-5. The calculated maximum concentration of TCE detected in vadose zone rock porewater was about 53,000 μg/L and occurred within a few feet below the top of bedrock.

TCE was detected in only three of the rock core samples collected from the saturated zone. Detected concentrations ranged from non-detect to about 350 μg/L in porewater (in the sample from about 266 feet bgs). The maximum concentration detected is more than three orders of magnitude below the aqueous solubility of TCE and provides confirmation that little to no immiscible phase TCE remains in the fractures below the water table at the FSDF. The maximum depth of TCE concentrations exceeding 5 μg/L in porewater and based on the methanol

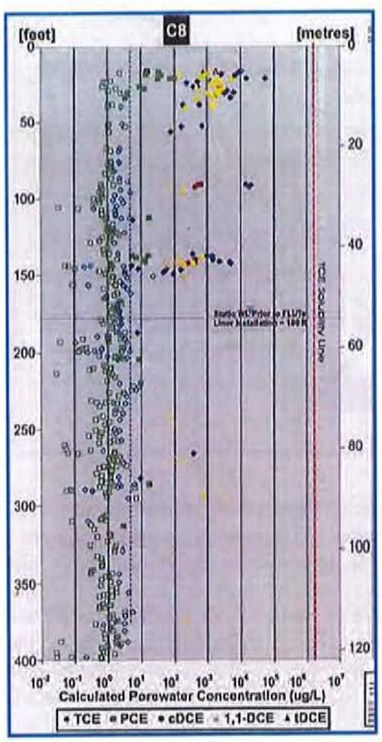



Figure 6-4

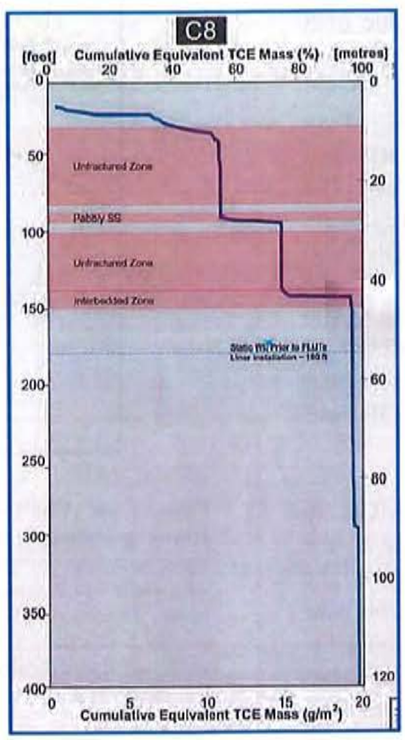



Figure 6-5

**Figures 6-4 and 6-5 C-8 Rock Porewater and Cumulative TCE Profiles**

Rock porewater chlorinated ethene results for corehole C-8, located within the footprint of the former Lower Pond, are shown on Figure 6-4. The results show that TCE is the most frequently and highest concentration VOC detected. The figure also shows the infrequent detections of TCE below the water table.

The cumulative equivalent TCE mass profile is shown on Figure 6-5 and shows that nearly all of the mass was encountered in the vadose zone. It is believed that the TCE Chatsworth formation groundwater plume at the FSDF likely results from both vapor transport from the bedrock vadose zone and dissolved aqueous phase transport via recharge waters.

extraction method was defined in C-8 at an approximate depth of 270 feet. It should be noted that the rock porewater data are not directly comparable to dissolved concentrations measured in groundwater samples collected from monitoring wells. Rock core sample results provide specific point measurements of TCE in the bedrock matrix at sometimes unknown distances from fractures. Alternately, monitoring wells with long open-intervals provide a blended concentration that results from the variability in the point measurements along with the formation transmissivity along the length of the borehole. Hence, a comparison of the rock core sample results to 5 µg/L is provided solely as a means of describing the measured concentrations relative to a regulatory standard and is not indicative of a concentration in a hypothetical domestic water supply well.

### 6.2.4 TCE in Chatsworth Formation Groundwater

The highest concentrations of TCE in Chatsworth formation groundwater in the FSDF area are from samples collected from RD-21, near the former concrete pool area. TCE has also been consistently detected above the MCL-based screening value of 5 µg/L at wells RD-23, RD-33A, RD-54A, RD-64, RD-65 and in samples collected from a multi-level monitoring system installed in corehole C-8. Plan view TCE isoconcentration contours in Chatsworth formation groundwater are shown on Figure 6-6. The area of the TCE plume depicted on the figure covers approximately 14 acres and the plume length from the upgradient extent near RD-21 to the downgradient extent north of RD-65 is about 1,100 feet. Vertically, the TCE plume is defined at concentrations below the MCL in wells RD-54B near the former potential source areas and at RD-33B near the downgradient extent of the plume.

TCE has not been detected above the MCL in upgradient well RD-50, bracketing the plume in the south. TCE has not been detected above the screening value of 5 µg/L in wells RD-22 to the west and RD-57 to the north, thus effectively defining the lateral extent of TCE in these directions. TCE has been detected above the screening value in wells RD-7 and RD-91 to the east, however these detections of TCE have not been connected with the occurrences identified at the FSDF because they are hydraulically upgradient and are believed to have separate source inputs. The absence of TCE in well RD-74 located to the north of RD-7 effectively delineates the downgradient extent of the localized TCE in Chatsworth formation groundwater in this area.

