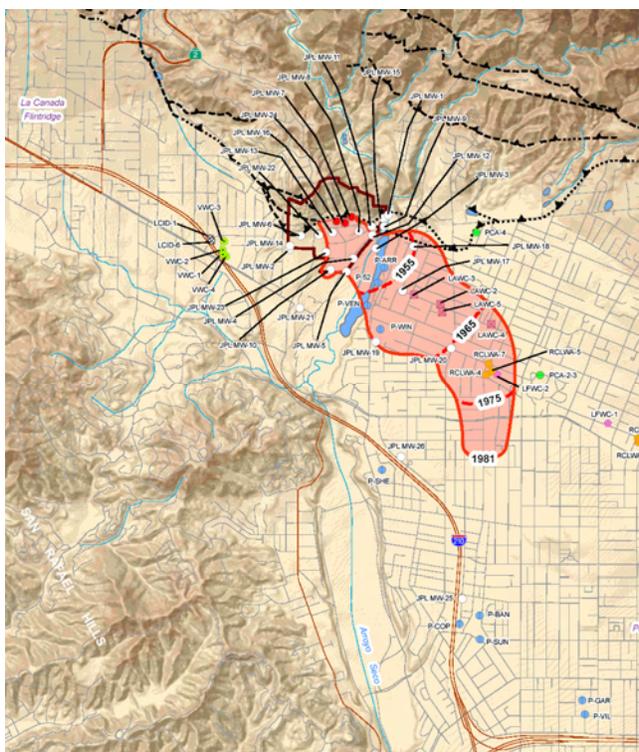


NASA / JPL Perchlorate Contamination of Ground Water in the Raymond Basin

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**NASA / JPL PERCHLORATE CONTAMINATION OF
GROUND WATER IN THE RAYMOND BASIN**

(VOLUME 1)

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NASA / JPL PERCHLORATE CONTAMINATION OF GROUND WATER IN THE RAYMOND BASIN

1.0 EXECUTIVE SUMMARY

The JPL facility was developed and operated by the United States Army between 1945 and 1957, with jurisdiction transferred to NASA in 1958. During that period of time, hazardous substances were disposed of within various “seepage pits” located throughout the property. The types of substances that were disposed of include various volatile organic compounds (VOCs), solid rocket fuel propellants (including perchlorate), cooling tower chemicals, sulfuric acid, Freon, mercury, and chemical laboratory wastes.

In 1990, significantly elevated levels of carbon tetrachloride, trichloroethene (TCE), tetrachlorethene (PCE), and other volatile organic compounds (VOCs) were detected in ground water both under and hydraulically downgradient of the facility. In the mid to late 1980s, four City of Pasadena wells in the Monk Hill subarea were shut down due to VOC contamination attributable to JPL (the Arroyo Well, Well 52, the Windsor Well, and the Ventura Well). Additionally, two Lincoln Avenue Water Company wells (Well No. 3 and Well No. 5) were shut down in 1987 due to VOCs attributable to JPL.

Prior to 1997, perchlorate had not been detected at low concentrations in ground water anywhere in the United States because an appropriate analytical method did not yet exist. In 1997, an improved perchlorate detection method was developed that was sensitive to four micrograms per liter ($\mu\text{g/L}$). Since that time, perchlorate has been detected in ground water in the Monk Hill subarea and portions of the Pasadena subarea. In the Pasadena subarea, there is a group of five wells near the Sunset Reservoir (Sunset, Bangham, Copelin, Villa, and Garfield) that have also been impacted by perchlorate.

A technical memorandum (TM) was issued by NASA in 2007 that investigated the downgradient (southern) extent of chemicals originating from the JPL facility and it evaluated if the occurrence of perchlorate in the Sunset Reservoir area ground water was associated with migration from the JPL facility. The NASA TM concluded that:

“...(1) the chemicals from the JPL facility are contained within the Monk Hill Subarea, and, (2) the perchlorate detected at the Sunset area wells is of a different origin than that used at, and originating from, JPL”

Furthermore, the 2007 NASA TM concluded that:

“The lack of biodegradation <in the study area> implies that the differences in isotopic composition between JPL perchlorate and the perchlorate in the Sunset, Bangham, and Garfield wells is not caused by biodegradation but is likely to reflect the presence of multiple, isotopically distinct sources of perchlorate in the Raymond Basin”

The purpose of this investigation was to:

1. Further evaluate the fate and transport of perchlorate contamination from NASA’s JPL facility;
2. Assess impacts to the City of Pasadena’s municipal water supply wells, specifically the Sunset Reservoir area wells; and
3. Provide a critical evaluation of the stable perchlorate isotope data presented in NASA’s 2007 Technical Memorandum and evaluate the implication of perchlorate source in the City of Pasadena’s Sunset Reservoir area wells.

The scope of work performed during this investigation included the following:

- Update of the Raymond Basin Management Board (RBMB) ground water model from 2002 to 2008;

- Estimation of a 1981 perchlorate plume front to facilitate particle tracking;
- Additional ground water modeling to evaluate perchlorate movement from/to JPL to the City's Sunset Reservoir area wells;
- Evaluation of JPL's methods and procedures for water quality sampling;
- Review of historical ground water quality data for conditions favorable to biodegradation of perchlorate;
- Critical analysis of the functional genomics testing asserted in NASA's 2007 TM;
- Analysis of isotopic signature shift due to perchlorate biodegradation;
- Analysis of isotopic signature shift due to mixing of multiple perchlorate sources; and
- Analysis of statistical significance of perchlorate isotope data set.

1.1 Raymond Basin Ground Water Model

In 2005, a ground water flow model was developed for the unconsolidated sediments of the entire Raymond Basin area, including a portion of the Main San Gabriel Basin. Since the model was prepared for the RBMB, it is referred to as the RBMB Model (GEOSCIENCE, 2005).

For purposes of this evaluation, the RBMB ground water flow model was updated from 2002 to 2008 to include the updated geohydrologic data. The updated RBMB ground water model was used to perform particle tracking on perchlorate movement from the JPL area. Specifically, this evaluation consisted of the following three tasks:

1. Forward tracking from 1981 to 2008 to assess the movement of perchlorate from the JPL area to the downgradient City of Pasadena Sunset Reservoir well field area;
2. Reverse particle tracking from the Sunset Reservoir area wells (2008 to 1981); and
3. Reverse tracking from the deep well screens (i.e., Screens 4 and 5) in monitoring well JPL MW-20.

Forward tracking was simulated using particles released at the January 1, 1981 boundary of the estimated extent of perchlorate contamination. The purpose of the forward particle tracking was

to evaluate the possibility that advective flow of perchlorate from JPL would reach City of Pasadena's Sunset Reservoir area wells. Particles released from the 1981 estimated extent of perchlorate contamination travel to the southeast in the direction of regional ground water flow.

Particles released at the northwestern portion of the January 1, 1981 estimated extent of perchlorate contamination were captured by the Bangham and Sunset wells (P-BAN and P-SUN) by 1996 and by the Garfield and Villa wells (P-GAR and P-VIL) by 2003. Particles released at the southwestern portion of the January 1, 1981 estimated extent of perchlorate contamination were captured by wells P-BAN and P-SUN by 1987 and by wells P-GAR and P-VIL by 1998. It should be noted that particle tracking does not account for hydrodynamic dispersion which results in a "spreading out" of plumes. As such, particle tracking results in a conservative footprints of contamination. This likely accounts for the fact that the particle tracks are not captured by the Copelin well (P-COP).

Backward (i.e., reverse) particle-tracking was simulated by releasing particles at the City of Pasadena Sunset Reservoir wells and JPL MW-20 on December 31, 2008. The purpose of the backward tracking was to delineate the source of recharge to both the Sunset Reservoir area wells and the deep well screens (i.e., Screens 4 and 5) of JPL MW-20.

Particles released at the Sunset Reservoir area wells P-BAN, P-SUN, P-COP on December 31, 2008 backward track to the JPL area in approximately 17 years (i.e., by 1992). Backward tracking particles from wells P-GAR and P-VIL do not reach the JPL area over the model period (i.e., January 1, 1981 through December 31, 2008). However, particles from P-GAR and P-VIL do intersect the estimated 1981 plume boundary in approximately 16 to 28 years. Based on the results of backward particle tracking from the Sunset Reservoir area wells, it is likely that the source of perchlorate in those wells is from the JPL area.

Particles released within the deep screen (i.e., screens 4 and 5) of JPL MW-20 backward track to the JPL area in 17 years (i.e., by 1992). This verifies that the source of perchlorate detected within the deep screens of JPL MW-20 is the JPL area.

1.2 Evaluation of Stable Perchlorate Isotope Data

The 2007 NASA TM reported stable perchlorate isotope ratios, which were measured from monitoring wells and production wells in the eastern portion of the Raymond Basin. Stable isotope ratios are reported in δ notation (i.e., “delta”), which represents the difference in measurements between a reference standard and the measured sample. Positive δ values result when the measured sample contains more of the heavy isotope than the standard sample. Negative δ values result when the sample measured contains less of the heavy isotopes than the standard sample. Stable isotope ratios may be measured for chlorine ($^{37}\text{Cl}/^{35}\text{Cl}$) and oxygen ($^{18}\text{O}/^{17}\text{O}/^{16}\text{O}$) contained in the perchlorate molecule.

Several studies have evaluated stable perchlorate isotope ratio analysis as a forensic tool for determining the source of perchlorate (i.e., natural or synthetic) in perchlorate-contaminated ground water¹. Measuring stable isotope ratios of chlorine and oxygen has been used to distinguish the origin of perchlorate from the following sources²:

1. Naturally-occurring perchlorate and nitrate salts found in deposits and fertilizers manufactured from natural salts;
2. Synthetic perchlorate, which is produced through electrolytic oxidation of chloride solutions (i.e., “man made”).

Perchlorate from natural and synthetic sources may biodegrade in soil and ground water under reducing conditions and in the presence of a suitable electron donor. (Sturchio et al., 2007, Coates and Achenbach, 2004, Coleman et al., 2003). Perchlorate biodegradation reduces chlorine contained in perchlorate to a chloride end product. A diverse group of microorganisms capable of reducing perchlorate are ubiquitous in soil and ground water. Therefore, biological reduction of perchlorate will usually occur in soil and ground water under the following conditions:

¹ Bao and Gu (2004); Sturchio et al. (2006)

² Bao and Gu (2004)

1. An electron donor source is present and;
2. Preferential electron acceptors—oxygen and usually nitrate—are first depleted.

Several studies have shown that perchlorate isotopic composition changes when biodegradation occurs (Sturchio et al., 2007, Hatzinger et al., 2009). When perchlorate undergoes biodegradation, $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ isotope ratios move along a line towards more positive values of both $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$. This isotopic shift has been observed in both laboratory and field studies. A shift in the same direction and with a similar slope would occur for a natural perchlorate source or for a mixture of natural and synthetic perchlorate.

1.2.1 Evaluation of Perchlorate Biodegradation in Raymond Basin Ground Water

Perchlorate biodegradation is known to occur under reducing conditions and in the presence of a suitable electron donor. Available water quality data were surveyed to determine the extent of reducing conditions in Raymond Basin ground water, which would be amenable to perchlorate biodegradation. Out of the 26 JPL monitoring wells surveyed, 24 showed reducing conditions amenable to perchlorate biodegradation (i.e., ORP < 0 mV, DO < 1 mg/L, or iron > 0.5 mg/L). JPL's historical quarterly monitoring data showed that out of 1,320 samples there were 205 reported ORP measurements less than 0 mV, 62 DO measurements less than 1 mg/L, and 400 reported iron measurements greater than 0.5 mg/L.

Reported measurements, which would show direct evidence of anaerobic respiration (i.e., biological reduction of nitrate, perchlorate, and sulfate) were only available from one sampling event in 2005 involving seven JPL monitoring wells. Samples collected from varying depths in JPL monitoring wells were analyzed for a range of parameters including perchlorate, nitrate, ammonia, and sulfide, and for biodegradation end products including ammonia, nitrite, and sulfide. Out of the seven JPL monitoring wells sampled, two wells (MW-20 and MW-25) showed evidence of perchlorate biodegradation in the lower zones.

Bender et. al. (2002) established a method of detecting the presence and activity of perchlorate reducing bacteria in the environment using functional genomics. They targeted a gene (*cld*) that codes for the production of chlorite dismutase (CD), an enzyme essential in the chemical pathway for perchlorate reduction. This enzyme has been found to be present on the outer membrane of perchlorate reducing bacteria, even when they were not actively reducing perchlorate (Bender et. al. 2002). However, the production of this enzyme is regulated by environmental conditions. This change in *cld* activity with environment means that measuring the *cld* mRNA, which control CD can serve as a measure of perchlorate reduction activity.

The functional genomics testing suggest that perchlorate reducing bacteria are ubiquitous in JPL ground water, which would be expected. The mRNA testing shows *cld* activity in two of nine wells, but without detailed sampling narratives, it cannot show lack of activity. Also, mRNA activity—suggesting that perchlorate reduction was occurring—was measured in MW-1, which is upgradient of any known perchlorate contamination. The functional genomics testing presented in the 2007 TM does not provide conclusive evidence regarding the presence or absence of active perchlorate biodegradation.

1.2.2 Perchlorate Biodegradation in Imported Water

The Metropolitan Water District of Southern California (Metropolitan) supplies imported water to the Utilities in the Raymond Basin, including the City of Pasadena. Water imported to the Raymond Basin from Metropolitan originates from the California State Water Project Canal and from the Colorado River. Historically, Colorado River water imported to Southern California contained low-levels of perchlorate resulting from synthetic perchlorate production at the Kerr-McGee facility (BMI complex) in Henderson NV. Metropolitan has been monitoring perchlorate in Colorado River water since 1997.

Historical water quality monitoring data collected at Lake Mathews were analyzed to determine if perchlorate biodegradation is occurring in Lake Mathews. Historical dissolved oxygen, perchlorate, and nitrate data from 1997 to 2009 were analyzed from various depths within the

lake. Perchlorate depth-profile measurements show that perchlorate exists in the upper levels and is below detection limits in the lower portions of the Lake. This result shows that perchlorate is biodegraded in the lower portions of Lake Mathews. Nitrate depth profiles show depletion of nitrate (< 0.1 mg/L) in the lower zones. Additionally, detectable levels of nitrite (> 0.02 mg/L) and ammonia (>0.2) are present in the lower zones, which indicate active biological nitrate reduction is occurring.

1.2.3 Perchlorate Origin in the Sunset Reservoir Area Wells

Perchlorate biodegradation has been reported to shift the isotopic signature with respect to chlorine and oxygen isotopes. Data reported in the literature show that the ($\epsilon^{18}\text{O}/\epsilon^{37}\text{Cl}$) fractionation factor ratio resulting from biodegradation is relatively consistent in studies conducted in the laboratory and in the field.

Data reported by Hatzinger et al. (2009) were used to predict the magnitude of isotopic shift, which would occur in perchlorate measured in the JPL area and Sunset Reservoir area. Results show that stable perchlorate isotope data measured in the Sunset wells are consistent with JPL-source perchlorate, which has undergone biodegradation. Additionally, the implication is made that following perchlorate biodegradation in Lake Mathews, imported water would likely show more positive $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ isotope ratios than the BMI complex samples and the Sunset Reservoir area.

A statistical analysis was made on stable perchlorate isotope data ($\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$) measured in wells in the JPL area and Sunset Reservoir area. The purpose of the statistical analysis was to:

1. Determine if there is a statistically significant difference in the stable perchlorate isotope data reported in the 2007 TM for wells in the JPL area and wells in the Sunset Reservoir Area;

2. Determine the effect of perchlorate biodegradation in Raymond basin ground water on the statistical significance of perchlorate stable isotope data reported for the JPL area and Sunset Reservoir area and;
3. Determine the extent of perchlorate biodegradation in Lake Mathews needed to shift the isotopic signature of BMI-source perchlorate so that it is distinct from the Sunset Reservoir wells.

A two-sample t-test assuming unequal variance was used to determine if there is a significant difference between the $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ stable isotope ratios reported from ground water measurements in the JPL area and in the Sunset Reservoir area. Results of the t-test analysis for statistical significance are summarized as follows:

1. With no biodegradation of perchlorate, the $\delta^{18}\text{O}$ stable isotope ratios measured in the JPL area and Sunset Reservoir area show a statistically significant difference;
2. The $\delta^{37}\text{Cl}$ stable isotope ratios measured in the JPL area and Sunset Reservoir area did not show a statistically significant difference and;
3. If 6 to 22 percent biodegradation of JPL perchlorate occurred, there would be no significant statistical difference between the $\delta^{18}\text{O}$ of the JPL source area.

A two-sample t-test assuming unequal variance was also used to determine if there is a significant difference between the isotopic concentrations of the Sunset Reservoir Area wells and the BMI Complex perchlorate. Based on the results of significance testing, the amount of biodegradation required for a statistically significant difference between the Sunset Reservoir Area perchlorate signature and the BMI Complex perchlorate signature is approximately 7 percent.

1.3 Findings

Findings identified during the course of this evaluation are summarized as follows:

1.3.1 Raymond Basin Ground Water Model

1. Forward particle tracking suggests that the JPL source area is the origin of perchlorate at the Sunset Reservoir area wells (P-COP, P-SUN, P-BAN, P-GAR, and P-VIL).
2. Backward particle tracking suggests that the JPL source area is the origin of perchlorate at the Sunset Reservoir area wells (P-COP, P-SUN, P-BAN, P-GAR, and P-VIL).
3. Backward particle tracking suggests that the JPL source area is the origin of perchlorate in the deep screen intervals of JPL MW-20.

1.3.2 Evaluation of Perchlorate Biodegradation in Raymond Basin Ground Water

1. Available ground water quality data show that reducing conditions, which are necessary for perchlorate biodegradation, occur extensively in the JPL and Sunset Reservoir areas.
2. Based on a sampling of seven wells in the Raymond Basin, two wells show direct evidence of perchlorate biodegradation.

1.3.3 Perchlorate Degradation in Imported Water

1. Perchlorate in Colorado River Water undergoes seasonal biodegradation in Lake Mathews.

1.3.4 Evaluation of Perchlorate Origin in the Sunset Reservoir Wells

1. Perchlorate in the Sunset Area wells is synthetic in origin.
2. Perchlorate measured in the Sunset Reservoir area wells is consistent with JPL-source perchlorate, which has undergone limited biodegradation.

3. Perchlorate isotope ratios in imported water are shifted as a result of biodegradation in Lake Mathews.

NASA / JPL PERCHLORATE CONTAMINATION OF GROUND WATER IN THE RAYMOND BASIN

2.0 INTRODUCTION

At the request of the City of Pasadena, GEOSCIENCE Support Services, Inc. has conducted further analysis and evaluation of the occurrence, fate, and transport of perchlorate contamination from National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) (see Figure 1).

2.1 Background

The JPL facility was developed and operated by the United States Army between 1945 and 1957, with jurisdiction transferred to NASA in 1958. During that period of time, hazardous substances were disposed of within various "seepage pits" located throughout the property. The types of substances that were disposed of include various volatile organic compounds (VOCs), solid rocket fuel propellants (including perchlorate), cooling tower chemicals, sulfuric acid, Freon, mercury, and chemical laboratory wastes.

In 1990, significantly elevated levels of carbon tetrachloride, trichloroethene (TCE), tetrachlorethene (PCE), and other volatile organic compounds (VOCs) were detected in ground water both under and hydraulically downgradient of the facility. In the mid to late 1980s, four City of Pasadena wells in the Monk Hill subarea were shut down due to VOC contamination attributable to JPL (the Arroyo Well, Well 52, the Windsor Well, and the Ventura Well). Additionally, two Lincoln Avenue Water Company wells (Well No. 3 and Well No. 5) were shut down in 1987 due to VOCs attributable to JPL.

Prior to 1997, perchlorate had not been detected at low concentrations in ground water anywhere in the United States because an appropriate analytical method did not yet exist. In 1997, an

improved perchlorate detection method was developed that was sensitive to 4 micrograms per liter ($\mu\text{g/L}$). Since that time, perchlorate has been detected in ground water in the Monk Hill subarea and portions of the Pasadena subarea (see Figure 1). In the Pasadena subarea, there is a group of five wells near the Sunset Reservoir (Sunset, Bangham, Copelin, Villa and Garfield) that have also been impacted by perchlorate (see Figure 1).

A technical memorandum (TM) was issued by NASA in 2007 that investigated the downgradient (southern) extent of chemicals originating from the JPL facility, and evaluated if the occurrence of perchlorate in the Sunset Reservoir area ground water was associated with migration from the JPL facility. That NASA TM concluded that:

“...(1) the chemicals from the JPL facility are contained within the Monk Hill Subarea, and, (2) the perchlorate detected at the Sunset area wells is of a different origin than that used at, and originating from, JPL”

Furthermore, the 2007 NASA TM concluded that:

“The lack of biodegradation <in the study area> implies that the differences in isotopic composition between JPL perchlorate and the perchlorate in the Sunset, Bangham, and Garfield wells is not caused by biodegradation but is likely to reflect the presence of multiple, isotopically distinct sources of perchlorate in the Raymond Basin”

2.2 Purpose and Scope

The purpose of this investigation was to:

1. Further evaluate the fate and transport of perchlorate contamination from NASA’s JPL facility;
2. Assess impacts to the City of Pasadena’s municipal water supply wells, specifically the Sunset Reservoir area wells; and

3. Provide a critical evaluation of the stable perchlorate isotope data presented in NASA's 2007 Technical Memorandum and evaluate the implication of perchlorate source in the City of Pasadena's Sunset Reservoir area wells.

The scope of work performed during this investigation included the following:

- Update of the RBMB ground water model from 2002 to 2008;
- Estimation of a 1981 perchlorate plume front to facilitate particle tracking;
- Additional ground water modeling to evaluate perchlorate movement from/to JPL to the City's Sunset Reservoir area wells;
- Evaluation of JPL's methods and procedures for water quality sampling;
- Review of historical ground water quality data for conditions favorable to biodegradation of perchlorate;
- Critical analysis of the functional genomics testing asserted in NASA's 2007 TM;
- Analysis of isotopic signature shift due to perchlorate biodegradation;
- Analysis of isotopic signature shift due to mixing of multiple perchlorate sources; and
- Analysis of statistical significance of perchlorate isotope data set.

2.3 Sources of Data

Data used for this study were obtained from multiple sources. The primary sources and the types of data provided by them are summarized as follows:

- NASA (2007). Technical Memorandum: Additional Investigation Results: perchlorate isotope data, analytical methodology.
- NASA (1996 to 2009). Quarterly Monitoring Reports (1st Quarter 2005 to 2nd Quarter 2009): ground water quality data and plume delineations.
- RBMB (2009). Raymond Basin Management Board Database: ground water quality data.
- California Department of Public Health (2009). Ground water quality data.

- USGS Water-Quality Data for the Nation (2009). Ground water quality data.
- California Department of Water Resources (2009). Ground water quality data.
- California State Water Resources Control Board Groundwater Ambient Monitoring Assessment (GAMA) Program (2009). Ground water quality data.

Data used to evaluate perchlorate biodegradation in imported water were obtained from historical reservoir monitoring conducted by Metropolitan's reservoir management group. All reported data were measured by Metropolitan Water District's La Verne, California water quality laboratory.

3.0 RAYMOND BASIN GROUND WATER MODEL

3.1 Model Update

3.1.1 Background

In 2005, a ground water flow model was developed for the unconsolidated sediments of the entire Raymond Basin area, including a portion of the Main San Gabriel Basin (see Figure 1). Since the model was prepared for the Raymond Basin Management Board (RBMB), it is referred to as the RBMB Model (GEOSCIENCE, 2005).

The primary purpose of the model was to make predictive analyses of potential changes in ground water levels and flow direction under various conjunctive uses scenarios. These conjunctive use scenarios evaluate methods of storing up to 75,000 acre-ft of additional water in the Raymond Basin using surface water recharge and ground water injection. This recharge project is known as the Raymond Basin Conjunctive Use Project (RBCUP).

The RBMB model consists of two distinct layers: Layer 1 – Upper alluvial aquifer system; Layer 2 – Lower alluvial aquifer system. A total of 74,520 model cells, each representing an area of two acres (300 ft x 300 ft), were used to simulate specified flux (i.e., wells, recharge and no-flow) and head-dependant (i.e., general head boundary) boundary conditions. Ground water flow was assumed to occur horizontally within each of the model layers while the layers maintain hydraulic connection to each other through vertical leakance. The Raymond and Eaton faults were modeled as a lower permeability feature using the Horizontal-Flow Barrier (HFB) package. The major creeks and rivers within the model area are all channelized and lined; therefore, no streamflow was included in the model. Evapotranspiration from ground water was also not simulated because depth to water is generally deeper than the extinction depth of evapotranspiration. The model was calibrated appropriately including steady-state model calibration (1980) and transient model calibration for the period from January 1981 through December 2002.

3.1.2 Purpose and Scope

For purposes of this evaluation, the RBMB ground water flow model was updated from 2002 to 2008 to include the updated geohydrologic data. The updated RBMB ground water model was used to perform particle tracking on perchlorate movement from the JPL area. Specifically, this evaluation consisted of the following three tasks:

1. Forward tracking from 1981 to 2008 to assess the movement of perchlorate from the JPL area to the down gradient City of Pasadena Sunset Reservoir well field area;
2. Reverse particle tracking from the Sunset Reservoir area wells (2008 to 1981); and
3. Reverse tracking from the deep well screens (i.e., Screens 4 and 5) in monitoring well JPL MW-20.

The results of the forward particle tracking will determine if the 1981 perchlorate plume front could have migrated to the Sunset Reservoir area wells. Results of the reverse particle tracking will determine if particles “backtrack” from the Sunset Reservoir area wells to the JPL area and assist in evaluating the origin of the perchlorate currently measured in the deep screen zones of JPL MW-20.

The scope of work for the model update includes the following:

- Extend the transient model calibration period from January 1981 through December 2002 to January 1981 through December 2008 with updated geohydrologic data;
- Refine model active and inactive cells in the Arroyo Seco Creek area utilizing updated geology;
- Add ground water flow barrier in the Arroyo Seco Creek area based on updated water level data;
- Recalibrate the model; and
- Conduct particle tracking using MODPATH.

3.1.3 Sources of Data

The model update incorporates data collected from multiple sources during the period from January 2003 through December 2008. The primary sources and types of data provided are summarized below:

- Raymond Basin Management Board and its member agencies (2009): Well locations, ground water level data, production data, water quality data, ground water injection data, and artificial spreading data.
- Los Angeles County Department of Public Works (2009): Precipitation data, evaporation data, and artificial spreading data.
- United States Geological Survey (2005): Geology of the Raymond and Main San Gabriel Basins, locations of faults, and streamflow data.
- NASA Jet Propulsion Laboratory (2009): Ground water level and quality data.

A complete list of references is included at the end of the written portion of this report.

3.1.4 Conceptual Model

The conceptual understanding of the geohydrology, ground water flow directions, inflows (recharge) and outflows (discharge) for the Raymond Basin were based on a thorough understanding of the Basin which was documented in the Raymond Basin Baseline Assessment (GEOSCIENCE, 2004).

The updated RBMB ground water model was developed for the unconsolidated sediments of the entire Raymond Basin and a portion of the Main San Gabriel Basin (see Figures 2a and 2c). The model was extended into the Main San Gabriel Basin to ensure the effect of Raymond Fault could be simulated accurately. Consolidated Miocene marine deposits (sedimentary rocks) and crystalline basement complex underlying and surrounding the basin are considered impermeable and are not part of the alluvial ground water flow system. The conceptual ground water model consists of two model layers:

- Layer 1 – Upper alluvial aquifer system
- Layer 2 – Lower alluvial aquifer system

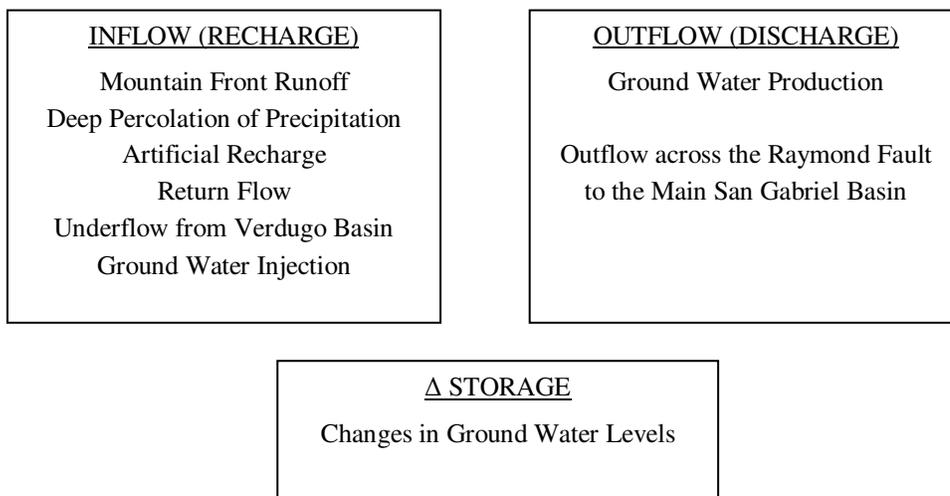
Both layers consist of boulders, sand, gravel, and clay. The boundary between the layers was delineated using bottom of the major fine-grained deposits identified from driller's logs in the southern Pasadena Subarea. In other areas such as the mountain front, the fine-grained deposits thin to extinction, and the two layers act as one.

Ground water flow is assumed to occur horizontally within the each of the model layers while the layers maintain hydraulic connection to each other through vertical leakance. The Raymond and Eaton faults were modeled as a lower permeability feature using the Horizontal-Flow Barrier (HFB) package.

The ground water flow model is an analytical expression of the conservation of mass, namely:

$$Inflow = Outflow \pm \Delta Storage$$

The various flux terms used in the development of the ground water flow model are summarized below.



Note that the major creeks and rivers within the model area are all channelized and lined; therefore, no streamflow was included in the model. Evapotranspiration from ground water was also not simulated because depth to water is generally deeper than the extinction depth of evapotranspiration.

3.1.5 Model Code

3.1.5.1 MODFLOW

MODFLOW, a block-centered, three-dimensional, finite-difference ground water flow model, was the computer code used in the updated RBMB model. Widely used and highly versatile, it was developed by the USGS (McDonald and Harbaugh, 1988) for the purpose of modeling ground water flow.

MODFLOW is modular in the sense that a standard format has been established for the interface between each module of the program, as well as for the common variables that must be accessible to all modules. Consequently, new modules (also called packages) may be added as necessary. Since its initial development, various modifications and the addition of new packages have been made (Hill, 1990; McDonald, et. al., 1991; Harbaugh, 1990; Hsieh and Freckleton, 1993; Harbaugh, 1992; Goode and Appel, 1992; and Leake, et. al., 1994).

The following modules or packages were used in the updated RBMB model:

- Basic (BAS1 by McDonald and Harbaugh, 1988);
- Block Centered Flow (BCF3 by McDonald and others, 1991);
- Preconditioned Conjugate-gradient Method (PCG2 by Hill, 1990);
- Well (WEL1 by McDonald and Harbaugh, 1988);
- General-Head Boundary (GHB1 by McDonald and Harbaugh, 1988);
- Recharge (RCH1 by McDonald and Harbaugh, 1988); and
- Horizontal-Flow-Barrier (HFB1 by Hsieh and Freckleton, 1993).

The Basic package (BAS1) handles most of the administrative tasks for the model. It accepts data that define the nature of the discrete model grid (number of rows, columns, and layers), the stress periods (simulation time intervals during which all external influences, e.g., well pumping, are presumed to be constant), time discretization (the finite-difference intervals for propagating through each stress period), and other major options to be used. Initial head levels for each cell are also specified in this module.

The Block Centered Flow package (BCF3) computes the conductance component of the finite-difference equations that determines flow between adjacent cells and allows a cell to be converted from no flow (inactive) to variable head (active). This package also computes the terms that determine the rate of movement of water to and from storage within each cell. In addition, the module accepts further definitions of the problem, including each cell's size (height and width), transmissivity, and storativity.

The Preconditioned Conjugate-gradient Method package (PCG2) solves equations produced by the model that determine hydraulic head using iterative methods that are less susceptible to round-off error, are more efficient for large problems, and require less computer storage. Both linear and nonlinear flow conditions may be simulated using this package.

The Well package (WEL1) simulates wells that withdraw water from the aquifer or inject water into the aquifer. The addition or subtraction of water to any cell during each stress period is accomplished at a rate that is assumed to be independent of the head of the cell.

The General-Head Boundary (GHB1) simulates the flow from an external source provided in proportion to the difference between the head in the cell and the head assigned to the external source. General-Head boundary (GHB1) was assigned to portions of the Raymond Basin ground water model where the aquifers extended beyond the bounds of the model area.

The Recharge package (RCH1) is used to simulate areally distributed recharge to the ground water system as a result of precipitation. For this model, it also includes recharge from mountain front runoff, return flow and artificial recharge.

The Horizontal-Flow-Barrier (HFB1) package was designed to simulate thin, vertical, low permeability geologic features that impede the horizontal flow of ground water. These geologic features are approximated as a series of horizontal-flow barriers conceptually situated on the boundaries between pairs of adjacent cells in the finite-difference grid.

3.1.5.2 Equations of Ground Water Flow

Horizontal ground water flow within the model layers is solved using the method of finite differences time-dependent equation of flow:

$$\nabla \cdot T \nabla h + Q = S(\partial h / \partial t) \quad (1)$$

This equation is the general parabolic differential equation governing the motion of ground water through porous media. The equation contains three fundamental terms:

- $\nabla \cdot T \nabla h$ represents the divergence of the gradient of hydraulic head (h) and denotes the net inward flux (i.e., inflow – outflow).
- Q is a flux term that incorporates natural inflow, outflow, well extractions, artificial recharge, and leakage into or out of the system.
- $S(\partial h / \partial t)$ is the term that describes the time dependent change of storage.

The first term, $\nabla \cdot T \nabla h$, represents flow into and out of a model grid block. The third term, $S(\partial h / \partial t)$, is governed by storativity and head change, and represents increases or decreases in ground water storage.

Leakage between layers (vertical flow) can be calculated using the following equation:

$$Q_L = (-K'/b') \times (h_u - h_l) \quad (2)$$

where:

- Q_L = leakage, [ft/day]
- K' = vertical hydraulic conductivity, [ft/day]
- b' = thickness of confining bed, [ft]
- K'/b' = leakance [day^{-1}]
- h_u = head in upper layer, [ft]
- h_l = head in lower layer, [ft]

3.1.5.3 Model Pre- and Post-Processors

The pre- and post-processors used to manipulate model input and output data arrays include the following:

- GIS (Geographical Information System);
- Groundwater Vistas; and
- Proprietary software developed by GEOSCIENCE.

The GIS software used was ArcView by ERSI. Groundwater Vistas, which was developed by Environmental Simulations, Inc., is a Windows graphical user interface for 3-D ground water flow and transport modeling. Fortran source codes, custom developed by GEOSCIENCE, were used to prepare MODFLOW model input data for the Well package, GHB package and Recharge package.

3.1.6 Model Cells, Layers, and Stress Periods

A two-layer model was constructed for the entire Raymond Basin area, including a portion of the Main San Gabriel Basin (see Figure 1). The model covers approximately 120 square miles and consists of 162 nodes (e.g., model cell) in the north-to-south direction (i-direction) and

230 nodes in the west-to-east direction (j-direction), for a total of 74,520 nodes (see Figure 1). Each model cell represents an area of two acres (300 ft x 300 ft).

The stress period (i.e., time period) used to vary model fluxes, such as pumping and recharge, occurred monthly.

3.1.7 Boundary Conditions

A boundary condition is any external influence or effect that either acts as a source or sink, adding or removing water from the ground water flow system. The boundary conditions used in the updated RBMB model are no-flow (inactive), wells, general head boundaries (GHB), and recharge (see Figure 3 for locations of different types of boundary conditions and Section 3.1.9.3 for details of the GHB). In general, ground water flow model boundary conditions can be grouped into three main types: 1) constant head (this type was not used in the RBMB ground water model), 2) specified flux (i.e., wells, recharge and no-flow), and 3) head-dependant with a limiting conductance or rate term (i.e., GHB).

For the existing RBMB model, the no-flow cells were delineated based on the bedrock boundaries from the geologic map constructed by the California Division of Mines and Geology (1969). For the updated RBMB model, the no-flow cells were changed in the vicinity of the NASA/JPL area based on the updated geologic map prepared by the USGS (2005; see Figures 2a and 2c).

The edge of the active model area immediately surrounding the area of interest is bounded by natural boundaries (contact between basin fill alluvium and bedrock). Farther away, to the northwest and southeast, where the model area does not continue to the natural edge of the basin, a GHB is used to simulate the observed long-term trends in ground water levels over time. There are two GHBs in different locations of the model. The first GHB represents inflow from the Verdugo Basin to the north of the Raymond Basin (see Figure 3). As there are no wells located near this boundary, historic ground water levels along the boundary were interpreted from

ground water elevation maps from the Raymond Basin Management Board annual reports. The second GHB represents the underflow inflow and outflow in the Main San Gabriel Basin located in the southeastern portion of the model area (see Figure 3). It was determined using long-term historic ground water elevation data obtained from purveyor wells (e.g., City of Arcadia, Sunny Slope Water Co. and City of Alhambra) near the boundary. Ground water elevation trends similar to those of selected wells near the boundary were used to simulate the ground water elevations at the model boundary.

3.1.8 Aquifer Parameters

3.1.8.1 General

Various aquifer parameters were necessary to simulate ground water flow. The following table summarizes the types of data used by the model:

Model Aquifer Parameters	
Parameters	Units of Model
Initial Water Level Elevation of Layers 1 and 2	ft amsl
Top Elevation of Layer 2	ft amsl
Bottom Elevation of Layer 2	ft amsl
Transmissivity of Layers 1 and 2	ft ² /day
Vertical Leakance between Layer 1 and Layer 2	day ⁻¹
Hydraulic Characteristic of Horizontal-Flow Barrier of Layers 1 and 2	ft/day

3.1.8.2 Model Layers

Top and bottom elevations for each of the two model layers were obtained primarily from drillers' logs. The elevation of the bottom of model layer 1 was determined based on fine-grained deposits described in drillers' logs (see geologic cross-section from Baseline Assessment, Plate 1, GEOSCIENCE, 2004), which separates the unconfined upper aquifer from the semi-confined to confined aquifer below the fine-grained deposits. Towards the mountains,

there are minimal fine-grained materials and, thus, the model layers are indistinguishable and have been modeled to act essentially as one layer.

The base of the model (and model layer 2) was determined based on bedrock elevations as delineated in the Baseline Assessment (GEOSCIENCE, 2004). Figure 4 shows the bottom elevation of model layers 1 and 2; and Figure 5 shows the thicknesses of model layers 1 and 2.

In the Raymond Basin, the thickness of model layer 1 ranges from approximately 100 ft at the boundary of alluvial fill and bedrock to approximately 800 ft in the center portion of the Pasadena Subarea. The thickest portion of model layer 2 is located at the southeast portion of the Pasadena Subarea with a thickness of approximately 700 ft. These thicknesses are also illustrated in Figure 6 which shows a cross-sectional depiction of the model layers through two sections of the Basin.

3.1.8.3 Transmissivity

Transmissivity values were estimated based on the spatial distribution of hydraulic conductivity and aquifer saturated thickness. Initial hydraulic conductivity values, prior to calibration, were obtained from specific capacity data published in reports from CH2M Hill (1990) and DWR (1969a), and the RBMB ground water model developed by Metropolitan. The transmissivity values were then modified within pre-established upper and lower bounds, during model steady-state and transient calibration, in order to match the observed ground water levels in the model area. The calibrated transmissivity values range from less than 1,000 ft²/day (7,480 gpd/ft) to 30,000 ft²/day (224,000 gpd/ft) for model layer 1, and less than 1,000 ft²/day (7,480 gpd/ft) to 20,000 ft²/day (149,600 gpd/ft) for model layer 2 (see Figure 7).

3.1.8.4 Storativity

Initial storativity values for each model layer were obtained from DWR (1969b) distribution of storativity. The model storativity values were then modified within pre-established upper and lower bounds, during model transient calibration, in order to match the observed ground water

levels in the model area. The final calibrated storativity values range from 0.029 to 0.2 for model layers 1 and 2 (see Figure 8).

3.1.8.5 Vertical Leakance between Aquifers

Vertical leakance between model layers 1 and 2 was estimated based on model calibration, as published estimates of vertical conductance between the model layers were not available. The final calibrated vertical leakance value between model layers 1 and 2 is 0.01 day^{-1} and was uniformly applied to entire model area (see Figure 9).

3.1.8.6 Horizontal-Flow Barriers

The Raymond Fault and the Eaton Fault were simulated in the RBMB model as partial barriers to ground water flow from the Raymond Basin to the Main San Gabriel Basin. For the updated RBMB model, an additional partial barrier to ground water was added in the area immediately east of the NASA/JPL area (see Figures 10 and 2b). This additional barrier is inferred from offset ground water levels between JPL monitoring wells MW-1, MW-15, MW-9 and MW-11, MW-12, and MW-3 (see Figure 11). These barriers were simulated in the ground water flow model using the Horizontal-Flow-Barrier (HFB) package by assigning a hydraulic characteristic value to the boundary of the barrier. For model layers 1 and 2, the hydraulic characteristic value is the barrier transmissivity divided by the width of the horizontal-flow barrier (units of ft/day).

The final calibrated hydraulic characteristic values of horizontal-flow barrier for model layer 1 range from 0.27 ft/day at the northwestern portion of the Eaton Fault to 0.0000435 ft/day at the southwestern portion of the Raymond Fault (see Figure 11). For model layer 2, the values range from 0.032 ft/day at the central portion of the Eaton Fault to 0.0001 ft/day along the unnamed fault (see Figure 11).

3.1.9 Model Recharge and Discharge

Recharge and discharge components in the updated RBMB model area (which incorporates the entire Raymond Basin and a portion of the Main San Gabriel Basin) include the following terms:

Recharge	Mountain Front Runoff
	Deep Percolation of Precipitation
	Artificial Recharge
	Return Flow
	Underflow from Verdugo Basin in the Northwestern Model Area
	Ground Water Injection Wells
Discharge	Ground Water Production
	Underflow Outflow in the Southeastern Model Area (in the Main San Gabriel Basin)

The following table shows the MODFLOW Package used for each term for both steady-state and transient model calibrations.

Model Terms and Packages	
Terms	MODFLOW Package Used
Deep Percolation of Precipitation	Recharge Package
Mountain Front Runoff	Recharge Package
Artificial Recharge	Recharge Package
Return Flow	Recharge Package
Underflow from Verdugo Basin	GHB Package
Ground Water Injection	Well Package
Ground Water Production	Well Package
Underflow Outflow in the Southeastern Model Area	GHB Package

3.1.9.1 Model Recharge

3.1.9.1.1 Deep Percolation of Precipitation

Deep percolation of precipitation is regionally distributed recharge to the ground water system as a result of precipitation. The amount of deep percolation of precipitation was estimated based on the following equation (Turner, 1991):

$$\text{Perc} = P - 2.32 P^{2/3} \quad \text{for } P \geq 11.9$$

$$\text{Perc} = 0 \quad \text{for } P < 11.9$$

Where:

Perc = Annual Deep Percolation, in./yr

P = Annual Precipitation, in./yr

The annual deep percolation was redistributed to each month based on the distribution of monthly precipitation at the Pasadena Station. The actual deep percolation assigned to each model cell was then calculated based on monthly deep percolation and impervious nature of various land use categories. An impervious area of 90%, 80%, 50%, 30% and 10% was assumed for the land uses of roads, cemeteries, residential, low density residential and parks, respectively (LACDPW, 2002). Figure 12 is the land use map used for the distribution of recharge for the model area (LACDPW, 2002). The monthly deep percolation for the model area ranged from zero to 6,000 acre-ft in January 1995 with an annual average of 3,900 acre-ft/yr during the period from 1981 to 2008 (see Figure 13).

3.1.9.1.2 Recharge from Mountain Front Runoff

Recharge from mountain front runoff is a component of recharge to the Raymond Basin which flows through the weathered and fractured bedrock as a result of areal recharge occurring in the essentially non-water-bearing surrounding mountains. The recharge from mountain front runoff for the Raymond Basin was estimated using a watershed model. The model code used was the

Hydrological Simulation Program – Fortran (HSPF; EPA, 1997). This program uses measured daily precipitation to estimate surface water runoff, evapotranspiration, and ground water recharge.

For purpose of this study, the adjacent mountainous watershed of the Raymond Basin was subdivided into 16 watershed subareas (see Figure 14). The HSPF model was calibrated using the measured runoff data at the Arroyo Seco and Santa Anita streamflow stations by adjusting the model parameters. The calibrated HSPF model parameters were then applied for each watershed subarea. The calculated monthly recharge from mountain front runoff for the Raymond Basin ranged from zero acre-ft to 5,500 acre-ft with an annual average recharge of 6,200 acre-ft/yr during the transient model calibration period from 1981 through 2008 (see Figure 15). The 6,200 acre-ft/yr of annual average recharge from mountain front runoff is consistent with the estimated recharge of 6,520 acre-ft/yr by DWR (1969).

The HSPF-modeled underflow recharge for the Arroyo Seco watershed subarea ranged from zero to 2,064 acre-ft with an average annual recharge of approximately 2,350 acre-ft per year during the period from 1981 through 2008. The estimated recharge from mountain front runoff was then re-distributed so that the underflow recharge for the Arroyo Seco channel was 300 acre-ft per year. The 300 acre-ft/yr underflow was estimated based on hydraulic conductivity, hydraulic gradient, and the cross-sectional area of the Arroyo Seco channel. The remaining recharge (i.e., 2,050 acre-ft) was applied uniformly to the remaining mountain front runoff areas of the Arroyo Seco Watershed.

3.1.9.1.3 Artificial Recharge

In the Raymond Basin, artificial recharge by surface spreading of runoff mainly includes recharge at spreading facilities at:

- Arroyo Seco,
- Eaton Wash,

- Sierra Madre spreading grounds, and
- Santa Anita spreading grounds.

Additional smaller facilities are also used for surface water spreading, but to a lesser extent than those previously listed. These are:

- Pasadena Glen,
- Pasadena Sludge Ponds,
- Rubio Canyon Debris Basin, and
- Millard Canyon.

Figure 1 shows the locations of the artificial recharge sites. The monthly artificial recharge data at each of the sites were obtained from annual reports published by Watermaster Service in Raymond Basin and Los Angeles County Department of Public Works. The monthly total artificial recharge ranges from less than 50 acre-ft in August 1985 to 5,300 acre-ft in June 1983 with an annual average of 11,000 acre-ft/yr during the transient model calibration period from 1981 through 2008 (see Figure 16).

3.1.9.1.4 Return Flow

Return flow from the use of water (including both ground water and imported water) was incorporated into the ground water flow model using the Recharge package. Distribution of return flow was dependent upon the location and purpose of water usage (i.e., applied waters, leaky distribution pipes and septic tanks).

It was assumed that the return flow is 17% of water usage: including 5% from applied water and 12% from leaky distribution pipes. The amount of return flow was then distributed to the model cells based on service areas of water purveyors (see Figure 17) and water usage for each water purveyor. The annual water usage for each water purveyor was obtained from annual reports prepared by Watermaster Service in Raymond Basin. As the water usage was only available on

an annual basis, 17% of annual water usage was redistributed to each month based on the pattern of average monthly ground water pumping during the period 1981 through 2002.

Return flow also includes ground water recharge from septic tank discharges from unsewered areas located mainly in the northwestern portion of the Raymond Basin (see Figure 18). The annual return flow for the unsewered areas was assumed to be 2,000 acre-ft (DWR, 1969c). The annual return flow from septic tanks was also redistributed to each month based on the pattern of average monthly ground water pumping.

Figure 19 shows the total monthly return flow for the model area. As shown, the total monthly return flow ranged from 400 acre-ft in February 1982 to 1,900 acre-ft in July 2000 with an annual average of 13,000 acre-ft/yr during the transient model calibration period from 1981 through 2008.

3.1.9.2 Model Discharge

3.1.9.2.1 Well Package

Input data for the Well package included the following:

- Ground Water Production; and
- Ground Water Injection.

The monthly volumes extracted and injected were obtained from the RBMB geohydrologic database. GEOSCIENCE developed in-house software to incorporate these data into the model input file for the Well Package of MODFLOW. Well locations are shown on Figure 3. For wells screened in multiple aquifers, a portion of the well's total production was apportioned to each aquifer according to the screened interval of the well.

Figure 20 shows the monthly total ground water injection and Figure 21 shows the monthly total ground water pumping for the model area. For the entire model area, the monthly total ground

water injection ranged from zero acre-ft to 500 acre-ft in October 1993 with an annual average of approximately 400 acre-ft/yr during the transient model calibration period from 1981 through 2008. The monthly total ground water production ranged from 500 acre-ft in February 1996 to 6,200 acre-ft in August 1995 with an annual average of approximately 39,100 acre-ft/yr during the period from 1981 through 2008.

3.1.9.3 General-Head Boundary

A general-head boundary (GHB) was assigned to portions of the updated RBMB ground water model where the aquifers extended beyond the bounds of the model area (see Figure 3). Areas of the updated RBMB ground water model where the GHB was used included: 1) The northwest edge of the model area to represent the interconnection between the Verdugo Basin and the Raymond Basin; 2) The southeastern portion of the model boundary to represent the ground water flow within the Main San Gabriel Basin. For the steady-state calibration, heads were assigned to the GHB based on the ground water elevation contour map from the Raymond Basin Management Board annual report for 1980. Changes in head over the transient model period were applied to the model based on hydrographs of changing water levels in the GHB index wells (see Figure 22) for the southwestern GHB. As there are no wells located near the northwestern GHB, historic ground water levels along this boundary were interpreted from ground water elevation maps from the Raymond Basin Management Board annual reports.

3.1.10 Model Calibration

Model calibration demonstrates that the model is capable of simulating field-measured heads and flows (Anderson and Woessner, 1992). Calibration is achieved by determining parameters and boundary conditions and it stresses that produce-simulated heads and fluxes that match measured values within a predetermined range of error. Calibration techniques available are:

- Manual trial-and-error adjustment of parameters, and
- Automated parameter estimation.

The calibration process requires the use of calibration target wells from which to match model generated head values against measured values. Target wells are selected based on their location and period of record. The target wells used for calibration of the model are located in hydrogeologically different areas and spread uniformly throughout the model area. A long period of ground water elevation data, from which to compare the model-generated water levels, was also required for selection of suitable target wells. The target wells selected for both the steady-state and transient calibration of the updated RBMB ground water flow model are shown on Figure 23.

3.1.10.1 Calibration Process

The method of calibration used by the updated RBMB model was the standard “history matching” technique. In this method, a steady state calibration of 1980 and a transient calibration period from 1981 to 2008 were chosen. Model-generated ground water levels were compared with measured levels for wells in both the Raymond and Main San Gabriel ground water basins. Adjustments in hydrogeologic parameters were then made within tolerable limits until a satisfactory match was obtained. Parameter changes during model calibration were assigned to groups of cells. Adjustment of individual parameters for individual model cells was not considered.

3.1.10.2 Steady-State Calibration

Initial steady-state calibration of the updated RBMB Ground Water Flow Model was carried out for the beginning of the model period (i.e., 1980). This calibration involved adjustment of horizontal hydraulic conductivity, hydraulic characteristic of horizontal-flow barriers (ground water leakage through the Raymond and Eaton Faults), and vertical leakance between layers 1 and 2 until a good match between measured and model-generated ground water elevation was observed.

The calibration process was aided by the use of the software package Visual PEST (Parameter ESTimation; Doherty, 2000), which used a range of plus and minus 50 percent of initial values

for its iterations. These resultant parameter values for the steady-state calibration were thereafter used as initial values for the transient calibration.

A graphical comparison between measured and model predicted heads (from 20 target wells) for the steady-state calibration is shown in Figure 24 and summarized in the table below. In Figure 24, the closer the heads fall on the straight line, the better the "goodness-of-fit."

**RBMB Ground Water Model
1980 Steady-State Calibration Statistics**

	1980 Steady-State Calibration (see Figure 24)
Mean Residual ¹	0.78 ft
Standard Deviation of Residual	36.8 ft
Relative Error ²	4.8 %

¹ Residual = measured head less predicted head

² Relative Error = standard deviation of the residuals divided by the observed head range

Apart from the calibration evaluation of "goodness of fit," another more qualitative approach is to calculate the relative error of the residuals (i.e., standard deviation of the residuals divided by the observed head range). Common modeling practice is to consider a good fit between historical and model predicted data if the relative error is below 10% (Spitz and Moreno, 1996; and Environmental Simulations, Inc., 1999). As seen in the table above, the relative error for 20 target wells is 4.8%, which is well below the recommended error of 10%.

3.1.10.3 Transient Calibration

The results of the initial steady-state calibration provided initial aquifer parameter estimates and ground water elevations for the transient calibration. Measured ground water elevation data from 1981 to 2008 was used in the transient calibration. Again, PEST was used to iteratively adjust horizontal hydraulic conductivity, barrier conductance, and storativity/specific yield until a good

match between measured and model-generated ground water elevation was achieved. The resultant calibration statistics are provided in the table below and on Figure 25. Appendix A contains the hydrographs of 20 target wells showing model-generated water levels compared to measured levels. Figure 26 shows a histogram of water level residuals and Figure 27 shows the spatial distribution of residuals for 1982, 1992, 2002, and 2008 using wells included in the well package for those years.

RBMB Ground Water Model
Transient (1981 – 2008) Calibration Statistics

	Transient Calibration 20 Target Wells (see Figure 25)	Transient Calibration 145 Target Wells
Mean Residual ¹	5.6 ft	-6.7 ft
Standard Deviation of Residual	35.0 ft	58.6 ft
Relative Error ²	4.3 % ³	5.7 % ³

¹ Residual = measured head less predicted head

² Relative Error = standard deviation of the residuals divided by the observed head range

³ Common modeling practice is to consider a good fit between historical and model predicted data if the relative error is below 10% (Spitz and Moreno, 1996; and Environmental Simulations, Inc., 1999)

The graphical comparison between measured and model predicted heads (from 20 target wells) for the transient calibration (see Figure 25) shows the 3,174 ground water level measurements mainly clustered around the straight line. In general, the measured and model predicted heads compared favorably, and the calibration is further supported by relative errors below 10%: 4.3 % for 20 target wells, and 5.7% for 145 target wells.

In order to show how the model calibration measured up to varying seasonal patterns (i.e., wet, dry, and normal), the average monthly water level residuals for all 145 wells were plotted in Figure 28. The cumulative departure from mean annual precipitation is also included on this figure to show climatic cycles from 1981 to 2008. Figure 28 shows that the average water level

residual is randomly distributed over the calibration period and is not particularly correlated with wet or dry periods.

Accepting the associated errors in the model calibration and its measurement, the calibration results indicate that the standard of the calibration achieved for this basin-wide scale model is suitable for the purposes for which it was developed (i.e., basin-wide ground water management).

3.2 Particle Tracking

Tracking of the temporal and spatial advective transport of perchlorate within ground water was simulated by the updated RBMB ground water flow model for the period from January 1, 1981 through December 31, 2008. The methodology used for simulating particle tracks included the use of MODPATH in conjunction with MODFLOW. MODPATH is a post-processing package developed to compute three-dimensional flow paths (i.e., particle-tracking) using output from the updated RBMB ground water flow model. MODPATH uses a semi-analytical particle-tracking scheme that allows an analytical expression of the particle's flow path to be obtained within each finite-difference grid cell. Particle paths are computed by tracking particles from one cell to the next until the particle reaches a boundary, an internal sink/source, or satisfies some other termination criterion. MODPATH does not take into account hydrodynamic dispersion, retardation, or half-life decay. The results of MODPATH simply provide an indication of the direction and rate of ground water flow and, thus, an indication of the direction and rate of contaminant flow through advective processes.

Forward particle tracking shows the advective pathway for particles traveling in the direction of ground water flow during the model simulation. Backward (i.e., reverse) particle tracking shows the source area of particles placed at locations of interest (e.g., pumping wells).

3.2.1 Delineation of Extent of Historical Perchlorate Movement

In order to perform particle tracking on perchlorate movement within the JPL area, it was necessary to develop an estimated historical extent of perchlorate contamination for January 1, 1981 (i.e., model initial starting conditions). As there is no perchlorate ground water quality data for that time period, the 1981 estimated extent of perchlorate contamination was estimated based on more recent documented plume movement and an assumed start date for initial perchlorate contamination at the JPL source area.

3.2.1.1 Conceptual Understanding of Plume Movement

Conceptually, the movement of perchlorate within the subsurface is affected by several factors such as the timing and location of disposal events, dispersion, advection, dilution, and biodegradation. As such, although NASA's recent quarterly reports show a defined 6- $\mu\text{g/L}$ perchlorate plume front extending southeast of the JPL site, it is postulated that the southern extent of this plume is not adequately defined and that historical plumes of varying perchlorate concentrations have previously migrated hydraulically downgradient. However, based on this conceptual understanding of how perchlorate contamination occurs, it is assumed that those variables governing movement of the recently delineated 6 $\mu\text{g/L}$ perchlorate plume fronts (Foster Wheeler Environmental Corporation, 1998, and Battelle, 2005 - 2009) are generally applicable to movement of historical plume fronts.

