

Hydrostratigraphic Investigation of the Aquifer Recharge Potential for Lakes C and D of the Chain of Lakes, Livermore, California



PREPARED IN COOPERATION WITH

Department of Water Resources
Local Groundwater Assistance Grant Program

BY

Zone 7 Water Agency
Livermore, California
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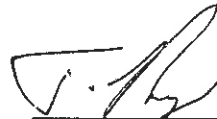
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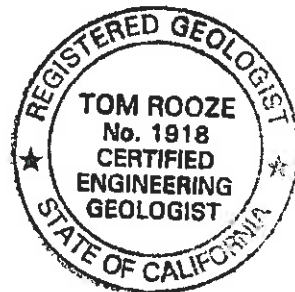


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ES Executive Summary

ES 1 Overview

Zone 7 has an ongoing project that, when complete, will consist of a series of abandoned gravel quarry pits converted into a chain of nine lakes (Chain of Lakes A through I) linked in series, and used for seasonal water storage and conveyance, and flood water detention and conveyance. As quarrying is completed, the designated lakes are to be transferred to Zone 7 for water supply purposes. The first one, which is located at the west end of the ‘chain’ (Lake I) has already been transferred. The last transfer is anticipated in about 2030. Preliminary designs for the lakes included augmenting Zone 7’s existing ‘artificial recharge’ with de-silted surface water diverted into Lake I and percolated through the lake’s sidewalls.

In 2004 Norfleet Consultants (Norfleet) completed a geological and sequence stratigraphy analysis of the subsurface in the area between Lakes H and I and Zone 7’s wellfield to the west of Lake I. During this study, Norfleet identified four sequences (from shallowest to deepest: Cyan, Gray, Purple, and Red) that were separated by unconformities. The results of that analysis show that there are several laterally continuous aquitards that potentially can act as barriers for recharge water from Lakes H and I to reach the wellfield. However, the proposed final mining depths at two future quarry pits (Lakes C and D, approximately 240 feet [ft] deep) are much deeper than Lake I’s (approximately 140 ft deep). It is possible that Lakes C and D could be mined below the barrier units, thus providing a more direct route for recharged water to migrate to the aquifer in which the municipal wells are completed.

On May 10, 2010, the Department of Water Resources (DWR) and Zone 7 Water Agency (Zone 7) entered into a grant agreement as part of the Local Groundwater Assistance (LGA) Program. The grant, which is funded by the State of California Proposition 84, provided Zone 7 with up to \$250,000 to perform a preliminary investigation of the potential for Lakes C and D to be effective aquifer recharge basins. The scope of work included drilling one exploratory borehole, performing borehole geophysical logging, and installing nested monitoring wells in the borehole. A pumping test was also performed to verify connectivity of hydrostratigraphic units. Zone 7 then evaluated the results to modify and extend Zone 7’s network of cross sections south through the study area (Figure ES-1). The new nested wells will remain an invaluable tool for future investigations in the area.

ES 2 Field Work

From October 18 to October 25, 2010, Cascade Drilling (Cascade) drilled a borehole to a total depth of about 615 feet below ground surface (ft bgs) using a combination of the air-rotary casing hammer

(ARCH) and mud-rotary methods. Geophysical logging (e-logging) of the borehole was performed on October 26, 2010 by Dewey Data, Inc. as a subcontractor to Cascade. Following Zone 7's field evaluation of the e-log data, Cascade installed four nested wells in the borehole. Intermediate annular seals were installed between each screened interval to prevent vertical movement of groundwater via the annular space surrounding the two-inch casings. Well development occurred at the site from November 15 to 19 using airlift pumping and bailing methods. Kier & Wright conducted a location and elevation survey of the top of each well casing on December 29. Blaine Tech Services sampled the new nested wells on January 21, 2011; however, due to what appeared to be poor correlation between the field and lab data, the wells were resampled on February 14.

Following the installation and development of the nested wells, Zone 7 performed a pumping test to verify the connectivity of hydrostratigraphic units and to help evaluate the potential for water in the lakes to recharge the drinking water aquifer. For the test, Zone 7 contracted with Western Strata Exploration (Westex) to supply the pumping equipment. Zone 7 coordinated with the two active mining companies in the area (CEMEX and Vulcan) to conduct the pumping test during the weekend to minimize potential interference from their active supply wells (Wells 14J1 and 14B1) which are frequently pumped during the week, and less or not at all on weekends. The pumping test, which was performed from December 11 to 12, consisted of a one-hour preliminary pumping test followed by a 2-hour recovery period and a 24-hour constant pumping rate test. At the beginning and end of the pumping test, Zone 7 took water samples from the pumping well using a sample port installed in the pump discharge pipe. The pressure transducers were left in the observation wells until December 21 to monitor the responses from other supply wells in the area.

ES 3 Observations

Zone 7 evaluated geophysical logs, historical groundwater level fluctuations, groundwater level responses during the pumping test, and groundwater quality results to modify and extend Zone 7's network of cross sections through the area (Figure ES-2). The following observations were made as a result of this study:

- The subsurface materials encountered in the study area correlate well with those encountered to the north. The cross sections prepared for this study show that the 'Sequences' defined by Norfleet and herein referred to as 'Units' (from shallowest to deepest: Cyan, Gray, Purple, Red) appear to extend and thin to the south and west. This is consistent with Zone 7's and Norfleet's interpretation that the study area represents a proximal (upstream) area of the alluvial fan deposits that comprise the Main Basin.
- Historically, water levels in deeper wells respond more significantly than shallower wells to pumping from nearby supply wells, presumably because the majority of the large scale pumping is from the deeper aquifers (Purple and Red Units). Also, vertical groundwater gradients are typically downward (i.e., water moves from the upper units down to the lower units, from the Cyan to Gray, Purple and Red), especially when more groundwater is pumped (for example, during the drier summer months). However in portions of the study area, the gradient appears to be upward from the lower units to the middle units (from Red to Purple in the 19D wellset or from Purple to Gray in the new 13P wellset). This is likely because pumping from nearby wells is preferentially extracting water from the middle units (Purple or Gray, respectively).

- Pumping from Well 14J3 (screened in the Purple and Red Units) showed a response in Well 14J1 (Cyan and Gray Units) and Well 13P6 (Gray Unit), even though they are screened in different units. However, only a slight response was observed in Well 13P7 which is screened in the one of the same units (Purple Unit). The reason for this is unknown, but may be because the majority of the water entering Well 14J3 during its pumping was from the Gray unit.
- The boundary between the Cyan and Gray Units appears to be less of a hydrostratigraphic flow boundary in the study area than it is to the north. This is evident by the fact that water levels in Wells 19D7 (Cyan) and 19D8 (Gray) tracked so closely together, but those in Wells 11G1 (Cyan) and 11G2 (Gray) to the north do not. This is likely because the aquitard between these units is thinner and/or was completely eroded (e.g., the interpreted ‘hole’ in the aquitard in Cross Section ZC, Figure 6-1) in the southern portion of the study area.
- The transmissivity and storativity calculated from the pumping test results were about 4,600 ft²/d and 0.0007 (unit-less), respectively. However, the water level response in the new nested wellset does not clearly indicate which aquifer unit(s) (Gray, Purple, and/or Red) were pumped. Using the 280-ft upper and 70-ft lower limits for aquifer thickness, hydraulic conductivities of 16 to 66 ft/d are calculated. This is representative of a well-sorted sand to well-sorted gravel, which is consistent with the materials encountered during drilling.
- The aquitards (both lacustrine and overbank deposits) that act as vertical flow boundaries appear to be thin or are non-existent to the south and east of the study area. This is true for both the lacustrine deposits that act as boundaries between the aquifer units and the overbank ‘stringer’ deposits within the aquifer.

ES 4 Lakes C and D as Recharge Ponds

The results of this study suggest that Lakes C and D can be effective recharge ponds, especially for recharging water into the upper portion of the Lower Aquifer (i.e., into the Gray Unit) because:

- The planned excavation depths of Lakes C and D span the entire Cyan Unit and into the upper portion of the Gray Unit,
- The aquitard between the Upper and Lower Aquifers (the Cyan and Gray Units) is relatively thin to non-existent (0 to 10 ft thick) in the Lakes C and D area, and
- The aquifers appear to consist of mostly coarse-grained materials that would transmit water freely vertically.

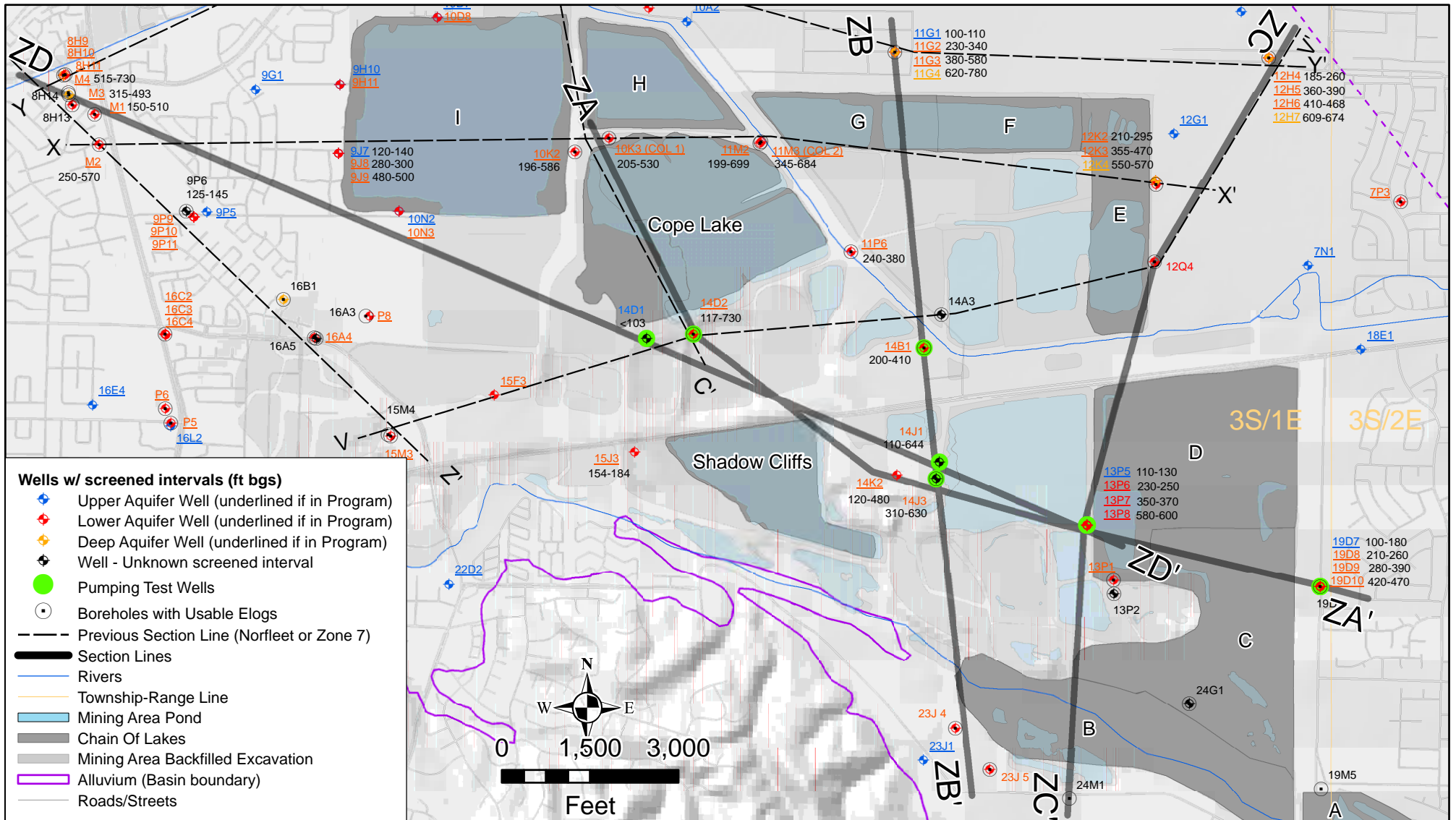
While the aquitards between the Gray and Purple Units and the Purple and Red Units appear to be more pronounced than between the Cyan and Gray Units; their total thicknesses are relatively thin, especially when compared to the stratigraphy below Lake I. Therefore, water discharged to Lakes C and D would migrate more freely to the Purple and Red Units, from which many of Zone 7’s supply wells are pumping, than water discharged to Lake I. There was some evidence that the Gray and Purple Units were in communication during the pumping tests, although the pathway is not fully understood. The downside

to using Lakes C and D as recharge ponds, however, is that Zone 7 won't be able to use them until after mining ceases in 2030, or later.

Attached Figures

Figure ES-1: Locations of Wells and Cross Sections

Figure ES-2: Cross Section ZD



ZONE 7 WATER AGENCY
 100 North Canyons Parkway
 Livermore, CA

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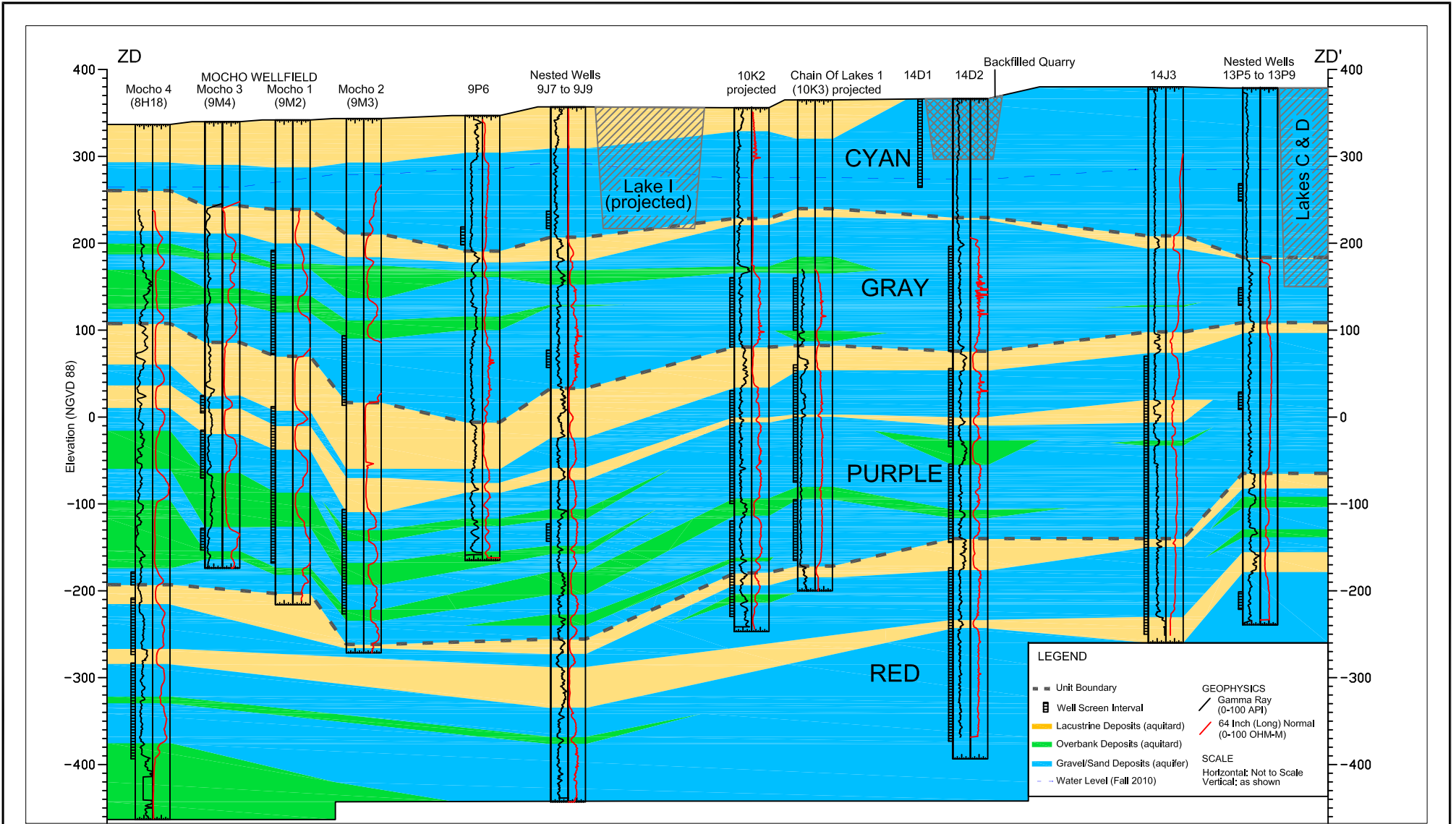
SCALE: 1 in ~ 2,400 ft


REVIEWED: TR, MK

DATE: Apr 14, 2011

FILE: E:\PROJECTS\VLGA Grant\GWStudy2010\Report\Figures\FigES-1-DWR Grant Project Map.mxd

Figure ES-1
Locations of Wells and Cross Sections
Hydrostratigraphic Investigation Lakes C/D



 <p>ZONE 7 WATER AGENCY 100 NORTH CANYONS PKWY LIVERMORE, CA 94551</p>	DWN: TR	SCALE: Horizontal: none; Vertical: 1" ~ 160'	<p>FIGURE ES-2 CROSS SECTION ZD Hydrostratigraphic Investigation for Lakes C and D</p>
	DES.: TR	DATE: May 20, 2011	
	CHK: MK	FILE: E:\GISProg\Zone7\GeoSections\ MainSections\Section-ZD.dwg	
	APPD: MK		

1 Introduction

On May 10, 2010, the Department of Water Resources' (DWR) and Zone 7 Water Agency (Zone 7) entered into a grant agreement as part of the Local Groundwater Assistance (LGA) Program. The grant, which is funded by the State of California Proposition 84, provided Zone 7 with up to \$250,000 to investigate the potential for two future gravel quarry pits (Lakes C and D) to be effective aquifer recharge basins. The scope of work included drilling one exploratory borehole, performing borehole geophysical logging, and installing nested monitoring wells in the borehole. A pumping test was also performed to verify connectivity of hydrostratigraphic units.