### 6.2.5 Summary of TCE Nature and Extent

In 1987, TCE was detected in four of eight soil matrix samples collected from within the Lower Pond and Western Burial Area at maximum concentrations of 730 and 22 mg/kg, respectively. In 1992, about 10,000 cubic yards of soil were excavated to the top of bedrock primarily from the Lower Pond but included sections of the Upper Pond, thus effectively removing any sources of TCE in soil at these locations. In 1996, 76 soil samples were collected on a grid that was established over the potential source areas within the FSDF. Neither TCE, nor any other VOC, was detected in any of these samples.

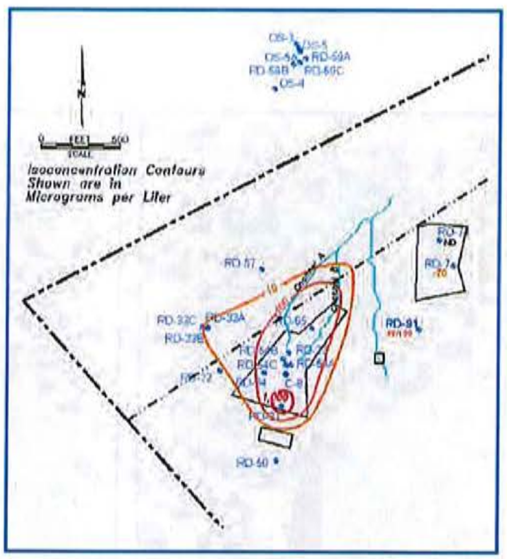



**Figure 6-6 Chatsworth Formation Groundwater TCE Isoconcentration Contours.** TCE isoconcentration contours for the Chatsworth formation groundwater are shown above along with wells and drainages. The plume covers an area of about 14 acres. Detections of TCE in wells RD-7 and RD-91 where not included with the FSDF isoconcentration contours because these wells are hydraulically upgradient and there are other potential sources of TCE that could have caused the groundwater impacts.

Additional soil excavations were conducted in 2000 to the top of bedrock that effectively removed all the potential source areas at the FSDF.

Groundwater samples have been collected and analyzed for TCE in near-surface groundwater monitoring wells at the FSDF starting in about 1988 from well RS-18. Additional wells and piezometers have been added to this monitoring network since then and have been sampled and analyzed for TCE. Samples collected from 5 of the 8 monitoring locations contain concentrations of TCE above the screening value of 5 µg/L. These data were used to create isoconcentration contours of TCE in near surface groundwater, which are shown on Figure 6-3. The TCE plume in near-surface groundwater is estimated to cover an area of about 4 acres and has a plume length of about 1,000 feet.

A corehole (C-8) was drilled within an area of the Lower Pond where TCE was believed to have entered the ground. Rock core samples (296) were collected to a depth of 400 feet and analyzed for TCE and a select set of additional VOCs. The analytical results indicate that nearly all of the mass was encountered in the vadose zone bedrock and that only three rock core samples contained TCE below the water table, with the maximum concentration of about 350 µg/L. Alternately, 41 rock core samples from the vadose zone contained TCE where the maximum concentration encountered was about 53,000 µg/L in rock porewater. The maximum concentrations measured were from typical sandstone samples. However, about 20% of the mass in the profile occurred within samples collected from a peebly sandstone bed at a depth of about 90 feet. Another 20% of the mass was found within an interval of interbedded sandstones, siltstones and shales at an approximate depth between 140 feet and 145 feet.

Groundwater samples have been collected and analyzed for TCE in Chatsworth formation groundwater monitoring wells at the FSDF starting in about 1988 from wells RD-21, 22 and 23. Additional wells have been added to this monitoring network since then and have been sampled and analyzed for TCE. Samples collected from 6 of 23 monitoring locations consistently contain concentrations of TCE above the screening value of 5 µg/L. These data were used to create isoconcentration contours of TCE in Chatsworth formation groundwater, which are shown on Figure 6-6. The TCE plume in Chatsworth formation groundwater is estimated to cover an area of about 14 acres and has a plume length of about 1,100 feet. It is believed that the TCE Chatsworth formation groundwater plume at the FSDF likely results from both vapor transport from the bedrock vadose zone and dissolved aqueous phase transport via recharge waters.

## 6.3 Analysis of Other Chemicals

A detailed analysis of other chemicals has been performed (see Appendix C), the results of which are summarized in Table 6-2. This analysis confirms that TCE provides the best representation as to the overall nature and extent of chemical impacts to groundwater at the FSDF. As noted in the table, TCE has been detected above its MCL-based screening level in 13 near-surface and Chatsworth formation groundwater monitoring locations. Two other chemicals, 1,1-DCE and cis-1,2-DCE (a TCE transformation product) are the second most frequently detected chemicals in groundwater at concentrations consistently exceeding screening values.

There are three wells were chemicals have been consistently detected above screening values where TCE is not present above its MCL. These locations and their corresponding chemicals are: perchlorate in RD-22, toluene in RD-54C and gasoline-range petroleum hydrocarbons in RD-50. Furthermore, two chemical groups, poly-chlorinated biphenyls (PCBs) and chlorinated dioxins and furans (PCDD/Fs) have been detected in soils at the FSDF but there have been no groundwater samples collected and analyzed for these chemicals. It is expected, however, that these chemicals will either not be present in groundwater or present at very low concentrations due to their strong adsorption to organic carbon in soils and bedrock.

