Orange County Water District

Technical Memorandum

Date: October 12, 2020

To: NWRI GWRS Independent Advisory Panel

From: Li Li, Senior Hydrogeologist
Jason Dadakis, P.G., C.HG., Executive Director of Water Quality & Technical Resources

Subject: Burris & Santiago Basins: GWRS Recycled Water Retention Time Modeling and Buffer Area Analysis

1 Introduction

The Orange County Water District (OCWD) is proposing to recharge recycled water into Burris, Riverview, and Santiago Basins and Santiago Creek (Burris/Santiago system), as shown in Figure 1. The Burris/Santiago system has been used primarily for Santa Ana River (SAR) storm water capture, as well as to dewater Santiago Basins during non-storm seasons. With the Groundwater Replenishment System Final Expansion (GWRSFE) project, additional recharge capacity of GWRS water is desired beyond the existing facilities (Talbert Barrier injection, Mid-Basin Injection; Kraemer, Miller, Miraloma, and La Palma Basins) permitted to recharge purified recycled water. A new GWRS Pipeline outlet at Burris Basin will be able to introduce recycled water into the Burris/Santiago system.

The purpose of this Technical Memorandum is to summarize the groundwater modeling results of subsurface retention times for the purposes of establishing the required primary and secondary buffer areas within which potable extraction is prohibited.

2 Model Description

The OCWD basin-wide groundwater flow model (Basin Model) was used for this evaluation. The Basin Model was developed, calibrated, and utilized by OCWD to manage the Orange County groundwater basin (basin). The Basin Model has proven to be a good representation of actual basin groundwater levels over the years.

The Basin Model is a transient numerical groundwater flow model using the widely-accepted United States Geological Survey (USGS) MODFLOW (Harbaugh and McDonald, 1996) code. The Basin Model accounts for spatial variations in aquifer properties as well as monthly variations in the volume of applied recharge, groundwater production, and boundary conditions along the edges of the model domain. An overview of the OCWD Basin Model was presented to the Panel in 2013 via a technical memorandum (Appendix B) and a meeting presentation (Appendix A) which provide additional background information. Additional information regarding the basin hydrogeology and construction of the Basin Model can also be found in Section 3 of the OCWD Groundwater Management Plan 2015 Update. (http://www.ocwd.com/media/3622/groundwatermanagementplan2015update_20150624.pdf)

In conjunction with the MODFLOW-based Basin Model, the USGS particle tracking code MODPATH (Pollock, 1994) can be used to visualize groundwater flow paths and estimate groundwater travel times. OCWD has used MODPATH for both the California Environmental Quality Act (CEQA) evaluations, as well as for DDW approved subsurface retention time assessments required under California Title 22 §60320.200 General Requirements, §60320.208 Pathogenic Microorganism Control, and §60320.224 Response Retention Time (RRT) for the Talbert Barrier, Kraemer Basin, Miller Basin, Miraloma Basin, La Palma Basin, and the Mid-Basin Injection (MBI) project.

3 Model Assumptions

The simulation includes existing facilities, including the four additional Mid-Basin injection wells in Centennial Park, GWRSFE, and a new GWRS Pipeline outlet to Burris Basin, from which GWRS water can be delivered to Riverview Basin, Santiago Basins and Santiago Creek.

Detailed model assumptions for this predictive simulation are listed below:

1. The simulation was carried out for a 9-year simulation period. This was equivalent to the length of the original 1990-1999 transient model calibration period. Also, 9 years was found to be sufficiently long for the recharge-induced water level changes to stabilize.
2. Accumulated overdraft (volume of empty storage below a full basin condition) was maintained at approximately 200,000 AF over the simulation duration; this represents a higher basin storage condition under which the diversion of GWRS flows for recharge to the Burris/Santiago system is most likely to occur.
3. Projected average hydrology condition was assumed: 52,000 AFY SAR base flow recharge; 51,600 AFY SAR storm flow recharge (Wildermuth, 2014);

   Unmeasured or incidental recharge was subdivided amongst the various components such as areal recharge from precipitation, recharge along the mountain-front boundaries of the basin, and winter unmeasured storm flow recharge in the Santa Ana River and Santiago Creek. These components were kept the same throughout the 9-year simulation.

   Actual measured monthly recharge volumes from SAR flows and imported water were adjusted and assigned to each OCWD recharge facility in the Anaheim and Orange Forebay areas. Monthly recharge adjustments were based on the statistical monthly water supply assumptions, but all recharge facilities were kept within their respective maximum operational capacities. Burris, Riverview, Santiago Basins and Santiago Creek were assumed to be recharged at or above the 90th percentile of their historical monthly recharge rate over the last 10 years for all months as the worst-case scenario (i.e., causing the highest anticipated groundwater velocities). GWRS water was recharged into currently permitted basins, i.e., Miraloma, La Palma, Kraemer, and Miller Basins, as well as Burris, Riverview, Santiago Basins, and Santiago Creek above Hart Park. All basins mentioned above except Miraloma and La Palma basins can also recharge water from other sources other than GWRS. Miraloma and La Palma basins are dedicated to GWRS water recharge only.

4. The simulation used actual WY 2012-13 (July - June) groundwater production as a starting point. During WY 2012-13, there was no coastal pumping transfer or other large-scale pumping shifts. Therefore, it was a good representation of the overall pumping distribution reflecting actual seasonal demand in different areas of the basin. Only existing active production wells were simulated (no planned/proposed/future wells). Minor adjustments were made to include new production wells installed after 2013 and eliminate wells that were permanently removed from service after 2013 or wells that will not be used in the future. Within the project area, production wells O-27 and IRWD-OPA1 were added, and SID-4 was removed from the simulation. The production data was then repeated for each of the nine years of the simulation.
5. The simulation is balanced, i.e., total water into the groundwater basin equals total water out. Basin storage was kept relatively constant.

   The annual production amount was adjusted to maintain a balanced (negligible basin storage change) condition. The adjustments were only applied to large system production wells excluding the water quality improvement wells. There are several wells in City of Tustin, City of Irvine, and Mesa Water District that receive treatment as a part of water quality projects (e.g., removal of salts, nitrates, and amber tint). The production amounts from these wells are limited by well capacities, treatment plant capacities, and/or by agreements between the participating agencies and OCWD. Therefore, typical production rates were used for these wells and kept unchanged during the simulation. Production from small system or domestic wells, or irrigation wells, was also kept unchanged at a selected typical rate as those in WY 2012-13.

   During each production adjustment, total water demand from each producer was considered as the upper pumping limit. Pumping capacity for existing production wells was not considered a limitation for simulated production. The final adjusted total annual basin production is 352,000 AF.
6. Actual recharge at the Talbert Barrier during WY 2011-12 (July - June) was used. In WY 2011-12, the Talbert injection rates (20,736 AF) were considered to be representative of typical injection operations under a low accumulated overdraft (“high basin”) condition and were sufficient to maintain protective elevations; these conditions represent the periods when the likelihood of using the Burris outlet is greatest. The basin accumulated overdraft in WY 2011-12 was approximately 179,000 AF. This injection condition was repeated for the nine-year duration of the simulation.
7. 65,000 AFY Metropolitan Water District (MWD) imported water for Forebay recharge.
8. GWRSFE capacity of 134,000 AFY distributed as follows:
   a. Talbert Barrier: 20,736 AFY
   b. Mid-Basin injection wells (MBI-1 through MBI-5): 8,400 AFY
   c. Kraemer/Miller/Miraloma/La Palma/Burris/Riverview/Santiago Basins/Santiago Creek above Hart Park: 104,864 AFY (not including MWD & SAR water).

9. Modeled monthly recharge rates for the Burris/Santiago system, including GWRS, SAR and MWD water, are at or above the 90th percentile of their historical monthly recharge rates over the last 10 years. The resulting annual total recharge for the Burris/Santiago system as a whole was at or slightly above the annual historical high over the last 10 years since no cleaning downtime was assumed in this evaluation. The modeled annual total recharge for each component of the Burris/Santiago system were as follows, with the historical maximum recharge over the last 10 years listed in parentheses:
    a. Burris Basin: 17,136 AF (13,523 AF)
    b. Riverview Basin: 3,252 AF (3,152 AF)
    c. Santiago Basins: 57,000 AF (40,206 AF)
    d. Santiago Creek: 6,480 AF (4,628 AF)

4 Modeling Results

4.1 Current Buffer Area Requirements

Current State of California’s regulations regarding Groundwater Replenishment Reuse Projects (GRRPs) requires the establishment of both primary and secondary boundaries (i.e., buffer areas); the primary boundary is the traditional area in which the construction of new drinking water wells is restricted, while the secondary boundary is a zone of potential controlled potable well construction, within which the operation of future new wells may extend which could subsequently affect the primary boundary, thereby requiring further study and potential mitigating activities prior to potable well construction. Monitoring wells along the flow path are also required. The specific requirements for these boundaries are found in the state’s Title 22 regulations §60320.200 General Requirements, §60320.208 Pathogenic Microorganism Control, and §60320.224 Response Retention Time (RRT).

An eight-month primary and a ten-month secondary boundary have been developed for this evaluation using the OCWD Basin Model, which correspond to 4- and 5-log virus removal, respectively, via subsurface retention using the 50% safety factor for numerical models stated in the state’s Title 22 Table 60320.208.

4.2 Modeling Approach

The particle tracking code MODPATH was used in conjunction with MODFLOW to estimate the underground retention time. An effective porosity of 0.25 was assigned to aquifer layers; this value represents the lower end of the 0.25 – 0.40 range for unconsolidated sand and gravel deposits comprising the study area aquifers (Freeze and Cherry, 1979: Table 2.4). Lower values of effective porosity result in greater groundwater velocities when hydraulic conductivity and gradient are held constant (i.e., greater velocity is required move the same volume of water through a lower porosity medium).

In order to estimate the shortest residence time to any active drinking water wells in the vicinity and the farthest estimated extent of the eight-month and ten-month buffer areas, high recharge rates were used as described in the model assumptions listed above. Particles were assigned laterally along the perimeter of each of the targeted recharged facilities within the Burris/Santiago system, and vertically at the bottom of each recharge facility for relatively shallow basins, i.e., Burris Basin, Riverview Basin, and Santiago Creek within the corresponding model layer. Recharge in Santiago Basins occurs primarily through the relatively deep side walls at elevations between 220 and 285 feet above mean sea level (msl) instead of the bottom; therefore, the particles were assigned vertically at three different depths, i.e., the upper portion, the mid-point, and the lower portion of the model layer, which represent the top, middle, and bottom elevations where recharge occurs, along the perimeter of these basins. This comprehensive particle placement is expected to simulate all possible flow paths in the Santiago Basins Area.

4.3 Particle Tracking Results

Burris/Riverview Basins

The result of the MODPATH simulation (Figure 2) at Burris and Riverview Basins shows that the flow paths are consistent with the groundwater gradient and hydrogeologic conditions; groundwater flows primarily westward in the Shallow Aquifer and to the south/southwest in the Principal Aquifer. Recharge in the northern half of Burris Basin migrated to the northwest within the Shallow Aquifer due to a mergence zone where the intervening aquitard between the Shallow and Principal aquifers is largely absent, thus causing the particles reaching this area to move vertically downward from the Shallow Aquifer to the Principal Aquifer.

There are several production and/or extraction wells down-gradient from Burris/Riverview Basins, including City of Anaheim production well A-46 and Pacific Scientific (PSCI) remediation wells. A-46 is screened in the Principal Aquifer. As shown in Figure 2, particles reaching A-46 in the Principal Aquifer originated from recharge into the northern half of Burris Basin and followed the flow path described above, i.e., traveling northwest within the Shallow Aquifer and then migrating vertically downward in the aforementioned mergence zone to the Principal Aquifer and then flowing south/southwest to A-46 in approximately 2,256 to 2,585 days. The PSCI remediation wells are all screened in the Shallow Aquifer. Particles travelled from Burris/Riverview Basins towards the west and reached these wells in approximately 496 to 509 days.

Two existing OCWD monitoring wells are proposed to fulfill the state’s GRRP monitoring requirements (CA Title 22 §60320.226). Schematic cross-sections showing local geology, well locations and well screens (Figure 3) are used to demonstrate that well OCWD-BP5 in the Shallow Aquifer and well AM-27 in the Principal Aquifer are located along the flow path towards production well A-46.

Santiago Basins

The result of the MODPATH simulation (Figure 4) at Santiago Basins shows a somewhat complicated flow pattern, but overall the flow paths are consistent with the known groundwater gradient and hydrogeologic conditions; groundwater flows towards the west and southwest in both the Shallow and Principal aquifers.

Santiago Basins are deep with a maximum depth of approximately 145 feet below the surrounding ground surface; recharge appears to be predominantly through the side walls from elevation 220 to 285 feet msl rather than through the bottom of the Basins. Therefore, as discussed in Section 4.2, the particles were placed at three different depths in model layer 1, corresponding to the top, middle, and bottom of the depth interval where most recharge occurs in these basins. Currently only the lower two basins are used for recharge operations. Only when water levels in the lower two basins reach a certain level, the northern-most basin will receive the overflow, which is very infrequent. Therefore, particles were not placed in the upper basin for this evaluation. With the lack of an extensive aquitard between the Shallow and Principal aquifers beneath and east of the upper two basins in Figure 4, a number of particles originating in this area migrated vertically down into the Principal Aquifer in a short time. Particle flow paths changed depending on the depth from which they originated. In general, the majority of the particles on the west side of the Basins remained in the Shallow Aquifer for a prolonged time and distance due to the modeled aquitard between the Shallow and Principal aquifers in this more westerly region. There were only a few particles released from the deeper part of model layer 1 on the west side of the Basins that migrated vertically downward to the Principal Aquifer.

There are eight production wells to the west and southwest in the immediate proximity of Santiago Basins: three Serrano Water District (formerly Serrano Irrigation District) wells SID-3, SID-4 and SWD-5; Irvine Ranch Water District well IRWD-OPA1; and City of Orange wells O-23, O-24, O-25, and O-27. There are two East Orange County Water District production wells to the south of Santiago Basins: EOCW-E and EOCW-W. All ten production wells are screened in the Principal Aquifer.

Located to the west-northwest of the Santiago Basins, well SID-4 has not been in operation regularly since 2011, and Serrano Water District staff have confirmed there is no intent to return this well to regular operation and that it will be properly destroyed in the future. Therefore, this well was treated as inactive in this simulation. Located farther west are Serrano wells SID-3 and SWD-5. The majority of the particles released from Santiago Basins travelled toward the west in the Shallow Aquifer and bypassed SID-3 and SWD-5, not migrating vertically down to the Principal Aquifer. However, a few particles released from the deeper part of model layer 1 at the northern end of the Santiago Basins migrated vertically down to the Principal Aquifer beneath the Basins after travelling in the Shallow Aquifer for only a short distance, and eventually travelled to the west arriving at SWD-5 in 568 to 1,757 days and SID-3 in 1,057 to 1,741 days (Figure 4).