3.2.1.2 Estimates of Ground Water Seepage Velocity

Movement of the 6 $\mu\text{g/L}$ perchlorate plume front as delineated in selected quarterly reports from the 4th Quarter 1998 through 2nd Quarter 2009 (Foster Wheeler Environmental Corporation, 1998, and Battelle, 2005 - 2009) was used to estimate the average ground water seepage velocity in the area to the southeast of JPL. For purposes of this analysis, it was assumed that the date for each plume front delineated was the midpoint of the date range provided in each respective quarterly report (e.g., the date of the plume associated with the April/May 2009 report was assumed to be May 1, 2009).

Estimates of seepage velocity based on recent plume movement range from 0.4 to 1.6 ft/day and averaged 0.8 ft/day as summarized on Figure 29 and in the following table:

Estimates of Average Seepage Velocity in the Vicinity of JPL

Time Period	Time Period (days)	Advancement of 6 µg/L Plume Front [ft]	Seepage Velocity [ft/day]
4Q98(L3) - 4Q05*	2,557	944	0.37
4Q98(L3) - 4Q08	3,653	2,672	0.73
4Q05 - 4Q06	380	240	0.63
4Q05 - 4Q08	1,096	1,728	1.58
4Q06 - 4Q07	365	176	0.48
4Q07 - 2Q09	532	640	1.20
AVERAGE			0.83

* 4th Quarter 1998 layer 3 - 4th Quarter 2005

3.2.1.3 Estimated Extent of Perchlorate Contamination in 1981

Limited production of perchlorate in the Los Angeles area began in early 1944 and had been ramped up by late 1944 (Schumacher, 1999). For purposes of analysis, it was assumed that perchlorate disposal (i.e., contamination) at the JPL site began on January 1, 1945. Using that start date and the average ground water seepage velocity of 0.83 ft/day, it was estimated that by January 1, 1981, perchlorate contamination may have traveled as far as 2.1 miles hydraulically downgradient of the JPL source area. The estimated extent of perchlorate contamination for January 1, 1981 is shown on Figure 30.

3.2.2 Forward Particle-Tracking

Forward tracking was simulated using particles released at the January 1, 1981 boundary of the estimated extent of perchlorate contamination shown in Figure 30. The purpose of the forward particle tracking was to evaluate the possibility that advective flow of perchlorate from JPL

would reach City of Pasadena's Sunset Reservoir area wells. Particles released from the 1981 estimated extent of perchlorate contamination travel to the southeast in the direction of regional ground water flow.

Particles released at the northwestern portion of the January 1, 1981 estimated extent of perchlorate contamination were captured by the Bangham and Sunset wells (P-BAN and P-SUN) by 1996 and by the Garfield and Villa wells (P-GAR and P-VIL) by 2003 (see Figure 31). Particles released at the southwestern portion of the January 1, 1981 estimated extent of perchlorate contamination were captured by wells P-BAN and P-SUN by 1987 and by wells P-GAR and P-VIL by 1998 (see Figure 31). It should be noted that particle tracking does not account for hydrodynamic dispersion which results in a "spreading out" of plumes. As such, particle tracking results in a conservative footprints of contamination. This likely accounts for the fact that the particle tracks shown on Figure 31 are not captured by the Copelin well (P-COP).

3.2.3 Backward Particle-Tracking

Backward (i.e., reverse) particle-tracking was simulated by releasing particles at the City of Pasadena Sunset Reservoir wells and JPL MW-20 on December 31, 2008. The purpose of the backward tracking was to delineate the source of recharge to both the Sunset Reservoir area wells and the deep well screens (i.e., Screens 4 and 5) of JPL MW-20.

Particles released at the Sunset Reservoir area wells P-BAN, P-SUN, P-COP on December 31, 2008 backward track to the JPL area in approximately 17 years (i.e., by 1992). Backward tracking particles from wells P-GAR and P-VIL do not reach the JPL area over the model period (i.e., January 1, 1981 through December 31, 2008). However, particles from P-GAR and P-VIL do intersect the estimated 1981 extent of perchlorate contamination in approximately 16 to 28 years. Based on the results of backward particle tracking from the Sunset Reservoir area wells, it is likely that the source of perchlorate in those wells is from the JPL area.

Particles released within the deep screen (i.e., screens 4 and 5) of JPL MW-20 backward track to the JPL area in 17 years (i.e., by 1992) (see Figure 33). This verifies that the source of perchlorate detected within the deep screens of JPL MW-20 is the JPL area.

4.0 EVALUATION OF STABLE PERCHLORATE ISOTOPE DATA

4.1 Background

4.1.1 Use of Perchlorate Isotope Ratios for Determining Source of Perchlorate

The 2007 NASA TM reported stable perchlorate isotope ratios, which were measured from monitoring wells and production wells in the eastern portion of the Raymond Basin. Isotopes may be measured for chlorine ($^{37}\text{Cl}/^{35}\text{Cl}$) and oxygen ($^{18}\text{O}/^{17}\text{O}/^{16}\text{O}$) contained in the perchlorate molecule. Stable isotope ratios are reported in δ notation (i.e., “delta”), which represents the difference in measurements between a reference standard and the measured sample. Positive δ values result when the measured sample contains more of the heavy isotope than the standard sample. Negative δ values result when the sample measured contains less of the heavy isotopes than the standard sample. Perchlorate stable isotope ratios for chlorine and oxygen are calculated as follows:

$$\delta^{37}\text{Cl} = [\text{R}_{\text{sample}} / \text{R}_{\text{standard}}] \times 1000$$

where:

$$\text{R}_{\text{sample}} = ^{37}\text{Cl} / ^{35}\text{Cl} \text{ in the sample}$$

$$\text{R}_{\text{standard}} = ^{37}\text{Cl} / ^{35}\text{Cl} \text{ in Standard Mean Ocean Chloride}$$

δ values are reported in ‰ (parts per thousand)

$$\delta^{18}\text{O} = [\text{R}_{\text{sample}} / \text{R}_{\text{standard}}] \times 1000$$

where:

$$\text{R}_{\text{sample}} = ^{18}\text{O} / ^{16}\text{O} \text{ in the sample}$$

$$\text{R}_{\text{standard}} = ^{18}\text{O} / ^{16}\text{O} \text{ in Vienna Standard Mean Ocean Water}$$

$$\delta^{17}\text{O} = [\text{R}_{\text{sample}} / \text{R}_{\text{standard}}] \times 1000$$

where:

$$\text{R}_{\text{sample}} = ^{17}\text{O} / ^{16}\text{O} \text{ in the sample}$$

$$\text{R}_{\text{standard}} = ^{17}\text{O} / ^{16}\text{O} \text{ in Vienna Standard Mean Ocean Water}$$

The $\Delta^{17}\text{O}$ value is a measure of mass-independent fractionation in perchlorate oxygen isotopes and is calculated as follows:

$$\Delta^{17}\text{O} = [[(1 + \delta^{17}\text{O}/1000) / (1 + \delta^{18}\text{O}/1000)^{0.525}] - 1] \times 1000$$

Several studies have evaluated stable perchlorate isotope ratio analysis as a forensic tool for determining the source of perchlorate (i.e., natural or synthetic) in perchlorate-contaminated ground water³. Measuring stable isotope ratios of chlorine and oxygen has been used to distinguish the origin of perchlorate from the following sources⁴.

1. Naturally-occurring perchlorate and nitrate salts found in deposits and fertilizers manufactured from natural salts;
2. Synthetic perchlorate, which is produced through electrolytic oxidation of chloride solutions (i.e., “man made”).

Naturally-occurring perchlorate is found in salt deposits in a number of areas in North America and South America. One of the more widely reported sources of natural perchlorate is the Atacama Desert in Chile. Perchlorate deposits in the Atacama Desert have been extensively mined and used as a source of agricultural fertilizer, which has been imported to Southern California. Synthetic perchlorate is used by military and aerospace for solid-rocket propellant and by a number of other industries for the production of road flares, matches, and munitions.

In literature-reported data⁵, a distinct difference has been found when comparing the $\Delta^{17}\text{O}$ values measured in perchlorate derived from natural and synthetic sources. The $\Delta^{17}\text{O}$ value is a measure of mass-independent fractionation in perchlorate oxygen isotopes. Mass-independent fractionation of perchlorate oxygen isotopes is attributed to atmospheric reactions involving

³ Bao and Gu (2004); Sturchio et al. (2006)

⁴ Bao and Gu (2004)

⁵ Bao and Gu (2004); Sturchio et al. (2006)

ozone, which has high concentrations of ^{17}O . Mass-independent fractionation during synthetic perchlorate manufacturing has been reported to be insignificant. Due to the atmospheric origin of perchlorate found in natural fertilizers, its $\Delta^{17}\text{O}$ values are substantially higher than $\Delta^{17}\text{O}$ values in synthetic perchlorate. Synthetic perchlorate has a 0.0 ± 0.1 ‰ reported $\Delta^{17}\text{O}$ value whereas $\Delta^{17}\text{O}$ values reported for perchlorate found in natural fertilizer range from approximately 9 ‰ to 10 ‰.

Known terrestrial perchlorate fractionation processes such as biodegradation, which have been reported to shift the $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ perchlorate isotope ratios (this occurs in synthetic and natural perchlorate), have not been reported to measurably change $\Delta^{17}\text{O}$ values. For this reason, and due to the substantial separation of $\Delta^{17}\text{O}$ values reported in natural and synthetic sources, $\Delta^{17}\text{O}$ values are a good indicator of perchlorate origin (i.e., natural or synthetic). Because $\Delta^{17}\text{O}$ values are conservative in terrestrial fractionation processes, intermediate $\Delta^{17}\text{O}$ values (i.e., greater than 0.1 ‰ and less than ~8 ‰) have been used to estimate the amount of mixing between natural and synthetic perchlorate.

The $\delta^{37}\text{Cl}$ isotope ratio may also be a useful parameter to distinguish natural and synthetic perchlorate sources. Reported $\delta^{37}\text{Cl}$ values range from -14.5 ‰ to -9.2 ‰ in natural perchlorate sources and from -3.1 ‰ to 1.6 ‰ in synthetic perchlorate.

An annotated bibliography of key documents concerning isotopic analysis of perchlorate is presented in Appendix B.

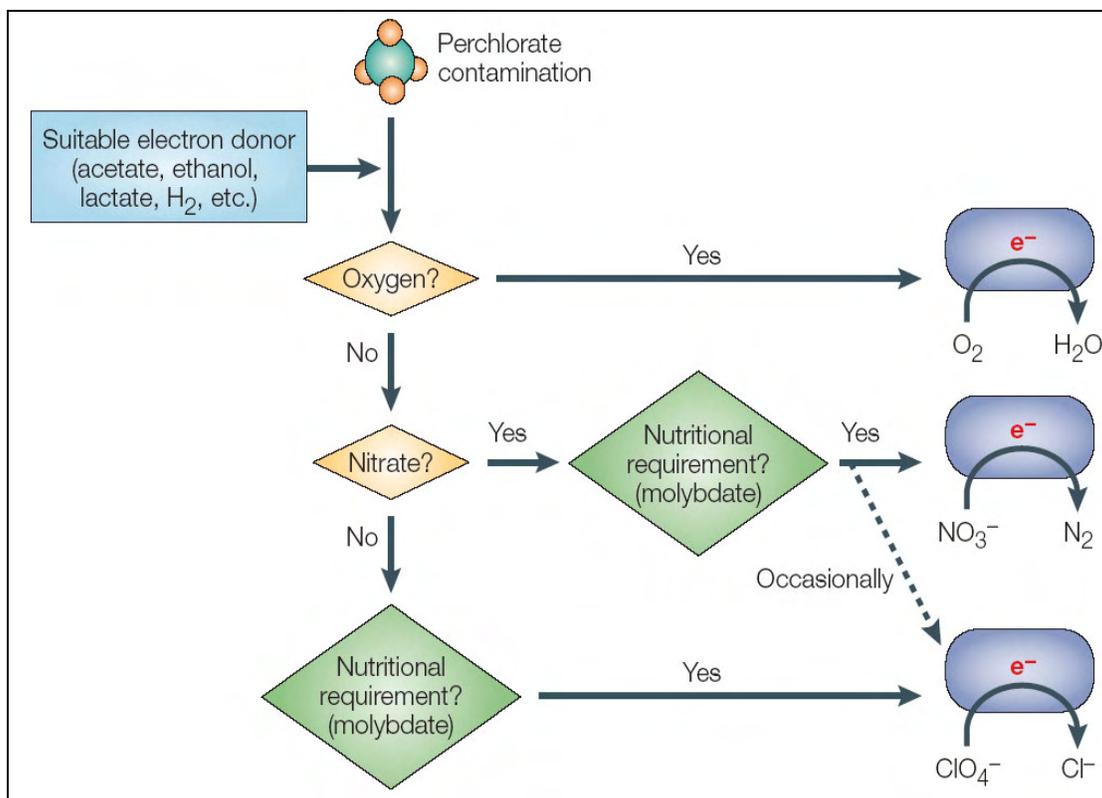
4.1.2 Perchlorate Biodegradation

Perchlorate from natural and synthetic sources may biodegrade in soil and ground water under reducing conditions and in the presence of a suitable electron donor (Sturchio et al., 2007, Coates and Achenbach, 2004, Coleman et al., 2003). Perchlorate biodegradation reduces chlorine contained in perchlorate to a chloride end product. A diverse group of microorganisms capable

of reducing perchlorate are ubiquitous in soil and ground water. Therefore, biological reduction of perchlorate will usually occur in soil and ground water under the following conditions:

1. An electron donor source is present and;
2. Preferential electron acceptors—oxygen and usually nitrate—are first depleted.

The following figure shows a schematic illustration of the conditions required for biological perchlorate reduction to occur. Electron donors may consist of a wide range of organic substrates, which include the assimilable organic carbon fraction of natural organic matter. Biological perchlorate reduction may also occur using hydrogen as the electron donor. Dissolved oxygen (DO) is always first used as an electron acceptor; when depleted, nitrate will then be used as the usual preferential electron acceptor before perchlorate. Chaudhuri et al (2002) reported that perchlorate reduction was completely inhibited at DO levels greater than 2 mg/L. Nitrate reduction usually occurs before perchlorate reduction although some perchlorate-reducing microorganisms have been reported to concurrently degrade perchlorate and nitrate (Coates and Achenbach, 2004).



Conditions required for biodegradation of perchlorate (Coates and Achenbach, 2004)

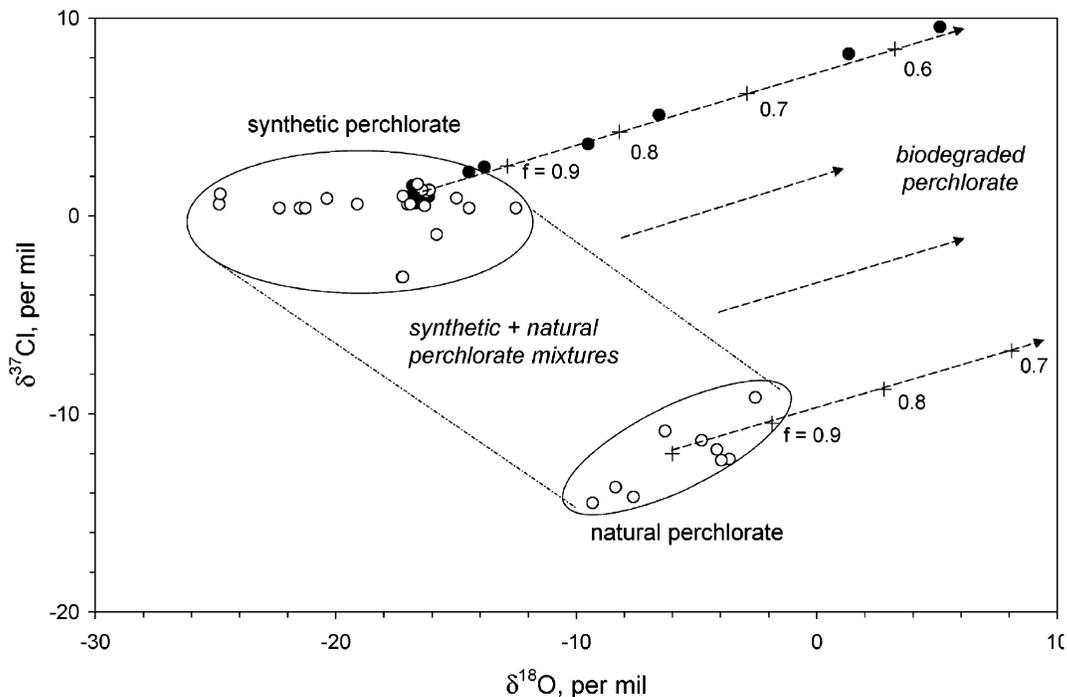
4.1.3 Shifts in Perchlorate Stable Isotope Ratio Resulting from Perchlorate Biodegradation

Several studies have shown that perchlorate isotopic composition changes when biodegradation occurs (Sturchio et al., 2007, Hatzinger et al., 2009). When perchlorate undergoes biodegradation, $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ isotope ratios move along a line towards more positive values of both $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$. This isotopic shift has been observed in both laboratory and field studies.

The following figure shows how the ratio of $\delta^{18}\text{O}/\delta^{37}\text{Cl}$ in natural and synthetic perchlorate shifts as biodegradation progresses⁶. The dashed-lines shown in the following figure represent the direction of shift in $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ as biodegradation occurs. Based on field and laboratory

⁶ This figure is based on data measured under laboratory conditions and is used to show the qualitative effect of biodegradation on stable perchlorate isotope ratios; data from field studies show a similar slope in isotopic shift; however, the magnitude of isotopic shift is substantially less than that shown in the figure.

studies, the slope of the line corresponding to the $\delta^{18}\text{O}/\delta^{37}\text{Cl}$ shift is relatively constant and has been reported to range between 2.4 to 2.6. However, the magnitude of isotopic shift which has been reported to occur may vary substantially. Studies conducted using pure cultures and under laboratory conditions showed a substantially larger shift than studies conducted in situ (Sturchio et al., 2007, Hatzinger et al., 2009).



Isotopic shift of synthetic and natural perchlorate undergoing biodegradation (Sturchio et al., 2007)

The “f” values shown in the figure (see dashed lines) indicate the remaining fraction of the original perchlorate remaining in solution. The fraction of perchlorate, which has been biodegraded, is equal to 1-f. For example, a synthetic perchlorate sample, which has been biodegraded by 20 percent would shift along the dashed line shown in the following figure from the beginning of the line (at $f = 1$ where no biodegradation has occurred) to the point shown at $f = 0.8$.

A shift in the same direction and with a similar slope would occur for a natural perchlorate source or for a mixture of natural and synthetic perchlorate. Based on the relationship shown in the above figure, the isotopic shift, which occurs from mixing natural and synthetic perchlorate sources, may be distinguished from the shift occurring from biodegradation as they would be approximately perpendicular to each other.

4.2 Methods and Calculations

4.2.1 Source of Perchlorate Isotope Data

The perchlorate isotope data used in the analysis were obtained from NASA (2007) and are listed in the following table. Isotope data ($\delta^{18}\text{O}$, $\delta^{37}\text{Cl}$, and $\Delta^{17}\text{O}$) was reported from 12 samples collected from wells in the Sunset Reservoir area and the JPL area. Isotopic data for other perchlorate sources (i.e., the BMI complex in Henderson, NV), which were measured in other studies, were also reported in the 2007 TM.

Summary of Wells Used by NASA (2007) for Perchlorate Analyses

Sample Location	Sample Date	Perchlorate Source as Attributed by NASA	Perchlorate Isotope Concentrations		
			$\delta^{18}\text{O}$ [‰]	$\delta^{37}\text{Cl}$ [‰]	$\Delta^{17}\text{O}$ [‰]
LAWC No. 3	3-Jun-05	JPL	-20.4	0.21	-0.3
MW-16	9-Feb-06	JPL	-21.8	0.4	0.023
MW-16	22-Nov-06	JPL	-20.7	0.1	-0.2
OUI-IN	22-Nov-06	JPL	-19.3	0.3	0.1
Bangham	2-Jun-05	Non-JPL	-10.2	-3.01	1.27
LFWC No. 2	3-Jun-05	Non-JPL	-13.4	1.1	-0.13
MW-19 zone 2	20-Jul-05	Non-JPL	-18.2	0.48	0.17
MW-25 zone 1	19-Jul-05	Non-JPL	-18.7	2.05	0.83
MW-25 zone 2	19-Jul-05	Non-JPL	-16.3	0.18	2
MW-25 zone 3	19-Jul-05	Non-JPL	-16.8	0.06	2.01
MW-25 zone 4	19-Jul-05	Non-JPL	-17.2	2.19	0.99
Sunset	2-Jun-05	Non-JPL	-17.8	0.27	-0.06
BMI Archive 1†	NA	Henderson, NV	-17.1	0.3	0
BMI Archive 2†	NA	Henderson, NV	-16.9	0.3	0
BMI Archive 3†	NA	Henderson, NV	-16.7	0.2	0
BMI Archive 4†	NA	Henderson, NV	-16.3	0.7	0
BMI Archive 5†	NA	Henderson, NV	-15.7	1.3	0
BMI Ground water†	NA	Henderson, NV	-15	0.8	0.02
Las Vegas Wash†	NA	Henderson, NV	-14.5	0.4	0

‰ - parts per thousand

† Approximate values estimated from Figures 16 and 17 of the 2007 NASA TM.

Source: NASA, 2007.

4.2.2 Statistical Analysis of Perchlorate Stable Isotope Data

A statistical analysis was performed to evaluate the isotopic signature of the Sunset Reservoir area perchlorate relative to both the JPL-attributed perchlorate and the imported Colorado River water perchlorate. The following statistical analysis tests the null hypotheses:

Null Hypotheses:

1. *The perchlorate measured in Sunset Reservoir area wells has the same isotopic signature as perchlorate found in the JPL wells*
2. *The isotopic signature of perchlorate in the Sunset Reservoir area wells is not related to imported water perchlorate which has been subject to biodegradation.*

4.2.2.1 Distribution of Data and Tests for Normality

The first step in the statistical analysis was determining the distribution of the isotope data to select an appropriate statistical test. Probability plots were made to determine whether the data were distributed normally, log-normally, or non-normally (U.S. EPA, 1992). Data for the plots were obtained from wells in the Sunset Reservoir area wells, JPL-attributed perchlorate, and BMI Complex perchlorate. Individual probability plots were made of the $\delta^{18}\text{O}$ data and $\delta^{37}\text{Cl}$ data (see Figures 34 through 39) by plotting the isotopic concentration on the x-axis versus the normal quantile⁷ on the y-axis. The normal quantile was calculated as:

$$y = \Phi^{-1}\left(\frac{i}{n+1}\right)$$

Where:

Φ^{-1} = the inverse of the cumulative Normal distribution.

n = the sample size.

i = rank of the ith ordered concentration.

If the data followed a normal distribution, the observations approximate a straight line on a probability plot. When plotted on a probability plot, the $\delta^{18}\text{O}$ data generally followed a straight line and were determined to have a normal distribution (see Figures 34 and 35). The $\delta^{37}\text{Cl}$ data on the other hand did not approximate a straight line and were determined to have either a non-

⁷ In probability theory, a quantile function of a probability distribution is the inverse F^{-1} of its cumulative distribution function (cdf) F.

normal or log-normal distribution (see Figures 36 and 37). To test for a log-normal distribution, the isotopic concentrations were transformed to their natural log and the normal quantiles were then calculated for the natural log of the data. The $\log \delta^{37}\text{Cl}$ data were found to be normally distributed (see Figures 38 and 39).

4.2.2.1.1 Tests for Normality: Anderson-Darling, Ryan-Joiner, and Kolomogov-Smirnov

Three additional tests of normality were performed using the statistical software *Minitab® 15*. These three tests of normality were the Anderson-Darling, Ryan-Joiner, and Kolomogov-Smirnov tests. All three tests serve to reject or accept the assumption that the data are normally distributed. This assumption is rejected when the p-value generated by the test is less than an alpha⁸ level of 0.05. The results are summarized in the following table:

⁸ Alpha is the probability of rejecting the hypothesis tested when that hypothesis is true. In this case, an alpha level of 0.05 was used (i.e., a probability of 95%).

Results of Normal Distribution Tests

Test	Data Set	Isotope	p-value	alpha	Distribution
Anderson-Darling	JPL Source Wells and Sunset Reservoir Area Wells	$\delta^{18}\text{O}$	0.343	0.05	normal
Ryan-Joiner		$\delta^{18}\text{O}$	>0.100	0.05	normal
Kolmogov-Smirnov		$\delta^{18}\text{O}$	>0.150	0.05	normal
Anderson-Darling		$\delta^{37}\text{Cl}$	<0.010	0.05	non-normal
Ryan-Joiner		$\delta^{37}\text{Cl}$	<0.010	0.05	non-normal
Kolmogov-Smirnov		$\delta^{37}\text{Cl}$	<0.010	0.05	non-normal
Anderson-Darling		Log $\delta^{37}\text{Cl}$	>0.150	0.05	normal
Ryan-Joiner		Log $\delta^{37}\text{Cl}$	>0.100	0.05	normal
Kolmogov-Smirnov		Log $\delta^{37}\text{Cl}$	>0.150	0.05	normal
Anderson-Darling	BMI Complex and Sunset Reservoir Area Wells	$\delta^{18}\text{O}$	0.058	0.05	normal
Ryan-Joiner		$\delta^{18}\text{O}$	0.034	0.05	non-normal
Kolmogov-Smirnov		$\delta^{18}\text{O}$	0.068	0.05	normal
Anderson-Darling		$\delta^{37}\text{Cl}$	<0.005	0.05	non-normal
Ryan-Joiner		$\delta^{37}\text{Cl}$	<0.010	0.05	non-normal
Kolmogov-Smirnov		$\delta^{37}\text{Cl}$	<0.010	0.05	non-normal
Anderson-Darling		Log $\delta^{37}\text{Cl}$	0.883	0.05	normal
Ryan-Joiner		Log $\delta^{37}\text{Cl}$	>0.150	0.05	normal
Kolmogov-Smirnov		Log $\delta^{37}\text{Cl}$	>0.100	0.05	normal

As can be seen in the above table, the results of these three tests of normality were generally consistent. For both data sets the results show that:

- $\delta^{18}\text{O}$ data are normally distributed and;
- $\delta^{37}\text{Cl}$ data are log-normally distributed.

4.2.2.2 Two Sample t-test Assuming Unequal Variance

Based on the normal distribution for $\delta^{18}\text{O}$ and the log-normal distribution for $\delta^{37}\text{Cl}$, a two-sample t-test assuming unequal variance was chosen as the statistical method. The two-sample t-test was chosen because it is suitable for small data sets that are independent of each other (Spiegel, 1961, and Davis, 1986). The two-sample t-test determines if statistically significant differences exist between the means of two data sets (i.e., stable isotopes of the JPL wells and Sunset area wells). A t-test can be performed assuming that the two data sets have

equal or unequal variance. If equal variance is assumed, the sample standard deviations from each data set are pooled to obtain a single estimate of standard deviation. Assuming equal variance produces a more powerful statistical result; however, serious error can occur if the variances are not equal (Minitab 15, 2007). For purposes of the statistical test, unequal variance was assumed because the variance between data sets was generally not the same.

The t-test accepts or rejects the null hypothesis (i.e., that there is no significant difference between the perchlorate measured in the Sunset Reservoir area wells and the JPL-attributed and BMI Complex perchlorate). The t-test does this by comparing the t-test statistic “t” to a critical t-value. The critical t-value is dependant on the degrees of freedom (df) of the two data sets where $df = n-2$, and the designated level of significance (95%). If the absolute value of the t-test statistic “t” is less than or equal to the critical t-value than the null hypothesis is accepted (i.e., cannot be rejected).

The t-test assuming unequal variance (Coombs et. al., 1996 as cited in Ruxton, 2006) may be calculated as follows:

$$t = \frac{\mu_1 - \mu_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where:

μ = mean of data set 1 and 2

s = variance of data set 1 and 2

n = number of observations in data set 1 and 2

4.2.3 Estimates of Shift in Stable Perchlorate Isotope Ratios from Biodegradation

When perchlorate biodegradation occurs, the $\delta^{18}\text{O} / \delta^{37}\text{Cl}$ ratio shifts along a line having consistent slope (discussed in Section 4.1.3). The amount of isotopic fractionation, which occurs from perchlorate biodegradation, is commonly expressed in terms of an isotopic fractionation

factor ($\epsilon^{18}\text{O}$ and $\epsilon^{37}\text{Cl}$). Sturchio et al. (2007) reported a fractionation factor ratio ($\epsilon^{18}\text{O}/\epsilon^{37}\text{Cl}$) ranging from 2.46 (at 10°C) to 2.5 (at 22°C) based on laboratory studies of perchlorate-reducing organisms isolated from samples taken at the JPL site. Hatzinger et al. (2009) reported a similar fractionation factor ratio (~2.6) for perchlorate biodegradation measured in field studies. Although the fractionation factor ratios were similar in laboratory and field studies, the magnitude of the $\epsilon^{18}\text{O}$ and $\epsilon^{37}\text{Cl}$ fractionation factors were substantially higher in laboratory studies as compared to field studies. Reported perchlorate fractionation factors from laboratory studies ranged from -29 to -36.6 for $\epsilon^{18}\text{O}$ and from -11.5 to -14.6 for $\epsilon^{37}\text{Cl}$ (Sturchio et al., 2007). Reported perchlorate fractionation factors reported from field studies ranged from -8.1 to -12 for $\epsilon^{18}\text{O}$ and from -3.1 to -4.6 for $\epsilon^{37}\text{Cl}$ (Hatzinger et al., 2009).

Shifts in the $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ stable isotope ratios occurring from biodegradation were calculated as follows (Sturchio et al., 2007 and Hatzinger et al., 2009):

$$\delta_f = [(f^{\alpha-1}) * (\delta_0 + 1)] - 1$$

Where:

δ_f = the isotopic concentration at any value of f

f = fraction of perchlorate isotope remaining

δ_0 = initial isotopic concentration before degradation (at f = 1)

$\alpha - 1 = \epsilon / 1000$; the minimum isotopic fraction factors given by Hatzinger et al. (2009) where $\epsilon^{18}\text{O} = -8.1$ and $\epsilon^{37}\text{Cl} = -3.1$

As an example, an estimate of the isotopic shift resulting from 10-percent biodegradation in LAWC No. 3, where the initial concentration of $\delta^{18}\text{O}$ was -20.4 ‰ and the initial concentration of $\delta^{37}\text{Cl}$ was 0.21 ‰, would be calculated as follows:

For $\delta^{18}\text{O}$ fractionation:

$$\delta_f = ((0.9^{(-8.1/1000)} * ((-20.4/1000)+1))-1)*1000 = -19.56 \text{‰}$$

For $\delta^{37}\text{Cl}$ fractionation:

$$\delta_f = ((0.9^{(-3.1/1000)} * ((0.21/1000)+1))-1)*1000 = 0.54\text{‰}$$

4.3 Evaluation of Perchlorate Biodegradation in Raymond Basin Ground Water

4.3.1 Extent of Reducing Ground Water Conditions in the Raymond Basin

Available water quality data were surveyed to determine the extent of reducing conditions in Raymond Basin ground water, which would be amenable to perchlorate biodegradation (see Table 1). The sources of available data surveyed are listed in Section 2.3 and include historical water quality data from NASA / JPL quarterly monitoring reports (Foster Wheeler Environmental Corporation, 1997-2000; Sota Environmental Technologies, Inc., 2001-2002; GEOFON, Inc., 2003-2004; and Battelle, 2005-2009). A review of analytical procedures used in the 2007 NASA TM for collecting ground water quality data is included in Appendix C.

As previously discussed, perchlorate biodegradation is known to occur under reducing conditions and in the presence of a suitable electron donor. Measurements of DO, Oxidation Reduction Potential (ORP), and dissolved iron were used as indicators of reducing conditions in ground water. The following table lists the literature-reported DO and ORP values which are considered to be amenable for perchlorate biodegradation.

Summary of Literature-Reported Water Quality Conditions Conducive to Perchlorate Degradation

Reference	Values Favorable to Perchlorate Biodegradation		
	pH (pH units)	Dissolved Oxygen (mg/L)	ORP Upper Threshold (mV)
Lieberman, et al. (2008)	6 to 8	< 1	-
Interstate Technology & Regulatory Council (2008)	6.5 to 7.5	-	0
Hagström (2006)	-	< 1	0

ORP = oxidation-reduction potential.

Dissolved iron is an indication of reducing conditions as the solubility of the reduced form of iron (ferrous iron; Fe^{2+}) is several orders of magnitude higher than the oxidized form of iron (ferric iron Fe^{3+}). Ferric iron solubility is pH dependant; however, at the pH levels found in ground water, ferric iron solubility is generally less than ~0.1 mg/L. Therefore, if dissolved iron is present in a ground water sample, it is indicative of reducing conditions. For the purposes of this analysis, a 0.5-mg/L iron level was used as a conservative value to indicate reducing ground water conditions.

The following table lists a summary of the JPL monitoring wells surveyed and the number of DO, ORP, and dissolved iron measurements in each well, which show reducing conditions amenable to perchlorate biodegradation. Historical water quality data from 1999 and 2003-2009 were used for DO, data from 2003-2009 were used for ORP, and historical monitoring data from 1996-2009 were used for iron. Out of the 26 JPL monitoring wells surveyed, 24 showed reducing conditions amenable to perchlorate biodegradation (i.e., $\text{ORP} < 0$ mV, $\text{DO} < 1$ mg/L, or $\text{iron} > 0.5$ mg/L). JPL's historical quarterly monitoring data showed that out of 1,320 samples there were 205 reported ORP measurements less than 0 mV, 62 DO measurements less than 1 mg/L, and 400 reported iron measurements greater than 0.5 mg/L.

**Summary of JPL Monitoring Wells in the Raymond Basin
With Conditions Favorable for Perchlorate Biodegradation**

Well Name	Number of pH Measurements Ranging from 6.0 to 8.0 pH Units	Number of DO Measurements ≤ 1.0 mg/L	Number of ORP Measurements ≤ 0 mV	Number of Total Iron Measurements ≥ 0.50 mg/L
JPLMW-1	18	-	-	2
JPLMW-3	31	3	9	33
JPLMW-4	23	5	10	51
JPLMW-5	24	-	2	6
JPLMW-6	37	-	-	6
JPLMW-7	30	1	2	7
JPLMW-8	41	-	2	1
JPLMW-9	17	-	-	3
JPLMW-10	36	-	-	1
JPLMW-11	38	6	16	23
JPLMW-12	36	4	12	21
JPLMW-13	38	1	2	1
JPLMW-14	34	5	6	27
JPLMW-15	41	1	3	-
JPLMW-16	40	1	1	-
JPLMW-17	18	1	7	40
JPLMW-18	40	2	12	8
JPLMW-19	25	8	11	49
JPLMW-20	34	-	48	7
JPLMW-21	44	7	3	26
JPLMW-22	19	6	13	21
JPLMW-23	35	3	7	26
JPLMW-24	35	3	19	33
JPLMW-25	28	3	18	5
JPLMW-26	9	2	2	3

Source: NASA Quarterly Monitoring Reports (1999 - 2009).

Figures 40, 41, and 42 show monitoring wells in the vicinity of JPL and in the Sunset Reservoir area, which show reducing conditions amenable to perchlorate biodegradation. The majority of monitoring wells in the JPL area show some indication of reducing ground water conditions. The two monitoring wells in the vicinity of the Sunset Reservoir (MW-25 and MW-26) both show DO, ORP, and iron values, which indicate reducing ground water. A more detailed discussion of DO, ORP, and iron levels measured in the JPL monitoring wells is given in the following sections.

4.3.1.1 Dissolved Oxygen

Figure 43 shows a “box-and-whisker” plot of DO data measured in JPL monitoring wells in 1999 and a six-year period from 2003 to 2009. The box-and-whisker plot shows a box representing the 25th percentile, median, and 75th percentile values for the data set. The whisker shows the minimum and maximum values in the data set. DO data measured in JPL monitoring wells showed substantial variability with most wells ranging from low values, which were less than 1 mg/L to values exceeding 20 mg/L. The median DO values were on the order of 10 mg/L and suggest that samples were marginally supersaturated with respect to DO levels measured at atmospheric pressure.

Measuring DO in anoxic well water requires using techniques where water samples are not exposed to air during field measurements. Sampling protocols described by NASA in the 2007 TM did not provide details of the procedures used to collect and measure DO samples, so it is not known how the field-measured DO data may have been biased by sampling procedures. If samples were collected in an open container, and not in a flow through cell, then air exchange would have occurred in the sample. The effect of air exchange during sample measurement would be to increase the DO levels in samples below ~9 mg/L and lower DO levels in samples greater than ~9 mg/L. The reported data are likely conservative with respect to DO as improper sampling techniques would have tended to increase the reported DO levels in anoxic ground water.

4.3.1.2 Oxidation-Reduction Potential

Figure 44 shows a box-and-whisker plot for ORP data measured in NASA monitoring wells in from 2003 to 2009. Based on literature-reported values, a negative ORP was assumed to be amenable to perchlorate biodegradation. A clear decreasing trend in ORP values can be seen in several of the monitoring wells as a function of depth. MW-20, which is located between the Sunset Reservoir area and JPL, shows the largest decrease in ORP as a function of sampling depth. Median ORP values in MW-20 decrease from approximately 50 mV in the upper zone (zone 1) to below -100 mV in the lowermost zone (zone 5). MW-22 and MW-25 have at least

one zone with a median ORP value conducive to perchlorate biodegradation (less than 0 mV). Most of the wells show some reported ORP data below the threshold value for perchlorate biodegradation.

ORP is a non-specific indicator of the state of all reductants and oxidants in a sample. Common reductants in ground water include dissolved iron, dissolved manganese, reduced sulfur (e.g., sulfide), and reduced nitrogen (e.g., ammonia). Oxidants in natural environments are usually limited to DO. ORP values are influenced by a number of parameters including the species and concentrations of oxidants and reductants as well as the sample pH. ORP is a pH-dependant parameter and will vary by roughly 30-60 mV for every 10-fold change in pH (e.g., pH 6 to pH 7). There is no practical method for normalizing ORP values with respect to pH without knowing the concentration of all oxidizing and reducing species in solution; therefore, data shown in Figure 41 were not normalized with respect to pH.

There is a disparity in the reported DO and ORP for some of the wells. For example, MW-20 shows consistently low ORP levels; however, the reported DO values are all above 1 mg/L. One possible explanation for the conflicting data is that dissolved oxygen was introduced to the sample during the sampling procedure. If this were the case, then the DO value may have been high; however, slowly-oxidizing⁹ reduced species (e.g., iron and/or manganese) would still be present. Because ORP reflects the presence of all reduced and oxidized species in solution, a low ORP may have been accurately measured even if DO were present.

4.3.1.3 Dissolved Iron

Most of the iron data reported in the JPL monitoring reports were total iron (i.e., not filtered before analysis) and some analyses were conducted specifically for reduced iron (Fe^{2+}). In ground water with low turbidity which does not produce sand or silt, total iron measurements may be used as a rough approximation of dissolved iron. As mentioned previously, a high

⁹ Iron oxidation is pH dependent; at pH 7 and at a 9-mg/L DO level, reduced iron oxidizes on the order of minutes and at pH 8, reduced iron oxidizes on order of seconds.

dissolved iron concentration implies the presence of reduced iron due to the low solubility (<0.1 mg/L) of oxidized iron (Fe^{3+}) at pH levels usually seen in ground water.

Figure 45 shows a box-and-whisker plot for iron measured in JPL monitoring wells from 1996 to 2009. A conservative estimate of 0.5 mg/L total iron was used as an indicator of the presence of reduced iron. Ten of the 26 JPL monitoring wells show one or more zones with median iron values above 0.5 mg/L, which indicates reducing conditions amenable to perchlorate biodegradation. MW-4, MW-17, and MW-23 each showed one zone having a 25th percentile value above 0.5 mg/L. Most of the 26 monitoring wells reported some iron results above 0.5 mg/L.

4.3.2 Direct Evidence of Limited Perchlorate Biodegradation in Raymond Basin Ground Water

Reported measurements, which would show direct evidence of anaerobic respiration (i.e., biological reduction of nitrate, perchlorate, and sulfate) were only available from one sampling event in 2005 involving seven JPL monitoring wells. Samples collected from varying depths in JPL monitoring wells were analyzed for a range of parameters including perchlorate, nitrate, ammonia, and sulfide, and for biodegradation end products including ammonia, nitrite, and sulfide. Out of the seven JPL monitoring wells sampled, two wells (MW-20 and MW-25) showed evidence of perchlorate biodegradation in the lower zones.

Figure 46 shows a vertical-profile plot of ammonia, sulfide, nitrate, perchlorate, and ORP measured at five different depths in MW-20. MW-20 is located south-east of JPL and north of the Sunset Reservoir area. Nitrate levels measured in MW-20 decreased from approximately 6 mg/L in the upper zones to below the 0.1-mg/L Method Reporting Limit (MRL) in the two lower zones. Perchlorate marginally decreased from detectable levels in the upper zone to levels below the 4- $\mu\text{g/L}$ MRL in the four lower zones. In the three lowermost zones of MW-20, mean ORP values are conducive to perchlorate biodegradation. The presence of ammonia measured in Zone 2 and Zone 3 suggest dissimilatory nitrate reduction may be occurring. The presence of

sulfide in Zone 4, along with the absence of nitrate and perchlorate, and low ORP is a strong indication that active biological sulfate reduction is occurring.

Biological sulfate reduction occurs subsequent to nitrate and perchlorate; therefore, perchlorate and sulfate would be first consumed. Sulfate data reported for MW-20 shows a decreasing trend with depth: sulfate decreases from approximately 80 mg/L in the upper zone to 5 mg/L in the lower zone. The decrease in sulfate concentration in the lower zones is consistent with biological sulfate reduction, which uses sulfate as an electron acceptor and converts it to a reduced-sulfur end product (e.g., sulfide).

Figure 47 shows a vertical-profile plot of ammonia, sulfide, nitrate, perchlorate, and ORP measured at five different depths in MW-25, which is located near the City of Pasadena's Sunset Wells. ORP values seen in lowermost zone in MW-25 are conducive to perchlorate biodegradation. The depth profile of nitrate shows a reduction from 13 mg/L in the upper zone to below the 0.1 mg/L MRL in the lower zone. Perchlorate shows a similar vertical profile to nitrate where a ~10 mg/L perchlorate was measured in the upper zone and ~4 mg/L was measured in the lower zone. Ammonia was measured in the upper zone suggesting that nitrate reduction may possibly be occurring. Reducing conditions of the lower zone in MW-25 coupled with the depletion of nitrate suggest that biological reduction is occurring in the lower zone.

4.3.2.1 Implications of Functional Genomic Testing

Results of function genomic testing conducted in the Monk Hill and Sunset Reservoir area were presented in the 2007 NASA TM. Nine wells were tested for the presence and activity of perchlorate reducing bacteria. The following table summarizes the results of function genomic testing presented in the 2007 NASA TM:

Results of Functional Genomic Testing Presented in the NASA 2007 TM

Sample	Presence of <i>cld</i> Gene	Presence of <i>cld</i> mRNA
Garfield	Absent	Absent
Sunset	Present	Absent
Bangham	Absent	Absent
LAWC No. 3	Absent	Absent
MW-1	Present	Present
LFWC No. 2	Present	Absent
MW-24-1	Present	Present
MW-25-3	Present	Absent
MW-17-3	Present	Absent

Bender et. al. (2002) established a method of detecting the presence and activity of perchlorate reducing bacteria in the environment using functional genomics. They targeted a gene that codes for the production of chlorite dismutase (CD), an enzyme essential in the chemical pathway for perchlorate reduction. This enzyme has been found to be present on the outer membrane of perchlorate reducing bacteria, even when they were not actively reducing perchlorate (Bender et. al. 2002). However, the production of this enzyme is regulated by environmental conditions. In laboratory experiments, *cld* activity decreased when oxygen was applied to a previously anaerobic environment. Similarly, *cld* activity increased when oxygen was replaced with nitrogen (Chaudhuri et. al., 2002). This change in *cld* activity with environment means that measuring the *cld* mRNA, which control CD can serve as a measure of perchlorate reduction activity.

The functional genomics testing suggest that perchlorate reducing bacteria are ubiquitous in JPL ground water, which would be expected. The mRNA testing shows *cld* activity in two of nine wells, but without detailed sampling narratives, it cannot show lack of activity. Also, mRNA activity—suggesting that perchlorate reduction was occurring—was measured in MW-1, which is upgradient of any known perchlorate contamination.

Exposure to oxygen stops *cld* activity (Chaudhuri et. al. 2002). Evaluation of DO and ORP data in NASA monitoring wells show that low ORP values were reported with high DO for some samples. This suggests that ground water samples collected from monitoring wells likely had some DO, which would diminish *cld* activity. As previously discussed, DO could have been introduced during sample collection. In summary, the functional genomics testing presented in the 2007 TM does not provide conclusive evidence regarding the presence or absence of active perchlorate biodegradation.

4.4 Perchlorate Biodegradation in Imported Water

4.4.1 Overview of Colorado River Conveyance System

Metropolitan supplies imported water to the Utilities in the Raymond Basin, including the City of Pasadena. Water imported to the Raymond Basin from Metropolitan originates from the California State Water Project Canal and from the Colorado River. Historically, Colorado River water imported to Southern California contained low-levels of perchlorate resulting from synthetic perchlorate production at the Kerr-McGee facility (BMI complex) in Henderson NV. Metropolitan has been monitoring perchlorate in Colorado River water since 1997.

Imported water from the Colorado River flows through a 240-mile conveyance from Lake Havasu on the Colorado River to Lake Mathews located in Riverside County, CA. Lake Mathews serves as the terminus for the Colorado River aqueduct and is one of Metropolitan's main water storage Reservoirs. Water from Lake Mathews is then sent to the Weymouth water treatment plant in La Verne, CA. Treated water is then supplied to the City of Pasadena and other utilities in Southern California. Figure 48 shows a map of the Colorado River, the Colorado River aqueduct, Lake Mathews, and other conveyance and distribution within southern California.

4.4.2 Perchlorate Biodegradation in Lake Mathews

At the outlet tower, Lake Mathews is over 130 ft deep and, due to this depth, seasonal stratification occurs in the lake. When stratification occurs, lower zones in the lake become anoxic and anaerobic biodegradation occurs. The outlet tower has nine discrete outlet ports and water may be released from a combination of ports; the outlet ports are also used to obtain depth-profile water quality samples in the Lake.

Historical water quality monitoring data collected at Lake Mathews were analyzed to determine if perchlorate biodegradation is occurring in Lake Mathews. Data used for the analysis were measured by Metropolitan's Water Quality Division as part of their reservoir management program (see Appendix D). Historical dissolved oxygen, perchlorate, and nitrate data from 1997 to 2009 were analyzed from Lake Mathews.

Figure 49 shows a box-and-whisker plot for perchlorate data measured at Lake Havasu, the West Portal of the San Jacinto Tunnel, and the Outlet of Lake Mathews. Data shown in Figure 49 are based on monthly perchlorate measurements taken from 1997 to 2009 (see Table 2). Median perchlorate levels in the Colorado River Conveyance remain relatively constant (approximately 5 µg/L) from Lake Havasu to the West Portal of the San Jacinto Tunnel suggesting that perchlorate levels are not changing in the Colorado River Aqueduct. A lower perchlorate median is seen at the outlet of Lake Mathews (approximately 4 µg/L) based on the 1997-2009 data set.

Figure 50 shows a box-and-whisker plot of the DO profile in Lake Mathews based on monthly monitoring data collected from 1988 to 2009. The DO profile shows a consistent trend with respect to depth where deeper zones have progressively lower DO levels. Closer examination of the data used to develop DO profiles shows seasonal effects where stratification occurs and lower portions of the lake become anoxic. Based on the yearly averages, DO levels conducive to perchlorate biodegradation (< 1 mg/L) occur from the 50-60 ft depth to the lowermost,

120-130 ft depth. Conditions favoring perchlorate biodegradation are not seen above 50 ft in Lake Mathews.

A vertical profile of perchlorate measured at the Lake Mathews outlet tower is shown in Figure 50. Three depth profiles are shown in Figure 50, which were measured in October 1997, April 1998, and October 1998. The perchlorate depth profiles:

1. Show that perchlorate biodegradation is occurring in the lower portion of Lake Mathews and;
2. Show the effect of seasonal stratification on the perchlorate profile.

Perchlorate depth-profile measurements taken during October 1997 and October 1998 show that perchlorate exists in the upper levels and is below detection limits in the lower portions of the Lake. This result shows that perchlorate is biodegraded in the lower portions of Lake Mathews. The perchlorate profile is consistent with the measured DO where perchlorate is measured at depths where oxygen exists and is depleted in the lower, anoxic zones. The perchlorate depth profile measured in April 2008 illustrates that perchlorate is measured at deeper levels in the lake as the lower portions of the lake contain more oxygen during spring. Depth profiles of nitrate support the conclusion that anaerobic biological reduction is occurring in Lake Mathews. Nitrate depth profiles show depletion of nitrate (< 0.1 mg/L) in the lower zones. Additionally, detectable levels of nitrite (> 0.02 mg/L) and ammonia (> 0.2) are present in the lower zones, which indicate active biological nitrate reduction is occurring.

4.5 Perchlorate Origin in the Sunset Reservoir Area Wells

4.5.1 Stable Isotope Ratios of Natural and Synthetic Perchlorate

The following table lists the range of literature-reported $\delta^{18}\text{O}$, $\delta^{37}\text{Cl}$, and $\Delta^{17}\text{O}$ perchlorate isotope ratios found in synthetic and natural perchlorate. The synthetic perchlorate isotope ranges shown in the following table are based on measurements of laboratory-grade synthetic perchlorate and commercial-grade synthetic perchlorate. Commercial-grade synthetic

perchlorate is used in the manufacture of solid propellant fuel for rockets, munitions, road flares, and fireworks. The natural perchlorate ranges are based on samples collected from perchlorate salt deposits in the Atacama Desert in Chile and from commercial fertilizers (which are manufactured using Atacama deposits). Chilean fertilizer has been imported and used extensively in Southern California.

Range of Isotopic Concentrations of Natural and Synthetic Perchlorate Sources

	Range of $\delta^{18}\text{O}$ [‰]	Range of $\delta^{37}\text{Cl}$ [‰]	Range of $\Delta^{17}\text{O}$ [‰]	Source
Natural Perchlorate	-9.3 to -2.2	-14.5 to -9.2	9 to 10	Böhlke et al., 2005; Sturchio et al., 2006
Synthetic Perchlorate	-24.8 to -12.5	-3.1 to 1.6	0 ± 0.1	Böhlke et al., 2005; Sturchio et al., 2006

‰ - parts per thousand

Figure 51 shows a plot of the oxygen and chlorine stable perchlorate isotope data reported in the 2007 TM and the reported isotopic ranges for natural and synthetic perchlorate (shown as shaded boxes in the figure). Most of the data measured in JPL monitoring wells and Raymond Basin production wells are within the reported isotopic range of synthetic perchlorate. MW-25 shows two Zones (1 and 4), which are within the reported range for $\delta^{18}\text{O}$; however, are approximately 1 ‰ above the upper-bound of the reported range for $\delta^{37}\text{Cl}$ in synthetic perchlorate. The $\delta^{37}\text{Cl}$ value reported for the Bangham well (-3.01‰) is at the lower range of values reported for synthetic perchlorate. The $\delta^{18}\text{O}$ value reported for the Bangham well is outside (by 2.3‰) the upper range reported for synthetic perchlorate.

The region that corresponds to mixtures of natural and synthetic perchlorate is shown in Figure 51. Reported $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ isotope data for the Bangham well suggest that some mixing with natural perchlorate may have occurred. Natural perchlorate has distinctive $\Delta^{17}\text{O}$ values when compared to synthetic perchlorate. Literature-reported natural perchlorate $\Delta^{17}\text{O}$ values

range from approximately 9‰ to 10‰ and reported synthetic perchlorate $\Delta^{17}\text{O}$ values are $0 \pm 0.1\%$.

Positive $\Delta^{17}\text{O}$ values suggest that the sample has undergone mass-independent isotopic fractionation. Other known perchlorate isotopic fractionation processes (e.g., biodegradation) have been reported to be mass dependent, which will not increase $\Delta^{17}\text{O}$ values. Therefore, the $\Delta^{17}\text{O}$ measurement has been used to evaluate the relative mixing of natural and synthetic perchlorate sources (Sturchio et al., 2005). Based on the literature reported $\Delta^{17}\text{O}$ values for natural perchlorate (average $\sim 9.5\%$) and the measured $\Delta^{17}\text{O}$ value in the Bangham well (1.27), synthetic perchlorate may have been mixed with approximately 10-15% natural perchlorate (see Figure 52).

4.5.2 Estimated Shifts in Isotopic Signature from Biodegradation

As previously discussed, perchlorate biodegradation has been reported to shift the isotopic signature with respect to chlorine and oxygen isotopes. Data reported in the literature show that the ($\epsilon^{18}\text{O}/\epsilon^{37}\text{Cl}$) fractionation factor ratio resulting from biodegradation is relatively consistent in studies conducted in the laboratory and in the field. However, studies conducted in the field have been reported to show a reduced magnitude of the individual $\epsilon^{18}\text{O}$ and $\epsilon^{37}\text{Cl}$ fractionation factors as previously discussed. The implication of this disparity in magnitude for isotopic fractionation factors measured in the laboratory (under homogeneous conditions) and in the field (under heterogeneous conditions) is as follows:

1. Perchlorate degradation in the lab and field will show a similar direction of shift (i.e., slope of the $\epsilon^{18}\text{O}/\epsilon^{37}\text{Cl}$ fractionation factor ratio) and;
2. The magnitude of the isotopic shift resulting from perchlorate biodegradation decreases as a result of the heterogeneity encountered under actual (field) conditions.

Data reported by Hatzinger et al. (2009) were used to predict the magnitude of isotopic shift, which would occur in perchlorate measured in the JPL area and Sunset Reservoir area. The

fractionation factors used to estimate isotopic shifts were -8.1 for $\epsilon^{18}\text{O}$ and -3.1 for $\epsilon^{37}\text{Cl}$. Values used for the isotopic fraction factors represent the lowest values reported in field studies and provide a conservative estimate (based on available data) of the isotopic shift, which will result from a given percentage of perchlorate biodegradation.

Figure 53 shows a plot of $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ stable isotope data reported in the 2007 NASA TM. The two shaded boxes shown in Figure 53 represent perchlorate sources, which NASA has attributed to JPL-derived perchlorate and non-JPL perchlorate. The arrow shown in Figure 53 shows the direction of isotopic shift resulting from biological perchlorate degradation. As seen in Figure 53, the direction of shift resulting from perchlorate biodegradation, shifts the $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ isotopes toward more positive values. The result of this shift is that isotopic data reported for wells in the JPL area would tend to move towards the Sunset Reservoir area. The implication of this result is that stable perchlorate isotope data measured in the Sunset wells are consistent with JPL-source perchlorate, which has undergone biodegradation.

Figure 54 shows the direction of isotopic shift in BMI source perchlorate (in Colorado River water) resulting from perchlorate biodegradation in Lake Mathews. The region corresponding to BMI source perchlorate is shown as the smaller box within the Sunset Reservoir Area box. Based on the measured isotopic values from BMI archive samples and the Las Vegas Wash, perchlorate biodegradation in Lake Mathews would shift the $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ isotopes towards more positive values of each isotope. The isotopic shift shown in Figure 54 implies that, after perchlorate biodegradation had occurred in Lake Mathews, imported water would likely show more positive $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ isotope ratios than the BMI complex samples and the Sunset Reservoir area.

4.5.3 Statistical Significance of Stable Isotope Data Measured in the 2007 NASA TM

A statistical analysis was made on stable perchlorate isotope data ($\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$) measured in wells in the JPL area and Sunset Reservoir area. The purpose of the statistical analysis was to:

1. Determine if there is a statistically significant difference in the stable perchlorate isotope data reported in the 2007 TM for wells in the JPL area and wells in the Sunset Reservoir Area;
2. Determine the effect of perchlorate biodegradation in Raymond basin ground water on the statistical significance of perchlorate stable isotope data reported for the JPL area and Sunset Reservoir area; and
3. Determine the extent of perchlorate biodegradation in Lake Mathews needed to shift the isotopic signature of BMI-source perchlorate so that it is distinct from the Sunset Reservoir wells.

4.5.3.1 Effect of Biodegradation on the Statistical Significance of Stable Perchlorate Isotope Data Measured in the JPL Area and Sunset Reservoir Area

A two-sample t-test assuming unequal variance was used to determine if there is a significant difference between the $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ stable isotope ratios reported from ground water measurements in the JPL area and in the Sunset Reservoir area. The analysis for statistical significance assumed varying degrees of perchlorate biodegradation originating from the JPL site. The isotopic shift in JPL-source perchlorate was calculated using the conservative isotopic fractionation factors reported by Hatzinger et al.(2009).

The data sets that were compared are listed in the following table. The t-test analysis compared the isotopic measurements reported from LAWC No. 3, MW-16 Samples 1 and 2, and OU1-IN to isotopic measurements reported from MW-25 zones 1-4, MW-19 zone 2, LFWC No. 2, Sunset, and Bangham.

t-Test Data Sets

Data Set 1	Data Set 2
JPL-Attributed Perchlorate Wells*	Sunset Reservoir Area Wells
LAWC No. 3	MW-25 zone 1
MW-16 sample 1	MW-25 zone 2
MW-16 sample 2	MW-25 zone 3
OUI-IN	MW-25 zone 4
-	LFWC No. 2
-	Sunset
-	MW-19 zone 2
-	Bangham ¹⁰

*The 2007 NASA TM acknowledges that these wells have perchlorate originating from the JPL site.