## Table 6-2
## Analysis of the Nature and Extent of Chemicals at the FSDF

| Chemical | Detections in soil | Near-Surface Groundwater: Wells | | | | Near-Surface Groundwater: Piezometers | | | | Chatsworth Formation Groundwater Monitoring Wells | | | | | | | | | | | | | | | | | | | No of wells detected |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RS-16 | RS-18 | RS-23 | RS-54 | PZ-98 | PZ-99 | RZ-100 | PZ-102 | C-8 | RD-7 | RD-21 | RD-22 | RD-23 | RD-33A | RD-33B | RD-33C | RD-50 | RD-54A | RD-54B | RD-54C | RD-57 | RD-59A | RD-59B | RD-59C | RD-64 | RD-65 | RD-74 | |
| **Halogenated Ethenes** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Tetrachloroethene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Trichloroethene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 13 |
| cis-1,2-Dichloroethene | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 8 |
| trans-1,2-Dichloroethene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 1,1-Dichloroethene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 8 |
| Vinyl chloride | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| **Halogenated Ethanes** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1,1,1-Trichloroethane | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 3 |
| 1,2-Dichloroethane | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 |
| 1,1-Dichloroethane | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 5 |
| Chloroethane | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 1,1,2-Trichlorotrifluoroethane (Freon 113 | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 |
| **1,4-Dioxane** | | ND* | ND* | ND* | ND* | | | | | | | | | | | | | | | | | | | | | | | | 3 |
| **Halogenated Methanes** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Carbon tetrachloride | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Chloroform | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 |
| Methylene chloride | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Chloromethane | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Trichlorofluoromethane (Freon 11 | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| **1,2,3-Trichloropropane** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| **Non-Halogenated VOCs** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Benzene | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Carbon disulfide | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Ethylbenzene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Toluene | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 |
| Xylene | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| **NDMA** | | | | | | ND* | ND* | | ND* | | | | | | | | | | | | | | | | | | | | 0 |
| **Perchlorate** | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 8 |
| **TPH** | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| C11-C14 (Kerosene Range) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| C14-C20 (Diesel Range) | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| C20-C30 (Lubricant Oil Range) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Gasoline Range Organics | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| **Metals** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cadmium | N | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Lead | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| Nickel | Y | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| Total number of chemicals detected in wells | | 0 | 7 | 0 | 13 | 1 | 2 | 0 | 1 | 4 | 2 | 6 | 1 | 5 | 3 | 0 | 0 | 1 | 9 | 0 | 1 | 0 | 0 | 0 | 0 | 6 | 8 | 0 | |

Notes:
ND*: Not detected, detection limit exceeds screening criteria
NS: Samples have not been collected and analyzed for this chemical at the well.
Brown shading indicates that consistent detections of this chemical have been measured in samples from the well at concentrations above the screening valu
Tan shading indicates that consistent detections of this chemical have been measured in samples from the well, but at concentrations below the screening value.
Empty cells indicate that the sample results from the well are either non-detect for this chemical or that the chemical was detected at low concentrations on a few occurrences.

# 7.0 SUMMARY AND CONCLUSIONS

## 7.1 Background

TCE was first discovered in water supply wells at the SSFL in 1984. Groundwater characterization has been on-going since then. Conventional fractured-rock characterization methods were solely used to investigate the groundwater beneath the SSFL until about 1997, when Rocketdyne retained the groundwater advisory panel. The Panel developed the site conceptual model for solute transport in fractured sedimentary rock shortly after being retained. Based on the site conceptual model, it is expected that molecular diffusion of TCE into the fractured porous sandstones of the Chatsworth formation causes TCE to be transported much more slowly than groundwater flowing through the fractured rock. Members of the panel developed and implemented new characterization methods in the late 1990's that provided initial confirmation regarding the site conceptual model. A Technical Memorandum was issued in April of 2000 (Montgomery Watson, 2000) that provided a description of the groundwater SCM, included field data that provided initial confirmatory results and integrated site-specific geology and hydrogeology. A work plan for characterization of the FSDF was developed based on the groundwater SCM, and submitted to DTSC for review and approval. The work plan was approved by DTSC in early 2002. Field investigations of the Chatsworth formation at the FSDF were initiated shortly thereafter and continued through June 2004. This report describes data collected to characterize groundwater at and near the FSDF consistent with that outlined in the work plan and incorporates previous data where appropriate. This report has been prepared in partial fulfillment of the requirement to characterize groundwater, established in the corrective action provisions of the hazardous waste operating permit for Area IV.

This report also includes a description of operations at the FSDF RFI site, including the identification of chemical usage areas, soil sampling locations for various chemicals, and analytical results describing the nature and extent of impacts to soil, bedrock and groundwater.

## 7.2 Physical Setting

Topographically, the SSFL lies atop the Simi Hills along a topographic high at about 1800 feet above mean sea level. The Simi Valley is located to the north-northwest and the San Fernando Valley is located to the east and southeast. The valleys are about 800 feet to 900 feet lower in elevation than the SSFL. The approximate elevation of the operational areas within the FSDF area is about 1850 feet above mean sea level. Surface water that drains from the FSDF area flows northward toward the Meier Canyon drainage, which discharges into Arroyo Simi in the Simi Valley. Surface water discharges are monitored under the NPDES program. Precipitation at the SSFL has averaged about 18.8 inches per year since 1960 and annual precipitation varied from a low of 5.7 inches to a high of 41.7 inches.