The results of this investigation were used to evaluate the potential for surface water discharged to Lakes C and D to percolate and subsequently recharge the aquifers tapped by the down-gradient municipal supply wells.

This report includes the following sections:

- **Section 1: Introduction** - this section.
- **Section 2: Background** – provides an overview of the project and the hydrogeologic setting.
- **Section 3: Well Construction** – provides an overview of the field work performed.
- **Section 4: Pumping Test and Water Levels**– describes the pumping test and the resulting water level responses in groundwater wells.
- **Section 5: Laboratory Results** – describes the results of the soil and water quality sampling and analysis.
- **Section 6: Data Interpretation** – describes the methodology used to evaluate the data and discusses the results.
- **Section 7: Conclusions** – provides conclusions and recommendations for future study.
- **Section 8: Sources of Information** – a list of reports or documents that were used to prepare this report.

The figures referenced in these sections can be found in the 'Figures' section at the end of the report.

Zone 7 uses the California's Well Numbering System, which includes the Township and Range, to name its wells (e.g., 3S/1E 13P 5). However, since the majority of the wells in the study area are in the 3S/1E

Township and Range (all except for the 3S/2E 19D nested wellset), for this report well names are abbreviated by omitting the Township and Range from their identification number (e.g., 13P5 instead of 3S/1E 13P 5).

2 Background

2.1 Overview

Zone 7 has actively managed the Livermore Valley Groundwater Basin (California Department of Water Resources Basin No. 2-10; a.k.a., Livermore-Amador Valley Groundwater Basin) for over 40 years. Zone 7 manages both surface and groundwater supplies for conjunctive use and reliability of water supplies. Groundwater typically makes up 15-25% of the water supplied by Zone 7 to its retail water supply agencies. In addition, two of the four retailers independently operate supply wells, as do other domestic and agricultural users, so total groundwater makes up a higher percentage of the total regional supply (typically 20-40%).

Zone 7 has water supply and flood control responsibilities for eastern Alameda County. It imports and treats water from the State Water Project (SWP), and operates several high capacity municipal wells to supply its retailers. Zone 7 conjunctively manages the local ground water basin, which has about 240,000 acre-feet of storage potential; about half of which is above the ‘historical lows’ and considered ‘operational storage’. Currently, the source water for Zone 7’s artificial recharge program is primarily from its SWP supplies, which are released from the South Bay Aqueduct (SBA) to several arroyos for shallow, in-stream percolation along a combined 16 miles of channel.

Zone 7 also has an ongoing project that, when complete, will consist of a series of abandoned gravel quarry pits converted into a chain of nine lakes (Chain of Lakes A through I), linked in series, and used for seasonal water storage and conveyance, and flood water detention and conveyance. As quarrying is completed, the designated lakes are to be transferred to Zone 7 for water supply purposes. The first one, which is located at the west end of the ‘chain’ (Lake I) has already been transferred. The last transfer is anticipated in about 2030. Preliminary designs for the lakes included augmenting Zone 7’s existing ‘artificial recharge’ with de-silted surface water diverted into Lake I and percolated through the lake’s sidewalls.

In 2004 Norfleet Consultants completed a geological and sequence stratigraphy analysis of the subsurface in the area between the Lakes H and I and Zone 7’s wellfield to the west of Lake I (*Norfleet, 2004*). The report identified four distinct sequences, herein referred to as ‘units’, in the Main Basin from shallowest to deepest: Cyan, Gray, Purple, and Red (Section 6.2). The results of this analysis show that there are several laterally continuous aquitards that potentially can act as barriers for recharge water from Lakes H and I to reach the lower aquifers in which the municipal supply wells are completed. However, the proposed final mining depths at future Lakes C and D (approximately 240 feet [ft] deep) are much deeper than Lake I’s (approximately 140 ft deep). It is possible that Lakes C and D could be mined below the barrier units, thus providing a more direct route for recharged water to migrate to the aquifer that the municipal wells are completed in. This project focused on investigating the potential hydraulic

communication between Lakes C and D and the drinking water aquifers by collecting additional geologic data, conducting a pumping test, and by extending the sequence stratigraphy cross sections first developed during the Norfleet 2004 study.

The results of this study will be folded into the Chain of Lakes Master Plan, and will likely have bearing on decisions currently being considered for Zone 7's StreamWISE (for stream management and flood protection) and Well Master Plan (*Zone 7, 2003 and 2005b*) Implementation projects. The results of the project will:

- Allow Zone 7 to append this knowledge to the existing Groundwater Management Plan (GWMP, *Zone 7, 2005*);
- Help Zone 7 evaluate groundwater basin management scenarios given different recharge alternatives;
- Help determine groundwater migration pathways from the shallow aquifers that are in communication with the mining area lakes to the deeper aquifers from which Zone 7 and the City of Pleasanton pump municipal supplies;
- Enhance Zone 7's existing groundwater budget;
- Provide better data to help refine Zone 7's groundwater model, especially in the mining area where little modeling target data is available; and
- Supply valuable precursor information for Zone 7's Chain of Lakes Master Plan.

2.2 Hydrogeology

2.2.1 Overview

The Livermore-Amador Valley (Valley), an east-west trending, inland alluvial basin located in northeastern Alameda County, is surrounded primarily by north-south trending faults and hills of the Diablo Range. The Valley covers about 42,000 acres, extends approximately 14 miles in an east-west direction, and varies from three to six miles in width. The Livermore Valley Groundwater Basin is located in the heart of the Valley and extends south into the hills south of Pleasanton and Livermore. The Main Basin (shown on Figure 2-1) is a portion of the Livermore Valley Groundwater Basin that contains the highest yielding aquifers and best quality groundwater. The geology of the Valley is described in detail in the GWMP and is summarized below.

2.2.2 Geology

The Valley is partially filled with recent alluvial fan, stream and lake deposits (of Pleistocene-Holocene age; less than about 1.6 million years old) that range in thickness from a few feet along the margins to nearly 800 ft in the west-central portion. The alluvium consists of unconsolidated gravel, sand, silt, and clay. The southeastern region of the Valley, the proximal (upstream) portion of the alluvial fan deposits, is the most important groundwater recharge area and consists mainly of sand and gravel that was deposited by the ancestral and present Arroyo Valle and Arroyo Mocho.

The Livermore Formation (Pleistocene age; 11,000 to 1.6 million years old), found below the majority of the alluvium in the groundwater basin, consists of beds of clayey gravels and sands, silts, and clays that are unconsolidated to semi-consolidated. This formation is estimated to be 4,000 ft thick in the southern and western portion of the basin. These sediments display lower yields in the upland areas.

The Tassajara and Green Valley Formations, located in the Tassajara Uplands north of the Valley, are roughly Pliocene in age (1.6 to 5.3 million years old). They basically consist of sandstone, tuffaceous sandstone/siltstone, conglomerate, shale, and limestone. Water movement from these formations to the alluvium of the fringe and Main Basins is minimized by faults and angular unconformities or by stratigraphic disconformities along the formation-alluvium contacts.

2.2.3 Aquifer Zones

Although multiple aquifers have been identified in the Main Basin alluvium, wells have been classified generally as being in one of two aquifer zones, separated by a relatively-continuous silty clay aquitard up to about 50 ft thick:

Upper Aquifer Zone - The upper aquifer zone consists of alluvial materials, including primarily sandy gravel and sandy clayey gravels. These gravels are usually encountered underneath the surficial clays typically 5 to 70 ft below ground surface [bgs] in the west and exposed at the surface in the east. The base of the upper aquifer zone is at about 80 to 150 ft bgs. Groundwater in this zone is generally unconfined; however when water levels are high, portions of the Upper Aquifer Zone in the western portion of the Main Basin can become confined. For this study the Upper Aquifer is the Cyan Unit.

Lower Aquifer Zone - All sediments encountered below the clay aquitard in the center portion of the basin have been known collectively as the Lower Aquifer Zone. The aquifer materials consist of semi-confined to confined, coarse-grained, water-bearing units interbedded with relatively low permeability, fine-grained units. It is believed that the Lower Aquifer Zone derives most of its water from the Upper Aquifer Zone through the leaky aquitard(s) when groundwater heads in the upper zone are greater than those in the lower zone. In this study, the Lower Aquifer includes the Gray, Purple, and Red Units.

Groundwater gradients of both aquifer zones are generally from east to west, and in the study area from southeast to northwest towards Zone 7's Chain of Lakes and Mocho Wellfields.

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3 Well Construction

3.1 Introduction

The majority of the site is on property owned by one of the two active mining companies located in Livermore. Zone 7 worked with the two mining owners to determine the optimum location of the project borehole, shown in Figure 3-1, such that:

1. There would be minimal impact to the owner/operator activities;
2. The new wellset was sited directly down-gradient of Lakes C and D;
3. The wells could be accessible for long-term monitoring and sampling;
4. They would provide data in an area not previously investigated;
5. The location was practical for extending Zone 7's existing network of cross sections.

The selected location was on property owned by CEMEX, with whom Zone 7 executed a Permit-to-Enter-and-Do-Work that required adhering to all the mining safety rules and completing site safety training prior to construction. The drilling contractor obtained a drilling permit for the nested wells from Zone 7's Well Permitting section. The project qualified for a Categorical Exemption under CEQA; therefore, Zone 7 filed a notice of exemption with the Department of Fish and Game.

Construction oversight of field activities was performed by Zone 7 staff. This included borehole logging, well installation and development observation, ensuring site safety, and field work coordination with the contractor. During the project, daily field logs were submitted by the contractor to track the progress of the project. A consultant, RGM & Associates, was onsite every week to perform Labor Compliance Program (LCP) monitoring and interviewing. RGM was present at the kickoff meeting, and Zone 7 coordinated with this consultant regularly throughout the project.

A summary of field work performed for this project is shown below and is described in more detail in Sections 3.2 to 3.7:

**Table 3-1
Chronology of Field Work**

DATE	ACTIVITY
September 15	Selected Cascade to drill borehole and construct well
October 18	Kick off site meeting, Labor Compliance Program (LCP) Orientation, mobilization, and start of drilling.
October 18 to 25	Drilled borehole to a final depth of 615 feet
October 26	Electrical logging of borehole. Begin installation of nested wellset.
October 27	Installed Nested Well #4 (3S/1E 13P 8)
October 28	Installed Nested Well #3 (3S/1E 13P 7)
October 29	Installed Nested Well #2 (3S/1E 13P 6)
November 1	Installed Nested Well #1 (3S/1E 13P 5)
November 2	Completed installation of nested wellset , installed cement grout sanitary seal, started demobilization of drilling operations equipment
November 15	Commenced air surge development, development of Well #1 and Well #2 completed.
November 18	Air surge development of Well #4
November 19	Air surge development of Well #3, installed wellhead stove pipe, traffic bollards, and concrete apron.
December 11-12	Pumping Test (pumped from Well 3S/1E 14J 3)
December 21	Removed pressure transducers in observation wells
December 29	Field survey of wellhead elevations
January 21, 2011	Well sampling
February 14	Resampling of wells

3.2 Borehole Drilling

Zone 7 prepared contract specifications for the project and adhered to the requirements of the Public Contract Code to obtain a drilling contractor with the technical capabilities to drill and construct the nested wellset. On September 15, 2010, Zone 7 selected Cascade Drilling (Cascade) as the drilling contractor. A kick-off meeting including the required LCP contractor orientation was held on October 18, 2010. Cascade commenced drilling on October 18 and reached the bottom depth of 615 ft bgs on October 25.

The borehole was drilled by a combination of the air-rotary casing hammer (ARCH) and mud-rotary methods as follows:

**Table 3-2
Borehole Drilling**

Depth (ft bgs)		Diameter	Drill Method	Notes
From	To			
0	200	15 inches	Air rotary casing hammer (ARCH)	13-3/8 inch conductor casing
200	377	12 ½ inches	Mud rotary	12 ½ inch bit
377	615	9 ¾ inches	Mud rotary	9 ¾ inch bit

Past experience with drilling in the Chain of Lakes/gravel quarry area has proven that the ARCH drilling method with the use of a temporary drive casing for the upper portion of the borehole is the most effective drilling method for penetrating the loose gravels present in this area and maintaining circulation of the drilling fluid. This drilling method comes with a higher cost, but saves time and money in the long run, and is typically a more successful method for installing monitoring wells under the site's conditions. The drive casing was left in place until the well casing, filter pack and intermediate annular seals were installed.

The mud-rotary drilling equipment included a portable mud system comprised of above-ground fluid tanks with de-sanders and shaker screens which separate the drill cuttings and suspended solids from the drilling fluid. A 12 ½ inch bit and a 9 ¾ inch bit were used at targeted depths to provide enough room in the borehole for the nested well completions. During drilling, particularly from approximately 300 to 400 ft, Cascade had to thicken the drilling mud to ensure removal of the coarse-grained gravels.

Formation samples, or drill cuttings, were obtained from the drilling-fluid returns for each five-foot interval and placed in gallon re-sealable plastic bags. Representative portions of each sample were placed in chip sample trays for archive purposes. The cuttings were logged (Figure 3-2) by a Professional Geologist registered with the State of California. Four soil samples (at 120, 195, 240, and 360 ft bgs) were submitted for sieve and permeability analysis to Consolidated Engineering Laboratories (Consolidated Lab), a materials testing firm with whom Zone 7 has an annual services contract. The results of this testing are presented in Appendix A and discussed in Section 5.1.

3.3 Geophysical Logging

Geophysical logging (e-logging, see Appendix B) of the borehole was performed on October 26, 2010 by Dewey Data, Inc. as a subcontractor to Cascade. Zone 7 staff witnessed the logging and provided QA/QC review of the e-log. Upon achieving the target depth in the proposed borehole, fresh drilling mud was circulated through the borehole until it was free of cuttings and filled above the interval to be logged. The resistivity of the fluid was recorded on the log header. The suite of e-logs consisted of resistivity, spontaneous potential and natural gamma radiation. Field copies and electronic versions of the data were provided to Zone 7 at the conclusion of logging. Zone 7 evaluated the e-log and lithologic log in the field to select the final screen-completion intervals and proper design for the nested wellset.

3.4 Installation of Nested Wells

Three nested wells were originally proposed, but since the preliminary cross section suggested that there may be four aquifer zones, Zone 7 added a fourth two-inch well to the nested wellset plan. Upon completion of drilling and e-logging, Cascade constructed a nested wellset consisting of four two-inch inner diameter (I.D.) Schedule 40 PVC well screens and riser casings at the intervals listed below (and shown in Figure 3-3), to target each significant aquifer zone. The well screens consisted of two-inch Schedule 40 PVC pipe with horizontally machined slots measuring 0.020 inches.