Well IRWD-OPA1 is located less than 600 feet southwest of Santiago Basins, and screened from 390 to 750 feet below ground surface within the Principal Aquifer. While currently inactive, this well is expected to return to operation in the future. Therefore, IRWD-OPA1 was simulated as active in this simulation with approximately 930 AF annual production (scaled up from annual production of 833 AF (July 2015 to June 2016)). Particles originating from the south end of the basins bypassed this well above the screened interval, remaining in the Shallow Aquifer, while some particles released from the northeast and east parts of the basins migrated down to the Principal Aquifer in a short time due to the lack of an intervening aquitard between the Shallow and Principal aquifers in this area. These particles subsequently travelled southward and arrived at IRWD-OPA1 in approximately 723 to 2,090 days. Well O-24, west of IRWD-OPA1, captured a few particles released from the northern part of the Basins in 2,298 to 3,155 days. One particle released from the east side of the lower basin arrived at well O-23, southwest of IRWD-OPA1, in the Principal Aquifer in 2,050 days. Well O-27 is located farther to the southwest from the Basins. Two particles released from the deeper portion of model layer 1 at the south end of the Basins travelled great distance in the Shallow Aquifer before migrating down to the Principal Aquifer and arrived at O-27 in 2,440 to 3,262 days. Well O-25 is located approximately 700 feet east of O-27 and was not impacted.

A few particles released from the north and east end of the Basins travelled slightly eastward and dove down into the Principal Aquifer and continued to travel southward, finally reaching production wells EOCW-E and EOCW-W in approximately 2,769 to 2,789 days, while some particles released from the south and east sides of the Basins reached these two wells in 799 to 1,433 days.

Particles released from Santiago Basins also arrived at two other production wells, ANGE-O and ABBY-A, which are both screened in the Shallow Aquifer and located west of Santiago Basins, in 1,337-1,407 days and 2,949-2,998 days, respectively.

Particle traces to the southwest away from Santiago Basins are also shown schematically in cross-section view (Figure 5).

Santiago Creek

The particle tracking results (Figure 4) show that groundwater flows to the east and southeast in the Shallow Aquifer in the vicinity of the creek. Particles were released from the bottom of the shallow Santiago Creek, and remained in the Shallow Aquifer for the duration of the 9-year model simulation, and no production wells in the area, screened in either the Shallow or Principal Aquifer, were impacted.

A summary of the simulated arrival time to the production wells discussed above is presented in Table 1. The production well with earliest arrival downgradient of each recharge area is highlighted in bold.

Table 1: Simulated Arrival Time at Selected Production Wells

Particle Release Area	Production Well	Aquifer	Simulated Arrival Time (days)
Burris/Riverview Basins	PSCI wells	Shallow	496-509
	A-46	**Principal**	**2,156-2,585**
Santiago Basins/Creek	ABBY-A	Shallow	2,949-2,998
	ANGE-O	Shallow	1,337-1,407
	SWD-5	**Principal**	**568-1,757**
	IRWD-OPA1	Principal	723-2,090
	EOCW-W	Principal	799-2,789
	EOCW-E	Principal	799-2,789
	SID-3	Principal	1,057-1,741

Particle Release Area	Production Well	Aquifer	Simulated Arrival Time (days)
	O-23	Principal	2,050
	O-24	Principal	2,298-3,155
	O-27	Principal	2,440-3,262

With SWD-5 determined to be the nearest and/or fastest travel time downgradient drinking water well from the Santiago Basins/Creek complex (Table 1), existing OCWD multiport monitoring well SCS-2 (Figure 6) is proposed to be the first of two required downgradient monitoring wells under the state's GRRP monitoring requirements (CA Title 22 §60320.226). With SCS-2 located between Santiago Basins and SWD-5, current MODPATH monitoring predicts a 30-day travel time to SCS-2 measurement port #1 (MP1) in the Shallow Aquifer and 210-day travel time to SCS-2 measurement port MP5 within the Principal Aquifer. The second required monitoring well would be newly constructed along the flow path from Santiago Basins between SCS-2 and SWD-5. Particle traces to well SWD-5 from Santiago Basins are shown schematically in cross-section view (Figure 7).

4.4 Buffer Areas

Primary and secondary buffer areas were generated using the model-derived particle locations in eight and ten months, respectively, after they were released, as shown in Figure 8 and Figure 9. From these figures, there are no existing production wells within either the primary or secondary buffer areas.

5 References

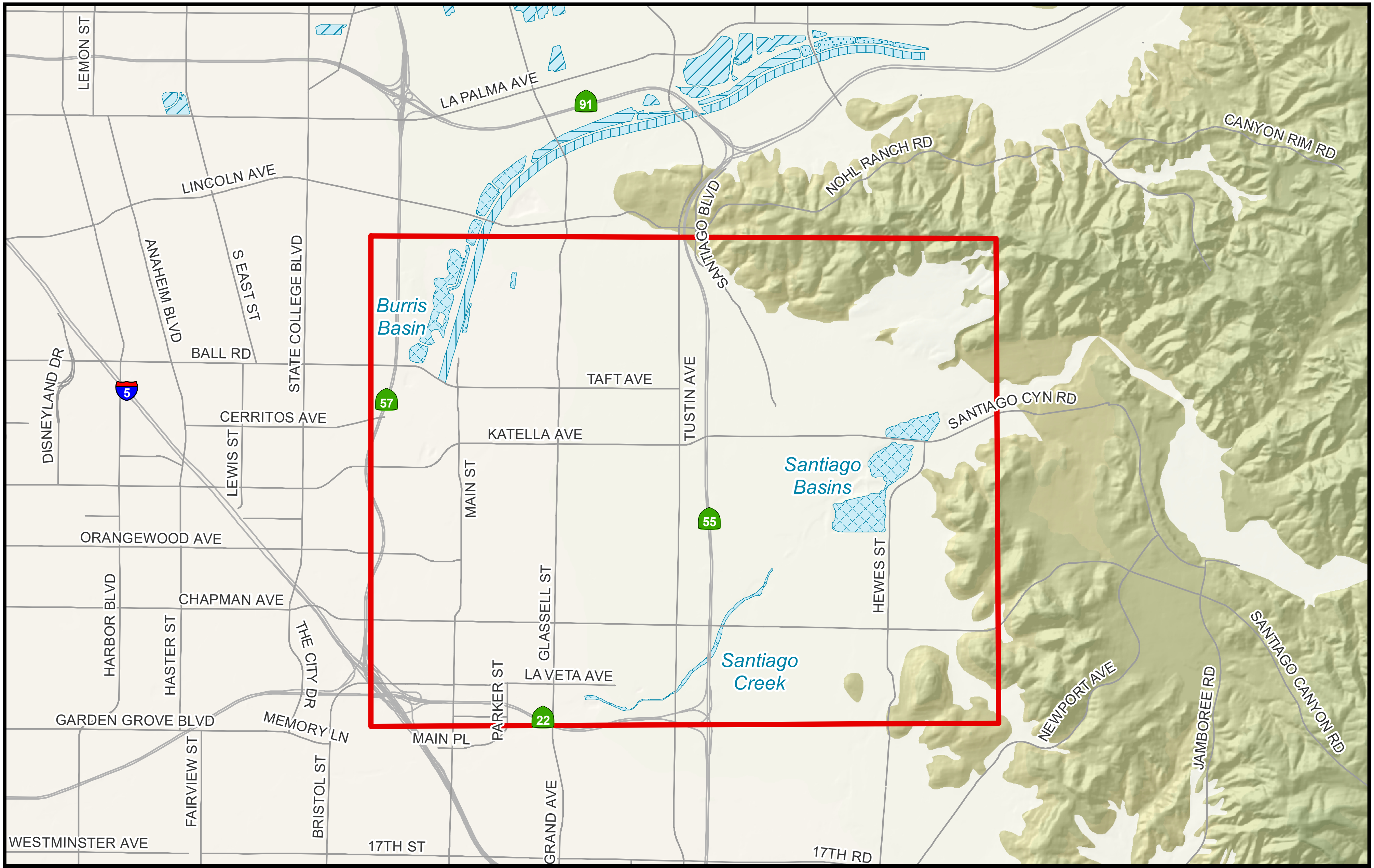
Freeze, R.A. and Cherry, J.A., 1979. *Groundwater* (No. 629.1 F7).

Harbaugh, A.W., and McDonald, M.G., 1996. User's Documentation for MODFLOW-96, An Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey, Open-File Report 96-485.

Pollock, D.W., 1994. *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U. S. Geological Survey finite difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464.*

Wildermuth Environmental Inc., 2014. Prado Basin Daily Discharge Estimates for 2021 and 2071 Using the Wasteload Allocation Model.

Figures



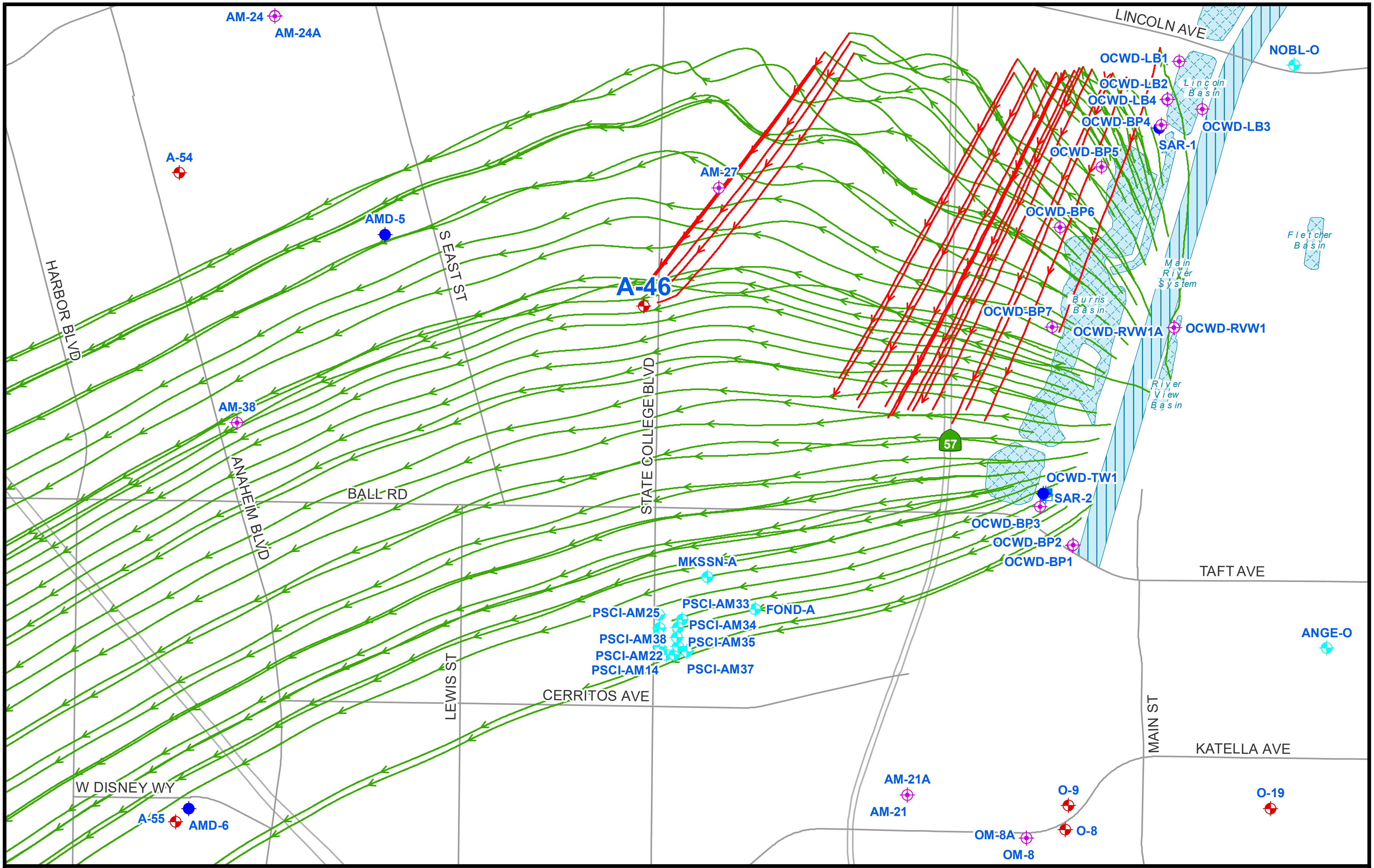
🟥 Site

Primary Streets/ Freeway

Figure 1

Project Area

4990



Particle Trace

🟩	Shallow Aquifer
🟥	Principal Aquifer

⊕	Active Large-System Production Well
⊕	Other Active Production Well
⊕	Monitoring Well
●	Multiport Monitoring Well