Calculations of the shift in isotopic composition resulting from perchlorate biodegradation in the JPL-attributed perchlorate were based on isotopic fractionation factors from both field- and laboratory-measured¹¹ studies. The magnitude of biodegradation observed in field-studies serves as a conservative estimate of perchlorate biodegradation.

Based on the results of significance testing (see tables below), the amount of biodegradation required for a statistically significant difference between the $\delta^{18}\text{O}$ Sunset Reservoir Area perchlorate signature and the JPL perchlorate signature ranges from approximately 6 to 22 percent depending on the conditions of the biodegradation (i.e., field or laboratory-measured fractionation magnitude). The $\delta^{37}\text{Cl}$ stable isotope ratios measured in the JPL area and Sunset Reservoir area did not show a statistically significant difference.

¹⁰ The Bangham Well was not included in the analysis of $\delta^{37}\text{Cl}$ because the $\delta^{37}\text{Cl}$ data needed to be log transformed to fit a normal distribution. The Bangham Well $\delta^{37}\text{Cl}$ concentration could not be log transformed because it has a negative value.

¹¹ Using perchlorate isotopic fractionation factors reported in laboratory studies results in a substantially greater $\delta^{37}\text{Cl}$ and $\delta^{18}\text{O}$ shift for a given amount of perchlorate biodegradation and serves as a lower-end estimate of biodegradation.

**Results of Significance Testing Assuming
Biodegradation of JPL-Attributed Perchlorate**

JPL-Attributed Perchlorate Biodegraded	Difference Between JPL-Attributed Perchlorate Undergoing Biodegradation and Sunset Reservoir Area Perchlorate			
	(FIELD-OBSERVED MAGNITUDE OF BIODEGRADATION)			
(%)	$\delta^{18}\text{O}$ t-value	$\delta^{18}\text{O}$ data	$\delta^{37}\text{Cl}$ t-value	$\delta^{37}\text{Cl}$
0	3.93	Significant Difference	1.34	No Significant Difference
5	3.57	Significant Difference	0.41	No Significant Difference
10	3.19	Significant Difference	0.28	No Significant Difference
15	2.79	Significant Difference	0.82	No Significant Difference
20	2.37	Significant Difference	1.27	No Significant Difference
25	1.92	No Significant Difference	1.66	No Significant Difference
30	1.44	No Significant Difference	2.00	No Significant Difference
t-critical	2.23	-	2.26	-

JPL-Attributed Perchlorate Biodegraded	Difference Between JPL-Attributed Perchlorate Undergoing Biodegradation and Sunset Reservoir Area Perchlorate			
	(LABORATORY-OBSERVED MAGNITUDE OF BIODEGRADATION)			
(%)	$\delta^{18}\text{O}$ t-value	$\delta^{18}\text{O}$ data	$\delta^{37}\text{Cl}$ t-value	$\delta^{37}\text{Cl}$
0	3.93	Significant Difference	1.34	No Significant Difference
1	3.62	Significant Difference	0.59	No Significant Difference
2	3.32	Significant Difference	0.15	No Significant Difference
3	3.00	Significant Difference	0.63	No Significant Difference
4	2.69	Significant Difference	1.02	No Significant Difference
5	2.37	Significant Difference	1.36	No Significant Difference
6	2.05	No Significant Difference	1.64	No Significant Difference
7	1.73	No Significant Difference	1.90	No Significant Difference
8	1.40	No Significant Difference	2.12	No Significant Difference
t-critical	2.23	-	2.26	-

Results of the t-test analysis for statistical significance are summarized as follows:

1. With no biodegradation of perchlorate, the $\delta^{18}\text{O}$ stable isotope ratios measured in the JPL area and Sunset Reservoir area show a statistically significant difference;
2. The $\delta^{37}\text{Cl}$ stable isotope ratios measured in the JPL area and Sunset Reservoir area did not show a statistically significant difference; and
3. If 6 to 22 percent biodegradation of JPL perchlorate occurred, there would be no significant statistical difference between the $\delta^{18}\text{O}$ of the JPL source area and the Sunset Reservoir area wells.

4.5.3.2 BMI Complex Perchlorate versus Sunset Reservoir Area Perchlorate

The purpose of this analysis is to determine how much biodegradation would need to occur in Lake Mathews for the isotopic signatures measured in BMI Complex¹² samples to be statistically different from Sunset Reservoir area perchlorate. The NASA 2007 TM implied that the isotopic signatures measured in the Sunset Reservoir Area wells are similar to those measured in BMI complex archive samples.

A two-sample t-test assuming unequal variance was used to determine if there is a significant difference between the isotopic concentrations of the Sunset Reservoir Area wells and the BMI Complex perchlorate. The t-test compared stable isotope data from the two data sets listed in the following table.

¹² The BMI Complex is located in Henderson, Nevada and is a known source of perchlorate contamination in the Colorado River Aqueduct.

t-Test Data Sets

Data Set 1	Data Set 2
Sunset Reservoir Area Wells	BMI Complex Samples
MW-25 zone 1	BMI Archive 1
MW-25 zone 2	BMI Archive 2
MW-25 zone 3	BMI Archive 3
MW-25 zone 4	BMI Archive 4
LFWC No. 2	BMI Archive 5
Sunset	BMI Groundwater Sample
MW-19 zone 2	Las Vegas Wash
Bangham ¹³	-

Calculations of the shift in isotopic composition resulting from perchlorate biodegradation in Lake Mathews were made using the isotopic data reported for the BMI Complex and Las Vegas Wash. For purposes of this analysis it was assumed that the factors which contribute to the heterogeneity affecting isotopic fractionation factors in ground water, may not be relevant for perchlorate degradation in lakes. As such, laboratory-measured fractionation factors were applied to the BMI Complex data (Sturchio et al., 2007).

Based on the results of significance testing (see table below), the amount of biodegradation required for a statistically significant difference between the Sunset Reservoir Area perchlorate signature and the BMI Complex perchlorate signature is approximately 7 percent.

¹³ The Bangham Well was not included in the analysis of $\delta^{37}\text{Cl}$ because the $\delta^{37}\text{Cl}$ data needed to be log transformed to fit a normal distribution. The Bangham Well $\delta^{37}\text{Cl}$ concentration could not be log transformed because it has a negative value.

BMI Complex Perchlorate Biodegraded	Difference Between BMI Complex Samples Undergoing Biodegradation and Sunset Reservoir Area Perchlorate			
	(LABORATORY-OBSERVED MAGNITUDE OF BIODEGRADATION)			
(%)	$\delta^{18}\text{O}$ t-value	$\delta^{18}\text{O}$ data	$\delta^{37}\text{Cl}$ t-value	$\delta^{37}\text{Cl}$
0	0.04	No Significant Difference	0.07	No Significant Difference
5	1.68	No Significant Difference	1.83	No Significant Difference
10	3.41	Significant Difference	2.80	Significant Difference
15	-	Significant Difference	-	Significant Difference
20	-	Significant Difference	-	Significant Difference
25	-	Significant Difference	-	Significant Difference
30	-	Significant Difference	-	Significant Difference
35	-	Significant Difference	-	Significant Difference
t-critical	2.16	-	2.18	-

5.0 FINDINGS

Findings identified during the course of this evaluation are summarized as follows:

RAYMOND BASIN GROUND WATER MODEL

1. Forward particle tracking suggests that the JPL source area is the origin of perchlorate at the Sunset Reservoir area wells (P-COP, P-SUN, P-BAN, P-GAR, and P-VIL):

- Particles released at the northwestern portion of the 1981 estimated extent of perchlorate contamination were captured by the Bangham and Sunset wells (P-BAN and P-SUN) by 1996 and by the Garfield and Villa wells (P-GAR and P-VIL) by 2003 (see Figure 31).
- Particles released at the southwestern portion of the 1981 estimated extent of perchlorate contamination were captured by wells P-BAN and P-SUN by 1987 and by wells P-GAR and P-VIL by 1998 (see Figure 31).

2. Backward particle tracking suggests that the JPL source area is the origin of perchlorate at the Sunset Reservoir area wells (P-COP, P-SUN, P-BAN, P-GAR, and P-VIL):

- Particles released at the Sunset Reservoir area wells P-BAN, P-SUN, P-COP on December 31, 2008 backward track to the JPL area in approximately 17 years (i.e., by 1992).
- Particles released at wells P-GAR and P-VIL do not reach the JPL area over the model period (i.e., January 1, 1981 through December 31, 2008). However, particles from P-GAR and P-VIL do backward track to the 1981 estimated extent of perchlorate contamination in approximately 16 to 28 years.
- Particles released within the deep screen (i.e., screens 4 and 5) of JPL MW-20 backward track to the JPL area in 17 years (i.e., by 1992) (see Figure 33).

3. Backward particle tracking suggests that the JPL source area is the origin of perchlorate in the deep screen intervals of JPL MW-20:

- Particles released at the Sunset Reservoir area wells P-BAN, P-SUN, P-COP on December 31, 2008 backward track to the JPL area in approximately 17 years (i.e., by 1992).

EVALUATION OF PERCHLORATE BIODEGRADATION IN RAYMOND BASIN GROUND WATER

1. Available ground water quality data show that reducing conditions, which are necessary for perchlorate biodegradation, occur extensively in the JPL and Sunset Reservoir areas:

- JPL's historical quarterly monitoring data showed that most of the wells sampled showed some indication of reducing conditions, which would be conducive to perchlorate biodegradation (i.e., ORP < 0 mV, DO < 1 mg/L, or iron > 0.5 mg/L).
- In wells with multiple sampling zones, reducing conditions were found in the deeper zones and not in the shallow zones.

2. Based on a sampling of seven wells in the Raymond Basin, two wells show direct evidence of perchlorate biodegradation:

- Data reported from JPL MW-20 and MW-25 show direct evidence of perchlorate biodegradation, which includes:
 - Depletion of nitrate and perchlorate in the deeper, reducing zones.
 - Presence of ammonia, a potential end product of dissimilatory nitrate reduction.
 - Depletion of sulfate in deeper zones and the presence of sulfide, consistent with biological sulfate reduction.

PERCHLORATE DEGRADATION IN IMPORTED WATER

1. Perchlorate in Colorado River Water undergoes seasonal biodegradation in Lake Mathews:

- Historical water quality monitoring data for Lake Mathews shows perchlorate biodegradation in deeper portions of the Lake has regularly occurred on a seasonal basis.
- Depth profiles measured in Lake Mathews showed a depletion of oxygen, nitrate, and perchlorate in the lower portions of the lake.

EVALUATION OF PERCHLORATE ORIGIN IN THE SUNSET RESERVOIR WELLS

1. Perchlorate in the Sunset Area wells is synthetic in origin:

- Stable isotope values for Perchlorate in the JPL wells and the Sunset Reservoir area wells are consistent with literature-reported values for synthetic perchlorate.
- The stable perchlorate isotope ratios reported for the Bangham well suggest that synthetic perchlorate may be mixed with 10-15% natural perchlorate.

2. Perchlorate measured in the Sunset Reservoir area wells is consistent with JPL-source perchlorate, which has undergone limited biodegradation:

- Perchlorate biodegradation has been reported to shift the $\delta^{18}\text{O}$ and $\delta^{37}\text{Cl}$ perchlorate stable isotope ratios.
- Water quality data show that limited perchlorate biodegradation is occurring in the Raymond Basin.
- Biodegradation of approximately 6% to 22% of the perchlorate from the JPL area would shift the perchlorate stable isotope values so that they are statistically indistinguishable from the Sunset Reservoir area perchlorate ratios.

3. Perchlorate isotope ratios in imported water are shifted as a result of biodegradation in Lake Mathews:

- The stable isotope ratios of perchlorate in Colorado River Water delivered to the Raymond Basin have not been measured.
- The isotopic values reported for perchlorate samples collected from the BMI complex in Henderson, NV are shifted as a result of biodegradation in Lake Mathews.
- Based on data reported for perchlorate samples taken from the BMI complex in Henderson, NV, if as little as 7% of the perchlorate entering Lake Mathews undergoes biodegradation, then the isotopic signature of perchlorate in imported water would be statistically different than the perchlorate measured in the Sunset Reservoir area wells.

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FIGURES

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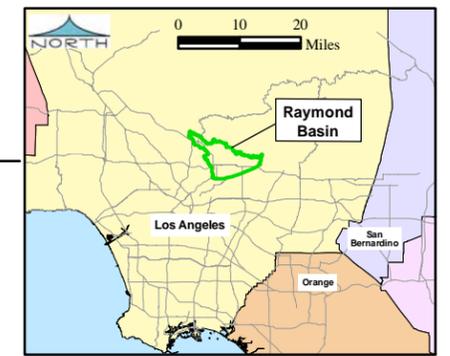
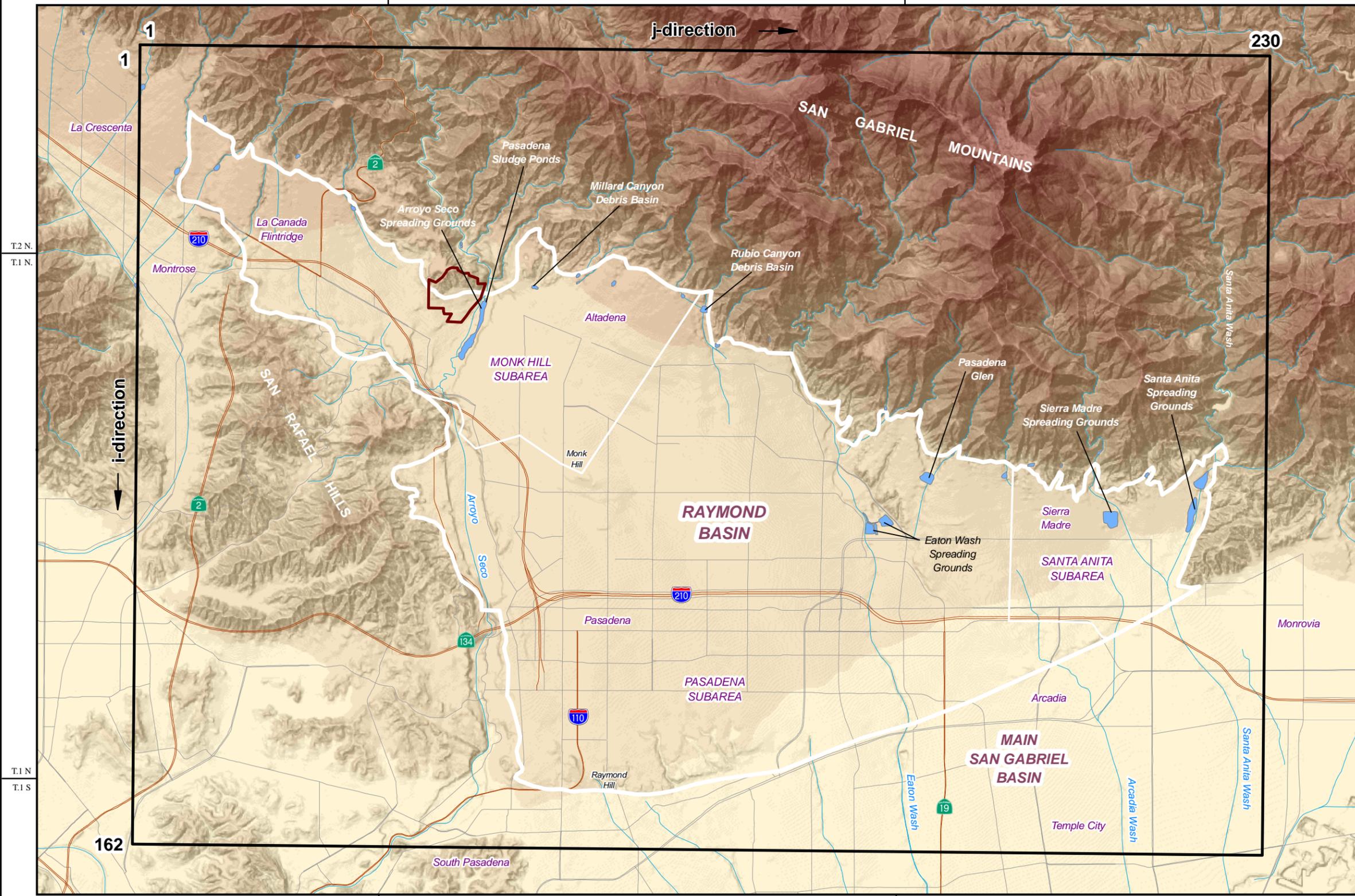
LOCATION AND GRID FOR THE RBMB GROUND WATER MODEL

EXPLANATION

300 ft  Model Cell Size
 300 ft  162 x 230 cells x 2 Layers
 = 74,520 Cells

Note: Model Grid Not Shown Due to Density of Model Cells

-  NASA/JPL Boundary
-  Raymond Basin Boundary
-  Raymond Basin Subareas
-  Spreading Grounds or Debris Basins



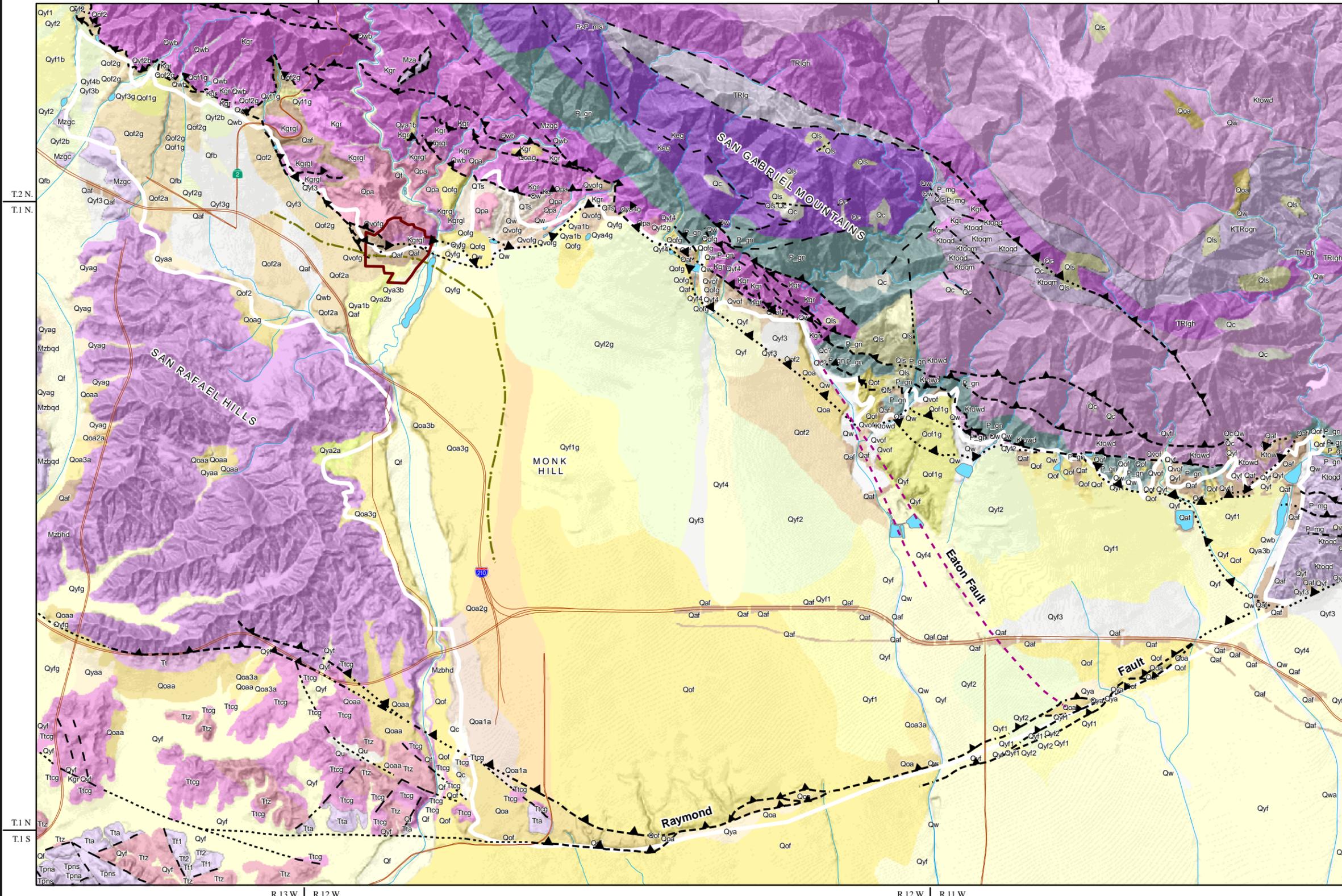
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Figure 1

**GEOLOGIC SETTING
OF THE RAYMOND
GROUND WATER BASIN**



EXPLANATION

*See Figure 2c for legend of geologic units from USGS 2005 surficial geology.

- NASA/JPL Boundary
- Axis of Buried Bedrock Valley
- Spreading Grounds or Debris Basins

- Fault Classification (USGS)¹**
- Inferred
- Concealed
- Indicates Thrust Fault

- Fault Classification (DWR)²**
- Eaton Wash Fault

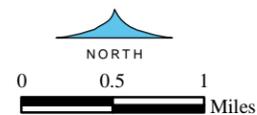
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(2) Modified from California Department of Water Resources (DWR) "Technical Information Record 1335-7-A-1." (Oct. 1969).

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Source: Faults and geology taken from Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California USGS, 2005.

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Figure 2a

GEOLOGIC LEGEND (USGS, 2005)*

Qaf	Artificial fill (late Holocene)	Keg	Echo granite (Cretaceous)
Qa	Alluvium, undifferentiated (late Holocene)	Mzbhd	Biotite-hornblende diorite (Mesozoic?)
Qw	Wash deposits (late Holocene)	Mzbqd	Biotite-quartz diorite (Mesozoic?)
Qf	Alluvial-fan deposits (Holocene)	Mza	Alaskite (Mesozoic?)
Qc	Colluvium (Holocene and late Pleistocene?)	Mzgd	Granodiorite (Mesozoic)
Qls	Landslide deposits (Holocene and late Pleistocene?)	Mzgc	Granitic complex (Mesozoic?)
Qu	Undifferentiated surficial deposits (Holocene and late Pleistocene?)	Tr1g	Mount Lowe intrusive suite, undivided (Triassic)
Qya	Young alluvium	Trlgh	Mount Lowe intrusive suite, orthoclase-hornblende facies
Qyf	Young alluvial-fan deposits, undivided (Holocene and late Pleistocene)	Pzp	Placerita Formation (Paleozoic)
Qoa	Old alluvium, undivided (late to middle Pleistocene)	PzPms	Siliceous metasedimentary rock (Paleozoic or Proterozoic)
Qof	Old alluvial-fan deposits, undivided (late to middle Pleistocene)	Pgn	Gneiss (Proterozoic?)
Qvof	Very old alluvial-fan deposits (middle to early Pleistocene)	Pmg	Mendenhall Gneiss (Proterozoic)
Qpa	Pacoima Formation (middle to early Pleistocene)	Tf2	Fernando Formation, member 2 (Pliocene)
QTs	Saugus Formation, undivided (early Pleistocene to late Pliocene)	Tf1	Fernando Formation, member 1 (Pliocene)
Kgr	Granitic rocks (late Cretaceous)	Tpns	Puente Formation, siliceous shale (early Pliocene)
Ktoqd	Tonalite and quartz diorite (late Cretaceous)	Tpna	Puente Formation, sandstone (late Miocene)
Ktoqm	Tonalite and monzogranite (late Cretaceous)	Ttcg	Topanga Group, conglomerate
Ktowd	Tonalite (Wilson Diorite of Miller, 1934) (late Cretaceous)	Tta	Topanga Group, sandstone
Kgrgl	Granitic rocks, leucocratic granodiorite (late Cretaceous)	Ttz	Topanga Group, siltstone
KTrogn	Mixed tonalite and Mount Lowe intrusive suite (Cretaceous and Triassic)		

** Source: Faults and geology taken from Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California. USGS, 2005.*

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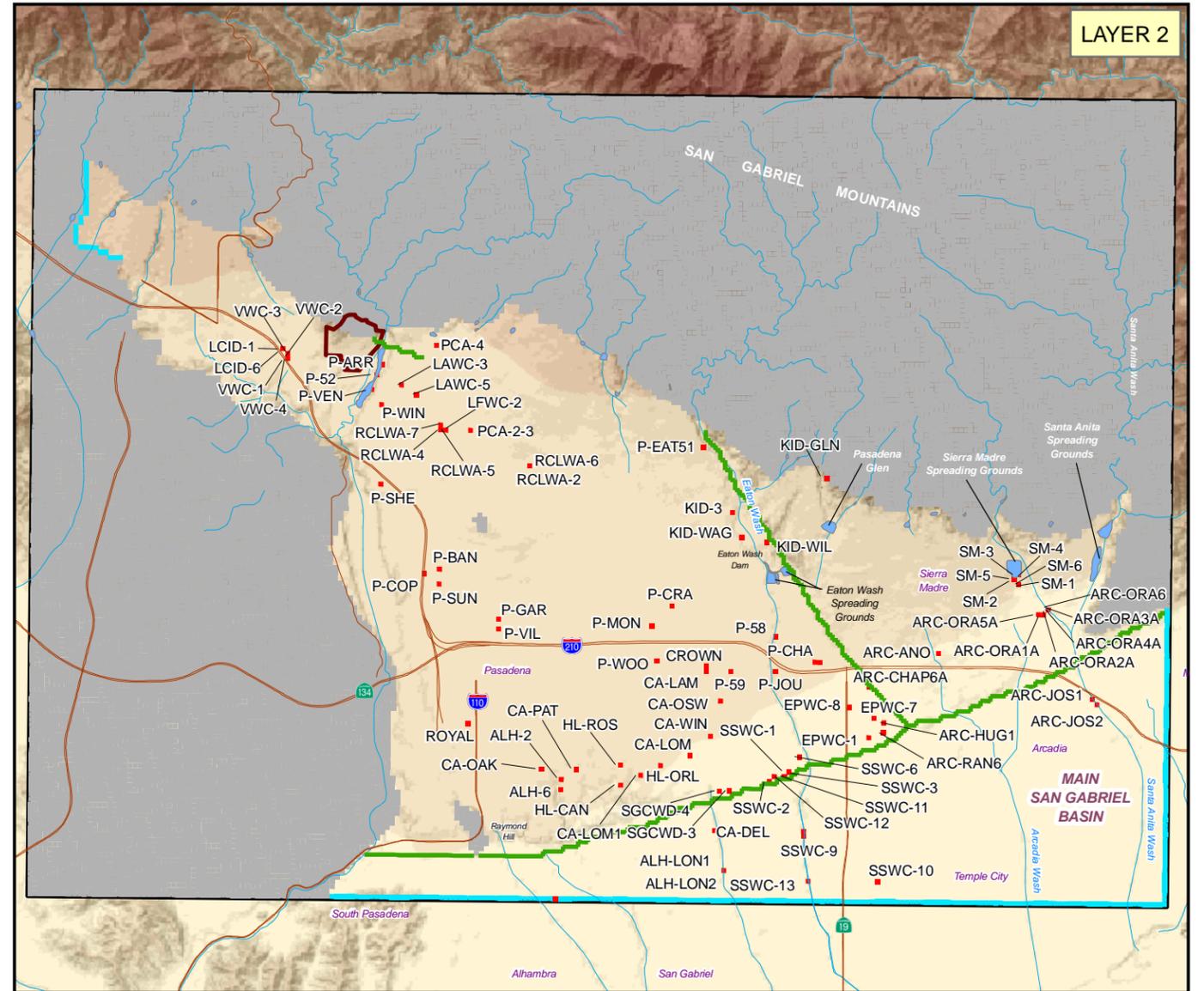
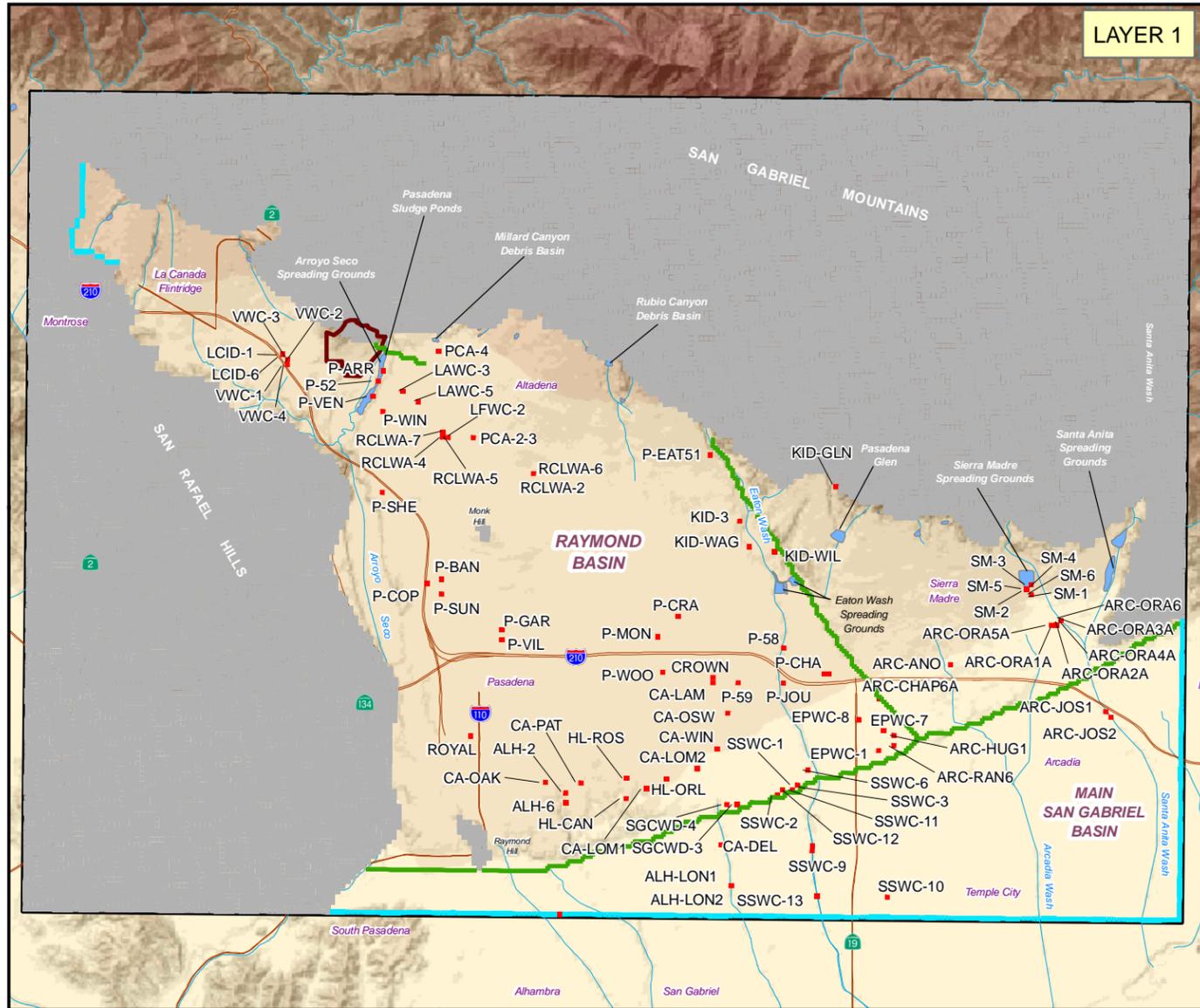
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Figure 2c

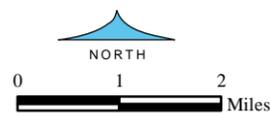
BOUNDARY CONDITIONS FOR
MODEL LAYER 1 AND
MODEL LAYER 2



EXPLANATION

- NASA/JPL Boundary
- Spreading Grounds or Debris Basins

- Model Boundary Conditions
- Horizontal Flow Barrier
 - General Head Boundary
 - Well Package (injection and production wells)
 - No Flow (inactive cells)



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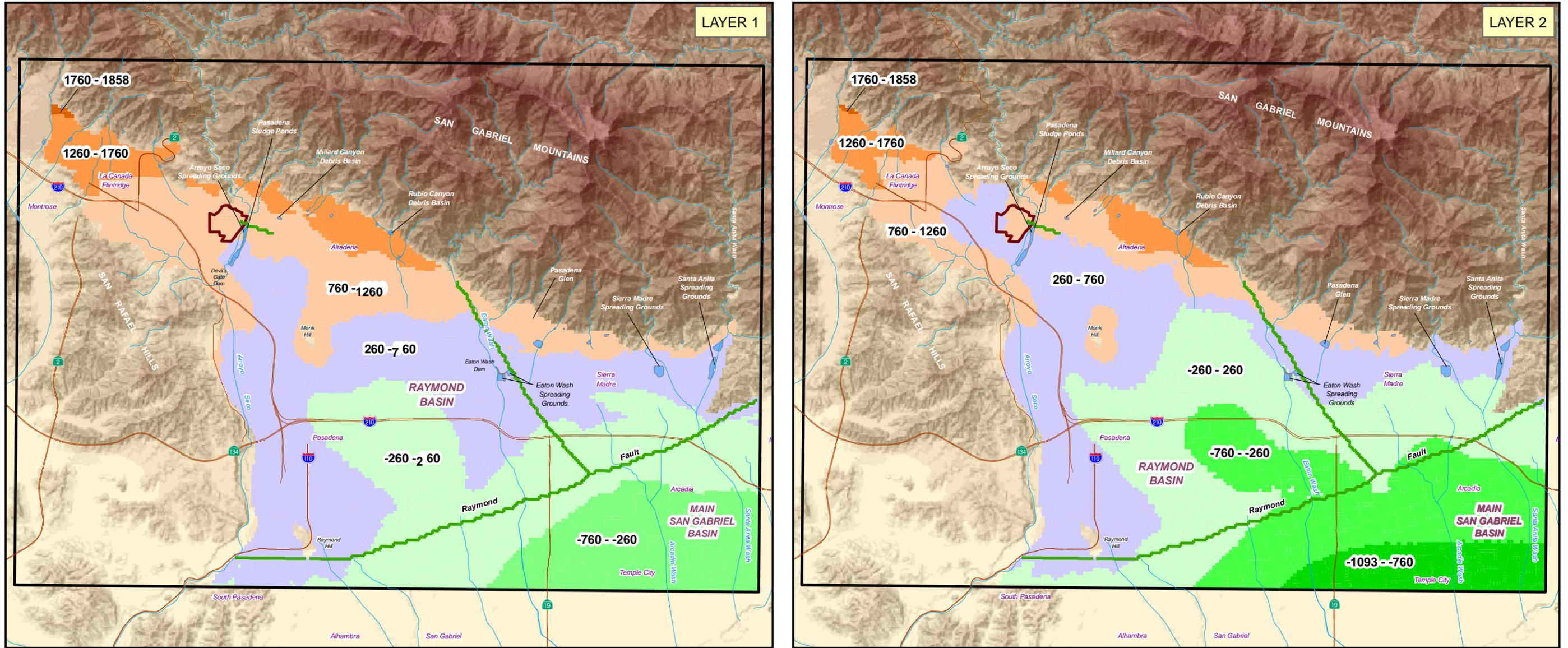
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Figure 3

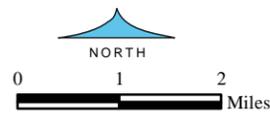


Model Layer Bottom Elevation (ft amsl)

- 1093 - -760
- 760 - 260
- 260 - 260
- 260 - 760
- 760 - 1260
- 1260 - 1760
- 1760 - 1858

EXPLANATION

- Model Boundary Conditions
- Horizontal Flow Barrier
- NASA/JPL Boundary
- Spreading Grounds or Debris Basins



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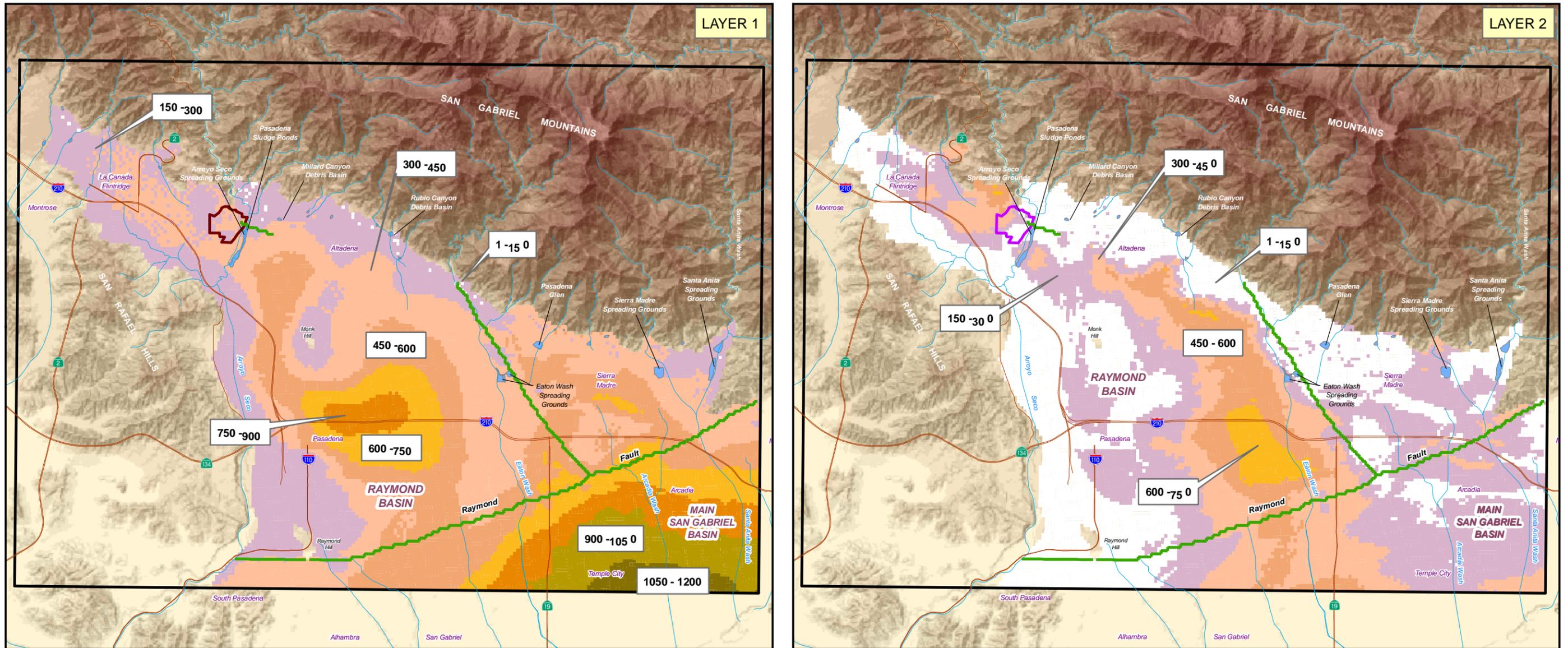
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Figure 4

**THICKNESS OF
MODEL LAYER 1 AND
MODEL LAYER 2**

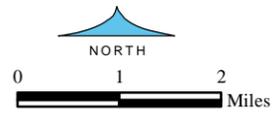


EXPLANATION

Model Layer Thickness (ft)

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150 -300	750 -900
300 -450	900 -1050
450 -600	1050 -120 0

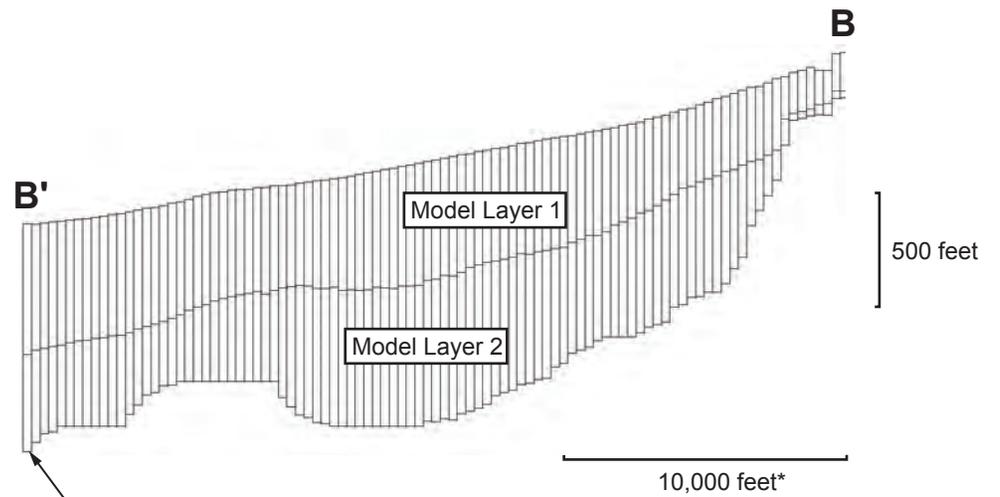
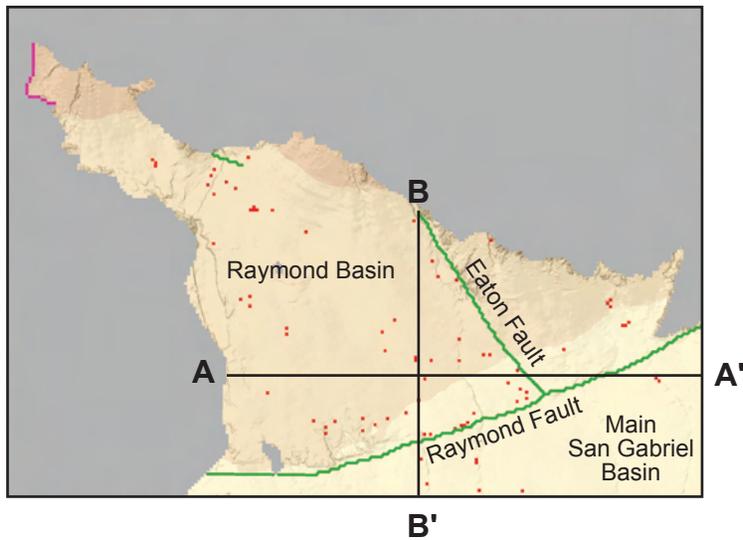
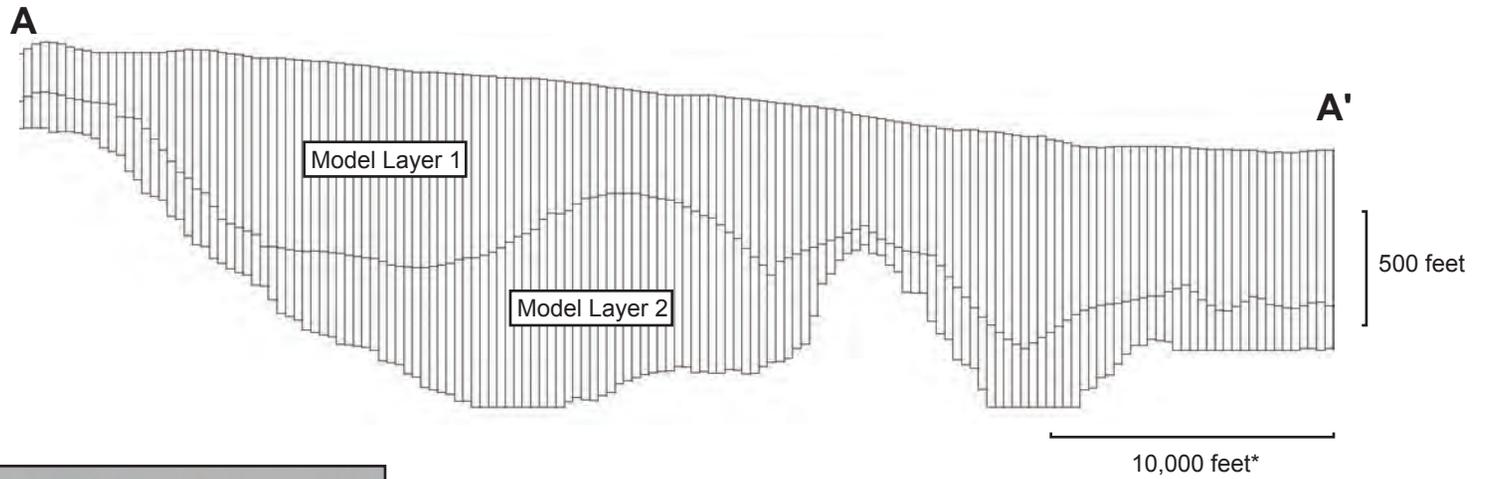
- Model Boundary Conditions
- Horizontal Flow Barrier
 - NASA/JPL Boundary
 - Spreading Grounds or Debris Basins



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Figure 5



* Each model cell represents 300 feet on the horizontal scale.

**Figure
6**

Drawn: JMM
 Checked: JK
 Approved:
 Date: 28-Oct-09

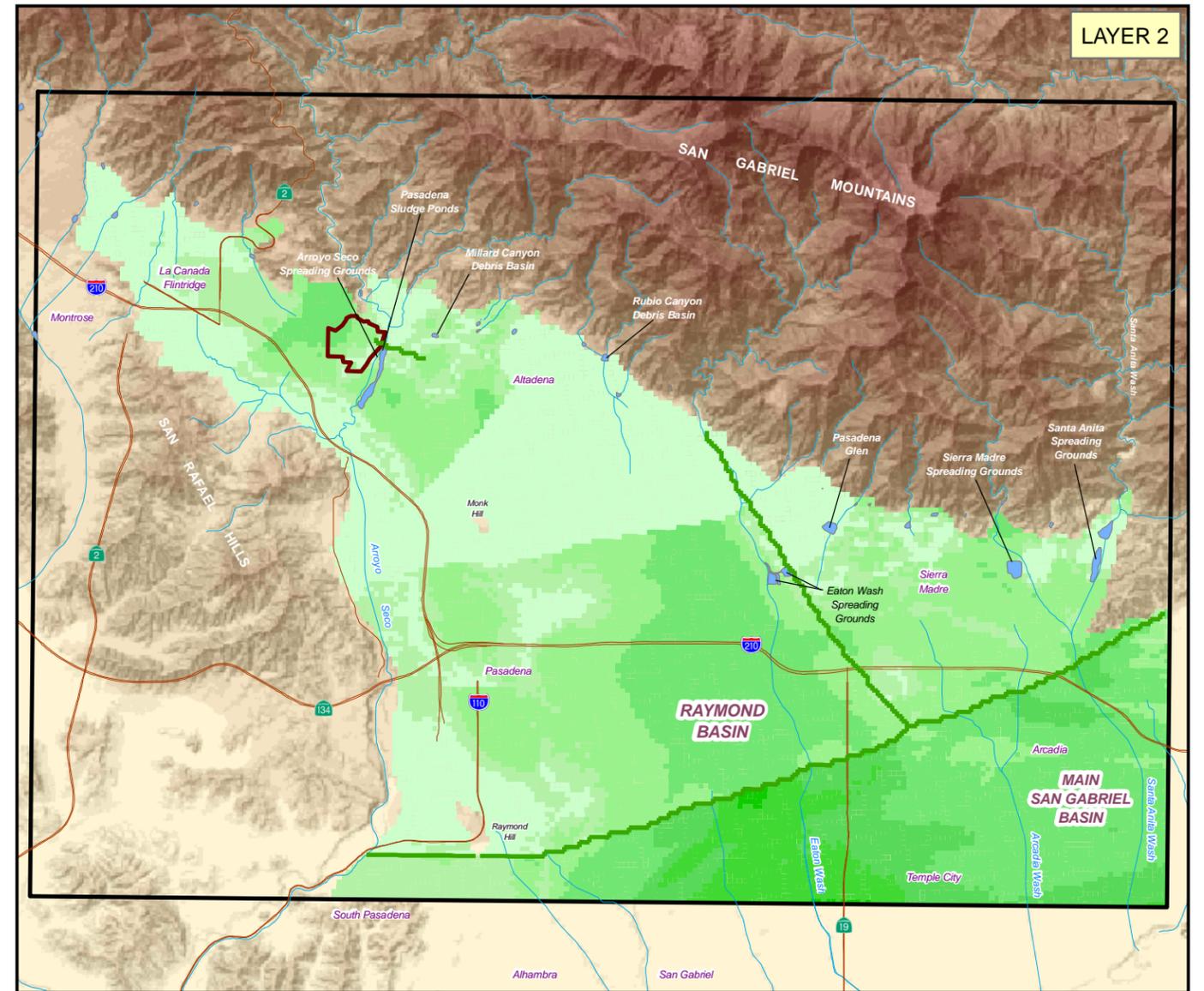
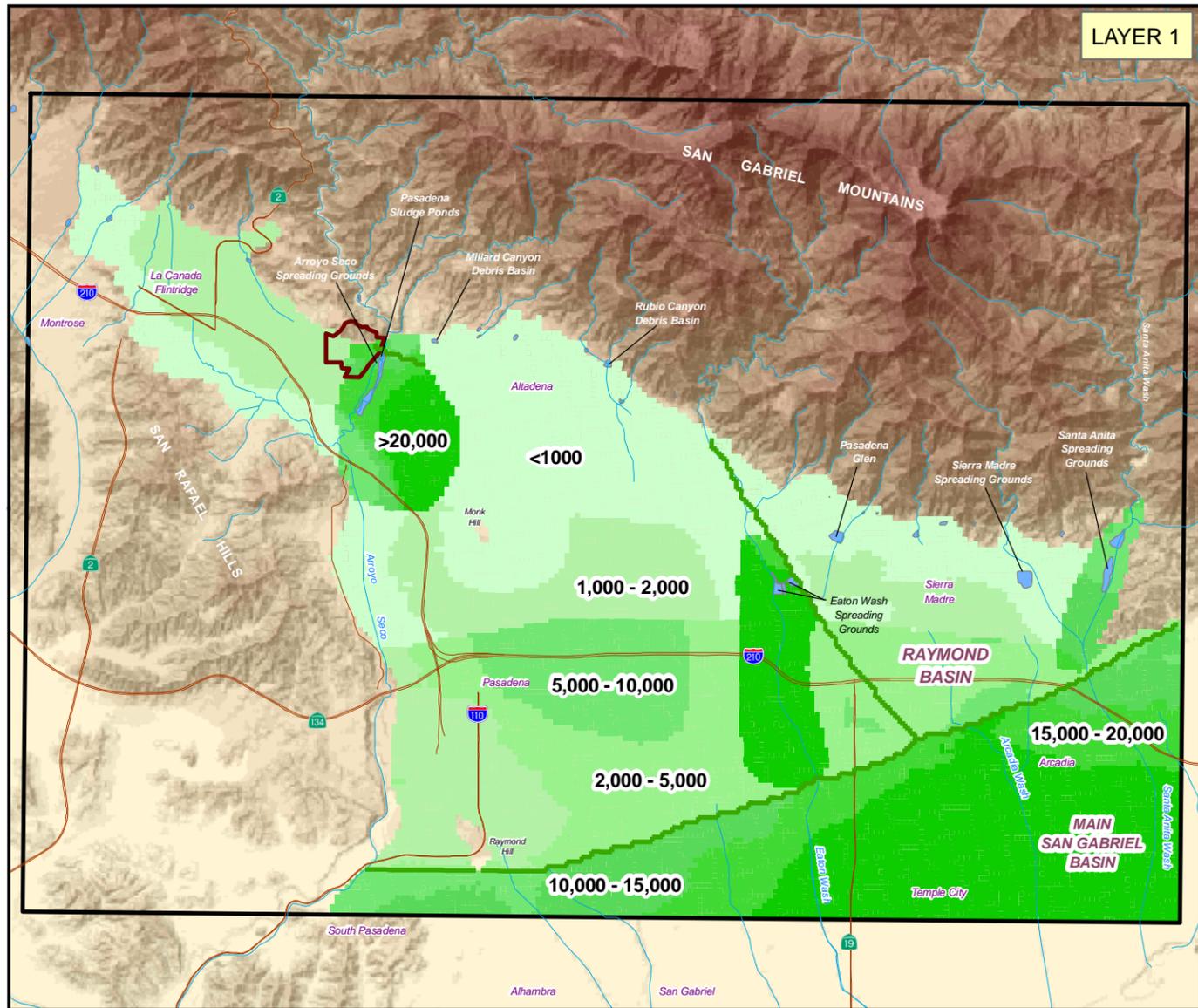
CITY OF PASADENA WATER AND POWER

MODEL LAYER CROSS SECTIONS

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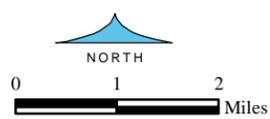
TRANSMISSIVITY OF
MODEL LAYER 1 AND
MODEL LAYER 2



EXPLANATION

Transmissivity (ft ² /day)	
	<1,000
	1,000 - 2,000
	2,000 - 5,000
	5,000 - 10,000
	10,000 - 15,000
	15,000 - 20,000
	>20,000

- Model Boundary Conditions
- Horizontal Flow Barrier
 - NASA/JPL Boundary
 - Spreading Grounds or Debris Basins



28-Oct-09

Prepared by: DWB

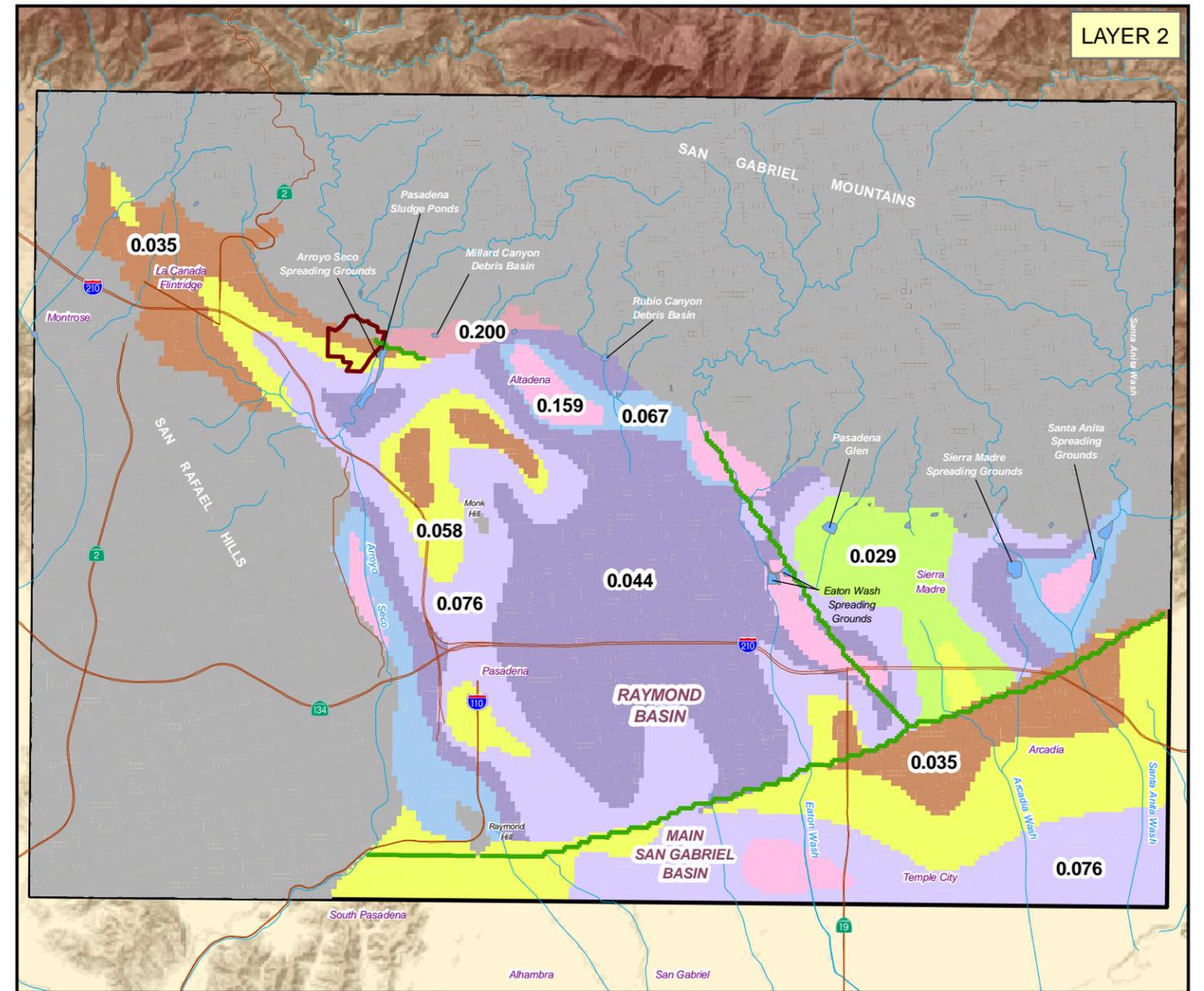
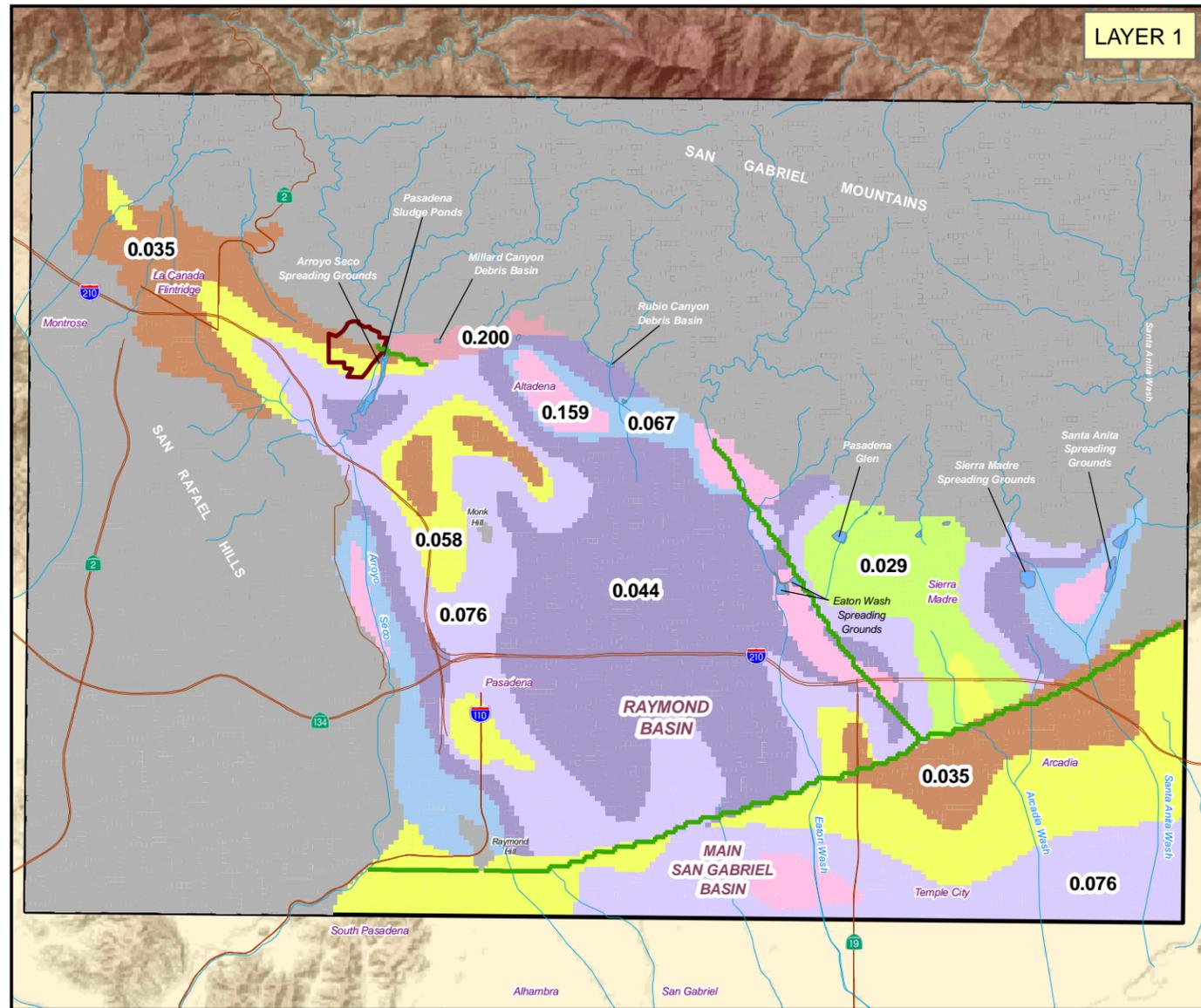
Map Projection: UTM 1927, Zone 11

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Figure 7

STORATIVITY OF
MODEL LAYER 1 AND
MODEL LAYER 2



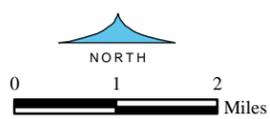
EXPLANATION

Model Boundary Conditions

-  Horizontal Flow Barrier
-  No Flow (inactive cells)
-  NASA/JPL Boundary
-  Spreading Grounds or Debris Basins

Storativity (fraction)

- | | |
|---|---|
|  0.029 |  0.066 |
|  0.035 |  0.076 |
|  0.044 |  0.159 |
|  0.058 |  0.200 |



28-Oct-09

Prepared by: DWB

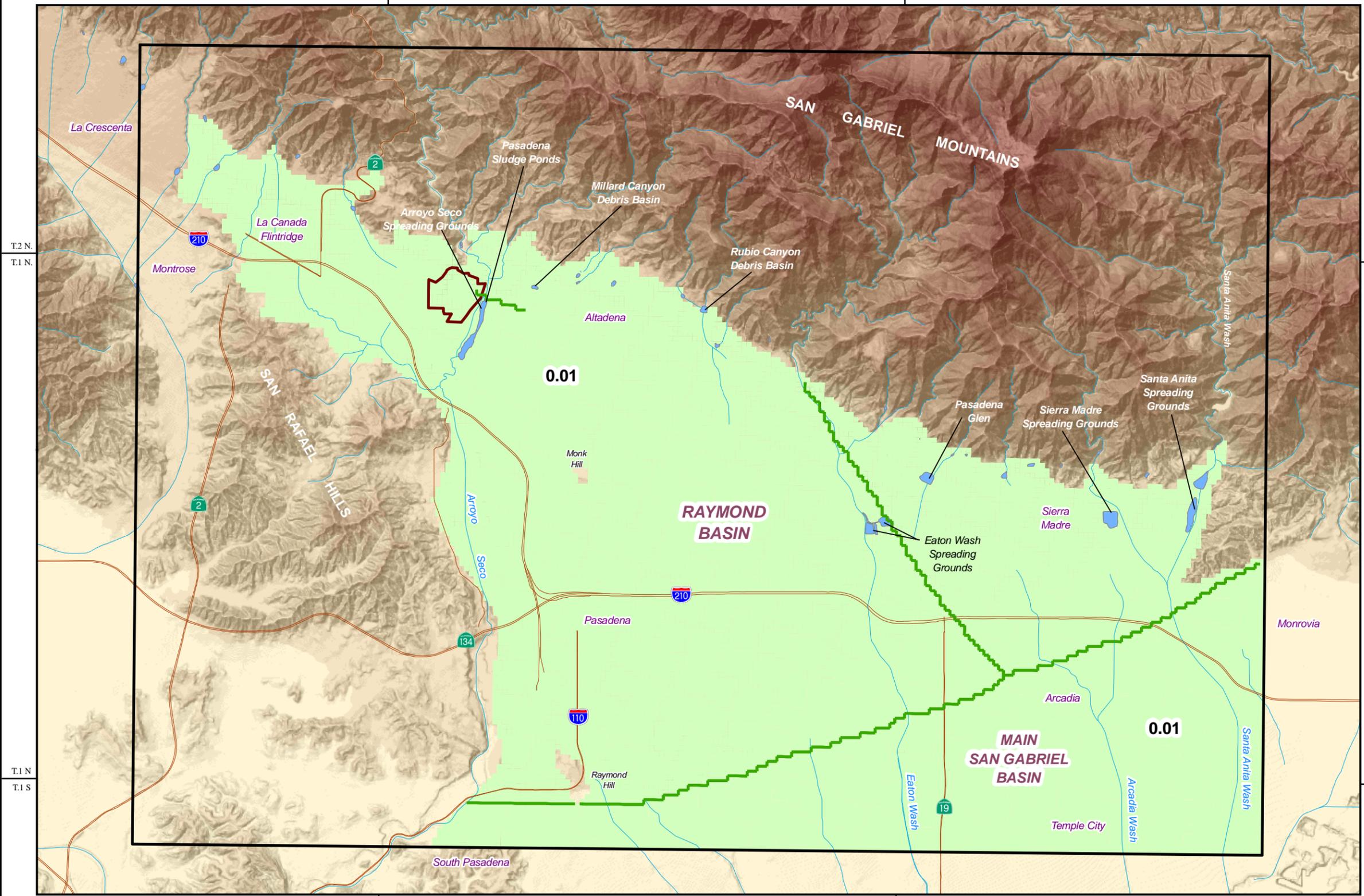
Map Projection: UTM 1927, Zone 11

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Figure 8

**VERTICAL LEAKANCE
VALUES BETWEEN
MODEL LAYER 1
AND MODEL LAYER 2**



EXPLANATION

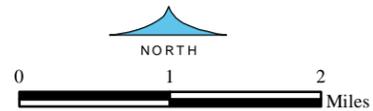
- 0.01 Vertical Leakance (day⁻¹)
- NASA/JPL Boundary
- Spreading Grounds or Debris Basins
- Horizontal Flow Barrier

T.2 N.
T.1 N.

