CONCEPTUAL HYDROGEOLOGIC MODEL

For

Environmental Investigation at the Formerly Used Defense Site (FUDS)
at the Benicia Arsenal, Benicia, California

FUDS Site Number: J09CA075600

FINAL

Prepared for:

DEPARTMENT OF DEFENSE
UNITED STATES ARMY ENGINEER DISTRICT, SACRAMENTO DISTRICT
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CONCEPTUAL HYDROGEOLOGIC MODEL
BENICIA ARSENAL, BENICIA, CALIFORNIA

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LIST OF ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
bgs	below ground surface
CALTRANS	California Department of Transportation
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CIMIS	California Irrigation Management Information System
DoD	Department of Defense
DCE	Design, Community, and Environment
DHS	Department of Health Services
DTSC	Department of Toxic Substances Control
DWR	Department of Water Resources
FA/BC	Forsgren Associates/Brown and Caldwell
ft	feet
ft/bgs	feet/below ground surface
ft/day	feet/day
ft/mi	feet/miles
ft/yr	feet/year
ft/ft	foot/foot
FUDS	Formerly Used Defense Site
GIS	Geographic Information System
gpd	gallons per day
gpm	gallons per minute
HLA	Harding Lawson and Associates
MCL	maximum contaminant level
mg/L	milligrams per liter
msl	mean sea level
PAHs	polyaromatic hydrocarbons
PCA	potential contaminating activity
PCB	polychlorinated biphenyl
ppb	parts per billion
ppm	parts per million
RCRA	Resource Conservation Recovery Act
RI/FS	Remedial Investigation/Feasibility Study
RRR	Records Research Report
RWQCB	Regional Water Quality Control Board

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

SCDEM	Solano County Department of Environmental Management
TCE	trichloroethene
TDS	total dissolved solids
TOC	top of casing
TPH	total petroleum hydrocarbon
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
V	velocity
VOC	volatile organic compound
WIRMS	Warehouses, Industrial, Revetment, Motor Pool, and Storage/Igloos

GLOSSARY OF TERMS

A

alluvium A general term for clay, silt, sand, gravel, or similar unconsolidated detrital material, deposited during comparatively recent geologic time by a stream or other body of running water, as a sorted or semi sorted sediment in the bed of the stream or on it's floodplain or delta, as a cone or fan at the base of a mountain slope.

aquitard A confining bed and/or formation composed of rock or sediment that retards but does not prevent the flow of water to or from an adjacent aquifer. It does not readily yield water to wells or springs but store ground water.

aquifer A body of rock or sediment that is sufficiently porous and permeable to store, transmit, and yield significant or economic quantities of groundwater to wells and springs.

artesian Pertaining to groundwater under sufficient hydrostatic pressure to rise above the aquifer containing it.

B

beneficial use One of many ways that water can be used either directly by people or for their overall benefit. The State Water Resources Control Board recognizes 23 types of beneficial use with water quality criteria for those uses established by the Regional Water Quality Control Boards.

bedrock A general term for the rock, usually solid, that underlies soil or other unconsolidated material.

C

competent bedrock Solid rock that does not crumble and underlies soil or other unconsolidated material.

conceptual hydrogeologic model A simplified representation of the groundwater flow system and the hydrostratigraphic units.

confined aquifer An aquifer that is bounded above and below by formations of distinctly lower permeability than that of the aquifer itself. An aquifer containing confined ground water. See artesian aquifer.

GLOSSARY OF TERMS (continued)

contaminant Any substance or property preventing the use or reducing the usability of the water for ordinary purposes such as drinking, preparing food, bathing, washing, recreation and cooling. Any solute or cause of change in physical properties that renders water unfit for a given use. (Generally considered synonymous with pollutant).

D

data quality objectives Criteria that data collection should satisfy to achieve the project objectives.

domestic well A water well used to supply water for the domestic needs of an individual residence or systems of four or less service connections.

E

electrical conductivity (EC) The measure of the ability of water to conduct an electrical current, the magnitude of which depends on the dissolved mineral content of the water.

effective porosity The volume of voids or open spaces in alluvium and rocks that is interconnected and can transmit fluids.

evapotranspiration Loss of water from the soil both by evaporation and by transpiration from the plants growing thereon.

G

groundwater basin An alluvial aquifer or a stacked series of alluvial aquifers with reasonably well-defined boundaries in a lateral direction and a definable bottom.

groundwater monitoring network A series of monitoring wells at appropriate locations and depths to effectively cover the area of interest. Scale and density of monitoring wells is dependent on the size and complexity of the area of interest.

groundwater table The upper surface of the zone of saturation in an unconfined aquifer.

GLOSSARY OF TERMS (continued)

groundwater Water that occurs beneath the land surface and fills the pore spaces of the alluvium, soil, or rock formation in which it is situated. It excludes soil moisture, which refers to water held by capillary action in the upper unsaturated zones of soil or rock.

H

hydraulic conductivity A measure of the capacity for a rock or soil to transmit water; generally has the units of feet/day or centimeter/second.

L

lithologic log A record of the lithology of the soils, sediments and/or rock encountered in a borehole from the surface to the bottom.

M

maximum contaminant level (MCL) The highest drinking water contaminant concentration allowed under Federal and State Safe Drinking Water Act regulations.

O

Overburden The loose soil, silt, sand, gravel, and other unconsolidated material overlying bedrock, either transported or formed in place.

P

permeability The capability of soil or other geologic formations to transmit water. See hydraulic conductivity.

porosity The ratio of the voids or open spaces in alluvium and rocks to the total volume of the alluvium or rock mass.

potentiometric surface The surface to which the water in a confined aquifer will rise in a tightly cased well.

GLOSSARY OF TERMS (continued)

R

recharge Water added to an aquifer or the process of adding water to an aquifer. Ground water recharge occurs either naturally as the net gain from precipitation, or artificially as the result of human influence. See artificial recharge.

recharge basin A surface facility constructed to infiltrate surface water into a groundwater basin.

S

salinity Generally, the concentration of mineral salts dissolved in water. Salinity may be expressed in terms of a concentration, total dissolved solids, or as electrical conductivity. When describing salinity influenced by seawater, salinity often refers to the concentration of chlorides in water. See also total dissolved solids.

saturated zone The zone in which all interconnected openings are filled with water, usually underlying the unsaturated zone.

T

total dissolved solids (TDS) A quantitative measure of the residual minerals dissolved in water that remain after evaporation of a solution. Usually expressed in milligrams per liter. See also salinity.

transmissivity The product of hydraulic conductivity and aquifer thickness; a measure of the ability of water to move through the aquifer. Transmissivity generally has the units of ft^2/day or gallons per day/ft. Transmissivity is a measure of the subsurface's ability to transmit groundwater horizontally through its entire saturated thickness and affects the potential yield of wells.

U

unconfined aquifer An aquifer which is not bounded on top by an aquitard. The upper surface of an unconfined aquifer is the water table.

unsaturated zone The zone below the land surface in which pore space contains both water and air.

GLOSSARY OF TERMS (continued)

W

water quality Description of the chemical, physical, and biological characteristics of water, usually in regard to its suitability for a particular purpose or use.

watershed A region or area bounded peripherally by a divide and draining ultimately to a particular watercourse or body of water.

water table See groundwater table.

well completion report A required, confidential report detailing the construction, alteration, abandonment, or destruction of any water well, cathodic protection well, groundwater monitoring well, or geothermal heat exchange well. The reports were called Water Well Drillers' Report prior to 1991 and are often referred to as "driller's logs." The report requirements are described in the California Water Code commencing with Section 13750.

wetlands Lands that may be covered periodically or permanently with shallow water and that include saltwater marshes, freshwater marshes, open or closed brackish water marshes, swamps, mudflats, fens, and vernal pools.

EXECUTIVE SUMMARY

This Conceptual Hydrogeologic Model (conceptual model) has been prepared for use in conducting Formerly Used Defense Site (FUDS) program investigation activities at the former Benicia Arsenal (Arsenal) in Benicia, California. This conceptual model is a comprehensive but simplified view of the current information available concerning the hydrogeology of the former Arsenal. The objective of the conceptual model is to provide a general hydrogeologic framework for future Arsenal site investigations and clean-up activities.

Seventeen piezometers were installed throughout the former Arsenal to collect groundwater elevation and water quality data for this study. Data from these piezometers have been incorporated into the conceptual model framework to help define a broad representation of the groundwater flow system for of the former Arsenal. The following approach was used to guide the development of the model.

- Compile information on the Arsenal's history, land use, surface hydrology, geology, hydrogeology, and contaminant distribution.
- Synthesize the available data into an initial Arsenal-wide conceptual model.
- Identify previous investigations and literature available for the former Arsenal.
- Install piezometers for a reconnaissance-level assessment of the former Arsenal's hydrogeology.
- Identify data gaps in hydrogeologic characterization of the former Arsenal.
- Report the water level and chemistry data collected from the 17 piezometers that were installed for this project.

The scope of work commissioned for this project does not represent an exhaustive study, but rather a reasonable inquiry, consistent with standard industry practice, in general accordance with the plan objectives. In developing this conceptual model, Brown and Caldwell relied almost solely on information from over 50 soil and groundwater investigations conducted by outside parties (regulatory agencies, interview sources, and other consulting firms) at and in the vicinity of the former Arsenal. Geologic information was obtained from well completion reports from the Department of Water Resources (DWR) for 99 wells installed within the area around the former Arsenal, as well as, from geologic maps and regional geologic reports from various sources.

The former Arsenal is located along the eastern margin of the Coast Range Geomorphic Province of California, in an area of low hills along the northern shore of the Carquinez Strait. The local topography controls the flow pattern of the surface water, and to a large degree, the flow direction of the groundwater. The most prominent fresh water surface features in the area are Lake Herman and Sulphur Springs Creek. Most of the former wetlands on the Arsenal have been filled in for development; but, some wetlands remain on the lowlands where Sulphur Springs Creek drainage meets Suisun Bay and along the Carquinez Strait.

The geology of the former Arsenal, from oldest to youngest, consists of the Cretaceous-age Great Valley Sequence and the Paleocene-age Vine Hill Sandstone (bedrock), overlain by alluvium, Bay Mud, or fill material.

In California, DWR has defined groundwater basins as the layered alluvial material deposited in valleys, and the boundaries of the groundwater basins as the bedrock material or foothills surrounding the valleys. For this report the fill material, alluvium, weathered (non clayey) bedrock, and fractured competent bedrock are considered to be the water-bearing units on the former Arsenal. The former Arsenal was divided into two hydrogeologic areas based on the geology, topography, groundwater occurrence and groundwater quality (Figure ES-1). These two hydrogeologic areas are:

- The Highlands, and
- The Lowlands.

The Highland area is the foothills of the former Arsenal (Figure ES-1). It is characterized by relatively thin deposits of (generally < 50 feet [ft] thick) alluvial material, weathered bedrock, or fill material (overburden) over the competent bedrock. Groundwater in the Highlands can be present in the overburden material. The top 50 feet of competent bedrock also has the potential to contain groundwater within the fractures. The hydrogeologic characteristics of the water contained in the bedrock is not known. Groundwater present in the overburden material has a relatively steep hydraulic gradient (ranging from approximately 0.005 foot/foot [ft/ft] to 0.05 ft/ft, or about 26 ft/mile [ft/mi] to 260 ft/mi). The groundwater flow velocities estimated from the relatively moderate hydraulic conductivity values range from 0.0123 ft/day to 3.09 ft/day (or 4.5 ft/yr to 1,128 ft/yr). Groundwater quality in the Highland area is typically freshwater (with concentrations of total dissolved solids [TDS] from 230 milligrams/Liter [mg/L] to 1,200 mg/L). Groundwater flow is toward the Sulphur Springs Creek drainage for most of the former Arsenal or toward the Carquinez Strait in the southern portion of the Arsenal.

The Lowland area is the former tidal flats and marshlands adjacent to Carquinez Strait and the lower part of the drainage area for Sulphur Springs Creek (Figure ES-1). The geology of the Lowland area above the bedrock is mostly comprised of artificial fill material and alluvium over Bay Mud. Locally, groundwater can be in confined conditions in the older alluvium or weathered bedrock below the Bay Mud. The Lowland areas have a relatively low horizontal hydraulic gradient as compared to the Highland area (approximately 0.0016 ft/ft, or about 8 ft/mi). The low relative hydraulic conductivity values of the overburden material in the Lowland area produces very slow groundwater flow velocities in the Bay Mud of approximately 1.5×10^{-6} ft/day to 1.6×10^{-4} ft/day (or 0.00055 ft/yr to 0.058 ft/yr). The estimated velocity for groundwater in the alluvial or fill material in the Lowland area is 1.5×10^{-5} ft/day to 0.8 ft/day (or 0.0055 ft/yr to 292 ft/yr). The quality of the groundwater in the Lowland area is brackish to saline with concentrations of TDS from 8,830 mg/L to 65,900 mg/L. Groundwater flow is generally toward Suisun Bay or the Carquinez Strait. Tidal influences on the groundwater may extend several hundred feet inland.

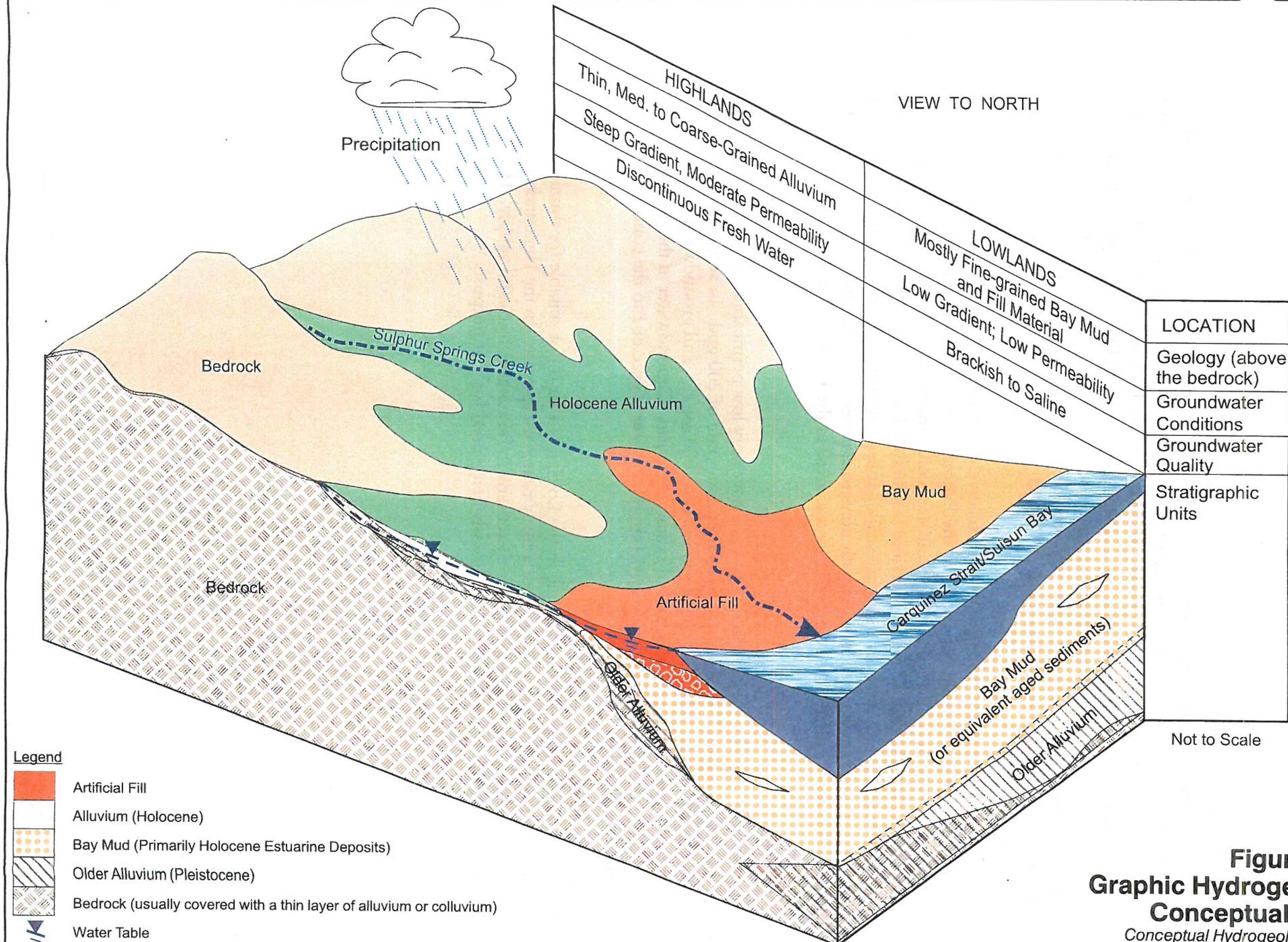


Figure ES-1
Graphic Hydrogeologic Conceptual Model
Conceptual Hydrogeologic Model
Former Benicia Arsenal

The conceptual model provides a basis for evaluating potential beneficial uses of groundwater beneath the former Arsenal. The Water Quality Control Plan for the San Francisco Bay Basin (RWQCB, 1995 and RWQCB, 2004) provides for exceptions to the assumption that all groundwater is considered suitable, or potentially suitable, for municipal or domestic water supply. Exceptions may be considered when naturally occurring constituents (such as TDS > 3,000 mg/L) make it unreasonable to expect that the groundwater would be suitable for a public system. Exceptions may also be considered in areas where a single well would be incapable of producing an average, sustained yield of 200 gallons per day (gpd) (RWQCB, 1995).

In the Highlands the natural groundwater is of relatively high quality and the sediments are of moderate permeability. Studies conducted at the Panoche Landfill, north of the Arsenal, indicate that wells located in the valleys of the Highland area could maintain a sustained yield greater than 200 gpd. However, the thin veneer of alluvium is generally less than 50 feet thick, and Department of Health Services (DHS) requires a sanitary seal of at least 50 feet for drinking water supply wells. A 100-foot seal is often required in areas with numerous potential contaminating activities (PCAs), and the Valero refinery and other current industrial areas in the Highlands would likely be such a case.

In the Lowlands most of the saturated sediments have very low permeability and many wells can be bailed dry; indicating they would not sustain a pumping rate of 200 gpd. In addition, water quality is poor (brackish to saline with TDS concentrations > 3,000 mg/L), and groundwater pumping for domestic use would likely induce increased salinity intrusion. Groundwater in the Lowlands cannot be reasonably expected to provide a potential drinking water source due to the concentration of TDS and low well yields.

Groundwater beneath the Benicia Arsenal in the Lowlands area is not suitable for municipal or domestic water supply and ingestion is not a likely route of exposure. In the Highlands groundwater can be of a quality and quantity that meets the criteria to be suitable for water supply. However, groundwater beneath the Arsenal is not currently being used for that purpose.

1.0 INTRODUCTION

This preliminary Conceptual Hydrogeologic Model (conceptual model) has been prepared for use in conducting Formerly Used Defense Site (FUDS) program investigation activities at the former Benicia Arsenal (Arsenal) in Benicia, California. The FUDS program investigation is being conducted by the United States Army Corps of Engineers (USACE) to comply with both Comprehensive Environmental Response Compensation and Liability Act (CERCLA) and Resource Conservation Recovery Act (RCRA) requirements. The investigation also complies with the latest FUDS and USACE guidance documents in order to promote consistency and comparability of all activities and to assure defensible data collection and production.

The former Arsenal is located immediately east of the City of Benicia and 25 miles northeast of San Francisco, California (Figure 1-1). The Arsenal's history is detailed in a Records Research Report (RRR) (Jacobs, 1999) and summarized in Section 2 of this document. The former Arsenal is divided into five areas known as the Warehouses, Industrial, Revetment, Motor Pool, and Storage/Igloos (WIRMS) areas for the RRR (Figure 1-1). The WIRMS designations are used in this report to provide consistency between documents.

The geology of the former Benicia Arsenal was described for each WIRMS area in the Investigation Workplan (Forsgren Associates/Brown and Caldwell [FA/BC], 1999c), and a summary of land use and topography of each is provided in Appendix A. The concepts in this report are not restricted by the boundaries of the WIRMS areas, which should be used as a guide for location and historical land use only.

1.1 Scope and Objectives

This conceptual model is a comprehensive but simplified view of the current information available concerning the hydrogeology of the former Arsenal. The conceptual model combines information about the hydrology and geology of the former Arsenal to provide a framework to aid in future site investigations, remedial investigations and feasibility studies (RI/FS). It is intended to be an evolving document that can be revised periodically as new data become available. The Preliminary Draft Site Hydrogeologic Model (FA/BC, 2001a) presented the initial compilation and synthesis of Arsenal-wide geologic and hydrogeologic data for review by the USACE, and was used to select the locations of 17 piezometers that were installed throughout the former Arsenal to collect groundwater elevation and water quality data. Data from the piezometers have been incorporated into the conceptual model framework.