**Table 3-3
Well Screen Intervals**

Well	Depth (ft bgs)		Screen size
	From	To	
3S/1E 13P 5	110	130	0.020 inch
3S/1E 13P 6	230	250	0.020 inch
3S/1E 13P 7	350	370	0.020 inch
3S/1E 13P 8	580	600	0.020 inch

Stainless steel centralizers were used to separate each casing and to create suitable annular space for the annular fill materials. Cascade then installed the annular fill materials as listed in the table below and shown in Figure 3-3.

**Table 3-4
Annular Fill Materials**

Depth (ft bgs)		Fill	Notes
From	To		
0	40	Cement	Portland
40	104	Bentonite chips	CETCO brand
104	141	Filter pack	CEMEX #3 Sand
141	225	Bentonite , sand seal	CETCO #8, CEMEX #2/16
225	258	Filter pack	CEMEX #3 Sand
258	345	Bentonite, sand seal	CETCO #8, CEMEX #2/16
345	377	Filter pack	CEMEX #3 Sand
377	575	Bentonite, sand seal	CETCO #8, CEMEX #2/16
575	615	Filter pack	CEMEX #3 Sand

An intermediate annular seal was installed between each screened interval to prevent vertical movement of groundwater via the annular space surrounding the two-inch casings. The intermediate annular seal

consisted of a mixture of equal parts of granular bentonite and sand with a minimum five-foot thick bentonite pellet or chip transition seal.

At a depth of about 100 ft the driller initially mixed and tremied a slurry seal (Volclay bentonite and water, within the contract specifications) into the annular seal. However, even after pumping approximately seven bags of this material into the annular seal, the material could not be detected and was assumed to have been lost into the neighboring native strata or to fill unknown borehole 'washouts'. Consequently, Cascade and Zone 7 staff elected to add bentonite chips to the slurry mix to ensure a proper seal.

The surface 'sanitary' seal consisted of neat-cement grout from a depth of 40 ft to ground surface. The wells were completed with a 15-inch diameter steel casing sticking up approximately four feet above ground surface and fitted with a lockable steel cover to protect the wells from damage and to secure access to the wells. Additionally, a concrete pad and concrete filled bollards painted yellow were installed around the wellhead to make the wells visible to any potential traffic nearby.

These well construction activities were conducted between October 26 and November 11, 2010. Field notes, field lithologic log, inspection reports and driller's daily reports are included in Appendix B. **Error! Reference source not found..**

3.5 Well Head Surveying

Kier & Wright, with whom Zone 7 has an annual services contract, conducted wellhead location and elevation surveys on December 29, 2010. Each PVC casing was notched or marked to indicate the point on the well that was surveyed and used as the reference point for water level measurements. Additional wells used as part of the pumping test were also surveyed.

Each well was surveyed to establish the map coordinates within the State Plane Coordinate Grid to within ± 1 foot on the horizontal control and referenced to the North American Datum (NAD) of 1983. The elevations of each well casing were surveyed to within ± 0.05 foot using the National Geodetic Vertical Datum (NGVD) of 1988. Results of the surveying are included in Appendix B.

3.6 Well Development, Groundwater Level Measurements, and Sampling

The new nested wells were developed from November 15 to 19. To develop the wells, Cascade used an airlift pumping method. Development began by air lifting in the unperforated casing immediately above each section of well screen. Development continued until no appreciable quantity of sand, silt or clay was brought into the well and the purge water was observed at the desired clarity. Zone 7 staff provided onsite oversight of these operations. Three of the wells (Wells 13P5, 13P6, and 13P8) were developed relatively quickly (all three within ten hours). The third well (Well 13P7, screened from 350-370 ft) took much longer to clear up than anticipated (approximately ten hours).

Blaine Tech Services, with whom Zone 7 has an annual services contract for groundwater sampling, initially sampled the new nested wells on January 21, 2011. However, the laboratory results from this sampling event did not pass QA/QC review because the lab pH and specific conductivity did not match those from the field measurements. The reason for this discrepancy is unknown, but it appears that Blaine Tech may have sampled the wells before field parameters had stabilized, suggesting that the wells were not purged sufficiently prior to sampling. Therefore, these results were flagged as 'suspect', and the wells were resampled on February 14, 2011. Some of the results from the second sampling event, during which field parameters had stabilized during purging, varied from the initial sampling event, suggesting that the initial sampling event was not representative of groundwater from the surrounding formation. The laboratory results from both sampling events are presented in Appendix C and discussed in Section 5.2.

3.7 Waste Handling

Zone 7 coordinated with CEMEX to allow onsite disposal of soil cuttings, drilling mud, and purge water from the wells; there was no reason to suspect contamination in the project area since the cuttings from the borehole were the same materials that are being mined on the property and the groundwater pumped from the wells is in communication with the onsite ponds. Cascade spread all solid waste on site and discharged all waste fluid (drilling mud) to the designated settling pond. Well development and pumping test purge water was also discharged to the settling pond with the owner's permission.

4 Pumping Test and Water Levels

4.1 Introduction

Following the installation and development of the nested wellset, Zone 7 performed a pumping test to verify the connectivity of hydrostratigraphic units and to help evaluate the potential for recharge water placed in the future pits to reach the drinking water aquifer. During the planning of the test, staff researched the construction features of several water supply wells in the study area. Only one well (Well 14J3) was found to be large enough for a high-capacity pump and had an appropriately limited screened interval so that the results would be easier to interpret. In addition to the four newly constructed monitoring wells, seven others were selected to be used as observation wells during the test. Water level recording transducers were placed in each of the observation wells.

Zone 7 coordinated with the two active mining companies in the area (CEMEX and Vulcan) for property access and well access. The test was run on a weekend to minimize interference from CEMEX's and Vulcan's active supply wells (Wells 14J1 and 14B1, respectively) which are frequently pumped during the week, and less or not at all on weekends.

4.2 Equipment

Zone 7 contracted with Western Strata Exploration (Westex) to supply and operate the pumping equipment. The pumping was performed in Well 14J3 using a six-inch submersible test pump powered by a diesel generator also supplied by Westex. On December 10, 2010, Westex installed the pump to a depth of 253 ft bgs. The pump discharge was regulated by varying the electric motor speed and observing the flow rate with a flow meter on the discharge line. Unfortunately, problems with the pump limited the pumping rate to a maximum of 500 gallons per minute (gpm) and a maximum drawdown of 67 ft in the pumping well.

Prior to the start of the pumping test, data logging pressure transducers (MiniTROLL™, LevelTROLLs™, or AquiStar PT2X) were installed in the observation and pumping wells listed below (and also shown in green on Figure 3-1).

Table 4-1
Pumping Test
Wells with Pressure Transducers

Well	Description	Screened (depth in ft)	Filter Pack (depth in ft)	Distance to 14J3 (ft)	Period (dates in December)
3S/1E 14J 3	Pumping test well	310-630	80-630	0	11-21
3S/1E 14J 1	CEMEX pumping well	110-644*	50-565?	290	11-21
3S/1E 14B 1	Vulcan pumping well	200-410*	180-435	2250	9-21
3S/1E 13P 5	Nested well #1	110-130	104-141	2680	9-21
3S/1E 13P 6	Nested well #2	230-250	225-250	2680	9-21
3S/1E 13P 7	Nested well #3	350-370	345-377	2680	9-21
3S/1E 13P 8	Nested well #4	580-600	575-605	2680	9-21
3S/1E 14D 1	Shallow test well	<103	unknown	5470	10-21
3S/1E 14D 2	South Cope Test	170-740*	165-760*	4800	10-21
3S/2E 19D 7	Isabel Nested well #1	100-180	90-195	6770	9-21
3S/2E 19D 8	Isabel Nested well #2	210-260	200-265	6770	9-13
3S/2E 19D10	Isabel Nested well #4	420-470*	405-475	6770	9-21

*multiple screened intervals (top of shallowest and bottom of deepest interval shown)

4.3 Pumping Test

The pumping tests, which were performed from December 11 to 12, consisted of a one-hour step-rate test followed by a 24-hour constant-rate test. Typically the step-rate test would involve multiple pumping rates, increased in a step-like fashion, to gauge the maximum pumping rate for the constant-rate test that would maximize the drawdown without dewatering the aquifer. However, in this case, the initial pumping rate of 500 gpm turned out to be the maximum rate, thus limiting the drawdown to 67 feet, about 230 ft less than the target drawdown for the test.

During the constant-rate test, Zone 7 staff periodically collected water level data manually using a water level meter (Solinst Model 101) and compared these data to the pressure transducers readings to confirm that the transducers were working correctly and to monitor drawdown in the field. Drawdown data collected from the pumping test observation wells were plotted in the field using *AquiferTest for Windows* (Version 2.50 by Waterloo Hydrogeologic, Inc.) to verify that the equipment was working properly.

At the beginning and end of the pumping test, water samples were collected from Well 14J3 using a sample port installed in the pump discharge pipe. The samples were submitted to Zone 7's Water Quality Laboratory for analysis of electrical conductivity (EC), pH, major minerals and metals. Sample results are discussed in Section 5.2.

Following the pumping test, the pressure transducers were left in selected wells until December 21 to monitor the responses from other supply wells pumping in the area (e.g., CEMEX's Well 14J1 and

Vulcan's Well 14B1 in the mining area and Zone 7's own Chain of Lakes wells). These water level responses are discussed in Section 4.4.2.

4.4 Water Levels in Observation Wells

4.4.1 Historical Water Levels

Within a nested wellset, the difference between water levels in wells screened in neighboring units may be related to the 'leakiness' and continuity of the boundaries between the units. Also, the water level gradient is representative of the direction of vertical water flow between the units; that is, water will flow from the unit with a higher water level to one with a lower level, regardless of whether that unit is above or below. Historical groundwater elevations in the observation wells are graphed in Figure 4-1 and are colored according to the unit within which they are screened (Cyan, Gray, Purple, and Red – see Section 6.2). These graphs suggest the following:

- Historically, water levels in deeper wells respond more significantly than shallower wells to pumping from nearby supply wells, presumably because the majority of the large scale pumping is from the deeper aquifers (Purple and Red Units). Also, vertical groundwater gradients are typically downward (i.e., water moves from the upper units down to the lower units, from the Cyan to Gray, Purple, and Red), especially when more groundwater is pumped (for example, during the drier summer months). However in portions of the study area, the gradient appears to be upward from the lower units to the middle units (from Red to Purple in the 19D wellset or from Purple to Gray in the new 13P wellset). This is likely because pumping from nearby wells is preferentially extracting water from the middle units (Purple or Gray, respectively).
- The boundary between the Cyan and Gray Units appears to be less of a hydrostratigraphic flow boundary in the study area than it is to the north. This is evident by the fact that water levels in Wells 19D7 (Cyan) and 19D8 (Gray) tracked so closely together, but those in Wells 11G1 (Cyan) and 11G2 (Gray) to the north do not.
- There is a significant difference between Well 19D8 (Gray Unit) and the two deeper wells in the nested set (Wells 19D9 and 19D10, Purple and Red, respectively). This suggests that the boundary between the Gray and Purple Units in this area is a significant hydrostratigraphic flow boundary, whereas the aquitard between the Purple and Red Units appears to be very leaky.

4.4.2 Pumping Test Water Levels

While the 24 hour pumping test was performed from December 11 to 12, the pressure transducers were left until December 21 to monitor responses from other nearby supply wells. The graphs of the water levels in all of the wells for the entire period are shown in Figure 4-2. Graphs of the water levels in just the new nested monitoring wells (Wells 13P5 to 13P8) are shown in Figure 4-3. The pumping periods of

the pumping test well 14J3 (screened in the Purple and Red Units), CEMEX's supply well 14J1 (screened in the Cyan and Gray Units) and Zone 7's Chain of Lakes 1 (COL1, in the Gray and Purple Units) and Chain of Lakes 2 (COL2, Purple and Red Units) Supply Wells are shown at the bottom of each of the graphs as horizontal bars. The results, which are discussed below, were used to help create hydrostratigraphic correlations between aquifer units for the cross sections (Section 6.2):

- Well 14J3 (the pumping well for the 24-hour constant rate test, screened in the Purple to Red Units) – during the pumping test, drawdown in the well reached a maximum of about 67½ ft and fully recovered after the test in less than two minutes. Following the test, pumping from Well 14J1 (CEMEX's well located approximately 290 ft to the north) generated a maximum drawdown in Well 14J3 of about 13½ ft. Pumping from either or both Zone 7's Chain of Lakes wells did not produce any noticeable response in this well. There were no unaccounted for responses in the water level record.
- Well 14J1 (CEMEX Supply Well, screened in the Cyan to Gray Units) – during the pumping test, drawdown in the well reached a maximum of about 5½ ft, however, surprisingly water levels appeared to rise slightly after 20.3 hours and lasting until the end of the test. After the conclusion of the test, Westex removed their pressure transducer from the well before water levels fully recovered (they rose to about 2½ ft below static). On December 13, Zone 7 transferred the pressure transducer that was in Well 19D8 (which appeared to be duplicating the water level responses in Well 19D7) to Well 14J1. Following the test, normal pumping from this well during the week (pumping rate unknown) generated a maximum drawdown of about 31½ ft. While there appeared to be sporadic short-term drops of about four additional feet during the pumping, these are considered to be anomalous 'blips' in the dataset. No other wells elicited an obvious response in this well; however, it is possible that the rise in water levels during the pumping test corresponded to the cessation of pumping in Zone 7's COL 2 well. It is also possible that Well COL 1 generated a response in this well on December 19 while the pump in Well 14J1 was off. The drawdown from this well was used to calculate aquifer transmissivity and storativity (Section 4.5).
- Well 14B1 (Vulcan Supply Well, screened in the Gray to Purple Units) – during the pumping test, drawdown in this well reached a maximum of about three feet; however, as in Well 14J1, water levels appeared to rise near the end of the test (at 20.3 hours) in response to COL 2 being turned off. Following the test, water levels in the well appeared to respond to Wells COL 1, COL 2 and 14J3 turning on and off. The short-term drops (spikes) of about five additional feet on December 16, 19 and 20, are probably due to pumping in Well 14B1 itself; and did not appear to affect water levels in any other wells.
- Well 13P5 (Shallow Nested Well, screened in the Cyan Unit) – While there is no obvious drawdown in this well from any of the other supply wells, there are some small, sharp drops in water elevation (about one foot or less) when Wells 14J3 and 14J1 are pumping. There also appears to be a slight downward trend during the pumping test, however, the timing of these drops does not correspond well with pumping times of Wells 14J3 and 14J1. These features may have to do with the operation of mining ponds located near the the new nested wellset.