T.1 N.
T.1 S.

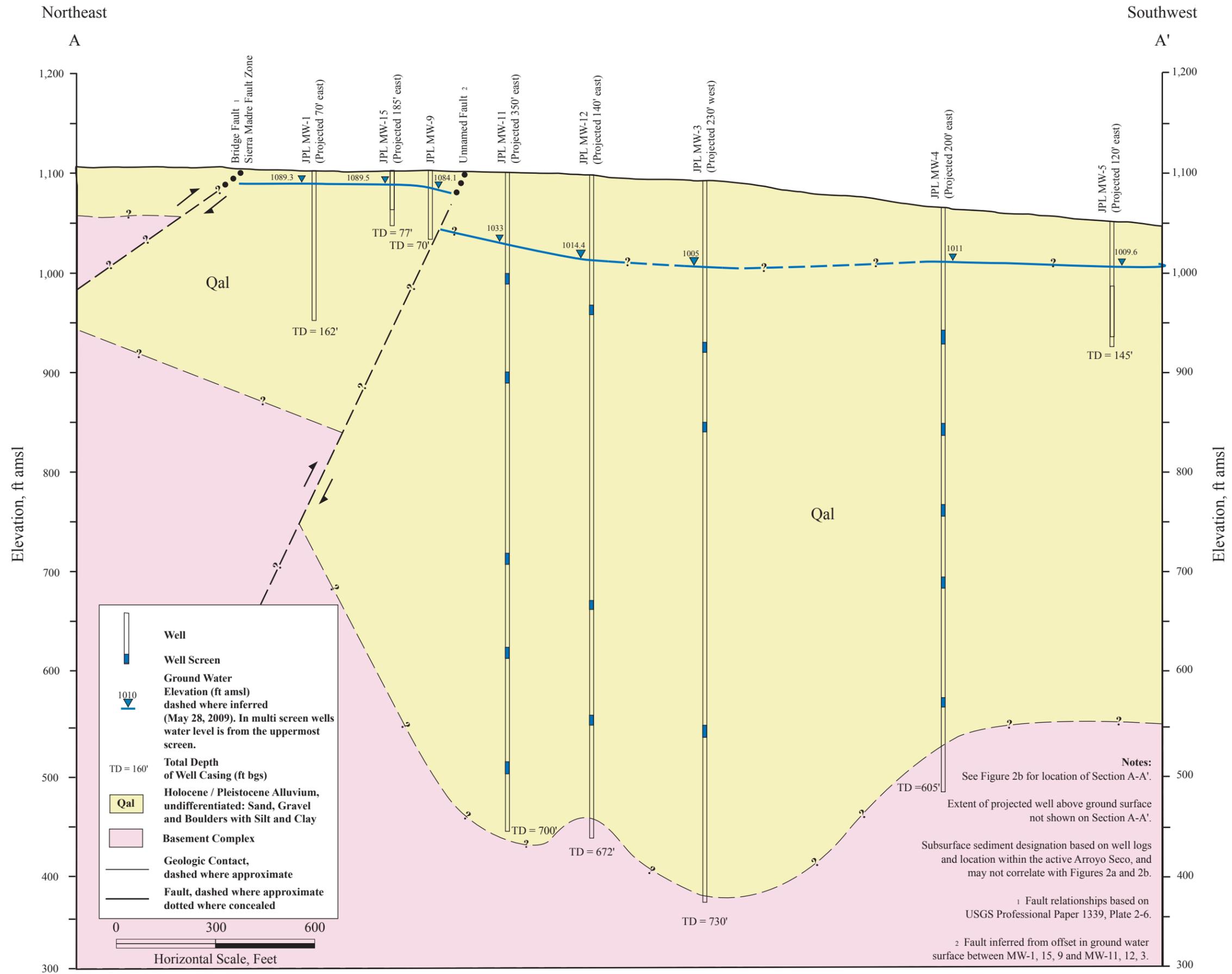
R.13 W. | R.12 W. | R.12 W. | R.11 W.

28-Oct-09
Prepared by: DWB
Map Projection: UTM 1927, Zone 11



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Figure 9

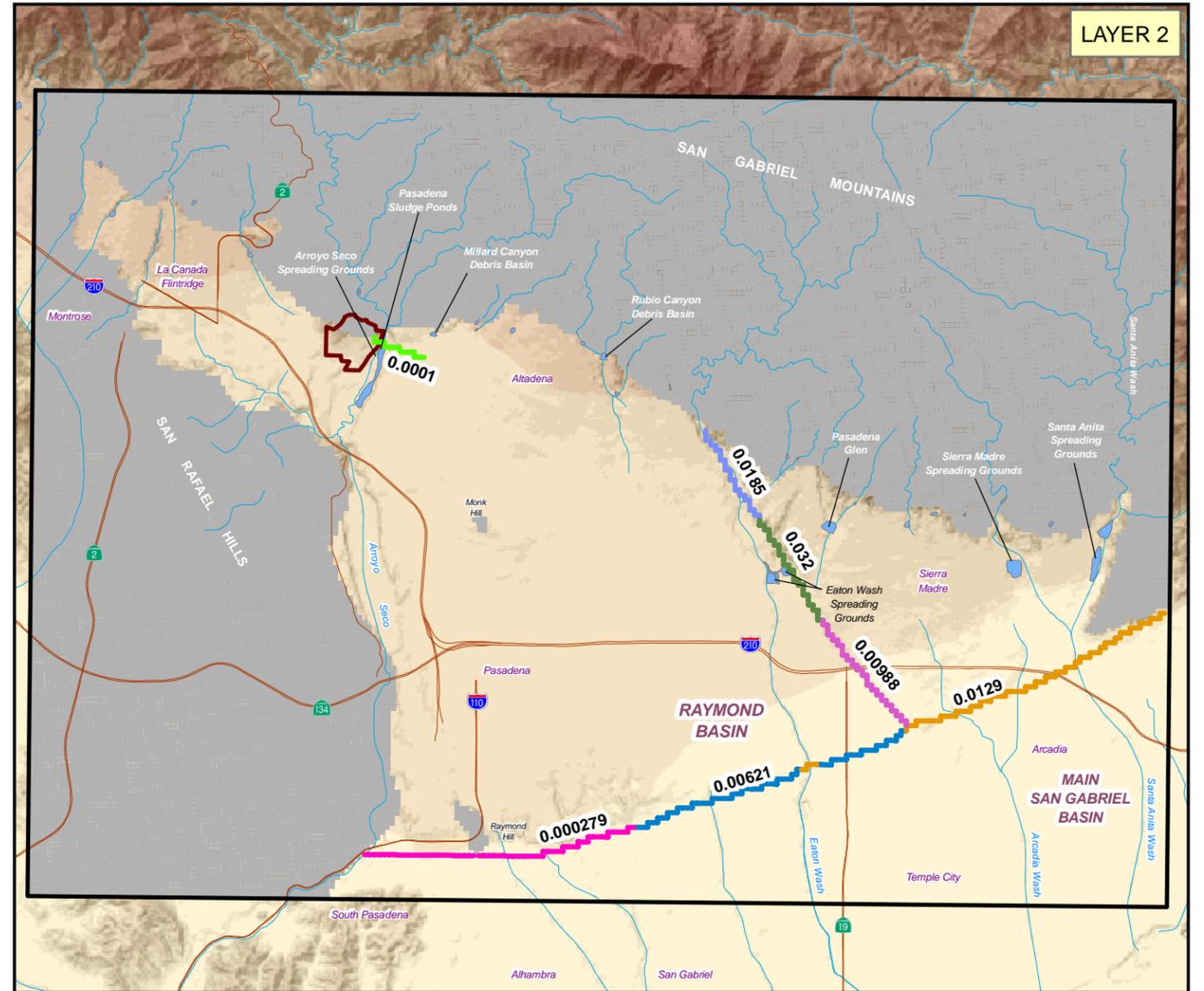
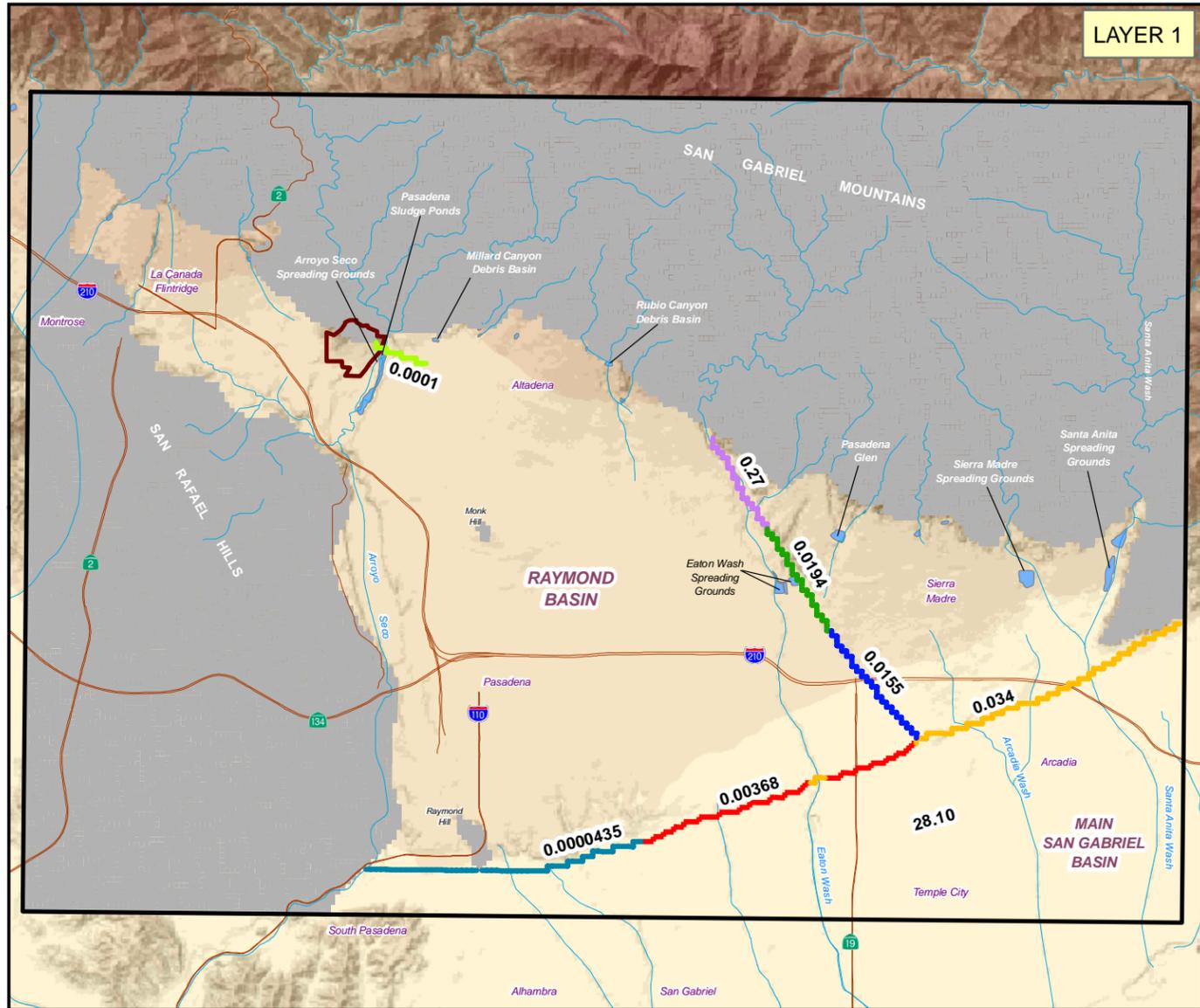


CITY OF PASADENA WATER AND POWER
WATER LEVEL PROFILE OF CROSS-SECTION A-A'

Drawn: LH
Checked: JK
Approved:
Date: 28-Oct-09

Figure 10

HYDRAULIC CHARACTERISTIC OF HORIZONTAL-FLOW BARRIER FOR MODEL LAYER 1 AND MODEL LAYER 2



EXPLANATION

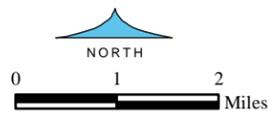
Hydraulic Characteristic of Horizontal-Flow Barrier Model Layer 1 (ft/day)

	0.27		0.00368
	0.0194		0.0000435
	0.0155		0.0001
	0.034		

	No Flow (inactive cells)
	NASA/JPL Boundary
	Spreading Grounds or Debris Basins

Hydraulic Characteristic of Horizontal-Flow Barrier Model Layer 2 (ft/day)

	0.0185		0.00621
	0.032		0.000279
	0.00988		0.0001
	0.0129		



28-Oct-09

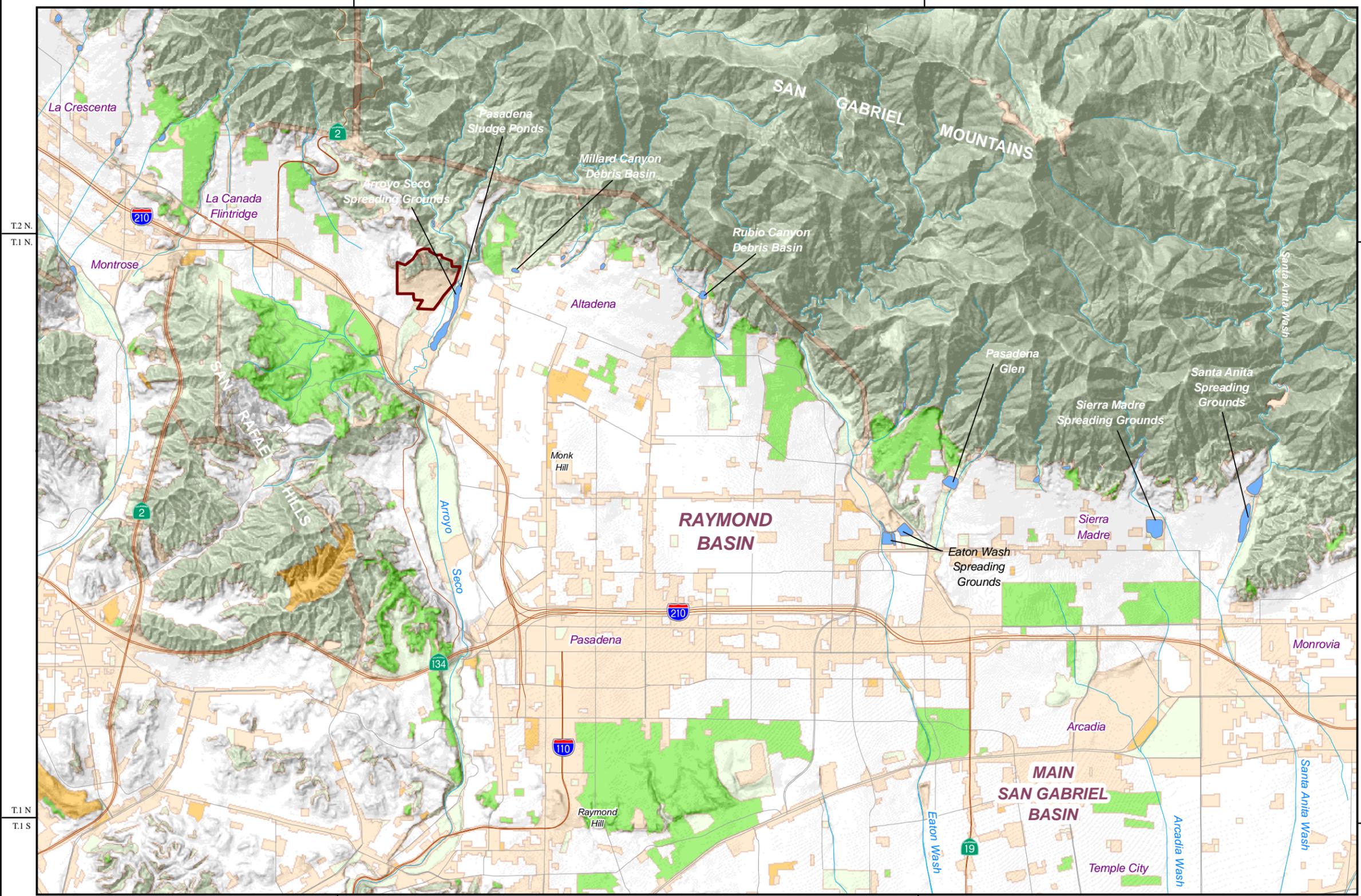
Prepared by: DW B

Map Projection: UTM 1927, Zone 11



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Figure 11



PERCENT IMPERVIOUS AREAS BASED ON LAND USE

EXPLANATION

Percent Impervious Surface Determined From Land Use

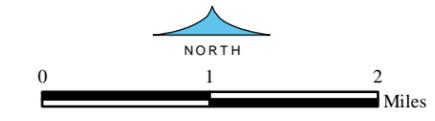
Light Green	10%
Green	30%
Light Grey	50%
Orange	80%
Dark Orange	90%

Source of Data: Los Angeles County of Public Works (2002). Land Use Shapefile with Impervious Index.

NASA/JPL Boundary

Spreading Grounds or Debris Basins

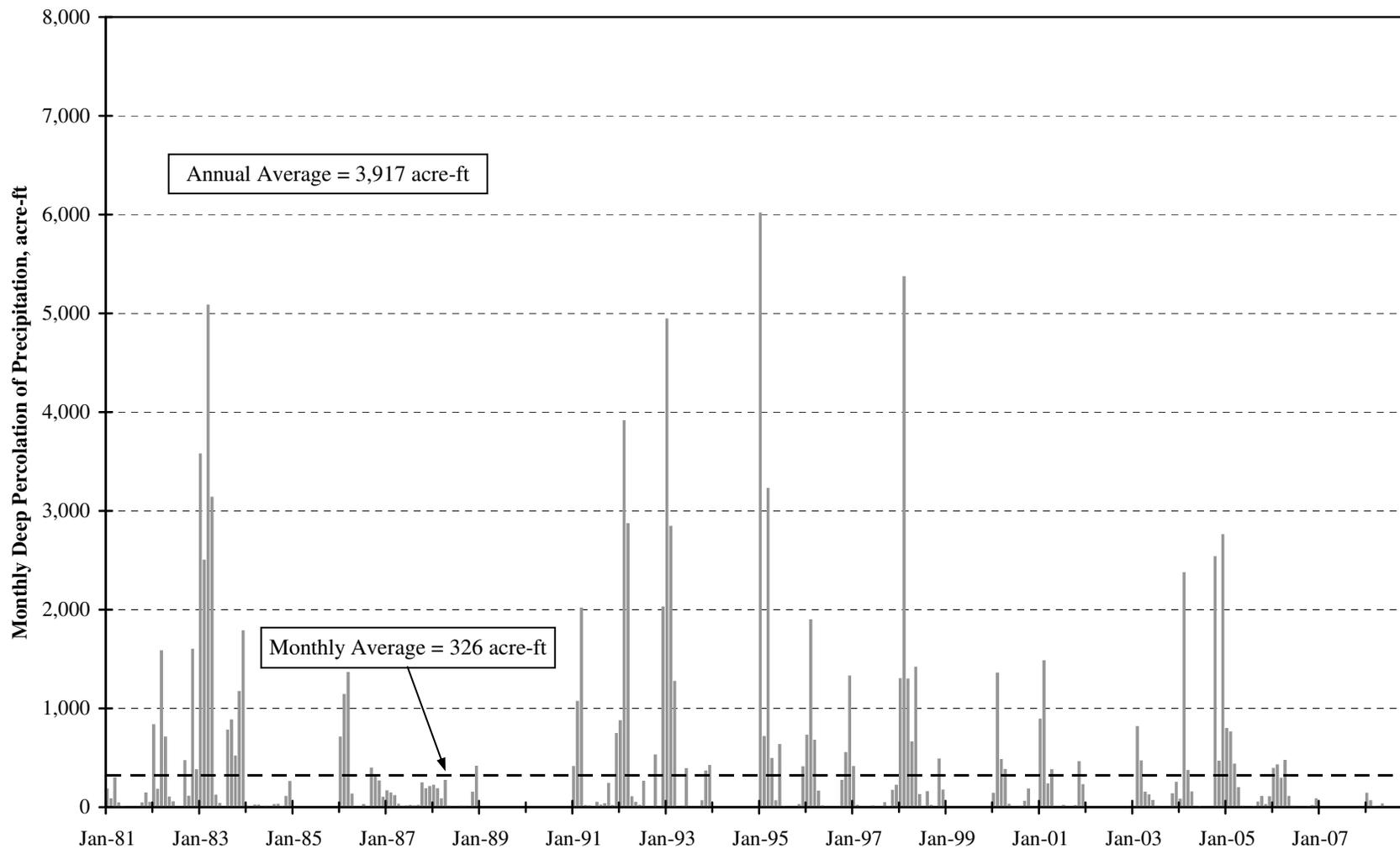
28-Oct-09
 Prepared by: DWB
 Map Projection: UTM 1927, Zone 11



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Figure 12

Monthly Deep Percolation of Precipitation - January 1981 through December 2008



Source: Los Angeles County Department of Public Works, Station 610B Pasadena - City Hall

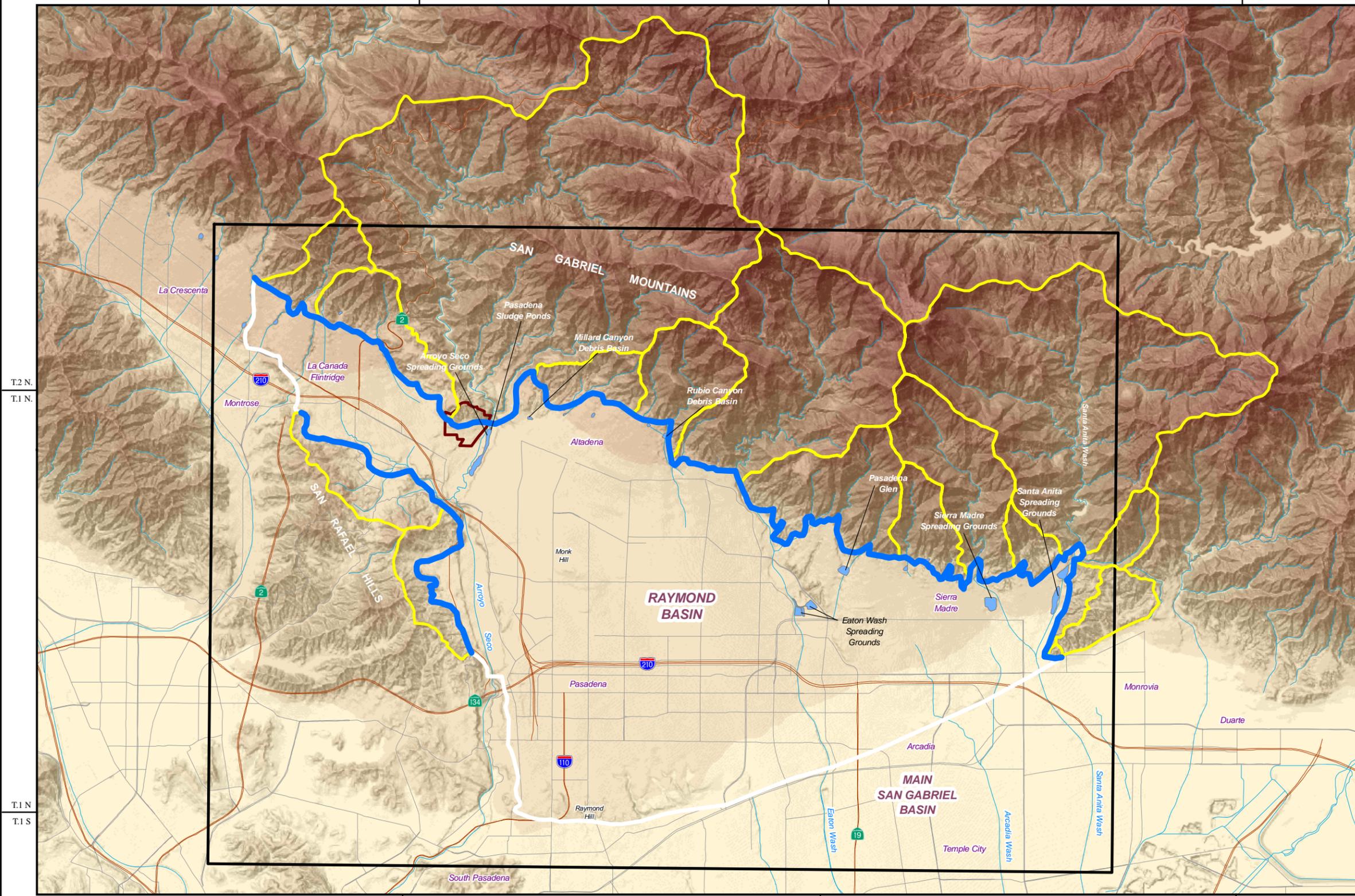
Figure 13

LOCATION OF WATERSHED SUBAREAS USED FOR HSPF MODEL

EXPLANATION

-  Watershed Subareas used for HSPF Model *
-  Location of Mountain Front Runoff
-  NASA/JPL Boundary
-  Raymond Basin Boundary
-  Spreading Grounds or Debris Basins

* HSPF = Hydrologic Simulation Program Fortran (EPA, 1997)

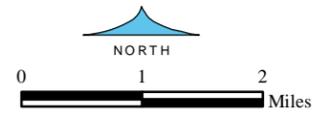


T.2 N.
T.1 N.

T.1 N.
T.1 S.

R.13 W. | R.12 W. | R.12 W. | R.11 W. | R.11 W. | R.10 W.

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Figure 14

Monthly Recharge from Mountain Front Runoff - January 1981 through December 2008

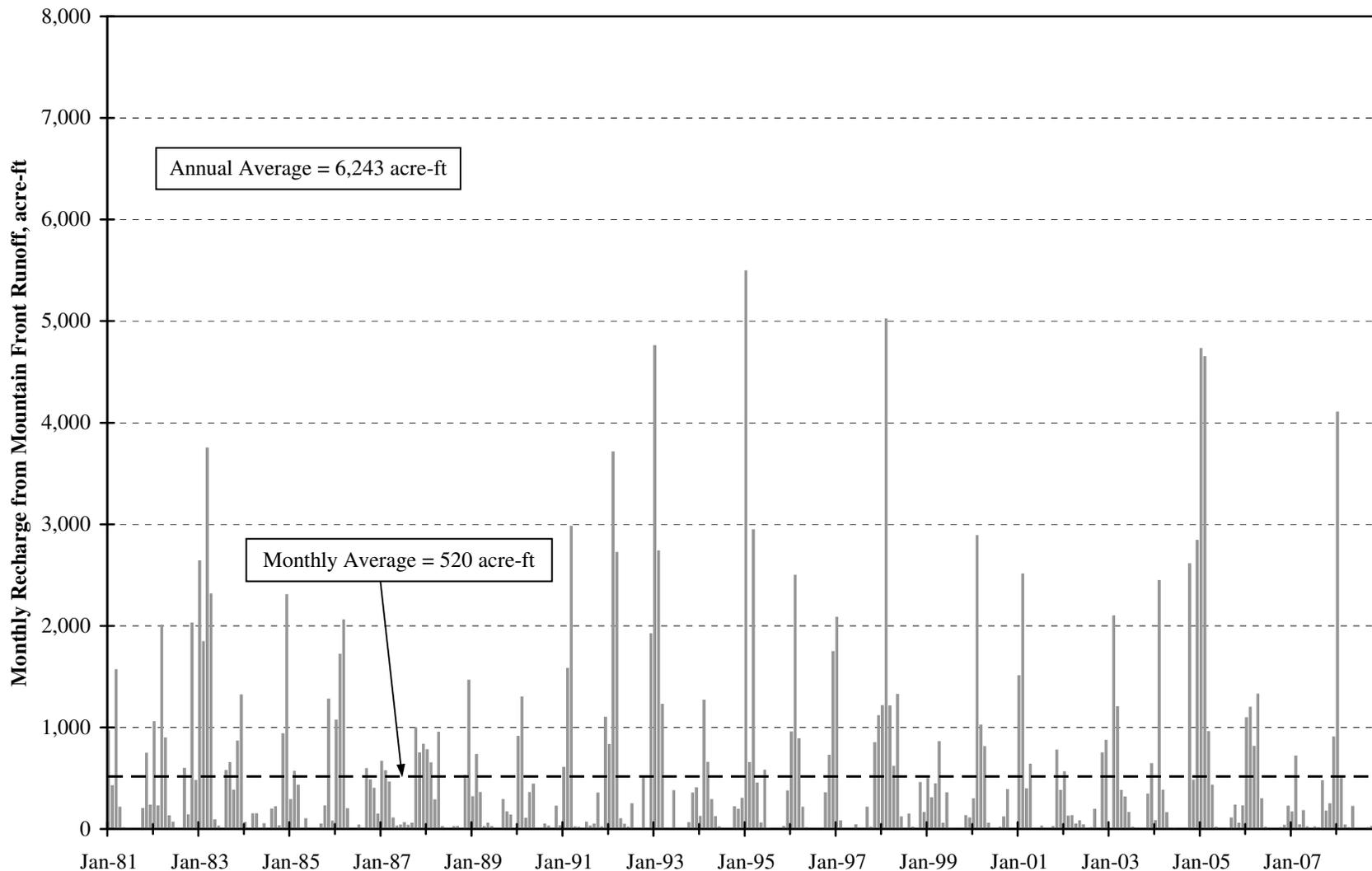


Figure 15

Monthly Artificial Recharge - January 1981 through December 2008

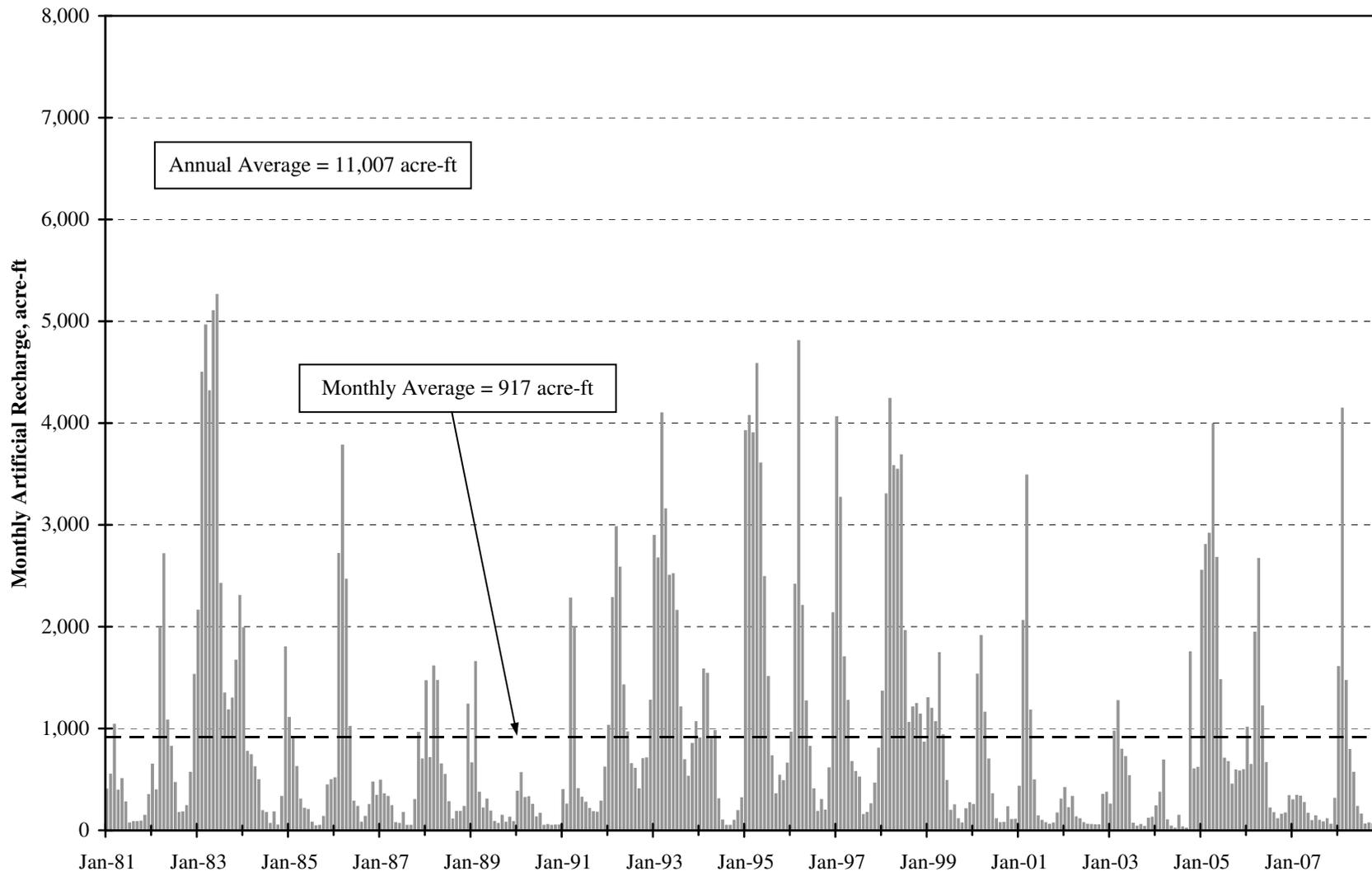
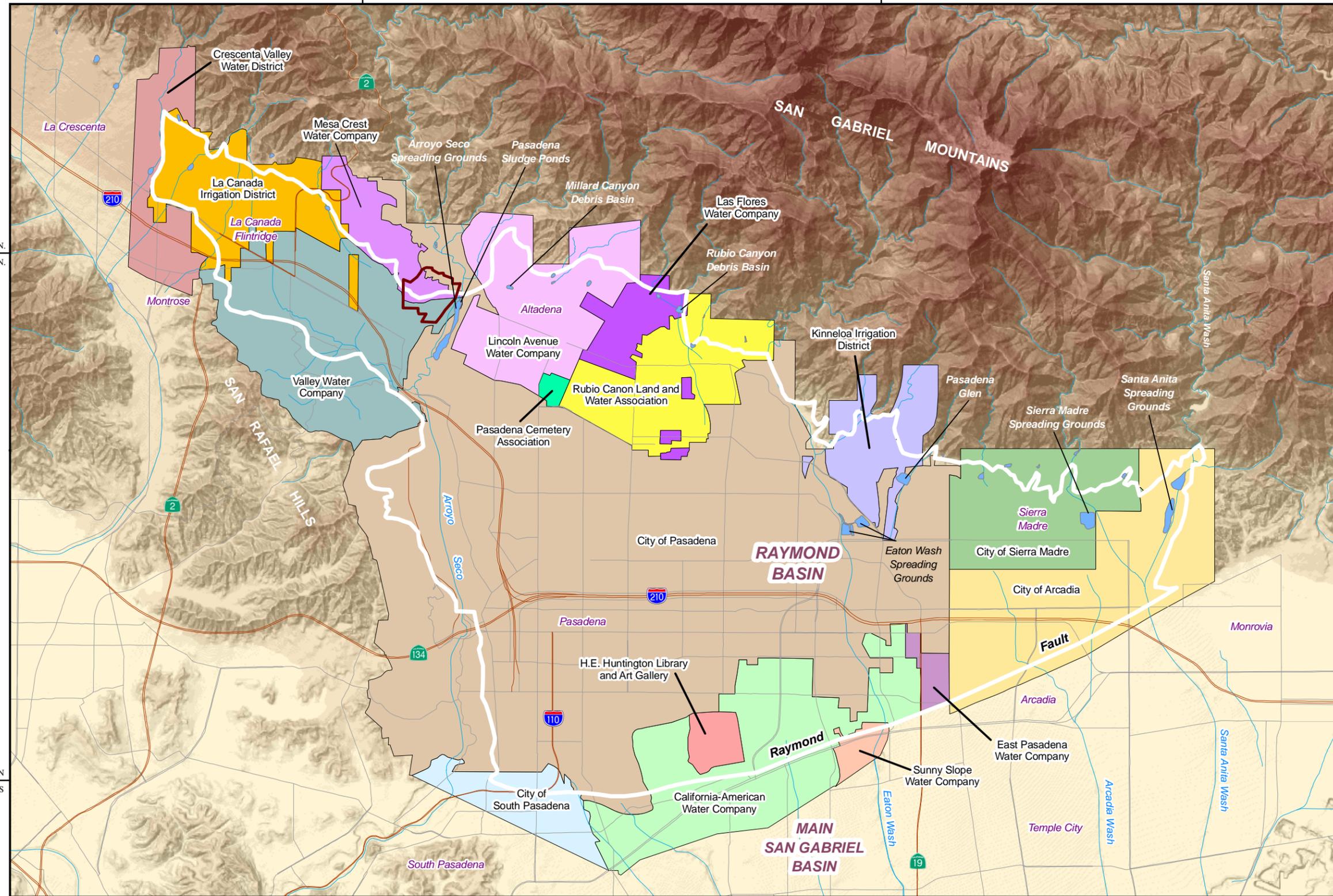


Figure 16



RAYMOND BASIN WATER PURVEYOR SERVICE AREAS

EXPLANATION

- Raymond Basin Water Purveyors (RBMB)
- California American Water Company
 - City of Arcadia
 - City of Pasadena
 - City of Sierra Madre
 - City of South Pasadena (not a member of RBMB)
 - Crescenta Valley Water District (not a member of RBMB)
 - East Pasadena Water Company
 - H.E. Huntington Library and Art Gallery
 - Kinneloa Irrigation District
 - La Canada Irrigation District
 - Las Flores Water Company
 - Lincoln Avenue Water Company
 - Mesa Crest Water Company (not a member of RBMB)
 - Pasadena Cemetery Association
 - Rubio Canon Land and Water Association
 - Sunny Slope Water Company
 - Valley Water Company

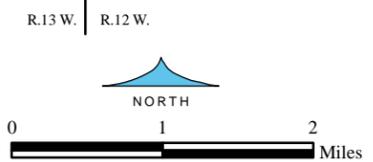
NOTE: City of Alhambra and San Gabriel County Water District are members of RBMB; however, their service areas are outside the Raymond Basin, but they have wells located within the basin.

- NASA/JPL Boundary
- Raymond Basin Boundary
- Spreading Grounds or Debris Basins

28-Oct-09

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Source of Purveyor Data:
Raymond Basin Management Board (2003)

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Figure 17

**LOCATION OF
UNSEWERED AREAS
AND RECHARGE BASINS**

EXPLANATION

 Location of Unsewered Areas

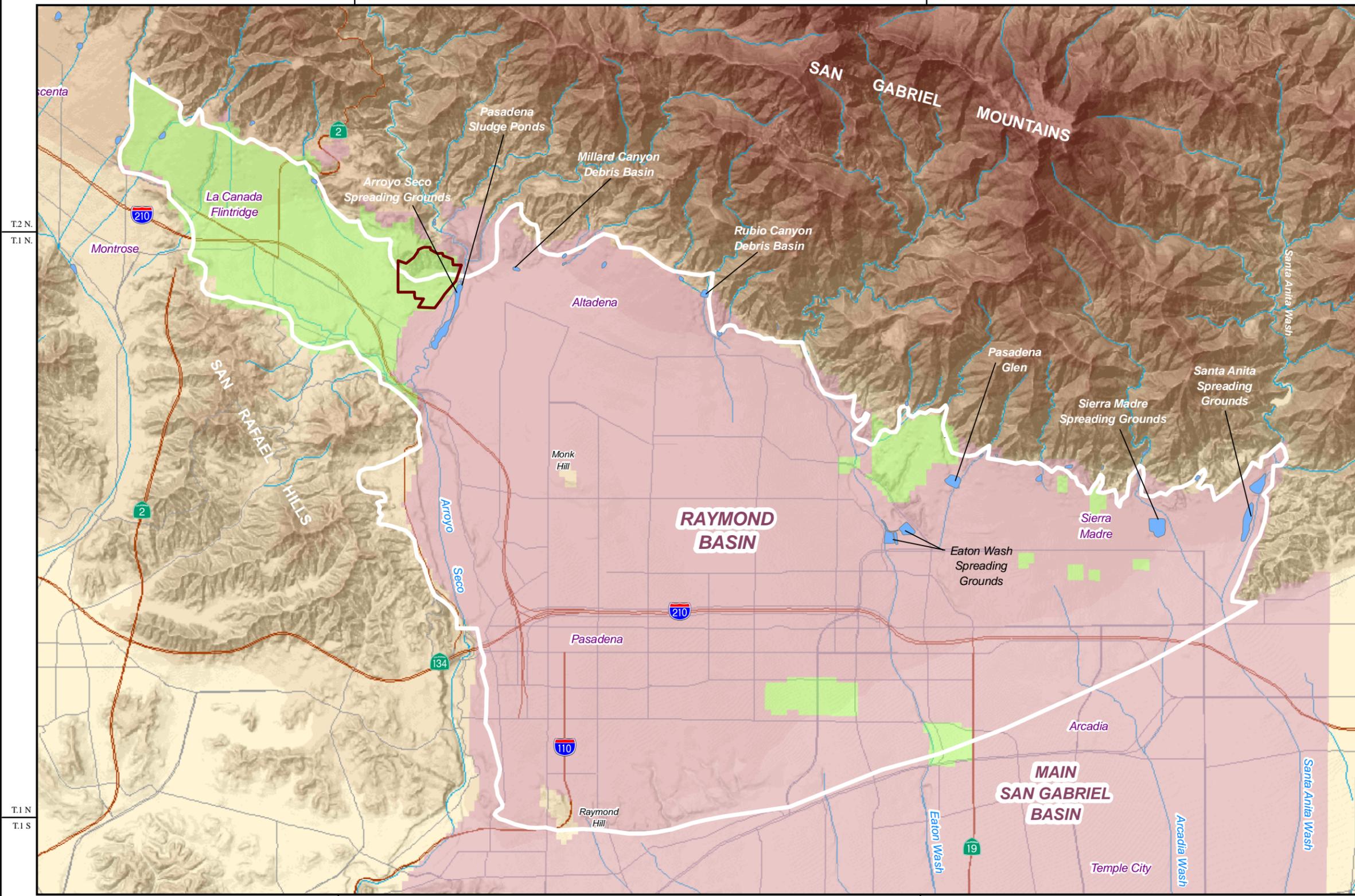
 Location of Sewered Areas

Source of Data:
Department of Water Resources (1969c).
CH2M Hill (1992)

 NASA/JPL Boundary

 Raymond Basin Boundary

 Spreading Grounds or Debris Basins



28-Oct-09
Prepared by: DWB
Map Projection: UTM 1927, Zone 11



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Figure 18

GIS_proj/city_of_pasadena_jpl_model_9-09/0_Fig_12_impervious_areas_10-09.mxd

Monthly Total Return Flow - January 1981 through December 2008

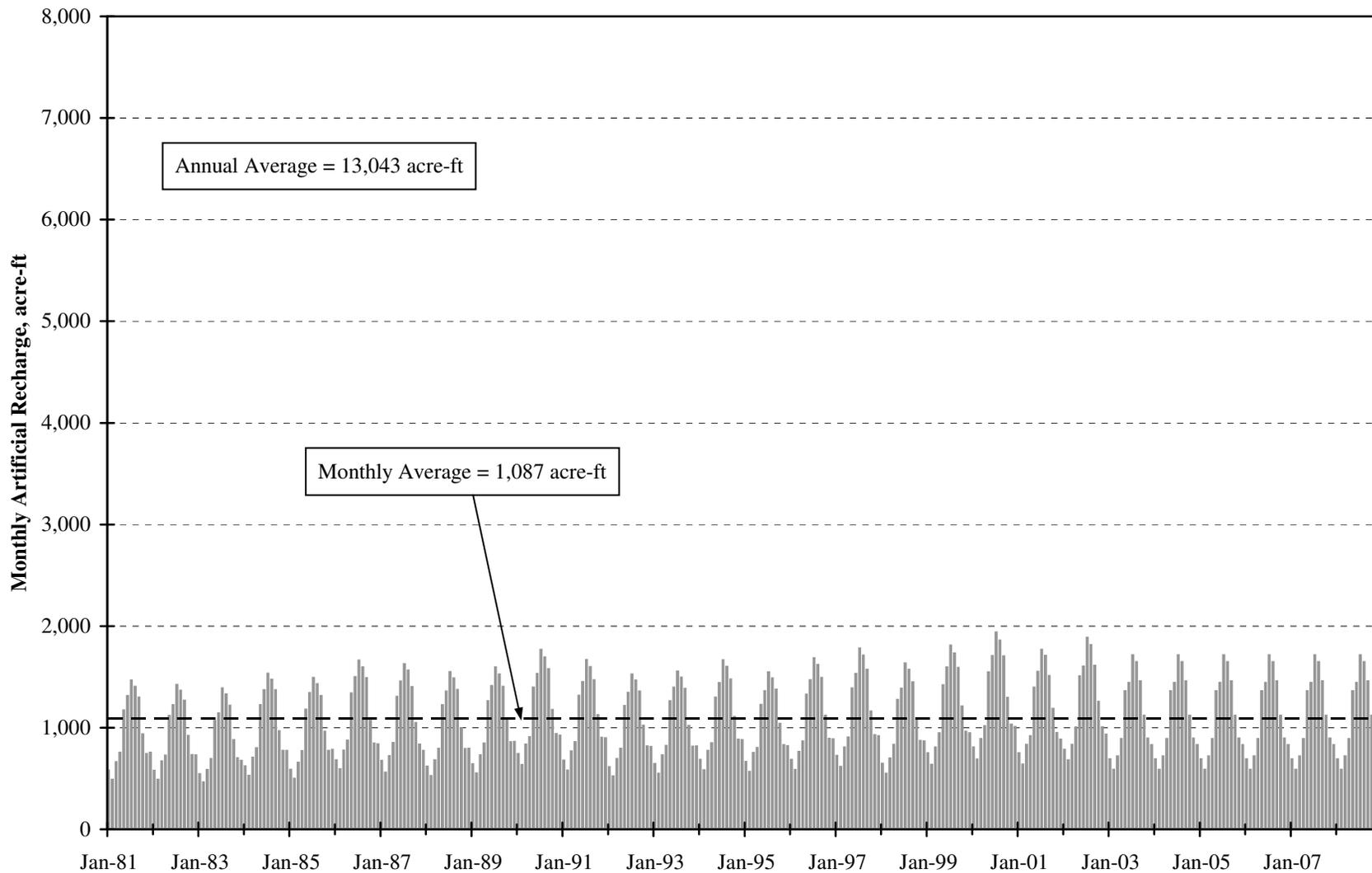
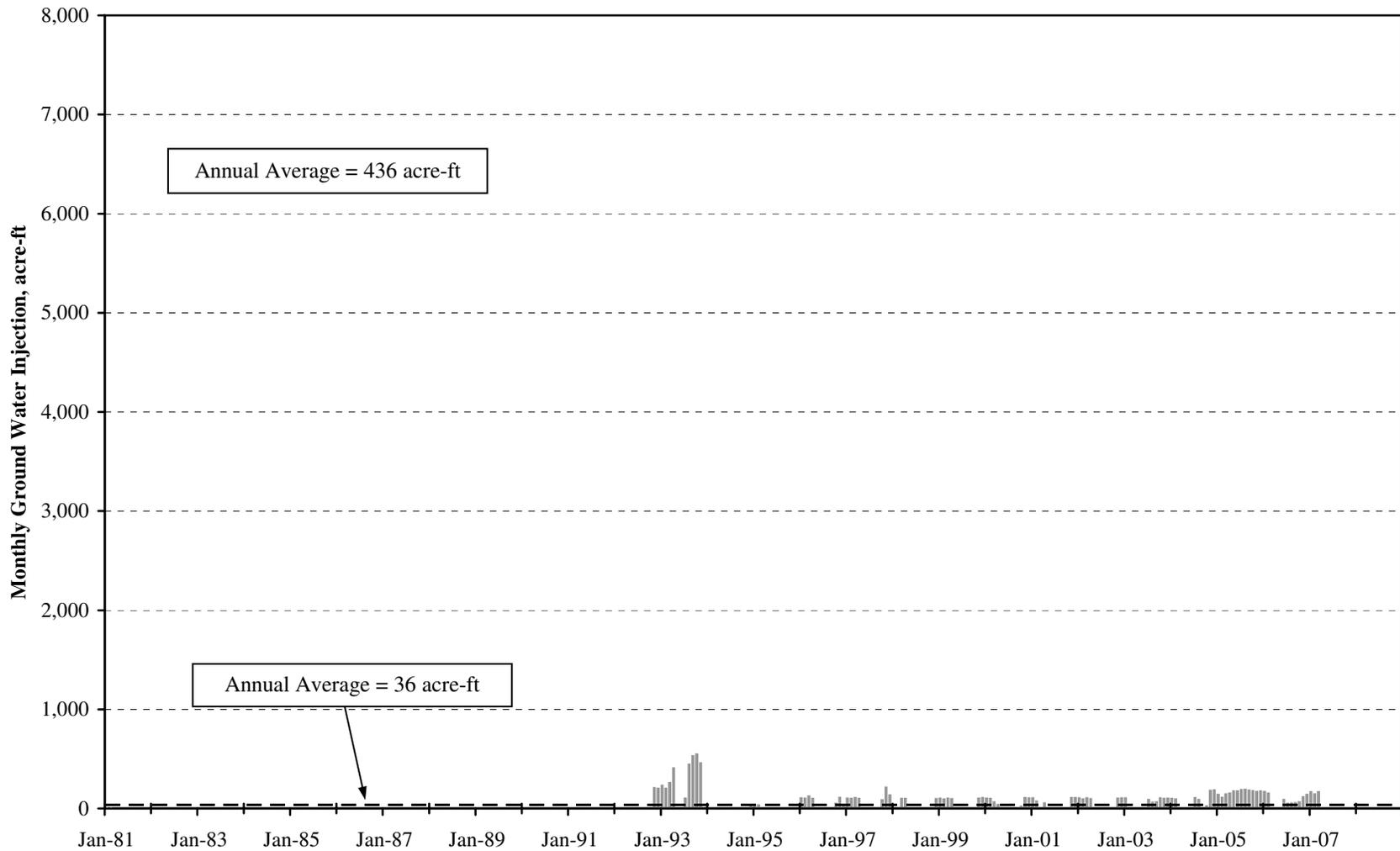