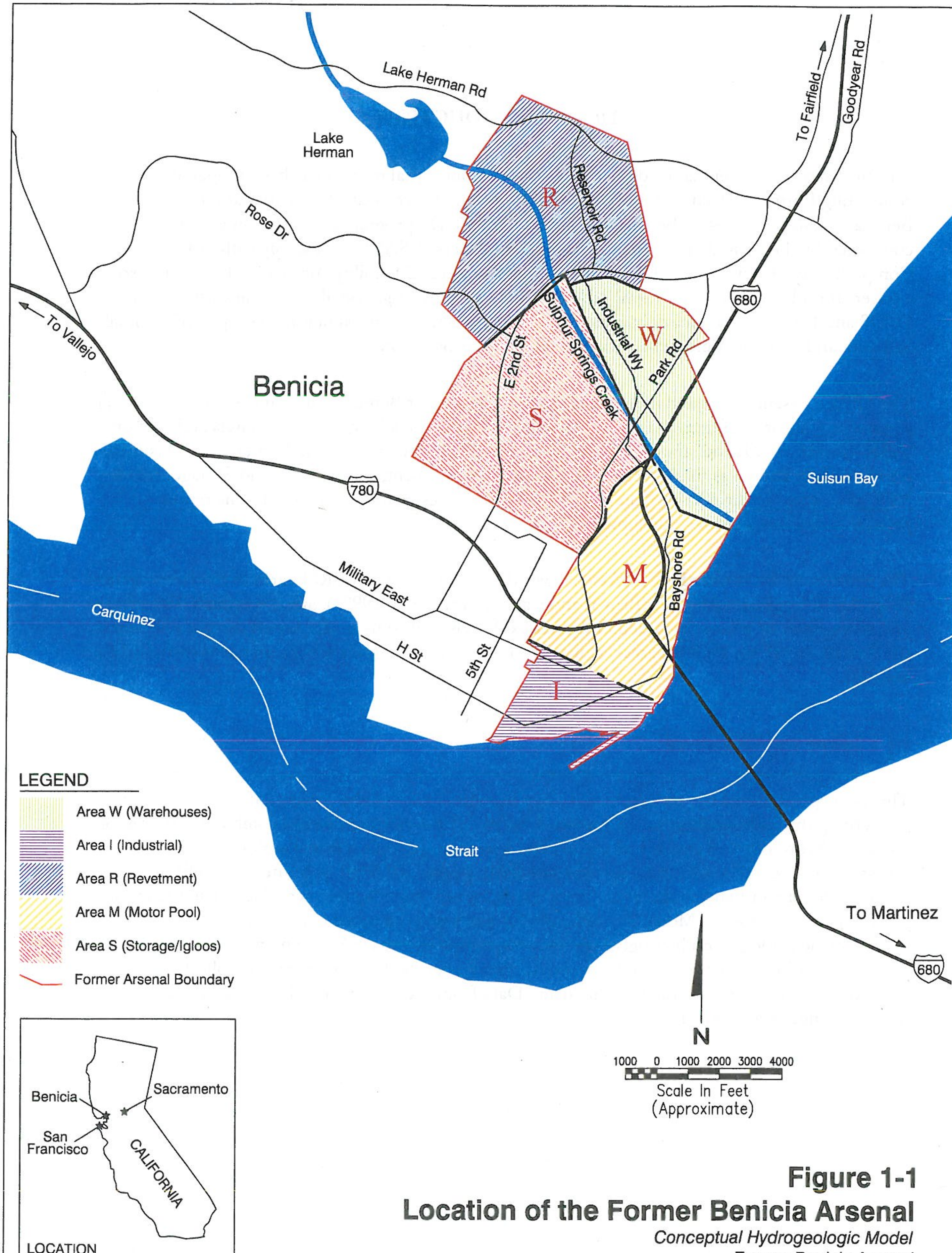


Figure 1-1
Location of the Former Benicia Arsenal
Conceptual Hydrogeologic Model
Former Benicia Arsenal

1.1.1 Scope

Several references were used as a guide in developing this conceptual model, including *The Standard Guide for Conceptualization of Ground-Water Systems* (American Society for Testing and Materials [ASTM], 1996) and the components of a conceptual hydrogeologic model as outlined in Anderson and Woessener (1992). The ASTM guide uses the following integrated approach for conceptualizing and characterizing groundwater systems:

- Define the objectives of the project;
- Define site boundaries;
- Gather data from existing sources; and,
- Organize and prepare data based on project objectives.

Anderson and Woessner (1992) outline the basic components of a conceptual model, which includes constructing a simplified pictorial representation of the groundwater flow system, and defining hydrostratigraphic units.

The intent of a conceptual model is to present the hydrogeology in qualitative terms in order to provide a general framework for site-specific investigations. The area of interest for the conceptual model includes the entire former Arsenal property. Some discussions include data from areas outside the former Arsenal to provide the regional framework of the groundwater and surface water drainage basins.

1.1.2 Objectives

The objective of the conceptual model is to provide a general hydrogeologic framework for future Arsenal site investigations and clean-up activities. The following approach was used to guide the development of this conceptual model:

- Compile information on the Arsenal's history, land use, surface hydrology, geology, hydrogeology, and contaminant distribution;
- Synthesize the available data into an initial Arsenal-wide conceptual model;
- Identify previous investigations and literature available for the former Arsenal;
- Install piezometers for a reconnaissance-level assessment of the former Arsenal's hydrogeology;
- Identify data gaps in hydrogeologic characterization of the former Arsenal;
- Report the water level and chemistry data collected from the 17 piezometers that were installed for this project; and,
- Modify and present the conceptual hydrogeologic model.

The data collected to date has been incorporated into a geographic information system (GIS) making the figures easier to modify as new data from site-specific investigations become available.

1.1.3 Limitations

The interpretation of the geologic and hydrogeologic data, as represented within this conceptual model, should be viewed in recognition of certain limiting conditions. The scope of work commissioned for this project does not represent an exhaustive study; but, rather a reasonable inquiry consistent with standard industry practice and in general accordance with the plan objectives. In developing this conceptual model Brown and Caldwell relied almost solely on information and investigations provided by outside parties (regulatory agencies, interview sources, and other consulting firms) collected prior to this FUDS investigation. The primary limitation of the data attained is the lack of completeness and the lack of consistency between investigations, especially between well completion reports. Brown and Caldwell has not made independent investigation as to the validity, completeness, or accuracy of these data, but has used professional judgment in selecting and interpreting third party results. In general, the data compiled for this conceptual model is assumed to be accurate unless contradictory evidence is specifically noted in this report.

1.2 Resources

The relevant geologic and hydrogeologic data and literature that were identified and reviewed for this investigation are presented in Table 1-1. The locations of the previous investigations in the vicinity of the former Arsenal are presented in Figure 1-2. A summary of the data resources used is provided in Appendix B. Summaries of selected previous investigations are presented in Appendix C. Investigations with summaries in Appendix C are indicated with an asterisk in Table 1-1. Locations of most of the wells with well completion reports within a half mile radius of the Arsenal boundary and filed with the DWR and used to assess the hydrogeology of the former Arsenal are presented on Figure 1-3.

Since the completion of the Draft Final version of the *Preliminary Conceptual Hydrogeologic Model* by FA/BC (FA/BC, 2003b), two reports concerning the quality and quantity of groundwater at the Panoche Landfill north of the former Arsenal was made available by the Department of Toxic Substances Control. The two reports are: *Monitoring Program Assessment for the Central Area Drainage Plan 12 and Report 5* (IT Corporation, 2001), and the *Hydrogeologic Assessment Report* (IT Corporation, 1987). Additional ideas concerning the hydrogeology of the former Arsenal were incorporated from the Expanded Site Investigation (Expanded SI) (Brown and Caldwell, 2005a), which focused primarily on groundwater impacts at the former Arsenal.

The concepts presented in the RWQCB San Francisco Bay Region (Region 2) Basin Plan (Basin Plan) (RWQCB, 1995) were considered during the writing of this document. The Basin Plan is the master policy document that contains descriptions of the legal, technical, and programmatic bases of water quality regulation in the San Francisco Bay region. The Basin Plan provides a definitive program of actions designed to preserve and enhance water quality, investigate the beneficial water uses, and to develop water quality objectives to protect the designated beneficial water uses.

Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
*1	1051 Tyler Street	Harding Lawson and Associates	Site Investigation and Risk Analysis Vicinity of Building 48, 49, and 99 Area, Benicia Industrial Park, Benicia, California	SCDEM/Records Research Report (Jacobs Engineering, 1999)	Building 48	1997	Lowland
2	294 Military East	Golden Gate Petroleum, Edd Clark and Associates, Inc.	Preliminary Site Investigation Workplan	SCDEM/Records Research Report (Jacobs Engineering, 1999)		2001	Highland
3	945 Teal Street	URS and Solano County Department of Environmental Management	Final Report, Geophysical Survey and Subsurface Investigation Location of Former USTs	SCDEM/Records Research Report (Jacobs Engineering, 1999)		2001	Lowland
4	116 West Channel Road	Golden Gate Petroleum	Additional Site Assessment and Groundwater Monitoring Report - First Quarter 2001	SCDEM/Records Research Report (Jacobs Engineering, 1999)		2001	Lowland
*5	Bridge No. 28-153	Caltrans - District 4	Log of Test Borings, Bridge No. 28-153, Benicia-Martinez Bridge, Sheets 1 through 7 of 7	Caltrans - Sol 680		1995	Highland and Lowland
*6	Bridge No. 23-125	Caltrans - District 4	As Above	Caltrans - Sol 681		1995	Highland
*7	Bridge No. 23-126	Caltrans - District 4	As Above	Caltrans - Sol 682		1995	Highland
*8	Bridge No. 23-127	Caltrans - District 4	As Above	Caltrans - Sol 683		1995	Highland
*9	Bridge No. 23-128	Caltrans - District 4	As Above	Caltrans - Sol 684		1995	Highland
*10	Bridge No. 23-129	Caltrans - District 4	As Above	Caltrans - Sol 685		1995	Highland
*11	Bridge No. 23-130	Caltrans - District 4	As Above	Caltrans - Sol 686		1995	Highland
*12	Bridge No. 23-158	Caltrans - District 4	As Above	Caltrans - Sol 687		1995	Highland
13	North of Bayshore Road Between Industrial and Sulfur Springs Road	United Soil Engineering	Soil and Foundation Investigation for Building, Phase IV North of Bayshore Road Between Industrial and Sulphur Springs Roads, Benicia, California	Benicia Public Works		1980	Lowland
14	NW Corner of Iowa Street and Stone Road	United Soil Engineering	Preliminary Soil and Foundation Investigation, Supplemental Report. Benicia Industrial Park, Area 8	Benicia Public Works		1978, 1982	Highland
15	3130 Bayshore Road	DCM Joyal Engineering	Preconstruction Geotechnical Engineering Investigation Report	Benicia Public Works		1990	Lowland
16	380 Industrial Court	Lowney Associates	Geotechnical Investigation	Benicia Public Works			Lowland

Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal (continued)

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
17	3671-3691 Industrial Way. 440 feet south of Lake Herman Road, north side of Industrial Way	Donald E. Banta and Associates	Foundation Investigation Industrial Buildings A and B Portion of Lot 10 - Industrial Way Fleetside Industrial Park, Benicia, California	Benicia Public Works		1989	Highland
18	5100 Park Road	Private		Benicia Public Works			Highland
19	4950 East 2nd Street	Engeo, Inc	Geotechnical Exploration	Benicia Public Works		1990	Highland
20	Industrial Way, approximately 0.5 mile south of Lake Herman Road (east of Arsenal)	Subsurface Consultants		Benicia Public Works		1989	Highland
21	250 West Channel Road	Kleinfelder and Associates	Geotechnical Engineering Investigation Parcel 3C-1 Warehouse and Office Buildings	Benicia Public Works		1986	Highland
22	Southeast corner of Wagner Street and Park Road (east of Arsenal)	Lowney Associates	Geotechnical Investigation for New IFS Building Benicia, California	Benicia Public Works		1995	Highland
23	605 Industrial Way and 4186 Park Road	Kleinfelder	Geotechnical Engineering Investigation Premium Tobacco Stores Loading Dock	Benicia Public Works		1996	Lowland
24	101 E. Channel Road	Hultgren-Tillis Engineers	Geotechnical Investigation - Shop Building Benicia Fabrication and Machine, Inc.	Benicia Public Works		2000	Lowland
25	3601 Park Road	Cooper Engineers	Draft of Geotechnical Investigation - Proposed Office and Warehouse Buildings, Benicia, California For Noyes Lumber	Benicia Public Works		1983	Lowland
26	4186 Park Road and 635 Indiana Street	Environmental Geotechnical Consultants	Geotechnical Study - Proposed Communication Facility Benicia Industrial Park Cell Site	Benicia Public Works		1995	Highland
27	Oak Road near Bayshore Road.	Private		Benicia Public Works			Lowland
28	Northeast corner of Industrial Way and Oregon Street	Harding Lawson and Associates	Soil Investigation - Planned Warehouse Buildings	Benicia Public Works		1979	Lowland
29	Lake Herman Road. and Goodyear Road	Youngdahl and Associates	Geotechnical Engineering Study for Jack in the Box #3482	Benicia Public Works		1998	Highland
30	6000 Egret Court at Industrial Way and Lake Herman Road	Harding Lawson and Associates	Geotechnical Investigation - Southern Solano Development Project Benicia, California	Benicia Public Works		1988	Highland

Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal (continued)

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
31	6050 Egret Court @ Industrial Way & Lake Herman Road	Harding Lawson and Associates	Geotechnical Investigation - Southern Solano Development Project Benicia, California	Benicia Public Works		1988	Highland
32	North of 680 & Southern Pacific Railroad	Private		Benicia Public Works			Highland
*33	2060 Camel Road	Harding Lawson and Associates	Assessment of Lead Contamination - Powder Magazine 1 Site		Camel Barn Museum, Powder Magazine 2	1988	Highland
*34	1 Oak Road	Harding Lawson and Associates	Case Closure Summary		Open Storage 14	1977	Highland
*35	700 Bayshore Road	Harding Lawson and Associates	Groundwater Monitoring			1997	Lowland
*36	2650 Harbor Way	SCDEH/ HLA	Case Closure Summary			1996	Lowland
*38	116 West Channel Road	Clearwater Group, Inc.				2001	Lowland
39	5200 East 2nd Street (east of Arsenal Boundary)	Lowney Associates	Geotechnical Investigation for East 2nd Street and Park Road Warehouse			1997	Highland
40	3150 Bayshore Road	Geomatrix	Results of Phase II Investigation			1994	Lowland
41	711 Jackson Street, Benicia Mini-Storage	RUST	Subsurface Investigation - Benicia Mini-Storage	Jacobs, 1999 [reference #479]		1996	Highland
42	433 Industrial Way, Ryder Truck Rental	SCDEM	Remedial Action Completion Certification, Underground Storage Tank Case Closure			1996	Lowland
43	4457 Park Road, The Customer Company	Kaprealian Engineering	Soil Sampling Report - The Customer Company			1989	Highland
44	2050 Park Road Building 175, Former Gasoline Service Station and Vicinity of Building T226 in Area M			Jacobs, 1999 (reference #481)		1998	Highland
45	3001 Bayshore Road, Irving Lutz Property (Building 155, Area M)	Aqua Science Engineers Inc.	Well Sampling Field Log	Jacobs, 1999 [reference #507]		1997	Highland
46	155 East Channel Way, Former Pie Truck Rental Terminal	SEC Donahue/ Blymer Engineers/ Groundwater Tecnology Inc.	Well Sampling Field Log			1996	Lowland

Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal (continued)

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
47	3781 Mallard Drive, L&M Pallet/Dresser Rand Company	SCDEM	File Summary 20053/Groundwater Monitoring wells			1989	Highland
48	100 Industrial Way	Tank Protect Engineering	Site Plan/Log of Exploratory Boring/ Record of Water Sampling			1997	Highland
49	865 Teal Court (east of Building W6, Area W)	Unknown	None	Jacobs, 1999 [reference #506]		1998	Highland
50	Drainage ditch south and east of Parcel 2-4A (Open Storage 28, Area M)	Private		Jacobs, 1999 [reference #526]		1998	Highland
51	Land between R/R tracks east of Lake Herman Road (east of Arsenal)	Harding Lawson and Associates		Benicia Public Works		1987	Highland
*52	Northeast 600 feet from existing pier to Army Point, north 600 feet	Dames & Moore	Soil and Foundation Investigation Report Part I - Conclusions and Recommendations, Proposed Marine Facilities		Crude Pier	1967	Lowland
*53	Product Pier, 0.5 mile off the shore, southwest of end of existing wharf	Dames & Moore	See above #52		Product Pier	1967	Lowland
54	2980 and 3100 Bayshore Road (Area M)	Private		Jacobs, 1999 [reference #478]		1998	Lowland
55	160 Teal Court	Kleinfelder & Associates	Groundwater Monitoring Investigation for W.R. Meadows of California	USACE		1986	Highland
56	4588 East 2nd Street	Brown & Mills	Geotechnical Investigation Proposed Mobile Radio Facility	USACE		1996	Highland
57	849 Jackson Street	Certified Environmental Consulting	Phase II: Soil and Groundwater Investigation	FA/BC		1993	Lowland
*B48 - B49	Adams Street and Bayshore Road	Harding Lawson and Associates	Site Investigation and Risk Analysis Vicinity of Building 48, 49, and 99 Area, Benicia Industrial Park, Benicia, California	FA/BC	Building 49	1988	Highland
*B99	North side of Tyler Street and Bayshore Road	Harding Lawson and Associates	See above B48 – B49	FA/BC	Building 99	1997	Lowland

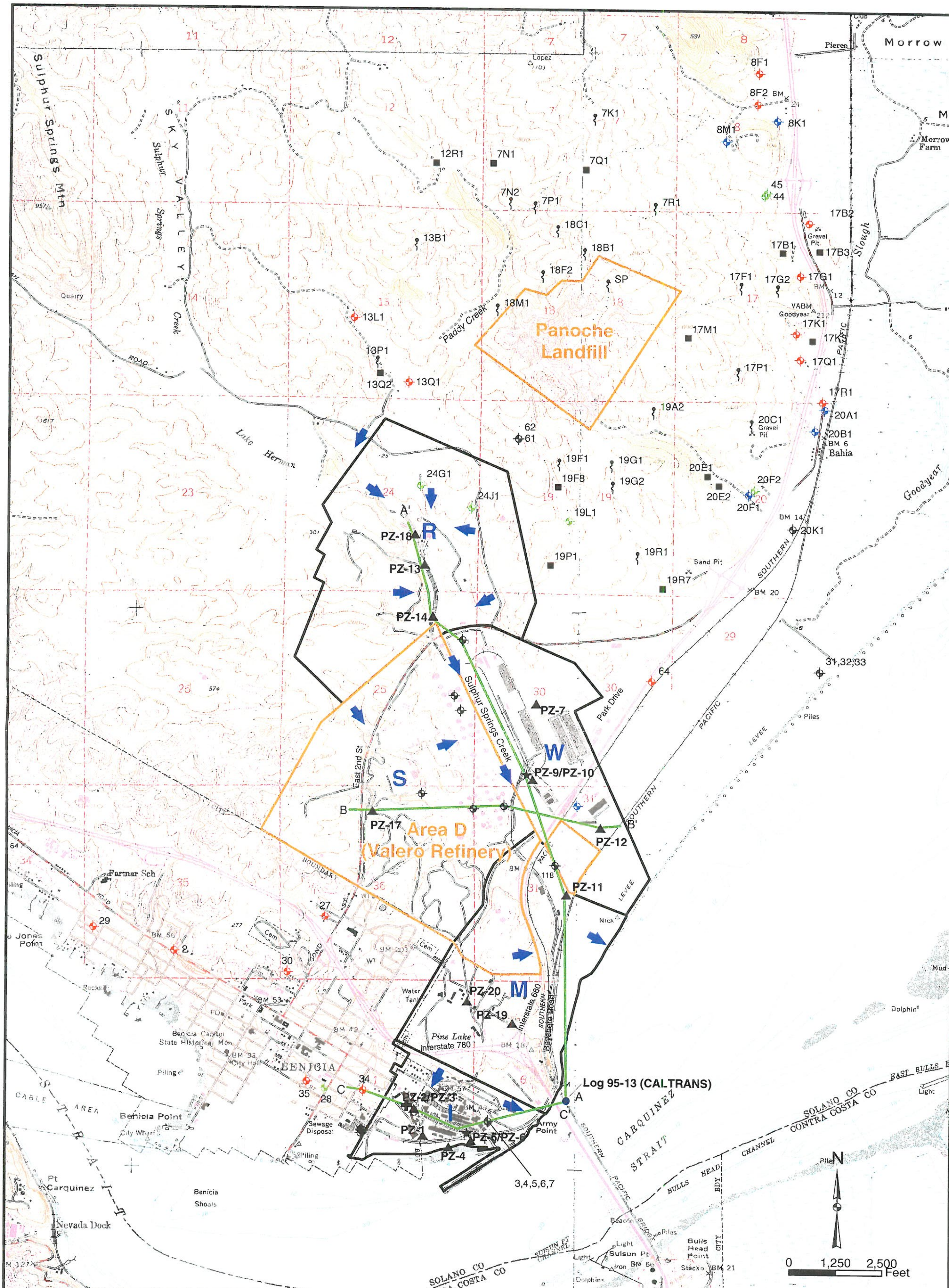
Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal (continued)

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
*50 Series	938-940 & 954 Tyler Street	Meredith/Boli and Associates, Inc.	Letter Report	FA/BC	50 Series Complex	1994	Highland
*50 Series	938-940 & 954 Tyler Street, 969-989 Lincoln Street	FA/BC	Building 50 Series Site Inspection	FA/BC	50 Series Complex	1999	Highland
L1		FA/BC	Field Investigation Report, Area I, LF1, LF2, Quarry 3 and Area M Quarry 1	FA/BC	Fillsite 1 (formerly Landfill 1)	2001	Lowland
L2		FA/BC	See above L1	FA/BC	Fillsite 2 (formerly Landfill 2)	2001	Lowland
Q1		FA/BC	See above L1	FA/BC	Quarry 1	2001	Highland
Q3		FA/BC	See above L1	FA/BC	Quarry 3	2001	Highland
B53		FA/BC	Technical Memorandum: Field Site Investigations for Area I Fuel Facilities, Buildings 53, 73, 103, and 154	FA/BC	Building 53	2000	Lowland
B73		FA/BC	See above B53	FA/BC	Building 73	2000	Highland
B103		FA/BC	See above B53	FA/BC	Building 103	2000	Lowland
B154		FA/BC	See above B53	FA/BC	Building 154	2000	Highland
B15		FA/BC	Draft Final Technical Memorandum, Field Site Investigation, Fuel Only Facilities (Area I Fuel Storage Facilities at Buildings 15, 25, 26, 27, 28, 45, 46(B), 54, 118(A), 152 and 178)	FA/BC	Building 15	2001	Highland
B26		FA/BC	See above B15	FA/BC	Building 26	2001	Highland
B28		FA/BC	See above B15	FA/BC	Building 28	2001	Highland
B54		FA/BC	See above B15	FA/BC	Building 54	2001	Lowland
B118(A)		FA/BC	See above B15	FA/BC	Building 118(A)	2001	Lowland
B152		FA/BC	See above B15	FA/BC	Building 152	2001	Highland
B178		FA/BC	See above B15	FA/BC	Building 178	2001	Highland
A	684 acres A.D. Seeno Property	Engeo Corporation	Preliminary Soils Exploration	Benicia Public Works		1990	Highland
B	3410 East Second Street	Exxon Company	Various Reports and boring logs	Valero Benicia Refinery	Exxon, Humble Oil		Highland/Lowland

Table 1-1. Summary of Previous Investigations in the Area of the Former Benicia Arsenal (continued)

Site ID # (a)	Address of Site	Author	Title of Report	Source	Alias	Year of Investigation	Hydrogeologic Area
*C	Industrial Way & Southern Pacific Railroad Tracks, adjacent to 4000 Industrial Way/4200 Industrial Way	GEOCON and Klienfelder	Supplemental Site Investigation Report, Benicia-Martinez Bridge, Wetlands Mitigation Risk Assessment, Benicia, Solano County, California	Caltrans	Wetlands	1999	Highland
*D	Valero Benicia Refinery, 3400 East Second Street	Valero	Log of Test Borings	Acton Mickelson Environmental, Inc.	-	1990-2001	Lowland/Highland
E	New Benicia-Martinez Bridge	Caltrans	Log of Test Borings	Caltrans		1995	Lowland/Highland
F	Tourtelot Property	EIP Associates	Southampton Tourtelot Property General Plan Land Use Amendment and Rezoning, Final Environmental Impact Report		Tourtelot	1989	Highland
G	Park Road from Bayshore to Industrial Way	Harding Lawson and Associates	Generalized Subsurface Section A-A', Park Road Sewer, Benicia, California			1990	Lowland/Highland
H	East Second Street Bridge, between Rose Drive and Reservoir Road	CH2M Hill	Geotechnical Exploration East 2nd Street Bridge Widening Project Between Rose Drive and Reservoir Road Benicia, California			1992	Highland
J	Northeast of Arsenal	IT Corporation	Monitoring Program Assessment for the Central Area Drainage Work Plan 12 and Report 5	DTSC	Panoche Landfill	2001	Highland
* J	Northeast of Arsenal	IT Corporation	Hydrogeologic Assessment Report	DTSC	Panoche Landfill	1987	Highland
*53 sites	Mostly Area I and W	Brown and Caldwell	Expanded Site Inspection Report	Brown and Caldwell		2005	Lowland/Highland
*11 Potential Fuel Storage Sites	Buildings: 27, 31, 42, 45, 45(W), 46(B), 47, 71, 88, 89, 161 and CL2.	Brown and Caldwell	Fuel Storage Tank Removal Action Report	Brown and Caldwell		2005	Area I

Notes:
(a) Site ID number corresponds to locations presented on Figure 1-2.
* Summary paragraph in Appendix C.