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W E
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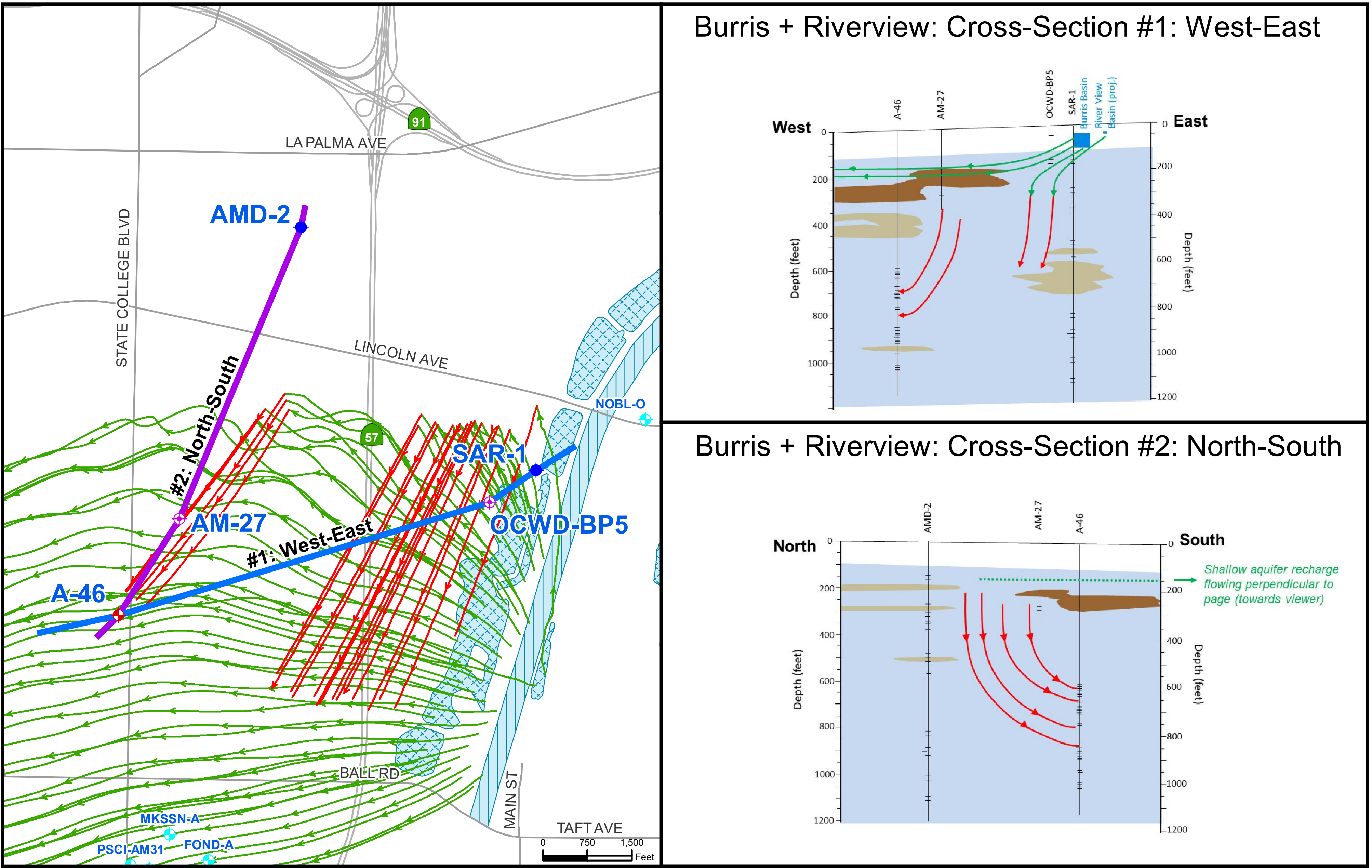
Figure 2

Burris/Riverview Basins Particle Trace

0 1,800 3,600 Feet

4990



Particle Trace

- Shallow Aquifer
- Principal Aquifer

Cross-Section

- #1: West-East
- #2: North-South

- Active Large-System Production Well
- Other Active Production Well
- Monitoring Well
- Multiport Monitoring Well

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Figure 3

Schematic Geologic Cross-Sections at Burris/Riverview Basins

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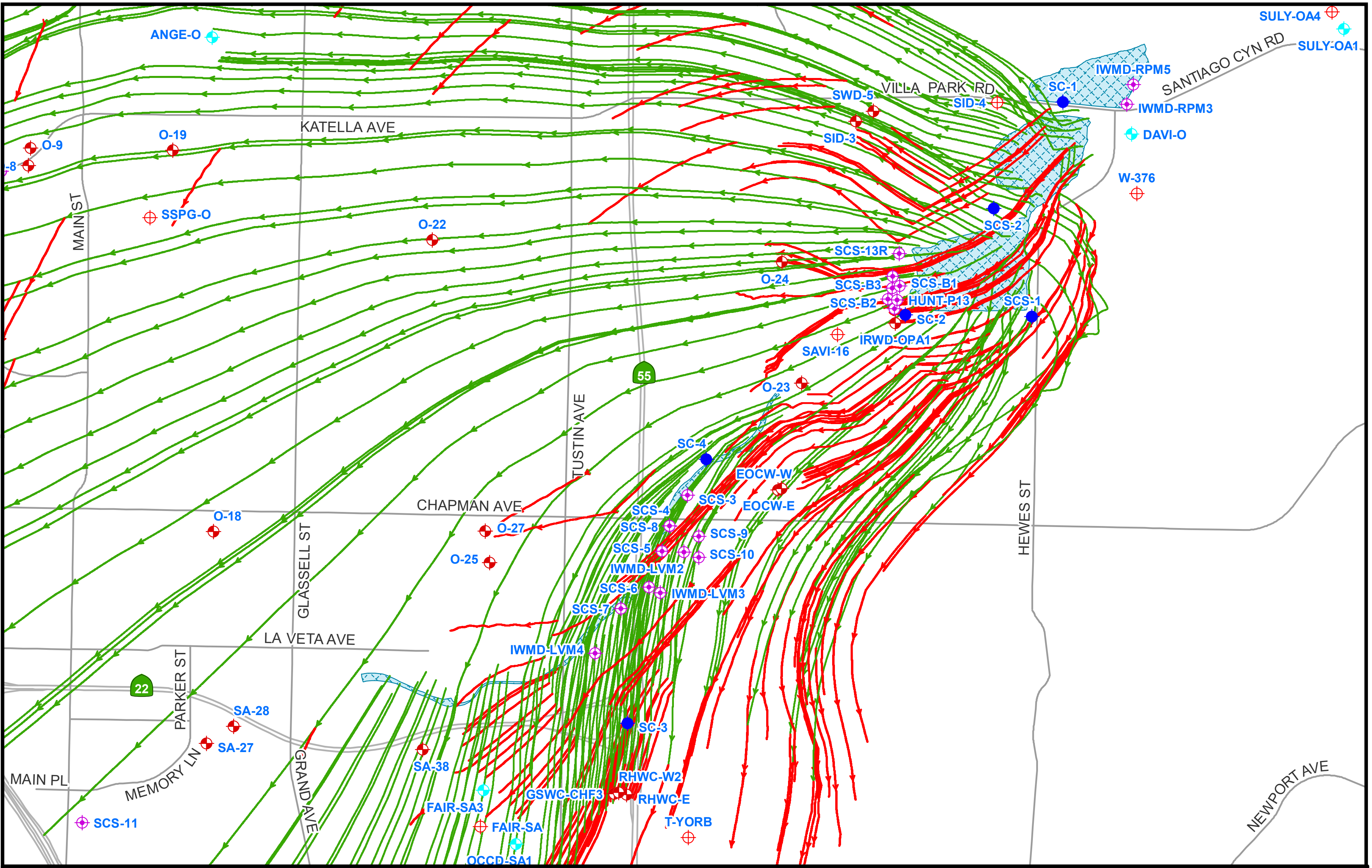

Figure 4

Santiago Basins and Creek Particle Trace

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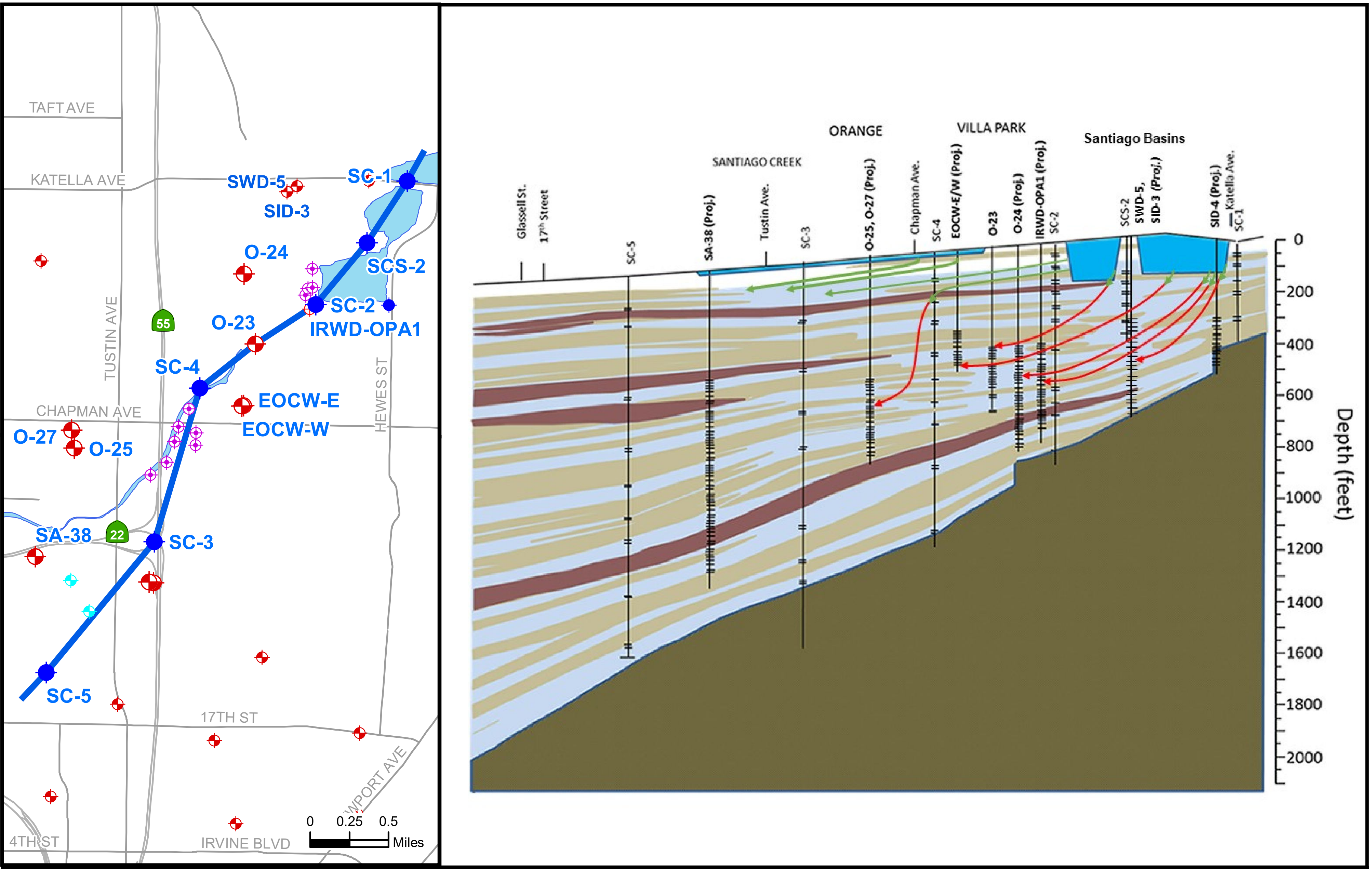

Particle Trace

- Shallow Aquifer
- Principal Aquifer

- Active Large-System Production Well
- Monitoring Well
- Multiport Monitoring Well
- Cross Section
- Recharge Areas

Figure 5

Geologic Cross-Section through Santiago Basins and Creek

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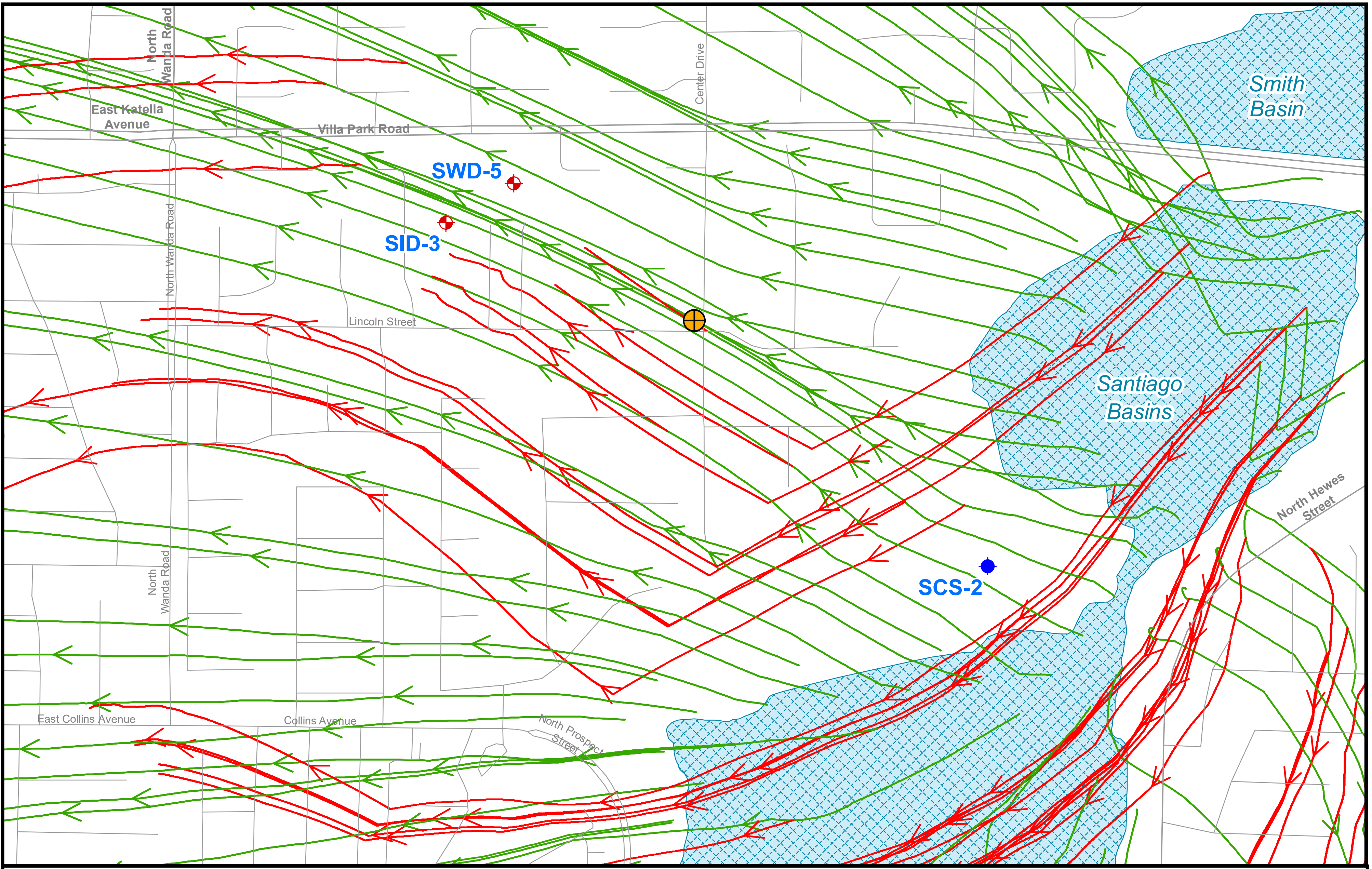