The primary geologic units present at the SSFL are the Quaternary alluvium, which is underlain by the Cretaceous Chatsworth formation. The Chatsworth formation is a deep-sea turbidite deposit that consists primarily of sandstone interbedded with lesser amounts of shale and siltstone. The Chatsworth formation strikes approximately N70$^0$E and dips 25$^0$ to 35$^0$ to the northwest. Fill soils up to 12 feet thick have been placed over excavated areas of the former ponds at the FSDF. Stratigraphically, the Burro Flats member underlies the FSDF, and the interbedded Shale 3 member lies above the Burro Flats member a short distance north of the FSDF. Structurally, the FSDF lies within the North fault zone, which consists of a series of thin deformation bands that produce minimal off-sets in the stratigraphy. The Burro Flats fault is present to the southwest of the FSDF. Two structures, labeled the Eastern and Western FSDF structures, are present just east of the FSDF area. These two features are referred to as structures because there are insufficient exposures in outcrop that can be used to determine the magnitude of off-set in the stratigraphy that these features may have created.

Laboratory measurements of the bedrock have been made on various samples collected from a corehole drilled within the FSDF (C-8) and throughout the SSFL. These measurements show that the porosity of the bedrock beneath the FSDF is about 14 percent (17 samples) and the matrix permeability is about $2.6 \times 10^{-7}$ cm/s (19 samples). Organic carbon is also present and the geometric mean is about 0.014 percent in the sandstones (12 samples) and about 0.3 percent in interbedded sandstone/siltstones (3 samples). A comparison of the measurements made on corehole C-8 samples to measurements made on samples collected from other parts of the SSFL shows similar values for porosity and wet and dry bulk density (i.e., the relative difference between the C-8 and site-wide results . is less than 5%). However, the fraction of organic carbon measurements from corehole C-8 samples are lower than in the site-wide sample set (i.e., 33% lower for the sandstones and 26% lower for the interbedded samples). Likewise, the matrix hydraulic conductivity measurements from the corehole C-8 sandstone samples are about 36% lower than the site-wide sample set.

Borehole geophysical logs were also used to estimate the matrix porosity and permeability at of the bedrock beneath the FSDF investigation area. The borehole log from RD-23 provided estimates of matrix porosity within the same range (i.e., about 15% on average) as the laboratory measurements. Estimates of matrix hydraulic conductivity were obtained from the logs using empirical correlations and were not calibrated against laboratory measurements. The primary benefit derived from these hydraulic conductivity estimates is the relative estimated values along the length of the borehole (as opposed to the absolute values depicted on the log).

### 7.3 Groundwater

Groundwater is locally present in weathered bedrock within the FSDF (defined as near-surface groundwater) and is perched above the Chatsworth formation groundwater as indicated by unsaturated intervals of the multi-level monitoring systems that were retrofitted into existing wells (see Figure 5-2). The near-surface groundwater is encountered at depths from about 8 feet below ground surface (RS-18) to about 23 feet below ground surface (RS-54).

The water table in the Chatsworth formation is quite variable and is encountered at depths ranging from about 25 feet below ground surface north of the FSDF (RD-59A) to nearly 345 feet below the ground surface (RD-57). The variability in the depth to Chatsworth formation groundwater is attributed one or a combination of the following:

- the presence of: steep slopes just north of the FSDF investigation area and lower permeability lithologies that may cause groundwater to perch,
- small scale geologic features that exhibit significant permeability contrasts and produce abrupt changes in hydraulic head on a local scale, and
- the low permeability of the rock formation.

The estimated recharge to the groundwater system is about 1 inch per year of the average annual precipitation of 18.8 inches. This estimate was derived using a chloride mass balance. This recharge rate converts to a flow rate of about 1.5 gallons per minute when applied over the 30 acres within the boundary of the FSDF investigation area. An evaluation of the distribution of chloride concentrations in groundwater did not reveal the presence of any zones of rapid recharge. Hydraulic responses measured in monitoring wells during years of above average precipitation can be large, up to 68 feet in some wells. The rate of decline in the water levels after recharge occurs is about 15 percent of the rate at which the water table rises for wells not located adjacent to drainages. The relatively rapid increase in water levels reflects the small storage capacity of the bedrock, while the gradual decline reflects the moderate permeability of the bedrock.

One spring (S21) lies within the FSDF investigation area boundary and two additional springs (S19 and S20) have been identified further to the north of the FSDF investigation area boundary. Flowing wells are also present near the RD-59 well cluster and further to the north, beyond the FSDF investigation boundary. It was estimated that the groundwater flow discharging from the springs and flowing wells was about 24 liters per minute (or about 6 gallons per minute) based on observations made during the fall of 2000. Phreatophyte vegetation (sycamores and willows) has also been identified in areas where springs/seeps and flowing wells have been found.

Hydraulic tests confirm that the Chatsworth formation at the FSDF is interconnected both vertically within a borehole/well and laterally across the monitoring well network. Vertical hydraulic responses were observed between test intervals and adjacent intervals using slug-type test methods within four existing wells that were retrofitted with multi-level monitoring systems. A pumping test was conducted at RD-54B by extracting groundwater at a rate of about 173 gallons per day for 165 days, and inducing a drawdown of about 160 feet. Pressure responses associated with the pumping were measured in six monitoring wells at distances of over 400 feet from the extraction well, showing that the formation is interconnected both horizontally and vertically over an appreciable area.