Figure 19

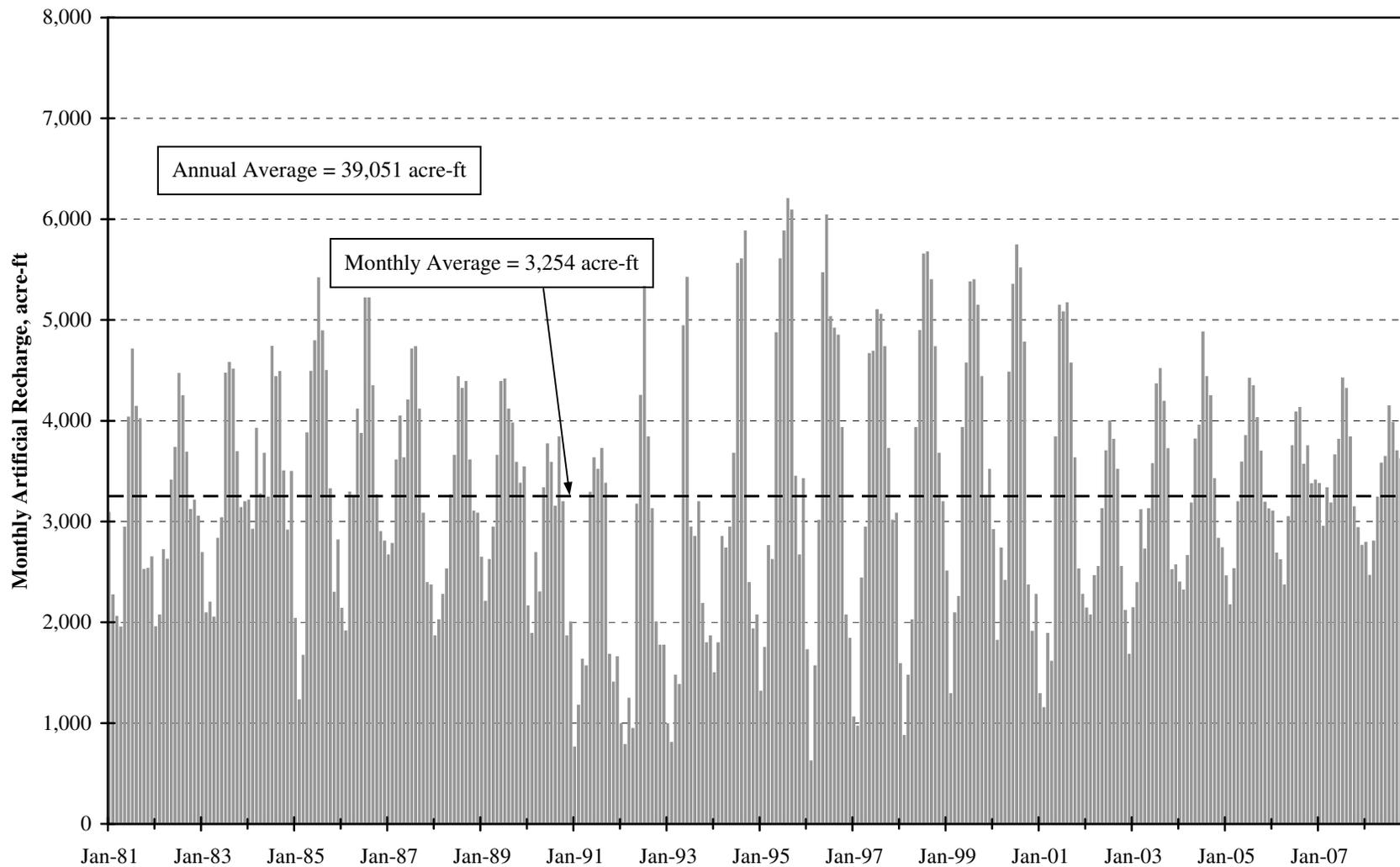
Monthly Ground Water Injection - January 1981 through December 2008



Source: Raymond Basin Management Board

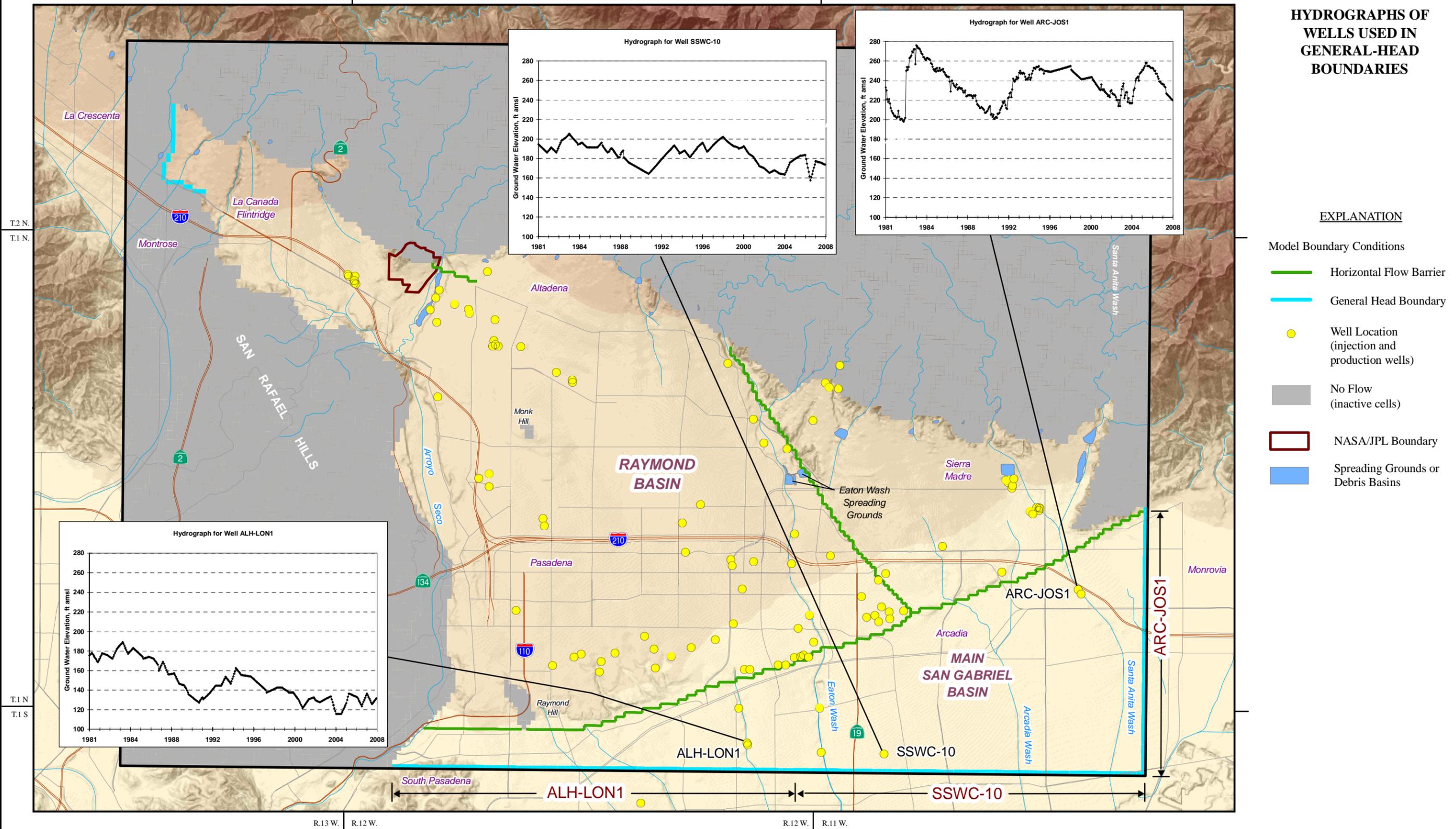
Figure 20

Monthly Ground Water Production - January 1981 through December 2008



Source: Raymond Basin Management Board

Figure 21

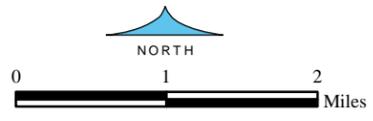


HYDROGRAPHS OF WELLS USED IN GENERAL-HEAD BOUNDARIES

EXPLANATION

- Model Boundary Conditions
- Horizontal Flow Barrier
 - General Head Boundary
 - Well Location (injection and production wells)
 - No Flow (inactive cells)
 - NASA/JPL Boundary
 - Spreading Grounds or Debris Basins

28-Oct-09
 Prepared by: DW B
 Map Projection: UTM 1927, Zone 11



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Figure 22

GIS_proj/city_of_pasadena_jpl_model_9-09/0_Fig_22_hydrograph_wells_GHB_10-09.mxd

Measured versus Model-Generated Water Levels - Steady-State Model Calibration (1980)

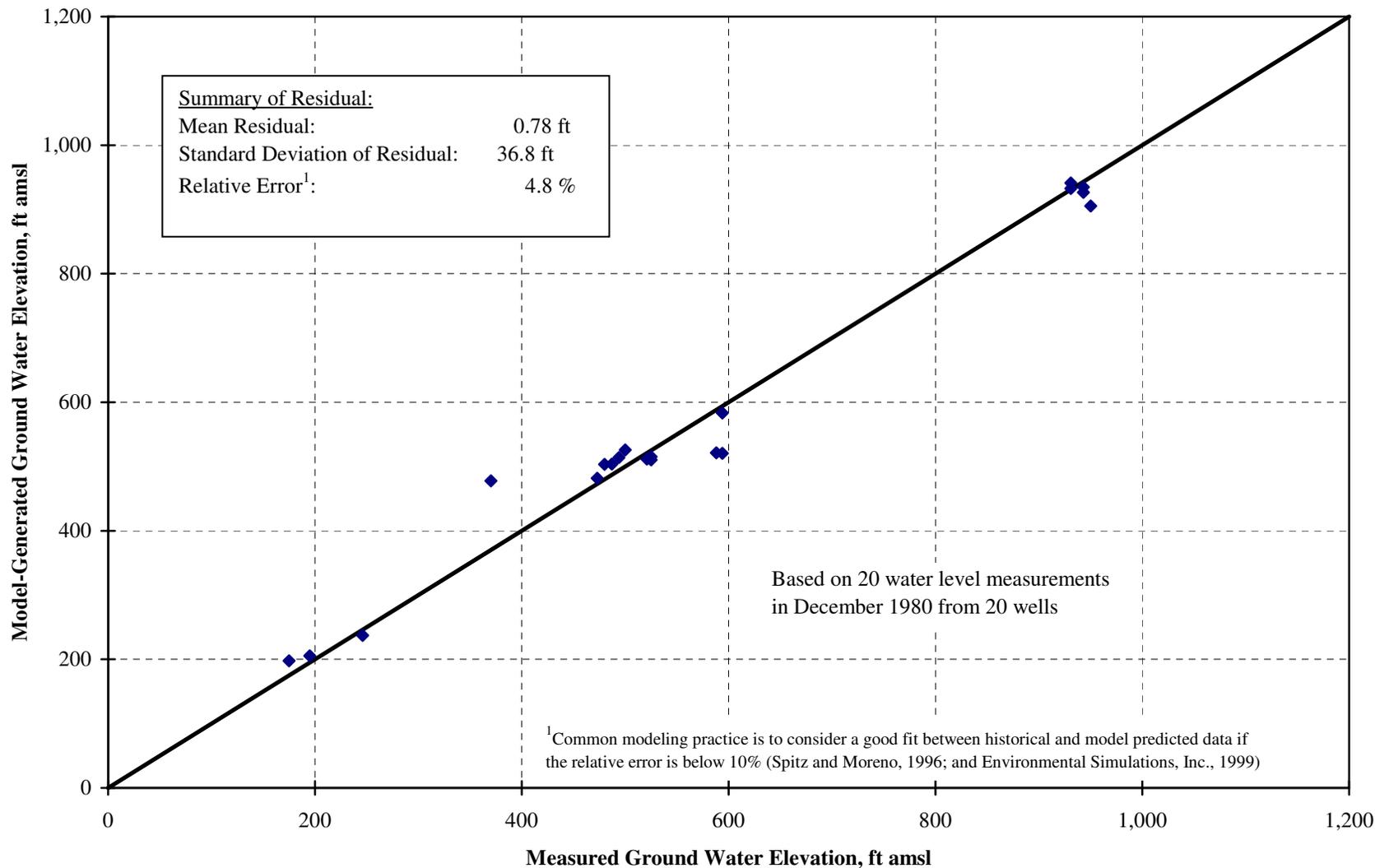


Figure 24

Measured versus Model-Generated Water Levels - Transient Model Calibration (January 1981 through December 2008)

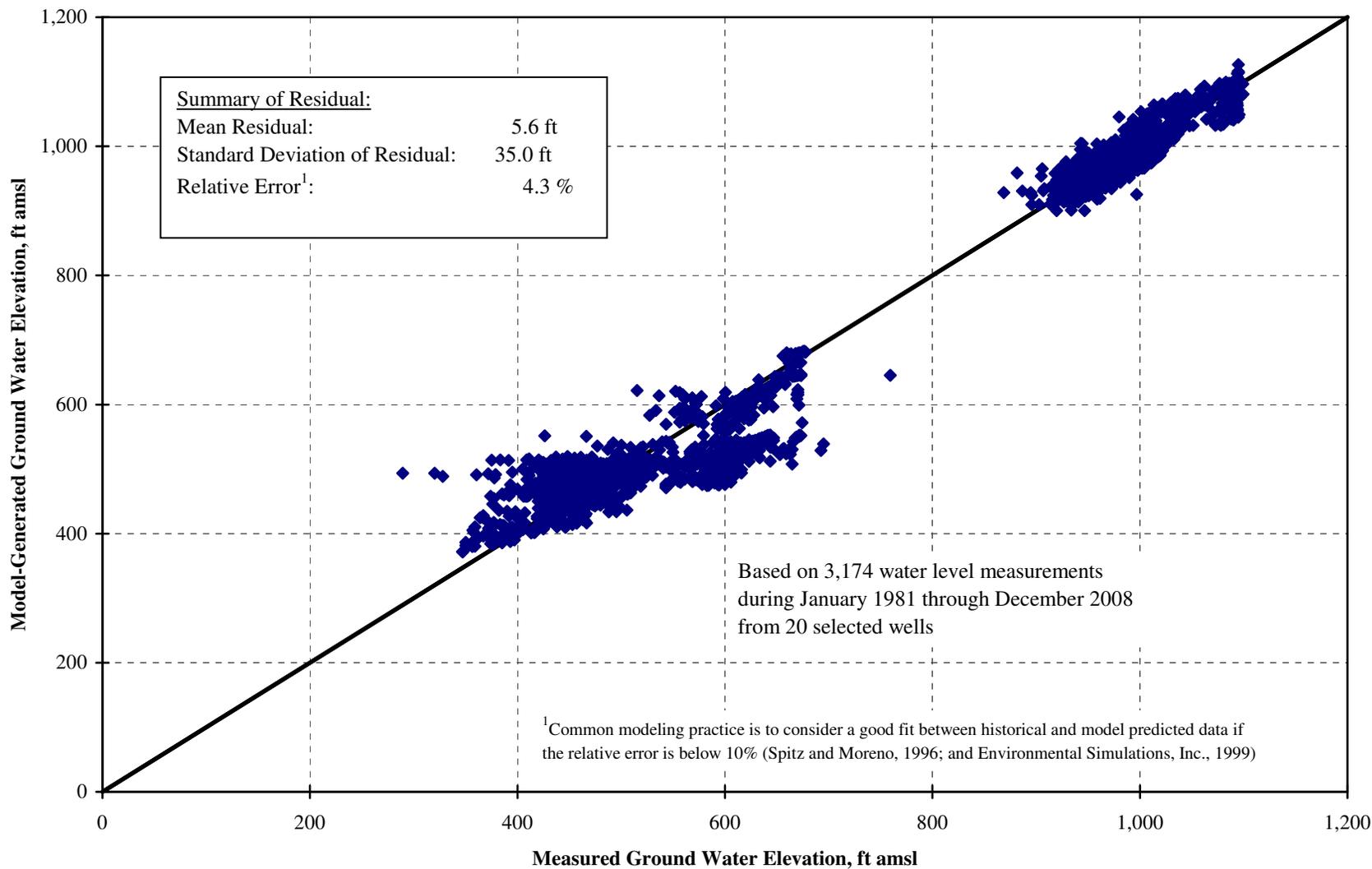


Figure 25

Histogram of Water Level Residuals Transient Model Calibration 1981 - 2008

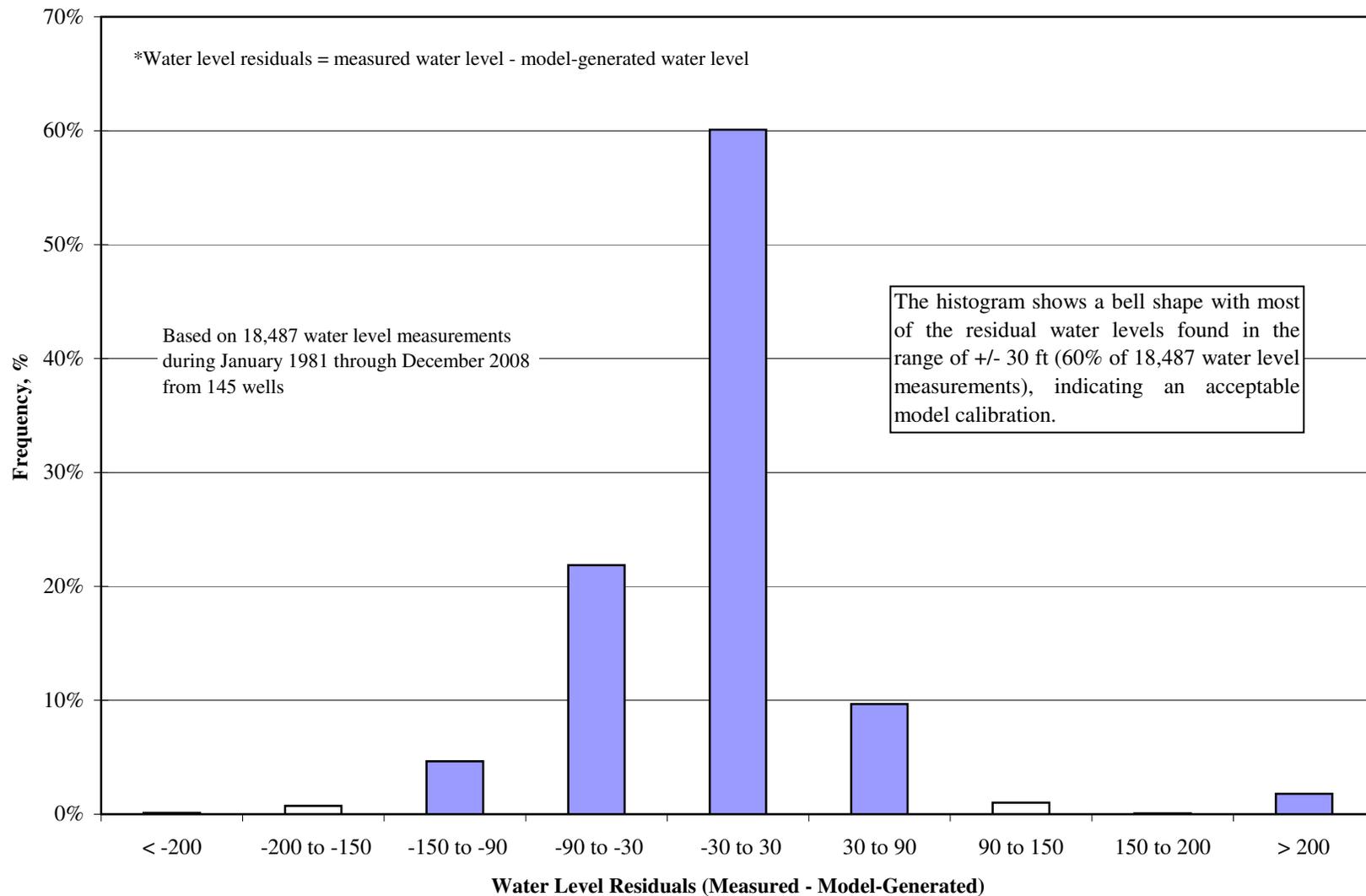
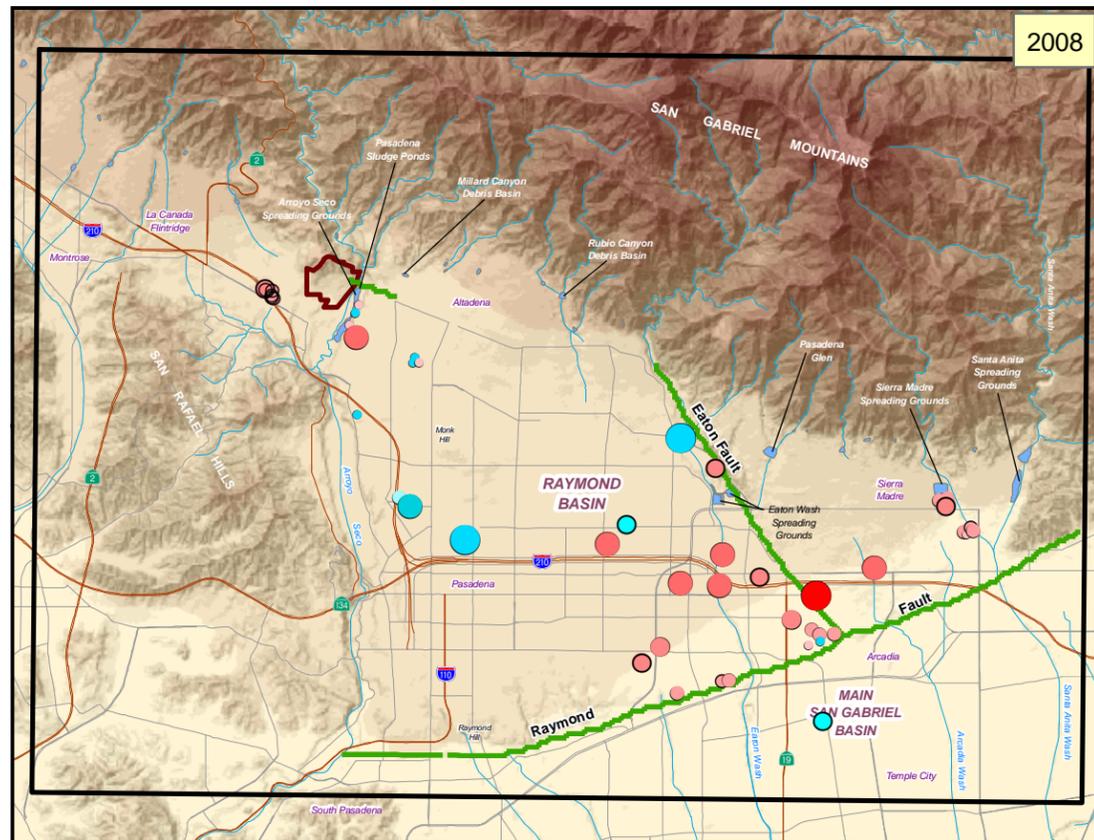
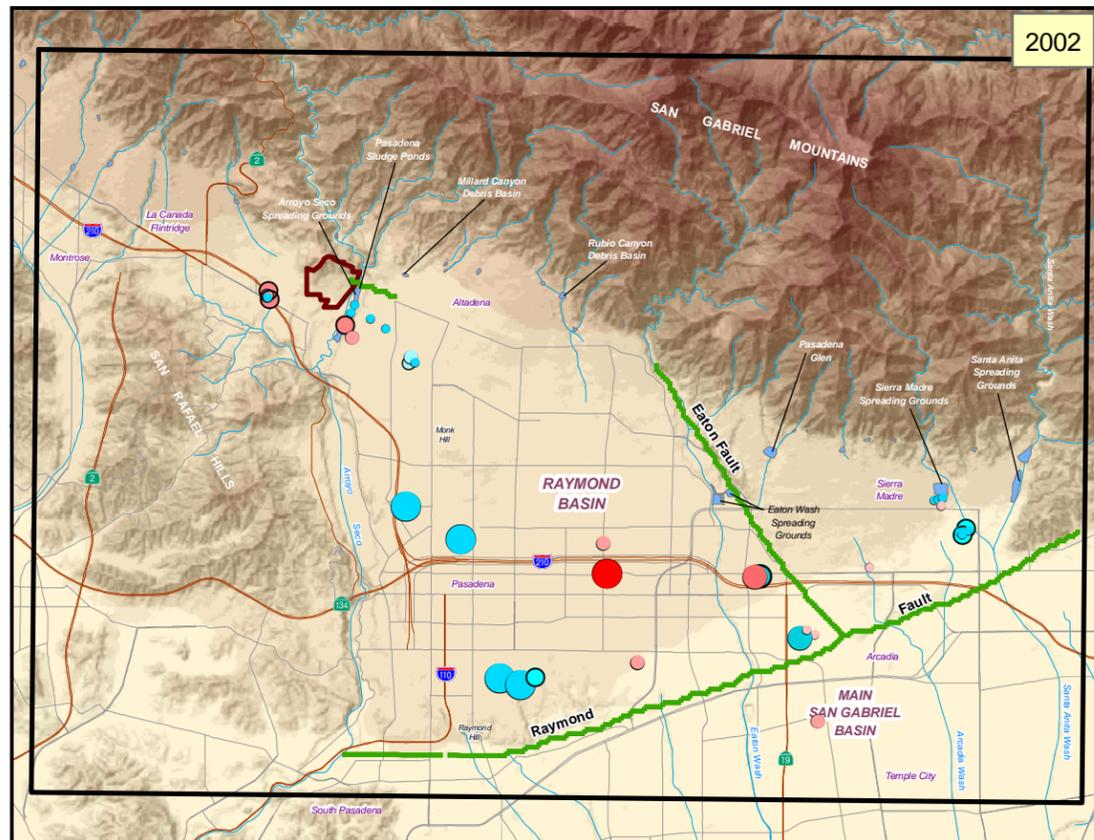
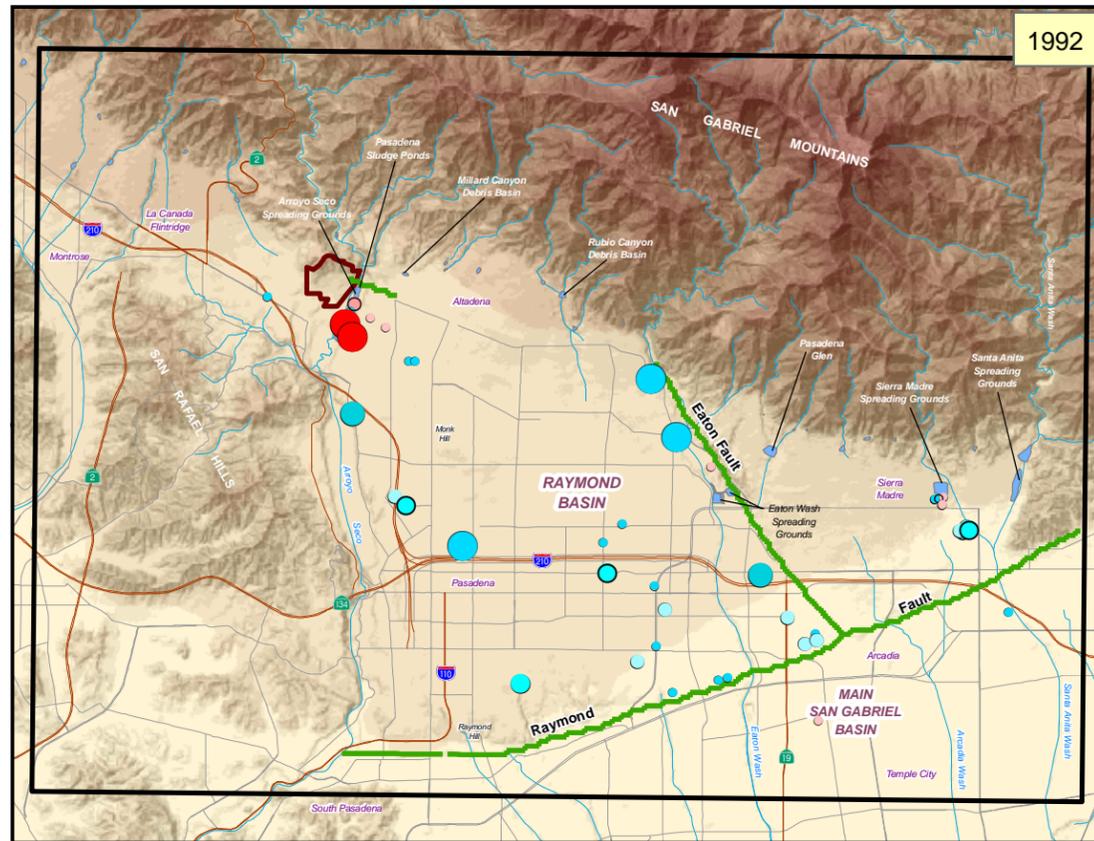
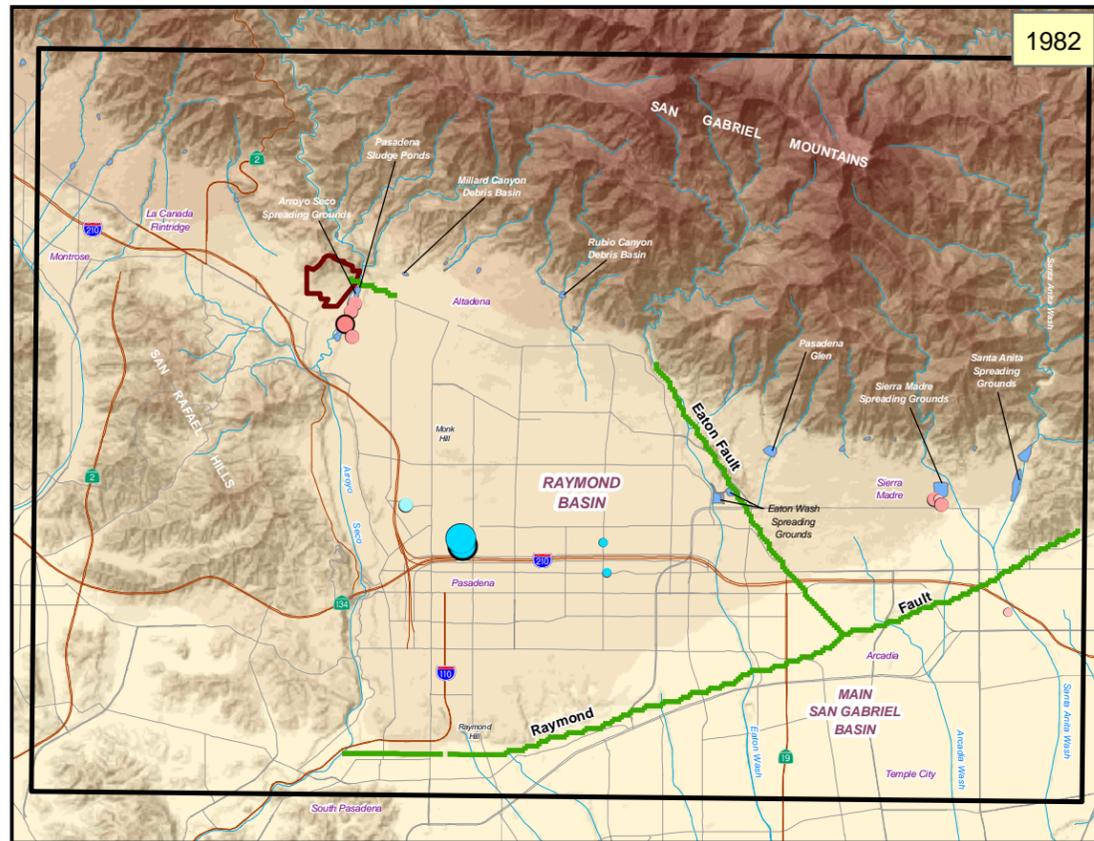


Figure 26



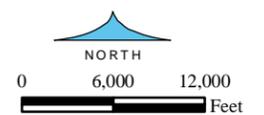
SPATIAL DISTRIBUTION OF GROUND WATER LEVEL RESIDUALS 1982, 1992, 2002 AND 2008

EXPLANATION

Ground Water Level Residual (ft)
(measured water levels minus model-generated water levels)

- <-100
- -100 - -75
- -75 - -50
- -50 - -25
- -25 - 0
- 0 -25
- 25 -50
- 50 -75
- 75 -100
- >100

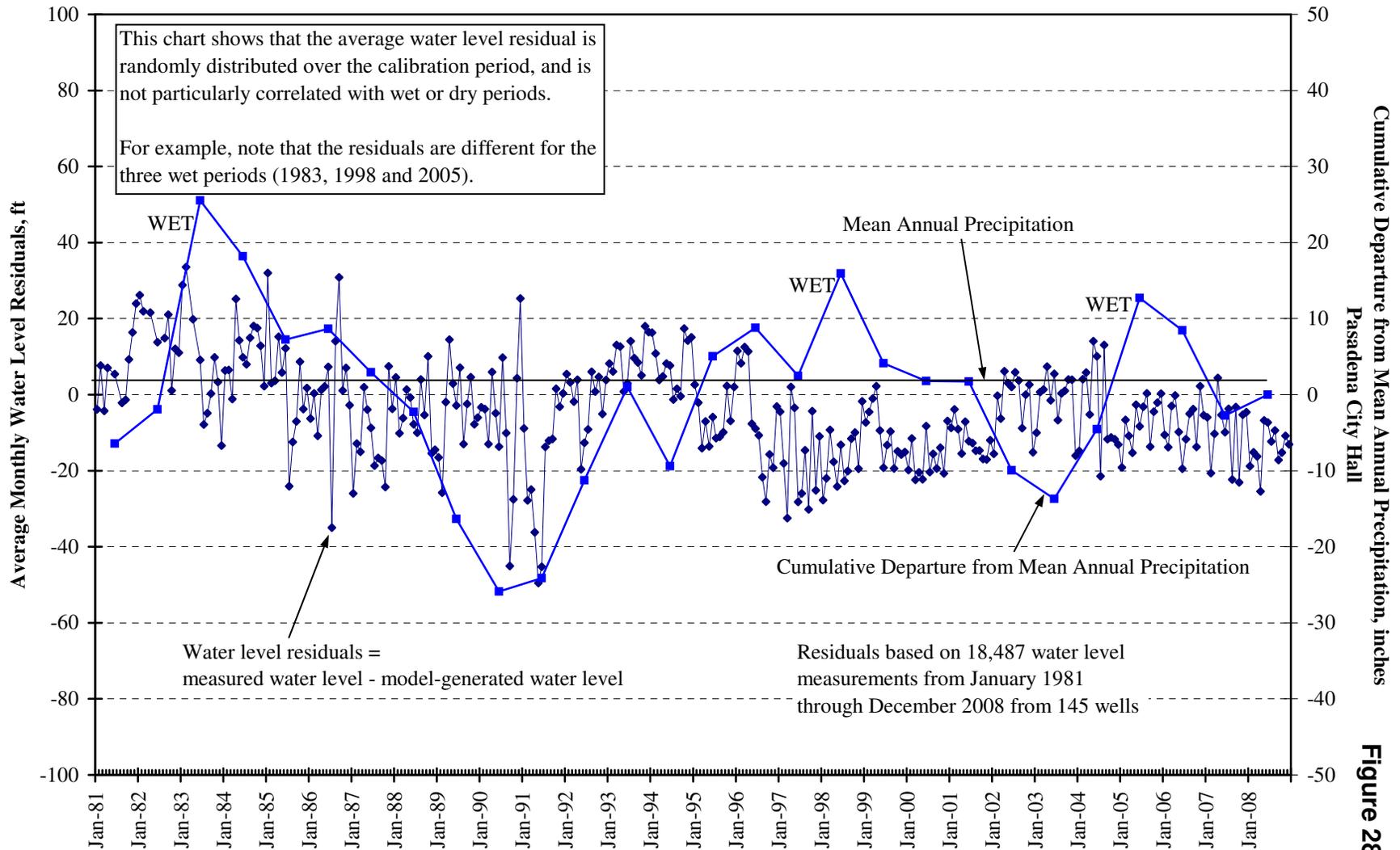
- NASA/JPL Boundary
- Spreading Grounds or Debris Basins
- Horizontal Flow Barrier

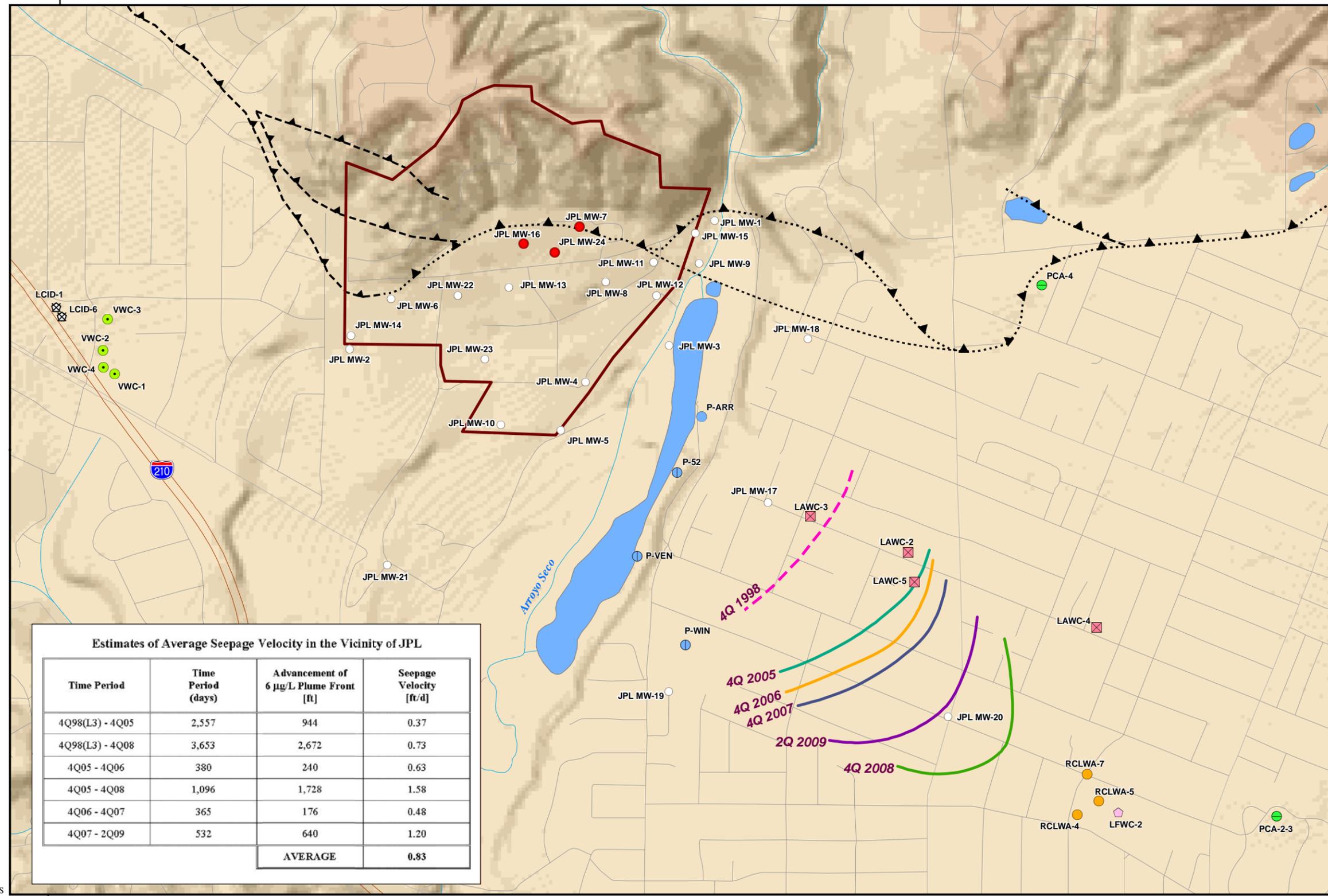


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Average Monthly Water Level Residuals - January 1981 through December 2008





ESTIMATES OF SEEPAGE VELOCITY

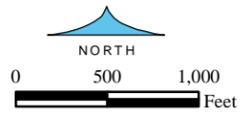
- EXPLANATION**
- Edge of 6 ug/L Perchlorate Plume Front
 - 4Q 1998 Layer 3 *
 - 4Q 2005
 - 4Q 2006
 - 4Q 2007
 - 4Q 2008
 - 2Q 2009
 - * = Leading edge of 6 ug/L 4th Quarter 1998 Layer 3 Plume.
Source: NASA Quarterly Monitoring Reports (1998-2009)
 - JPL Source Area Monitoring Well (Source: NASA TM, 2007)
 - JPL Monitoring Well (Source: NASA, 2009)
 - Raymond Basin Water Purveyors (RBMB)
 - City of Pasadena
 - Kinneloa Irrigation District
 - La Canada Irrigation District
 - Las Flores Water Company
 - Lincoln Avenue Water Company
 - Pasadena Cemetery Association
 - Rubio Canon Land and Water Association
 - Valley Water Company
 - NASA/JPL Boundary
 - Spreading Grounds or Debris Basins
 - Fault Classification (USGS)¹
 - Known
 - Inferred
 - Concealed
 - Indicates Thrust Fault

Estimates of Average Seepage Velocity in the Vicinity of JPL

Time Period	Time Period (days)	Advancement of 6 µg/L Plume Front [ft]	Seepage Velocity [ft/d]
4Q98(L3) - 4Q05	2,557	944	0.37
4Q98(L3) - 4Q08	3,653	2,672	0.73
4Q05 - 4Q06	380	240	0.63
4Q05 - 4Q08	1,096	1,728	1.58
4Q06 - 4Q07	365	176	0.48
4Q07 - 2Q09	532	640	1.20
AVERAGE			0.83

T.1 S
R.13 W. | R.12 W.

28-Oct-09
Prepared by: DWB
Map Projection: UTM 1927, Zone 11

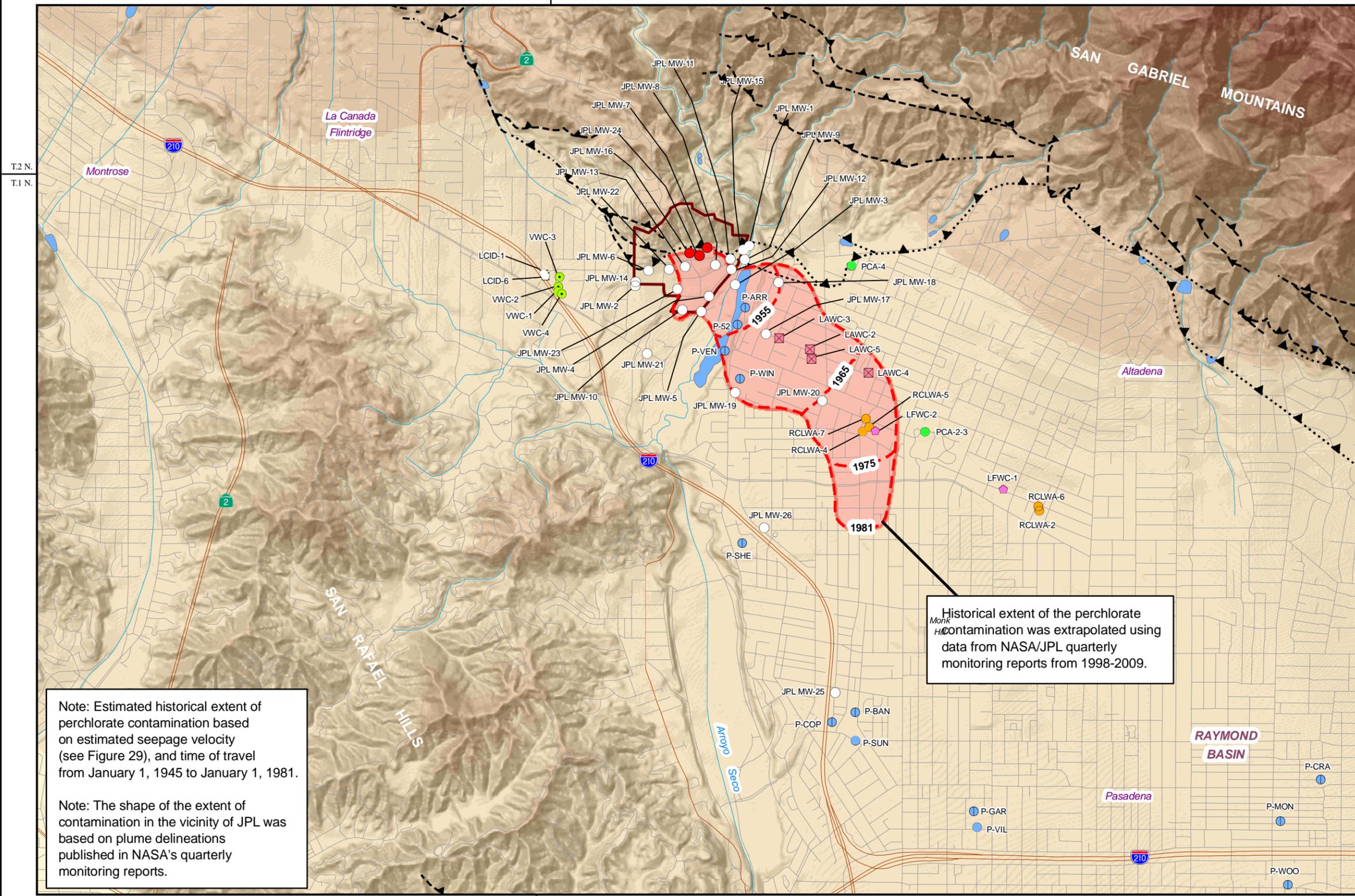


(1) USGS OFR 2005-1019. "Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California". 2005.

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Figure 29

ESTIMATED HISTORICAL EXTENT OF PERCHLORATE CONTAMINATION



EXPLANATION

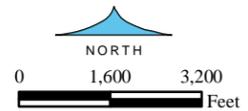
- Estimated Extent of Perchlorate Contamination (January 1, 1945 to January 1, 1981)
 - 1965 - Estimated Historical Extent of Perchlorate Contamination (Year)
 - JPL Source Area Monitoring Well (Source: NASA TM, 2007)
 - JPL Monitoring Well (Source: NASA, 2009)
- Raymond Basin Water Purveyors (RBMB)**
- ⓘ City of Pasadena
 - ⊠ Kinneloa Irrigation District
 - ⊠ La Canada Irrigation District
 - ⊠ Las Flores Water Company
 - ⊠ Lincoln Avenue Water Company
 - Pasadena Cemetery Association
 - Rubio Canon Land and Water Association
 - Valley Water Company
- NASA/JPL Boundary
 - Spreading Grounds or Debris Basins
- Fault Classification (USGS)¹**
- Known
 - Inferred
 - Concealed
 - ▲ Indicates Thrust Fault

Note: Estimated historical extent of perchlorate contamination based on estimated seepage velocity (see Figure 29), and time of travel from January 1, 1945 to January 1, 1981.

Note: The shape of the extent of contamination in the vicinity of JPL was based on plume delineations published in NASA's quarterly monitoring reports.

Historical extent of the perchlorate contamination was extrapolated using data from NASA/JPL quarterly monitoring reports from 1998-2009.

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 Map Projection: UTM 1927, Zone 11

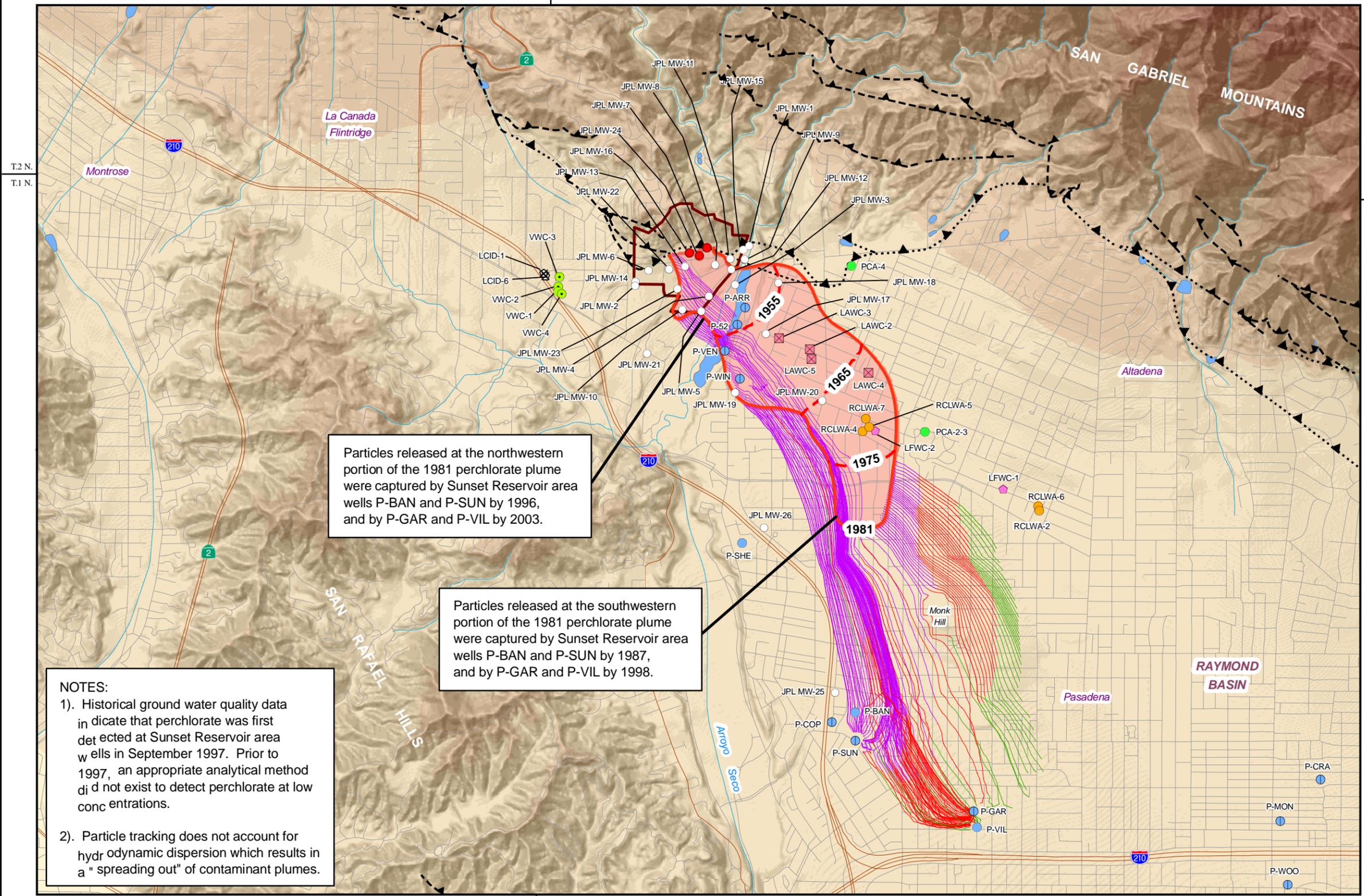


(1) USGS OFR 2005-1019. "Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California". 2005.

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Figure 30

FORWARD PARTICLE TRACKING FROM THE 1981 ESTIMATED LEADING EDGE OF THE JPL PERCHLORATE PLUME (JANUARY 1, 1981 TO DECEMBER 31, 2008)



EXPLANATION

Forward Particle Track From the 1981 Estimated Leading Edge of the JPL Perchlorate Plume (January 1, 1981 to December 31, 2008)

- 1981 -1991
- 1991 -2001
- 2001 -2008
- Estimated Extent of Perchlorate Contamination (Jan. 1, 1945 to Jan. 1, 1981)
- - - Estimated Downgradient Extent of Perchlorate Plume (Year)
- JPL Source Area Monitoring Well (Source: NASA TM, 2007)
- JPL Monitoring Well (Source: NASA, 2009)

- Raymond Basin Water Purveyors (RBMB)
- City of Pasadena
 - Kinneloa Irrigation District
 - La Canada Irrigation District
 - Las Flores Water Company
 - Lincoln Avenue Water Company
 - Pasadena Cemetery Association
 - Rubio Canon Land and Water Association
 - Valley Water Company

- NASA/JPL Boundary
- Spreading Grounds or Debris Basins
- Fault Classification (USGS) ¹**
- Known
- - - Inferred
- · · · · Concealed
- ▲ Indicates Thrust Fault

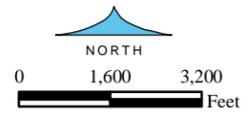
Particles released at the northwestern portion of the 1981 perchlorate plume were captured by Sunset Reservoir area wells P-BAN and P-SUN by 1996, and by P-GAR and P-VIL by 2003.

Particles released at the southwestern portion of the 1981 perchlorate plume were captured by Sunset Reservoir area wells P-BAN and P-SUN by 1987, and by P-GAR and P-VIL by 1998.

NOTES:

- 1). Historical ground water quality data indicate that perchlorate was first detected at Sunset Reservoir area wells in September 1997. Prior to 1997, an appropriate analytical method did not exist to detect perchlorate at low concentrations.
- 2). Particle tracking does not account for hydrodynamic dispersion which results in a "spreading out" of contaminant plumes.

28-Oct-09
 Prepared by: DW B
 Map Projection: UTM 1927, Zone 11



(1) USGS OFR 2005-1019. "Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California". 2005.

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Figure 31

BACKWARD PARTICLE TRACKING FROM THE SUNSET RESERVOIR AREA WELLS (DECEMBER 31, 2008 TO JANUARY 1, 1981)

EXPLANATION

Backward Particle Track From the Sunset Reservoir Area Wells (December 31, 2008 to January 1, 1981)

- 2008 - 1999
- 1999 - 1989
- 1989 - 1981

Estimated Extent of Perchlorate Contamination (Jan. 1, 1945 to Jan. 1, 1981)

Estimated Downgradient Extent of Perchlorate Plume (Year)

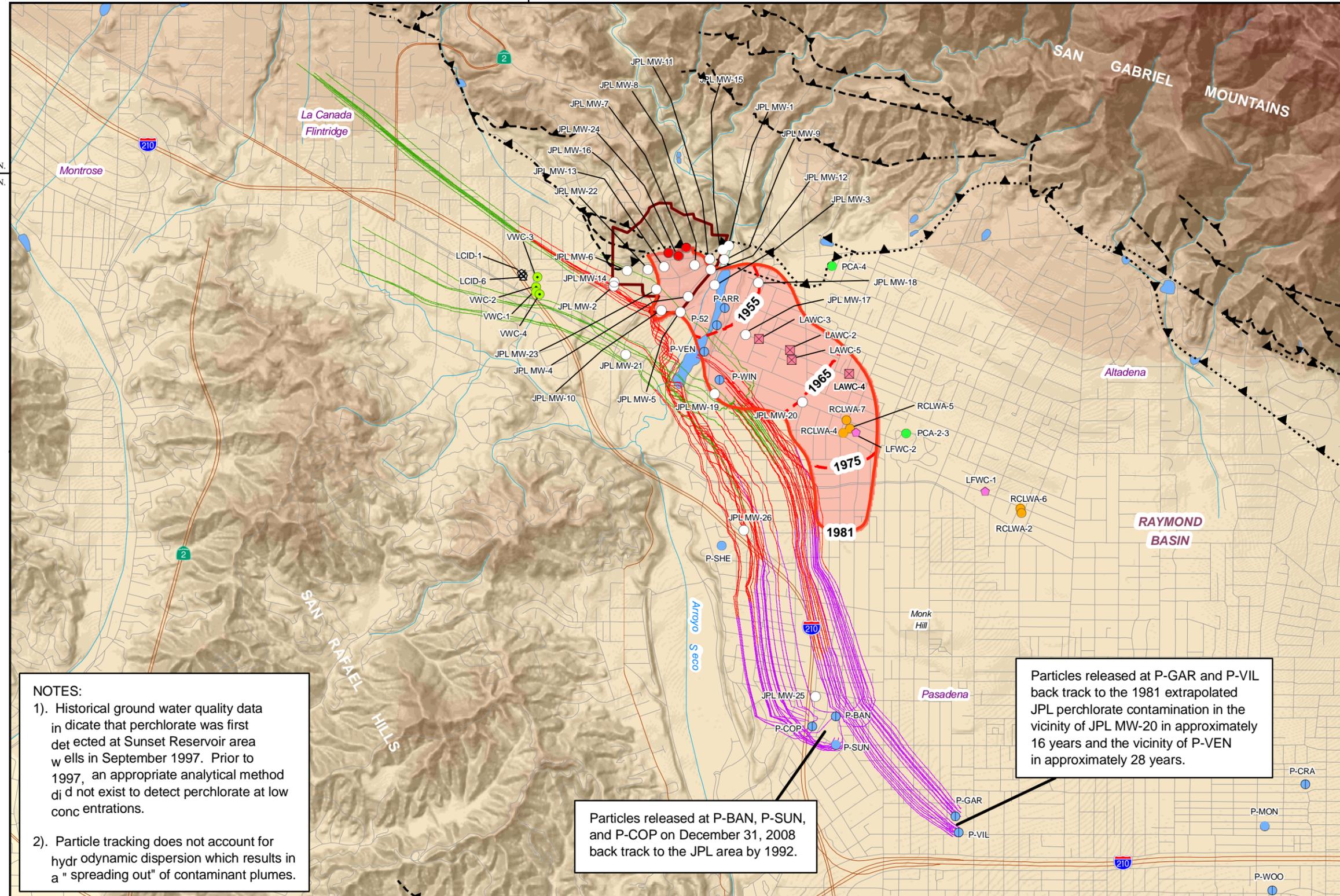
- JPL Source Area Monitoring Well (Source: NASA TM, 2007)
- JPL Monitoring Well (Source: NASA, 2009)

Raymond Basin Water Purveyors (RBMB)

- City of Pasadena
- Kinneloa Irrigation District
- La Canada Irrigation District
- Las Flores Water Company
- Lincoln Avenue Water Company
- Pasadena Cemetery Association
- Rubio Canon Land and Water Association
- Valley Water Company

- NASA/JPL Boundary
- Spreading Grounds or Debris Basins

- Fault Classification (USGS) ¹**
- Known
 - Inferred
 - Concealed
 - ▲ Indicates Thrust Fault

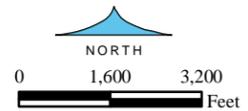


NOTES:

- 1). Historical ground water quality data indicate that perchlorate was first detected at Sunset Reservoir area wells in September 1997. Prior to 1997, an appropriate analytical method did not exist to detect perchlorate at low concentrations.
- 2). Particle tracking does not account for hydrodynamic dispersion which results in a "spreading out" of contaminant plumes.