Figure 6

Santiago Basins Particle Trace near Production Well SWD-5

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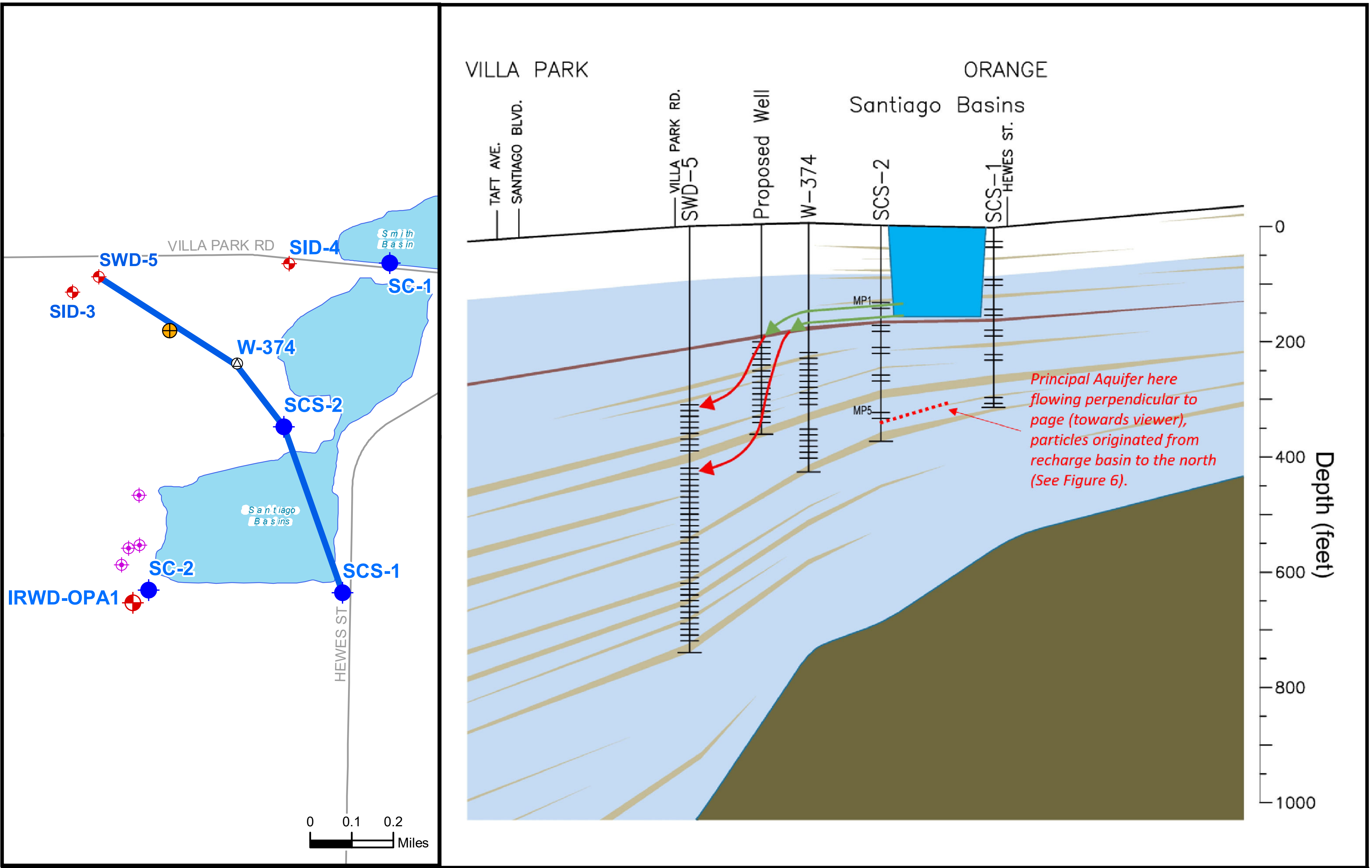

Principal Aquifer here flowing perpendicular to page (towards viewer), particles originated from recharge basin to the north (See Figure 6).

Particle Trace

🟩	Shallow Aquifer
🟥	Principal Aquifer
⊕	Active Large-System Production Well
⊕	Monitoring Well
●	Multiport Monitoring Well
⊕	Proposed Monitoring Well
▬	Cross-Section
▨	Recharge Areas

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Figure 7

Geologic Cross-Section from Santiago Basins to Production Well SWD-5

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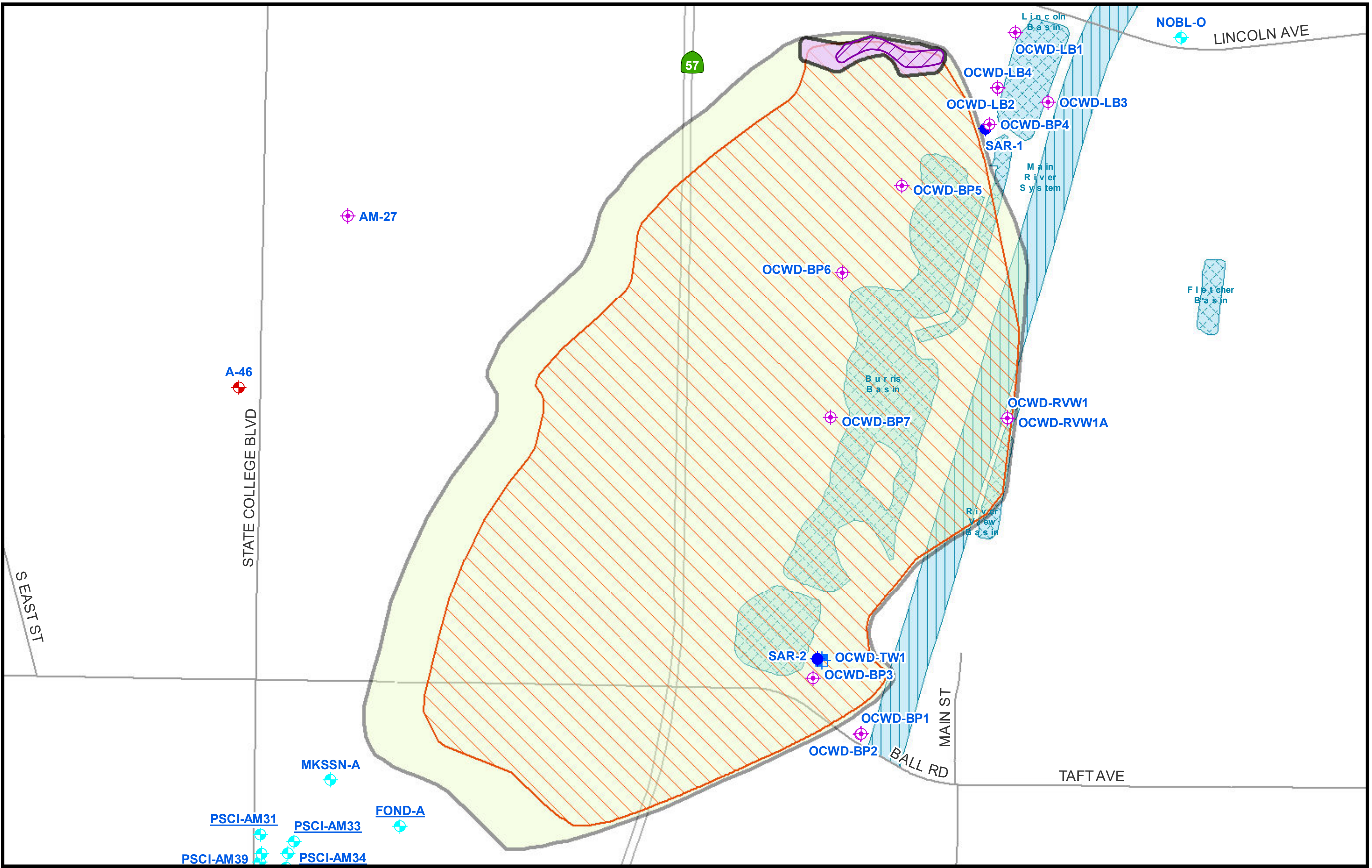

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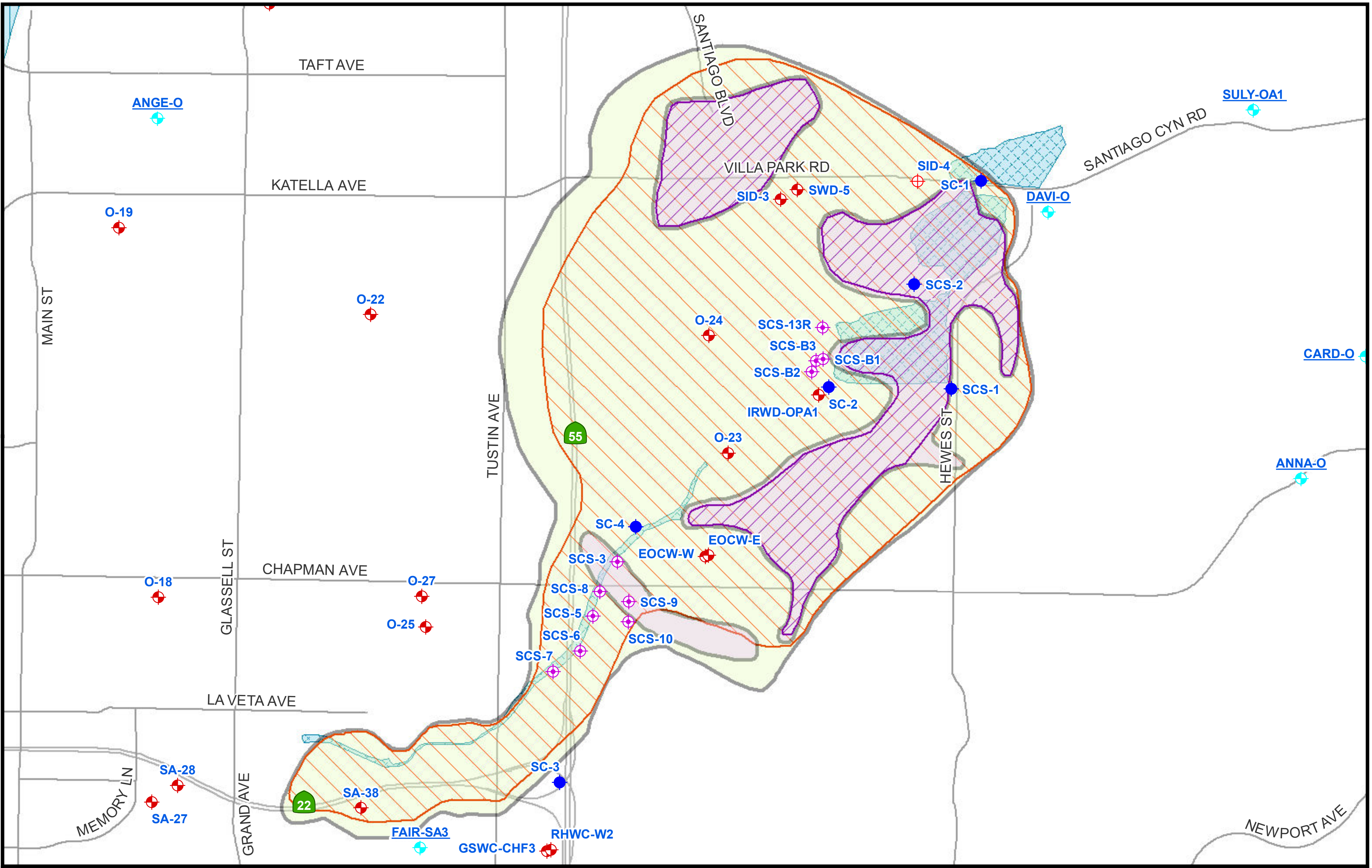
Figure 8

Burris/Riverview Basins Primary & Secondary Buffer Areas in both Shallow and Principal Aquifers



- ⌖ Active Large-System Production Well
- ⌖ Other Active Production Well
- ⌖ Inactive Production Well
- ⌖ Monitoring Well
- ● Multiport Monitoring Well

Particle Trace Buffer Area

Principal Aquifer

▨ Primary

▭ Secondary

Shallow Aquifer

▨ Primary

▭ Secondary

*Well names with underline are in shallow aquifer

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Figure 9

Santiago Basins and Santiago Creek Primary & Secondary Buffer Areas in both Shallow and Principal Aquifers

0 0.5 1
Miles

Path: K:\GIS\DataStore\OCWD\Hydrogeology\LiL\Mxd\ParticleTrace\Fig9_SantiagoBasinsAndCreekBufferAreasinShallowPrincipalAquifer.mxd (10/12/2020)

Appendix A

Overview of Groundwater Models in the OC Groundwater Basin

Groundwater Replenishment System
NWRI Independent Advisory Panel
August 26-27, 2013

Roy Herndon
Chief Hydrogeologist
Orange County Water District

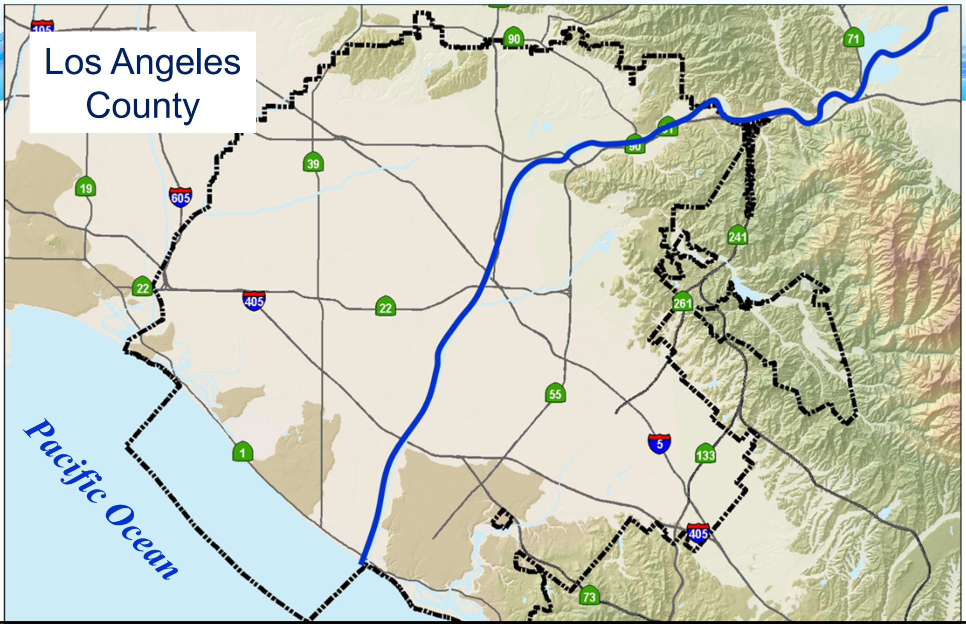
Outline:

- ▶ Basin hydrogeology
- ▶ Basin model development
- ▶ Basin model GWRS applications
- ▶ Talbert model development
- ▶ Talbert model applications
- ▶ Q & A