- Well 13P6 (Second Nested Well, screened in the Gray Unit) - during the pumping test, drawdown in the well reached a maximum of about 2½ ft. Unlike Wells 14J1 and 14B1, water levels did not rise during the test, but there does seem to be a slight change in slope of the drawdown curve around the same time. Following the test, water levels responded noticeably from pumping in Well 14J1, dropping by as much as six feet. There did not appear to be any response from pumping at Wells COL 1 or COL 2. The drawdown curve from this well was also used to calculate aquifer transmissivity and storativity (Section 4.5). It is unclear why water levels in Well 13P6 responded to pumping from Well 14J3 while Well 13P7's (see below) did not, especially since the aquifer unit that Well 13P7 is completed in (Purple) correlates with those in which Well 14J3 is completed (Purple and Red) and not Well 13P6 (Gray). It is possible, however, that since the filter pack in Well 14J3 extends up to 80 ft bgs, that at least some of the pumping in Well 14J3 comes from the aquifer zone in which Well 13P6 is screened (Gray) and that very little of the water comes from the Purple Unit.
- Well 13P7 (Third Nested Well, screened in the Purple Unit) – during the pumping test, there was a delayed and much attenuated drawdown in this well that reached its maximum at about 0.2 ft. Following the test, water levels did not appear to respond to any pumping from other supply wells. It is also interesting to note that water levels in Well 13P7 were higher than those in Well 13P6 (Gray) and 13P8 (Red), and that the overall water elevation change pattern does not match or correlate with any of the other wells. Considering that it was extremely difficult to develop this well, one conclusion may be that the well completion may still be experiencing significant well bore damage from the drilling process.
- Well 13P8 (Deep Nested Well, screened in the Red Unit) – during and after the pumping test, water levels in Well 13P8 did not respond noticeably to pumping from any supply wells. Instead the water level rose approximately six feet during the study, same as observed in 19D10. This suggests that this well and Well 19D10 are screened in a distinct aquifer unit below the units from which Wells 14J3 and 14J1 pump.
- Well 14D1 (Shallow Aquifer Well northwest of Well 14J3, screened in the Cyan Unit) – water levels in this well varied only slightly (less than 0.6 ft) throughout the entire length of the test. The water level change pattern matches that of 19D9 (Cyan).
- Well 14D2 (Lower Aquifer Well northwest of Well 14J3, screened in the Gray, Purple, and Red Units) - during the pumping test, drawdown reached a maximum of about 8½ ft, however, as in Well 14J1, water levels appeared to rise during the later hours of the test in response to COL 2 turning off. Following the test, water levels in the well appeared to respond to pumping in Wells COL 1 (Gray and Purple) and COL 2 (Purple and Red), but not from Well 14J1 (Cyan and Gray).
- Well 19D7 (Shallow Nested Well east of Well 14J3, screened in the Cyan Unit) – Water levels in this well were very similar to those in Well 14D1 (Cyan), where water levels varied only slightly (less than 0.6 ft) throughout the entire length of the test. This suggests that this well is screened in the same aquifer unit as Well 14D1 (Cyan).
- Well 19D8 (Second Nested Well east of Well 14J3, screened in the Gray Unit) – historically and during the test, this well has showed similar trends as Well 19D7. Consequently, the pressure

transducer was moved to Well 14J1 to replace the Westex's pressure transducer that was removed following the pumping test. The close tracking of Well 19D8's water levels with 19D7's suggest that there is no significant hydrostratigraphic boundary between the Cyan and Gray Units in this area.

- Well 19D9 (Third Nested Well east of Well 14J3, screened in the Purple Unit) – During the test, this nested well casing was obstructed preventing the installation of a transducer. Therefore, it could not be used for the test.
- Well 19D10 (Deep Nested Well east of Well 14J3, screened in the Red Unit) – the water level graph in this well is very similar to that in Well 13P8, suggesting that both wells are screened in the same aquifer unit even though the screened interval in Well 19D10 is 110 ft higher than that in Well 13P8.

4.5 Aquifer Property Calculations

While the pumping test was primarily designed to identify which aquifer units responded during pumping, aquifer properties were calculated in wells where water level responses during the pumping test were obvious and measurable (i.e., in Wells 14J1, 14J3, and 13P6). The program *AQTESOLV* was used to calculate transmissivity and storativity (using the Theis and Cooper-Jacob methods). As a check, Figure 4-4 shows the pumping test aquifer property calculations for Well 13P6 using the Cooper-Jacob straight-line method. The results are shown in the table below.

Table 4-2
Aquifer Property Calculations from Pumping Test

Well	Method	Transmissivity (ft ² /d)	Storativity (unit-less)
3S/1E 14J1	Cooper-Jacob	6700	0.0009
3S/1E 14J1	Theis	6900	0.0007
3S/1E 14J3	Theis	2400	0.001
3S/1E 13P6	Cooper-Jacob	4000/4097*	0.0003/0.00012*
3S/1E 13P6	Theis	3000	0.0004

* From Figure 4-4

The average transmissivity and storativity from the values listed above are:

$$\text{Transmissivity} = 4,600 \text{ ft}^2/\text{d}$$

$$\text{Storativity} = 0.0007$$

Hydraulic conductivity, a measure of the capacity for soil to transmit water and a useful parameter for Zone 7's groundwater model, can also be calculated using the formula below:

$$K = T/b$$

Where:

K = hydraulic conductivity

T = Transmissivity

b = aquifer thickness

The aquifer thickness corresponds to the thickness of the aquifer units that were pumped. The thicknesses that were used for these calculations are as follows:

Table 4-3
Thicknesses of Aquifer Materials
in Borehole for 13P Nested Wellset

Sequence/Unit	Aquifer	Thickness (ft)
Gray	2 nd	70
Purple	3 rd	160
Red	4 th	50

The pumping well 14J3 is screened in the Purple and Red Units, respectively; however, during the pumping test water levels only definitively responded in Well 13P6, which is screened in the Gray Unit. The total value for b for these three units is about 280 ft. However, since there was no response in Wells 13P7 (Purple Unit) and 13P8 (Red Unit), it is possible that pumping only occurred from the Gray Unit, which is 70 ft thick. These two values can be used as upper and lower limits of aquifer thickness to calculate the hydraulic conductivity (K). Solving for K using these two limits:

$$K = \frac{(4,600 \text{ ft}^2/\text{d})}{280 \text{ ft}} = 16 \text{ ft/d}$$

$$K = \frac{(4,600 \text{ ft}^2/\text{d})}{70 \text{ ft}} = 66 \text{ ft/d}$$

These values for K correspond with a well-sorted sand to well-sorted gravel, which is consistent with the materials encountered during drilling and e-logging.

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5 Laboratory Results

5.1 Sieve Analyses

Four soil samples were selected for grain-size and distribution analysis and submitted to Consolidated Engineering Laboratories to confirm field logging observations. Results are shown in Appendix A and are summarized in the table below:

Table 5-1
Results of Sieve Analyses

Sample	Depth (ft bgs)	Soil Classification (USCS)	Field Log
#120	120	GP	Brown sandy gravel (Cyan)
#195	195	N/A	Brown, clayey gravel with sand (Cyan/Gray boundary)
#240	240	SP	Brown sandy gravel (Gray)
#360	360	N/A	Brown sandy gravel (Purple)

These results were consistent with the materials observed during drilling except for Sample #195 (at about 195 ft bgs). This sample was submitted to characterize the fine-grained zone observed at about 195 ft bgs. However, the testing results vary little from the other coarser-grained samples. It is possible, therefore, that this sample is not indicative of the actual lithology because it was collected from the discharge return of the mud rotary rig where many of the fines may have been lost; or the inferred hydrostratigraphic boundary between the Cyan and Gray Units is not a significant boundary to groundwater flow between these units at this locale.

5.2 Water Quality

All water samples were submitted to Zone 7's Water Quality Laboratory (ELAP Certified) for analysis of electrical conductivity (EC), pH, major minerals, and metals. This analytical suite is consistent with analyses performed for Zone 7's groundwater monitoring program. The laboratory results are presented in

Figure 5-1. Laboratory Data Sheets, Chain of Custodies, and Laboratory Methods and Limits are presented in Appendix C. Analytical results from the most recent sampling results from each of the study wells are plotted on a Trilinear Piper Diagram (Figure 5-2). In that figure, samples are color-coded by the unit from which they were taken. The water quality results suggest the following:

- The Trilinear Piper diagram shows that there is no dominant (i.e., over 50%) cation in all of the samples except for 12H7's which is dominant in sodium. Calcium is the principal (i.e., most abundant) cation in the wells sampled for this study (Wells 14J1, 14J3, and the new nested wells) with the exception of Well 13P7, where sodium is the principal cation at 18%.
- For all of the samples, bicarbonate is the dominant and principal anion.
- The Trilinear Piper diagram shows no obvious or distinct, water quality characteristics that uniquely distinguish each well or aquifer unit; other than Wells 12H7 and 13P7 having a higher-sodium content than the other samples.
- Constituent concentrations in the wells sampled for this study are consistent with concentrations found in nearby monitoring wells that Zone 7 samples as part of its Groundwater Monitoring Program.

6 Data Interpretation

6.1 Database Management

Zone 7 uses a proprietary database and Geographical Information Systems (GIS) program, *GIS\Key*, specifically designed for storing and presenting environmental and geologic data (www.giskey.com). Data collected from the borings and wells were entered into Zone 7's *GIS\Key* database. This includes:

- Lithologic data from boring log
- Borehole geophysics
- Well construction
- Surveyed locations and elevations
- Water levels
- Water quality analytical data

GIS\Key was then used to create the boring log in Figure 3-2 and cross sections in Figure 6-1 and Figure 6-2.

6.2 Hydrostratigraphic Evaluation

6.2.1 Methodology

6.2.1.1 Background

To evaluate the stratigraphy, Zone 7 used a technique called sequence stratigraphy introduced to Zone 7 by Norfleet Consultants (2004) during their study for Zone 7. A description of sequence stratigraphy from that report is included below:

A crucial component in the assessment of a groundwater resource is an accurate representation of the geology and hydrogeology within a groundwater basin. A pure stratigraphic evaluation focuses on the geologic components of the subsurface and may miss the nuances of the inter-relationships of aquifers and other hydrologic components. Therefore, it is important to integrate the components of a hydrologic system into a stratigraphic evaluation to develop an accurate understanding of the hydrostratigraphy.

Sequence stratigraphy is a method of relating the depositional environment of sediments to the stratigraphic framework in which they were deposited. A sequence is a fundamental stratal unit for stratigraphic analysis defined as a relatively conformable, genetically related succession of strata bounded by unconformities. A sequence includes all genetically related lithologies (lithofacies) between the defining unconformities.

For this type of stratigraphic analysis, e-logs are used as the primary correlation tool for identifying similar log patterns in the closest wells. These patterns in combination with the lithologic logs can help determine the nature of the depositional packages, (e.g., whether they are fining-upward or coarsening-upward packages) and the connectivity of the units.

For their 2004 study Norfleet Consultants generated two cross sections and identified four sequences (from shallowest to deepest: Cyan, Gray, Purple, and Red) that were separated by unconformities. Since then, as more e-logging has been performed in the area, Zone 7 (with consulting support from Skyline Ridge) extended and/or created new cross sections across the northern portion of the mining area and Zone 7's Mocho Wellfield (Figure 3-1).

6.2.1.2 Sequence versus Flow Boundary

For the majority of the area studied so far in the Main Basin, sequence boundaries correspond with the tops of fine-grained lacustrine deposits that provide a hydrostratigraphic flow boundary. However, in some cases, overlying coarse-grained alluvial deposits have eroded the top of the underlying lacustrine deposits, depositing gravel on top of gravel. In this case, the sequence boundary does not represent a hydrostratigraphic flow boundary. Since the primary focus of this study is to identify the nature of the hydrostratigraphic boundaries, Zone 7 modified some of these boundaries as discussed in the next paragraph. Also, to avoid confusion between Norfleet's and Zone 7's methods for interpreting the boundaries, the zones between these boundaries will herein be referred to as 'Units', and not as 'sequences'.

For large areas where the sequence boundary does not correspond with a hydrostratigraphic boundary, Zone 7 moved the sequence boundaries down to correspond with the next significant hydrostratigraphic flow boundary. This was especially true for the boundary between the Cyan and Gray Units; Norfleet showed this boundary to be predominantly gravel-on-gravel at a depth much shallower than what is shown in this report. Zone 7 moved this boundary down to the next hydrostratigraphic flow boundary. This has the added benefit that the Cyan Unit now corresponds with the Upper Aquifer, and those units below the Cyan Unit correspond collectively with the Lower Aquifer.

However, for smaller areas where the sequence boundary does not correspond with a hydrostratigraphic flow boundary, the boundary is interpolated across, and not down. For example, the boundary between the Cyan and Gray Units in the vicinity of Well 24G1 (Cross Section ZC in Figure 6-1) is gravel-on-gravel that appears to be only a localized erosion of the underlying lacustrine deposits and only represents a relatively small 'hole' between the units.

6.2.2 Hydrostratigraphic Interpretation

For this project Zone 7 extended its network of cross sections (Figure 3-1) south to help identify if and how water from future Lakes C and D will migrate to the lower aquifers from which Zone 7 pumps. Zone 7 evaluated the e-logs, historical groundwater fluctuations (Figure 4-1), and groundwater level responses during the pumping test (Figure 4-2, Figure 4-3, and discussed in Section 4.4) to create the hydrostratigraphic interpretation shown on Figure 6-1 (Cross Sections ZA to ZC) and Figure 6-2 (Cross Section ZD).

The subsurface materials encountered in the study area correlate well with those encountered to the north. The cross sections show that the lacustrine deposits at the top of the Gray, Purple, and Red Units appear to thin and, in at least one case, are non-existent (e.g., between the Cyan and Gray Units) to the south and east of the mining area. The fine-grained overbank deposits within the Cyan, Gray, and Purple Units, also appear to thin and/or have been completely eroded to the south and east. The thicknesses of the units also decrease to the south and west. This suggests that these units were deposited under higher-energy flows, probably representative of proximal alluvial fan deposits.

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7 Conclusions

7.1 Summary of Findings

The results of this study are summarized as follows:

- The subsurface materials encountered in the study area correlate well with those encountered to the north. The cross sections prepared for this study show that the ‘Sequences’ defined by Norfleet, and herein referred to as ‘Units’ (from shallowest to deepest: Cyan, Gray, Purple, Red), appear to extend and thin to the south and west. This is consistent with Zone 7’s and Norfleet’s interpretation that the study area represents a proximal (upstream) area of the alluvial fan deposits that comprise the Main Basin.
- Historically, water levels in deeper wells respond more significantly than shallower wells to pumping from nearby supply wells, presumably because the majority of the large scale pumping is from the deeper aquifers (Purple and Red Units). Also, vertical groundwater gradients are typically downward (i.e., water moves from the upper units down to the lower units, from the Cyan to Gray, Purple, and Red), especially when more groundwater is pumped (for example, during the drier summer months). However in portions of the study area, the gradient appears to be upward from the lower units toward the middle units (from Red to Purple in the 19D wellset or from Purple to Gray in the new 13D wellset). This is likely because pumping from nearby wells is preferentially extracting water from the middle units (Purple or Gray, respectively).
- Pumping from Well 14J3 (screened in the Purple and Red Units) showed a response in Well 14J1 (Cyan and Gray Units) and Well 13P6 (Gray Unit), even though they are screened in different units. However, only a slight response was observed in Well 13P7 which is screened in the one of the same units (Purple Unit). The reason for this is unclear, but there may be three possible explanations:
 1. Wells 14J1, 14J3, and 13P6 are actually screened in the Purple Unit, while Well 13P7 is screened in the Red Unit. While this may be possible, the geophysical signatures of Wells 14J1 and 14J3 strongly suggest that a fine-grained unit (presumably one aquitard) is continuous between and separates the perforated interval of Wells 14J1 and 14J3.
 2. The boundary between the Gray and Purple Units does not provide much of a hydrostratigraphic flow boundary, in combination with the possibility that Well 13P7 was not developed sufficiently to be communicating adequately with the Purple Unit. There were some difficulties developing Well 13P7 and, when the water quality results are plotted on a Trilinear Piper Diagram, Well 13P7 plots different from that of other Purple Unit wells in the

study area. This suggests that perhaps this well is not yielding water representative of the surrounding unit, in which case it may need to be developed further, or it was not completed in the Purple Unit.

3. The majority of the water entering Well 14J3 during its pumping was from the Gray unit. While this initially seems unlikely because of the depths of its perforations, the filter pack in this well does extend up to 80 ft bgs (into the Gray and Cyan Units). Since water levels in nearby Well 14J1 (Gray Unit) responded immediately to the pumping in Well 14J3 (and vice versa) the communication between them seems to be greater than that of a leaky aquitard.
- During the pumping test, water levels in several wells dropped due to the pumping from Well 14J3, but then started to rise about 20 hours into the 24 hour test. This may be a response to the cessation of pumping from Zone 7's COL 2 well, north of the study area.
 - The boundary between the Cyan and Gray Units appears to be less of a hydrostratigraphic flow boundary in the study area than it is to the north. This is evident by the fact that water levels in Wells 19D7 (Cyan) and 19D8 (Gray) tracked so closely together (Figure 4-1), but those in Wells 11G1 (Cyan) and 11G2 (Gray) to the north do not. This is likely because the aquitard between these units is thinner and/or was completely eroded during deposition (e.g., the interpreted 'hole' in the aquitard in Cross Section ZC, Figure 6-1) in the southern portion of the study area.
 - The transmissivity and storativity calculated from the pumping test results were about 4,600 ft²/d and 0.0007 (unit-less), respectively. However, the water level response in the new nested wellset does not clearly indicate which aquifer unit(s) (Gray, Purple, and/or Red) were pumped. Using the 280-ft upper and 70-ft lower limits for aquifer thickness, hydraulic conductivity is calculated to be 16 to 66 ft/d. This is representative of a well-sorted sand to well-sorted gravel, which is consistent with the materials encountered during drilling.
 - Water quality data collected from the study wells suggests that there are no obvious or distinct water quality characteristics or signature that clearly distinguishes each of the units. This suggests that there is either mixing between the units or that the source water is the same for each of the units. The reason for the higher percentage of sodium in Wells 13P7 (Purple) and 12H7 (Red), however, is unknown; but will be further evaluated as part of Zone 7 Groundwater Monitoring program as additional results are available.
 - The aquitards (both lacustrine and overbank deposits) that act as vertical flow boundaries appear to thin or are completely eroded to the south and east of the study area. This is true for both the lacustrine deposits that act as boundaries between the aquifer units and the overbank 'stringer' deposits within the aquifer. The tables below show the thicknesses of these aquitards relative to those underneath Lake I to the northwest of the study area.