Particles released at P-BAN, P-SUN, and P-COP on December 31, 2008 back track to the JPL area by 1992.

Particles released at P-GAR and P-VIL back track to the 1981 extrapolated JPL perchlorate contamination in the vicinity of JPL MW-20 in approximately 16 years and the vicinity of P-VEN in approximately 28 years.



(1) USGS OFR 2005-1019. "Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California". 2005.

BACKWARD PARTICLE TRACKING FROM JPL MW-20 (SCREENS 4 AND 5)

EXPLANATION

Backward Particle Track from JPL MW-20 (Screens 4 and 5) (December 31, 2008 to January 1, 1981)

- 2008 - 1999
- 1999 - 1989
- 1989 - 1981

Estimated Extent of Perchlorate Contamination (Jan. 1, 1945 to Jan. 1, 1981)

Estimated Downgradient Extent of Perchlorate Plume (Year)

- JPL Source Area Monitoring Well (Source: NASA TM, 2007)
- JPL Monitoring Well (Source: NASA, 2009)

Raymond Basin Water Purveyors (RBMB)

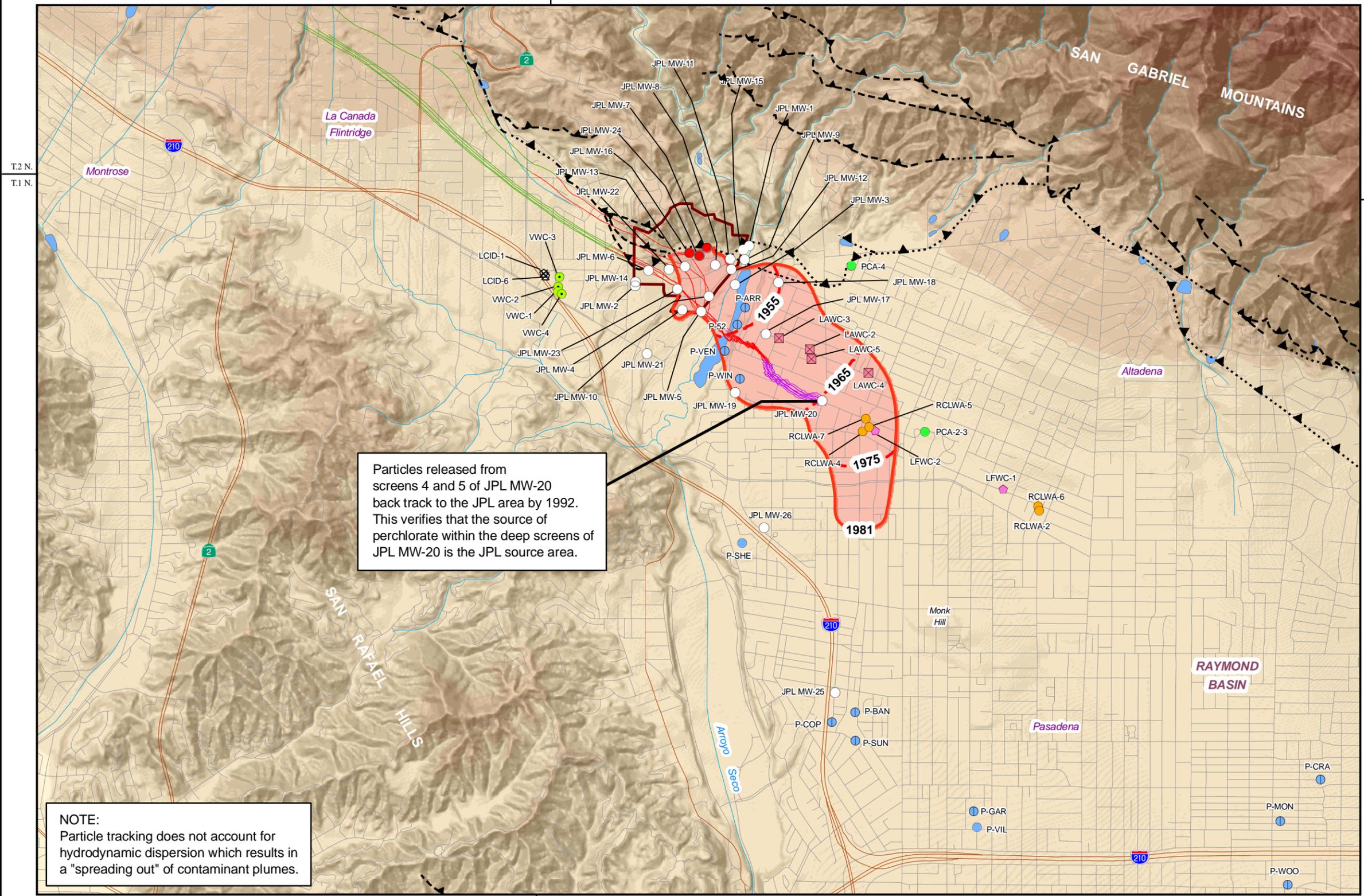
- Ⓜ City of Pasadena
- Ⓜ Kinneloa Irrigation District
- Ⓜ La Canada Irrigation District
- Ⓜ Las Flores Water Company
- Ⓜ Lincoln Avenue Water Company
- Ⓜ Pasadena Cemetery Association
- Ⓜ Rubio Canon Land and Water Association
- Ⓜ Valley Water Company

- NASA/JPL Boundary
- Spreading Grounds or Debris Basins

- Fault Classification (USGS) ¹**
- Known
 - Inferred
 - Concealed
 - ▲ Indicates Thrust Fault

Particles released from screens 4 and 5 of JPL MW-20 back track to the JPL area by 1992. This verifies that the source of perchlorate within the deep screens of JPL MW-20 is the JPL source area.

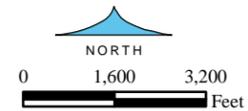
NOTE:
Particle tracking does not account for hydrodynamic dispersion which results in a "spreading out" of contaminant plumes.



28-Oct-09

Prepared by: DW B

Map Projection: UTM 1927, Zone 11



(1) USGS OFR 2005-1019. "Preliminary Geologic Map of Los Angeles 30' x 60' Quadrangle, Southern California". 2005.

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Figure 33

Probability Plot of $\delta^{18}\text{O}$ Data from JPL and Sunset Reservoir Area Wells

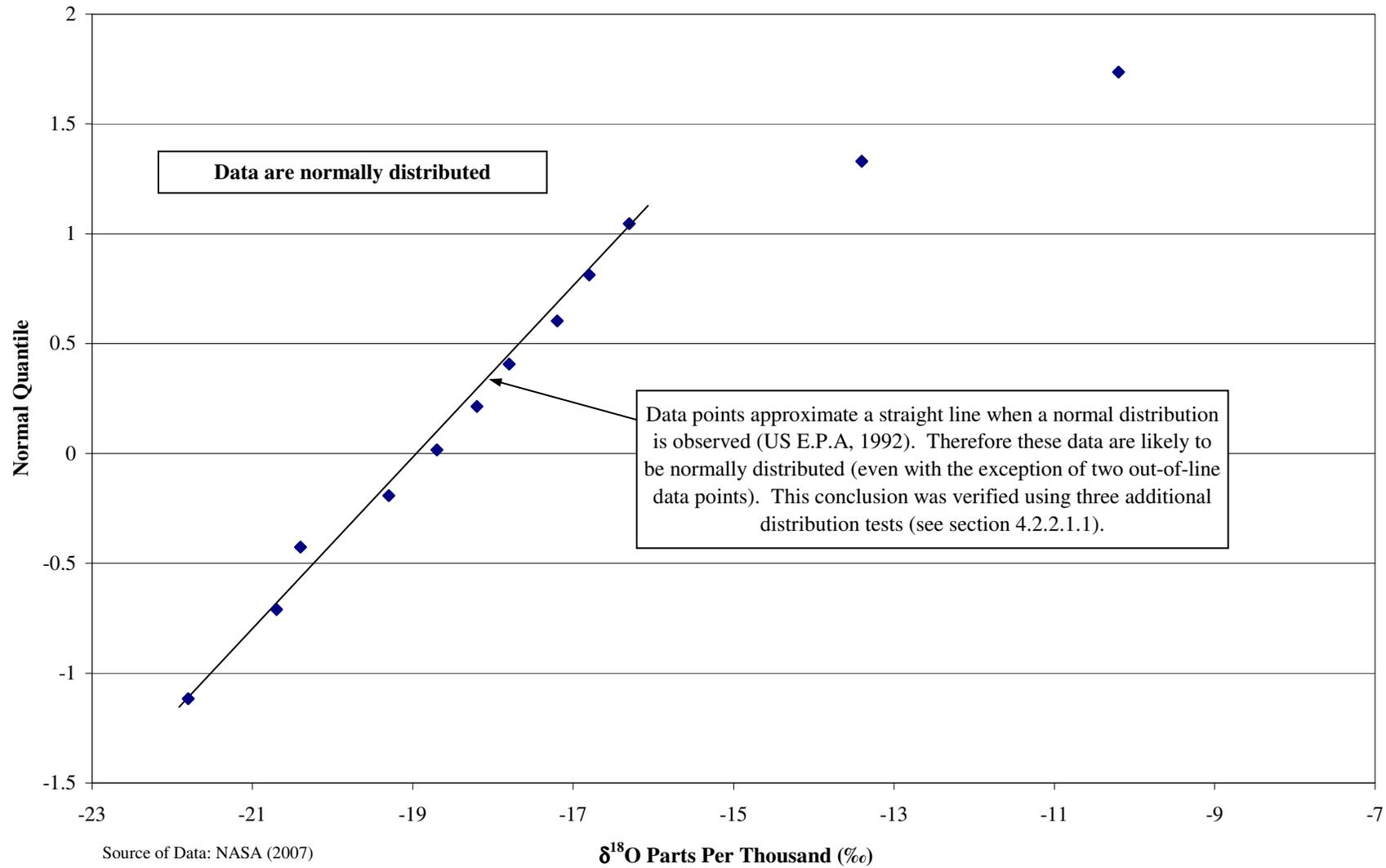


Figure 34

Probability Plot of $\delta^{18}\text{O}$ Data from BMI Complex and Sunset Reservoir Area Wells

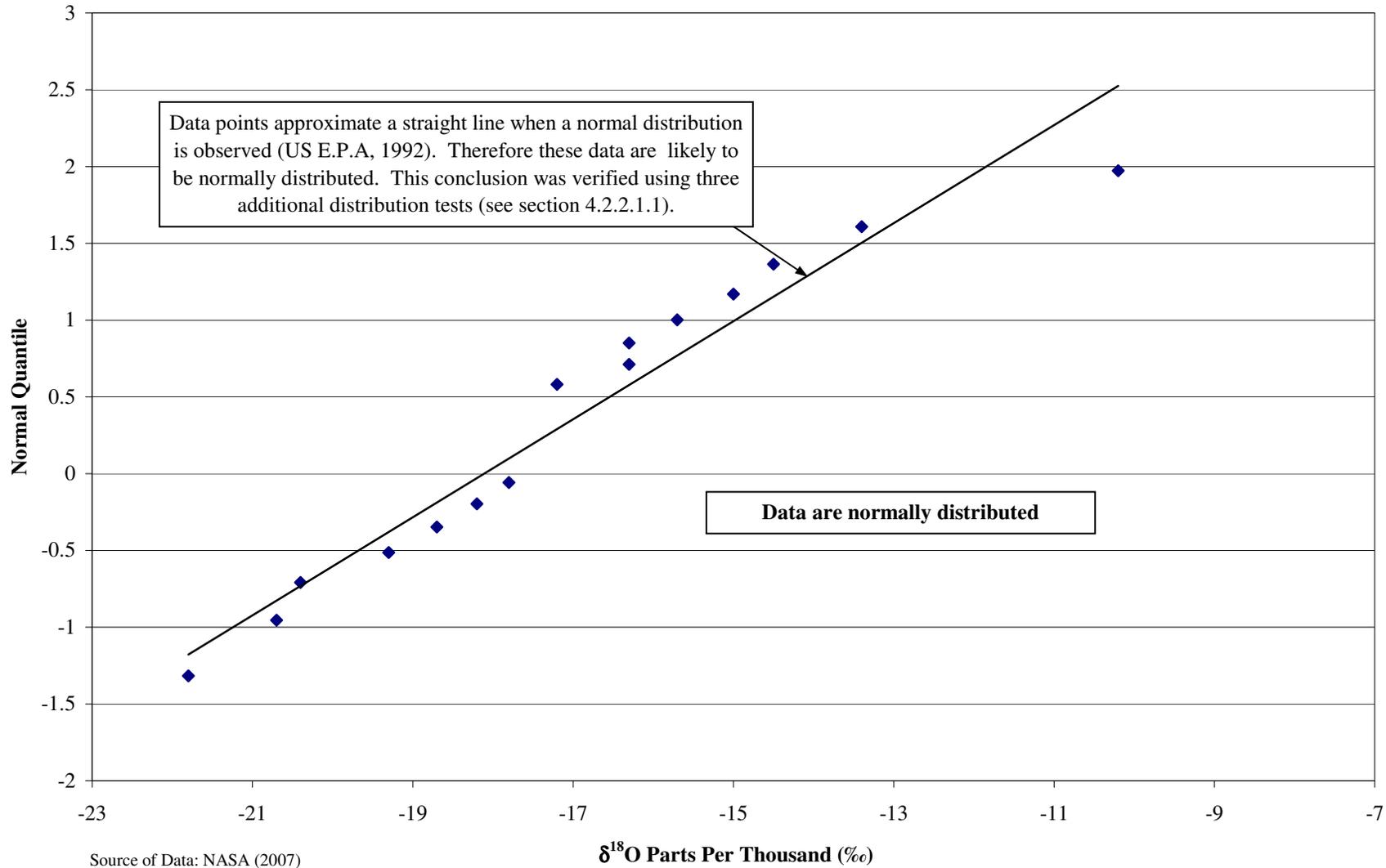


Figure 35

Probability Plot of $\delta^{37}\text{Cl}$ Data from JPL and Sunset Reservoir Area Wells

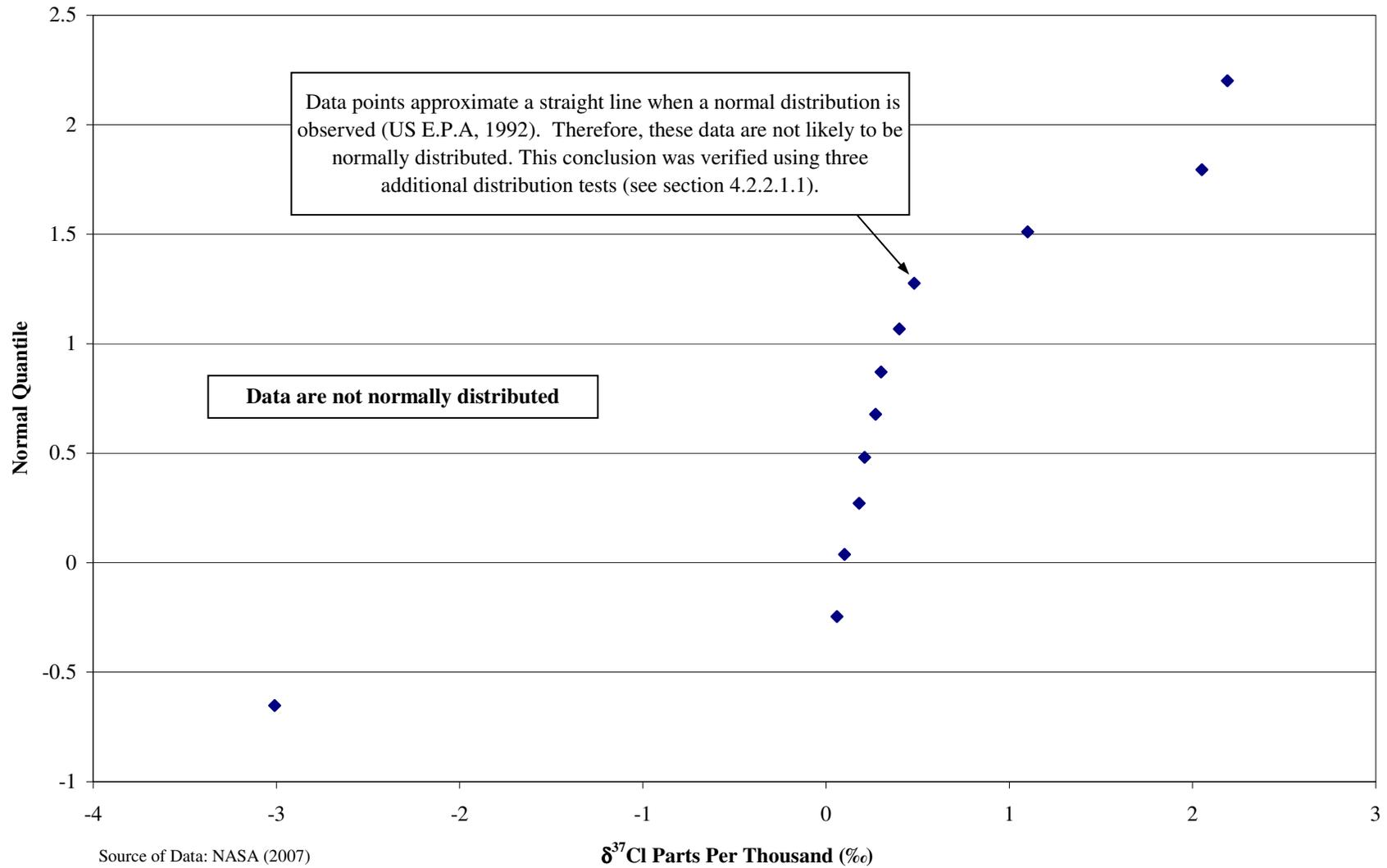


Figure 36

Probability Plot of $\delta^{37}\text{Cl}$ Data from BMI Complex and Sunset Reservoir Area Wells

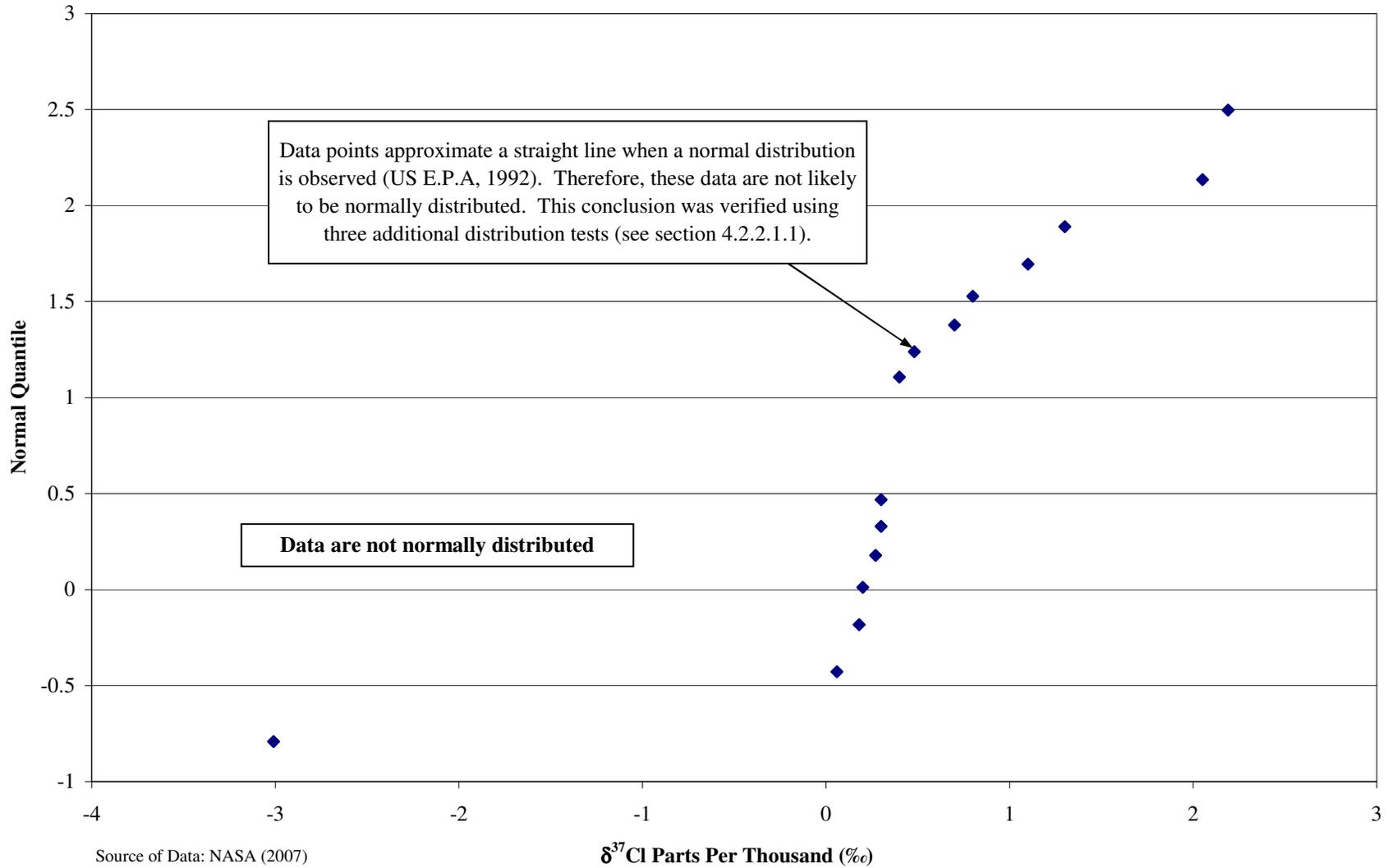


Figure 37

Probability Plot of Log $\delta^{37}\text{Cl}$ Data from JPL and Sunset Reservoir Area Wells

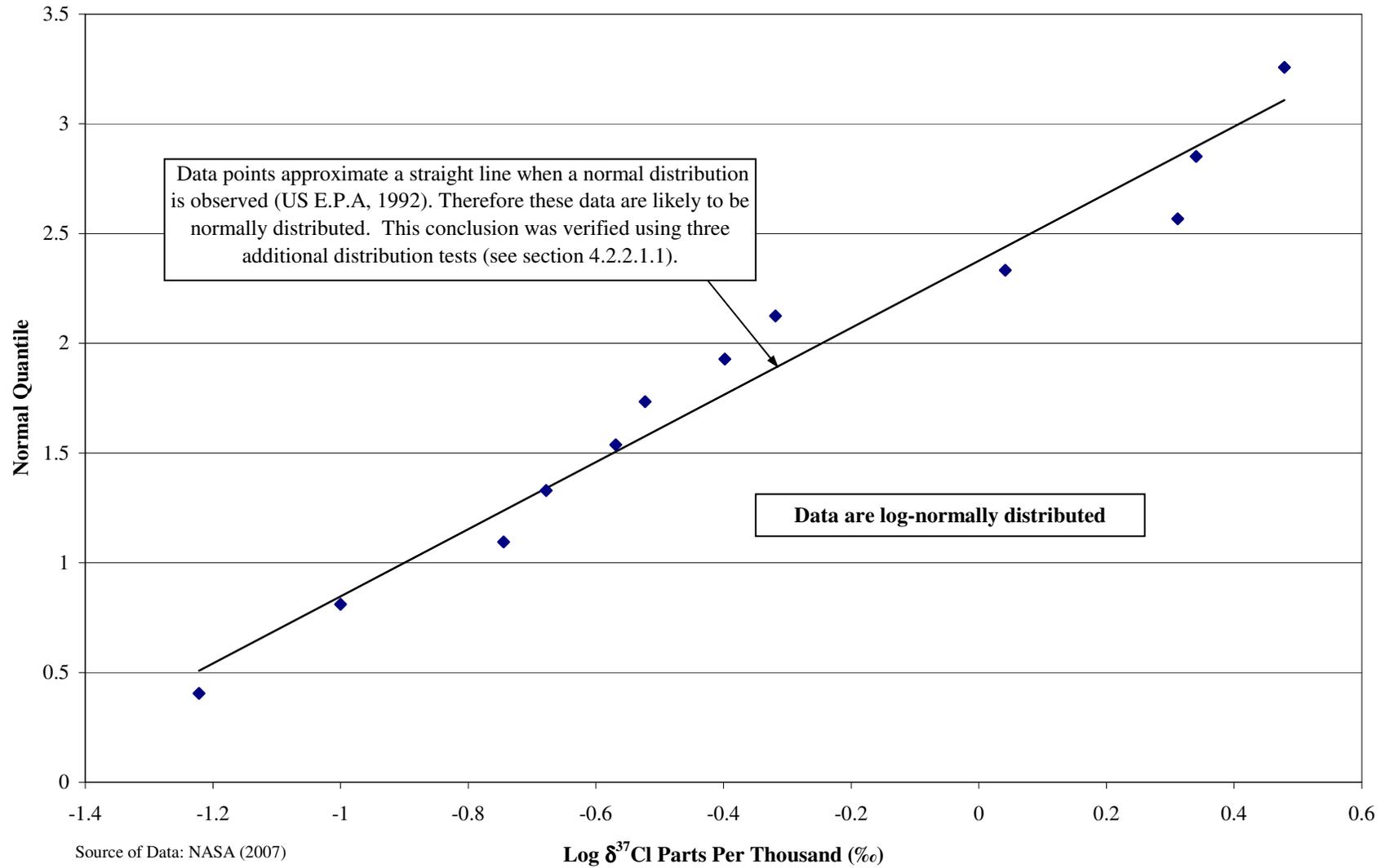


Figure 38

Probability Plot of Log $\delta^{37}\text{Cl}$ Data from BMI Complex and Sunset Reservoir Area Wells

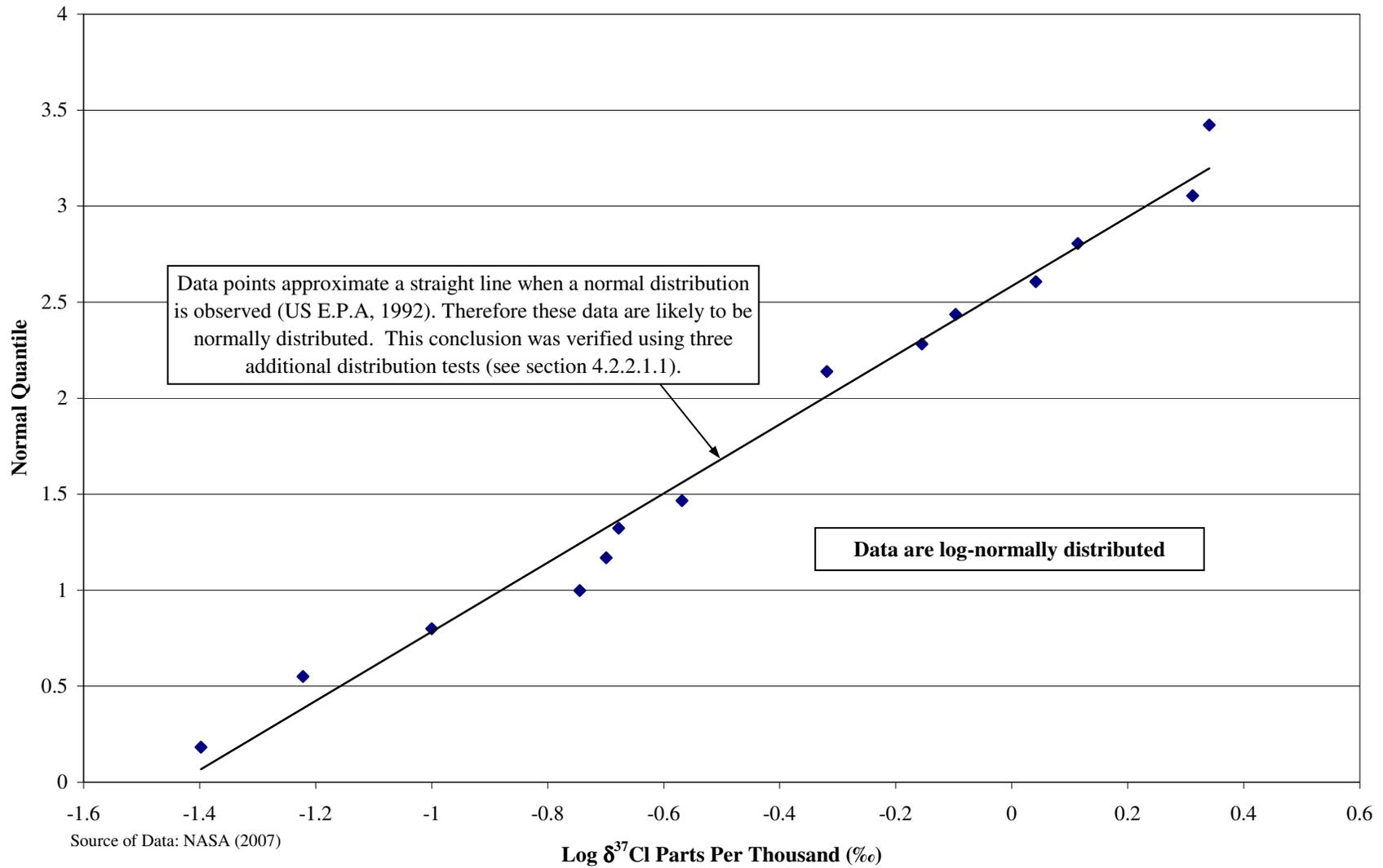
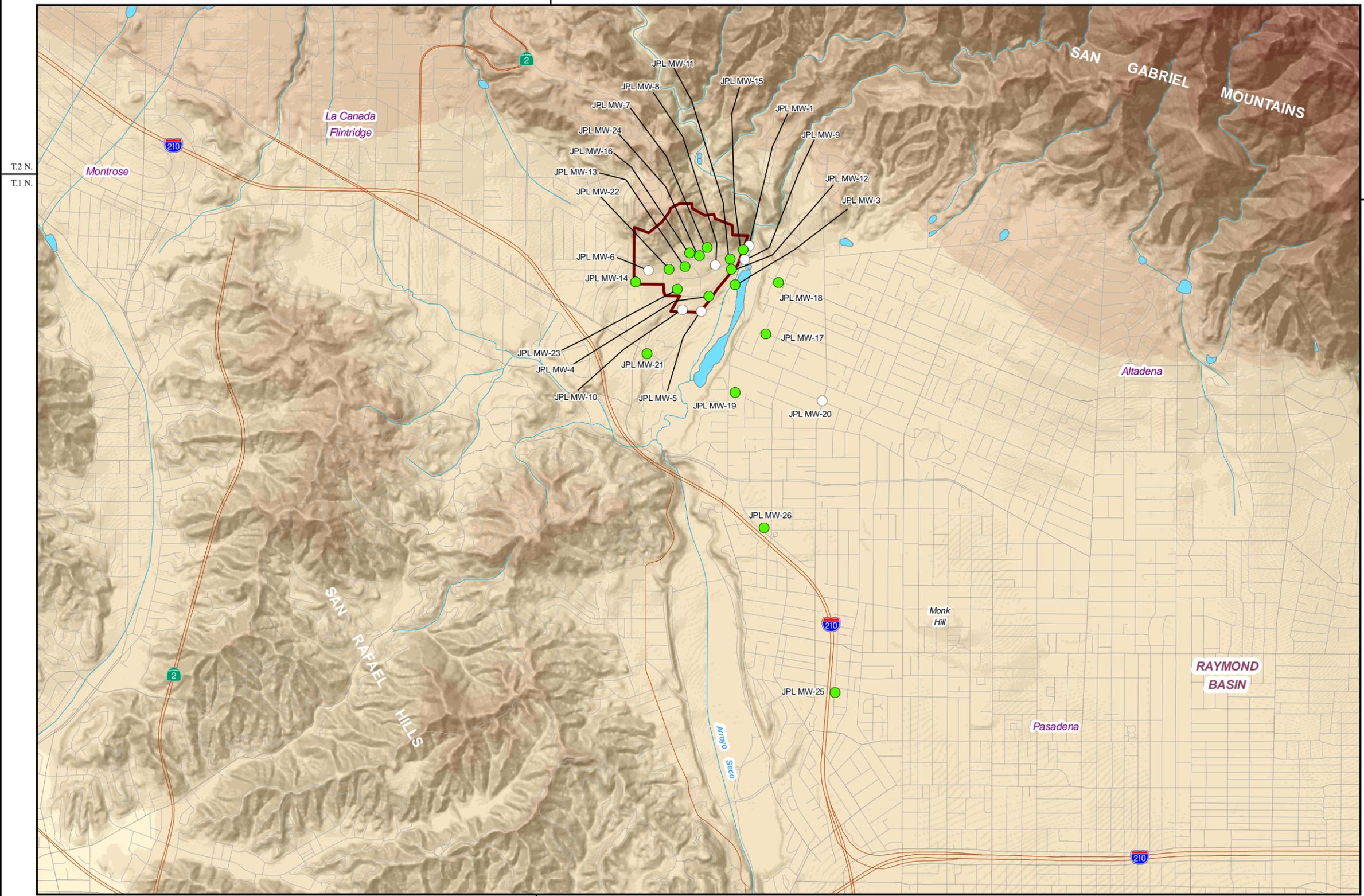


Figure 39

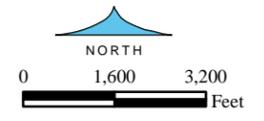


WELLS IN RAYMOND BASIN THAT EXHIBIT DISSOLVED OXYGEN CONCENTRATIONS FAVORABLE FOR PERCHLORATE BIODEGRADATION

EXPLANATION

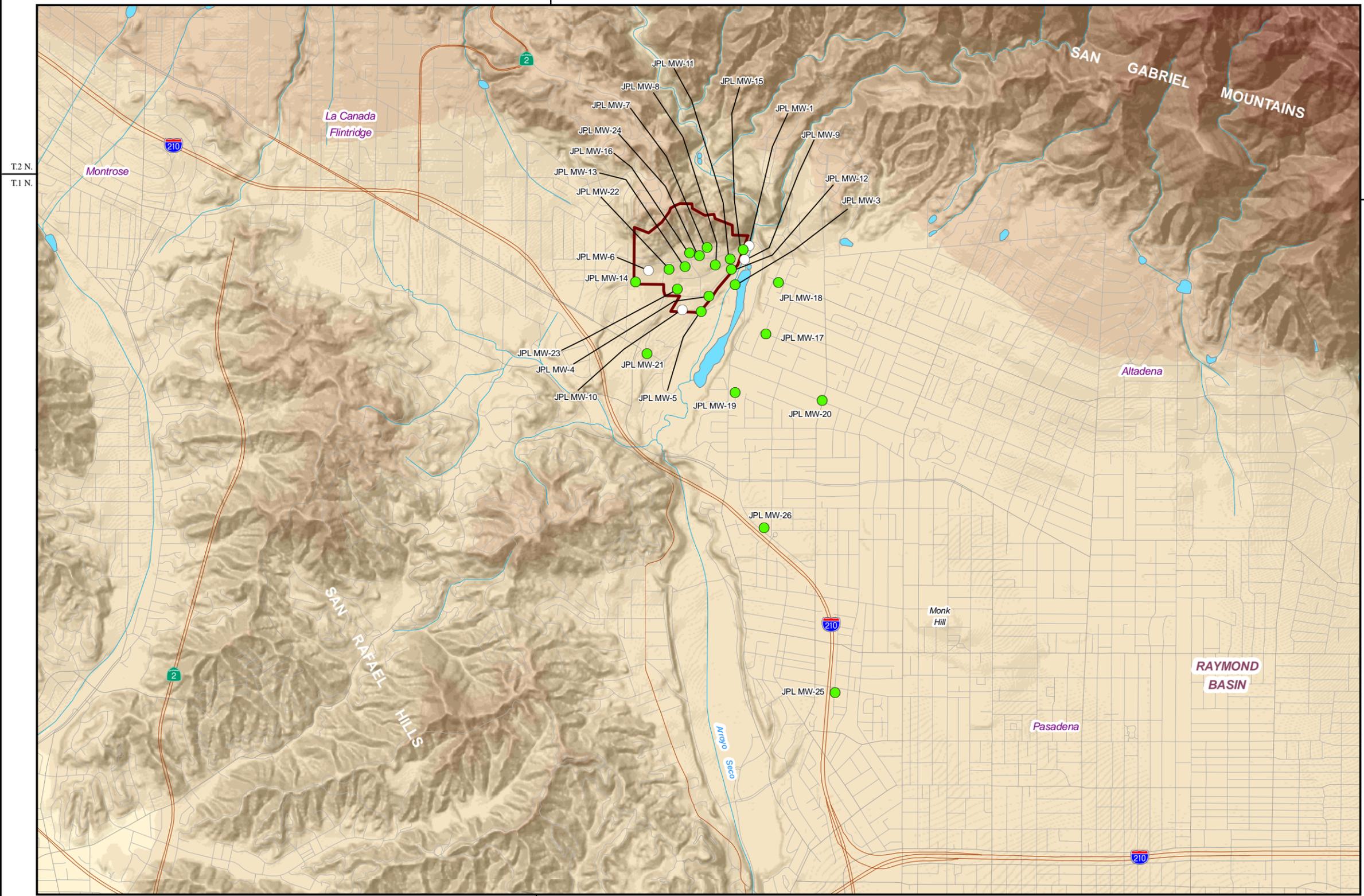
- JPL Monitoring Well That Exhibits DO Concentrations Favorable for Perchlorate Biodegradation (i.e. ≤ 1 mg/L)
- JPL Monitoring Well That Does Not Exhibit DO Concentrations Favorable for Perchlorate Biodegradation (i.e. > 1 mg/L)
- NASA/JPL Boundary
- Spreading Grounds or Debris Basins

28-Oct-09
 Prepared by: DWB
 Map Projection: UTM 1927, Zone 11



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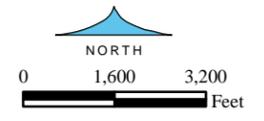
Figure 40



WELLS IN RAYMOND BASIN THAT EXHIBIT OXIDATION REDUCTION POTENTIAL FAVORABLE FOR PERCHLORATE BIODEGRADATION

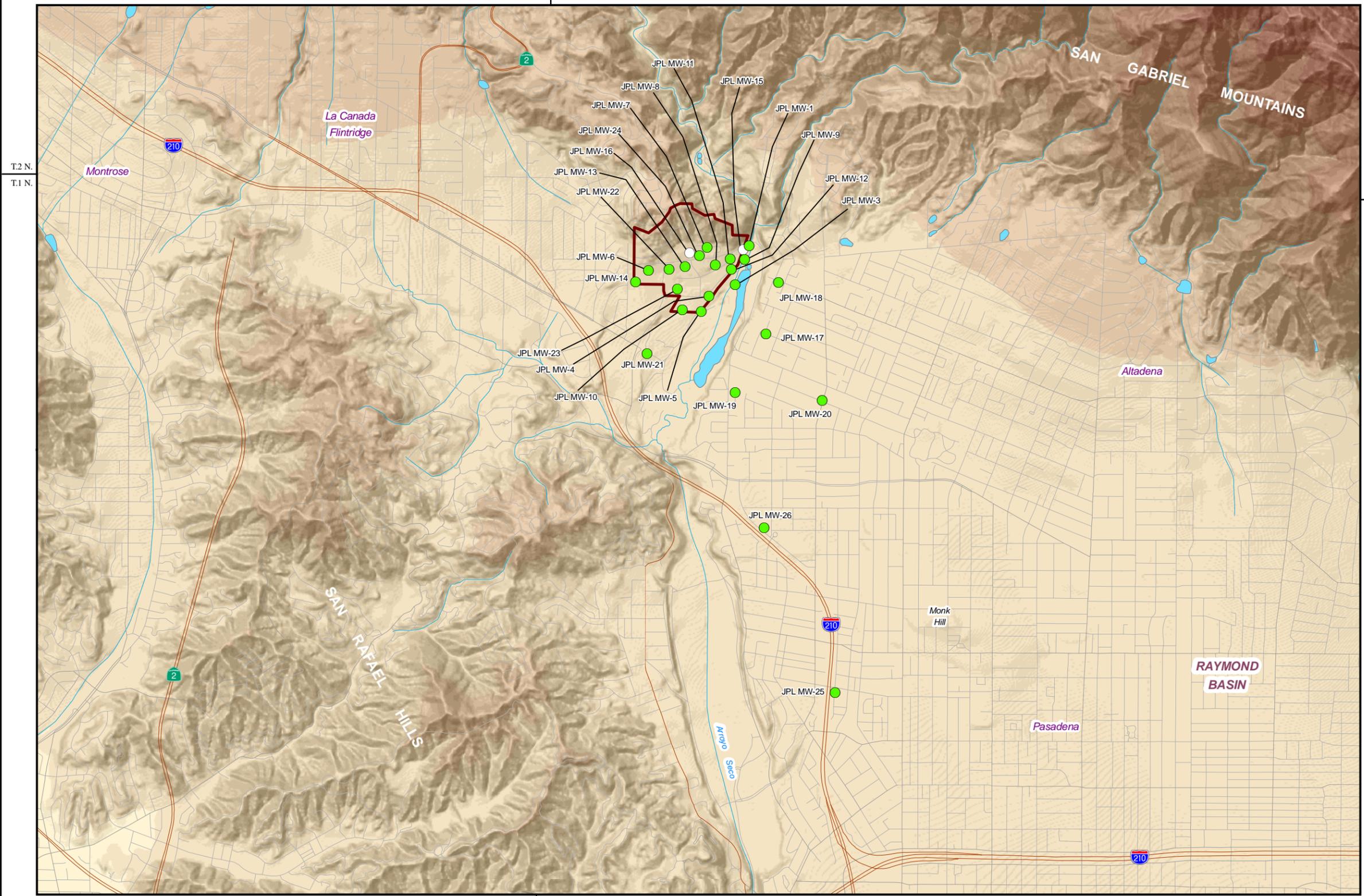
- EXPLANATION**
- JPL Monitoring Well That Exhibits Oxidation-Reduction Potential (ORP) Favorable for Perchlorate Biodegradation (i.e., less than or equal to a threshold of 0 mV)
 - JPL Monitoring Well That Does Not Exhibit ORP Favorable for Perchlorate Biodegradation (i.e., greater than a threshold of 0 mV)
 - NASA/JPL Boundary
 - Spreading Grounds or Debris Basins

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Figure 41

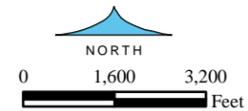


WELLS IN RAYMOND BASIN THAT EXHIBIT HIGH IRON CONCENTRATIONS INDICATIVE OF REDUCING CONDITIONS FAVORABLE FOR PERCHLORATE BIODEGRADATION

EXPLANATION

- JPL Monitoring Well That Exhibits High Iron Concentrations Indicative of Reducing Conditions Favorable for Perchlorate Biodegradation (i.e. ≥ 0.5 mg/L)
- JPL Monitoring Well That Does Not Exhibit High Iron Concentrations Indicative of Reducing Conditions (i.e. < 0.5 mg/L)
- NASA/JPL Boundary
- Spreading Grounds or Debris Basins

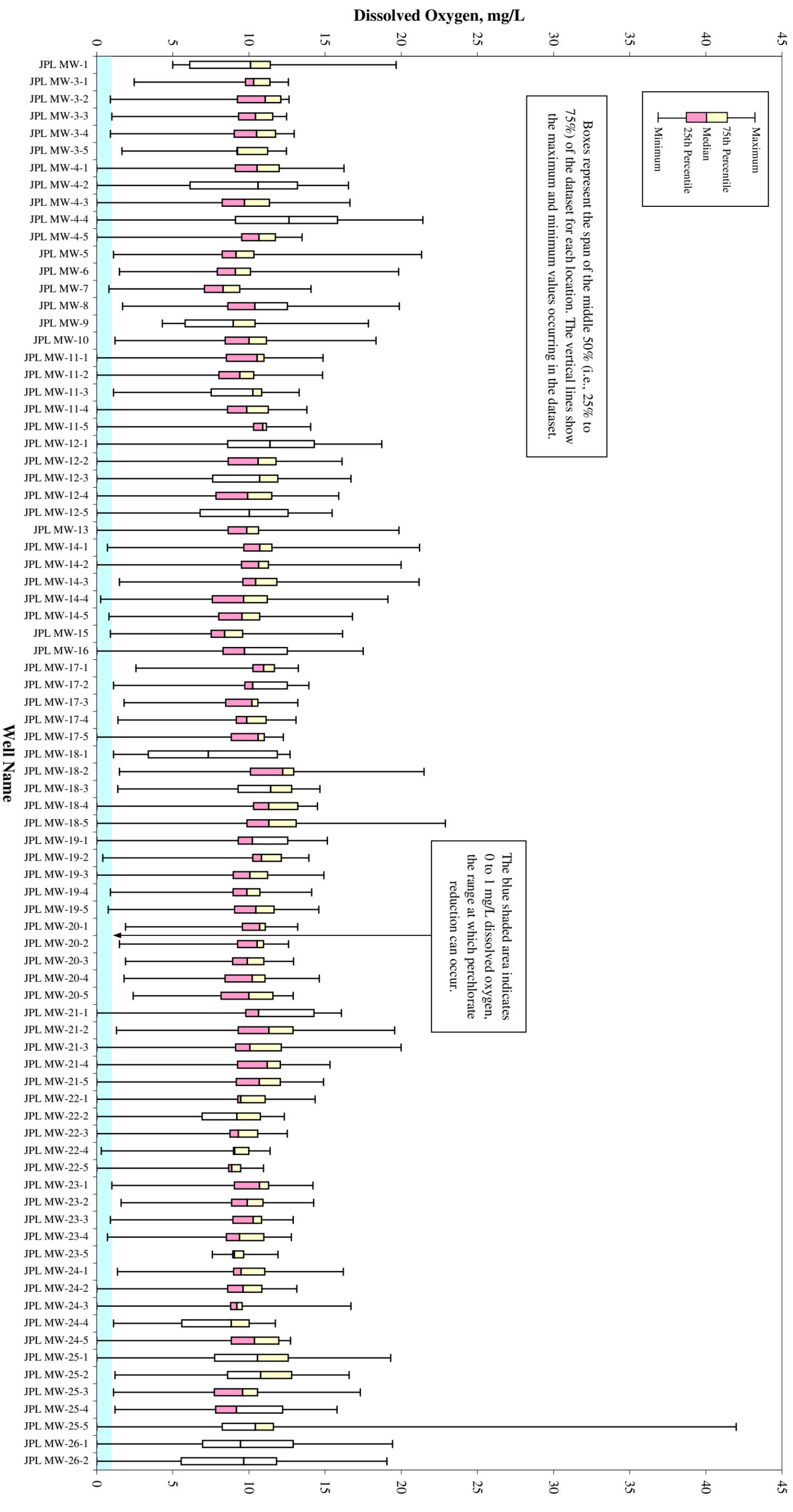
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 Prepared by: DWB
 Map Projection: UTM 1927, Zone 11



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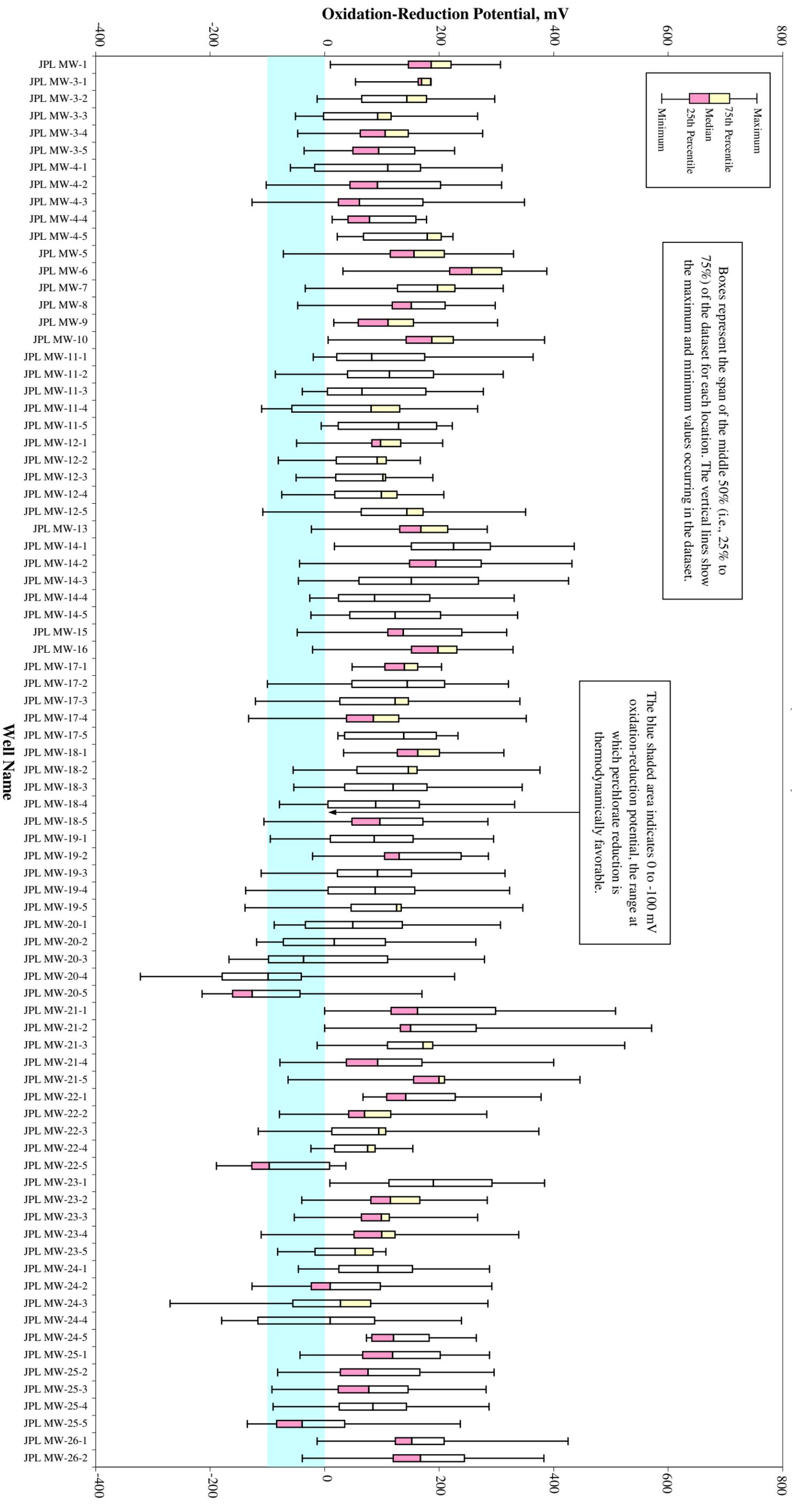
Figure 42

Distribution of Field-Measured Dissolved Oxygen Concentrations in the Raymond Basin
 (1999, 2003 - 2009)



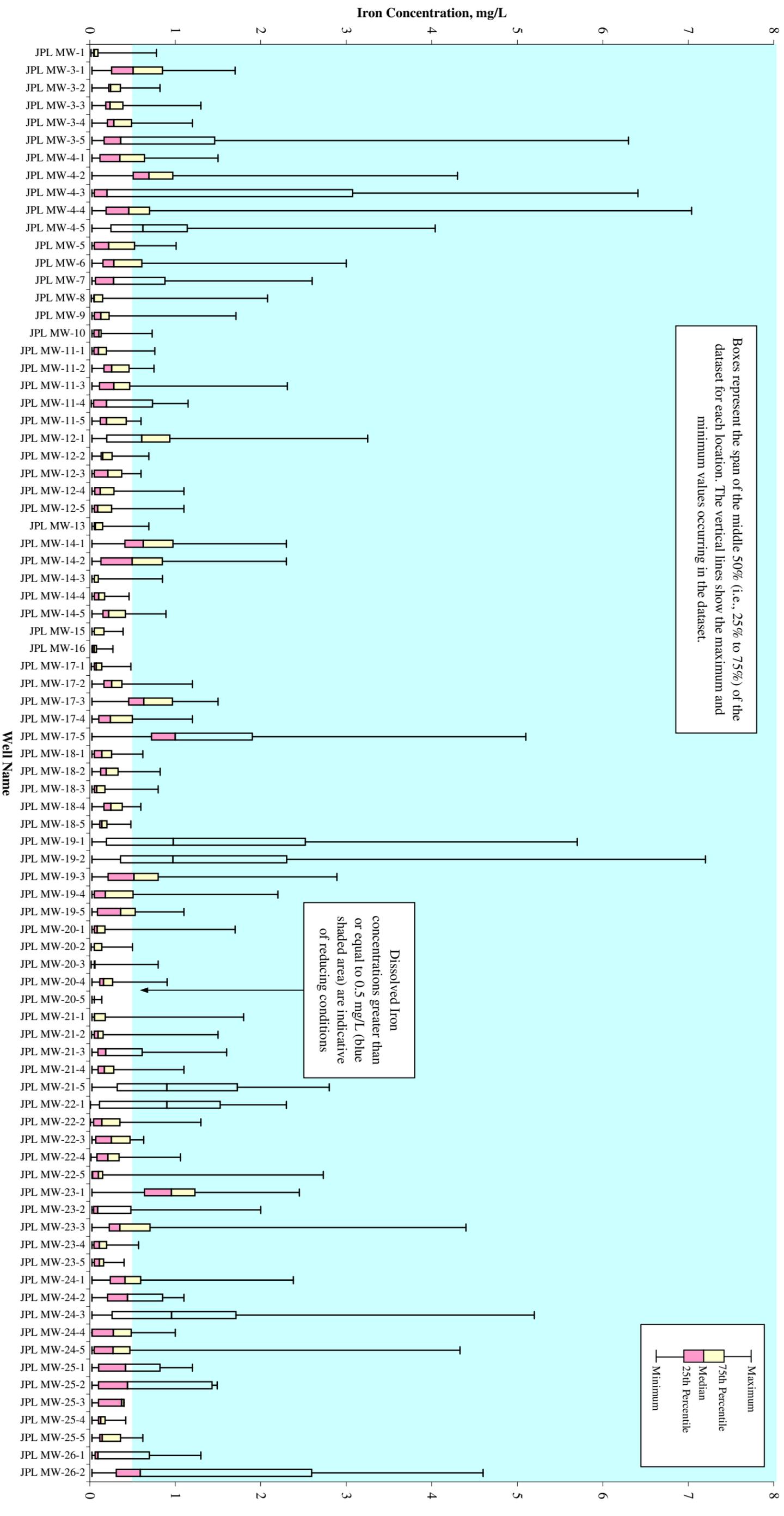
Source: NASA Quarterly Monitoring Reports (1999, 2003 - 2009).