Hydraulic conductivity estimates derived from the RD-54B pumping test show that the permeability of the fractured rock system beneath the FSDF is low, and is likely in the range of $6x10^{-7}$ cm/s for the Upper Burro Flats member of the Chatsworth formation. This value is 1.7 times higher than the hydraulic conductivity rock matrix. These data indicate that the fracture network at the FSDF imparts little appreciable increase in the bulk hydraulic conductivity of the Chatsworth formation.

## 7.4 Nature and Extent of TCE

Discussions on the nature and extent of TCE in various environmental media are presented in the main body of this report because TCE has been detected with the greatest frequency in bedrock and groundwater, and at the highest relative concentrations. Potential releases to the subsurface from waste management facilities at the FSDF were primarily investigated through the collection and analysis of soil matrix samples in 1987 and again in 1996. Potential sources of TCE and other VOCs in soil at the FSDF have been removed during two separate excavations in 1992 and 2000, each encompassing about 10,000 cubic yards of soil. The soils were transported and disposed off-site in accordance with applicable regulations.

A corehole was drilled within the area of the former Lower Pond where TCE and other VOCs are believed to have entered the ground. Rock core samples were collected at approximately 1.3 feet intervals and analyzed for the presence and concentration of TCE and a select subset of VOCs. Nearly all of the TCE mass encountered was found in the vadose zone at this location, where the maximum TCE concentration encountered was about 53,000 μg/L in porewater. Below the water table, which was encountered at a depth of about 180 feet, TCE was detected in only three rock core samples, where the maximum TCE concentration encountered was 350 μg/L in porewater. The highest concentrations of TCE detected in rock core was from the vadose zone and was about a factor of 21 below the aqueous solubility (estimated at 1,100 milligrams per liter), providing evidence that little to no immiscible phase TCE liquid remains in the fractures at the FSDF.

Review of the near-surface groundwater monitoring results from wells and piezometers showed that there is a plume of TCE above 5 μg/L that covers approximately four acres.

Isoconcentration contours of TCE in Chatsworth formation groundwater were developed. These isoconcentration contours show an area of TCE-impacted groundwater that extends about 1,100 feet and covers an area of about 14 acres. The vertical extent of TCE beneath the former potential source areas at the FSDF has been defined by samples collected from wells RD-54B and RD-54C. The vertical extent of TCE is defined at the plume periphery by results of samples collected from wells RD-33B and RD-33C.

It is believed that the TCE plume in the Chatsworth formation likely results from both vapor transport from the bedrock vadose zone and dissolved aqueous phase transport via recharge waters. This is based on the infrequent and relatively low concentrations of TCE detected in the rock core samples collected from below the water table from corehole C-8, which do not indicate the penetration of immiscible phase TCE. The lack of immiscible phase TCE flow through the fracture network into and below the saturated zone in bedrock is likely attributable to a relatively small volumetric release and/or small fracture apertures.

## 7.5 Nature and Extent of Other Chemicals

The lateral and vertical extent of other chemicals in groundwater beneath the FSDF that are present above screening values is less laterally extensive than TCE.

As an example, the second-most frequently detected chemical is cis-1,2-DCE and the area encompassed by a plume defined by a 10 microgram per liter isoconcentration contour is 4.1 acres or about 30 percent of the area covered by the TCE plume. All other chemicals exhibit similar behavior in that they are detected at concentrations above screening values at fewer wells than TCE and thus create smaller plumes within the TCE plume footprint.

There are three well locations at the SSFL where chemicals have been periodically detected above screening values where TCE has not been detected above its screening value. These locations and their corresponding chemicals are: perchlorate in RD-22, toluene in RD-54C and gasoline-range petroleum hydrocarbons in RD-50.

### 7.6 Conclusions

Many samples have been collected to characterize potential releases of chemicals to the surficial media and Chatsworth formation operable units. Sample locations were based on either known or potential chemical use areas. These areas were determined through various investigative efforts including historical photograph reviews and site inspections, review of facility operating records and interviews with current and former site workers. Reduction and analysis of data collected to characterize releases to the subsurface show that TCE is the chemical that has been detected most frequently and at the highest relative concentration consistent with its wide-spread use at the SSFL.

New methods have been employed since about 1997 to characterize the groundwater system at the SSFL and evaluate the groundwater site conceptual model developed primarily by the SSFL groundwater advisory panel (Drs. John Cherry, David McWhorter and Beth Parker). These new methods supplement the continued use of conventional fractured rock characterization methods. Available data collected from the FSDF groundwater characterization program continue to substantiate the groundwater site conceptual model that was presented in a Technical Memorandum in April of 2000. Results of the investigations conducted to date warrant the conclusion that the overwhelming majority of the TCE mass released to the subsurface remains proximal, or close to the locations where the releases occurred. The TCE is dissolved into the water that occupies the pore spaces of the sandstone rock. Available data also indicate that the lateral extent of TCE in groundwater remains close to where TCE was released (i.e., within a thousand feet).

Significant progress has been made toward resolving the problem statement that was developed and presented in the Chatsworth formation work plan for the FSDF (Montgomery Watson Harza, 2001). The problem statement is: Comply with regulatory requirements by developing an accurate site conceptual model that describes and predicts the transport and fate of chemicals of concern in the Chatsworth formation operable unit. Substantiate the site conceptual model and determine appropriate actions for the site.