Legend

- Spring Locations
- Pond Locations

Wells
- Domestic Well
- Industrial/Irrigation/Stock Well
- Monitoring Wells
- Unknown Well Use

- Water Table Piezometer
- Water Table and Deep Piezometer
- Water Table and Bedrock Piezometer
- Approximate surface water flow direction
- Cross Section Line
- Areas of Special Interest (D, J)
- Former Arsenal Boundary

Figure 1-3
Location of Existing Wells, New Piezometers, Surface Water Features, and Hydrogeologic Cross Sections

Conceptual Hydrogeologic Model

Former Benicia Arsenal

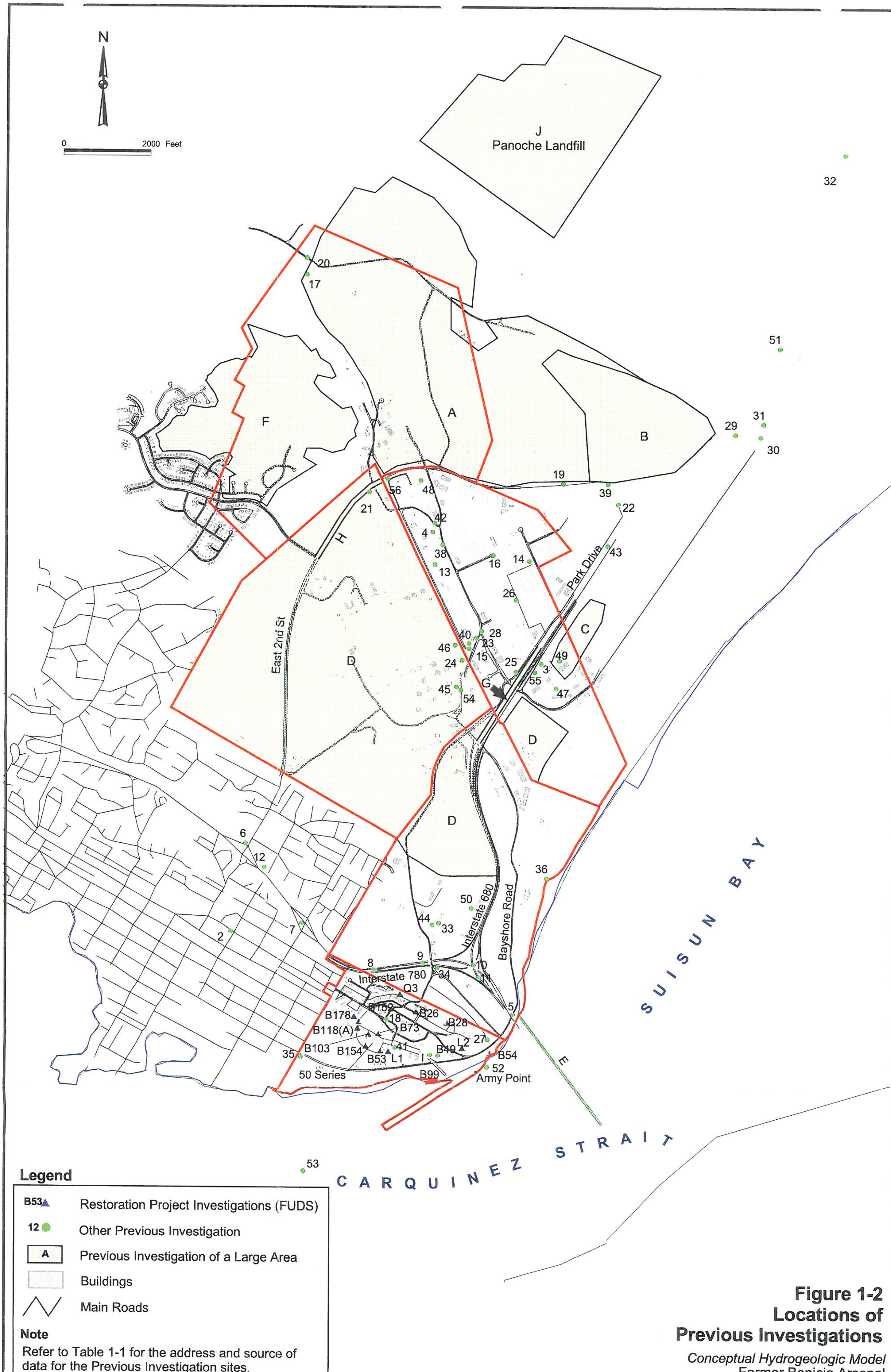


Figure 1-2
Locations of Previous Investigations

Conceptual Hydrogeologic Model
Former Benicia Arsenal

1.3 Organization of the Report

This report contains the following six sections:

- Section 1. Scope of the report and its main objectives.
- Section 2. Historical background information of the former Arsenal (including previous investigations, soil data, climate information, topography, and the locations of wetlands in the Benicia area).
- Section 3. Regional and local geology (stratigraphy and structural geology).
- Section 4. Regional and local hydrogeology.
- Section 5. Summary of the Conceptual Hydrogeologic Model.
- Section 6. References.

The appendices contain the back-up information for the geologic, hydrogeologic, and climate data used to compile this report. Appendix A briefly describes the historic land use in the WIRMS areas. Resources used in the investigation are presented in Appendix B. Tabulation of previous investigations is presented in Table 1-1 and Appendix C. Appendix D contains climate information for Martinez Water Plant and the Port Chicago Naval Depot (the closest weather recording stations) from Desert Research Institute and the Western Regional Climate Center. Well construction logs for the new piezometers that were installed for this project are presented in Appendix E. Appendix F is the analytical results of groundwater samples collected from the piezometers. Appendix G is transducer data collected over a 48-hour period to estimate the tidal fluctuation in selected piezometers. Appendix H is a compilation of the water level elevation measurements collected from January 2002 through November 2002 for the 17 piezometers installed for this project.

2.0 SITE BACKGROUND

This section contains brief descriptions of the historical background of the former Arsenal since its closure in 1964: surface water features, wetlands, climate and soil information, and previous investigations. The former Arsenal is bounded on the west by the city of Benicia; to the north by rolling hills and new residential developments; to the south by the Carquinez Strait; and to the east by Suisun Bay (Figure 1-1). State highways 680 and 780 intersect within the southern part of the former Arsenal, and state highway 680 continues south across the Carquinez Strait on the Benicia-Martinez Bridge. In the RRR, the former Arsenal is divided into five areas as shown on Figure 1-1 based on their current land use. These are the "WIRMS" areas:

- W (Warehouses),
- I (Industrial),
- R (Revetment),
- M (Motor Pool), and
- S (Storage/Igloos).

2.1 Historical Development of the Former Benicia Arsenal

The land used for the Benicia Arsenal was acquired by the U.S. government in 1849 with a land transfer of 345 acres from the founders of the City of Benicia. Originally referred to as "the Post at Point near Benicia, California," the post was later designated Benicia Barracks (Jacobs, 1999). In 1862, President Lincoln ordered that a plot of land at Benicia be segregated from the public lands for the purpose of a military reservation. Between 1849 and 1958, the United States acquired 1,790.48 fee acres, 351.12 public domain acres, 6.40 license acres, and 580.04 easement acres, for a total of 2,728.04 acres (Jacobs, 1999).

The former Arsenal served as the principal depot for ordnance, issuance (supplies, ammunition, small arms parts and accessories), the testing of small arms, mobile and seacoast artillery targets, and vehicle maintenance for the Division of the Pacific. A massive expansion took place at the Arsenal during World War II. Physical expansion included the addition of 1,847 acres and over 200 structures. Another full-scale expansion took place, just prior to and following the Korean Conflict, with the addition of approximately 40 to 50 structures. Many of these additions were warehouses for inert materials and transitory shelters. Throughout the Arsenal's history, in response to changing government needs, the functions of many buildings and operation areas changed.

The Arsenal was continuously occupied by the military from its establishment in 1849 to its closure in 1964. Benicia Arsenal was declared excess by DoD and was reported to the General Services Administration on January 11, 1963. Deactivation and closure of the Arsenal was completed on March 31, 1964 (Jacobs, 1999). Discussions concerning the current and historic land use of the WIRMS areas of the former Arsenal are presented in Appendix A.

Land use and topography of the WIRMS areas are summarized in Appendix A. Most of the former marshland and wetland areas, (on the former Arsenal) in the Sulphur Springs Creek drainage area and bordering the Carquinez Strait, were filled in throughout the history of the Arsenal. Four interpretations of the areas that were filled are shown on Figure 2-1 and discussed briefly below.

- Aerial photographs dated 1928, 1945, 1947, and 1952 were used to interpret marshland areas that were filled.
- Edward Schwafel Engineers (Schwafel, 1969) used numerous boreholes to interpret an area in the Sulphur Springs Creek drainage that contained artificial fill over Bay Mud.
- The geologic map shows areas mapped as artificial fill (Graymer et. al., 1999).
- Areas with artificial fill over Bay Mud interpreted to have a very high liquefaction potential were mapped by Knudsen (2000).

Areas with artificial fill are of special interest because they are the areas with the greatest density of industry and thus have high potential for contamination of the groundwater due to anthropogenic activities.

2.1.1 Historical Groundwater Wells and Well Surveys

In 1872, the Army attempted to develop a water source by drilling a well at the south edge of Area M. During drilling, groundwater was first encountered at a depth of 960 feet. However, this water was determined to be unfit for human consumption and the well was blocked off to a depth of 960 feet using cement, sand, and grain sacks (Cowell, 1963). This well was only used to produce water for boilers and irrigation.

Nine water supply wells and a pump house were identified in the RRR for the former Arsenal on a 1944 map (Jacobs, 1999). The 1944 map locates these wells in an east-west line across Sulphur Springs Creek approximately 100 feet north of East Second Street (formerly Highway 21). This is the only known reference to these wells. The well construction details and use of the wells are not known. On October 8, 2003, Brown and Caldwell personnel performed a site inspection to locate these wells. None of the wells could be located and no features resembling abandoned wells were observed.

Nineteen wells were identified within one mile of the Panoche Landfill (Figure 1-3) (IT Corporation, 1987). These wells were identified after the draft final version of the conceptual model (FA/BC, 2003b). These wells are identified with a number and letter on Figure 1-3 and Table 2-1. Two of the three stock wells are located in Area R (24G1 and 24J1); the other well is located just east of Area R (19L1). Nine wells are identified as domestic wells, however only two of these wells are located within ½ mile of the former Arsenal (13L1 and 13Q1). These two wells are located just north of the former Arsenal within the drainages of Paddy Creek and Sulphur Springs Creek. The remaining wells are located more than one mile northeast of the Arsenal along Highway 680 west of Goodyear Slough. All of the wells are located in valleys in the Highland area. Information about usage, depth of the wells, and purge rates are not available for all of the wells. The geologic unit interpreted to be supplying water for each well is based on the location and depth of the well (Table 2-1).

Nearly all the 99 well completion reports obtained from the DWR for wells located within ½ mile of the former Arsenal (identified on Figure 1-3 and Table 2-1 with just a number and no letters), were installed for monitoring or testing purposes (Table 2-1). The exceptions are: three of the existing wells were installed for industrial purposes, one well was installed for irrigation purposes, and seventeen wells were installed for domestic (or stock) purposes. None of the domestic wells identified in this survey are located on the former Arsenal. One domestic well was documented as 'destroyed' (well 26). Six of the potentially existing (not documented as 'destroyed') domestic wells are located within downtown Benicia (west of the Arsenal), an area now served by the State Water Project. One domestic well is located east of the former Arsenal (well 64). Most of the wells that were located on the Valero Refinery (Figure 1-2, area D) are not named or shown individually because there are hundreds of wells associated with this site.

2.2 Previous Investigations

More than 50 soil and groundwater investigations have been conducted inside the boundaries of the former Arsenal. The locations of all the known investigations are shown on Figure 1-2, and included in Table 1-1. The previous investigations are referenced in Table 1-1 by a single number (e.g., 21) or a site number (B103, which stands for Building 103). The numbered investigations were conducted primarily by private landowners, or public agencies (e.g. California Department of Transportation [Caltrans]). The building investigations were conducted as part of the Benicia Arsenal FUDS Project under the direction of the USACE. Investigations that covered large areas (both on and off the Arsenal) are denoted by letters A through J on Figure 1-2 and on Table 1-1. Sites with an asterisk on Table 1-1 have a brief description in Appendix C. Sources of information for the previous investigations are presented in Appendix B.

2.3 Climate

Much of California has a Mediterranean climate, with warm, dry summers and mild, wet winters. Climate data presented in Appendix D was recorded for the Martinez Water Plant (for the years 1970 to 2000) and for the Port of Chicago Naval Depot (for the years 1948 to 1975) which is located just across the Carquinez Strait from Benicia (Desert Research Institute, 2000). The average amount of yearly precipitation for the Martinez site was 19.67 inches per year, with a maximum of 39.09 inches and a minimum of 7.80 inches.

1928 - 1952

Marshlands that were filled
as interpreted from aerial photographs
dated 1928, 1945, 1947, and 1952 (Jacobs,1999).

1969

Artificial Fill over Bay Mud as mapped by Schwafel (1969)
for the Sulphur Springs Creek Drainage Area.

1999

Artificial fill from the geologic map (Figure 3-1, this report)
(Graymer et. al., 1999).

2000

Artificial fill over Bay Mud, mapped as having very
high liquefaction potential (Knudsen, 2000).

Figure 2-1
Areas Interpreted to Contain Fill Material
Conceptual Hydrogeologic Model
Former Benicia Arsenal

Table 2-1. Well Information by Well Type in the Area of the Former Benicia Arsenal

Well ID #	Address	Type of Well	Year Well Drilled	Casing Diameter (inch)	Depth of Well (ft bgs)	Depth of Boring (ft bgs)	Well Destroyed	Estimated Discharge (gpm)	Producing Formation	Note
	Monitoring Wells									
3	Bayshore Street and Taylor Road	monitoring	1995	2	12.5	12.5	no	ND	ND	
4	Bayshore Street and Taylor Road	monitoring	1995	2	15	15	no	ND	ND	
5	Bayshore Street and Taylor Road	monitoring	1995	2	15	15	no	ND	ND	
6	Bayshore Street and Taylor Road	monitoring	1995	2	20	20	yes (ID #53)	ND	ND	
7	Bayshore Street and Taylor Road	monitoring	1995	2	40	40	yes (ID #54)	ND	ND	
8	203 Teal Court	monitoring	ND	ND	ND	16	yes	ND	ND	
9	203 Teal Court	monitoring	ND	ND	ND	16	yes	ND	ND	
10	203 Teal Court	monitoring	ND	ND	ND	16	yes	ND	ND	
13	614 East Fifth Street	monitoring	1996	6	10	10	yes	ND	ND	
15	100 Industrial Way	monitoring	1996	2	20	21.5	yes	ND	ND	
16	100 Industrial Way	monitoring	1996	2	20	25.5	yes	ND	ND	
17	100 Industrial Way	monitoring	1996	2	27	30	yes	ND	ND	
18	100 Industrial Way	monitoring	1996	2	20	21.5	yes	ND	ND	
31	Lake Herman Road and Suisun Bay	monitoring	1992	2	9	9	no	ND	ND	
32	Lake Herman Road and Suisun Bay	monitoring	1992	2	9.5	9.5	no	ND	ND	
33	Lake Herman Road and Suisun Bay	monitoring	1992	2	9	9	no	ND	ND	
36	614 East Fifth Street	monitoring	1990	4	14.5	14.5	yes (ID #11)	ND	ND	
37	614 East Fifth Street	monitoring	1990	4	16	16	yes (ID #12)	ND	ND	
38	1500 East Fifth Street	monitoring	ND	ND	ND	ND	yes	NA	ND	
39	1500 East Fifth Street	monitoring	ND	ND	ND	ND	yes	NA	ND	
40	1500 East Fifth Street	monitoring	ND	ND	ND	ND	yes	NA	ND	-
41	East Channel Road	monitoring	1992	2	15	16	no	ND	ND	-
42	East Channel Road	monitoring	1992	2	15	16	no	ND	ND	
50	700 Bayshore Road	monitoring	2000	ND	22	22	yes	ND	ND	

Table 2-1. Well Information by Well Type in the Area of the Former Benicia Arsenal (continued)

Well ID #	Address	Type of Well	Year Well Drilled	Casing Diameter (inch)	Depth of Well (ft bgs)	Depth of Boring (ft bgs)	Well Destroyed	Estimated Discharge (gpm)	Producing Formation	Note
				Monitoring Wells						
51	700 Bayshore Road	monitoring	2000	ND	18	19.5	yes	ND	ND	
60	2251 Lake Herman Road (IT Panoche Landfill)	monitoring	1989	ND	44	44	yes	ND	ND	
61	2251 Lake Herman Road (IT Panoche Landfill)	monitoring	1984	4	49.5	50.7	no	ND	ND	
62	2251 Lake Herman Road (IT Panoche Landfill)	monitoring	1985	4	25	26	no	ND	ND	
D	3400 Second Street (Valero Refinery)	monitoring	1990-1992	2 and 4	60 (max)	70 (max)	no	ND	ND	
J	2251 Lake Herman Road (Panoche Landfill)	monitoring	1984-1996	2 and 4	200 (max)	200 (max)	no	0.01 to 4.5	Alluvium and Panoche Formation	a
				Domestic Wells						
2	490 West M Street	domestic	2001	6.25	172	180	no	ND	ND	
26	1502 East Second Street	domestic	1994	ND	ND	50	yes	ND	ND	
27	West U St and East Second Street	domestic	1976	6	145	145	no	20	ND	
29	801 West K Street	domestic	1977	ND	120	120	no	10	ND	
30	P Street. and Second Street	domestic	1964	6	240	240	no	20	ND	
34	690 East K Street	domestic	1966	6	40	40	no	20	ND	
35	433 East I Street	domestic	1962	6	40	40	no	ND	ND	
64	Hwy 680 and Lake Herman Road	domestic	1969	6 5/8	110	110	no	3	ND	
8F1	No Data Available	domestic/ stock	1979	8	ND	225	no	20	Volcanics	a
8F2	No Data Available	domestic/ stock	1977	8	ND	230	no	8	Volcanics	a
13L1	No Data Available	domestic	ND	ND	ND	162	no	ND	Panoche ?	a
13Q1	No Data Available	domestic	ND	ND	ND	17	no	ND	Panoche or Alluvium	a
17B2	No Data Available	domestic	ND	ND	ND	ND	no	ND	Volcanics	a
17G1	No Data Available	domestic	ND	ND	ND	ND	no	ND	Volcanics	a

Table 2-1. Well Information by Well Type in the Area of the Former Benicia Arsenal (continued)

Well ID #	Address	Type of Well	Year Well Drilled	Casing Diameter (inch)	Depth of Well (ft bgs)	Depth of Boring (ft bgs)	Well Destroyed	Estimated Discharge (gpm)	Producing Formation	Note
17K1	No Data Available	domestic/ stock	1985	ND	ND	<150	no	20	Volcanics	a
17Q1	No Data Available	domestic	1867	10 ft	ND	12	no	10	Volcanics ?	a
17R1	No Data Available	domestic	ND	ND	ND	ND	no	ND	Volcanics	a
Irrigation/Industrial/Stock Wells										
28	475 East I Street	irrigation	1963	6	205	205	no	20	ND	
43	Military West and Bayshore	industrial	1978	6	225	225	yes	20	ND	
44	Parrish Road and Lopes Road	industrial	1980	6	250	250	no	275	ND	
45	Parrish Road and Lopes Road	industrial	1980	6	300	300	no	20	ND	
19L1	No Data Available	stock	ND	ND	ND	3	no	ND	Alluvium	a
20F2	No Data Available	stock	ND	6	ND	270	no	40	Domengine	a
24G1	No Data Available	stock	ND	8 ft	ND	13	no	ND	Panoche or Alluvium	a
24J1	No Data Available	stock	ND	8 ft	ND	20.5	no	ND	Panoche or Alluvium	a
Unknown Well Use										
1	1117 Dominic Court	ND	ND	ND	ND	107.7	yes	ND	ND	
8K1	No Data Available	not in use	ND	4	ND	300	no	ND	Volcanics	a
8M1	No Data Available	ND	ND	ND	ND	ND	no	ND	Volcanics ?	a
20A1	No Data Available	ND	ND	ND	ND	ND	no	ND	Volcanics ?	a
20B1	No Data Available	ND	ND	ND	ND	ND	no	ND	Volcanics ?	a
20F1	No Data Available	ND	ND	4	ND	ND	no	ND	Domengine	a
20K1	No Data Available	ND	ND	ND	ND	ND	no	ND	Domengine ?	a

Notes: ft bgs - feet below ground surface
gpm – gallons per minute
ND - no data available
MSL - mean sea level
(a) IT Corporation, 1987.

The Benicia area is located in evapotranspiration zone 8, classified as inland San Francisco Bay Area with some marine influence by the California Irrigation Management Information System (CIMIS). Total evapotranspiration is about 49.4 inches per year (CIMIS, 1999). Total evapotranspiration is more than the precipitation because of the marine influence.