**Table 7-1
Comparison of Aquitard Thickness
Between Aquifer Units**

Boundary Between	Aquitard Thickness (ft)	
	Lake I Area	Lakes C/D Area
Cyan/Gray	20-30	0-10
Gray/Purple	40-60	15-25
Purple/Red	10-20	10-20

**Table 7-2
Total Thickness of Aquitard Materials
in Aquifer Units (including boundaries between units)**

Within Unit	Aquitard Thickness (ft)	
	Lake I Area	Lakes C/D Area
Cyan	0	0
Gray	50-55	0-5
Purple	65-115	10-45
Red	60-65	50-130

7.2 Lakes C and D as Recharge Ponds

The results of this study suggest that Lakes C and D can be effective recharge ponds, especially for recharging water into the upper portion of the Lower Aquifer (i.e., into the Gray Unit) because:

- The planned excavation depths of Lakes C and D span the entire Cyan Unit and into the upper portion of the Gray Unit,
- That the aquitard between the Upper and Lower Aquifers (the Cyan and Gray Units) is relatively thin to non-existent (0 to 10 ft thick) in the Lakes C and D area, and
- The aquifers appear to consist of mostly coarse-grained materials that would transmit water freely vertically.

While the aquitards between the Gray and Purple Units and the Purple and Red Units appear to be more pronounced than the aquitard between the Cyan and Gray Units; their total thicknesses are relatively thin, especially when compared to the stratigraphy below Lake I. Therefore, water discharged to Lakes C and D would migrate more freely to the Purple and Red Units, from which many of Zone 7's supply wells are pumping, than water discharged to Lake I. There was some evidence that the Gray and Purple Units were in communication during the pumping tests, although the pathway between them is not fully understood.

The downside to using Lakes C and D as recharge ponds, however, is that Zone 7 won't be able to use them until after mining ceases in 2030, or later.

7.3 Recommendations

While the evidence collected for this study suggests that Lakes C and D can be effective recharge ponds, especially when compared to Lake I; Zone 7 recommends the following actions or future studies:

- Continue to monitor the new nested wellset for water levels (at least semi-annually) and water quality (annually) as part of Zone 7's existing groundwater monitoring program. These results will be incorporated and further evaluated as part of Zone 7's Annual Reports for the Groundwater Management Program.
- Continue to modify and add to the network of cross sections as more data (especially e-logs from new borings drilled in the Main Basin and water level data in the new nested wellset) becomes available.
- Incorporate this data into Zone 7's groundwater model. This may include adding additional layers to the model that correspond with each of the aquifer units and boundary aquitards.
- Coordinate and plan with the mining companies so mining operators can be aware of and accommodate Zone 7's needs. Also, Zone 7 staff should work with mining operators to confirm that the materials excavated for Lakes C and D are consistent with the interpretations of this study.
- A follow-up pumping test may provide additional evidence regarding the connectivity of the aquifer units. This test could include using a more powerful pump in CEMEX Well 14J3, extending the test for longer than 24 hours, or using the existing pump in Well 14J1 if the pumping rate can be measured and held constant. This test could also include a fluid-entry survey in Well 14J3 to assess why a response was observed in Wells 14J1 and 13P6, which are screened in the units above those in which 14J3 is screened, during this study's pumping test; but not in Well 13P7 or 13P8, both of which are screened in the same units that Well 14J3 is screened.
- Ultimately, conduct tracer tests to verify the path and speed of recharge water as it migrates both vertically and laterally through and between the aquifers.

8 Sources of Information

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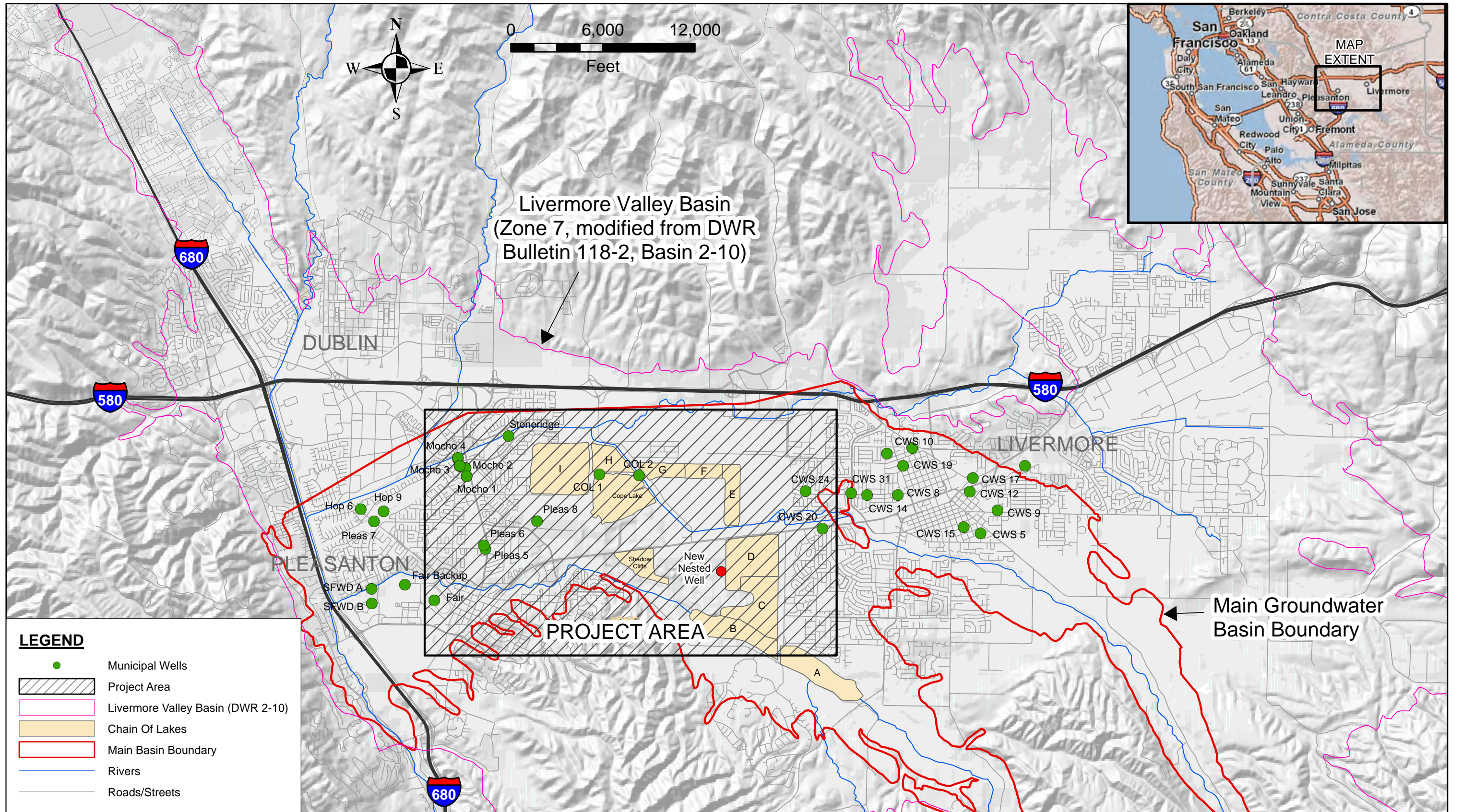
_____. *2005a. Groundwater Management Plan. Prepared by Jones & Stokes and Zone 7 Water Agency.*

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Figures

- Figure 2-1: Groundwater Basin Map
- Figure 3-1: Locations of Wells and Cross Sections
- Figure 3-2: Borehole Log for 3S/1E 13P 9
- Figure 3-3: As-Built Well Construction Log for 3S/1E 13P 5 to 8
- Figure 4-1: Historical Water Elevation Graphs in Study Wells
- Figure 4-2: Water Level Graphs in Pumping Test Wells (December 9 to 21)
- Figure 4-3: Water Level Graphs in 13P Nested Wellset (December 9 to 21)
- Figure 4-4: Pumping Test Calculations for Observation Well 3S/1E 13P 6
- Figure 5-1: Chemistry Results for Groundwater Samples
- Figure 5-2: Trilinear Piper Diagram Recent Samples from Study Wells
- Figure 6-1: Cross Sections ZA to ZC
- Figure 6-2: Cross Section ZD

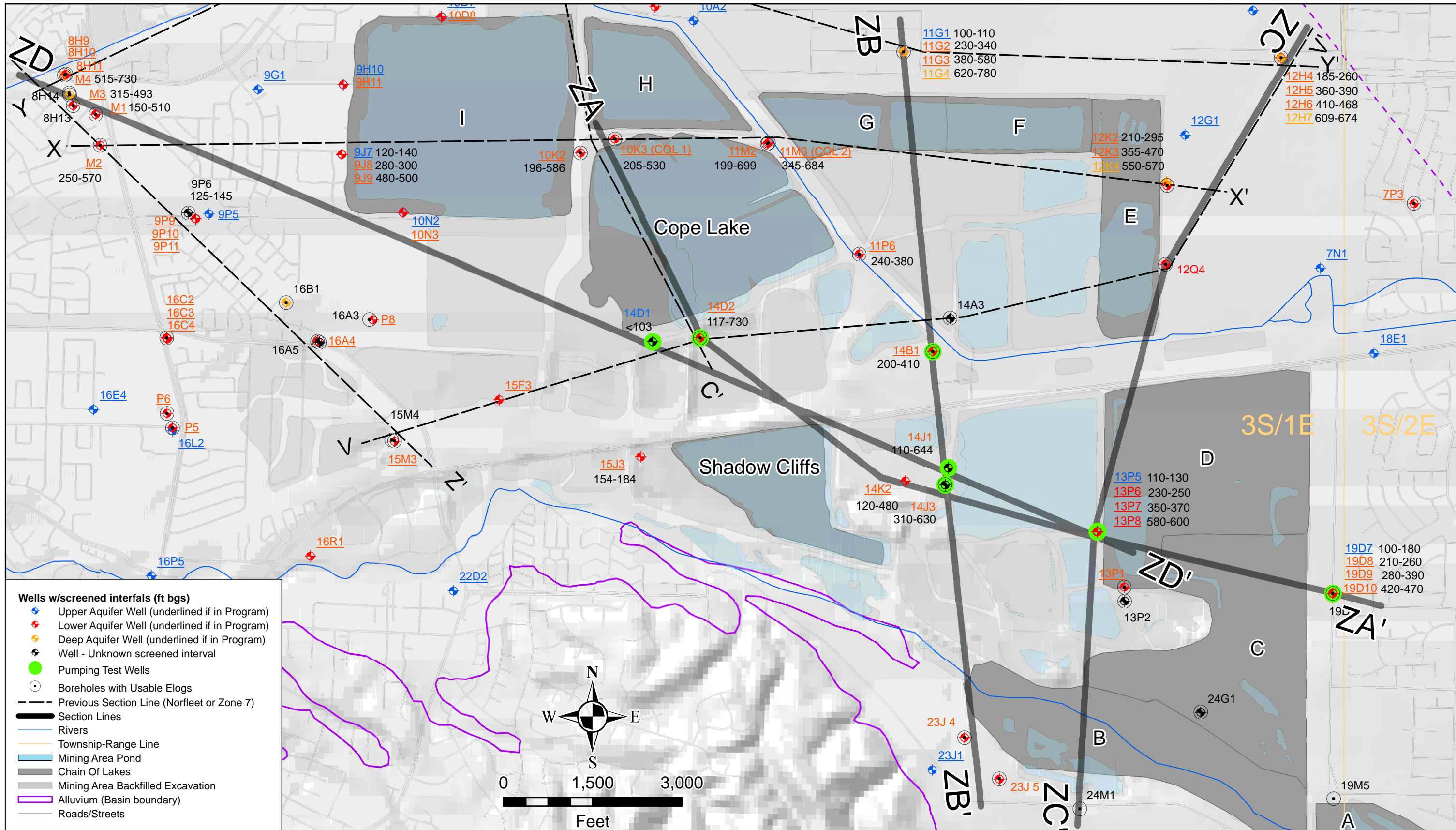


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100 North Canyons Parkway
Livermore, CA

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REVIEWED: TR
FILE: E:\PROJECTS\LGAGrantGWStudy2010\Report\Figures\Fig2-1-BasinProjectArea.mxd