**Distribution of Field-Measured Oxidation-Reduction Potential (ORP) in the Raymond Basin
 (2003 - 2009)**



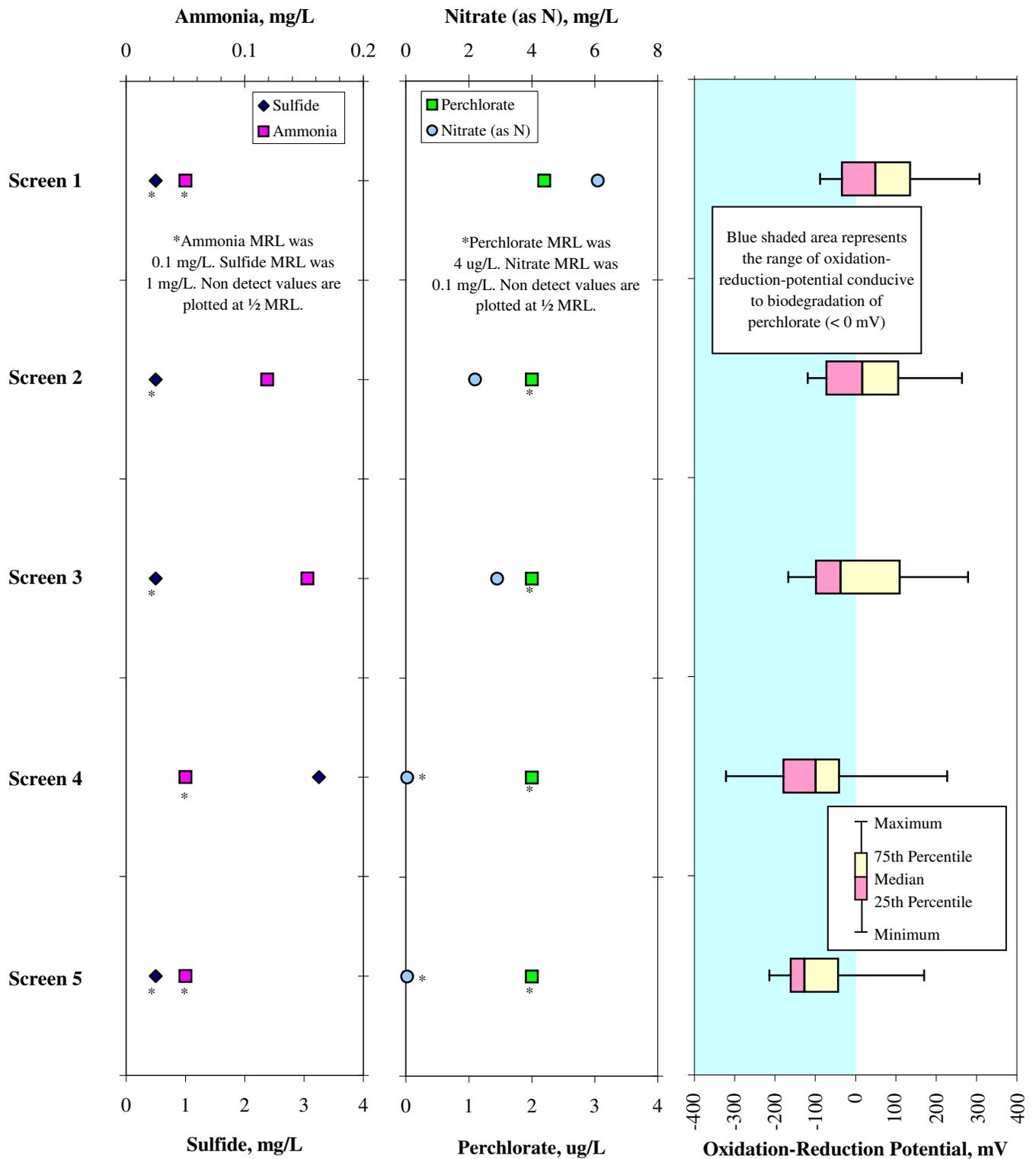
Source: NASA Quarterly Monitoring Reports (2003 - 2009).

Distribution of Iron Concentrations in the Raymond Basin
 (1996-2009)



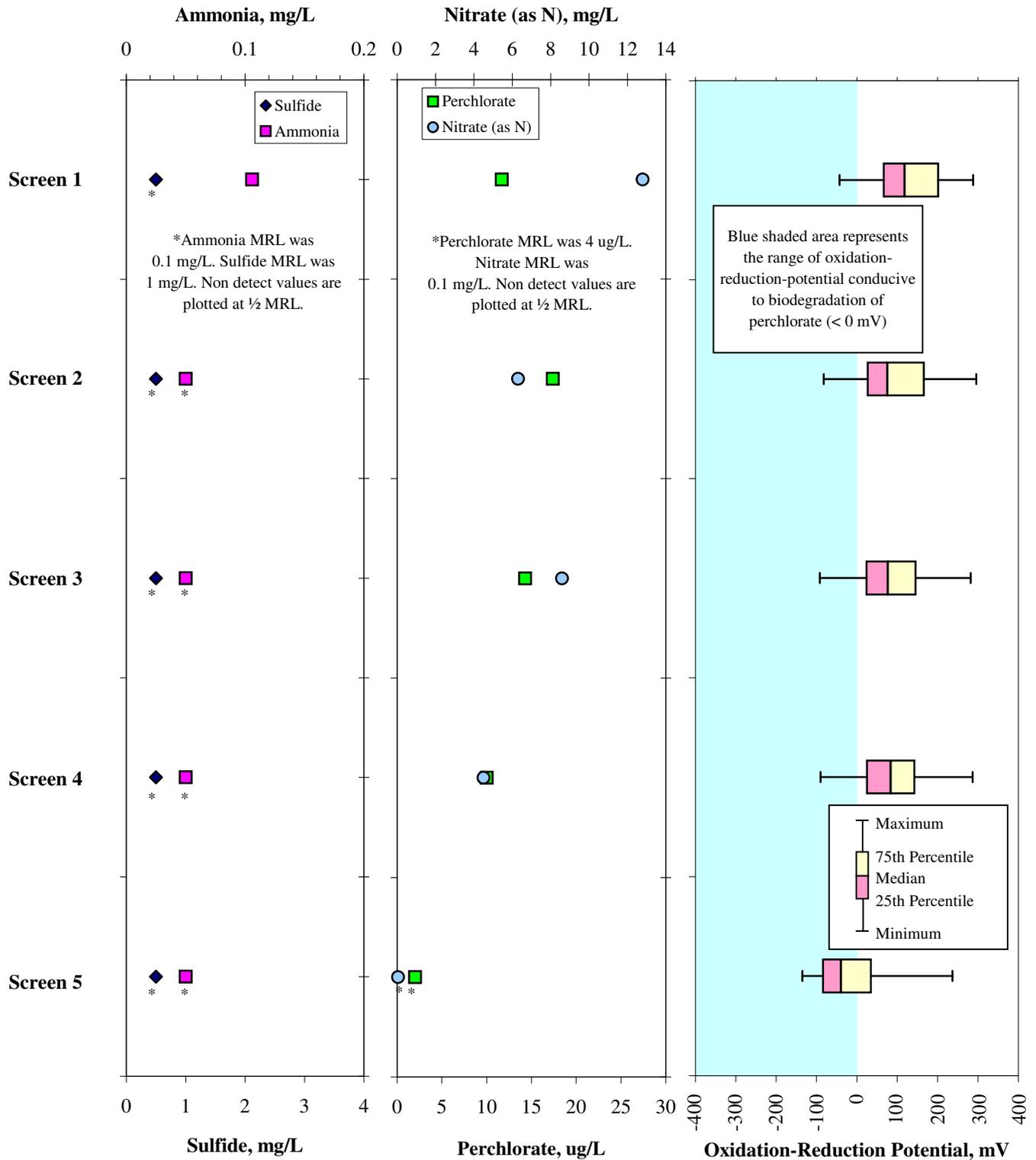
Source: NASA Quarterly Monitoring Reports (1996 - 2009).

**Vertical Distribution of Oxidation-Reduction Potential, Ammonia, Sulfide, and Nitrate
 in JPL MW-20**



Source: NASA Quarterly Monitoring Reports (2003-2009) and NASA (2007).
 MRL - Method Reporting Limit.

**Vertical Distribution of Oxidation-Reduction Potential, Ammonia, Sulfide, and Nitrate
 in JPL MW-25**



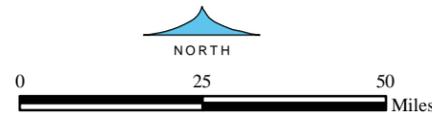
Source: NASA Quarterly Monitoring Reports (2003-2009) and NASA (2007).
 MRL - Method Reporting Limit.

COLORADO RIVER WATER CONVEYANCE SYSTEM TO RAYMOND BASIN



- EXPLANATION**
- Colorado River Water Conveyance System
 - Raymond Basin Boundary
 - ▲ BMI Complex
 - Weymouth Treatment Plant

28-Oct-09
 Prepared by: DWB
 Map Projection: UTM 1923, Zone 11



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Figure 48

Perchlorate Concentrations in the Colorado River Water Conveyance System (1997 - 2009)

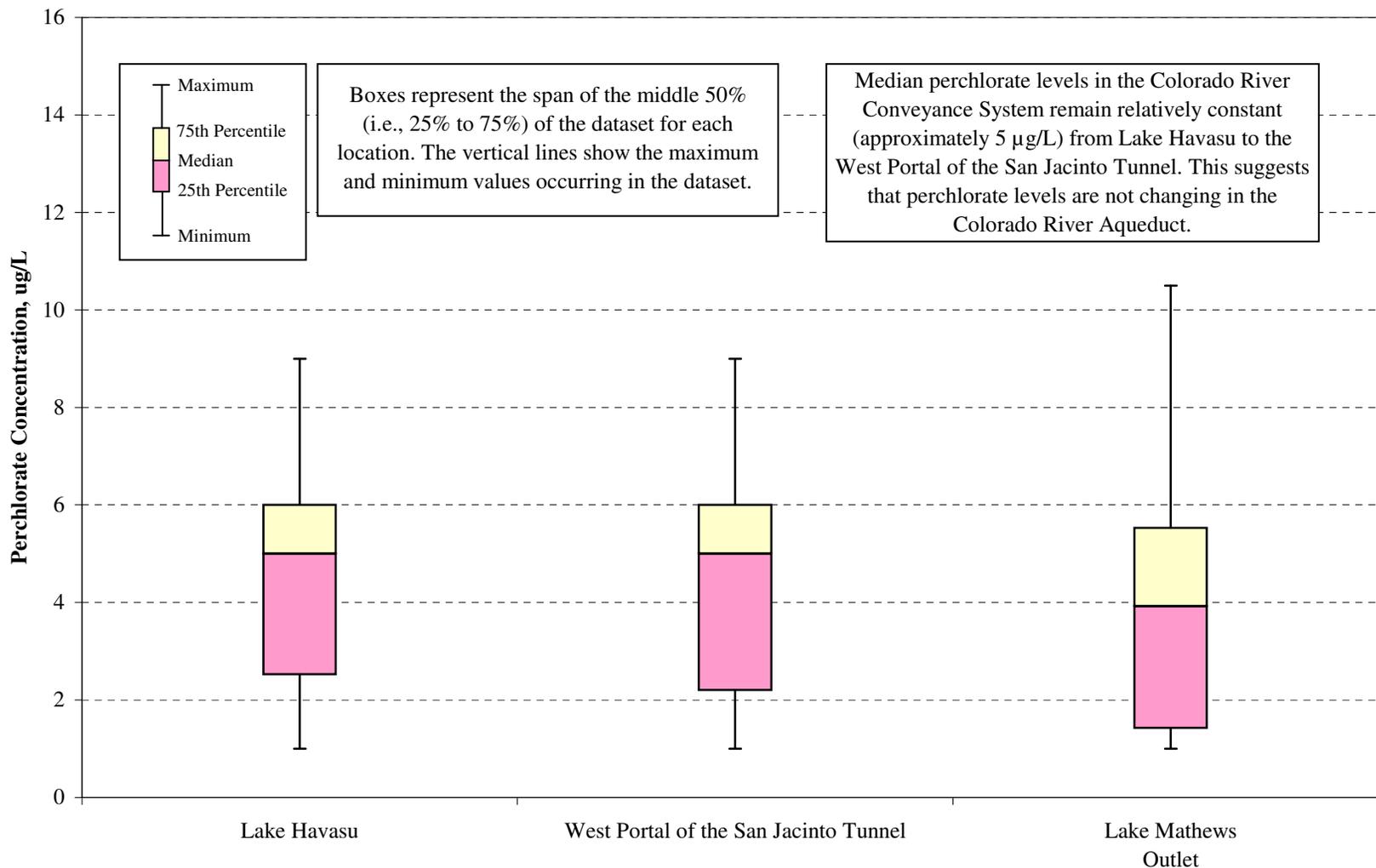
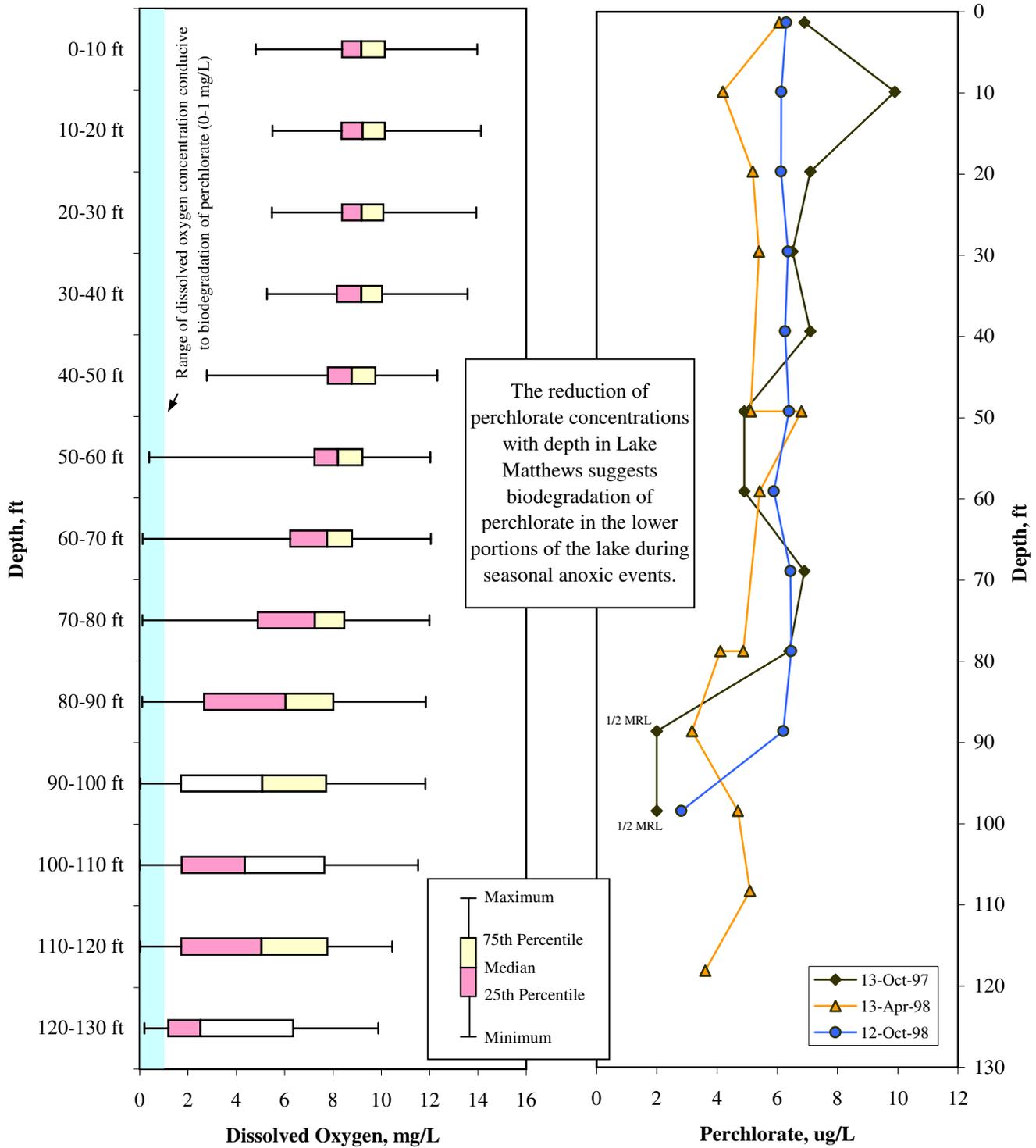


Figure 49

Source: Metropolitan Water District of Southern California (2009).

**Vertical Profiles of Dissolved Oxygen and Perchlorate
 at Lake Mathews Outlet Tower**



Note: Concentrations measured in depth-specific samples collected from the Lake Mathews Outlet Tower.

MRL - method reporting limit.

Source: Metropolitan Water District of Southern California (2009).

Isotopic Signatures of Natural and Synthetic Perchlorate

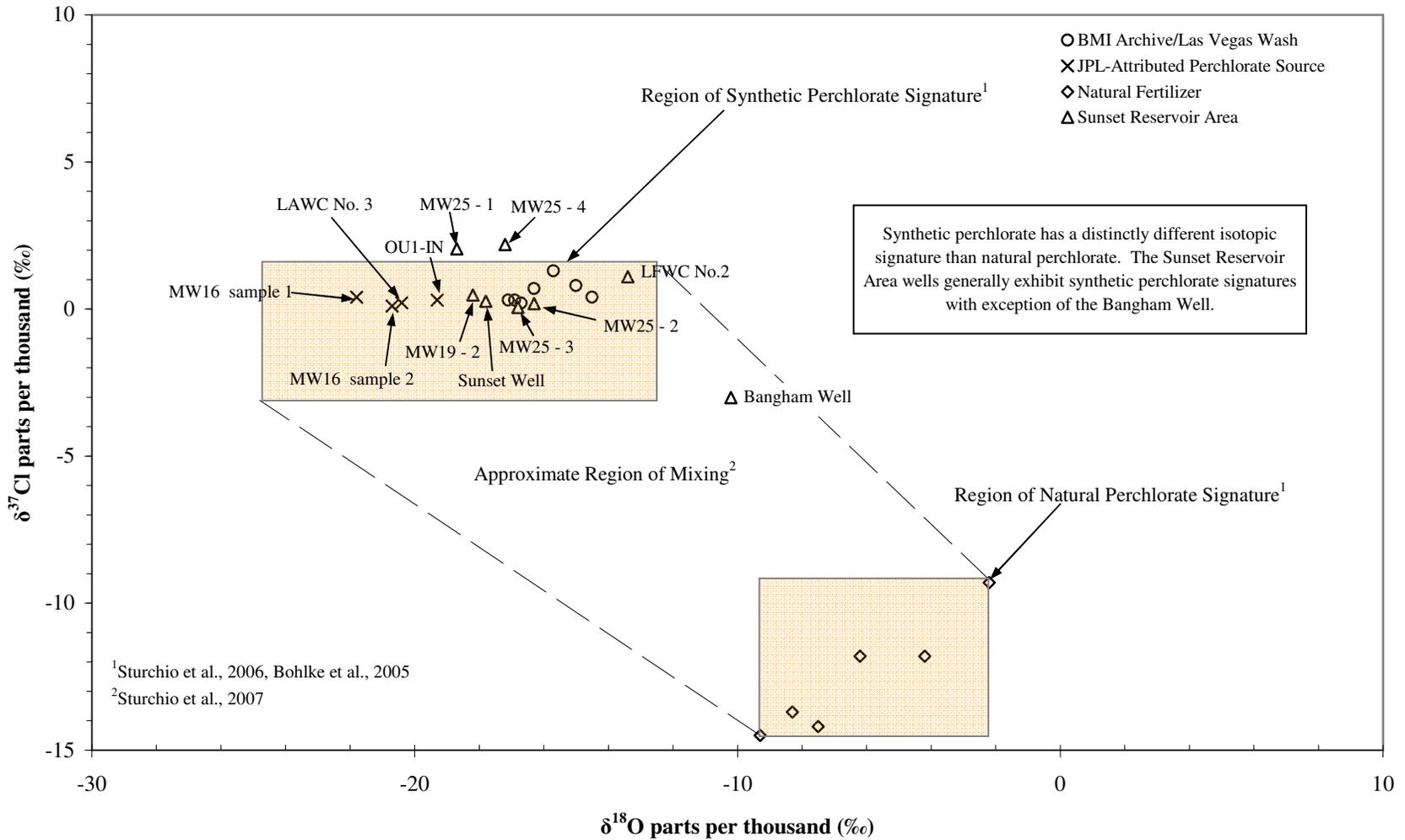
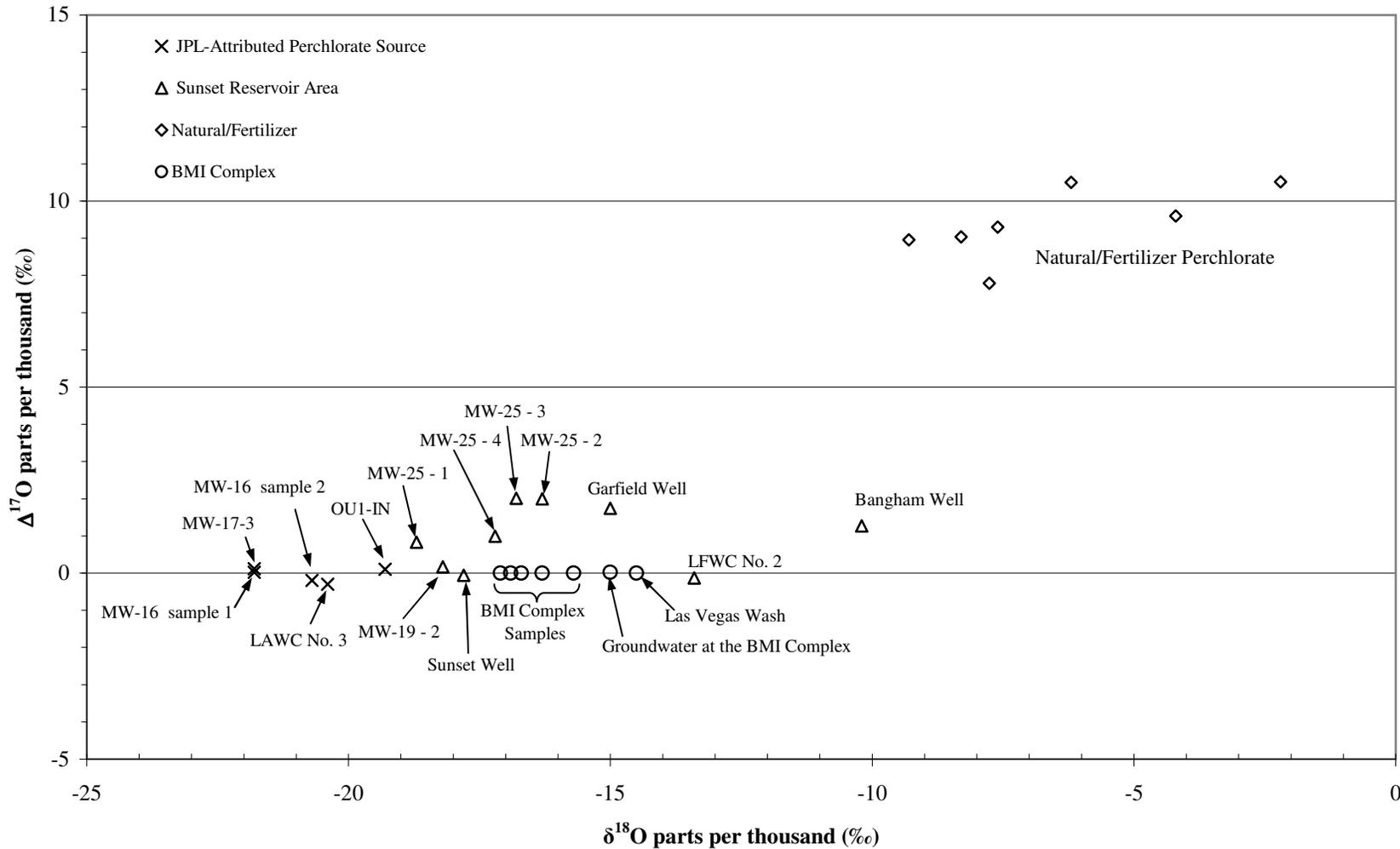


Figure 51

Oxygen Isotope Ratios Presented in NASA TM (2007)



All Data from NASA, 2007.

Figure 52

Shift in JPL Stable Isotope Ratios Resulting from Perchlorate Biodegradation

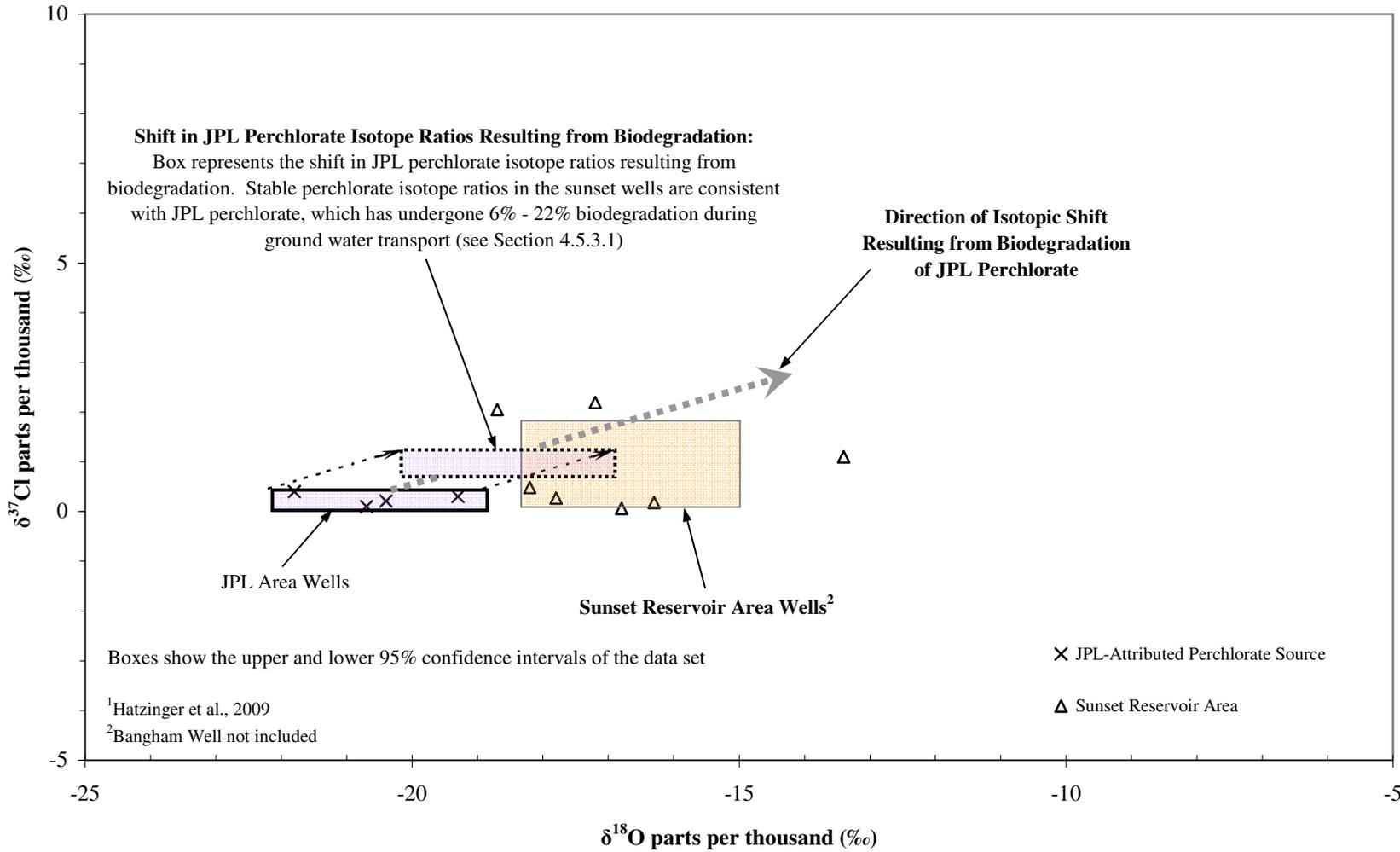


Figure 53

Shift in Stable Perchlorate Isotope Ratios Resulting from Biodegradation of BMI Complex Perchlorate in Lake Mathews

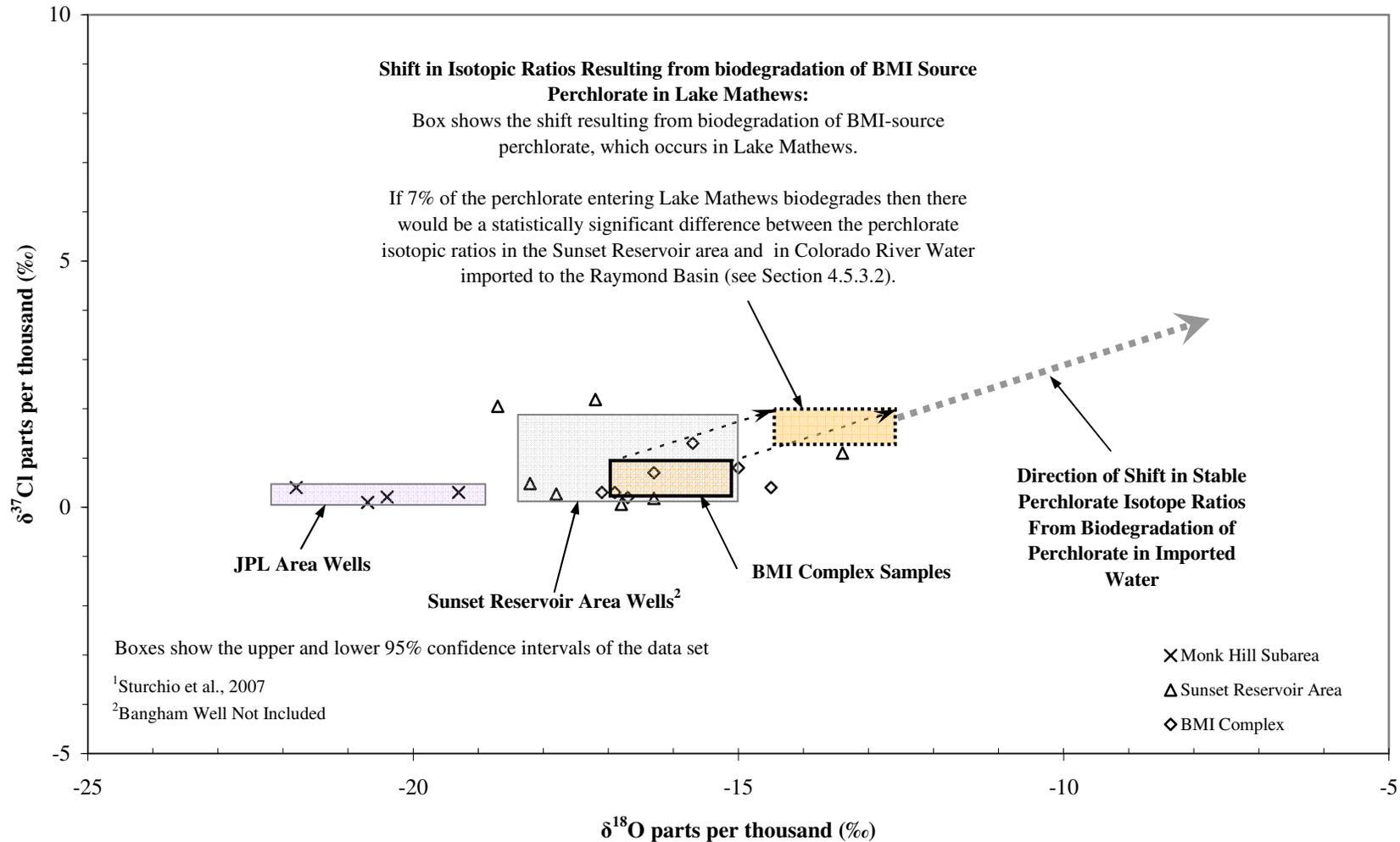


Figure 54

TABLES

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**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-1	2Q04	-	-	-	7.86
JPLMW-1	2Q05	-	-	-	6.22
JPLMW-1	2Q05	-	-	-	6.55
JPLMW-1	2Q05	-	-	-	6.72
JPLMW-1	2Q05	-	-	-	6.89
JPLMW-1	2Q08	-	-	-	6.16
JPLMW-1	2Q09	-	-	0.51	-
JPLMW-1	2Q99	-	-	-	7.47
JPLMW-1	3Q07	-	-	-	6.15
JPLMW-1	3Q98	-	-	0.78	-
JPLMW-1	4Q03	-	-	-	7.53
JPLMW-1	4Q05	-	-	-	6.68
JPLMW-1	4Q05	-	-	-	6.88
JPLMW-1	4Q05	-	-	-	6.98
JPLMW-1	4Q05	-	-	-	6.86
JPLMW-1	4Q05	-	-	-	6.97
JPLMW-1	4Q05	-	-	-	6.96
JPLMW-1	4Q06	-	-	-	6.4
JPLMW-1	4Q07	-	-	-	6.03
JPLMW-1	4Q08	-	-	-	7.15
JPLMW-3-1	2Q03	-	-	1.16	-
JPLMW-3-1	1Q01	-	-	1.09	-
JPLMW-3-1	1Q97	-	-	1.7	-
JPLMW-3-1	1Q98	-	-	0.65	-
JPLMW-3-1	1Q99	-	-	1.1	-
JPLMW-3-1	2Q07	-	-	-	6.88
JPLMW-3-1	2Q08	-	-	-	6.06
JPLMW-3-1	2Q09	-	-	0.71	-
JPLMW-3-1	2Q99	-	-	-	7.59
JPLMW-3-1	3Q00	-	-	1.1	-
JPLMW-3-1	3Q98	-	-	0.55	-
JPLMW-3-1	4Q05	-	-	-	6.6
JPLMW-3-1	4Q07	-	-	-	6.66
JPLMW-3-1	4Q96	-	-	0.67	-
JPLMW-3-1	4Q98	-	-	0.77	-
JPLMW-3-2	1Q06	0.9	-	-	6.93
JPLMW-3-2	1Q08	-	-	-	6.42
JPLMW-3-2	1Q09	-	-9	-	6.03
JPLMW-3-2	1Q97	-	-	0.51	-
JPLMW-3-2	1Q98	-	-	0.82	-
JPLMW-3-2	2Q07	-	-	-	7.1
JPLMW-3-2	2Q07	-	-	-	6.66
JPLMW-3-2	2Q09	-	-	0.68	-
JPLMW-3-2	2Q99	-	-	-	7.61
JPLMW-3-2	3Q06	-	-13	-	-
JPLMW-3-2	3Q07	-	-	-	6.84
JPLMW-3-2	3Q08	-	-	-	6.93

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-3-2	4Q05	-	-	-	6.37
JPLMW-3-2	4Q07	-	-	-	6.46
JPLMW-3-2	4Q98	-	-	0.59	-
JPLMW-3-3	1Q02	-	-	0.58	-
JPLMW-3-3	1Q06	1	-12	-	6.88
JPLMW-3-3	1Q08	-	-	-	6.39
JPLMW-3-3	1Q09	-	-37	-	6.06
JPLMW-3-3	1Q98	-	-	1.3	-
JPLMW-3-3	2Q07	-	-51	-	7.04
JPLMW-3-3	2Q07	-	-	-	6
JPLMW-3-3	2Q97	-	-	0.66	-
JPLMW-3-3	3Q06	-	-33	-	-
JPLMW-3-3	3Q07	-	-	-	6.85
JPLMW-3-3	3Q08	-	-	-	6.95
JPLMW-3-3	3Q97	-	-	0.66	-
JPLMW-3-3	4Q05	-	-	-	6.06
JPLMW-3-3	4Q07	-	-	-	6.01
JPLMW-3-4	1Q06	0.9	-	-	6.13
JPLMW-3-4	1Q08	-	-	-	6.19
JPLMW-3-4	1Q09	-	-47	-	-
JPLMW-3-4	1Q97	-	-	0.83	-
JPLMW-3-4	1Q99	-	-	0.54	-
JPLMW-3-5	2Q03	-	-	0.789	-
JPLMW-3-4	2Q04	-	-	0.541	-
JPLMW-3-4	2Q07	-	-17	-	6.79
JPLMW-3-4	2Q09	-	-	0.68	-
JPLMW-3-4	3Q07	-	-	-	6.74
JPLMW-3-4	3Q08	-	-	-	6.94
JPLMW-3-4	4Q07	-	-	-	6.04
JPLMW-3-4	4Q96	-	-	1.2	-
JPLMW-3-5	1Q01	-	-	1.64	-
JPLMW-3-5	1Q02	-	-	1.32	-
JPLMW-3-5	1Q99	-	-	1.1	-
JPLMW-3-5	2Q04	-	-	29.4	-
JPLMW-3-5	2Q05	-	-	3.12	-
JPLMW-3-5	2Q08	-	-	4.08	-
JPLMW-3-5	2Q09	-	-	6.3	-
JPLMW-3-5	2Q09	-	-36	-	-
JPLMW-3-5	3Q00	-	-	1.6	-
JPLMW-3-5	4Q06	-	-	-	6.08
JPLMW-3-5	4Q98	-	-	0.86	-
JPLMW-4-1	1Q01	-	-	0.76	-
JPLMW-4-1	1Q06	-	-	-	6.1
JPLMW-4-1	1Q09	-	-60	-	-
JPLMW-4-2	2Q03	-	-	0.592	-
JPLMW-4-1	2Q04	-	-	1.32	-
JPLMW-4-1	2Q05	-	-	0.573	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-4-1	2Q07	-	-50	-	6.07
JPLMW-4-1	2Q07	-	-	-	7.09
JPLMW-4-1	2Q08	-	-	-	6.38
JPLMW-4-1	2Q09	-	-	0.77	-
JPLMW-4-1	2Q09	-	-	-	7.33
JPLMW-4-1	2Q97	-	-	1.5	-
JPLMW-4-1	3Q00	-	-	0.6	-
JPLMW-4-1	3Q06	-	-30	-	6.71
JPLMW-4-1	3Q07	-	-	-	6.31
JPLMW-4-1	3Q08	0.1	-	-	6.93
JPLMW-4-1	4Q05	-	-	-	7.15
JPLMW-4-1	4Q06	-	-	-	6.77
JPLMW-4-1	4Q07	-	-	-	6.79
JPLMW-4-1	4Q08	-	-30	-	6.23
JPLMW-4-1	4Q96	-	-	0.82	-
JPLMW-4-2	1Q01	-	-	1.02	-
JPLMW-4-2	1Q06	0.7	-	-	-
JPLMW-4-2	1Q09	-	-102	-	-
JPLMW-4-2	1Q97	-	-	0.57	-
JPLMW-4-2	1Q99	-	-	0.62	-
JPLMW-4-3	2Q03	-	-	6.41	-
JPLMW-4-2	2Q04	-	-	0.85	-
JPLMW-4-2	2Q05	-	-	0.954	-
JPLMW-4-2	2Q07	-	-36	-	-
JPLMW-4-2	2Q07	-	-	-	6.59
JPLMW-4-2	2Q09	-	-	1.3	-
JPLMW-4-2	2Q97	-	-	0.67	-
JPLMW-4-2	2Q98	-	-	0.71	-
JPLMW-4-2	2Q99	-	-	0.71	-
JPLMW-4-2	2Q99	-	-	-	6.15
JPLMW-4-2	3Q00	-	-	2	-
JPLMW-4-2	3Q08	0	-	-	6.44
JPLMW-4-2	3Q97	-	-	0.81	-
JPLMW-4-2	3Q98	-	-	3.3	-
JPLMW-4-2	4Q05	-	-	-	6.22
JPLMW-4-2	4Q06	-	-	-	6.47
JPLMW-4-2	4Q07	-	-	-	6.41
JPLMW-4-2	4Q08	-	-30	-	-
JPLMW-4-2	4Q96	-	-	4.3	-
JPLMW-4-2	4Q98	-	-	0.59	-
JPLMW-4-3	1Q01	-	-	36.1	-
JPLMW-4-3	1Q02	-	-	14.2	-
JPLMW-4-3	1Q06	1	-	-	-
JPLMW-4-3	1Q09	-	-127	-	-
JPLMW-4-3	2Q04	-	-	4.48	-
JPLMW-4-3	2Q05	-	-	4.45	-
JPLMW-4-3	2Q07	-	-39	-	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-4-3	2Q07	-	-	-	6.09
JPLMW-4-3	2Q08	-	-	3.95	-
JPLMW-4-3	2Q09	-	-	3.9	-
JPLMW-4-3	3Q00	-	-	0.59	-
JPLMW-4-3	3Q08	0	-	-	-
JPLMW-4-3	4Q05	-	-	-	6.19
JPLMW-4-3	4Q06	-	-	-	6.07
JPLMW-4-3	4Q07	-	-	-	6.13
JPLMW-4-3	4Q08	-	-31	-	-
JPLMW-4-4	1Q01	-	-	7.04	-
JPLMW-4-4	1Q99	-	-	0.72	-
JPLMW-4-5	2Q03	-	-	1.28	-
JPLMW-4-4	2Q04	-	-	0.691	-
JPLMW-4-4	2Q05	-	-	0.537	-
JPLMW-4-4	2Q09	-	-	0.62	-
JPLMW-4-4	2Q97	-	-	0.66	-
JPLMW-4-4	3Q96	-	-	0.82	-
JPLMW-4-4	4Q96	-	-	1.3	-
JPLMW-4-4	4Q98	-	-	2	-
JPLMW-4-5	1Q01	-	-	1.55	-
JPLMW-4-5	1Q02	-	-	2.33	-
JPLMW-4-5	1Q97	-	-	0.65	-
JPLMW-4-5	1Q98	-	-	0.54	-
JPLMW-4-5	2Q04	-	-	17.5	-
JPLMW-4-5	2Q05	-	-	0.637	-
JPLMW-4-5	2Q08	-	-	4.04	-
JPLMW-4-5	2Q09	-	-	3.7	-
JPLMW-4-5	2Q09	-	-	-	7.94
JPLMW-4-5	2Q97	-	-	0.87	-
JPLMW-4-5	3Q96	-	-	0.62	-
JPLMW-4-5	3Q98	-	-	1	-
JPLMW-5	1Q02	-	-	1.01	-
JPLMW-5	1Q03	-	-72	-	7.46
JPLMW-5	1Q05	-	-	-	6.19
JPLMW-5	1Q05	-	-	-	6.42
JPLMW-5	1Q05	-	-	-	6.59
JPLMW-5	1Q05	-	-	-	6.7
JPLMW-5	1Q09	-	-30	-	-
JPLMW-5	1Q99	-	-	0.59	-
JPLMW-6	2Q03	-	-	0.785	-
JPLMW-5	2Q04	-	-	0.696	-
JPLMW-5	2Q04	-	-	-	6.87
JPLMW-5	2Q05	-	-	-	6.15
JPLMW-5	2Q05	-	-	-	6.25
JPLMW-5	2Q05	-	-	-	6.42
JPLMW-5	2Q07	-	-	-	6.28
JPLMW-5	2Q09	-	-	0.5	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-5	2Q99	-	-	-	7.47
JPLMW-5	3Q03	-	-	-	7.58
JPLMW-5	3Q04	-	-	-	6.82
JPLMW-5	3Q05	-	-	-	6.14
JPLMW-5	3Q05	-	-	-	6.24
JPLMW-5	3Q06	-	-	-	7.02
JPLMW-5	3Q07	-	-	-	6.15
JPLMW-5	3Q07	-	-	-	6.03
JPLMW-5	3Q98	-	-	0.73	-
JPLMW-5	4Q03	-	-	-	7.25
JPLMW-5	4Q05	-	-	-	6.11
JPLMW-5	4Q05	-	-	-	6.07
JPLMW-5	4Q06	-	-	-	6.43
JPLMW-5	4Q07	-	-	-	6.14
JPLMW-5	4Q08	-	-	-	6.62
JPLMW-5	4Q98	-	-	0.6	-
JPLMW-6	1Q02	-	-	1.88	-
JPLMW-6	1Q03	-	-	-	7.21
JPLMW-6	1Q06	-	-	-	6.09
JPLMW-6	1Q08	-	-	-	6.48
JPLMW-6	1Q08	-	-	-	7.21
JPLMW-6	1Q08	-	-	-	7.4
JPLMW-6	1Q08	-	-	-	7.39
JPLMW-6	1Q08	-	-	-	7.43
JPLMW-6	1Q08	-	-	-	6.99
JPLMW-6	1Q08	-	-	-	7.23
JPLMW-6	1Q09	-	-	-	6.04
JPLMW-6	2Q04	-	-	1.34	-
JPLMW-6	2Q04	-	-	-	7.33
JPLMW-6	2Q05	-	-	-	7.02
JPLMW-6	2Q05	-	-	-	7.11
JPLMW-6	2Q05	-	-	-	7.07
JPLMW-6	2Q05	-	-	-	6.25
JPLMW-6	2Q05	-	-	-	6.59
JPLMW-6	2Q05	-	-	-	6.86
JPLMW-6	2Q07	-	-	-	6.44
JPLMW-6	2Q08	-	-	0.551	-
JPLMW-6	2Q09	-	-	3	-
JPLMW-6	2Q99	-	-	-	6.71
JPLMW-6	3Q00	-	-	0.85	-
JPLMW-6	3Q03	-	-	-	7.08
JPLMW-6	3Q04	-	-	-	7.66
JPLMW-6	3Q05	-	-	-	6.42
JPLMW-6	3Q05	-	-	-	6.62
JPLMW-6	3Q05	-	-	-	6.75
JPLMW-6	3Q05	-	-	-	6.67
JPLMW-6	3Q05	-	-	-	6.69

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-6	3Q05	-	-	-	6.07
JPLMW-6	3Q06	-	-	-	6.63
JPLMW-6	3Q07	-	-	-	6.65
JPLMW-6	3Q07	-	-	-	6.21
JPLMW-6	3Q08	-	-	-	6.37
JPLMW-6	4Q03	-	-	-	6.73
JPLMW-6	4Q05	-	-	-	6.03
JPLMW-6	4Q05	-	-	-	6.19
JPLMW-6	4Q06	-	-	-	6.8
JPLMW-6	4Q07	-	-	-	6.46
JPLMW-6	4Q08	-	-	-	6.82
JPLMW-7	1Q03	-	-33	-	7.83
JPLMW-7	1Q05	-	-	-	6.36
JPLMW-7	1Q05	-	-	-	6.5
JPLMW-7	1Q05	-	-	-	6.89
JPLMW-7	1Q05	-	-	-	6.94
JPLMW-7	1Q05	-	-	-	7.18
JPLMW-7	1Q06	0.8	-	-	6.22
JPLMW-7	1Q08	-	-	-	6.14
JPLMW-7	1Q09	-	-34	-	-
JPLMW-7	2Q04	-	-	1.47	-
JPLMW-7	2Q04	-	-	-	7.48
JPLMW-7	2Q05	-	-	-	7.74
JPLMW-7	2Q07	-	-	-	6.41
JPLMW-7	2Q08	-	-	1.1	-
JPLMW-7	2Q08	-	-	-	6.44
JPLMW-7	2Q09	-	-	0.66	-
JPLMW-7	2Q98	-	-	0.88	-
JPLMW-7	2Q99	-	-	0.88	-
JPLMW-7	2Q99	-	-	-	6.78
JPLMW-7	3Q00	-	-	1.8	-
JPLMW-7	3Q03	-	-	-	7.33
JPLMW-7	3Q04	-	-	-	7.41
JPLMW-7	3Q05	-	-	-	6.71
JPLMW-7	3Q05	-	-	-	6.91
JPLMW-7	3Q05	-	-	-	6.89
JPLMW-7	3Q05	-	-	-	7.02
JPLMW-7	3Q05	-	-	-	7.18
JPLMW-7	3Q05	-	-	-	7.11
JPLMW-7	3Q06	-	-	-	6.63
JPLMW-7	3Q07	-	-	-	6.37
JPLMW-7	3Q07	-	-	-	6.15
JPLMW-7	3Q08	-	-	-	6.47
JPLMW-7	3Q98	-	-	2.6	-
JPLMW-7	4Q03	-	-	-	7.28
JPLMW-7	4Q05	-	-	-	6.13
JPLMW-7	4Q06	-	-	-	6.27

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-7	4Q07	-	-	-	6.23
JPLMW-7	4Q08	-	-	-	6.89
JPLMW-8	1Q01	-	-	2.08	-
JPLMW-8	1Q03	-	-47	-	7.57
JPLMW-8	1Q05	-	-	-	7.34
JPLMW-8	1Q05	-	-	-	7.24
JPLMW-8	1Q05	-	-	-	7.29
JPLMW-8	1Q05	-	-	-	7.38
JPLMW-8	1Q05	-	-	-	7.52
JPLMW-8	1Q05	-	-	-	7.44
JPLMW-8	1Q06	-	-	-	6.54
JPLMW-8	1Q08	-	-	-	6.53
JPLMW-8	1Q09	-	-27	-	-
JPLMW-8	2Q04	-	-	-	7.59
JPLMW-8	2Q05	-	-	-	7.96
JPLMW-8	2Q05	-	-	-	7.45
JPLMW-8	2Q05	-	-	-	7.49
JPLMW-8	2Q05	-	-	-	7.91
JPLMW-8	2Q05	-	-	-	7.98
JPLMW-8	2Q07	-	-	-	6.72
JPLMW-8	2Q08	-	-	-	6.86
JPLMW-8	2Q09	-	-	-	6.63
JPLMW-8	2Q99	-	-	-	7.17
JPLMW-8	3Q03	-	-	-	7.33
JPLMW-8	3Q04	-	-	-	7.38
JPLMW-8	3Q05	-	-	-	7.29
JPLMW-8	3Q05	-	-	-	7.26
JPLMW-8	3Q05	-	-	-	7.22
JPLMW-8	3Q05	-	-	-	7.23
JPLMW-8	3Q05	-	-	-	7.31
JPLMW-8	3Q05	-	-	-	7.21
JPLMW-8	3Q06	-	-	-	7.08
JPLMW-8	3Q07	-	-	-	6.8
JPLMW-8	3Q07	-	-	-	6.48
JPLMW-8	3Q08	-	-	-	6.43
JPLMW-8	4Q03	-	-	-	7.37
JPLMW-8	4Q05	-	-	-	6.55
JPLMW-8	4Q05	-	-	-	6.48
JPLMW-8	4Q05	-	-	-	6.56
JPLMW-8	4Q05	-	-	-	6.63
JPLMW-8	4Q05	-	-	-	6.79
JPLMW-8	4Q05	-	-	-	6.71
JPLMW-8	4Q06	-	-	-	6.77
JPLMW-8	4Q07	-	-	-	6.66
JPLMW-8	4Q08	-	-	-	7.2
JPLMW-9	1Q01	-	-	1	-
JPLMW-9	2Q03	-	-	0.832	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-9	2Q04	-	-	1.71	-
JPLMW-9	2Q04	-	-	-	7.33
JPLMW-9	2Q05	-	-	-	6.88
JPLMW-9	2Q05	-	-	-	6.97
JPLMW-9	2Q05	-	-	-	7.01
JPLMW-9	2Q05	-	-	-	7.03
JPLMW-9	2Q05	-	-	-	7.19
JPLMW-9	2Q05	-	-	-	7.11
JPLMW-9	2Q08	-	-	-	6.06
JPLMW-9	2Q09	-	-	-	6.02
JPLMW-9	2Q99	-	-	-	6.96
JPLMW-9	3Q07	-	-	-	6.61
JPLMW-9	4Q03	-	-	-	6.95
JPLMW-9	4Q05	-	-	-	6.14
JPLMW-9	4Q05	-	-	-	6.24
JPLMW-9	4Q06	-	-	-	6.66
JPLMW-9	4Q07	-	-	-	6.38
JPLMW-9	4Q08	-	-	-	6.98
JPLMW-10	1Q03	-	-	-	7.21
JPLMW-10	1Q05	-	-	-	6.45
JPLMW-10	1Q05	-	-	-	6.52
JPLMW-10	1Q05	-	-	-	6.68
JPLMW-10	1Q05	-	-	-	6.87
JPLMW-10	1Q06	-	-	-	6.21
JPLMW-10	1Q08	-	-	-	6.11
JPLMW-10	2Q04	-	-	-	6.89
JPLMW-10	2Q05	-	-	-	7.12
JPLMW-10	2Q05	-	-	-	7.79
JPLMW-10	2Q05	-	-	-	7.62
JPLMW-10	2Q05	-	-	-	7.57
JPLMW-10	2Q05	-	-	-	7.61
JPLMW-10	2Q07	-	-	-	6.66
JPLMW-10	2Q08	-	-	-	6.3
JPLMW-10	2Q09	-	-	0.73	-
JPLMW-10	2Q09	-	-	-	6.43
JPLMW-10	2Q99	-	-	-	7.01
JPLMW-10	3Q03	-	-	-	6.17
JPLMW-10	3Q04	-	-	-	7.54
JPLMW-10	3Q05	-	-	-	6.27
JPLMW-10	3Q05	-	-	-	6.42
JPLMW-10	3Q05	-	-	-	6.62
JPLMW-10	3Q05	-	-	-	6.7
JPLMW-10	3Q05	-	-	-	6.76
JPLMW-10	3Q05	-	-	-	7.12
JPLMW-10	3Q06	-	-	-	6.77
JPLMW-10	3Q07	-	-	-	6.14
JPLMW-10	3Q07	-	-	-	6.15

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-10	3Q08	-	-	-	6.59
JPLMW-10	4Q03	-	-	-	6.84
JPLMW-10	4Q05	-	-	-	6.05
JPLMW-10	4Q05	-	-	-	6.17
JPLMW-10	4Q05	-	-	-	6.29
JPLMW-10	4Q06	-	-	-	6.3
JPLMW-10	4Q07	-	-	-	6.08
JPLMW-10	4Q08	-	-	-	6.52
JPLMW-11-1	1Q06	0.9	-	-	-
JPLMW-11-1	1Q08	-	-	-	6.94
JPLMW-11-1	1Q09	-	-20	-	-
JPLMW-11-1	2Q07	-	-6	-	6.87
JPLMW-11-1	2Q07	-	-	-	6.95
JPLMW-11-1	2Q08	-	-	-	6.04
JPLMW-11-1	2Q09	-	-	0.52	-
JPLMW-11-1	2Q99	-	-	-	7.92
JPLMW-11-1	3Q06	-	-12	-	7.21
JPLMW-11-1	3Q07	-	-	-	6.78
JPLMW-11-1	3Q08	-	-	-	7.08
JPLMW-11-1	3Q97	-	-	0.76	-
JPLMW-11-1	4Q05	-	-	-	6.3
JPLMW-11-1	4Q06	-	-	-	7.19
JPLMW-11-1	4Q07	-	-	-	7.18
JPLMW-11-1	4Q08	0	-	-	6.33
JPLMW-11-2	1Q08	-	-	-	6.61
JPLMW-11-2	1Q09	-	-16	-	-
JPLMW-11-2	1Q99	-	-	0.75	-
JPLMW-11-3	2Q03	-	-	2.31	-
JPLMW-11-2	2Q04	-	-	0.5	-
JPLMW-11-2	2Q07	-	-	-	6.72
JPLMW-11-2	2Q07	-	-	-	6.62
JPLMW-11-2	2Q09	-	-	0.6	-
JPLMW-11-2	2Q97	-	-	0.7	-
JPLMW-11-2	2Q99	-	-	-	7.92
JPLMW-11-2	3Q06	-	-8	-	7.19
JPLMW-11-2	3Q07	-	-	-	6.73
JPLMW-11-2	3Q08	-	-	-	6.91
JPLMW-11-2	4Q05	-	-	-	6.44
JPLMW-11-2	4Q06	-	-	-	6.44
JPLMW-11-2	4Q08	0	-86	-	6.18
JPLMW-11-2	4Q96	-	-	0.71	-
JPLMW-11-3	1Q01	-	-	0.87	-
JPLMW-11-3	1Q08	-	-	-	6.57
JPLMW-11-3	1Q09	-	-15	-	-
JPLMW-11-3	2Q04	-	-	1.14	-
JPLMW-11-3	2Q05	-	-	0.815	-
JPLMW-11-3	2Q07	-	-39	-	6.54

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-11-3	2Q07	-	-	-	6.12
JPLMW-11-3	3Q06	-	-9	-	7.13
JPLMW-11-3	3Q07	-	-	-	6.58
JPLMW-11-3	3Q08	-	-	-	6.65
JPLMW-11-3	4Q06	-	-	-	6.18
JPLMW-11-3	4Q08	-	-20	-	6.03
JPLMW-11-4	1Q06	1	-	-	-
JPLMW-11-4	1Q09	-	-96	-	-
JPLMW-11-4	1Q97	-	-	0.95	-
JPLMW-11-4	1Q98	-	-	0.83	-
JPLMW-11-4	2Q07	-	-110	-	6.49
JPLMW-11-4	2Q09	-	-47	-	-
JPLMW-11-4	2Q97	-	-	0.98	-
JPLMW-11-4	3Q06	-	-61	-	6.96
JPLMW-11-4	3Q07	-	-	-	6.53
JPLMW-11-4	3Q08	0	-	-	6.57
JPLMW-11-4	3Q97	-	-	1.15	-
JPLMW-11-4	3Q98	-	-	0.7	-
JPLMW-11-4	4Q06	-	-	-	6.23
JPLMW-11-4	4Q07	-	-	-	6.01
JPLMW-11-4	4Q08	-	-68	-	6.09
JPLMW-11-4	4Q96	-	-	0.98	-
JPLMW-11-4	4Q98	-	-	0.63	-
JPLMW-11-5	1Q99	-	-	0.6	-
JPLMW-11-5	2Q05	-	-	0.597	-
JPLMW-11-5	2Q07	-	-	-	6.04
JPLMW-11-5	2Q98	-	-	0.53	-
JPLMW-11-5	2Q99	-	-	0.53	-
JPLMW-11-5	4Q08	0	-6	-	-
JPLMW-11-5	4Q96	-	-	0.54	-
JPLMW-12-1	1Q01	-	-	3.25	-
JPLMW-12-1	1Q06	0.8	-	-	6.12
JPLMW-12-1	1Q08	-	-	-	6.59
JPLMW-12-1	1Q09	-	-49	-	6.22
JPLMW-12-1	1Q99	-	-	0.89	-
JPLMW-12-1	2Q03	-	-	0.572	-
JPLMW-12-1	2Q04	-	-	0.507	-
JPLMW-12-1	2Q07	-	-	-	7.13
JPLMW-12-1	2Q08	-	-	-	6.03
JPLMW-12-1	2Q09	-	-	0.87	-
JPLMW-12-1	2Q97	-	-	1.4	-
JPLMW-12-1	2Q98	-	-	0.64	-
JPLMW-12-1	2Q99	-	-	0.64	-
JPLMW-12-1	2Q99	-	-	-	7.29
JPLMW-12-1	3Q00	-	-	2.1	-
JPLMW-12-1	3Q06	-	-	-	7.37
JPLMW-12-1	3Q07	-	-	-	7.17