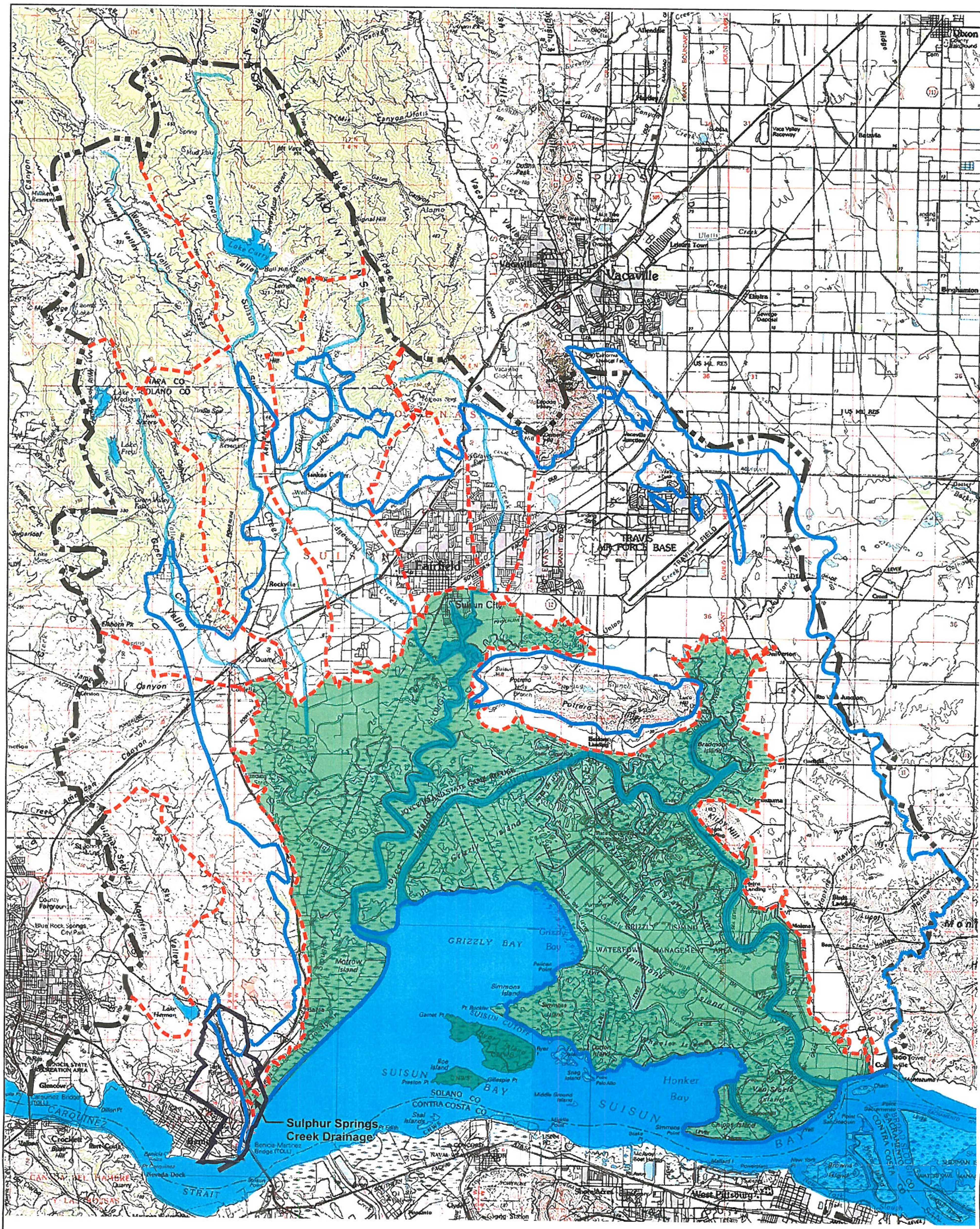
2.4 Topography and Surface Water Features

The Benicia area is located along the eastern margin of the Coast Range Geomorphic Province of California in an area of low hills along the northern shore of the Carquinez Strait. North-northwest trending hills and valleys are approximately parallel to the San Andreas Fault system. The local topography controls the flow patterns of the surface water, and to a large degree, the flow directions of the groundwater. The east-west trending Carquinez Strait is a notable exception to the northwest trending valleys. The Carquinez Strait was created by erosion from the Sacramento and San Joaquin rivers during Pleistocene periods of relatively low sea levels (Norris and Webb, 1990).

The southernmost portion of the former Arsenal (Area I) rises from sea level at the Carquinez Strait to an elevation of approximately 160 feet above mean sea level (msl) in the low-lying foothills near the location of former Pine Lake (Figure 1-3). The foothills rise to an elevation of over 400 feet in the western part of the former Arsenal. The foothills are cut by natural and man-made drainages that flow into the tidal flats and marshlands of the Carquinez Strait and Suisun Bay. The surface water drainage in the northwestern part of the Arsenal (western Areas S and R) is toward the east into the Sulphur Springs Creek drainage channel. The northeastern corner of the former Arsenal is comprised of low-lying hills up to 250 feet in elevation (eastern Area R), with surface drainage generally toward the west into the Sulphur Springs Creek drainage.

Regional surface water drainages and the approximate boundary of the Suisun surface water drainage basin are shown on Figure 2-2. The groundwater basin (DWR Basin #2-3) is also shown, which includes the Sulphur Springs Creek drainage (Figure 2-2).

Figure 1-3 shows the general flow directions of surface water at the former Arsenal. The most prominent fresh water surface features in the area are Lake Herman and Sulphur Springs Creek. Sulphur Springs Creek and its main tributary, Paddy Creek, form the largest watershed in the Benicia area. Their confluence is located just northwest of the former Arsenal below (southeast of) Lake Herman. All of the tributaries that flow into Sulphur Springs Creek exhibit intermittent flow during the winter rainy season (DCE, 1998) and are dry in the summer and fall. Sulphur Springs Creek originates near the summit of Sulphur Springs Mountain and flows south-southwest to its outlet at Suisun Bay; its flow is controlled by Lake Herman Dam. Sulphur Springs Creek drainage channel is partially lined with concrete at its upper reaches near East Second Street (Figure 1-3). Southeast of the former Arsenal are tidal flats and marshlands of Suisun Bay, some of which have been filled in and developed (FA/BC, 1999c).



- Former Benicia Arsenal Boundary
- Suisun Surface Water Drainage Basin (DWR Basin #7)
- Surface Water Features
- Subwatershed Boundary
- Suisun Marsh (wetland)
- Suisun-Fairfield Groundwater Basin #2-3 (DWR, 2003)

NORTH

0 6,000 12,000

Scale in Feet

Source:
Background - DeLorme 3-D TopoQuads
Suisun Marsh - RWQCB, 1995

Figure 2-2
Suisun Surface Water Drainage Basin and Suisun-Fairfield Groundwater Basin
Conceptual Hydrogeologic Model
Former Benicia Arsenal

Lake Herman is a reservoir impounded by an earth fill dam, with a storage capacity of 1,780 acre-feet (DCE, 1998). Local watershed runoff and excess imported surface water from the California State Water Project's North Bay Aqueduct are stored in Lake Herman. The principal role of the reservoir is water storage, and it is the city of Benicia's back-up water supply (DCE, 1998), the primary water supply is imported surface water from the State Water Project.

Pine Lake was constructed in 1939 by the Army initially as a reservoir in case of fire (Figure 1-3). Water was pumped from the Carquinez Strait into the reservoir. In the 1940s, an increasing demand for domestic water was needed at the Arsenal. The water was filtered and chlorinated to augment the potable water supply and to reduce the quantity of water purchased (Jacobs, 1999). The man-made lake was drained and filled in the 1970s.

The Carquinez Strait, just south of the former Arsenal, is a tidally influenced outlet to the San Francisco Bay for the Sacramento and San Joaquin Rivers. Water quality in Carquinez Strait and Suisun Bay (just east of the Arsenal) is monitored by the DWR in accordance with the requirements of Water Rights Decision 1485 issued in August 1997 (DCE, 1998). The 100-year flood line, as defined by the Federal Emergency Management Administration, encompasses low-lying flood-prone areas along the Carquinez Strait, along Sulphur Springs Creek drainage almost up to Lake Herman, and on the east side of Industrial Way (DCE, 1998).

Flow rates were estimated for the creeks and springs north of the former Arsenal within a one mile radius of the Panoche Landfill. Flow rates varied from trace to 10 gallons per minute (gpm), with most springs and streams averaging less than 1 gpm. Flow rates estimated in Paddy Creek ranged from 135 to 2,900 gpm during the spring and summer. In the area around the Panoche Landfill, there is probably interaction between stream flow and groundwater flow in the main stream channel and the underlying alluvium. Except during very wet periods, flow rates in the streams are typically less than 0.5 gpm, with the majority of the water consumed by evapotranspiration, or by water percolating back into the alluvium. In 1986, several springs were reported to have year round flow rates of 0.6 to 7.5 gpm in the spring, and 0.3 to 0.5 gpm in the late summer (IT Corporation, 1987).

Surface water features outside of the Panoche Landfill were sampled for water quality; most were sampled between March 1986 and January 1987. The surface sampling locations were divided into three general drainage areas for analyses: Paddy Creek (11 sites), Goodyear Slough (12 sites), and lower Sulphur Springs Creek (2 sites). The TDS values from the samples collected from Paddy creek ranged from 410 mg/L to 1,000 mg/L. The TDS values from the samples collected from Goodyear Slough ranged from 450 mg/L to 1,100 mg/L. The TDS values from the samples collected from lower Sulphur Springs creek ranged from 590 mg/L to 1,041 mg/L (IT Corporation, 1987). Goodyear Slough and lower Sulphur Springs creek are considered to be in the Lowland area.

2.5 Wetlands

Under the California Wildlife Protection Act "wetlands" are defined as lands that may be covered periodically or permanently with shallow water and include saltwater marshes, freshwater marshes, open or closed brackish water marshes, swamps, mudflats, fens, and vernal pools (Fish and Game Code 2785). Generally wetlands are lands where saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface (Cowardin, 1979).

The Suisun Marsh, located just east and northeast of the former Arsenal (Figure 2-2) is the largest wetland in California. In 1974, the California Legislature recognized the threat of urbanization and enacted the Suisun Marsh Preservation Act, requiring that a protection plan be developed for the Suisun Marsh. Sensitive biological resources have been identified just east of the Highway 680 Benicia Bridge that extend up into the Suisun Bay and Suisun Marsh area. Special status plant and animal species that may be affected by development in this area are listed in the Benicia General Plan (DCE, 1998).

In 1978, the State Water Resources Control Board issued D-1485, setting water salinity standards for Suisun Marsh. In 1984, DWR published the Plan of Protection for the Suisun Marsh, which included an Environmental Impact Report. Most recently *the Suisun Marsh Preservation Agreement* was authorized by an Act of Congress in PL 99-546 (California Wetlands Information Center, 1996).

Coastal management of the San Francisco Bay is provided by the San Francisco Bay Conservation and Development Commission. The primary state law governing the commission, the McAteer-Petris Act, outlines the jurisdiction respective for wetlands. "Managed wetlands consisting of all areas which have been diked off from the bay and have been maintained during the three years immediately preceding the effective date of the amendment of this section during the 1969 Regular Session of the Legislature as a duck hunting preserve, game refuge or for agriculture" (Gov.Code 66610(b)).

Most of the former wetlands of the Suisun Marsh on the Arsenal have been filled in for development (Figure 2-1), but some wetlands remain on the Lowlands where the Sulphur Springs Creek drainage meets Suisun Bay and along the Carquinez Strait in Areas W and M. These wetlands are not specifically protected at this time, although the bridge expansion for State Highway 680 from Benicia to Marquinez has precipitated relocating wetland habitat to a lowland area in the southeastern part of the former Arsenal (Caltrans and GEOCON Consultants, Inc., 2001) (Figure 1-2, Area C).

2.6 Soil Types and Related Vegetation

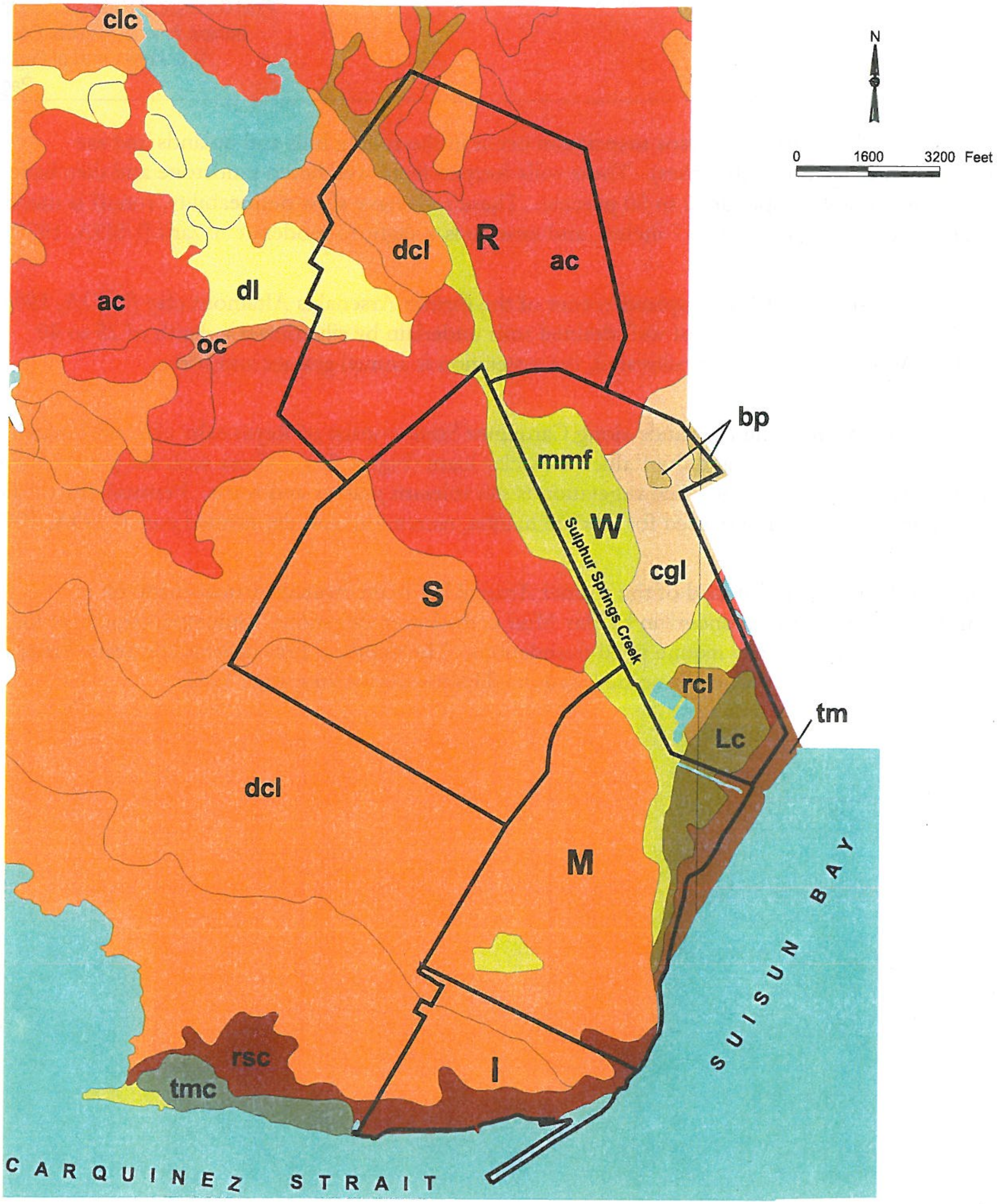
The properties of soil type of an area can be used to estimate the amount of surface water runoff, infiltration, and evapotranspiration of water from the soil. The soil types for the Benicia area outlined on Figure 2-3 are simplified from the original United States Department of Agriculture (USDA) designations. The dominant soil types found in the former Arsenal area consist of soils in the Dibble-Los Osos association, Altamont clay, man-made fill, and the Reyes association (Solano County Soil Survey [USDA, 1977]).

The soils in the Dibble-Los Osos association occur in the rolling hills and uplands and are moderately deep (30 to 40 inches). These soils formed from weathered sandstone and they have a loam surface soil. Slopes are 2 to 50 percent. These soils have slow permeability, runoff is medium, available water capacity is 5 to 7 inches, and erosion is a slight to moderate hazard (USDA, 1977).

The surface soil in northwest upland corner of the former Arsenal is Altamont clay (USDA, 1977). The Altamont series consists of well-drained soils underlain by siltstone at a depth of 25 to 40 inches. Where the soil is not cultivated, the vegetation is annual grasses and forbs.

The soils in much of the Lowlands along Carquinez Strait consist of Reyes salty clay, tidal marsh soils, Tampa mucky clay, and the Valdez salty clay loam (Figure 2-3). These soils are poorly drained and strongly acidic or saline. The vegetation is salt tolerant grasses and forbs. Permeability of the soil is slow. Reyes soils are used for wildlife habitat, recreation, and dry farmed oats (USDA, 1977).

Most of the relatively flat land of the former Arsenal has been created by man-made fill (anthropogenic) material underlain by Bay Mud at the lower elevations. Industrial structures located on fill over Bay Mud may require piled foundations. The depth to firm bearing for heavy loads varies, but it exceeds 100 feet in some locations (Harstad Associates, Inc., 1962).



Legend

- Water
- Former Benicia Arsenal Boundary

Soil Names (USDA, 1977)

- Altamont Clay - ac
- Clear Lake Clay - clc
- Corning Gravelly Loam - cgl
- Dibble-Los Osos Clay Loams -dcl
- Dibble-Los Osos Loams - dl
- Valdez Silty Clay Loam - Lc
- Omni Clay - oc
- Reyes Silty Clay - rsc
- Rincon Clay Loam - rcl
- Tamba Mucky Clay -tmc
- Tidal Marsh - tm
- Borrow Pit - bp
- Man-Made Fill - mmf

Figure 2-3

Soil Types in the Benicia Area

Conceptual Hydrogeologic Model

Former Benicia Arsenal

3.0 GEOLOGIC SETTING

The geology of the former Arsenal was described for each WIRMS area in the Investigation Workplan (FA/BC, 1999c) and is reiterated and expanded in this section. The former Arsenal is located in the southern part of the northern coast range of California where the geologic history has been complicated by stresses associated with the San Andreas strike-slip fault system. The complex geology has naturally resulted in some discrepancies between geologists concerning the names of the stratigraphic units (Dibblee, 1980; Sims et. al., 1973; and Graymer et. al., 1999). However, the various geologic interpretations generally agree on the relative ages and types of material for the stratigraphic units. For consistency, the stratigraphic names from the most recent geologic publication in the area (Graymer et. al., 1999) are used in this report (Figure 3-1).

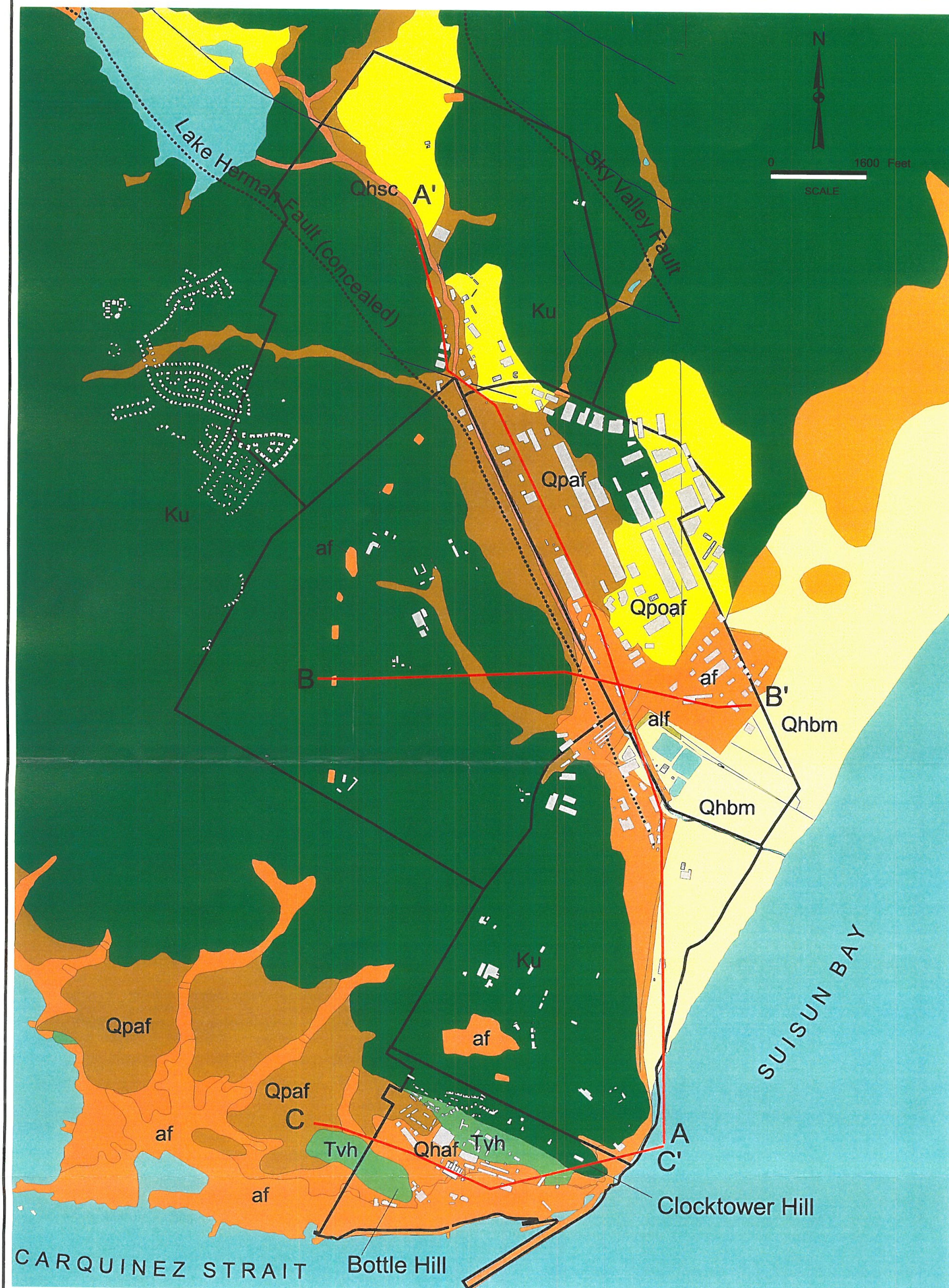
3.1 Regional Geology

The regional geology of the area was updated by Graymer et. al. (1999) and is presented in Figure 3-1. The geologic discussions in this report are focused on the structural geology (faults and folds) and stratigraphy (sedimentary units) of the area. Cross sections are presented in the hydrogeology section of this report (Section 5) where the hydrostratigraphic units are defined. The hydrostratigrahic units are derived from the stratigraphic units, but are defined by the relative permeability of the material.