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DATE: Apr 14, 2011

FIGURE 2-1
Livermore Valley Groundwater Basin and Project Area

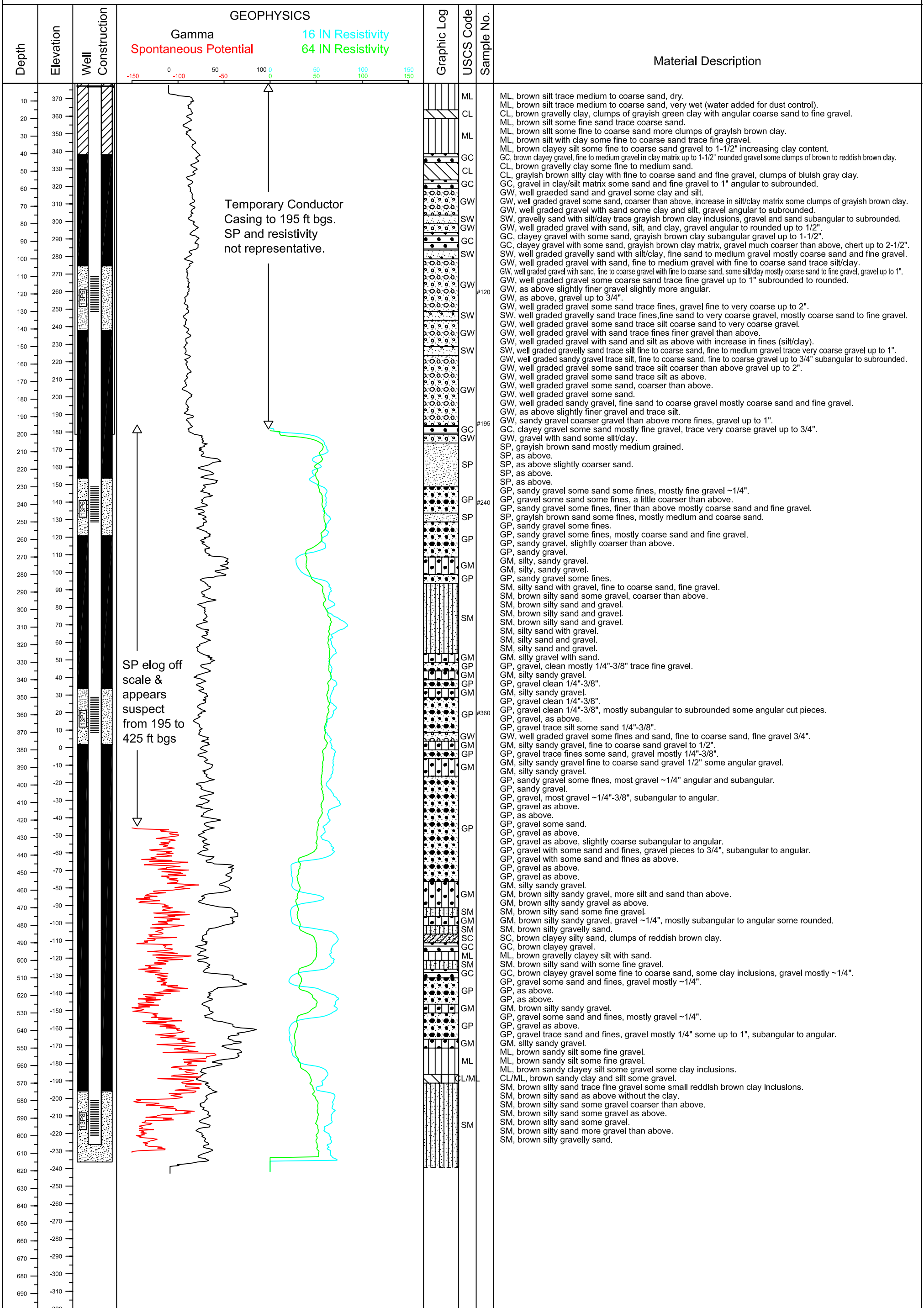


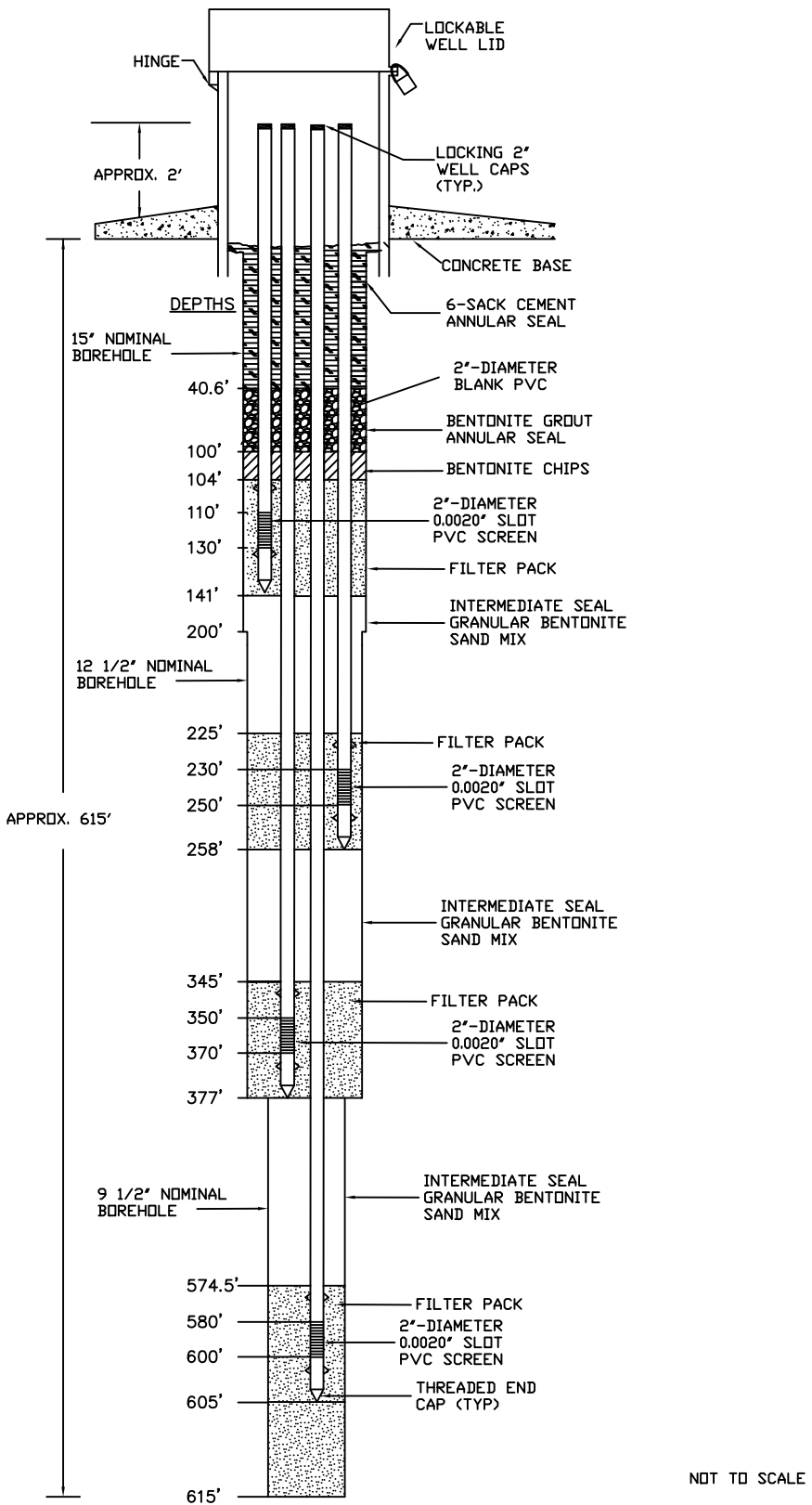
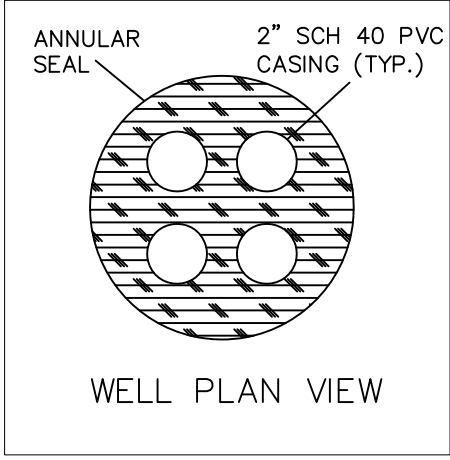
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 100 North Canyons Parkway
 Livermore, CA

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REVIEWED: TR, MK	DATE: Apr 11, 2011
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Figure 3-1
Locations of Wells and Cross Sections
Hydrostratigraphic Investigation Lakes C/D

Site Id: 3S/1E 13P 5-8	Date(s): 10/18/10 - 11/02/10	Borehole Dia.: 15, 12, and 9.75 in	Completed Depth: 605.00'
Alias: Borehole for 13P Nested Wells	Contractor: CASCADE DRILLING	Measuring Point: 0.00'	Total Depth: 618.00'
Location: CEMEX - West of Future Lake D	Drilling Method: MUD ROTARY / ARCH	Ground Elevation: 378.70'	Notes: 200' of temporary conductor casing was removed. Completed as four separate 2" wells: 13P5 to 13P8.
Coords (NAD83): 6180144.84, 2068351.84	Permit: 2010098	10/15/10	Logged By: Colleen Winey





6		
5		
4		
3		
2	As-Built	3/20
1	As-Built	3/8
REVISIONS		



ZONE 7 WATER AGENCY
 100 North Canyons Parkway
 Livermore, CA 94551

FIGURE 3-3
 As-Built Well Construction Log
 For 3S/1E 13P 5 to 8

DRAWN:	CDIZON
DESIGNED:	CDIZON
CHECKED:	TROOZE
APPROVED:	MKATEN
DATE:	03/08/2011
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	1 OF 1

FIGURE 4-1
Historical Groundwater Elevations (ft NGVD 88) in Study Wells

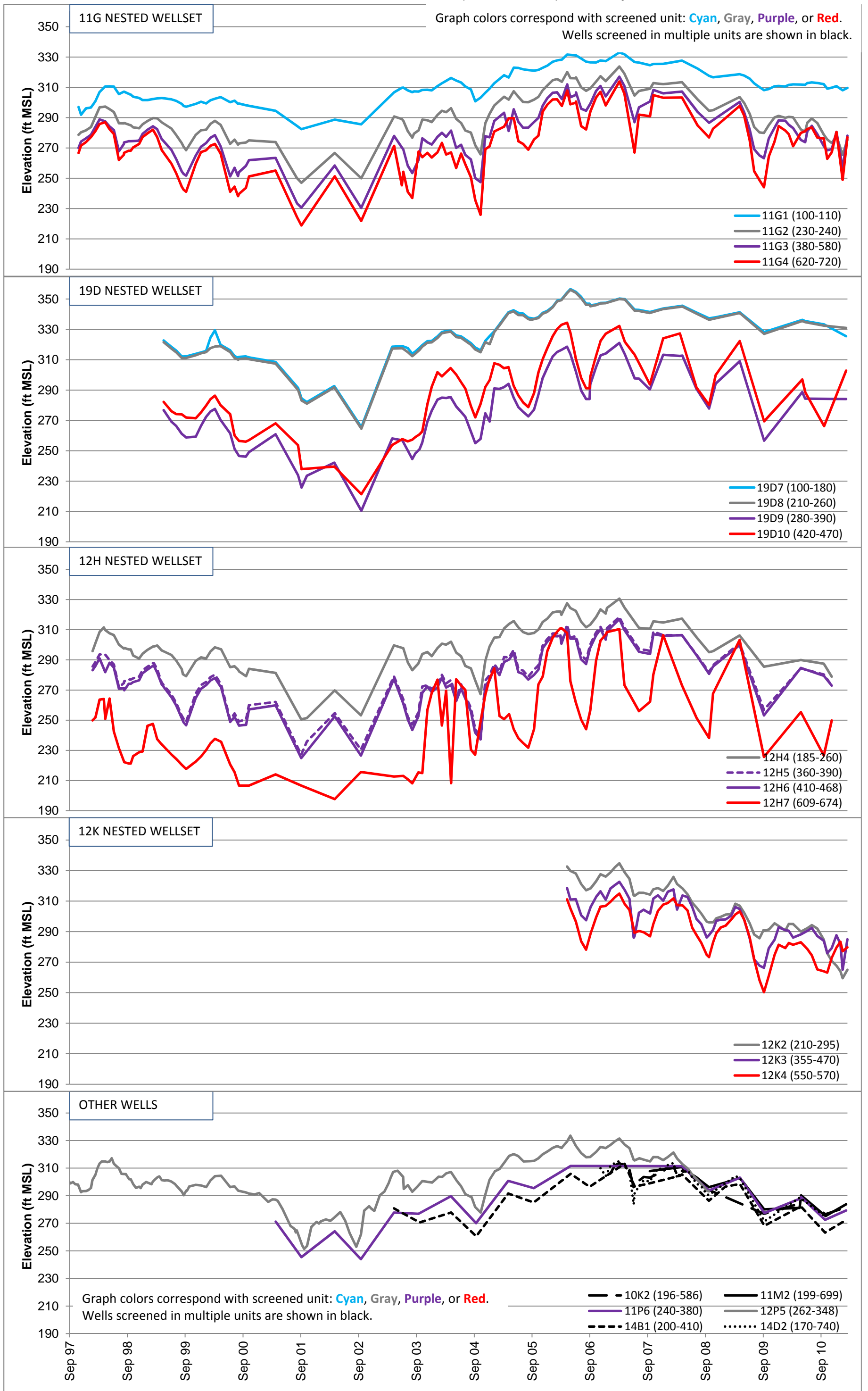


FIGURE 4-2
WATER LEVEL GRAPHS IN PUMPING TEST WELLS (Dec 9 to 21, 2010)