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-12-1	3Q08	-	-	-	6.36
JPLMW-12-1	3Q98	-	-	1.3	-
JPLMW-12-1	4Q05	-	-	-	6.45
JPLMW-12-1	4Q07	-	-	-	6.43
JPLMW-12-1	4Q08	-	-47	-	6.12
JPLMW-12-1	4Q98	-	-	0.95	-
JPLMW-12-2	1Q06	0.8	-	-	-
JPLMW-12-2	1Q08	-	-	-	6.46
JPLMW-12-2	1Q09	-	-49	-	6.09
JPLMW-12-2	2Q07	-	-42	-	7.05
JPLMW-12-2	2Q07	-	-	-	7.01
JPLMW-12-2	2Q09	-	-	0.69	-
JPLMW-12-2	3Q06	-	-	-	7.21
JPLMW-12-2	3Q07	-	-	-	6.99
JPLMW-12-2	3Q08	-	-	-	6.24
JPLMW-12-2	3Q97	-	-	0.67	-
JPLMW-12-2	4Q05	-	-	-	6.29
JPLMW-12-2	4Q06	-	-	-	6.74
JPLMW-12-2	4Q08	-	-81	-	-
JPLMW-12-3	1Q06	0.9	-	-	-
JPLMW-12-3	1Q09	-	-50	-	-
JPLMW-12-3	1Q99	-	-	0.54	-
JPLMW-12-3	2Q07	-	-35	-	6.95
JPLMW-12-3	2Q07	-	-	-	6.83
JPLMW-12-3	2Q09	-	-	0.6	-
JPLMW-12-3	2Q97	-	-	0.5	-
JPLMW-12-3	2Q99	-	-	-	7.55
JPLMW-12-3	3Q06	-	-	-	7.09
JPLMW-12-3	3Q07	-	-	-	6.75
JPLMW-12-3	4Q05	-	-	-	6.11
JPLMW-12-3	4Q06	-	-	-	6.23
JPLMW-12-3	4Q08	-	-6	-	-
JPLMW-12-4	1Q02	-	-	0.59	-
JPLMW-12-4	1Q06	0.6	-	-	-
JPLMW-12-4	1Q09	-	-75	-	-
JPLMW-12-4	1Q98	-	-	1.1	-
JPLMW-12-4	2Q07	-	-56	-	6.77
JPLMW-12-4	2Q09	-	-	0.6	-
JPLMW-12-4	2Q99	-	-	-	7.7
JPLMW-12-4	3Q06	-	-	-	6.78
JPLMW-12-4	3Q07	-	-	-	6.23
JPLMW-12-4	4Q06	-	-	-	6.34
JPLMW-12-4	4Q08	-	-39	-	-
JPLMW-12-5	1Q09	-	-108	-	-
JPLMW-12-5	2Q04	-	-	0.544	-
JPLMW-12-5	2Q07	-	-	-	6.67
JPLMW-12-5	2Q09	-	-	1.1	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-12-5	2Q99	-	-	-	7.7
JPLMW-12-5	3Q06	-	-	-	6.64
JPLMW-13	1Q02	-	-	0.69	-
JPLMW-13	1Q03	-	-17	-	7.79
JPLMW-13	1Q05	-	-	-	7.26
JPLMW-13	1Q05	-	-	-	7.3
JPLMW-13	1Q05	-	-	-	7.33
JPLMW-13	1Q05	-	-	-	7.34
JPLMW-13	1Q05	-	-	-	7.38
JPLMW-13	1Q05	-	-	-	7.21
JPLMW-13	1Q06	-	-	-	6.52
JPLMW-13	1Q08	-	-	-	6.06
JPLMW-13	1Q09	-	-23	-	-
JPLMW-13	2Q04	-	-	-	7.03
JPLMW-13	2Q05	-	-	-	7.43
JPLMW-13	2Q05	-	-	-	7.72
JPLMW-13	2Q05	-	-	-	7.84
JPLMW-13	2Q05	-	-	-	7.95
JPLMW-13	2Q05	-	-	-	6.14
JPLMW-13	2Q07	-	-	-	6.53
JPLMW-13	2Q08	-	-	-	6.24
JPLMW-13	2Q09	-	-	-	6.5
JPLMW-13	2Q99	-	-	-	6.41
JPLMW-13	3Q03	-	-	-	6.66
JPLMW-13	3Q04	-	-	-	6.83
JPLMW-13	3Q05	-	-	-	6.1
JPLMW-13	3Q05	-	-	-	6.25
JPLMW-13	3Q05	-	-	-	6.3
JPLMW-13	3Q06	-	-	-	6.66
JPLMW-13	3Q07	-	-	-	6.3
JPLMW-13	3Q07	-	-	-	6.1
JPLMW-13	3Q08	0	-	-	6.06
JPLMW-13	4Q03	-	-	-	6.38
JPLMW-13	4Q05	-	-	-	6.25
JPLMW-13	4Q05	-	-	-	6.33
JPLMW-13	4Q05	-	-	-	6.4
JPLMW-13	4Q05	-	-	-	6.51
JPLMW-13	4Q05	-	-	-	6.59
JPLMW-13	4Q05	-	-	-	6.15
JPLMW-13	4Q06	-	-	-	6.36
JPLMW-13	4Q07	-	-	-	6.22
JPLMW-13	4Q08	-	-	-	6.67
JPLMW-14-1	1Q06	0.7	-	-	-
JPLMW-14-1	1Q07	-	-	-	6.34
JPLMW-14-1	1Q08	-	-	-	6.64
JPLMW-14-1	1Q09	-	-	-	6.3
JPLMW-14-1	1Q97	-	-	0.66	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-14-1	1Q98	-	-	0.74	-
JPLMW-14-1	1Q99	-	-	0.73	-
JPLMW-14-1	2Q04	-	-	0.916	-
JPLMW-14-1	2Q05	-	-	1.01	-
JPLMW-14-1	2Q07	-	-	-	6.83
JPLMW-14-1	2Q08	-	-	-	7.03
JPLMW-14-1	2Q09	-	-	0.96	-
JPLMW-14-1	2Q97	-	-	2.3	-
JPLMW-14-1	2Q98	-	-	0.59	-
JPLMW-14-1	2Q99	-	-	0.59	-
JPLMW-14-1	2Q99	-	-	-	6.54
JPLMW-14-1	3Q06	-	-	-	6.61
JPLMW-14-1	3Q07	-	-	-	6.58
JPLMW-14-1	3Q07	-	-	-	6.29
JPLMW-14-1	3Q08	-	-	-	7.33
JPLMW-14-1	3Q97	-	-	1.4	-
JPLMW-14-1	3Q98	-	-	1.5	-
JPLMW-14-1	4Q05	-	-	-	6.21
JPLMW-14-1	4Q06	-	-	-	6.31
JPLMW-14-1	4Q07	-	-	-	6.12
JPLMW-14-1	4Q08	-	-	-	6.88
JPLMW-14-1	4Q98	-	-	1.8	-
JPLMW-14-2	1Q07	-	-	-	6.09
JPLMW-14-2	1Q08	-	-	-	6.09
JPLMW-14-2	1Q09	-	-	-	6
JPLMW-14-2	1Q97	-	-	1.4	-
JPLMW-14-2	1Q98	-	-	0.5	-
JPLMW-14-2	2Q07	-	-	-	6.8
JPLMW-14-2	2Q09	-	-	0.99	-
JPLMW-14-2	2Q97	-	-	2.3	-
JPLMW-14-2	2Q98	-	-	0.6	-
JPLMW-14-2	2Q99	-	-	0.6	-
JPLMW-14-2	2Q99	-	-	-	6.92
JPLMW-14-2	3Q06	-	-44	-	6.45
JPLMW-14-2	3Q07	-	-	-	6.31
JPLMW-14-2	3Q07	-	-	-	6.04
JPLMW-14-2	3Q08	0	-	-	6.95
JPLMW-14-2	3Q96	-	-	1.4	-
JPLMW-14-2	3Q97	-	-	1.9	-
JPLMW-14-2	3Q98	-	-	0.8	-
JPLMW-14-2	4Q06	-	-	-	6.08
JPLMW-14-2	4Q07	-	-	-	6.02
JPLMW-14-2	4Q08	-	-	-	6.71
JPLMW-14-2	4Q96	-	-	0.58	-
JPLMW-14-3	1Q06	-	-1	-	-
JPLMW-14-3	1Q09	-	-	-	6.2
JPLMW-14-3	2Q07	-	-	-	6.08

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-14-3	2Q09	-	-	0.85	-
JPLMW-14-3	2Q99	-	-	-	7.61
JPLMW-14-3	3Q06	-	-46	-	6.02
JPLMW-14-3	3Q07	-	-	-	6.04
JPLMW-14-3	3Q08	-	-	-	6.5
JPLMW-14-4	1Q06	0.9	-	-	-
JPLMW-14-4	1Q07	-	-7	-	-
JPLMW-14-4	2Q99	-	-	-	7.72
JPLMW-14-4	3Q06	-	-26	-	-
JPLMW-14-4	3Q08	-	-	-	6.06
JPLMW-14-4	4Q08	0.26	-	-	-
JPLMW-14-5	1Q01	-	-	0.57	-
JPLMW-14-5	1Q06	0.8	-	-	-
JPLMW-14-5	1Q98	-	-	0.89	-
JPLMW-14-5	1Q99	-	-	0.5	-
JPLMW-14-5	2Q09	-	-24	-	-
JPLMW-14-5	3Q97	-	-	0.64	-
JPLMW-15	1Q03	-	-48	-	7.59
JPLMW-15	1Q05	-	-	-	6.08
JPLMW-15	1Q05	-	-	-	6.31
JPLMW-15	1Q05	-	-	-	6.42
JPLMW-15	1Q05	-	-	-	6.7
JPLMW-15	1Q05	-	-	-	6.8
JPLMW-15	1Q06	0.9	-8	-	6.23
JPLMW-15	1Q08	-	-	-	6.51
JPLMW-15	1Q09	-	-28	-	6.2
JPLMW-15	2Q04	-	-	-	7.3
JPLMW-15	2Q05	-	-	-	7.41
JPLMW-15	2Q05	-	-	-	7.42
JPLMW-15	2Q05	-	-	-	7.46
JPLMW-15	2Q05	-	-	-	7.51
JPLMW-15	2Q05	-	-	-	7.45
JPLMW-15	2Q05	-	-	-	7.52
JPLMW-15	2Q07	-	-	-	6.96
JPLMW-15	2Q08	-	-	-	6.8
JPLMW-15	2Q09	-	-	-	6.76
JPLMW-15	2Q99	-	-	-	7.16
JPLMW-15	3Q03	-	-	-	7.06
JPLMW-15	3Q04	-	-	-	7.53
JPLMW-15	3Q05	-	-	-	6.91
JPLMW-15	3Q05	-	-	-	7.06
JPLMW-15	3Q05	-	-	-	7.11
JPLMW-15	3Q05	-	-	-	7.09
JPLMW-15	3Q05	-	-	-	7.15
JPLMW-15	3Q05	-	-	-	7.22
JPLMW-15	3Q06	-	-	-	7.22
JPLMW-15	3Q07	-	-	-	7.11

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-15	3Q07	-	-	-	6.67
JPLMW-15	3Q08	-	-	-	6.72
JPLMW-15	4Q03	-	-	-	7.13
JPLMW-15	4Q05	-	-	-	6.06
JPLMW-15	4Q05	-	-	-	6.23
JPLMW-15	4Q05	-	-	-	6.43
JPLMW-15	4Q05	-	-	-	6.59
JPLMW-15	4Q05	-	-	-	6.66
JPLMW-15	4Q05	-	-	-	6.7
JPLMW-15	4Q06	-	-	-	7.07
JPLMW-15	4Q08	-	-	-	7.31
JPLMW-16	1Q03	-	-21	-	7.74
JPLMW-16	1Q05	-	-	-	7.7
JPLMW-16	1Q05	-	-	-	7.64
JPLMW-16	1Q05	-	-	-	7.65
JPLMW-16	1Q05	-	-	-	7.65
JPLMW-16	1Q05	-	-	-	7.63
JPLMW-16	1Q05	-	-	-	7.69
JPLMW-16	1Q06	-	-	-	6.75
JPLMW-16	1Q08	-	-	-	6.75
JPLMW-16	2Q04	-	-	-	7.59
JPLMW-16	2Q05	-	-	-	7.11
JPLMW-16	2Q05	-	-	-	7.2
JPLMW-16	2Q05	-	-	-	7.25
JPLMW-16	2Q05	-	-	-	7.18
JPLMW-16	2Q05	-	-	-	7.36
JPLMW-16	2Q05	-	-	-	7.51
JPLMW-16	2Q05	-	-	-	7.48
JPLMW-16	2Q07	-	-	-	6.78
JPLMW-16	2Q08	-	-	-	6.89
JPLMW-16	2Q09	-	-	-	6.27
JPLMW-16	2Q99	-	-	-	6.58
JPLMW-16	3Q03	-	-	-	7.02
JPLMW-16	3Q04	-	-	-	7.93
JPLMW-16	3Q05	-	-	-	6.05
JPLMW-16	3Q05	-	-	-	6.21
JPLMW-16	3Q05	-	-	-	6.28
JPLMW-16	3Q06	-	-	-	7.07
JPLMW-16	3Q07	-	-	-	7.01
JPLMW-16	3Q07	-	-	-	6.84
JPLMW-16	3Q08	0	-	-	6.63
JPLMW-16	4Q03	-	-	-	6.41
JPLMW-16	4Q05	-	-	-	6.41
JPLMW-16	4Q05	-	-	-	6.51
JPLMW-16	4Q05	-	-	-	6.6
JPLMW-16	4Q05	-	-	-	6.72
JPLMW-16	4Q05	-	-	-	6.66

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-16	4Q05	-	-	-	6.69
JPLMW-16	4Q06	-	-	-	6.89
JPLMW-16	4Q07	-	-	-	6.77
JPLMW-16	4Q08	-	-	-	7.31
JPLMW-17-1	2Q07	-	-	-	6.66
JPLMW-17-1	2Q08	-	-	-	6.32
JPLMW-17-1	2Q99	-	-	-	7.39
JPLMW-17-1	4Q05	-	-	-	6.5
JPLMW-17-1	4Q06	-	-	-	7.29
JPLMW-17-1	4Q07	-	-	-	6.11
JPLMW-17-1	4Q08	-	-	-	6.15
JPLMW-17-2	1Q06	-	-	-	6.52
JPLMW-17-2	1Q07	-	-42	-	6.28
JPLMW-17-2	1Q09	-	-100	-	-
JPLMW-17-2	1Q97	-	-	1.2	-
JPLMW-17-2	1Q98	-	-	0.65	-
JPLMW-17-2	2Q07	-	-	-	6.27
JPLMW-17-2	2Q09	-	-	0.71	-
JPLMW-17-2	2Q99	-	-	-	7.93
JPLMW-17-2	3Q06	-	-	-	6.21
JPLMW-17-2	3Q96	-	-	0.54	-
JPLMW-17-2	3Q98	-	-	0.69	-
JPLMW-17-2	4Q05	-	-	-	6.08
JPLMW-17-3	1Q01	-	-	0.65	-
JPLMW-17-3	1Q02	-	-	0.7	-
JPLMW-17-3	1Q06	-	-	-	6.38
JPLMW-17-3	1Q07	-	-28	-	-
JPLMW-17-3	1Q09	-	-121	-	-
JPLMW-17-3	1Q99	-	-	1.2	-
JPLMW-17-3	2Q03	-	-	0.822	-
JPLMW-17-3	2Q04	-	-	0.786	-
JPLMW-17-3	2Q05	-	-	1.14	-
JPLMW-17-3	2Q07	-	-	-	6.04
JPLMW-17-3	2Q08	-	-	1.27	-
JPLMW-17-3	2Q09	-	-	1.2	-
JPLMW-17-3	2Q97	-	-	0.58	-
JPLMW-17-3	2Q99	-	-	-	7.97
JPLMW-17-3	3Q06	-	-33	-	-
JPLMW-17-3	3Q96	-	-	0.91	-
JPLMW-17-3	3Q97	-	-	0.61	-
JPLMW-17-3	4Q96	-	-	1.5	-
JPLMW-17-3	4Q98	-	-	0.51	-
JPLMW-17-4	1Q06	-	-	-	6.31
JPLMW-17-4	1Q09	-	-133	-	-
JPLMW-17-4	1Q97	-	-	0.61	-
JPLMW-17-4	1Q99	-	-	0.76	-
JPLMW-17-4	2Q03	-	-	0.639	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-17-4	2Q07	-	-15	-	-
JPLMW-17-4	3Q96	-	-	1.2	-
JPLMW-17-4	3Q97	-	-	0.73	-
JPLMW-17-5	1Q01	-	-	2.58	-
JPLMW-17-5	1Q97	-	-	2.9	-
JPLMW-17-5	1Q98	-	-	0.65	-
JPLMW-17-5	1Q99	-	-	1.6	-
JPLMW-17-5	2Q03	-	-	1.28	-
JPLMW-17-5	2Q04	-	-	18.1	-
JPLMW-17-5	2Q05	-	-	0.956	-
JPLMW-17-5	2Q08	-	-	0.997	-
JPLMW-17-5	2Q09	-	-	1.6	-
JPLMW-17-5	2Q97	-	-	0.72	-
JPLMW-17-5	2Q98	-	-	1.9	-
JPLMW-17-5	2Q99	-	-	1.9	-
JPLMW-17-5	3Q96	-	-	2.3	-
JPLMW-17-5	3Q97	-	-	0.82	-
JPLMW-17-5	3Q98	-	-	0.75	-
JPLMW-17-5	4Q06	-	-	-	6.29
JPLMW-17-5	4Q08	0	-	-	-
JPLMW-17-5	4Q96	-	-	5.1	-
JPLMW-17-5	4Q98	-	-	0.72	-
JPLMW-18-1	1Q06	-	-	-	6
JPLMW-18-1	2Q07	-	-	-	6.58
JPLMW-18-1	2Q08	-	-	-	6.23
JPLMW-18-1	2Q09	-	-	0.62	-
JPLMW-18-1	2Q09	-	-	-	6.42
JPLMW-18-1	2Q99	-	-	-	7.53
JPLMW-18-1	4Q05	-	-	-	6.72
JPLMW-18-1	4Q06	-	-	-	6.31
JPLMW-18-1	4Q07	-	-	-	6.37
JPLMW-18-1	4Q08	-	-	-	6.09
JPLMW-18-2	1Q07	-	-17	-	7.51
JPLMW-18-2	1Q08	-	-	-	6.4
JPLMW-18-2	1Q09	-	-55	-	6.71
JPLMW-18-2	2Q05	-	-	0.823	-
JPLMW-18-2	2Q07	-	-	-	6.13
JPLMW-18-2	2Q09	-	-	-	6.25
JPLMW-18-2	2Q99	-	-	-	7.74
JPLMW-18-2	3Q06	-	-	-	7.07
JPLMW-18-2	3Q07	-	-	-	6.76
JPLMW-18-2	3Q08	-	-	-	6.53
JPLMW-18-2	3Q96	-	-	0.52	-
JPLMW-18-2	4Q05	-	-	-	6.51
JPLMW-18-2	4Q06	-	-	-	6.44
JPLMW-18-2	4Q07	-	-	-	6.13
JPLMW-18-3	1Q07	-	-30	-	7.37

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-18-3	1Q08	-	-	-	6.21
JPLMW-18-3	1Q09	-	-54	-	-
JPLMW-18-3	2Q09	-	-	0.53	-
JPLMW-18-3	2Q09	-	-	-	6.15
JPLMW-18-3	3Q06	-	-35	-	6.94
JPLMW-18-3	3Q07	-	-	-	6.6
JPLMW-18-3	3Q08	-	-	-	6.43
JPLMW-18-3	3Q96	-	-	0.8	-
JPLMW-18-3	4Q96	-	-	0.64	-
JPLMW-18-4	1Q07	-	-77	-	7.38
JPLMW-18-4	1Q08	-	-	-	6.12
JPLMW-18-4	1Q09	-	-79	-	6.72
JPLMW-18-4	2Q07	-	-11	-	-
JPLMW-18-4	2Q08	-	-	0.597	-
JPLMW-18-4	2Q09	-	-	0.51	-
JPLMW-18-4	3Q06	-	-43	-	6.8
JPLMW-18-4	3Q07	-	-	-	6.54
JPLMW-18-4	3Q08	-	-	-	6.26
JPLMW-18-4	4Q06	-	-	-	6.2
JPLMW-18-4	4Q08	0	-	-	-
JPLMW-18-5	1Q07	-	-67	-	7.28
JPLMW-18-5	1Q08	-	-	-	6.19
JPLMW-18-5	1Q09	-	-106	-	-
JPLMW-18-5	3Q06	-	-34	-	6.82
JPLMW-18-5	3Q07	-	-	-	6.54
JPLMW-18-5	3Q08	-	-	-	6.2
JPLMW-18-5	4Q06	-	-	-	6.04
JPLMW-18-5	4Q08	0	-	-	-
JPLMW-19-1	1Q01	-	-	2.31	-
JPLMW-19-1	1Q02	-	-	3.24	-
JPLMW-19-1	1Q06	-	-	-	6.18
JPLMW-19-1	1Q08	-	-95	-	-
JPLMW-19-1	1Q08	-	-	-	6.38
JPLMW-19-1	1Q99	-	-	5.7	-
JPLMW-19-1	2Q03	-	-	2.5	-
JPLMW-19-1	2Q04	-	-	3.5	-
JPLMW-19-1	2Q05	-	-	2.58	-
JPLMW-19-1	2Q07	-	-63	-	6.6
JPLMW-19-1	2Q07	-	-	-	6.3
JPLMW-19-1	2Q09	-	-	1.1	-
JPLMW-19-1	2Q98	-	-	1	-
JPLMW-19-1	2Q99	-	-	1	-
JPLMW-19-1	2Q99	-	-	-	7.71
JPLMW-19-1	3Q06	-	-	-	7.05
JPLMW-19-1	3Q07	-	-	-	7.08
JPLMW-19-1	3Q08	-	-	-	6.49
JPLMW-19-1	3Q96	-	-	2.7	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-19-1	3Q98	-	-	0.67	-
JPLMW-19-1	4Q05	-	-	-	6.53
JPLMW-19-1	4Q07	-	-	-	6.25
JPLMW-19-1	4Q08	0	-	-	6.05
JPLMW-19-1	4Q96	-	-	0.51	-
JPLMW-19-1	4Q98	-	-	0.95	-
JPLMW-19-2	1Q01	-	-	2.27	-
JPLMW-19-2	1Q02	-	-	1.01	-
JPLMW-19-2	1Q06	0.4	-	-	-
JPLMW-19-2	1Q08	-	-	-	6.23
JPLMW-19-2	1Q97	-	-	2.4	-
JPLMW-19-2	1Q98	-	-	1.6	-
JPLMW-19-2	1Q99	-	-	0.91	-
JPLMW-19-2	2Q03	-	-	3.15	-
JPLMW-19-2	2Q04	-	-	0.973	-
JPLMW-19-2	2Q05	-	-	0.792	-
JPLMW-19-2	2Q07	-	-	-	6.23
JPLMW-19-2	2Q07	-	-21	-	-
JPLMW-19-2	2Q09	-	-	4.6	-
JPLMW-19-2	2Q98	-	-	0.97	-
JPLMW-19-2	2Q99	-	-	0.97	-
JPLMW-19-2	2Q99	-	-	-	6.85
JPLMW-19-2	3Q06	-	-	-	6.78
JPLMW-19-2	3Q07	-	-	-	6.54
JPLMW-19-2	3Q08	-	-	-	6.06
JPLMW-19-2	3Q96	-	-	5.5	-
JPLMW-19-2	4Q05	-	-	-	6.19
JPLMW-19-2	4Q96	-	-	7.2	-
JPLMW-19-3	1Q01	-	-	2.89	-
JPLMW-19-3	1Q02	-	-	0.69	-
JPLMW-19-3	1Q06	0.9	-	-	-
JPLMW-19-3	1Q08	-	-111	-	-
JPLMW-19-3	1Q99	-	-	1.5	-
JPLMW-19-3	2Q07	-	-53	-	6.1
JPLMW-19-3	2Q07	-	-43	-	-
JPLMW-19-3	2Q09	-	-	0.58	-
JPLMW-19-3	2Q99	-	-	-	7.11
JPLMW-19-3	3Q00	-	-	1.2	-
JPLMW-19-3	3Q06	-	-	-	6.74
JPLMW-19-3	3Q96	-	-	0.75	-
JPLMW-19-3	3Q97	-	-	0.62	-
JPLMW-19-3	3Q98	-	-	0.95	-
JPLMW-19-3	4Q05	-	-	-	6.14
JPLMW-19-3	4Q08	0	-	-	-
JPLMW-19-3	4Q96	-	-	1.6	-
JPLMW-19-3	4Q98	-	-	0.62	-
JPLMW-19-4	1Q06	0.9	-	-	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-19-4	1Q08	-	-138	-	-
JPLMW-19-4	1Q98	-	-	0.5	-
JPLMW-19-4	1Q99	-	-	0.52	-
JPLMW-19-4	2Q07	-	-51	-	-
JPLMW-19-4	2Q07	-	-41	-	-
JPLMW-19-4	2Q09	-	-	0.5	-
JPLMW-19-4	2Q97	-	-	2.2	-
JPLMW-19-4	3Q06	-	-9	-	6.61
JPLMW-19-4	3Q96	-	-	0.97	-
JPLMW-19-4	3Q97	-	-	1.3	-
JPLMW-19-4	4Q08	0.93	-	-	-
JPLMW-19-4	4Q96	-	-	0.8	-
JPLMW-19-5	1Q06	0.9	-	-	-
JPLMW-19-5	1Q08	-	-139	-	-
JPLMW-19-5	2Q03	-	-	0.616	-
JPLMW-19-5	2Q04	-	-	0.563	-
JPLMW-19-5	2Q05	-	-	0.952	-
JPLMW-19-5	2Q09	-	-	0.7	-
JPLMW-19-5	2Q97	-	-	0.52	-
JPLMW-19-5	2Q99	-	-	-	7.78
JPLMW-19-5	3Q06	-	-	-	6.1
JPLMW-19-5	3Q97	-	-	1.1	-
JPLMW-19-5	4Q08	0.76	-	-	-
JPLMW-20-1	1Q06	-	-88	-	6.59
JPLMW-20-1	1Q07	-	-76	-	6.39
JPLMW-20-1	1Q09	-	-40	-	6.63
JPLMW-20-1	2Q07	-	-16	-	6.35
JPLMW-20-1	2Q99	-	-	-	7.91
JPLMW-20-1	3Q06	-	-13	-	6.22
JPLMW-20-1	3Q08	-	-72	-	-
JPLMW-20-1	3Q96	-	-	1.7	-
JPLMW-20-1	4Q05	-	-	-	6.12
JPLMW-20-1	4Q06	-	-	-	6.15
JPLMW-20-1	4Q07	-	-	-	6.11
JPLMW-20-1	4Q08	-	-	-	7.54
JPLMW-20-2	1Q06	-	-119	-	6.38
JPLMW-20-2	1Q07	-	-113	-	6.28
JPLMW-20-2	1Q09	-	-49	-	-
JPLMW-20-2	2Q07	-	-74	-	6.03
JPLMW-20-2	3Q06	-	-30	-	6.31
JPLMW-20-2	3Q08	-	-68	-	-
JPLMW-20-2	3Q97	-	-	0.5	-
JPLMW-20-2	4Q05	-	-	-	6.13
JPLMW-20-2	4Q06	-	-102	-	6.04
JPLMW-20-2	4Q07	-	-	-	6
JPLMW-20-2	4Q08	-	-	-	7.61
JPLMW-20-3	1Q06	-	-135	-	6.13

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-20-3	1Q07	-	-114	-	6.03
JPLMW-20-3	1Q09	-	-167	-	-
JPLMW-20-3	2Q07	-	-76	-	-
JPLMW-20-3	2Q09	-	-35	-	-
JPLMW-20-3	2Q97	-	-	0.8	-
JPLMW-20-3	3Q06	-	-79	-	6.03
JPLMW-20-3	3Q08	-	-9	-	-
JPLMW-20-3	4Q05	-	-	-	6.13
JPLMW-20-3	4Q06	-	-105	-	-
JPLMW-20-3	4Q07	-	-	-	6.2
JPLMW-20-3	4Q08	-	-39	-	-
JPLMW-20-4	1Q02	-	-	0.75	-
JPLMW-20-4	1Q06	-	-237	-	6.25
JPLMW-20-4	1Q07	-	-182	-	6.53
JPLMW-20-4	1Q08	-	-58	-	-
JPLMW-20-4	1Q09	-	-322	-	-
JPLMW-20-4	2Q03	-	-	0.673	-
JPLMW-20-4	2Q04	-	-	0.905	-
JPLMW-20-4	2Q05	-	-	0.56	-
JPLMW-20-4	2Q07	-	-104	-	6.16
JPLMW-20-4	2Q08	-	-35	-	-
JPLMW-20-4	2Q09	-	-171	-	-
JPLMW-20-4	3Q06	-	-94	-	6.38
JPLMW-20-4	3Q07	-	-	-	6.14
JPLMW-20-4	3Q08	-	-119	-	6.14
JPLMW-20-4	4Q05	-	-35	-	6.27
JPLMW-20-4	4Q06	-	-191	-	6.26
JPLMW-20-4	4Q07	-	-22	-	6.14
JPLMW-20-4	4Q08	-	-80	-	7.97
JPLMW-20-5	1Q06	-	-214	-	-
JPLMW-20-5	1Q07	-	-164	-	-
JPLMW-20-5	1Q08	-	-46	-	-
JPLMW-20-5	1Q09	-	-199	-	-
JPLMW-20-5	2Q07	-	-143	-	-
JPLMW-20-5	2Q08	-	-42	-	-
JPLMW-20-5	2Q09	-	-152	-	-
JPLMW-20-5	3Q06	-	-143	-	-
JPLMW-20-5	3Q08	-	-111	-	-
JPLMW-20-5	4Q05	-	-39	-	-
JPLMW-20-5	4Q06	-	-190	-	-
JPLMW-20-5	4Q07	-	-12	-	-
JPLMW-20-5	4Q08	-	-82	-	6.16
JPLMW-21-1	1Q06	-	-	-	6.9
JPLMW-21-1	1Q07	-	-	-	6.74
JPLMW-21-1	1Q08	-	-	-	6.77
JPLMW-21-1	2Q07	-	-	-	7.34
JPLMW-21-1	2Q08	-	-	-	6.15

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-21-1	2Q09	-	-	1.8	-
JPLMW-21-1	2Q09	-	-	-	6.03
JPLMW-21-1	2Q99	-	-	-	6.81
JPLMW-21-1	3Q06	-	-	-	6.92
JPLMW-21-1	3Q07	-	-	-	6.54
JPLMW-21-1	3Q08	0	-	-	6.75
JPLMW-21-1	4Q05	-	-	-	6.41
JPLMW-21-1	4Q06	-	-	-	6.84
JPLMW-21-1	4Q07	-	-	-	6.32
JPLMW-21-1	4Q08	0.73	-	-	6.4
JPLMW-21-2	1Q06	-	-	-	6.72
JPLMW-21-2	1Q07	-	-	-	6.32
JPLMW-21-2	1Q08	-	-	-	6.47
JPLMW-21-2	1Q09	-	-	-	6.2
JPLMW-21-2	2Q04	-	-	0.601	-
JPLMW-21-2	2Q07	-	-	-	7.23
JPLMW-21-2	2Q09	-	-	1.5	-
JPLMW-21-2	2Q99	-	-	-	7.43
JPLMW-21-2	3Q06	-	-	-	6.7
JPLMW-21-2	3Q07	-	-	-	6.45
JPLMW-21-2	3Q08	-	-	-	6.48
JPLMW-21-2	3Q98	-	-	0.91	-
JPLMW-21-2	4Q05	-	-	-	6.1
JPLMW-21-2	4Q06	-	-	-	6.5
JPLMW-21-2	4Q07	-	-	-	6.05
JPLMW-21-2	4Q08	-	-	-	6.38
JPLMW-21-2	4Q98	-	-	0.88	-
JPLMW-21-3	1Q06	-	-	-	6.54
JPLMW-21-3	1Q07	-	-	-	6.25
JPLMW-21-3	1Q08	-	-	-	6.16
JPLMW-21-3	1Q09	-	-	-	6.1
JPLMW-21-3	1Q97	-	-	1.6	-
JPLMW-21-3	1Q98	-	-	1.4	-
JPLMW-21-3	2Q07	-	-	-	6.49
JPLMW-21-3	2Q09	-	-	1.2	-
JPLMW-21-3	2Q97	-	-	0.87	-
JPLMW-21-3	2Q99	-	-	-	7.28
JPLMW-21-3	3Q06	-	-	-	6.36
JPLMW-21-3	3Q07	-	-	-	6.27
JPLMW-21-3	3Q08	0	-	-	6.11
JPLMW-21-3	3Q96	-	-	0.83	-
JPLMW-21-3	4Q06	-	-13	-	-
JPLMW-21-3	4Q08	-	-	-	6.07
JPLMW-21-3	4Q96	-	-	0.54	-
JPLMW-21-4	1Q06	-	-78	-	6.54
JPLMW-21-4	1Q07	-	-	-	6
JPLMW-21-4	1Q97	-	-	0.91	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-21-4	2Q09	-	-	1.1	-
JPLMW-21-4	2Q99	-	-	-	7.28
JPLMW-21-4	3Q06	-	-	-	6.28
JPLMW-21-4	3Q07	-	-	-	6.13
JPLMW-21-4	3Q08	0	-	-	-
JPLMW-21-4	4Q08	0.39	-	-	-
JPLMW-21-5	1Q01	-	-	0.93	-
JPLMW-21-5	1Q06	-	-64	-	6.43
JPLMW-21-5	1Q97	-	-	2.7	-
JPLMW-21-5	1Q98	-	-	2.1	-
JPLMW-21-5	1Q99	-	-	1.6	-
JPLMW-21-5	2Q09	-	-	0.87	-
JPLMW-21-5	2Q97	-	-	1.5	-
JPLMW-21-5	2Q98	-	-	0.83	-
JPLMW-21-5	2Q99	-	-	0.83	-
JPLMW-21-5	2Q99	-	-	-	7.62
JPLMW-21-5	3Q08	0	-	-	-
JPLMW-21-5	3Q96	-	-	2.8	-
JPLMW-21-5	3Q97	-	-	1.14	-
JPLMW-21-5	3Q98	-	-	1.2	-
JPLMW-21-5	4Q08	0.45	-	-	-
JPLMW-21-5	4Q96	-	-	2.1	-
JPLMW-21-5	4Q98	-	-	2.4	-
JPLMW-22-1	1Q01	-	-	0.782	-
JPLMW-22-1	1Q02	-	-	0.73	-
JPLMW-22-1	1Q98	-	-	1.6	-
JPLMW-22-1	1Q99	-	-	1.9	-
JPLMW-22-1	2Q04	-	-	1.02	-
JPLMW-22-1	2Q07	-	-	-	6.13
JPLMW-22-1	2Q07	-	-	-	6.24
JPLMW-22-1	2Q08	-	-	-	6.03
JPLMW-22-1	2Q09	-	-	1.5	-
JPLMW-22-1	2Q98	-	-	2.3	-
JPLMW-22-1	2Q99	-	-	2.3	-
JPLMW-22-1	2Q99	-	-	-	6.79
JPLMW-22-1	3Q00	-	-	1.5	-
JPLMW-22-1	3Q06	-	-	-	6.21
JPLMW-22-1	4Q05	-	-	-	6.4
JPLMW-22-1	4Q06	-	-	-	6.54
JPLMW-22-1	4Q07	-	-	-	6.16
JPLMW-22-1	4Q08	0	-	-	6.28
JPLMW-22-1	4Q98	-	-	1.2	-
JPLMW-22-2	1Q09	-	-79	-	-
JPLMW-22-2	1Q98	-	-	1.3	-
JPLMW-22-2	1Q99	-	-	0.62	-
JPLMW-22-2	2Q07	-	-29	-	6.13
JPLMW-22-2	2Q07	-	-	-	6.1

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-22-2	2Q99	-	-	-	7.73
JPLMW-22-2	3Q08	0	-	-	-
JPLMW-22-2	3Q97	-	-	0.69	-
JPLMW-22-2	4Q05	-	-	-	6.31
JPLMW-22-2	4Q06	-	-	-	6.09
JPLMW-22-2	4Q08	0.87	-	-	6.22
JPLMW-22-3	1Q01	-	-	0.52	-
JPLMW-22-3	1Q09	-	-116	-	-
JPLMW-22-3	1Q98	-	-	0.63	-
JPLMW-22-3	2Q07	-	-2	-	-
JPLMW-22-3	2Q07	-	-39	-	-
JPLMW-22-3	2Q99	-	-	-	7.8
JPLMW-22-3	4Q08	0	-63	-	-
JPLMW-22-3	4Q98	-	-	0.52	-
JPLMW-22-4	1Q99	-	-	1.06	-
JPLMW-22-4	2Q07	-	-21	-	6.14
JPLMW-22-4	2Q98	-	-	0.92	-
JPLMW-22-4	2Q99	-	-	0.92	-
JPLMW-22-4	2Q99	-	-	-	7.67
JPLMW-22-4	4Q05	-	-	-	6.02
JPLMW-22-4	4Q08	0.3	-24	-	-
JPLMW-22-5	1Q01	-	-	2.73	-
JPLMW-22-5	2Q07	-	-97	-	-
JPLMW-22-5	2Q08	-	-114	-	-
JPLMW-22-5	2Q09	-	-189	-	-
JPLMW-22-5	3Q97	-	-	1.53	-
JPLMW-22-5	4Q07	-	-7	-	-
JPLMW-22-5	4Q08	0	-141	-	-
JPLMW-23-1	1Q01	-	-	2.45	-
JPLMW-23-1	1Q02	-	-	1.32	-
JPLMW-23-1	1Q06	1	-	-	-
JPLMW-23-1	1Q09	-	-	-	6.2
JPLMW-23-1	1Q98	-	-	1.7	-
JPLMW-23-1	1Q99	-	-	1.03	-
JPLMW-23-1	2Q04	-	-	0.988	-
JPLMW-23-1	2Q05	-	-	0.62	-
JPLMW-23-1	2Q07	-	-	-	6.17
JPLMW-23-1	2Q07	-	-	-	6.81
JPLMW-23-1	2Q08	-	-	0.645	-
JPLMW-23-1	2Q08	-	-	-	6.97
JPLMW-23-1	2Q09	-	-	1.2	-
JPLMW-23-1	2Q98	-	-	0.69	-
JPLMW-23-1	2Q99	-	-	0.69	-
JPLMW-23-1	2Q99	-	-	-	6.76
JPLMW-23-1	3Q00	-	-	0.92	-
JPLMW-23-1	3Q06	-	-	-	6.52
JPLMW-23-1	3Q07	-	-	-	6.57

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-23-1	3Q08	-	-	-	6.63
JPLMW-23-1	3Q98	-	-	1	-
JPLMW-23-1	4Q05	-	-	-	6.52
JPLMW-23-1	4Q06	-	-	-	6.18
JPLMW-23-1	4Q07	-	-	-	6.12
JPLMW-23-1	4Q08	-	-	-	7.81
JPLMW-23-1	4Q98	-	-	1.96	-
JPLMW-23-2	1Q09	-	-36	-	6.22
JPLMW-23-2	1Q99	-	-	0.54	-
JPLMW-23-2	2Q07	-	-40	-	-
JPLMW-23-2	2Q07	-	-	-	6.59
JPLMW-23-2	2Q08	-	-	-	6.54
JPLMW-23-2	2Q09	-	-	0.75	-
JPLMW-23-2	2Q99	-	-	-	7.22
JPLMW-23-2	3Q06	-	-	-	6.24
JPLMW-23-2	3Q07	-	-	-	6.26
JPLMW-23-2	3Q97	-	-	2	-
JPLMW-23-2	4Q05	-	-	-	6.52
JPLMW-23-2	4Q06	-	-	-	6
JPLMW-23-2	4Q08	-	-	-	7.34
JPLMW-23-2	4Q98	-	-	0.61	-
JPLMW-23-3	1Q01	-	-	0.803	-
JPLMW-23-3	1Q06	0.9	-	-	-
JPLMW-23-3	1Q09	-	-53	-	-
JPLMW-23-3	1Q99	-	-	0.55	-
JPLMW-23-3	2Q03	-	-	0.677	-
JPLMW-23-3	2Q04	-	-	1.48	-
JPLMW-23-3	2Q05	-	-	0.785	-
JPLMW-23-3	2Q07	-	-43	-	-
JPLMW-23-3	2Q07	-	-	-	6.54
JPLMW-23-3	2Q99	-	-	-	7.54
JPLMW-23-3	3Q07	-	-	-	6.09
JPLMW-23-3	3Q97	-	-	4.4	-
JPLMW-23-3	3Q98	-	-	0.6	-
JPLMW-23-3	4Q05	-	-	-	6.35
JPLMW-23-3	4Q08	-	-	-	7.44
JPLMW-23-4	1Q06	0.7	-	-	-
JPLMW-23-4	1Q09	-	-111	-	-
JPLMW-23-4	1Q98	-	-	0.55	-
JPLMW-23-4	2Q07	-	-	-	7.41
JPLMW-23-4	2Q08	-	-	-	6.2
JPLMW-23-4	2Q99	-	-	-	7.81
JPLMW-23-4	3Q97	-	-	0.57	-
JPLMW-23-4	4Q05	-	-	-	6.86
JPLMW-23-4	4Q06	-	-	-	6.4
JPLMW-23-4	4Q07	-	-	-	6.57
JPLMW-23-5	2Q07	-	-	-	6.18

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-23-5	2Q09	-	-67	-	-
JPLMW-23-5	4Q05	-	-	-	6.78
JPLMW-23-5	4Q08	-	-82	-	7.41
JPLMW-24-1	1Q05	-	-	-	6.32
JPLMW-24-1	1Q08	-	-	-	6.23
JPLMW-24-1	1Q09	-	-14	-	-
JPLMW-24-1	1Q98	-	-	0.53	-
JPLMW-24-1	1Q99	-	-	0.95	-
JPLMW-24-1	2Q05	-	-	0.508	-
JPLMW-24-1	2Q07	-	-46	-	6.39
JPLMW-24-1	2Q07	-	-	-	7.01
JPLMW-24-1	2Q08	-	-	2.38	-
JPLMW-24-1	2Q08	-	-	-	7.89
JPLMW-24-1	2Q09	-	-	0.57	-
JPLMW-24-1	2Q09	-	-	-	6.46
JPLMW-24-1	2Q98	-	-	0.67	-
JPLMW-24-1	2Q99	-	-	0.67	-
JPLMW-24-1	2Q99	-	-	-	7.2
JPLMW-24-1	3Q06	-	-	-	6.32
JPLMW-24-1	3Q08	-	-	-	6.19
JPLMW-24-1	4Q05	-	-	-	6.66
JPLMW-24-1	4Q06	-	-	-	6.48
JPLMW-24-1	4Q07	-	-	-	6.06
JPLMW-24-1	4Q08	-	-7	-	6.32
JPLMW-24-2	1Q05	-	-	-	6.16
JPLMW-24-2	1Q09	-	-127	-	-
JPLMW-24-2	1Q98	-	-	0.96	-
JPLMW-24-2	1Q99	-	-	1.1	-
JPLMW-24-2	2Q07	-	-62	-	-
JPLMW-24-2	2Q07	-	-	-	6.86
JPLMW-24-2	2Q08	-	-23	-	-
JPLMW-24-2	2Q09	-	-	-	6.37
JPLMW-24-2	2Q98	-	-	0.86	-
JPLMW-24-2	2Q99	-	-	0.86	-
JPLMW-24-2	3Q00	-	-	0.85	-
JPLMW-24-2	3Q06	-	-24	-	6.02
JPLMW-24-2	3Q08	-	-5	-	-
JPLMW-24-2	3Q97	-	-	0.58	-
JPLMW-24-2	3Q98	-	-	0.84	-
JPLMW-24-2	4Q05	-	-	-	6.4
JPLMW-24-2	4Q06	-	-	-	6.31
JPLMW-24-2	4Q08	0	-85	-	6.29
JPLMW-24-2	4Q98	-	-	0.74	-
JPLMW-24-3	1Q02	-	-	1.74	-
JPLMW-24-3	1Q09	-	-241	-	-
JPLMW-24-3	1Q98	-	-	1.8	-
JPLMW-24-3	1Q99	-	-	5.2	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-24-3	2Q07	-	-79	-	-
JPLMW-24-3	2Q07	-	-	-	6.83
JPLMW-24-3	2Q08	-	-	1.76	-
JPLMW-24-3	2Q08	-	-270	-	-
JPLMW-24-3	2Q09	-	-	-	6.3
JPLMW-24-3	2Q98	-	-	1.3	-
JPLMW-24-3	2Q99	-	-	1.3	-
JPLMW-24-3	2Q99	-	-	-	7.5
JPLMW-24-3	3Q00	-	-	0.5	-
JPLMW-24-3	3Q97	-	-	0.61	-
JPLMW-24-3	3Q98	-	-	1.7	-
JPLMW-24-3	4Q05	-	-	-	6.3
JPLMW-24-3	4Q06	-	-	-	6.26
JPLMW-24-3	4Q07	-	-	-	6.01
JPLMW-24-3	4Q08	0	-102	-	6.23
JPLMW-24-3	4Q98	-	-	1.5	-
JPLMW-24-4	1Q09	-	-180	-	-
JPLMW-24-4	1Q99	-	-	0.53	-
JPLMW-24-4	2Q07	-	-62	-	-
JPLMW-24-4	2Q07	-	-	-	6.41
JPLMW-24-4	2Q08	-	-124	-	7.85
JPLMW-24-4	2Q09	-	-130	-	-
JPLMW-24-4	2Q98	-	-	1	-
JPLMW-24-4	2Q99	-	-	1	-
JPLMW-24-4	3Q08	-	-120	-	-
JPLMW-24-4	3Q98	-	-	0.57	-
JPLMW-24-4	4Q05	-	-	-	6.14
JPLMW-24-4	4Q06	-	-	-	6.12
JPLMW-24-4	4Q08	-	-107	-	-
JPLMW-24-5	1Q01	-	-	0.587	-
JPLMW-24-5	1Q98	-	-	0.63	-
JPLMW-24-5	1Q99	-	-	0.75	-
JPLMW-24-5	2Q08	-	-	-	6.34
JPLMW-24-5	2Q99	-	-	-	7.55
JPLMW-24-5	3Q97	-	-	4.33	-
JPLMW-24-5	4Q08	0	-	-	-
JPLMW-25-1	1Q06	1	-	-	-
JPLMW-25-1	1Q08	-	-	-	6.35
JPLMW-25-1	1Q09	-	-43	-	-
JPLMW-25-1	2Q07	0	-	-	6.4
JPLMW-25-1	2Q08	-	-	0.821	-
JPLMW-25-1	2Q08	-	-	-	7.43
JPLMW-25-1	2Q09	-	-	1.2	-
JPLMW-25-1	3Q06	-	-	-	7.35
JPLMW-25-1	3Q07	-	-	-	6.42
JPLMW-25-1	3Q07	-	-	-	6.26
JPLMW-25-1	3Q08	-	-	-	6.3

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-25-1	4Q05	-	-	-	6.5
JPLMW-25-1	4Q06	-	-	-	6.75
JPLMW-25-1	4Q08	-	-	-	7.75
JPLMW-25-2	1Q05	-	-	1.49	-
JPLMW-25-2	1Q06	-	-	-	6.13
JPLMW-25-2	1Q09	-	-82	-	6
JPLMW-25-2	2Q05	-	-	1.43	-
JPLMW-25-2	2Q07	-	-40	-	6.1
JPLMW-25-2	2Q08	-	-	-	7.39
JPLMW-25-2	3Q06	-	-4	-	7.52
JPLMW-25-2	3Q07	-	-	-	6.09
JPLMW-25-2	3Q08	-	-	-	6.16
JPLMW-25-2	4Q05	-	-	-	6.38
JPLMW-25-2	4Q06	-	-	-	6.44
JPLMW-25-2	4Q08	-	-	-	7.83
JPLMW-25-3	1Q09	-	-92	-	-
JPLMW-25-3	2Q07	-	-32	-	-
JPLMW-25-3	2Q08	-	-	-	7.11
JPLMW-25-3	3Q06	-	-18	-	7.43
JPLMW-25-3	4Q05	-	-	-	6.03
JPLMW-25-3	4Q08	-	-	-	7.14
JPLMW-25-4	1Q09	-	-90	-	-
JPLMW-25-4	2Q07	-	-22	-	-
JPLMW-25-4	2Q08	-	-	-	6.7
JPLMW-25-4	3Q06	-	-22	-	7.44
JPLMW-25-4	4Q08	-	-	-	6.73
JPLMW-25-5	1Q05	-	-	0.62	-
JPLMW-25-5	1Q06	-	-51	-	-
JPLMW-25-5	1Q08	-	-54	-	-
JPLMW-25-5	1Q09	-	-135	-	-
JPLMW-25-5	2Q07	-	-94	-	-
JPLMW-25-5	2Q08	-	-109	-	6.52
JPLMW-25-5	3Q06	-	-45	-	7.34
JPLMW-25-5	3Q08	0	-34	-	-
JPLMW-25-5	4Q08	-	-97	-	6.43
JPLMW-26-1	1Q08	-	-	-	6.64
JPLMW-26-1	1Q09	-	-13	-	-
JPLMW-26-1	2Q07	0	-	-	-
JPLMW-26-1	2Q09	-	-	1.3	-
JPLMW-26-1	3Q06	-	-	-	6.35
JPLMW-26-1	3Q07	-	-	-	6.72
JPLMW-26-1	3Q08	-	-	-	6.77
JPLMW-26-1	4Q05	-	-	-	6.39
JPLMW-26-1	4Q08	-	-	-	6.99
JPLMW-26-2	1Q08	-	-	-	6.58
JPLMW-26-2	1Q09	-	-39	-	-
JPLMW-26-2	2Q05	-	-	0.59	-

**Summary of Historical Ground Water Quality Data from JPL Monitoring Wells
 Favorable to Perchlorate Biodegradation**

Well Name and Zone	Sample Quarter and Year	Dissolved Oxygen [mg/L]	Oxidation Reduction Potential [mV]	Total Iron [mg/L]	pH [pH units]
JPLMW-26-2	2Q07	0	-	-	-
JPLMW-26-2	2Q09	-	-	4.6	-
JPLMW-26-2	3Q07	-	-	-	6.49
JPLMW-26-2	3Q08	-	-	-	6.58

NC = Not Collected

Source: NASA Quarterly Monitoring Reports (1996 to 2009).

**Summary of Water Quality Data from the
 Colorado River Water Conveyance System**

Date	Perchlorate Concentrations [µg/L]		
	Lake Havasu	San Jacinto Tunnel West Portal	Lake Mathews Outlet
1-Jun-97	9	9	8
1-Aug-97	NC	7	9
6-Oct-97	5	4	10
3-Nov-97	NC	6	11
1-Dec-97	7	8	12
5-Jan-98	5	5	13
3-Feb-98	6	4	14
2-Mar-98	NC	7	15
6-Apr-98	6	6	6
4-May-98	9	7	ND
1-Jun-98	6	7	4
6-Jul-98	NC	8	5
3-Aug-98	5	7	6
8-Sep-98	5	7	7
5-Oct-98	6	6	6
2-Nov-98	6	5	5
7-Dec-98	6	7	6
4-Jan-99	5	6	6
1-Feb-99	7	6	7
1-Mar-99	8	6	8
5-Apr-99	8	7	6
3-May-99	6	8	6
7-Jun-99	5	6	4
6-Jul-99	8	7	7
2-Aug-99	7	7	7
7-Sep-99	6	7	7
4-Oct-99	5	5	5
1-Nov-99	6	6	6
6-Dec-99	5	5	4
3-Jan-00	6	6	5
7-Feb-00	6	5	4
6-Mar-00	7	6	6
3-Apr-00	7	6	5
1-May-00	7	6	5
5-Jun-00	7	7	5

**Summary of Water Quality Data from the
 Colorado River Water Conveyance System**

Date	Perchlorate Concentrations [µg/L]		
	Lake Havasu	San Jacinto Tunnel West Portal	Lake Mathews Outlet
3-Jul-00	8	8	7
7-Aug-00	6	6	6
5-Sep-00	7	6	6
2-Oct-00	5	5	5
6-Nov-00	6	5	6
4-Dec-00	5	5	5
10-Jan-01	5	4	5
5-Feb-01	7	6	5
5-Mar-01	6	6	5
2-Apr-01	7	6	5
7-May-01	7	7	7
4-Jun-01	7	5	6
2-Jul-01	7	6	5
6-Aug-01	6	6	6
4-Sep-01	5	5	5
2-Oct-01	7	6	6
5-Nov-01	6	5	5
3-Dec-01	6	NA	5
1-Jan-02	4	4	6
1-Feb-02	5	5	5
2-Mar-02	6	5	ND
2-Apr-02	5	6	ND
2-May-02	7	7	6
2-Jun-02	6	7	6
2-Jul-02	6	5	5
2-Aug-02	6	5	4
2-Sep-02	6	6	6
2-Oct-02	5	ND	5
2-Nov-02	4	ND	4
2-Dec-02	4.3	4.5	4.1
3-Jan-03	ND	ND	ND
3-Feb-03	4.5	ND	ND
3-Mar-03	5.5	4.4	ND
3-Apr-03	5.7	4.5	ND
3-May-03	5.3	5.4	4.3

**Summary of Water Quality Data from the
 Colorado River Water Conveyance System**

Date	Perchlorate Concentrations [µg/L]		
	Lake Havasu	San Jacinto Tunnel West Portal	Lake Mathews Outlet
3-Jun-03	5.6	5.1	5.1
3-Jul-03	5.4	5.3	ND
3-Aug-03	5.1	5.4	4.5
3-Sep-03	4.4	4.2	4.1
1-Oct-03	4.2	3.5	3.7
1-Nov-03	3.8	3.6	3
1-Dec-03	3.6	3.5	3
1-Jan-04	3.5	2.4	2.2
1-Feb-04	3.9	3.9	3.1
1-Mar-04	5	4.5	2.8
1-Apr-04	5.6	5.8	3
1-May-04	4.6	4.7	2.8
1-Jun-04	3.7	3.9	3.6
1-Jul-04	3.2	3.6	3.6
1-Aug-04	3.4	3.4	3.1
1-Sep-04	3.1	3	3.2
1-Oct-04	2.5	2.5	2.5
1-Nov-04	2.2	2.3	2.4
1-Dec-04	2.7	ND	2.7
1-Jan-05	2.2	2.5	2.1
1-Feb-05	2.2	2.1	ND
1-Mar-05	ND	ND	ND
1-Apr-05	2.7	ND	2.1
1-May-05	3.3	3	2.2
1-Jun-05	3.1	3.4	ND
1-Jul-05	3	2.8	ND
1-Aug-05	2.6	2.6	ND
1-Sep-05	2.3	2.1	ND
1-Oct-05	ND	ND	2
1-Nov-05	2	ND	ND
1-Dec-05	ND	ND	ND
1-Jan-06	ND	ND	ND
1-Feb-06	ND	ND	ND
1-Mar-06	ND	ND	ND
1-Apr-06	2.3	ND	ND

**Summary of Water Quality Data from the
 Colorado River Water Conveyance System**

Date	Perchlorate Concentrations [µg/L]		
	Lake Havasu	San Jacinto Tunnel West Portal	Lake Mathews Outlet
1-May-06	2.2	2.2	ND
1-Jun-06	ND	ND	ND
1-Jul-06	ND	ND	ND
1-Aug-06	ND	ND	ND
1-Sep-06	ND	ND	ND
1-Oct-06	1.7*	1.8*	1.9*
1-Nov-06	ND	ND	ND
1-Dec-06	ND	ND	ND
1-Jan-07	2.1*	1.6*	1.4*
7-Apr-07	2.6*	2.1*	1.4*
7-Jul-07	2.0*	2.2*	1.3*
7-Oct-07	1.8*	1.6*	1.5*
1-Jan-08	1.6*	1.5*	1.3*
1-Apr-08	2.3*	2.2*	1.5*
1-Jul-08	1.9*	2.1*	1.7*
8-Oct-08	1.3*	1.3*	1.5*
6-Jan-09	1.2*	1.2*	1.0*

Source: MWD (2009)

µg/L = micrograms per liter

ND = Not detected.

NC = Not collected

NA = Not analyzed

* Results by USEPA Method 331 or 332. All other results are by USEPA method 314.0. USEPA method 314.0 minimum reporting level was 4 ppb from 1997 to August 2003, unless otherwise indicated. Analytical method was improved to be capable of measuring 2 ppb as of September 2003.