3.1.1 Physical Geology and Geomorphology

The geologic history of the California coast is a result of complex plate boundary interactions. During much of the Mesozoic era, the western edge of California was under compression as the Pacific Plate migrated eastward and was subducted beneath the North American Plate. Parts of the Pacific Plate were scraped onto the North American Plate and were folded and faulted into the complex Mesozoic-age Franciscan Assemblage.

Beginning about 140 million years ago in the mid-Jurassic period, a transform plate boundary began to develop along the western edge of the North American plate. The subduction zone gradually moved east under the North American Plate (Harden, 1997) and the San Andreas Fault system subsequently became the major plate tectonic feature on the western margin of the North American Plate along the California coast. The San Andreas transform fault and related strike-slip (horizontal) faults (e.g. the Green Valley Fault and the Concord Fault) trend north-northwest. Thrust and reverse faults (low-angle and high-angle compressional faults) are present in the eastern portion of the Coast Range, one of which is the Lake Herman Fault (Figure 3-1). Active faulting in the Benicia area seems to be confined to the Green Valley Fault zone and associated faults north of the city of Cordelia (Graymer et. al., 1999). Benicia is within the 50 kilometer radius of damage from historical seismic activity of the San Andreas Fault to the west (California Department of Conservation, Division of Mines and Geology, 1996).



Legend

Surficial Geologic Units (Graymer et. al., 1999)

- Artificial fill - af (Historic)
- Artificial levee fill - alf (Historic)
- Alluvial fan and fluvial deposits - Qhaf (Holocene)
- Bay Mud - Qhbm (Holocene)
- Stream channel deposits - Qhsc Qasc(Holocene)
- Alluvial fan and fluvial deposits - Qpaf and Qpf (Pleistocene)
- Older alluvial fan deposits - Qpoaf (Pleistocene)
- Vine Hill Sandstone of Weaver (1953) Tvh (Paleocene)
- Great Valley Sequence - undivided sandstone and shale - Ku (Cretaceous)

- Faults
- Anticline
- Water
- Cross Section Lines
- Buildings

Figure 3-1
Geologic Map of the Benicia Area
Conceptual Hydrogeologic Model
Former Benicia Arsenal

Brown and Caldwell
P:\US Army Corps\Benicia Arsenal\SHM\CHM maps geo.apr

Final
July 2005

Two faults were identified in the Benicia area by Graymer et. al. (1999): the Sky Valley Fault and the Lake Herman Fault (Figure 3-1). The Lake Herman Fault is a west-dipping thrust fault that is mostly equivalent to the West Sulphur Springs Valley thrust fault of Weaver (1949a). Lake Herman Fault trends north-northwest from Carquinez Strait up the drainage channel of Sulphur Springs Creek and then cuts across the foothills to the northwest beneath Lake Herman (Figure 3-1). Bedrock outcrops on the western side of the fault dip to the west-southwest at angles of 35 to 65 degrees, and outcrops on the eastern side dip to the east or northeast at angles of about 25 to 40 degrees (Graymer et. al., 1999).

The Sky Valley Fault is an east-dipping oblique reverse fault; it has both vertical and horizontal (strike-slip) offsets. A section of this fault cuts across the northeastern corner of the former Arsenal (Figure 3-1). Neither fault cuts Quaternary strata (Graymer et. al., 1999).

The Benicia area contains few, if any, large mapped landslides, but locally contains scattered small landslides (Wentworth et. al., 1997). Frizzell et. al. (1974) mapped several small landslide features (approximately 200 feet to 500 feet in the longest dimension) from aerial photographs south of Pine Lake, northeast of Pine Lake, south of Lake Herman, and in the northeast corner of the former Arsenal.

3.1.2 Regional Stratigraphy

The Franciscan Assemblage, of Mesozoic age, forms the structural basement in the eastern portion of the Coast Range below the Cretaceous-age Great Valley Sequence throughout the San Francisco Bay Area (Bailey et. al., 1964). The Franciscan Assemblage is a complex mixture of different rock types that have been structurally interlayered (a mélange). The most abundant rock types are sandstone and shale. The Franciscan Assemblage is not exposed in the Benicia area; therefore, not included on Table 3-1, which lists the stratigraphy of the area.

The Great Valley Sequence overlies the Franciscan Assemblage and consists of steeply dipping siltstone, sandstone, shale, and mudstone. Marine fossils and characteristic sedimentary features indicate that they accumulated in an ocean basin that lay west of the Mesozoic North American plate margin (Harden, 1997). The area mapped as undifferentiated Great Valley sequence around Benicia was formerly mapped as the Panoche Formation by Dibblee (1980), and as the Knoxville Formation (FA/BC, 1998).

In Area I, the Great Valley Sequence is unconformably overlain by steeply-dipping siltstones and sandstones of the Vine Hill Sandstone (formerly the Martinez Formation of Dibblee, 1980) (Table 3-1). The Great Valley Sequence and the Vine Hill Sandstone are considered to be bedrock, for the purposes of this report.

Table 3-1. Stratigraphy of the Former Benicia Arsenal

Era	Millions of Years Ago (Start)	Period	Epoch	Stratigraphic Unit	Map Unit	Description
Cenozoic	0.012	Quaternary	Historic	Artificial Fill	af	Loose to very well consolidated gravel, sand, silt, clay, rock fragments, organic matter, and man-made debris in various combinations. Thickness is variable and may exceed 50 feet in places. Some fill is compacted and quite firm, but fill made before 1965 is widespread, not compacted, and consists of dumped materials.
				Artificial Levee Fill	alf	Man-made deposits of various materials and ages, forming artificial levees as much as 6.5 meters high. Some are compacted and quite firm, but fills made before 1965 are not compacted and consists of dumped materials.
				Artificial Fill over Bay Mud[2]	afbm	Artificial fill cover on Bay Mud. Stiff brown silty clay, brown silt, sand, clay and gravel, as much as 15 to 20 ft thick, low to medium permeability.
			Holocene (recent)	Stream Channel Deposits, Alluvial Fan and Fluvial Deposits	Qhsc & Qhasc	Poorly to well-sorted sand, silt, silty sand, or sandy gravel with minor cobbles. Cobbles are more common in the mountainous valleys. Many stream channels are lined with concrete or rip rap. Engineering works such as diversion dams, energy dissipaters and percolation ponds also modify the original channel. Many stream channels have been straightened, and these are labeled Qhasc. The straightening is especially prevalent in the lower reaches of streams entering the estuary. The mapped distribution of stream channel deposits is controlled by the depiction of major creeks on the most recent U.S. Geological Survey 7.5-minute quadrangle maps. Only deposits related to major creeks are mapped. In some places these deposits are under shallow water for some or all of the year.
				Bay Mud	Qhbm	Estuarine mud, predominantly gray, green and blue clay and silty clay underlying marshlands and tidal mud flats of Suisun Bay. The upper surface is covered with cordgrass (Spartina sp.) and pickleweed (Salicornia sp.). The mud also contains a few lenses of well-sorted, fine sand and silt, a few shelly layers (oysters), and peat. The mud interfingers with and grades into fine-grained deposits at the distal edge of Holocene alluvial fans, and was deposited during the post-Wisconsin rise in sea-level, about 12,000 years ago to present (Imbrie et. al., 1984).
				Alluvial Fan and Fluvial Deposits	Qhaf	Alluvial fan deposits are brown or tan, medium dense to dense, gravely sand or sandy gravel that generallly grades upward to sandy or silty clay. Near the distal fan edges, the fluvial deposits are typically brown, never reddish, medium dense sand that fines upward to sandy or silty clay.
	1.8		Pleistocene	Alluvial Fan and Fluvial Deposits	Qpaf & Qpf	Brown dense gravely and clayey sand or clayey gravel that fines upward to sandy clay. These deposits display variable sorting and are located along most stream channels in the county. All Qpaf deposits can be related to modern stream courses. They are distinguished from younger alluvial fans and fluvial deposits by higher topographic position, greater degree of dissection, and stronger soil profile development. They are less permeable than Holocene deposits, and locally contain fresh water mollusks and extinct late Pleistocene vertebrate fossils. They are overlain by Holocene deposits on lower parts of the alluvial plain, and incised by channels that are partly filled with Holocene alluvium on higher parts of the alluvial plain.
				Older Alluvial Fan Deposits	Qpoaf	Brown dense gravely and clayey sand or clayey gravel that fines upward to sandy clay. These deposits display various sorting qualities. All Qpoaf deposits can be related to modern stream courses. They are distinguished from younger alluvial fans and fluvial deposits by higher topographic position, greater degree of dissection, and stronger profile development. They are less permeable than younger deposits, and locally contain fresh-water mollusks and extinct Pleistocene vertebrate fossils.
	65	Tertiary	Pliocene	Sonoma Volcanics[1]	Tsv, Tst	Tsv - andesitic flows and flow-breccia. Tst - andesitic tuff breccia.
			Miocene			
			Eocene	Domengine Sandstone[1]	Tds	Tan, arkosic sandstone.
			Paleocene	Vine Hill Sandstone (Martinez Formation[1])	Tvh	Glauconitic sandstone and shale present only south of the Lake Herman Fault in the Bottle Hill area.
Mesozoic	140	Cretaceous		Great Valley Sequence (Panoche Formation[1] or Knoxville Formation[3])	Ku	Undivided sandstone and shale (Early and Late Cretaceous) - Interbedded carbonaceous-biotite wacke, white-mica-carbonaceous sandstone, greenish-gray mudstone and shale, laminated fine-grained sandstone and gray shale, carbonaceous siltsone, black shale, and fine-grained mica wacke. Locally includes hard laminated clean white quartz-lithic-biotite sandstone and fossil-hash gritstone.

Notes:
From Graymer et.al., 1999 unless noted (Figure 3-1).
[1] Geology from Dibblee, 1980. [2] from Schwafel, 1969. [3] FA/BC, 1998

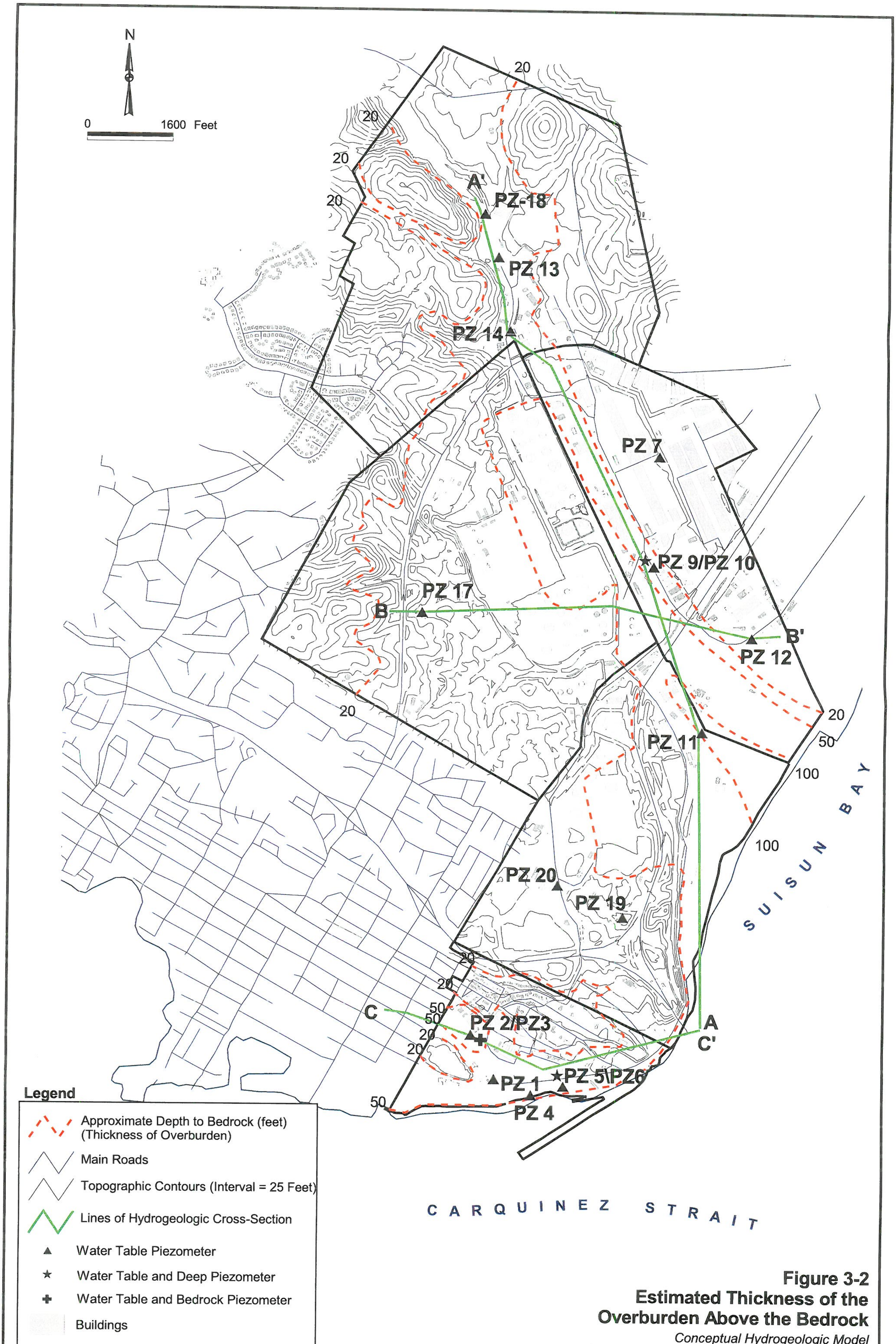


Figure 3-2
Estimated Thickness of the Overburden Above the Bedrock
Conceptual Hydrogeologic Model
Former Benicia Arsenal

A relatively thin veneer of alluvial and fluvial deposits cover the Great Valley Sequence in the foothills (Highlands) of the former Arsenal. The depth to the surface of the bedrock was estimated using the geologic logs and from previous investigations (Figure 3-2). Slopes and bottoms of ravines are filled with colluvium and alluvium derived from downslope movement of the residual material eroded from the bedrock hills (Hultgren Geotechnical Engineers, 1995). There appears to be over 40 feet of alluvium or fill on top of the bedrock on the northern side of the Clocktower Hill, and the depth to bedrock in some areas beneath Sulphur Springs Creek Drainage is greater than 100 feet.

In the lower reaches of the Sulphur Springs Creek drainage and in the southern edge of Area I, older Pleistocene alluvial and fluvial deposits are present in channels on the surface of the bedrock (Figure 3-1). The alluvial deposits are gravelly and clayey sand or clayey gravel that fine upward into sandy or silty clay. These deposits are denser and less permeable than the more recent Holocene alluvial deposits due to weathering and compaction (Graymer et. al., 1999).

The Holocene (Recent) Bay Mud, an estuarine deposited mud, is predominantly gray, green, and blue clay or silty clay that was deposited in the marshlands, tidal mud flats, and the bay itself. The mud may contain lenses of well-sorted fine sand and silt, a few shelly layers (oysters) and peat (Graymer et. al., 1999). In Area I and Area M, these lenses have not been found (Brown and Caldwell, 2005a). In contrast, the alluvial clays are lean and usually silty or sandy. The Bay Mud sediments deposited in the Carquinez Strait include more silts and sands due to the stronger currents depositing coarser material through the strait.

The Bay Mud is covered in most areas by Holocene stream-channel deposits (which consist of unconsolidated sands, silts, silty sand, and sandy gravel) or by artificial fill material deposited during historical times. Artificial fill in the area usually consists of a mixture of clay, silt, sand, and gravel. The younger fill material sometimes contains bricks, concrete and other construction debris (Figure 2-1). The older fill material is often firm and very stiff (Harding Lawson Associates [HLA], 1990).

3.2 Geologic Areas of the Former Arsenal

The geology of the former Arsenal was described in the Investigation Workplan (FA/BC, 1999c) for each of the WIRMS areas. For the purposes of developing a conceptual model it is necessary to define geologic areas based on physical characteristics, which do not coincide with the WIRMS land use designations. The geologic areas outlined in this report are shown on Figure 3-3 (along with groundwater elevations discussed in Section 4.5) and discussed below. The geologic areas are as follows:

- Lowlands
- Highlands

The Lowland and Highland areas are further discussed in the hydrogeology section. The boundaries of the geologic areas are flexible; for this report, they are set along changes in the geology and topography (e.g. the break from flatlands to foothills). Geologic descriptions of the former Arsenal are focused primarily on the sediments that overlie the bedrock material. Few boreholes with geologic logs were advanced into the bedrock material. Information used to interpret the local geology came from the following sources:

- Well completion reports obtained from DWR,
- Test boring logs for the Benicia-Martinez Bridge obtained from Caltrans,
- Information collected during the drilling and installation of the new piezometers (summarized in Table 3-2 , Figure 1-3, and Appendix E),
- Previous investigation reports (listed in Table 1-1 and Appendix C), and
- Geologic mapping of the area (Graymer et. al., 1999; and Dibblee, 1980).

A spoils area was designated in 1967 in the southernmost portion of Area W, adjacent to the Sulphur Springs Creek drainage canal and Suisun Bay (Figure 3-4). Humble Oil and Refining Company (Humble) was granted the right to dump dredgings in this location, Spoils Area 4 (Figure 3-4). Based on a 1969 aerial photograph, spoils were dumped in Spoils Area 4 and in an adjacent site to the southwest, Spoils Area 3 (Figure 3-4). This material was generated during the construction of the nearby Humble oil refinery in Area S. Humble later became Exxon and is now Valero. The volume and origin of the material in Spoils Areas 3, 4, and 5 is not known (Jacobs, 1999).

The stratigraphy of the Lowlands in southern Area I is similar to the Sulphur Springs Creek drainage area with pockets of alluvium on top of bedrock, overlain by Bay Mud, which is overlain by alluvial deposits or fill material. The bedrock material in this area is the Vine Hill Sandstone, which is present in outcrops on the hills (Graymer et el., 1999). The thickness of the deposits above the bedrock in southern Area I varies from a few feet to more than 80 feet (Brown and Caldwell, 2005a).

3.2.1 Geology of the Lowland Area

The major part of the Lowland area consists of the Sulphur Springs Creek drainage. The Lowland area extends from East Second Street south to Suisun Bay as outlined on Figure 3-3. The Lowland area also includes the former marshlands in the southern part of Area I. The geology of the Lowland area is characterized by artificial fill and/or Holocene-age alluvial and fluvial deposits overlying the Bay Mud. The Bay Mud may lie directly on the bedrock, weathered bedrock, or on older Pleistocene-age alluvial deposits (Older Alluvial Fan Deposits, Table 3-1).

The Sulphur Springs Creek drainage is thought to be an ancestral valley that follows the trace of the now buried Lake Herman Thrust Fault (Graymer et. al., 1999). The valley gradually filled with alluvium and Bay Mud, and most recently has been covered by artificial fill. The lithology from the surface down generally consists of fill or alluvial material overlying Bay Mud, which overlies bedrock or weathered bedrock of the Great Valley Sequence. Occasional lenses of alluvial sands and silts maybe present within the Bay Mud.

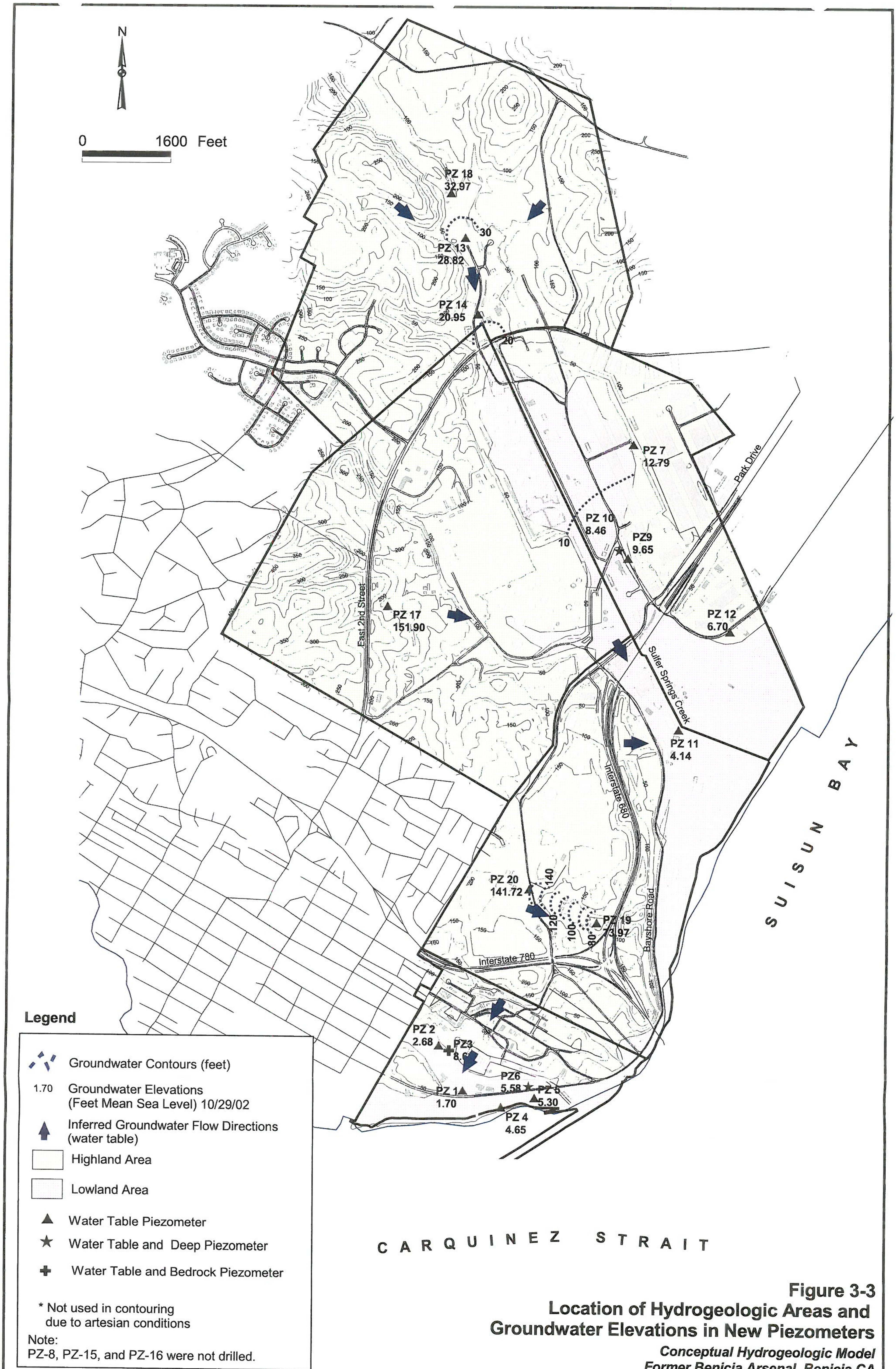


Figure 3-3
Location of Hydrogeologic Areas and Groundwater Elevations in New Piezometers
Conceptual Hydrogeologic Model
Former Benicia Arsenal, Benicia CA