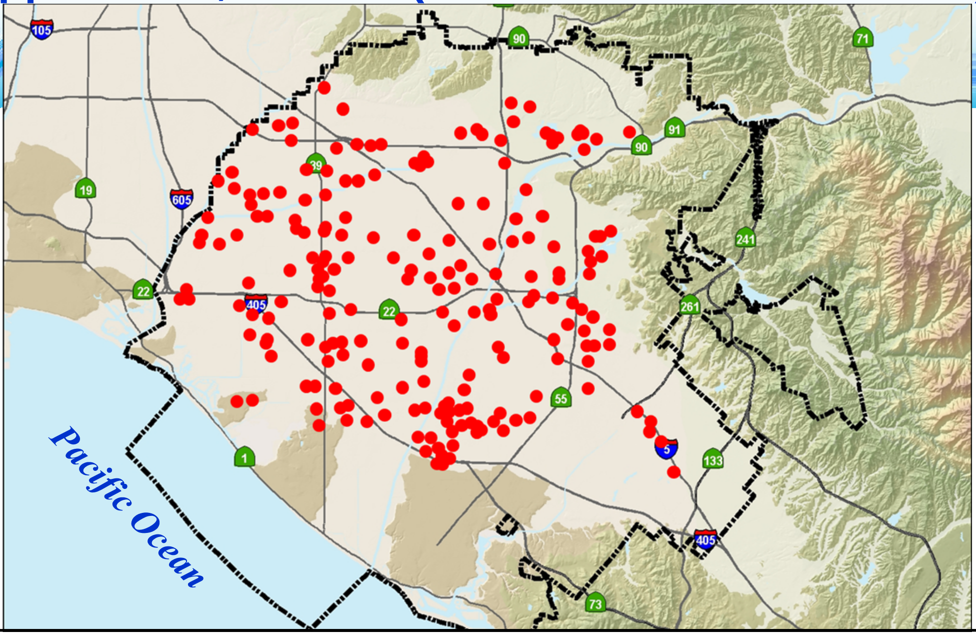
Guiding Principle

The accuracy and reliability of OCWD’s groundwater models are dependent upon our understanding of the basin’s hydrogeology and continued hydrologic monitoring.

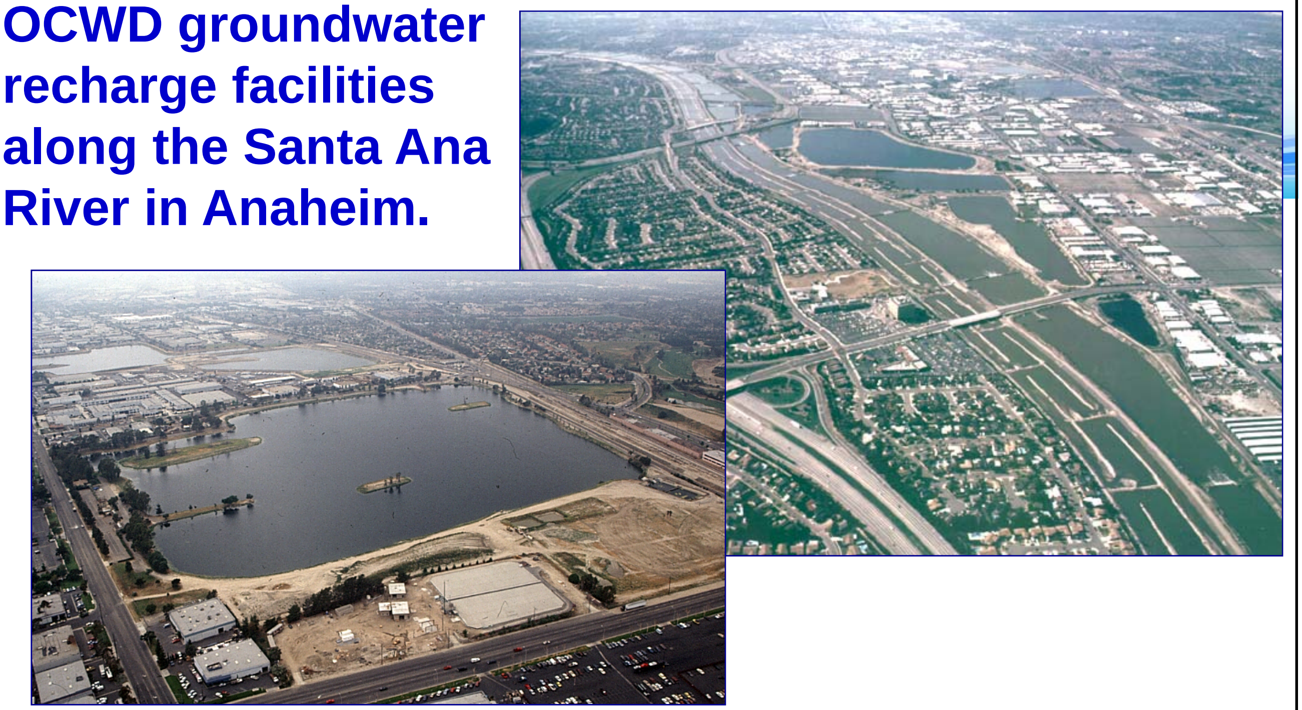
The OC groundwater basin covers 350 sq miles and is hydraulically continuous across the LA County line.



200 retain water agency wells produce approx. 300,000 AFY (70% of total water demand).



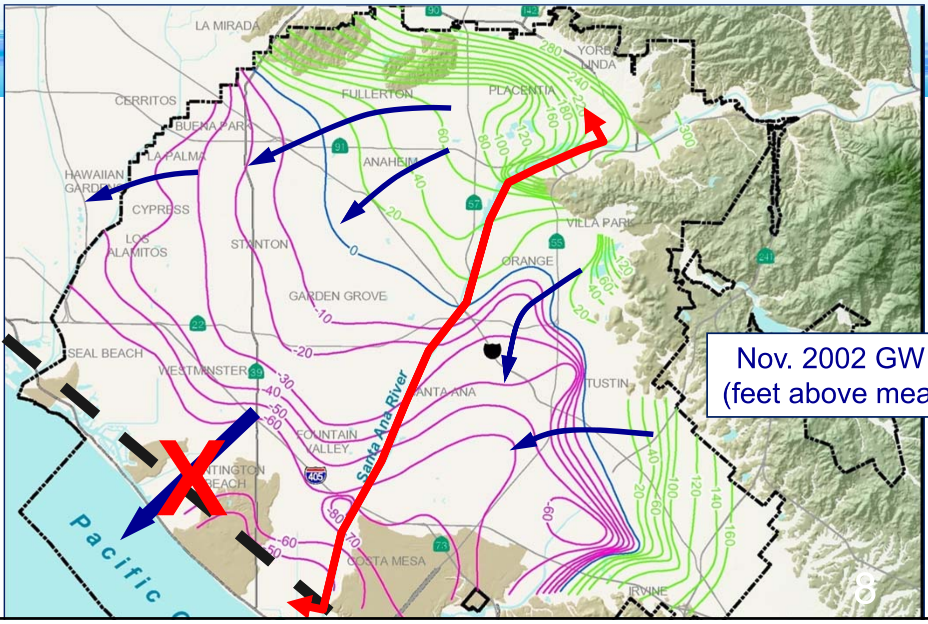
OCWD groundwater recharge facilities along the Santa Ana River in Anaheim.



Sources of recharge to the groundwater basin:

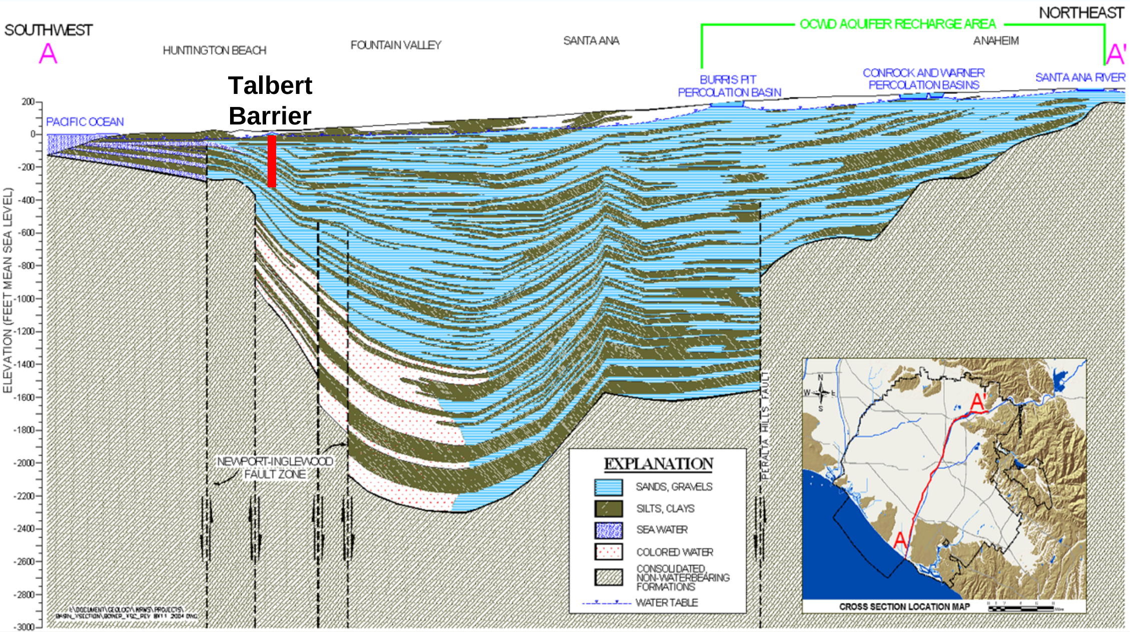
Recharge Source	Avg %
River storm flow	17
River base flow (mostly treated effluent from upstream cities)	33
GWRS water	23
Imported water	7
Rainfall and irrigation water natural infiltration	20
Total	100%

Groundwater flows from recharge areas toward the coast – little is lost.

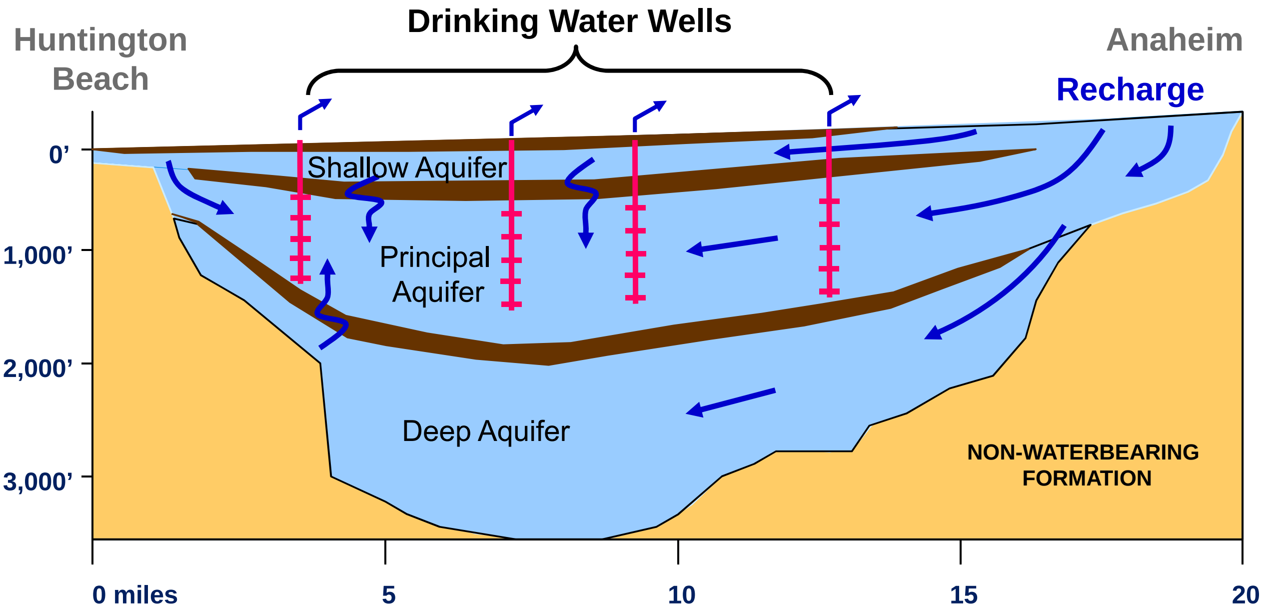


Nov. 2002 GW Elevations
(feet above mean sea level)

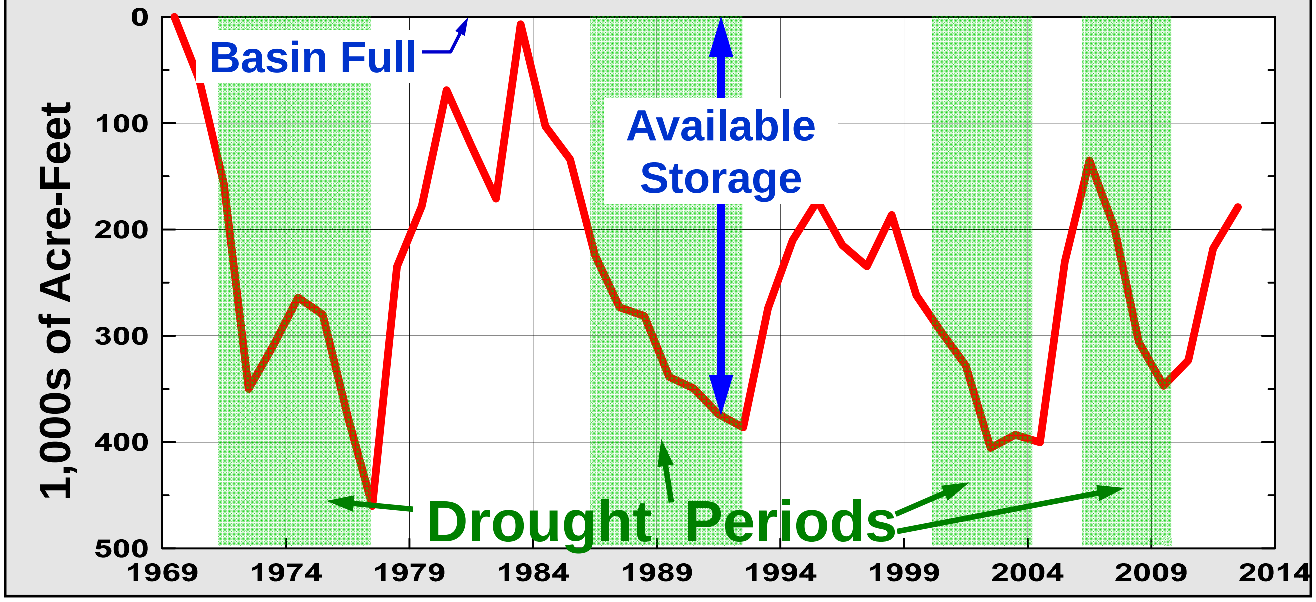
The basin aquifers are composed of >2,000 feet of unconsolidated, folded, and faulted sediments from marine and alluvial deposition.