Data collected during this investigation provided confirmation that the TCE mass at the FSDF remains close to where it was released. The rock core results from corehole C-8 show the overwhelming majority of the TCE mass remains in the vadose zone. The rock core results from C-8, along with the results of frequent collection and analysis of water samples from the RD-54 and RD-33 well clusters, provide data that characterize the maximum depth of chemical impacts at the FSDF. The measurements made on the permeability of the Chatsworth formation at the FSDF show the bulk hydraulic conductivity over 2 times greater than the matrix hydraulic conductivity. The low permeability of the formation causes chemicals to move very slowly and has likely caused the resultant plumes to become stable. The monitoring well hydrographs and chemical concentration graphs are useful tools for assessing both the temporal and spatial characteristics of chemical solutes and can be used as a basis for revisiting the groundwater sampling and analysis program.

Work continues on analyzing available data from the FSDF and throughout the SSFL to answer the remaining decision questions that were identified in the work plan. The nature and extent of TCE and other chemicals has been sufficiently defined such that work can be initiated on a corrective measures study.

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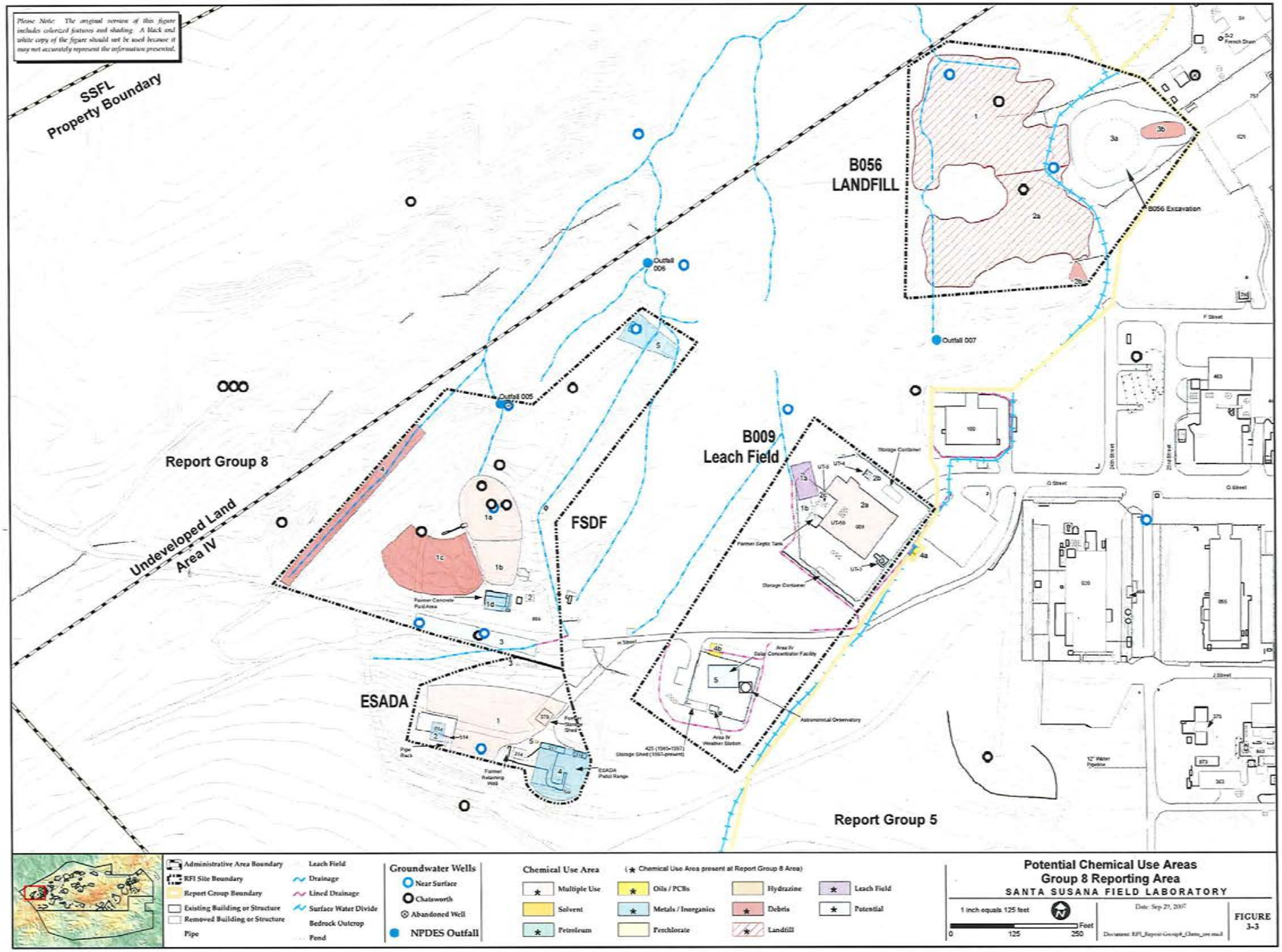
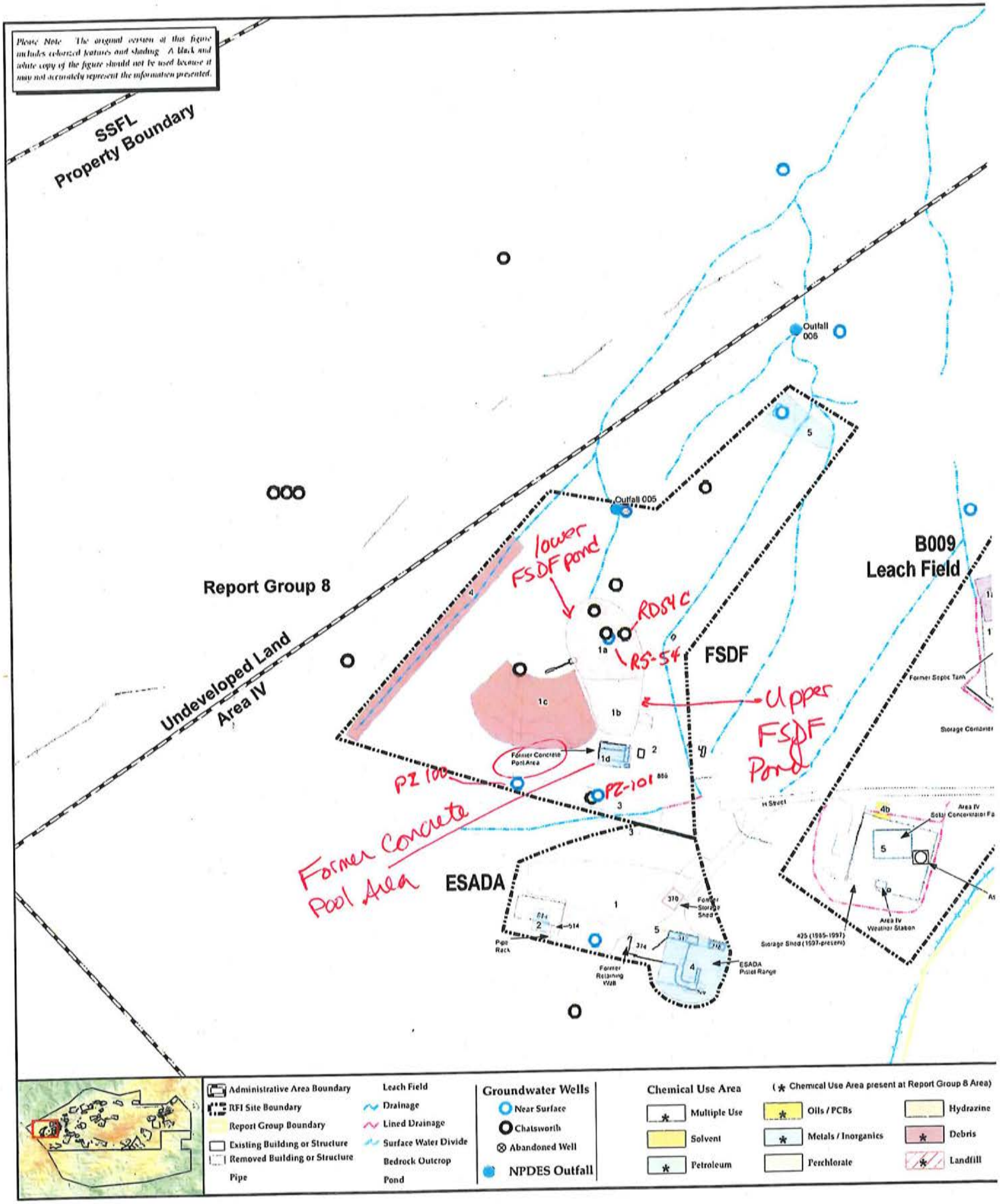
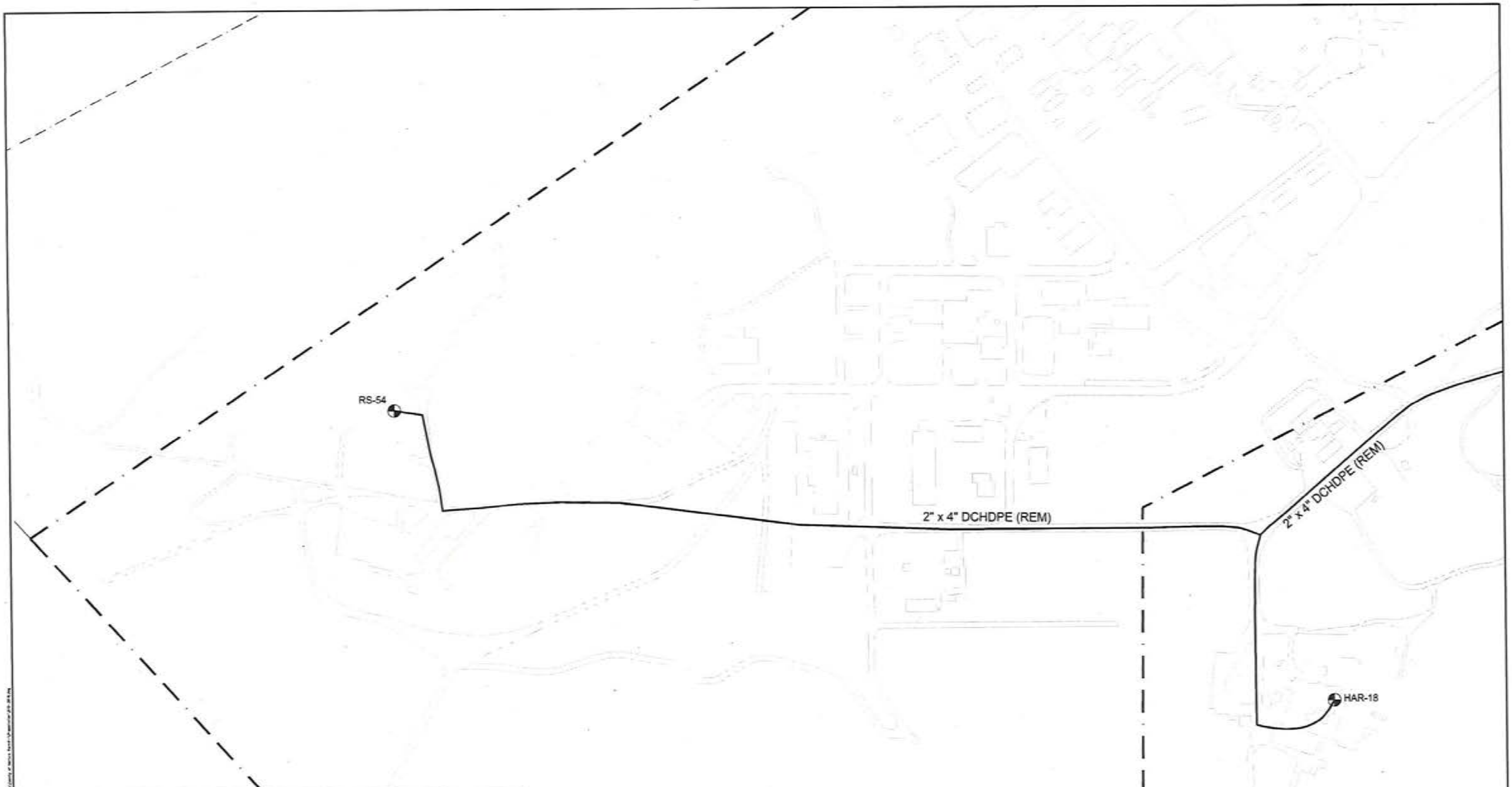