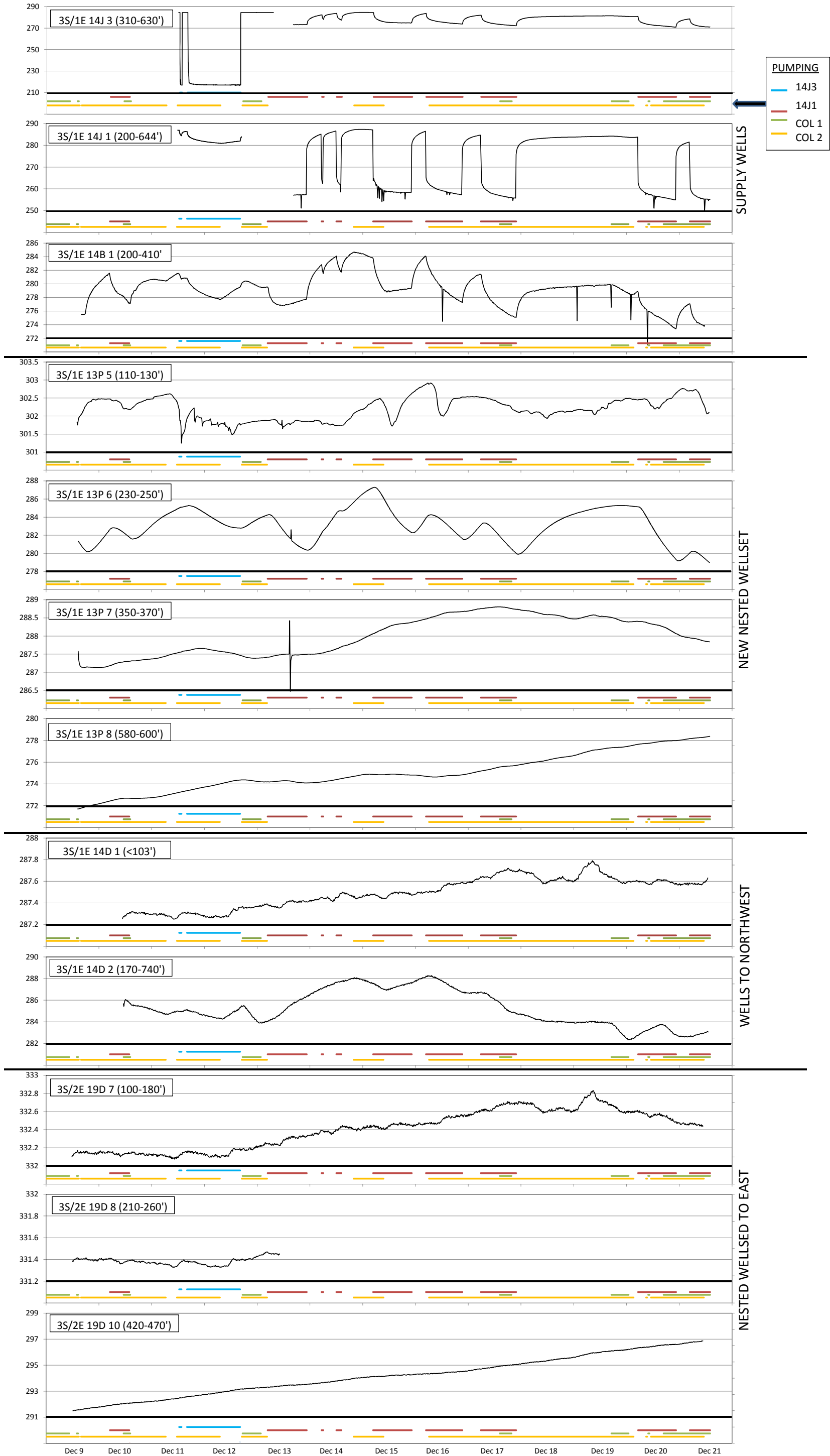
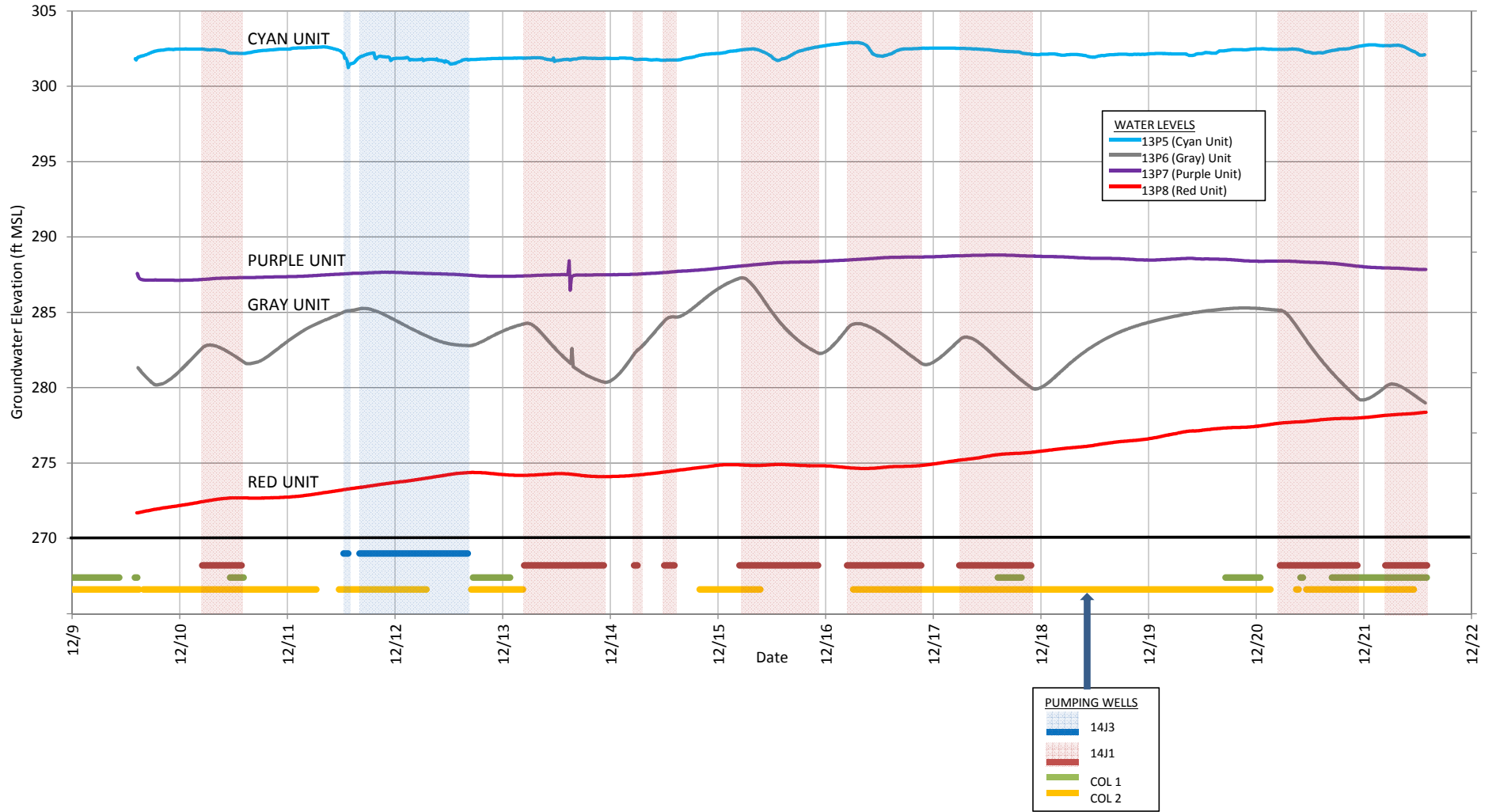
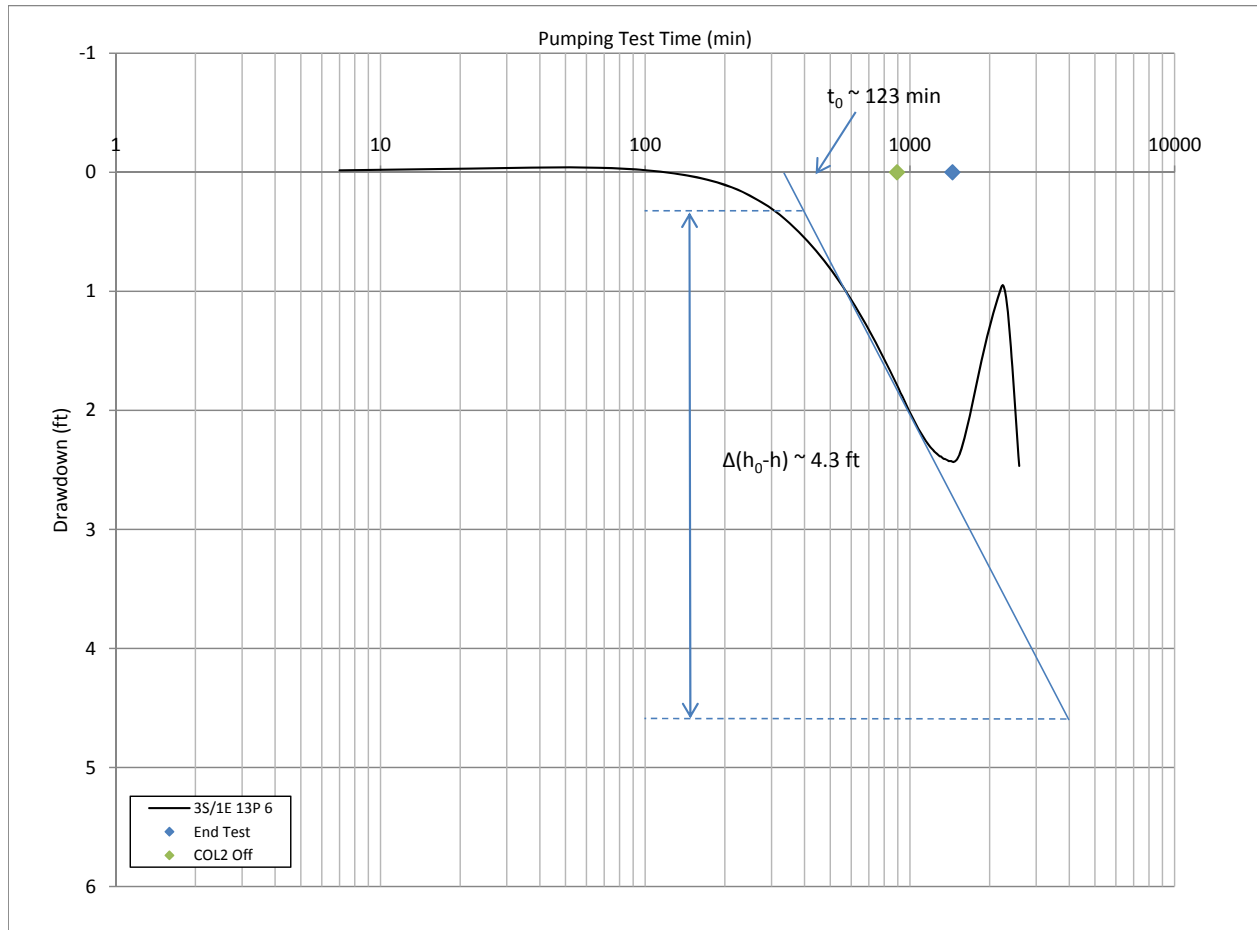


FIGURE 4-3
 Water Level Graphs for 13P Nested Wellset
 (Dec 9 to 21, 2011)



Note: Spikes on 12/13 due to transducer maintenance.

FIGURE 4-4
Pumping Test Calculations for Observation Well 3S/1E 13P 6



$$T = \frac{2.3Q}{4\pi\Delta(h_0-h)} = \frac{2.3(500 \text{ gpm})}{4\pi(4.3 \text{ ft})} = 21 \text{ gpm/ft} \times \frac{1440 \text{ gpd}}{1 \text{ gpm}} = 30,647 \text{ gpd/ft} \times \frac{1337 \text{ ft}^3}{1 \text{ gal}} = 4097 \text{ ft}^2/\text{d}$$

$$S = \frac{2.5Tt_0}{r^2} = \frac{2.5(21 \text{ gpm/ft})(123 \text{ min})}{(2677 \text{ ft})^2} \times \frac{1 \text{ ft}^3}{7.481 \text{ g}} = 0.00012$$

$$K = \frac{T}{b} = \frac{30,647 \text{ gpd/ft}}{230 \text{ ft}} = 133 \text{ gpd/ft}^2 \times \frac{0.134 \text{ ft}^2/\text{d}}{1 \text{ gpd/ft}^2} = 17.9 \text{ ft/d}$$

Assumptions

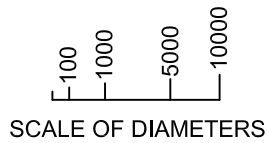
Drawdown rate would have been consistent if test was extended

**FIGURE 5-1
CHEMISTRY RESULTS FOR GROUNDWATER SAMPLES**

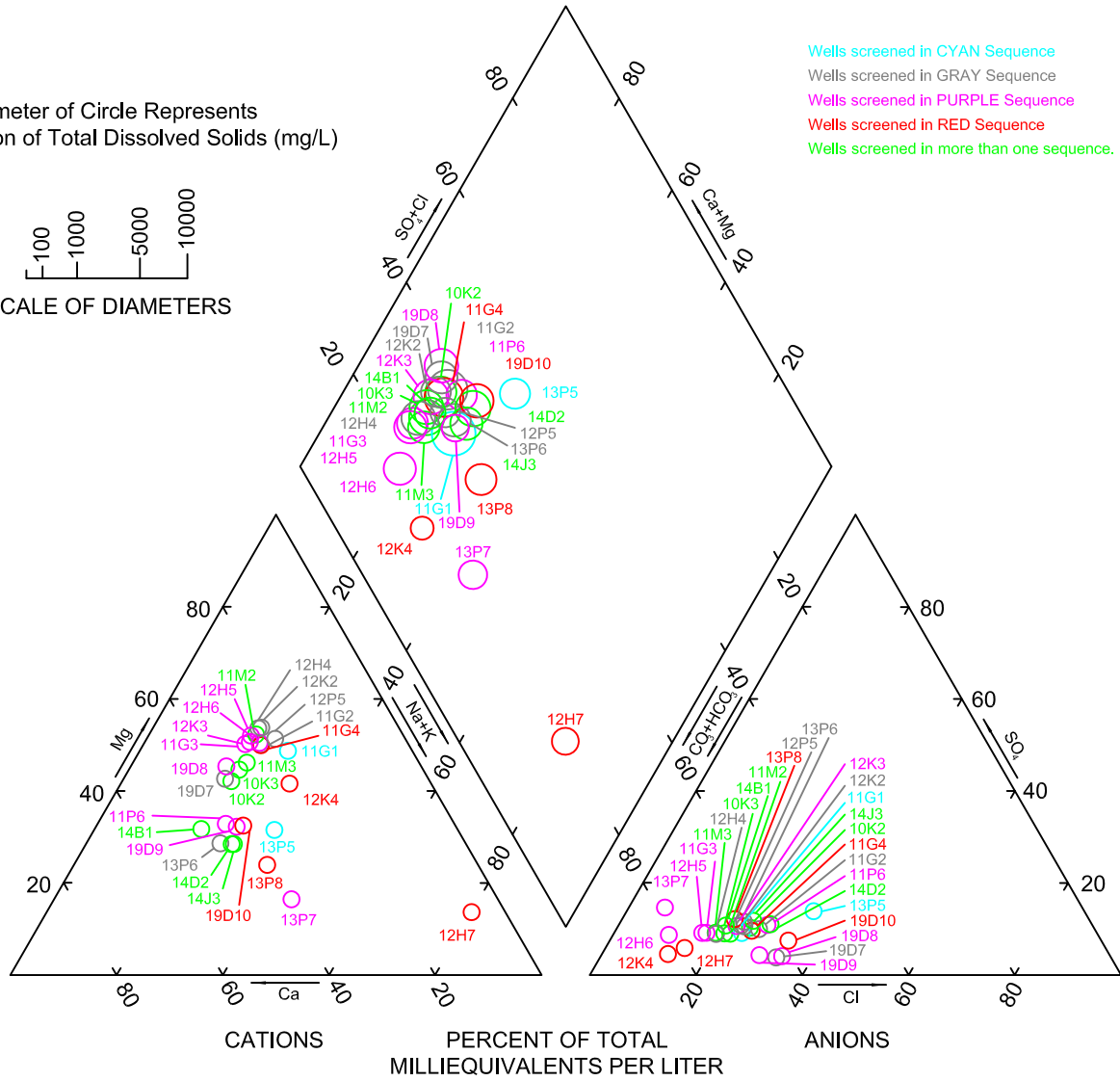
SITE ID	DATE	Field				Mineral Constituents (mg/L)											Select Metals (mg/L)				Principal		%	TDS		Calc Sum	Hard mg/L	TDS/EC	Cat Eq	An Eq	% Diff	
		GWE	T	EC	pH	Lab	EC	pH	Ca	Mg	Na	K	HCO3	SO4	Cl	NO3	SiO2	B	As	Fe	Mn	Cat		An	mg/L							ROE
3S/1E 13P 5	14-Feb-11	301.76	18.0	680	7.3	ZONE7	651	7.4	46	24	45	1.4	175	46	86	0.53	14.4	0.35	<0.001	<0.05	<0.01	Ca	HCO3	15%	350	354	349	213	0.54	1.88	5.04	0.46
3S/1E 13P 6	14-Feb-11	274.69	18.8	762	7.3	ZONE7	738	7.3	72	26	39	1.8	269	46	68	3.90	20.7	0.30	<0.001	0.099	0.032	Ca	HCO3	10%	410	410	410	288	0.56	2.25	6.34	0.48
3S/1E 13P 7	14-Feb-11	280.7	19.1	561	7.6	ZONE7	536	7.6	44	11	54	1.8	244	44	15	0.58	22.3	0.19	<0.001	0.49	0.057	Na	HCO3	18%	314	321	313	156	0.59	1.79	4.98	0.47
3S/1E 13P 8	14-Feb-11	252.85	19.6	677	7.4	ZONE7	643	7.4	54	19	51	2.0	239	42	54	4.56	24.6	0.27	<0.001	0.12	0.069	Ca	HCO3	15%	369	351	369	211	0.57	2.03	5.57	0.47
3S/1E 14J 3	11-Dec-10	NM	18.4	697	7.1	ZONE7	712	7.9	64	25	49	2.0	218	57	94	4.16	17.8	0.39	<0.001	<0.05	0.013	Ca	HCO3	13%	422	394	420	264	0.59	2.26	6.12	0.46
3S/1E 14J 3	12-Dec-10	NM	16.9	668	7.1	ZONE7	683	7.8	66	25	42	1.8	250	45	70	8.50	20.3	0.35	<0.001	<0.05	<0.01	Ca	HCO3	12%	403	384	402	269	0.59	2.18	6.12	0.47
Field Parameter Doesn't Correspond to Lab Value																																
3S/1E 13P 5	21-Jan-11	301.48	20.4	696	8.5	ZONE7	646	7.6	50	27	48	1.7	173	47	91	0.71	15.3	0.41	<0.001	<0.05	<0.01	Ca	HCO3	15%	366	396	366	236	0.57	2.05	5.11	0.43
3S/1E 13P 6	21-Jan-11	277.94	19.5	1098	8.9	ZONE7	847	7.5	56	22	90	2.8	270	83	90	3.72	19.3	0.39	<0.001	0.17	0.13	Na	HCO3	20%	500	526	500	229	0.59	2.75	7.32	0.45
3S/1E 13P 7	21-Jan-11	279.41	19.1	690	8.6	ZONE7	613	7.6	32	10	103	2.3	253	72	26	0.66	19.9	0.30	<0.001	0.38	0.1	Na	HCO3	29%	391	399	390	120	0.64	2.38	5.76	0.42
3S/1E 13P 8	21-Jan-11	283.88	19.0	688	8.0	ZONE7	625	7.4	46	17	73	2.2	240	48	56	0.80	22.9	0.33	<0.001	<0.05	0.16	Na	HCO3	21%	385	411	384	183	0.62	2.23	5.65	0.43

GWE	Groundwater Elevation (in feet NGVD88)	Ca	Calcium	B	Boron	Cat	Cation	TDS	Total Dissolved Solids
EC	Specific Conductivity (in umhos/cm)	Mg	Magnesium	As	Arsenic	An	Anion	ROE	Residual on Evaporation
T	Temperature in °C	Na	Sodium	Fe	Iron			Hard	Hardness
pH	pH in standard units	K	Potassium	Mn	Manganese			Eq	Equivalent
NM	Not measured	HCO3	Bicarbonate					Diff	Difference
		SO4	Sulfate					Calc Sum	Calculated sum of TDS components
		Cl	Chloride						
		NO3	Nitrates						
		SiO2	Silica						
		mg/L	milligrams per liter						

Diameter of Circle Represents
Concentration of Total Dissolved Solids (mg/L)



- Wells screened in CYAN Sequence
- Wells screened in GRAY Sequence
- Wells screened in PURPLE Sequence
- Wells screened in RED Sequence
- Wells screened in more than one sequence.