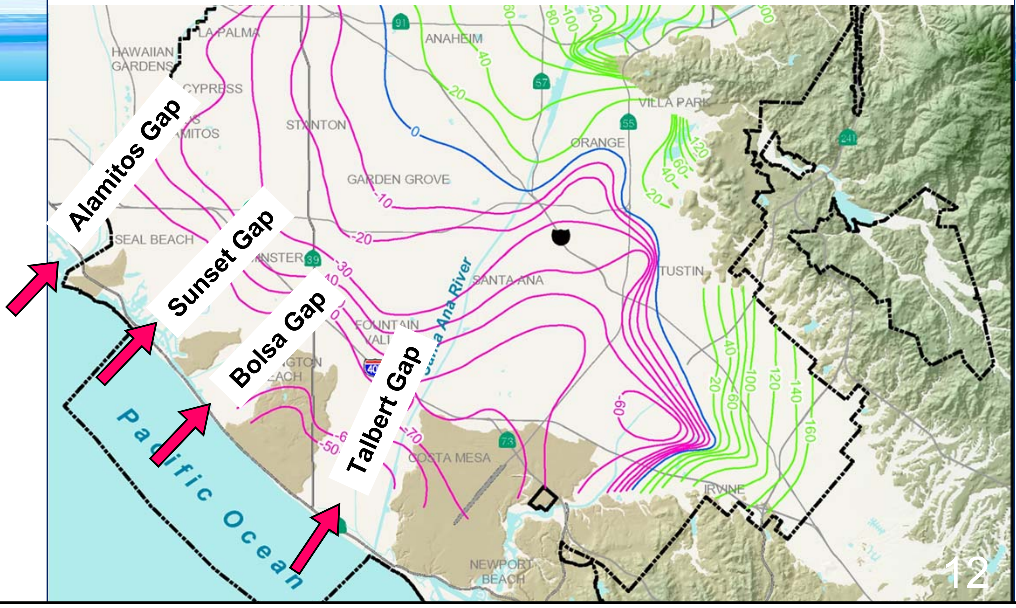
The basin is composed of three major aquifer systems.



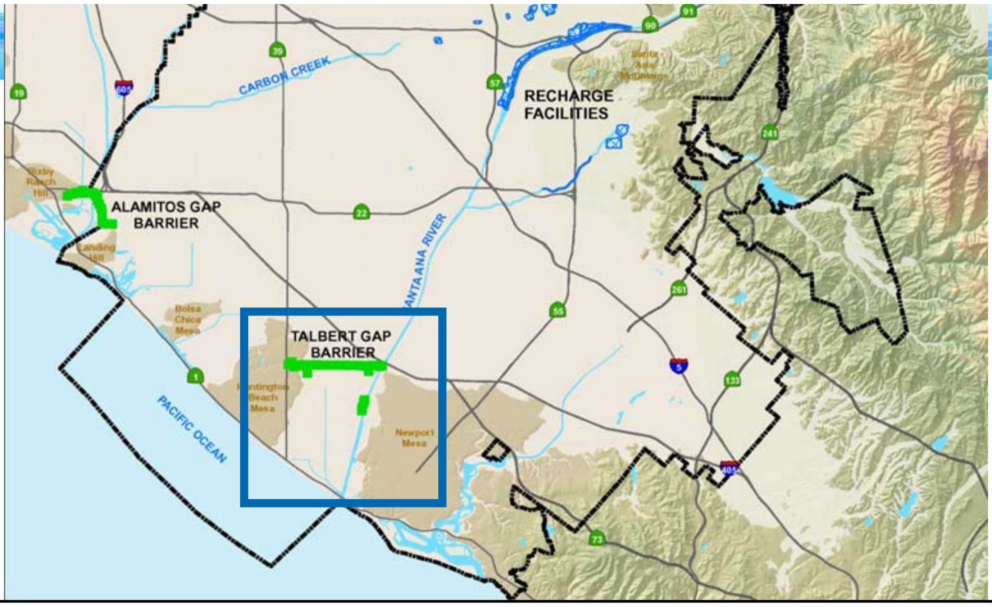
Basin storage is estimated based on measured and estimated inflows and outflows and groundwater level changes.

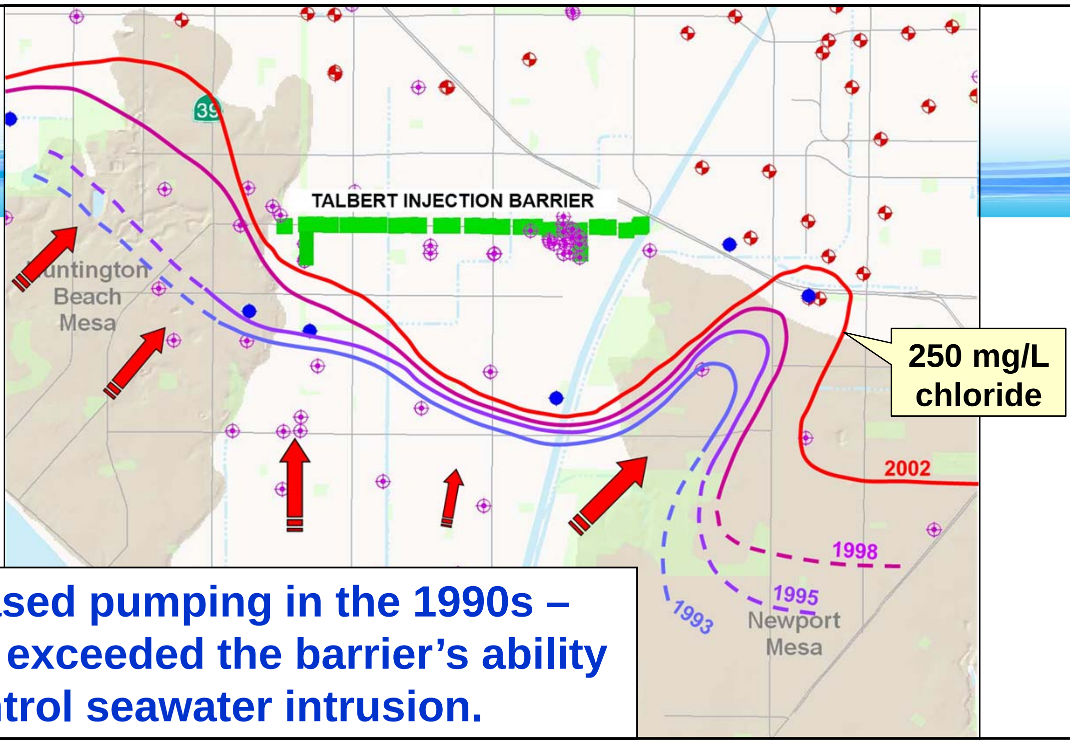


Seawater intrusion remains a constant basin management concern.



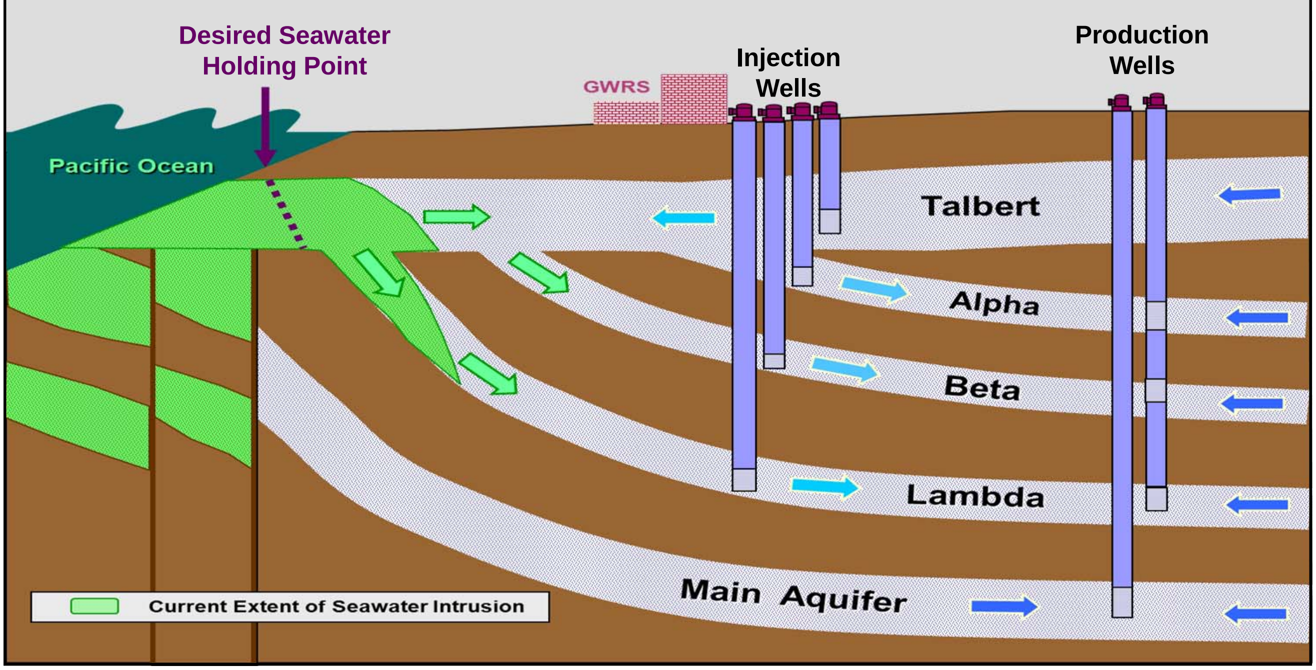
Two seawater barriers using injection wells are operated to protect the groundwater basin.



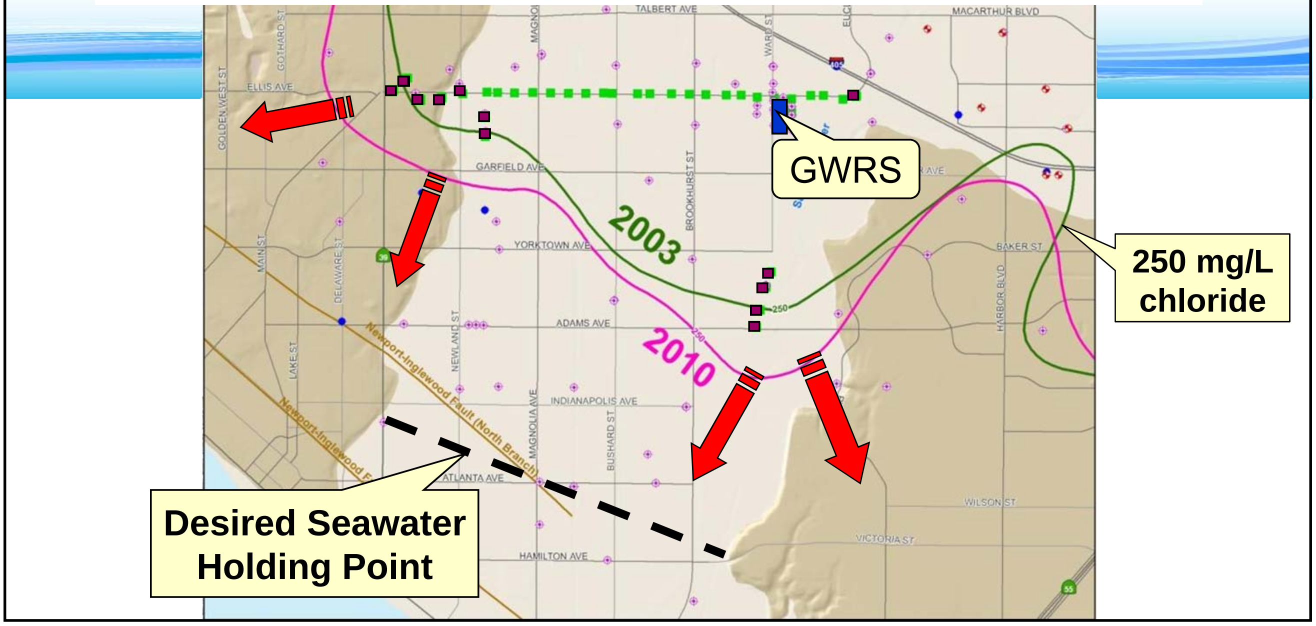


Increased pumping in the 1990s – 2000s exceeded the barrier’s ability to control seawater intrusion.

Seawater can move into deeper aquifers through mergence zones.



Doubling injection to 30+ mgd has begun to reverse seawater intrusion.

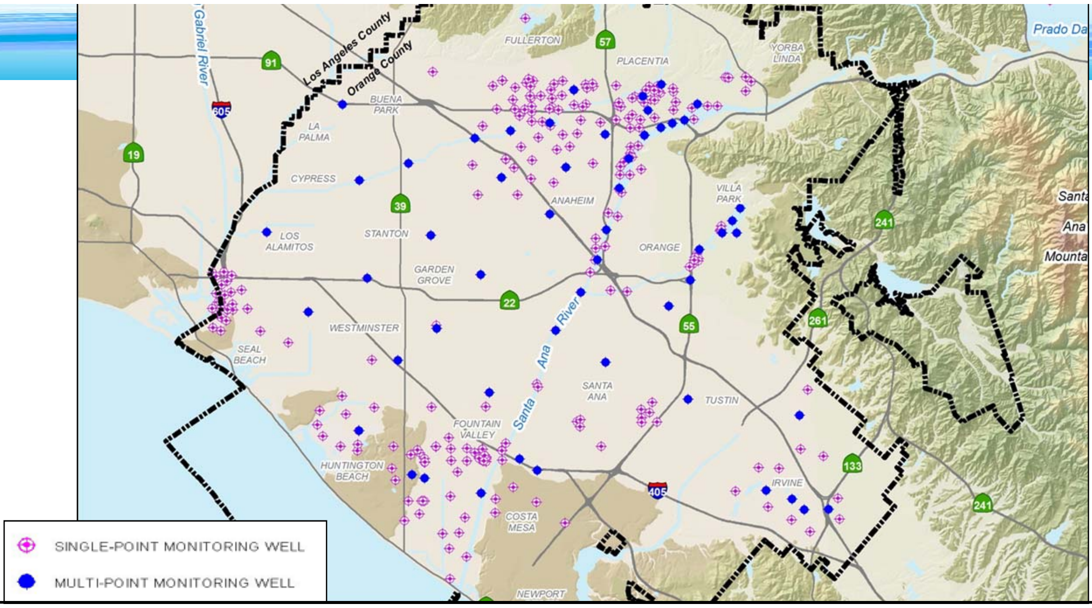


GWRS

250 mg/L chloride

Desired Seawater Holding Point

OCWD operates over 500 monitoring wells for water level and quality monitoring.