Table 3-2. Summary of New Piezometer Installation and Selected Parameter Values

Name	General Location	Screen Interval - Hydrologic	Borehole Depth (ft bgs)	Well Depth (ft bgs)	Screen Interval (ft bgs)	TOC Elevation (ft msl)	Screen Interval* Geologic	Salinity (TDS, mg/L)	pH	Purge Rate during Development (gpm)	Relative Permeability (ft/day)
PZ-1	Area I, Lowland	Across water table	16	15	5-15	6.09	Organic clay and silt/old marsh	Saline (12,100)	7.02	bailed dry	0.14*
PZ-2	Area I, Lowland	Across water table	20	20	10-20	8.02	Organic clay/old marsh	Brackish (8,830)	6.6	bailed dry	Not Estimated
PZ-3	Area I, Lowland	Top of sandstone bedrock	64	64	54-64	8.05	Clay/sandstone boundary	Brackish (9,270)	6.2	4	Not Estimated (artesian)
PZ-4	Area I, Lowland	Across water table	20	15	5-15	5.7	Organic clay/old marsh	Saline (26,000)	6.58	bailed dry	0.14*
PZ-5	Area I, Lowland	Across water table	15	15	5-15	8.75	Silty sand	Brackish (4,940)	7.04	1.2	1.44**
PZ-6	Area I, Lowland	Middle of alluvium	34.5	34	24-34	8.45	Clay (beneath old marsh)	Saline (10,600)	6.86	bailed dry	0.43*
PZ-7	Area W, Highland	Across water table	20	18	8-18	24.73	Clayey sand, lean clay, silt	Fresh (599)	7.16	>1	12.36**
PZ-8	Not drilled, Right-of-Entry permission not granted.										
PZ-9	Area W, Lowland	Across water table	20	20	10-20	15.45	Clay and sandy silt /sandstone bedrock boundary	Saline (20,300)	6.51	0.9	0.30**
PZ-10	Area W, Lowland	Across sandstone bedrock/alluvial boundary	34	34	24-34	15.47	Weathered bedrock of sandstone, siltstone, and claystone	Saline (65,900)	6.3	0.9	0.29**
PZ-11	Area W, Lowland	Across water table	20	20	10-20	11.99	Clay	Brackish (9,820)	6.84	bailed dry	0.29*
PZ-12	Area W, Highland	Across water table	19	16	5-15	14.59	Silty sand	Fresh (960)	7.37	1.8	9.34**
PZ-13	Area R, Highland	Across water table	20	20	10-20	40.05	Lean clay	Not Sampled	7.33	>2	2.56**
PZ-14	Area R, Highland	Across water table	25.5	25.5	15.5-25.5	30.01	Clay/ sandstone bedrock boundary	Not Sampled	6.98	>1	6.46**

Table 3-2. Summary of New Piezometer Installation and Selected Parameter Values (continued)

Name	General Location	Screen Interval - Hydrologic	Borehole Depth (ft bgs)	Well Depth (ft bgs)	Screen Interval (ft bgs)	TOC Elevation (ft msl)	Screen Interval* Geologic	Salinity (TDS, mg/L)	pH	Purge Rate during Development (gpm)	Relative Permeability (ft/day)
PZ-15		Not drilled, shallow bedrock at PZ-14.									
PZ-16		Not drilled, shallow bedrock at PZ-14.									
PZ-17	Area S, Highland	Across water table	23.5	15.5	5.5-15.5	163.32	Interbedded clay and sand	Fresh	6.86	1.6 (724)	0.74**
PZ-18	Area R, Highland	Across water table	20	20	10-20	44.63	Sandy clay	Not Sampled	7.25	>2	2.38**
PZ-19	Area M, Highland	Across water table	35	31	20.5-30.5	91.28	Lean clay/weathered claystone	Fresh	7.16	1 (565)	1.10**
PZ-20	Area M, Highland	Across water table	34.5	34.5	24.5-34.5	163.54	Silt with gravel	Fresh	7.11	2.1 (769)	1.51**

Notes:
TOC - top of casing
* Relative Permeability based on recovery rate of well during development
**Relative Permeability based on equation modified from Driscoll (1987), Appendix 16.D, using well development data.
PH measured in January and February 2002.
bgs - below ground surface
msl - mean sea level
gpm - gallons per minute
TDS - Total Dissolved Solids
Groundwater Classifications from DWR, 2003: Fresh (<1,000 mg/L TDS), Brackish (1,000 to 10,000 mg/L TDS), Saline (>10,000 mg/L TDS)

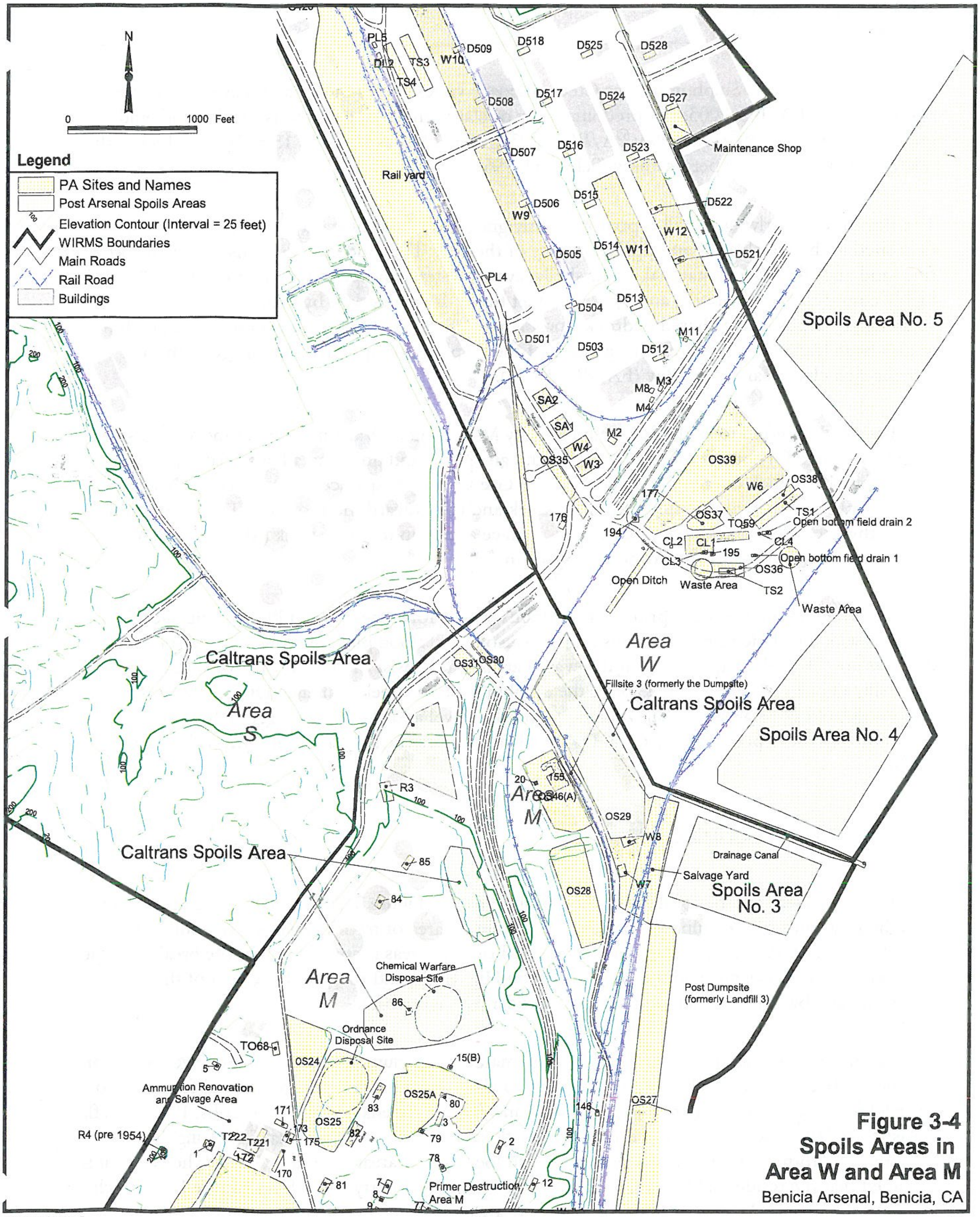


Figure 3-4
Spoils Areas in Area W and Area M
Benicia Arsenal, Benicia, CA

The fill material in the Sulphur Springs Creek drainage varies across the area; it may consist of gravel and road base (FA/BC, 2003a) or predominantly of clay with varying amounts of silt, sand, and gravel (Montgomery Watson, 1995; FA/BC, 2003a). The fill is as much as 15 to 20 feet thick with relatively low to medium permeability (Schwafel, 1969).

The Bay Mud underlying the fill is predominantly gray, green, and blue clay or silty clay that was deposited in the marshlands and tidal mud flats of the bay. The mud contains lenses of well-sorted fine sand and silt, organic material, a few shelly layers (oysters) and peat (Graymer et. al., 1999). It is highly compressible, saturated, and up to 100 feet thick. It is underlain by firm to stiff alluvial sedimentary deposits, weathered bedrock, and bedrock (Schwafel, 1969). In general, the Bay Mud grades from lean clay in the northern portion of the Sulphur Springs Creek Drainage to more organic-rich clays near Suisun Bay (FA/BC, 2003a).

The Bay Mud, referred to as the Bay Sediments by Montgomery Watson (1995) at the Valero site (Figure 1-2, area D) consists of an upper clay and an upper sand unit, and a lower clay and lower sand unit; all of which overlie the bedrock of the Great Valley Sequence. The Valero area sediments are up to 50 feet thick near Sulphur Springs Creek and thin toward the foothills. The lower sand unit in this area fills in valleys on the bedrock surface and is up to 5 feet thick (Montgomery Watson, 1995), and may represent Pleistocene-age alluvium.

Also identified in the Sulphur Springs Creek drainage are Holocene-age and Pleistocene-age alluvial deposits which include terrace deposits and unconsolidated flood plain deposits. The terrace deposits are relatively flat, isolated, and elevated areas that consist of generally unconsolidated gravel, sand, silt, and clay and are located above the Sulphur Springs Creek drainage (DCE, 1998). The unconsolidated floodplain deposits include sand, silt, gravel and clay, and are generally equivalent in age to the terrace deposits (SEC, 1996; Insured Transporters Inc., 1997; Montgomery Watson, 1995).

3.2.2 Geology of the Highland Area

The Highland areas are the foothills of the former Arsenal (Figure 3-3). The Highland areas drain into the Lowlands of the Sulphur Springs Creek drainage area or to the Lowlands of southern Area I. The boundary between the Highland and Lowland areas is approximately the break in slope between the flat Lowlands and the foothills of the Highlands, and roughly the extent of the Holocene-age Bay Mud, which underlies the Lowlands (Figure 3-3).

The geology of the Highland area consists of fill material, alluvium, or colluvium over weathered or competent bedrock. The fill material is gravelly to clayey material that may be several feet thick to over 50 feet thick. According to a local resident and former Arsenal employee (Jacobs, 1999), the flat areas in the Highlands in Area R were covered with several tons of fill material following Arsenal closure. The former employee was not specific in locating the areas altered in Area R; however, it is assumed that the residential housing built on the Tourtelot property (Area F on Figure 1-2), which overlaps the former Arsenal, is likely one of these areas.

Fill material in the highlands consists of four documented sites were designated for the disposal of construction material generated by Caltrans from the construction of Highway 680 in 1965. The four spoils areas (fill material) were located in Area M, near the boundary of Areas W and M, and on the land now occupied by the Valero refinery (Figure 3-4). One of these spoils disposal areas is located on the Preliminary Assessment site OS29. The other three Caltrans spoils areas are located to the west and south of OS29. The land agreement between the USACE and the State of California (Licensee) stated that the spoils areas were "for excess excavation material which the Licensee might accumulate during the period the Licensee is constructing a road (freeway), a bridge, bridge approaches, and other related and appurtenant facilities across a portion of said installation". The agreements were signed June 1964 and September 1964 and included a map with the four Caltrans spoils areas (Figure 3-4).

The alluvial and colluvial material over the bedrock in the Highland area consists of sandy silt interbedded with clay, or as cemented sand with seams of gravel layers. Unconsolidated fluvial deposits of clay, silt, sand and gravel cover the bedrock along the creek valleys.

The predominant bedrock of the Highland areas (except in Area I) is steeply dipping beds of the Great Valley Sequence (formerly the Panoche Formation of Dibblee, 1980). It consists of massive sandstone, with interbedded mudstone, shale, and some conglomerate. The bedrock is described as weathered, closely fractured, friable, and weak. More resistant sandstones and conglomerates form the cores of the hills (EIP Associates, 1989). Steeply dipping beds of siltstone and sandstone of the Vine Hill Sandstone are present as bedrock in Area I (Figure 3-1) (Graymer et. al., 1999).

4.0 HYDROGEOLOGY

An understanding of the components of the groundwater system is essential to understanding the hydrogeology of an area. Groundwater is water beneath the earth's surface in the voids (pore spaces) of the rocks or sediments. The porosity is defined as the ratio of the volume of the pore spaces to the total volume of the rock or sediment, which determines how much water can be stored. The effective porosity is the interconnected porosity that is actually available for fluid flow (roughly equivalent to the specific yield, a measurement of the amount of water that will drain from the sediment). The hydraulic conductivity of the material is a measure of the sediment's ability to transmit water. An aquifer is a body of rock or sediment that yields significant or economic amounts of groundwater (DWR, 2003). An aquitard is a body of rock or sediment that is typically capable of storing water but does not yield significant or economic amounts of water, and impedes groundwater flow (DWR, 2003).

Groundwater in the area of the Arsenal, and in California in general, is mainly present in alluvial valleys. Groundwater in shallow alluvial basins is generally at the same pressure as the atmosphere, a condition known as unconfined. The water pressure in the deeper parts of larger alluvial basins is often confined, which means that the water level in a well penetrating the aquifer will rise above the bottom of the aquitard (confining unit). A confined aquifer can also have artesian conditions in which the water pressure in the aquifer is great enough so that water rises above the ground surface.

Recharge to the groundwater flow system enters permeable sediments at the valley margins primarily as precipitation runoff from the surrounding mountains and hills. Other sources of recharge are precipitation that falls directly on permeable deposits in low-lying areas of the valleys, seepage through streambeds (Planert and Williams, 1995), and recharge from irrigation or other anthropogenic sources such as septic systems, storm drains, or leaky water pipes.

As a general rule, groundwater in California is considered usable for municipal or domestic supply when the concentration of TDS is below 3,000 mg/L, natural and anthropogenic contaminants are not above treatable levels, and the water source can provide sufficient water to supply a single well with an average sustained yield of 200 gpd extraction rate (RWQCB, 1995). TDS was used to characterize the natural groundwater quality for the former Arsenal for this conceptual model.

4.1 Regional Hydrogeology

Most of California's groundwater is present in alluvial deposits such as sand and gravel that make up the aquifers. The finer grained clay and silt deposits are relatively poor sources of water and typically form the aquitards (DWR, 2003). A groundwater basin in California, as defined in the updated Bulletin 118 (DWR, 2003), is an alluvial aquifer or stacked series of alluvial aquifers with reasonably well-defined lateral boundaries and a definable bottom. California's groundwater basins usually include one or a series of alluvial aquifers with intermingled aquitards. Bedrock material, such as the Great Valley Sequence or the Vine Hill Sandstone in the Benicia area, underlie the alluvial sediments. The upper part of the bedrock (usually, the upper 50 feet) can be weathered and a source for groundwater. The competent unweathered bedrock has relatively low permeability and forms the lateral and bottom boundaries of the groundwater basins. The permeability and extent of water-yielding deposits can vary considerably within alluvial groundwater basins (Planert and Williams, 1995).

As presented in Figure 2-2, the former Arsenal is on the western edge of the Suisun-Fairfield groundwater basin (basin #2-3; DWR, 2003). The Lowlands of the Sulphur Springs Creek Drainage are located within the basin boundary (Figure 2-2). The Highland areas of the former Arsenal are not within the basin boundary; although such areas may be considered "groundwater source areas", if they are significant as a source of groundwater (DWR, 2003). The State Water Project provides the City of Benicia and the former Arsenal with its municipal water supply.

4.2 Hydrogeology of the Former Arsenal

Geologic logs for 99 wells filed with the DWR in the area of the former Arsenal and reports from the Panoche Landfill were reviewed to assess the use of the wells and the local stratigraphy of the area. Most of the wells installed in the Benicia area are monitoring wells, or industrial or irrigation wells. To further investigate the hydrogeology of the former Arsenal, 17 piezometers were installed for this project in 2001 (Figure 1-3). Water levels were collected from the new piezometers monthly from January to November 2002 (Appendix H). Groundwater samples were collected for water quality analyses from the new piezometers in February 2002.

The geology combined with the hydrogeologic characteristics (including water quality) was used to delineate the two hydrogeologic areas on the former Arsenal as follows:

- Lowland area - delineated as the Sulphur Springs Creek drainage area and the former marshlands of Area I and Area M that are composed mostly of Bay Mud.
- Highland area – delineated as the foothills on the former Arsenal that are not underlain by the Bay Mud and are above approximately 40 ft msl.

The two hydrogeologic areas were characterized using the following criteria:

- The groundwater quality based on the TDS.
- The relative permeability of the hydrostratigraphic units.
- The groundwater flow directions and velocities.

Information from numerous studies conducted at the Panoche Landfill located north of the former Arsenal was used to update the hydrogeology of the former Arsenal from the *Preliminary Conceptual Hydrogeologic Model* (FA/BC, 2003b). It was previously thought that wells located in the Highland area could not produce enough water to be considered a water source (> 200 gpd); however, several wells located in the valleys of the Highland area north of the Arsenal can produce enough water to be considered a water source, as noted from studies at the Panoche landfill (IT Corporation, 1987).

4.2.1 Groundwater Quality

Groundwater quality samples were collected from 14 of the 17 new piezometers and analyzed for VOCs, total petroleum hydrocarbons as gasoline, total petroleum hydrocarbon as diesel, inorganic compounds, and metals (FA/BC, 2003a). All of the groundwater analytical data are presented in Appendix F. TDS data was also collected from springs, creeks, and wells in the Highlands at the Panoche Landfill (IT Corporation, 1987).

The results of the analysis of TDS in groundwater indicate that shallow groundwater in the Lowland areas is brackish to saline and the groundwater in the Highland areas is predominantly fresh (Figure 4-1). The freshwater-brackish water interface along the coast is typically near the boundary between the Highland and Lowland areas (Figure 3-3). TDS concentrations of 0 mg/L to 1,000 mg/L are considered freshwater and concentrations of 1,000 mg/L to 10,000 mg/L are considered brackish water (Driscoll, 1986). Water with TDS values greater than 10,000 mg/L is considered to be saline. The TDS values from all of the groundwater samples collected in the piezometers ranged from 599 mg/L at PZ-7 to 65,900 mg/L at PZ-10 (Figure 4-1). Chloride concentrations are also posted on Figure 4-1 and show a distribution similar to TDS. The RWQCB defines groundwater with a TDS concentration less than 3,000 mg/L as usable for domestic or municipal use.

Water quality samples were collected from 12 of the 20 water supply wells located within one mile of the Panoche Landfill. The values for TDS ranged from 230 mg/L to 1,200 mg/L (IT Corporation, 1987). The landfill is located in the Highland area north of the former Arsenal.

The remaining groundwater analytical results collected from the piezometers reflect impacts primarily from industrial or commercial practices in the area and would not broaden the conceptual hydrogeologic model for the former Arsenal.

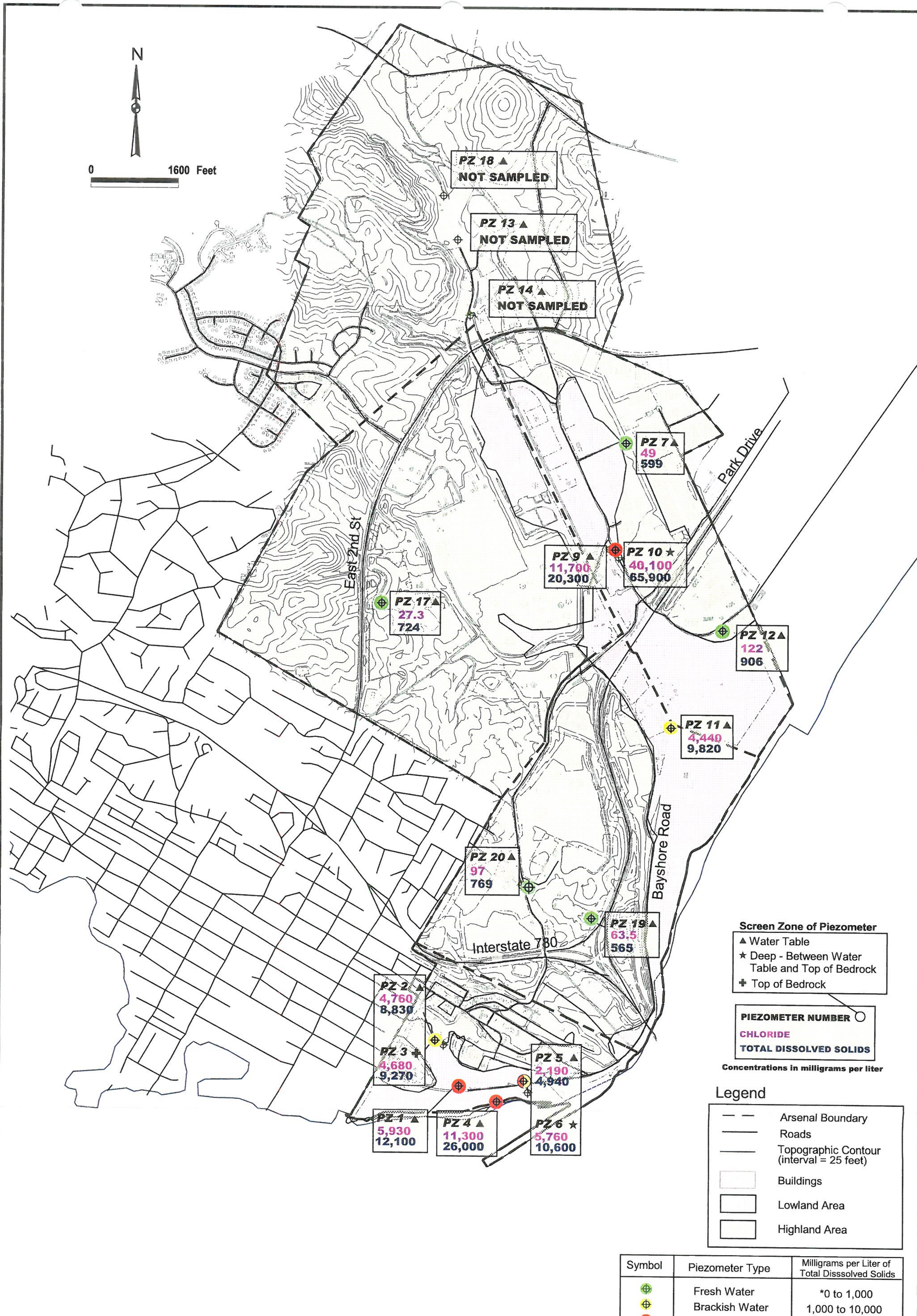
4.2.2 Hydrostratigraphic Units

Hydrostratigraphic units are geologic units grouped together or split apart based primarily on their relative permeability. Several geologic formations may be grouped into a single hydrostratigraphic unit, or one geologic formation may be divided into several hydrostratigraphic units (Fetter, 1988). For the purpose of this conceptual hydrogeologic model, the geologic units have been grouped into three relatively permeable hydrostratigraphic units:

- Artificial fill,
- Non-cemented and non-compacted alluvium or colluvium, and
- Weathered bedrock (non-clayey), or fractured unweathered bedrock.