Please Note: The original version of this figure includes colorized features and shading. A black and white copy of the figure should not be used because it may not accurately represent the information presented.
SSFL Property Boundary
Undeveloped Land Area IV
Report Group 8
Report Group 5
B056 LANDFILL
B056 Excavation
B009 Leach Field
FSDF
ESADA
Outfall 005
Outfall 006
Outfall 007
Storage Container
Former Septic Tank
Former Concrete Pad Area
Area IV Solar Concentrator Facility
Astronomical Observatory
Area IV Weather Station
425 (1965-1997) Storage Shed (1997-present)
ESADA Pistol Range
Former Retaining Well
Pipe Rack
Former Storage Shed
H Street
G Street
F Street
J Street
24th Street
23rd Street
12" Water Pipeline
Administrative Area Boundary
RFI Site Boundary
Report Group Boundary
Existing Building or Structure
Removed Building or Structure
Pipe
Leach Field
Drainage
Lined Drainage
Surface Water Divide
Bedrock Outcrop
Pond
Groundwater Wells
Near Surface
Chatsworth
Abandoned Well
NPDES Outfall
Chemical Use Area
(* Chemical Use Area present at Report Group 8 Area)
Multiple Use
Solvent
Petroleum
Oils / PCBs
Metals / Inorganics
Perchlorate
Hydrazine
Debris
Landfill
Leach Field
Potential
Potential Chemical Use Areas
Group 8 Reporting Area
SANTA SUSANA FIELD LABORATORY
1 inch equals 125 feet
0 125 250 Feet
Date: Sep 27, 2007
FIGURE 3-3



Please Note: The original version of this figure includes colorized features and shading. A black and white copy of the figure should not be used because it may not accurately represent the information presented.
SSFL Property Boundary
Undeveloped Land Area IV
Report Group 8
Outfall 006
Outfall 005
lower FSDF pond
RD54C
RS-54
FSDF
Upper FSDF Pond
Former Concrete Pool Area
PZ 100
PZ-101
Former Concrete Pool Area
ESADA
B009 Leach Field
Former Septic Tank
Storage Container
H Street
Area IV Solar Concentrator Fa
Area IV Weather Station
425 (1985-1997) Storage Shed (1997-present)
Former Storage Shed
Pipe Rack
Former Retaining Wall
ESADA Pistol Range
Administrative Area Boundary
RFI Site Boundary
Report Group Boundary
Existing Building or Structure
Removed Building or Structure
Pipe
Leach Field
Drainage
Lined Drainage
Surface Water Divide
Bedrock Outcrop
Pond
Groundwater Wells
Near Surface
Chatsworth
Abandoned Well
NPDES Outfall
Chemical Use Area
(* Chemical Use Area present at Report Group 8 Area)
Multiple Use
Solvent
Petroleum
Oils / PCBs
Metals / Inorganics
Perchlorate
Hydrazine
Debris
Landfill




**EXPLANATION**

- SSFL PROPERTY BOUNDARY
- SUB-AREA BOUNDARY
- EXISTING ABOVE GRADE CONVEYANCE PIPELINE
- PROPOSED NEW BELOW GRADE CONVEYANCE PIPELINE
- EXISTING EXTRACTION WELL

ACRONYMS/ABBREVIATIONS

DCHDPE = DOUBLE CONTAINED HIGH DENSITY POLYETHYLENE (PIPE)
DIS = TREATED GROUNDWATER DISCHARGE PIPELINE
GET = GROUNDWATER EXTRACTION AND TREATMENT
GWIM = GROUNDWATER INTERIM MEASURES
HDPE = HIGH DENSITY POLYETHYLENE (PIPE)
REM = EXTRACTED GROUNDWATER PIPELINE
SSFL = SANTA SUSANA FIELD LABORATORY

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