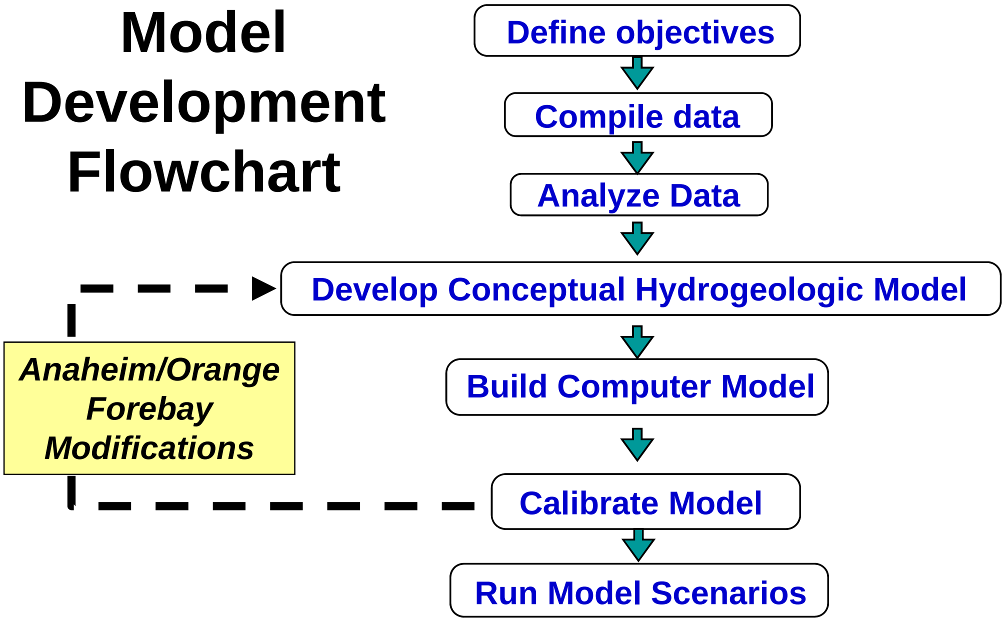


Basin Model

Uses of the basin model include:

- Drawdown from proposed increased pumping
- Mounding from proposed increased recharge
- Effects of seasonal pumping
- Seawater intrusion control
- Effects of drought (low basin conditions)
- Flow across county line
- Storage change estimates

Model Development Flowchart



Define objectives

Compile data

Analyze Data

Develop Conceptual Hydrogeologic Model

Build Computer Model

Calibrate Model

Run Model Scenarios

Anaheim/Orange Forebay Modifications

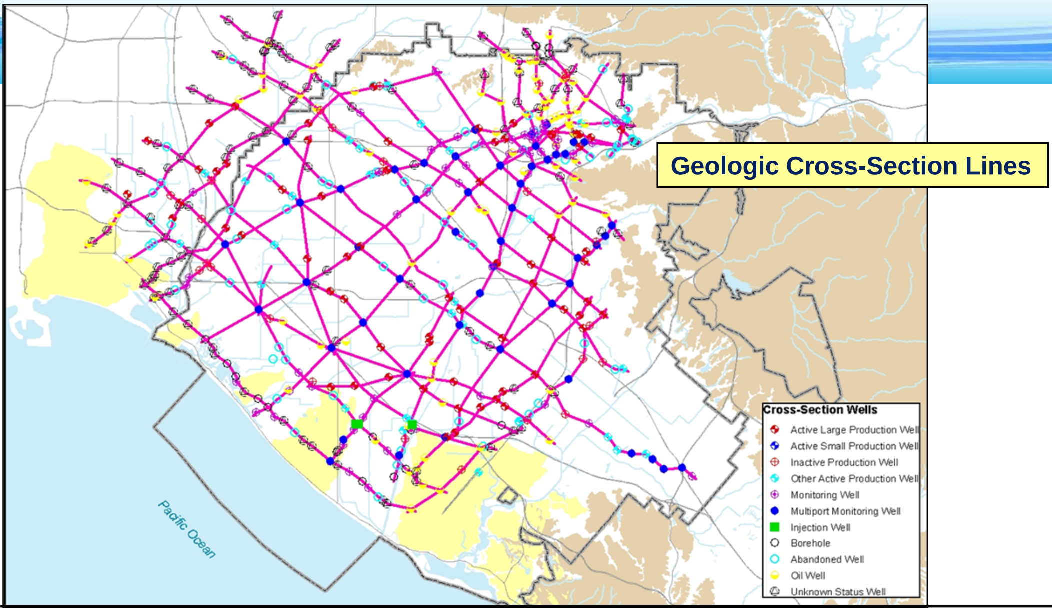
The basin model uses MODFLOW-96

- Finite difference model simulates groundwater flow
- Most widely used and accepted model code
- Developed by the USGS
- Well documented
- 3rd party model interface software (input/output)
- 3 model layers represent major aquifer systems
- Transient (time-variable flow conditions)

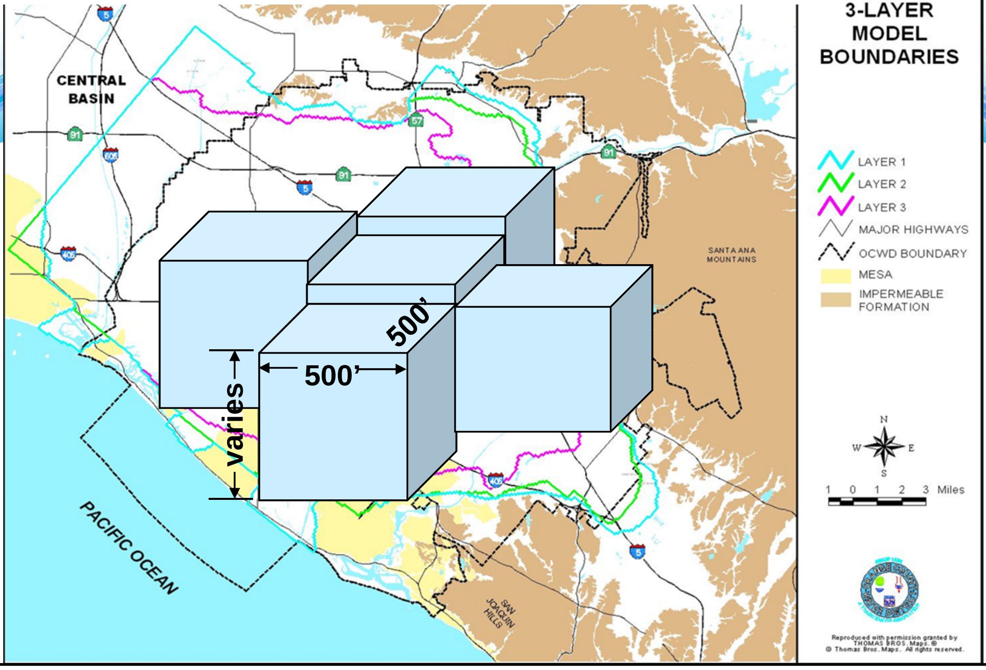
Model development and calibration were overseen by a technical advisory panel.

- Dr. Brendan Harley (CDM)
- Mr. Ralph Phraner
- Mr. Robert Stollar
- Dr. Eric Reichard (USGS)

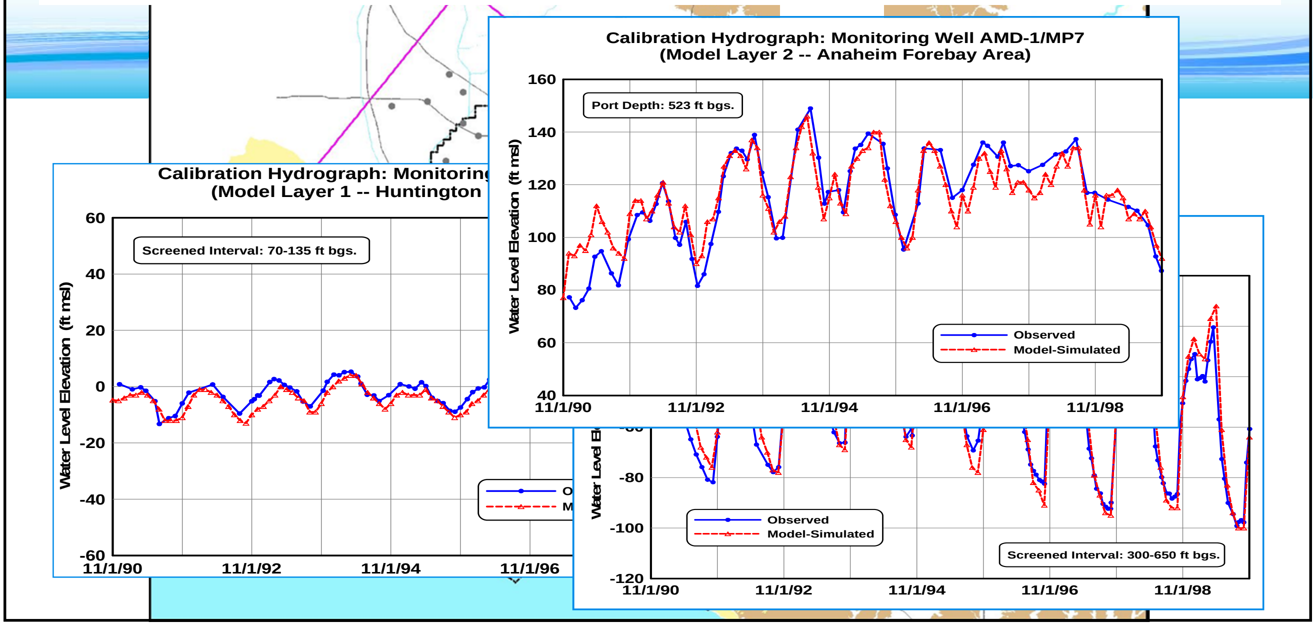
Over 25 geologic cross sections through the basin were interpreted from well logs.