Two relatively non-permeable hydrostratigraphic units have also been identified:

- The Bay Mud, and
- Competent bedrock and bedrock that has weathered to clay.



* TDS concentrations <3,000 mg/l are considered suitable as drinking water (RWQCB, 1995)

DATE	PROJECT NO.	SITE	
7/8/2005	124785	Conceptual Hydrogeologic Model Former Benicia Arsenal, Benicia, California	**Figure 4-1**
BROWN AND CALDWELL	2701 Prospect Park Drive Rancho Cordova, CA 95670 (916) 444-0123 (916) 635-8805	TITLE Groundwater Quality of the Former Arsenal Based on Concentration of Total Dissolved Solids	

Three cross sections (Figures 4-2, 4-3, 4-4) present the stratigraphy or hydrostratigraphic units of the of the former Arsenal. They were constructed using information from well logs obtained from the DWR, previous investigation reports, and from the geologic logs for the new piezometers installed for this project. The locations of the cross sections in relation to the wells and piezometers are shown on Figure 1-3.

Fill material shown on the cross sections may be relatively permeable or nonpermeable based on the ratio of gravel, sand, silt, and clay. Some judgement was exercised in interpreting the relative permeability of the fill material from the geologic logs. The weathered bedrock can also be relatively permeable or relatively nonpermeable. Depending on the type of bedrock, it can weather to a clayey unit that is relatively nonpermeable, or it can weather to a sandy or silty unit that is relatively permeable. Weathered bedrock grouped with the alluvium and colluvium is described on logs as sandy or silty soil and is considered to be relatively permeable. Clayey weathered bedrock was included in the nonpermeable bedrock category on the cross sections. The sandstone bedrock was originally permeable because of its grain size, but cementation reduces the permeability. The amount of fracturing of the bedrock is unknown, but may locally create secondary permeability.

Geologic studies conducted at the Panoche Landfill, northeast of the Arsenal, and in the Highland area identified two water-bearing zones. The primary or upper water-bearing zone consists of the near surface weathered bedrock and overlying surficial deposits. The second water-bearing zone is made up of unweathered bedrock. Small amounts of water occur in the unweathered bedrock in a '*very few, isolated, open fracures*' that could extend 25 to 50 feet below the top of the unweathered bedrock (IT Corporation, 1987). The same document reports that:

> *Neither water bearing zone* (upper and second) *should be considered a viable aquifer, as groundwater production from wells is commonly limited from less than 0.1 to 1 gpm* (144 gpd to 1440 gpd).

The hydrogeologic studies of the Panoche facility have established that the primary or upper water-bearing zone is the predominant horizon for groundwater movement. The unweathered bedrock has significantly lowered hydraulic conductivity; although, it is saturated with groundwater it behaves as an aquitard and acts as a barrier to fluid migration. Water in the unweathered bedrock is most common in fractured zones in the upper 25 feet of the unweathered zone and increasingly rare with depth (IT Corporation, 2001).

Figure 3-2 presents the approximate thickness of the overburden above the unweathered bedrock for the entire Arsenal. Since most of the available groundwater is present in the overburden above the bedrock, this map can be used to estimate where groundwater is present.

4.2.3 Hydraulic Parameters

In general, the Highland areas have steep gradients and relatively higher permeability as compared to the Lowland areas which have relatively shallow gradients and lower permeability. The hydrogeologic information gathered to characterize the areas may not apply to unique areas within the Highland and Lowland areas.

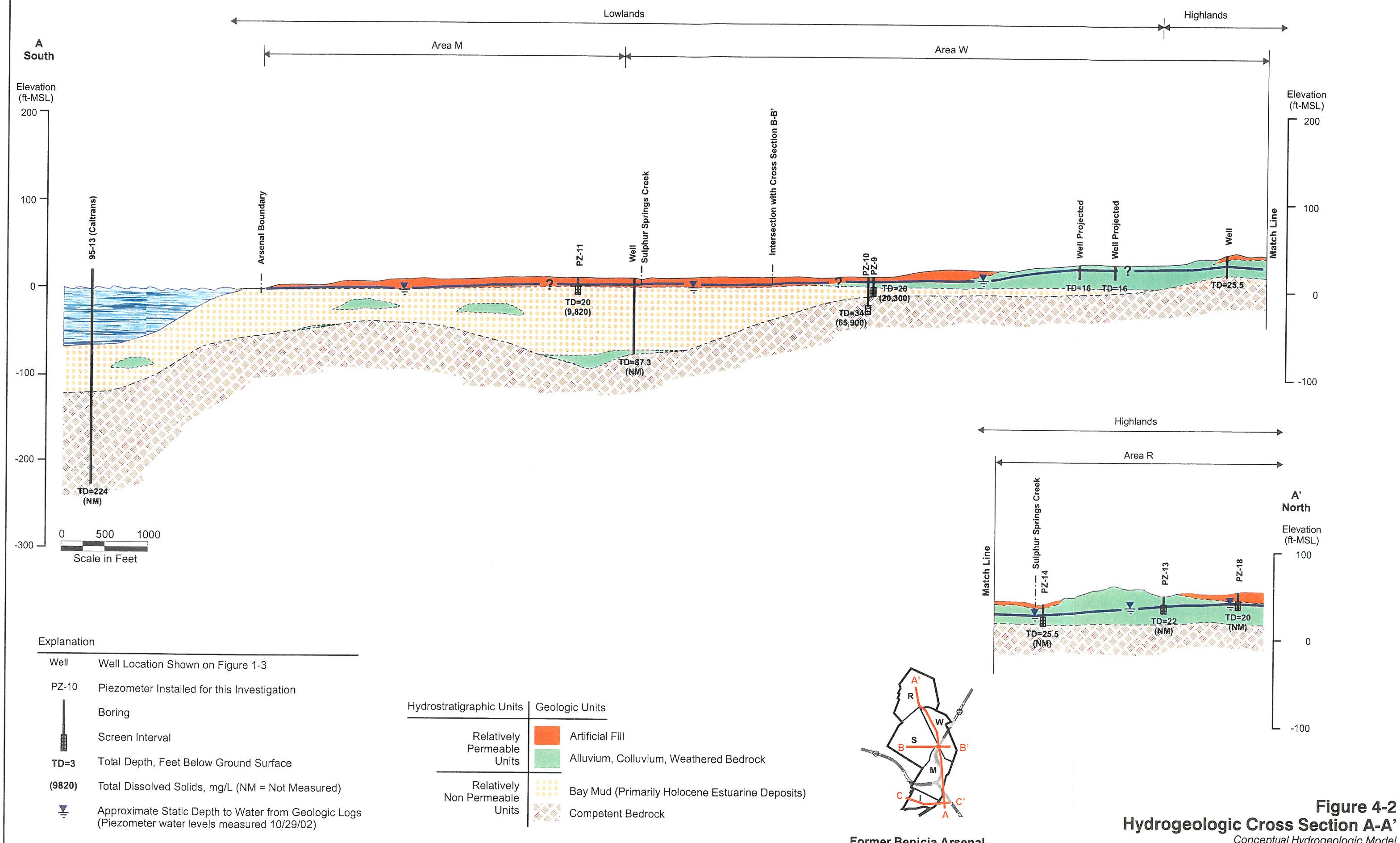
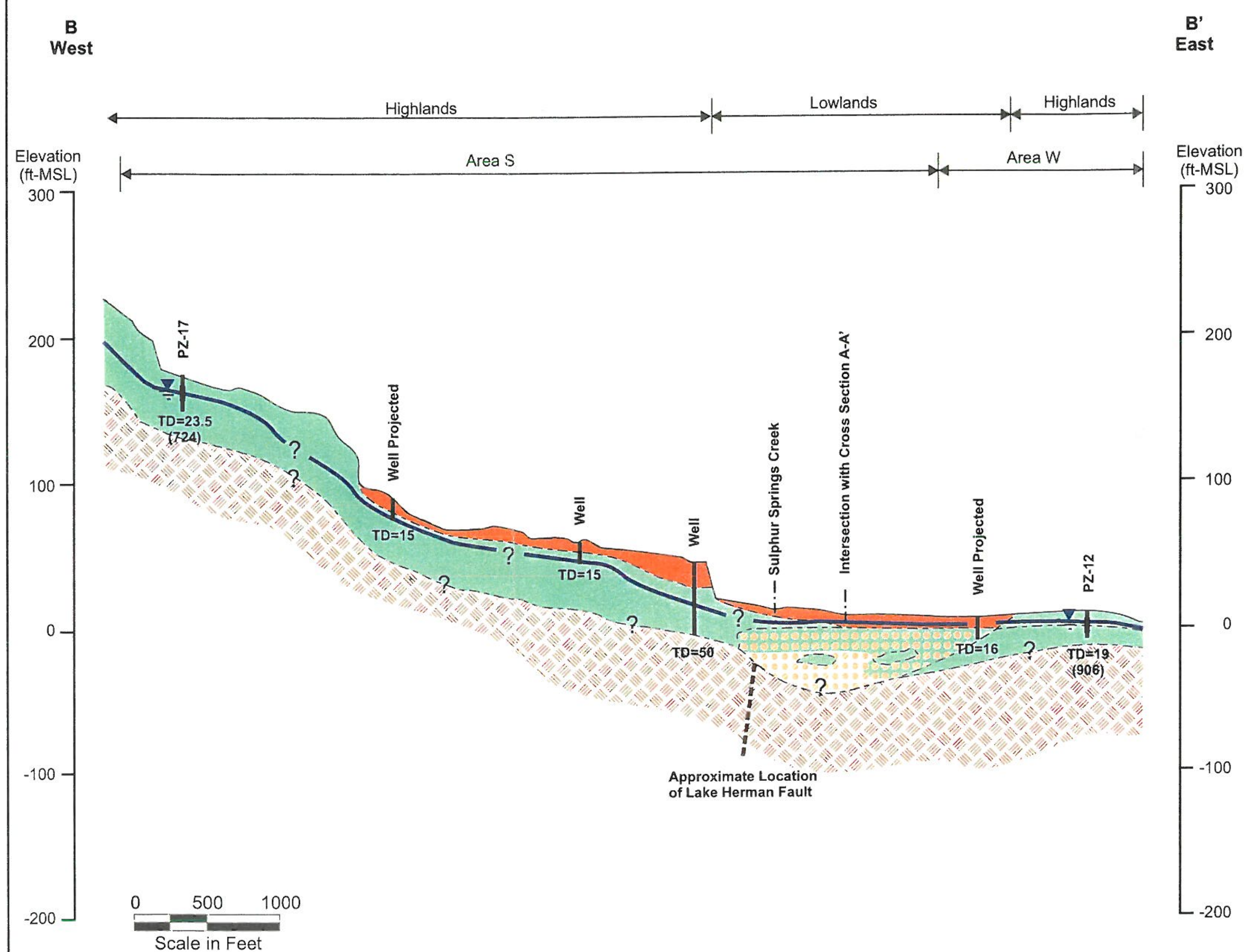


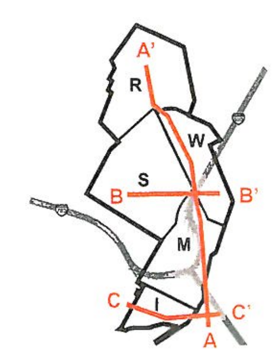
Figure 4-2
Hydrogeologic Cross Section A-A'
Conceptual Hydrogeologic Model
Former Benicia Arsenal



Explanation

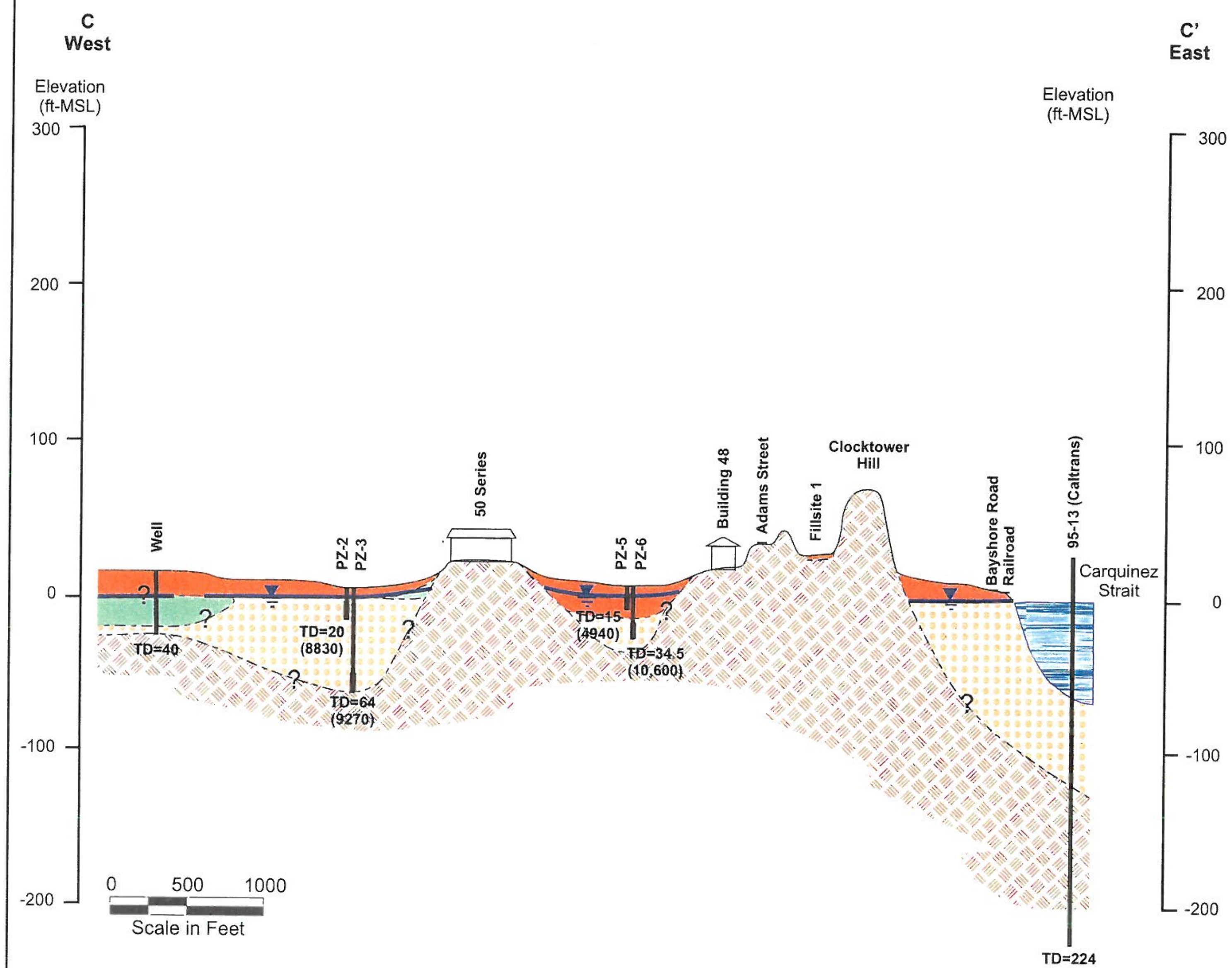
Well	Well Location Shown on Figure 1-3
PZ-10	Piezometer Installed for this Investigation
	Boring
	Screen Interval
TD=30	Total Depth, Feet Below Ground Surface
(2970)	Total Dissolved Solids, mg/L
	Approximate Static Depth to Water from Geologic Logs (Piezometers water levels measured 10/29/02)
	Fault

Hydrostratigraphic Units	Geologic Units
Relatively Permeable Units	Artificial Fill
	Alluvium, Colluvium, Weathered Bedrock
Relatively Non Permeable Units	Bay Mud
	Competent Bedrock



Former Benicia Arsenal

Figure 4-3
Hydrogeologic Cross Section B-B'
Conceptual Hydrogeologic Model
Former Benicia Arsenal

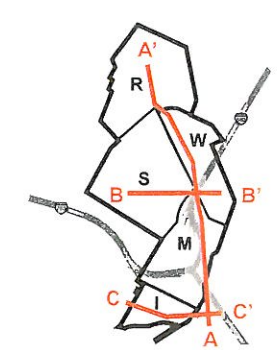


Explanation

Well	Well Location Shown on Figure 1-3
PZ-3	Piezometer Installed for this Investigation
	Boring
	Screen Interval
TD=30	Total Depth, Feet Below Ground Surface
(2970)	Total Dissolved Solids, mg/L
	Approximate Static Depth to Water from Geologic Logs (Piezometers water levels measured 10/29/02)

Hydrostratigraphic Units	Geologic Units
Relatively Permeable Units	Artificial Fill
	Alluvium, Colluvium, Weathered Bedrock
Relatively Non Permeable Units	Bay Mud
	Competent Bedrock

Note: The geology is projected on to the line of section.



Former Benicia Arsenal

Figure 4-4
Hydrogeologic Cross Section C-C'
Conceptual Hydrogeologic Model
Former *Benicia Arsenal*

The direction of groundwater flow on the former Arsenal is generally similar to the direction of the surface water flow, from topographic highs toward topographic lows (from the Highlands to the Lowlands). The DWR defines the groundwater basins in California as stacked alluvial deposits, and the bedrock foothills serve as the boundaries to the groundwater basins (DWR, 2003). The majority of the groundwater flow is through the permeable units like the artificial fill or alluvium, on top of, and controlled by, the bedrock surface.

Well Production. In the shallow flow zone at the Panoche Landfill recovery wells RW-1, RW-2, and RW-3 produced averages of 0.3 gpm, 0.7 gpm and 4.5 gpm (432 gpd, 1,008 gpd, and 6,480 gpd); respectively, over a 12 month period from February 2000 to February 2001. Wells in the smaller drainage ways or on hillsides could not produce as much (IT Corporation, 2001).

Hydraulic Conductivity. Hydraulic conductivities measured at the Panoche Landfill ranged from 5.6 ft/day to 0.0057 ft/day in the surficial deposits and weathered bedrock material using slug tests. In the unweathered bedrock, hydraulic conductivities were measured using packer tests and ranged from 0.0057 ft/day to 1.08×10^{-4} ft/day (IT Corporation, 2001).

Well development data or recovery rate data collected during the well development were used to provide a very rough estimate of the hydraulic conductivity (Driscoll, 1987) of the overburden material for the 17 piezometers installed for this project on the former Arsenal (Figure 4-5). The piezometers screened in the Lowland area (PZ-1 through PZ-6, and PZ-9 through PZ-11) had lower estimated hydraulic conductivity values of 0.14 ft/day to 1.44 ft/day (average 0.43 ft/day), than the wells screened in the Highland area, estimated hydraulic conductivity values of 0.74 ft/day to 12.36 ft/day (average 4.56 ft/day) (PZ-7, and PZ-12 through PZ-20) (Table 4-1 and Table 3-3, Figure 4-5). The hydraulic conductivity values for PZ-2 and PZ-3 were not estimated because there was not enough information; PZ-2 was bailed dry during development and PZ-3 is artesian.

Table 4-1. Estimated Hydraulic Conductivity Values

Source	Hydrogeologic Area	Range of Hydraulic Conductivity (ft/day)	Comments
PZ-1, PZ-4 through PZ-6, PZ-9, PZ-11	Lowland	0.14 to 1.44	Bay Mud and fill material
PZ-7, PZ-12 through PZ-20	Highland	0.74 to 12.36	Alluvium and fill material
Panoche Landfill	Highland	0.0057 to 5.6	Surficial deposits and weathered bedrock.
Panoche Landfill	Highland	1.08×10^{-4} to 0.0057	Unweathered bedrock
Bldg. 48 (area I)	Lowland	0.0096 to 4.5	Fill material (HLA, 1997a)
Treatability Study (Brown and Caldwell 2005b)	Lowland	0.0018 to 0.0157	Bay Mud and/ or Alluvium
Freeze and Cherry, 1979	Book value	0.0001 to 0.001	Estimate for silt and clay
Freeze and Cherry, 1979	Book value	0.001 to 5	Silty sand to sand

Hydraulic conductivity values were measured using slug test data in a previous investigation near Building 48 in Area I (location #1 on Figure 1-2; HLA, 1997). The range of hydraulic conductivity values measured for the fill material was 9.6×10^{-3} ft/day to 4.5 ft/day. Vertical hydraulic conductivity values measured for the Bay Mud in the same area were 2.8×10^{-4} ft/day and

1.5×10^{-4} ft/day. These slug test datas are considered more reliable than the well development data for the Bay Mud in the Lowland area, and are more similar to typical estimates for silt and clay in the range of 10^{-3} ft/day to 10^{-4} ft/day (Freeze and Cherry, 1979; Fetter, 1988). The horizontal hydraulic gradients measured at this site were 0.005 ft/ft to 0.01 ft/ft.