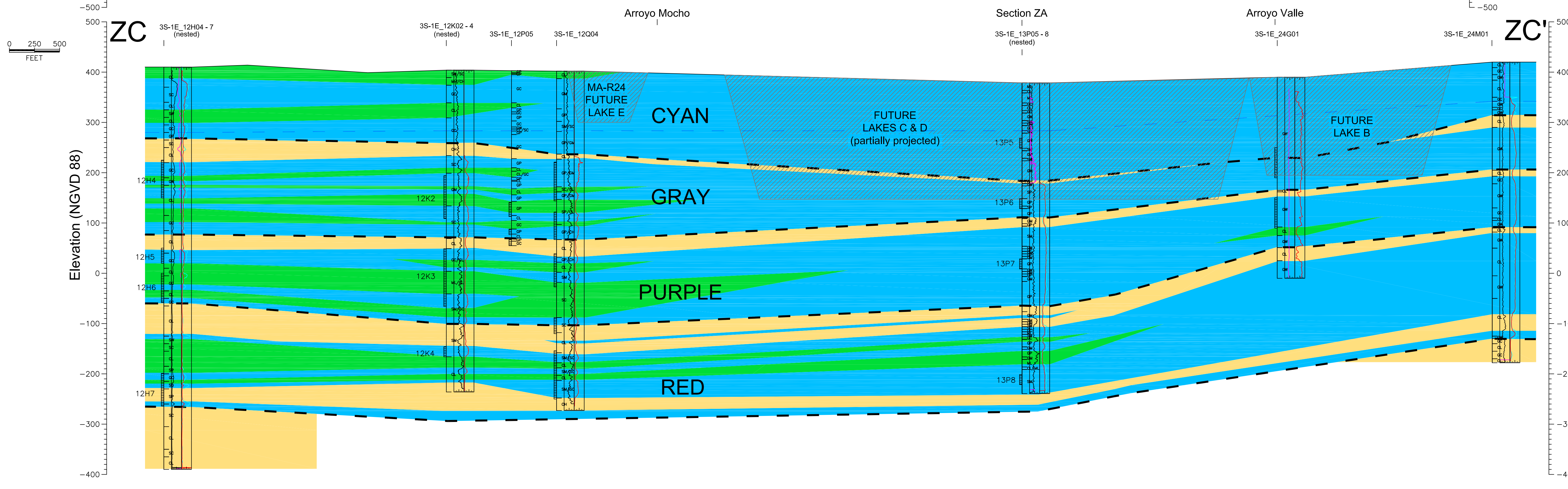
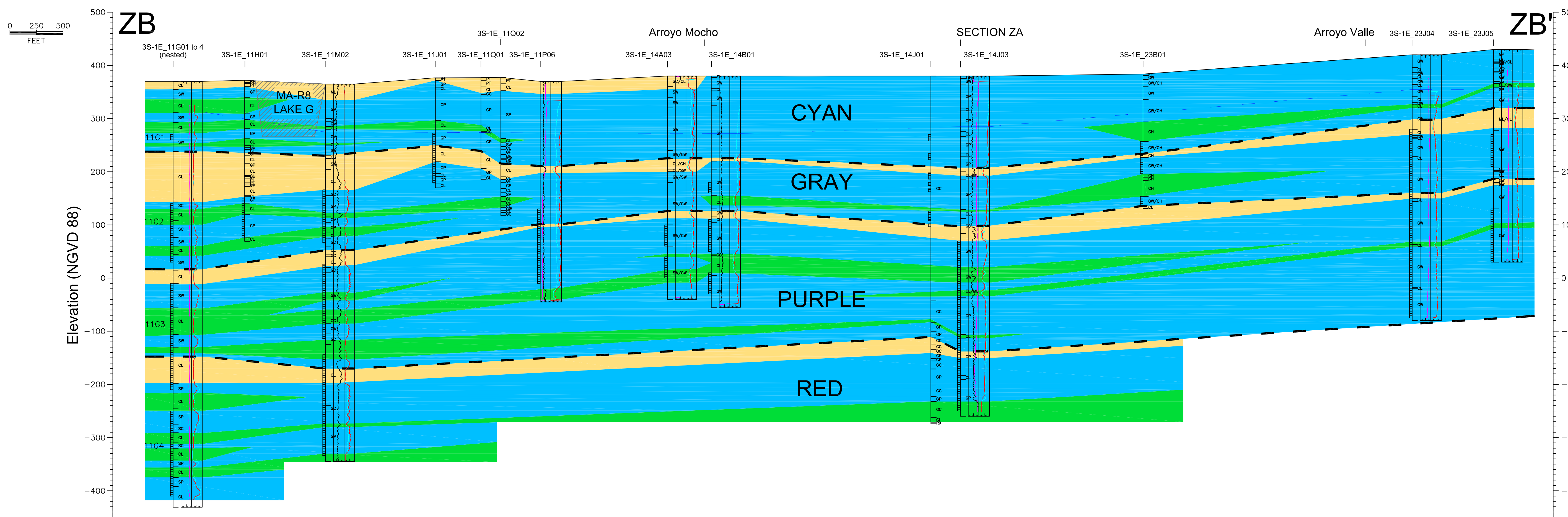
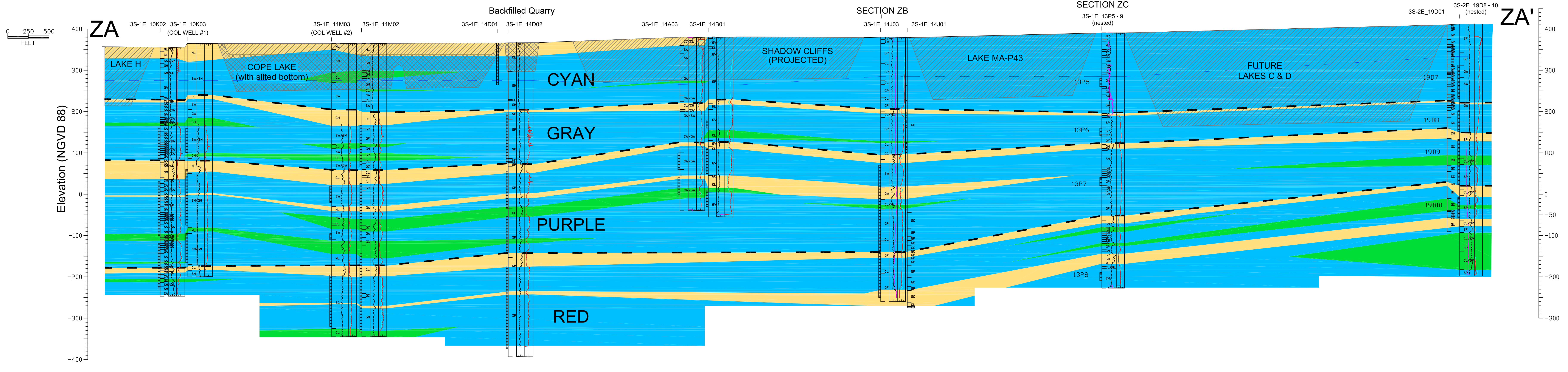
ZONE 7 WATER AGENCY
100 N. CANYONS PARKWAY
LIVERMORE, CA 94551

TRILINEAR PIPER DIAGRAM OF RECENT SAMPLES FROM STUDY WELLS

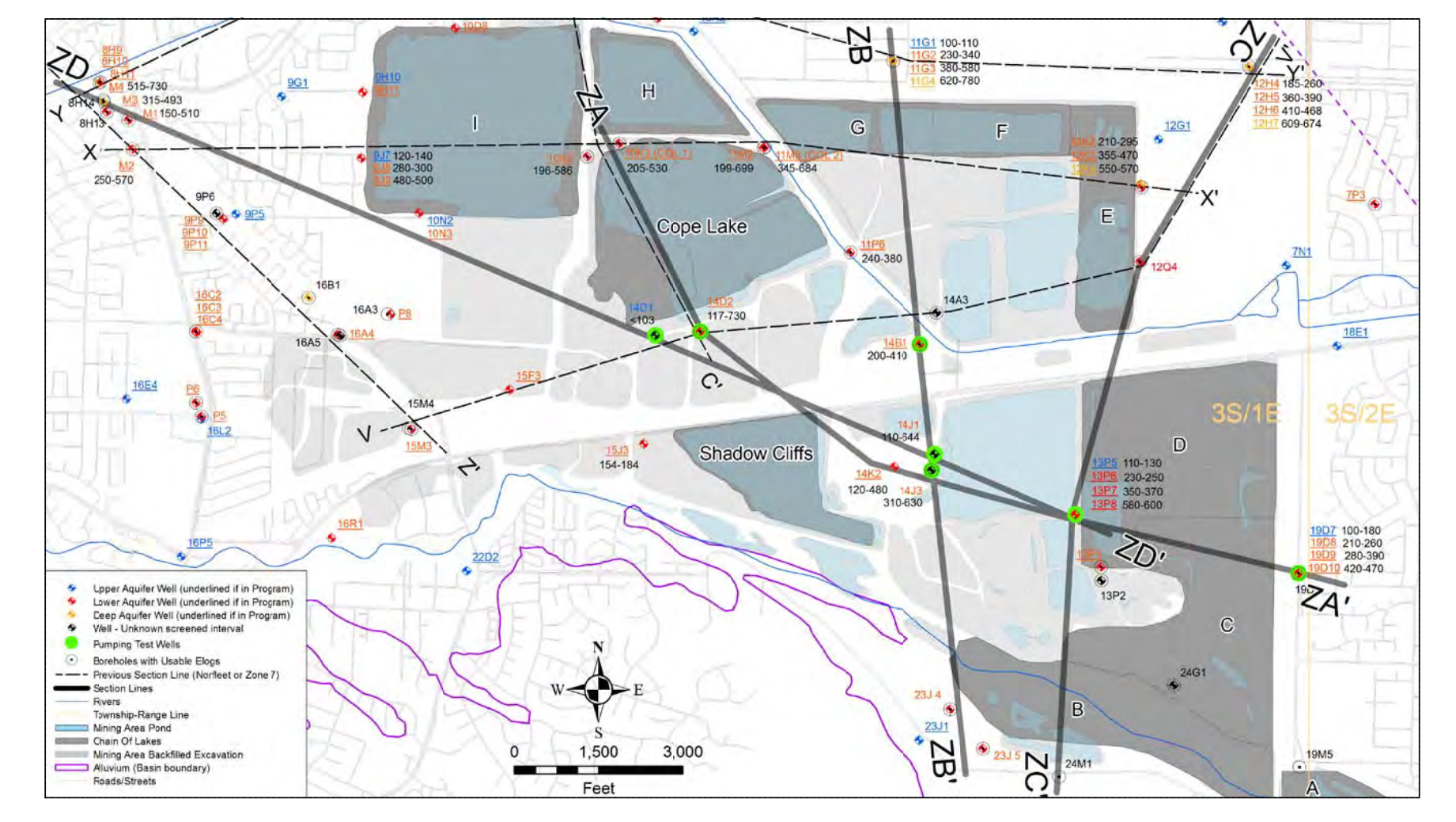
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Mar 20, 2011

Hydrostratigraphic Investigation of
Aquifer Recharge Potential of
Lakes C and D

FIGURE NO.:
5-2



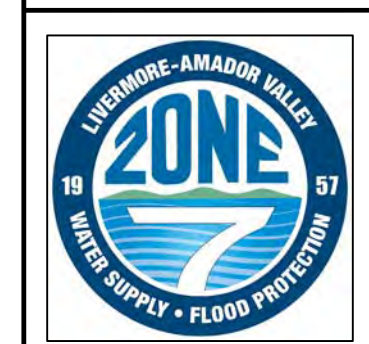
Locations of Cross Sections



LEGEND

GENERAL	GEOPHYSICS	SOIL UNITS
Unit Boundary	COLUMN 1	FE Fill
Well Screen Interval	Spontaneous Potential Log (50 to 50 MV)	CM: Clay / Silty Clay
Lucasine Deposits (equifer)	Gamma Ray Log (0 to 100 APR GR)	CL: Gravelly Clay/Sandy Clay/Silty Clay/Clay
Overbank Deposits (aquifer)		ML: Silty / Clayey Silt / Sandy Silt
Gravel/Sand Deposits (aquifer)	COLUMN 2	MS: Silty Clayey Silt
Water Level (Fall 2016)	16 Inch (Short) Normal Log (0 to 100 CHM-M)	SC: Yellow Clayey Sand
	64 Inch (Long) Normal Log (0 to 100 CHM-M)	SW: Gravelly Sand / Sand
		SP: Gravelly Sand / Sand
		GC: Orange Clayey Gravel
		GS: Silty Gravel
		GP: Gravel / Sandy Gravel
		GK: Gravel / Sandy Gravel

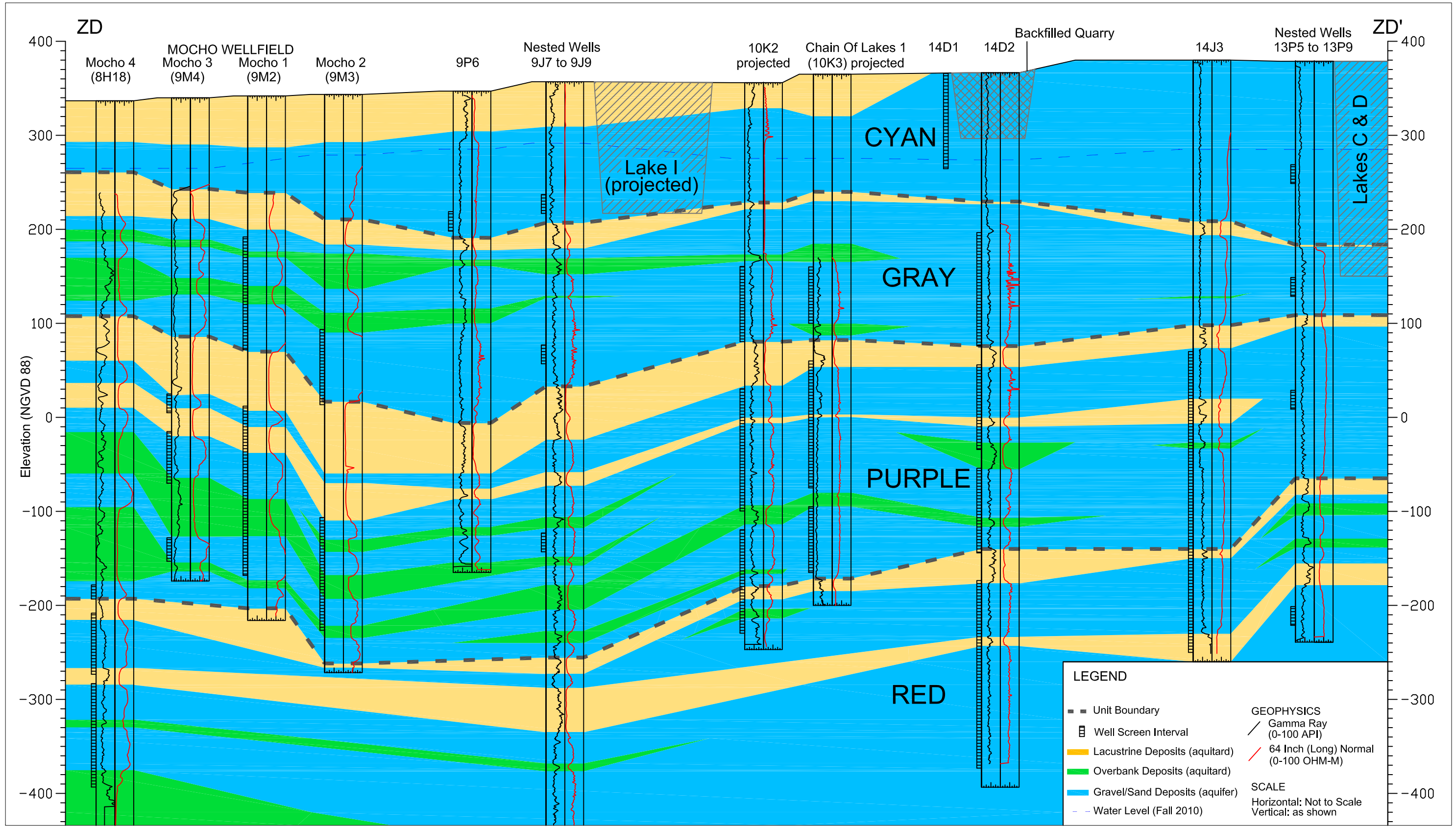
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 Vertical Exaggeration = 5



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Cross Sections ZA to ZC

PROJECT: Hydrostratigraphic Investigation of the Aquifer Recharge Potential For Lakes C and D
 FIGURE NO.: 6-1



ZONE 7 WATER AGENCY
100 NORTH CANYONS PKWY
LIVERMORE, CA 94551

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APPD:	MK

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FIGURE 6-2
CROSS SECTION ZD
Hydrostratigraphic Investigation for Lakes C and D