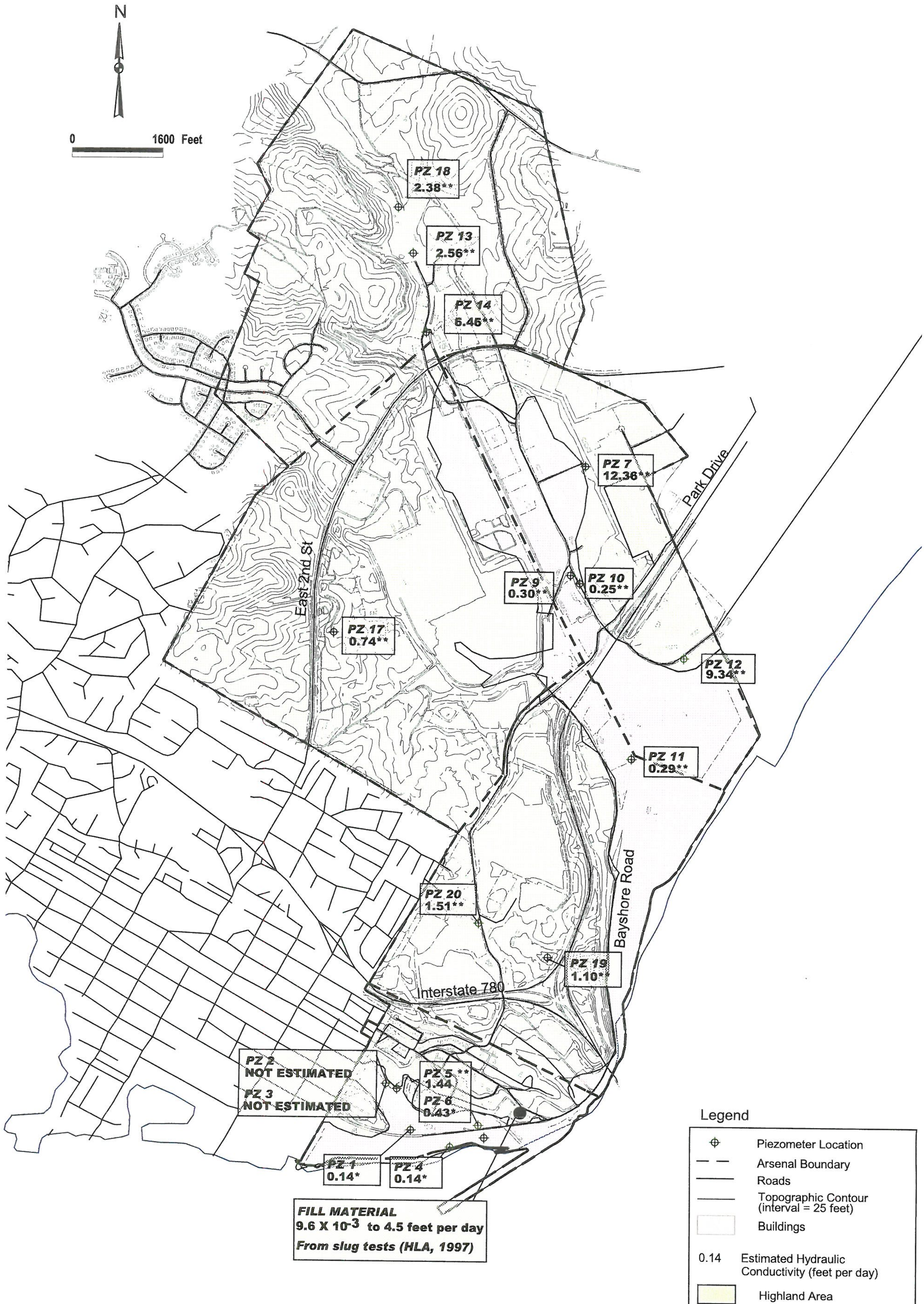
Eight soil samples were collected from four soil borings at various depths in July 2005 (Table 4-2). The soil samples were sent to PTS Laboratories for hydraulic conductivity analyses using ASTM method D5084. The boreholes are all located in the Lowlands of Area I and are part of the Treatability Study (Brown and Caldwell, 2005b). The lithology for the soil samples collected for the hydraulic conductivity analyses were correlated to CPT logs that were conducted in nearby boreholes, except for the samples collected from FS001HP015. The hydraulic conductivity results for the alluvium are similar to the results from the Bay Mud for these analyses (Table 4-2).

Table 4-2. Native State Hydraulic Conductivity of soil samples from the Lowland Area

Borehole	Depth of Sample (feet)	Lithology from CPT Log	Native State Effective Hydraulic Conductivity	
			cm/s	ft/day
B165HP007	16 – 16.5	Silty Clay / Clay (alluvium)	6.37 E-07	0.0018
B165HP007	36.5 - 37	Clayey Silt / Sandy Silt (older alluvium)	1.4 E-06	0.004
FS001HP014	31.5 - 32	Clayey Silt / Silty Clay (older alluvium)	1.3 E-06	0.0037
FS001HP015	8.5 – 9	Clayey Silt	9.69 E-07	0.0027
FS001HP015	20.5 - 21	Bay Mud?	5.55 E-06	0.0157
FS001HP015	39 - 40	Silt (alluvium)	1.23 E-06	0.0035
B004HP004	11 – 11.5	Silty Clay / Clay	1.12 E-06	0.0032
B004HP004	34.5 - 35	Bay Mud	1.14 E-06	0.0032

Comparison of the hydraulic conductivities estimated from the slug test and well development data suggest that the well development data overestimates the hydraulic conductivity. This would be expected since during well development, the data is collected during a very short pumping period. These estimates should be considered maximum values and used only as relative comparisons for estimating groundwater flow velocities. Site-specific estimates should be developed from site-specific aquifer tests for detailed remedial investigations.

Hydraulic Gradient. The horizontal hydraulic gradient is the steepness of the water table surface (the ratio of the change in the water level elevation between horizontal and the vertical distance). Hydraulic gradients based on the water levels measured in the piezometers were estimated, where possible, on October 29, 2002. In general, the hydraulic gradients in the Highland area are approximately 0.05 ft/ft to 0.005 ft/ft, and are steeper than the gradients in the Lowland areas, which are approximately 0.0016 ft/ft. Hydraulic gradients measured at the Panoche Landfill northeast of the former Arsenal, and considered to be representative of the Highland area, ranged between 0.1 ft/ft to 0.023 ft/ft (IT Corporation, 2001).



* Hydraulic conductivity based on recovery rate of well during development.
** Hydraulic conductivity based on specific capacity equation modified from Driscoll (1987).

DATE	PROJECT NO.	SITE	
5/27/2005	124785	Conceptual Hydrogeologic Model Former Benicia Arsenal, Benicia, California	Figure 4-5
BROWN AND CALDWELL	2701 Prospect Park Drive Rancho Cordova, CA 95670 (916) 444-0123 (916) 635-8805	TITLE Estimated Hydraulic Conductivity of the Overburden Material	

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Porosity. The effective porosity of the hydrostratigraphic units has not been measured, but is assumed to be in the range of 0.01 to 0.1 for the Bay Mud in the Lowlands and 0.2 to 0.3 for the alluvium in the Highlands. This uncertainty will not significantly affect estimates of flow velocity below. Nineteen wells were identified with one mile of the Panoche Landfill (Figure 1-3). All of the wells are located in valleys in the Highland area. The geologic unit interpreted to be supplying water for each well is based on the location and depth of the well (Table 2-1). One well located west of Highway 680, east of the Panoche Landfill, is screened at about 270 ft bgs in the Domengine Sandstone and produces about 40 gpm (57,600 gpd). Most of the water supply wells are screened in the Sonoma Volcanics (approximately 1.5 miles east of the landfill) or in the Panoche Formation. Three wells, two located in Area R on the Arsenal (24G1 and 24J1) and one located within one mile north of the Arsenal (13Q1), are hand dug and appear to be completed within the alluvium or in the weathered Panoche Formation (Figure 1-3). These wells have 'small yields and are used for domestic water supply and livestock watering' (IT Corporation, 1987).

4.2.4 Groundwater Flow Velocity

The above estimates of hydraulic parameters can be used with Darcy's Law to estimate typical groundwater flow velocity (V) using the following equation:

$$V = Ki/n_e$$

Where:
V=Average linear velocity of groundwater flow (ft/day)
K = estimated hydraulic conductivity (10^{-3} to 10^{-4} ft/day for Bay Mud in the Lowlands; 0.1 to 10 ft/day for alluvium in the Lowlands or the Highlands)
i =horizontal hydraulic gradient (approximately 0.0015 to 0.0016 for Lowlands; 0.005 to 0.05 for the Highland area, ft/ft)
n_e=effective porosity (0.01 to 0.1 for Lowlands; 0.2 to 0.3 for Highlands).

The above equation yields an estimated groundwater flow velocity (based on the book values from Table 4-1) of approximately 1.5×10^{-6} ft/day to 1.6×10^{-4} ft/day (or 0.00055 ft/yr to 0.058 ft/yr) for the Bay Mud in the Lowlands. The screen zone and the soil samples collected for hydraulic conductivity measurements are a mixture of Bay Mud and alluvial or fill material, therefore the book values from Table 4-1 were used to estimate the groundwater velocities. The estimated velocity for ground water in the alluvial or fill material in the Lowland area is 1.5×10^{-5} ft/day to 0.8 ft/day (or 0.0055 ft/yr to 292 ft/yr). The estimated velocity for ground water in the alluvial or fill material in the Highland area is approximately 0.0123 ft/day to 3.09 ft/day (or 4.5 ft/yr to 1,128 ft/yr).

The groundwater velocities are based on well development and slug test data and are intended to be used as rough order-of-magnitude estimates for the purpose of this Arsenal-wide characterization only. They are not a substitute for site-specific investigation. It should also be noted that these estimates represent advective transport only, and contaminants may travel faster (due to dispersion) or slower (due to retardation) than the velocity of the groundwater.

4.3 Tidal Influence

Wells screened in areas adjacent to the coast typically respond to tidal fluctuations to some degree, depending on their location and local hydraulic parameters. The water levels in the piezometers screened in or near the Lowlands were evaluated for tidal influences to assess the interconnectedness of the groundwater with the tidally influenced water in the Carquinez Strait and Suisun Bay. Pressure transducers were installed in four piezometers to monitor for tidal fluctuations. Water elevation readings (as pressure) were collected every 10 minutes for 48 hours from PZ-4 (Lowlands of Area I), from PZ-9 and PZ-11 (Lowlands of the Sulphur Springs Creek drainage), and PZ-12 just adjacent to the Lowlands in Sulphur Springs Creek. The data is presented on hydrographs in Appendix G.

Piezometer PZ-4 is located within 100 feet of the Carquinez Strait (Figure 1-3). The water levels measured in PZ-4 rose and fell at approximately the same time as the tides, with fluctuations of about 0.04 feet to 0.08 feet between high and low tides. PZ-11 and PZ-12 are each about 2,000 feet inland from the Suisun Bay, and PZ-9 is about 5,000 feet inland from the Bay. Water level fluctuations in PZ-9, PZ-11, and PZ-12 do not appear to be related to the tidal fluctuations. Piezometers PZ-9 and PZ-12 show daily water level fluctuations that are probably due to changes in barometric pressure. PZ-11 appears to show some influence from the tides because of its proximity to Sulphur Springs Creek and some influence from barometric pressure changes. Tidal influences in the Lowlands appear to be limited to less than 2,000 feet from the Carquinez Strait/Suisun Bay.

4.4 Piezometer Installation

As part of this investigation to assess the hydrogeology of the former Arsenal, 17 piezometers were installed Arsenal-wide (Figure 1-3). The rationale for installing the piezometers and the details about the drilling and monitoring of the piezometers are presented in the *Technical Memorandum Letter, Piezometer Installation and Sampling for the Site Hydrogeologic Model for the Benicia Arsenal* (FA/BC, 2003a). Piezometers PZ-8, PZ-15 and PZ-16 were not drilled as indicated in Table 3-2. Right-of-entry was not granted for the PZ-8 location, piezometers PZ-15 and PZ-16 were supposed to be drilled next to PZ-14 as a shallow, medium, and deep cluster; however, bedrock was encountered at 25 feet and only one piezometer (PZ-14) was installed. The well construction and geologic logs for the piezometers are presented in Appendix E of this report.

Three piezometers were installed in the Lowland area in the Sulphur Springs Creek drainage area (PZ-9, PZ-10, and PZ-11), and six piezometers were installed in the Lowlands in Area I (PZ-1 through PZ-6). The remaining piezometers were installed in the Highland area, as shown on Figure 1-3. Information collected from these piezometers formed the primary data set for this conceptual model.

4.5 Water Level Elevations in the Piezometers

Water level elevations were measured in the piezometers monthly from January 2002 until November 2002. The groundwater elevation data measured on October 29, 2002 is shown on

Figure 3-3. The piezometers are too far apart and the hydrostratigraphic units too discontinuous to construct groundwater contours across most of the former Arsenal. Depth to groundwater beneath the former Arsenal ranges from less than 5 ft bgs in many Lowland areas to greater than 20 ft bgs in some Highland areas.

Hydrographs showing the elevation of the water levels in the piezometers from January 2002 through November 2002 are presented in Appendix H. As shown on the hydrographs, the water level elevations do not fluctuate much seasonally in most of the piezometers. Water levels in most of the Highland piezometers decreased through the dry summer and fall months of 2002 as compared to the winter and spring months. Very little precipitation occurred during the January 2002 through November 2002 measurement period. Significant rainfall did not occur until December 2002.

5.0 SUMMARY OF THE CONCEPTUAL HYDROGEOLOGIC MODEL

This section presents a synthesis of the geologic and hydrogeologic data collected for the former Arsenal in the form of a conceptual hydrogeologic model, which is presented graphically in Figure 5-1. In California, the DWR has defined groundwater basins as the layered alluvial material deposited in valleys and the boundaries of the groundwater basins as the bedrock material or foothills surrounding the valley. For this report, the overburden material above the bedrock is considered to be the dominant water-bearing unit on the former Arsenal. The weathered bedrock and fractured unweathered bedrock can also be water-bearing units. The former Arsenal was divided into two hydrogeologic areas based on the geology, topography, groundwater occurrence, and groundwater quality. These two hydrogeologic areas are:

- The Highlands, and
- The Lowlands.

The Highland area is the foothills of the former Arsenal (Figure 5-1). The topography ranges from about 40 to over 400 ft msl. The elevation of the water table varies widely, especially at the higher elevations. The Highland area is characterized by relatively thin (< 50-feet thick) alluvial or fill material (overburden) over the bedrock. The groundwater is present primarily in discontinuous alluvial deposits mainly in the valleys of the Highlands. Groundwater present in the overburden material has a relatively steep hydraulic gradient, ranging from approximately 0.005 ft/ft to 0.05 ft/ft (about 26 ft/mi to 260 ft/mi). The groundwater flow velocities estimated from the relatively moderate hydraulic conductivity values range from 0.0123 ft/day to 3.09 ft/day (or 4.5 ft/yr to 1,128 ft/yr). Groundwater quality in the Highland area is typically freshwater (with TDS concentrations ranging from 230 mg/L to 1,200 mg/L). Groundwater flow is toward the Sulphur Springs Creek drainage for most of the former Arsenal (or toward the Carquinez Strait in Area I).

The Lowland area is the former tidal flats and marshlands adjacent to Carquinez Strait and the lower part of the drainage area for Sulphur Springs Creek. The geology of the Lowland area above the bedrock is mostly comprised of artificial fill material or alluvium over Bay Mud. Locally, groundwater can be in confined conditions in older alluvium below the Bay Mud (Figure 5-1). The Lowland areas have a relatively low horizontal hydraulic gradient as compared to the Highland area (approximately 0.0016 ft/ft, or 8 ft/mi). The low relative hydraulic conductivity values of the overburden material in the Lowland area produces very slow groundwater flow velocities in the Bay Mud of approximately 1.5×10^{-6} ft/day to 1.6×10^{-4} ft/day (or 0.00055 ft/yr to 0.058 ft/yr). The estimated velocity for groundwater in the alluvial or fill material in the Lowland area is 1.5×10^{-5} ft/day to 0.8 ft/day (or 0.0055 ft/yr to 292 ft/yr). The quality of the groundwater in the Lowland area is brackish to saline (with concentrations of TDS ranging from 8,830 mg/L to 65,900 mg/L). Groundwater flow is generally toward Suisun Bay or the Carquinez Strait. Water level elevations fluctuate minimally seasonally compared to the Highlands, and tidal influences may extend several thousand feet inland.

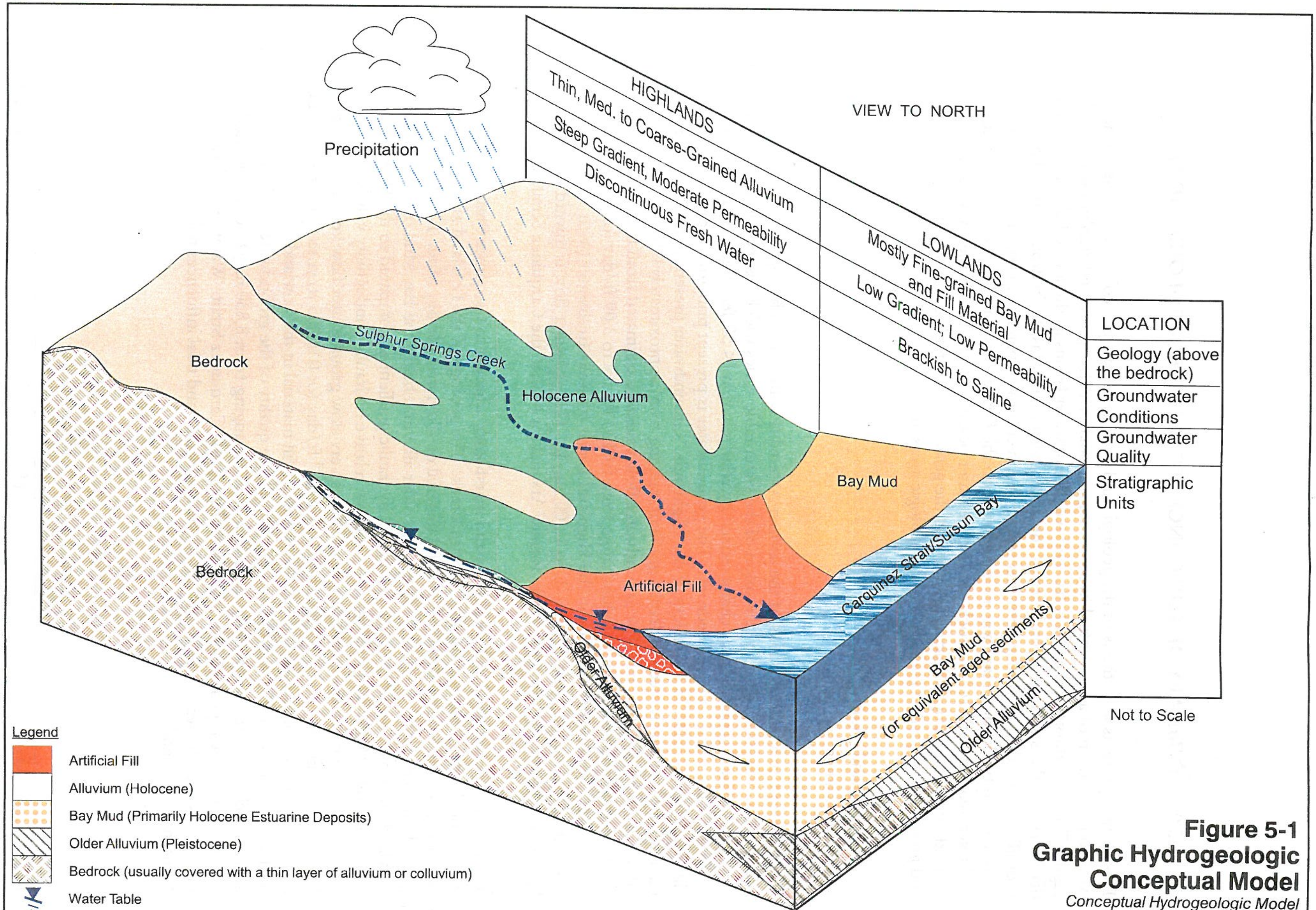

Figure 5-1
Graphic Hydrogeologic Conceptual Model
Conceptual Hydrogeologic Model
Former Benicia Arsenal

The conceptual hydrogeologic model provides a basis for evaluating potential beneficial uses of groundwater beneath the former Arsenal. The Water Quality Control Plan for the San Francisco Bay Basin (RWQCB, 1995) provides for exceptions to the assumption that groundwater is considered suitable, or potentially suitable, for municipal or domestic water supply. Exceptions may be considered when naturally occurring constituents (such as TDS > 3,000 mg/L) make it unreasonable to expect that the groundwater could supply a public system. Exceptions may also be considered in areas where a single well would be incapable of producing an average, sustained yield of 200 gpd (RWQCB, 1995).

In the Highlands, the natural groundwater is of relatively high quality and the sediments are of moderate permeability. Studies conducted at the Panoche Landfill, indicate that wells located in the valleys of the Highland area could maintain a sustained yield greater than 200 gpd. However, the thin veneer of alluvium is generally less than 50 feet thick, and DHS requires a sanitary seal of at least 50 feet for drinking water supply wells. A 100-foot seal is often required in areas with numerous PCAs, and the Valero refinery and other current industrial areas in the Highlands would likely be such a case.

In the Lowlands, most of the saturated sediments have very low permeability and many wells can be bailed dry, indicating that they would not sustain a pumping rate of 200 gpd. In addition, water quality is poor; TDS concentrations are greater than 3,000 mg/L, the water is brackish to saline, and groundwater pumping for domestic use would likely induce increased salinity intrusion. Groundwater in the Lowlands cannot be expected to provide a potential drinking water source due to high TDS concentrations and low sustained yield in wells.

Groundwater beneath the Arsenal in the Lowland areas is not suitable for municipal or domestic water supply and ingestion is not a likely route of exposure. In the Highlands areas, groundwater is of quality and quantity to be suitable for water supply. However, groundwater beneath the former Arsenal is not currently being used for municipal purposes.

Previous to this conceptual model there had been no Arsenal-wide compilation of the hydrogeologic data. This conceptual model is based on all known DoD investigations; as well as, previous investigations, conducted by private parties, on and near the Arsenal. As a result, this conceptual model is a broad Arsenal-wide framework that can be used for current and future remedial investigations. Much of the data used for this conceptual model was developed by other parties and could not be independently verified; however it is appropriate for the purposes of this study. Any future site investigations should use verifiable data collected specific to that site. In particular, limited information is available for groundwater flow parameters because very few aquifer tests have been conducted in either in the Highland or Lowland areas. Groundwater flow parameters discussed in this conceptual model are rough estimates based on well development data, slug test data, and published aquifer parameters. Hydrogeologic data is missing in some areas of the Arsenal because of a paucity of information. These data gaps did not prevent the development of this broad conceptual model. This conceptual model is preliminary and intended as a living document, subject to update as new data becomes available from site-specific investigations.

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