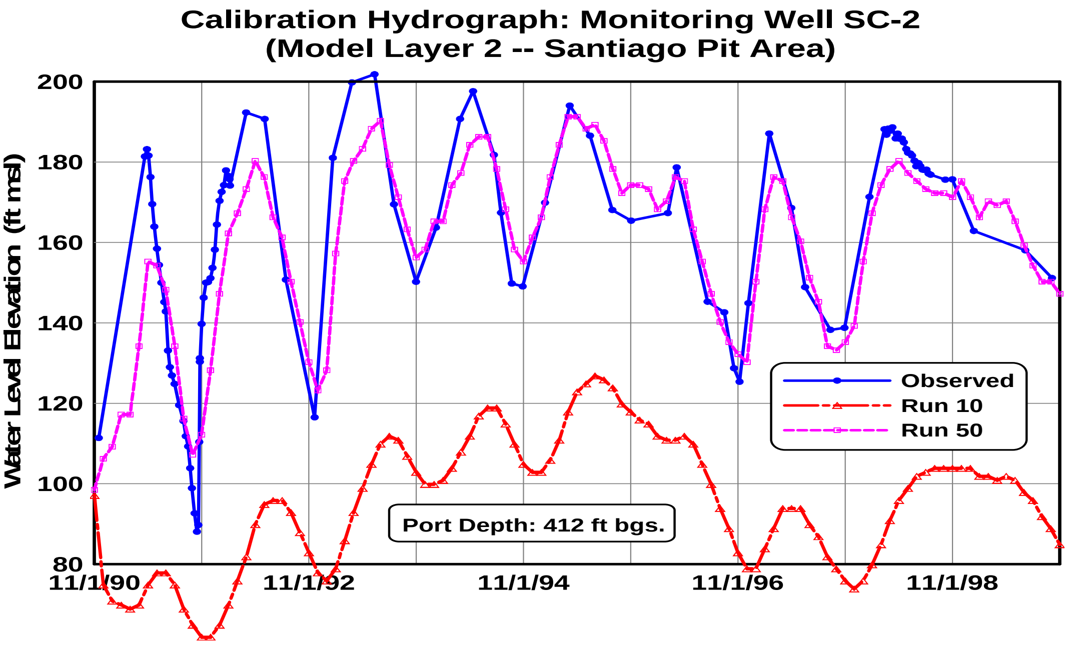


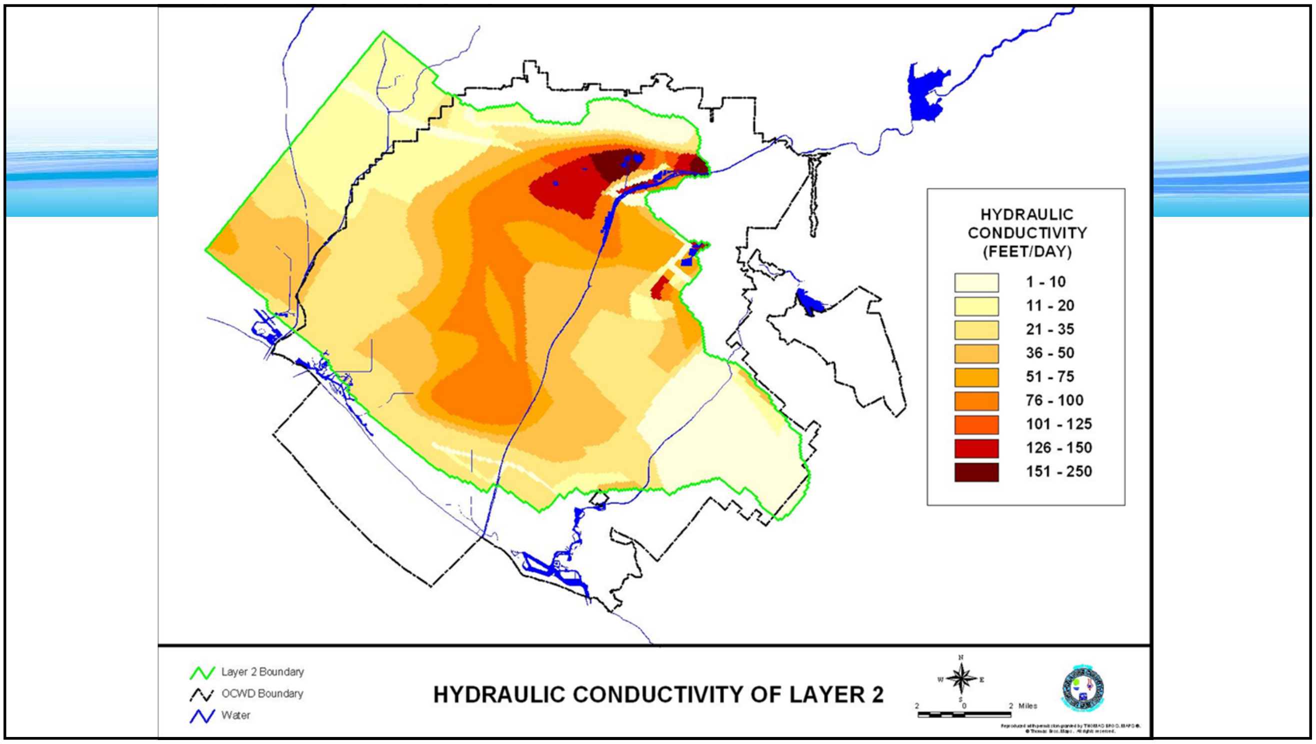
The model has >90,000 grid cells



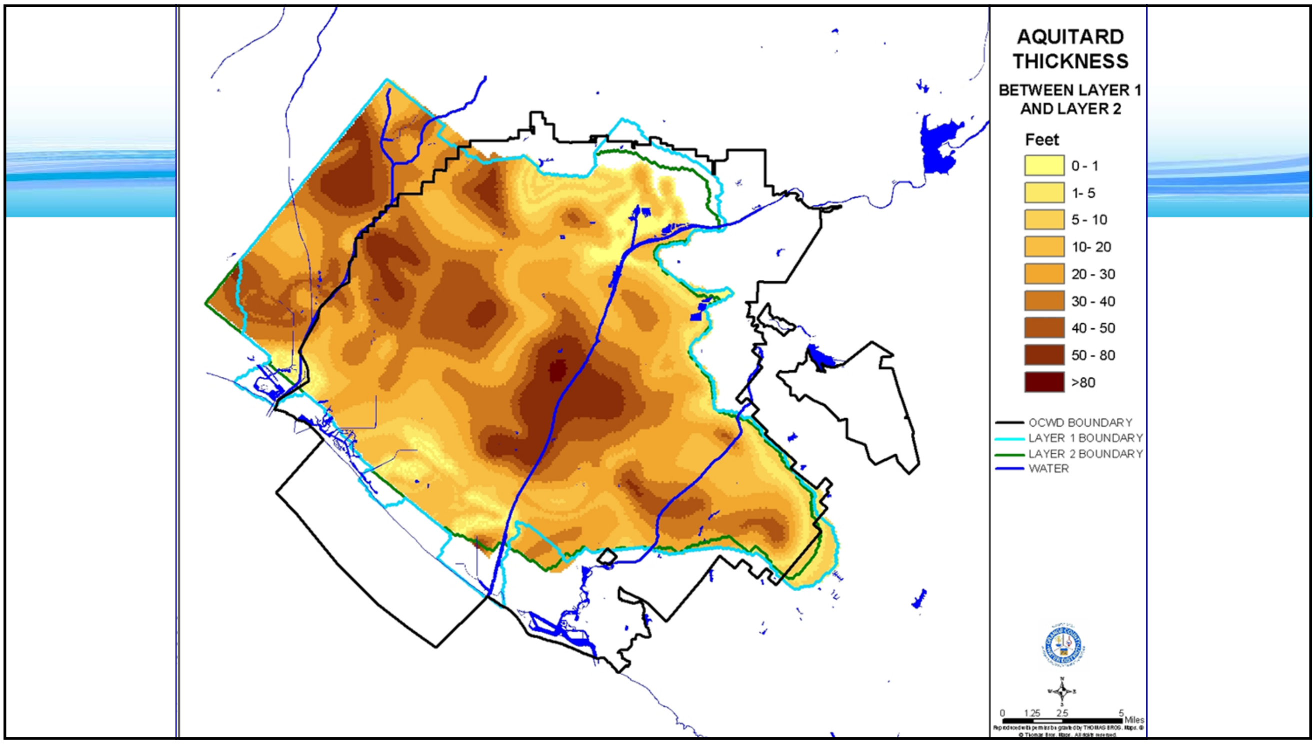
Over 50 calibration runs were needed to closely reproduce historical water levels at numerous well locations.







HYDRAULIC CONDUCTIVITY OF LAYER 2

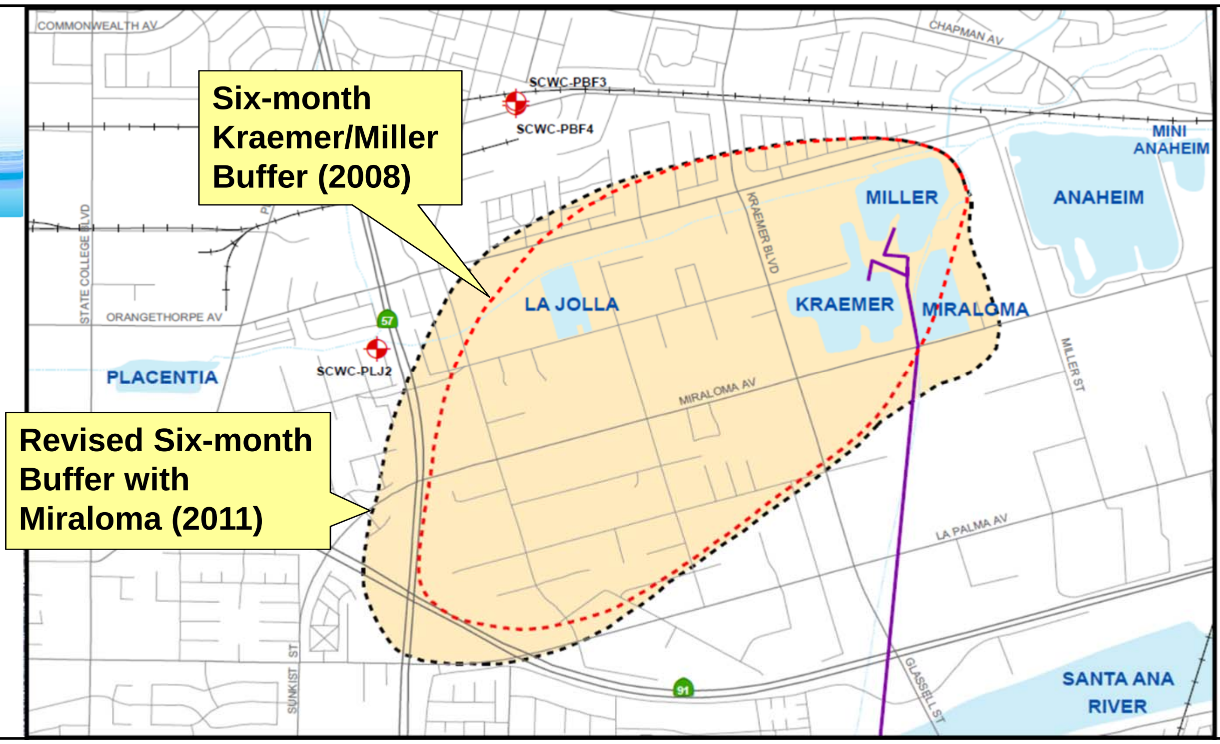


AQUITARD THICKNESS

BETWEEN LAYER 1 AND LAYER 2

The Basin Model was used in 2011 to update the six-month subsurface retention time buffer area in the Anaheim Forebay to reflect new Miraloma Basin.

- Current GWRS permit requires minimum six months of subsurface retention time prior to potable extraction of GWRS water
- Used 2008 artificial tracer (SF_6) test-determined retention time buffer area as baseline condition
- Basin Model predicted the incremental change due to Miraloma
- Added model-predicted change to 2008 buffer area to create new area


Six-month Kraemer/Miller Buffer (2008)

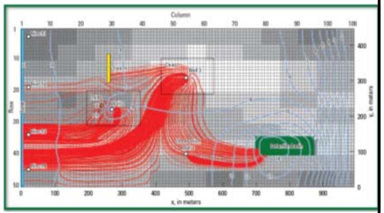
Revised Six-month Buffer with Miraloma (2011)

Miraloma Basin Analysis: Two Basin Model Scenarios

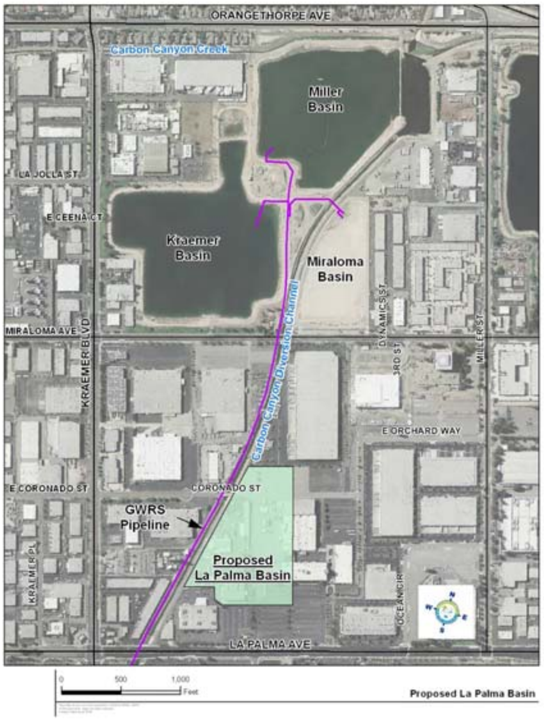
- **Baseline Condition (without Miraloma):**
  - Actual recharge conditions from 2008 tracer test
  - 6-month period: January through June 2008
- **Miraloma Recharge Condition:**
  - Same as baseline except added Miraloma recharge
  - Constant additional rate for Miraloma

Used supporting USGS MODPATH code with MODFLOW scenario results to assess differences in recharge flow paths and distances

- MODPATH simulates advective transport via particle tracking
- Simulation results are a series of flow paths



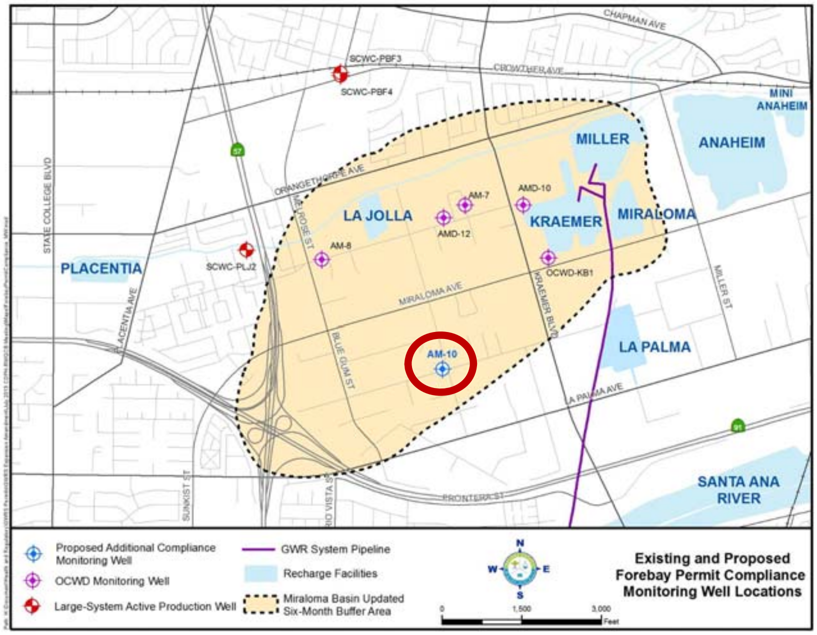
- Compared MODPATH results for two scenarios
  - Recharge area flow path directions did not change significantly except right at Miraloma Basin
  - Calculated percent change of six-month travel distance due to Miraloma ranged from 0 to 10% along buffer area margin
- Applied the percent change along margin of 2008 buffer area
- Updated buffer area extends 0 to 10% further to the southwest than in 2008



Proposed La Palma Basin

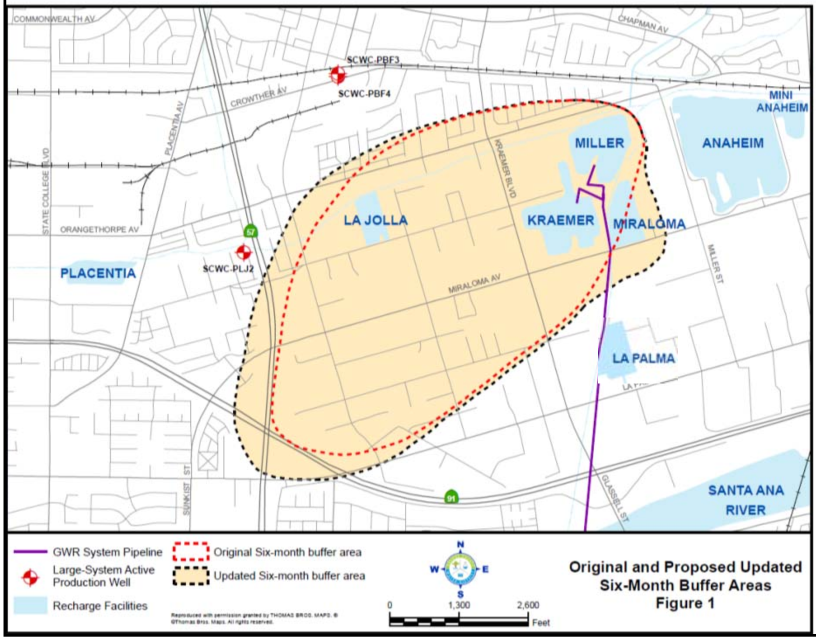
- 17-acre site
- Former Boeing property
  - Numerous past env. investigations
  - RWQCB NFA letter for soil and GW
  - RWQCB has “no objection” to recharge
  - OCWD considering pollution liability insurance
- Property purchase is in escrow period
- Hope for “Miraloma-like” percolation
- Projected online for GWRS by early 2015

Additional permit compliance monitoring well for La Palma Basin



- Existing OCWD monitoring well AM-10
  - Screen:217-235 ft bgs
  - Est. travel time from La Palma: 2-3 months
- Also constructing monitoring well on La Palma site for voluntary water quality testing and water level monitoring

Propose to revise retention time buffer area for La Palma Basin in the same manner as used for Miraloma

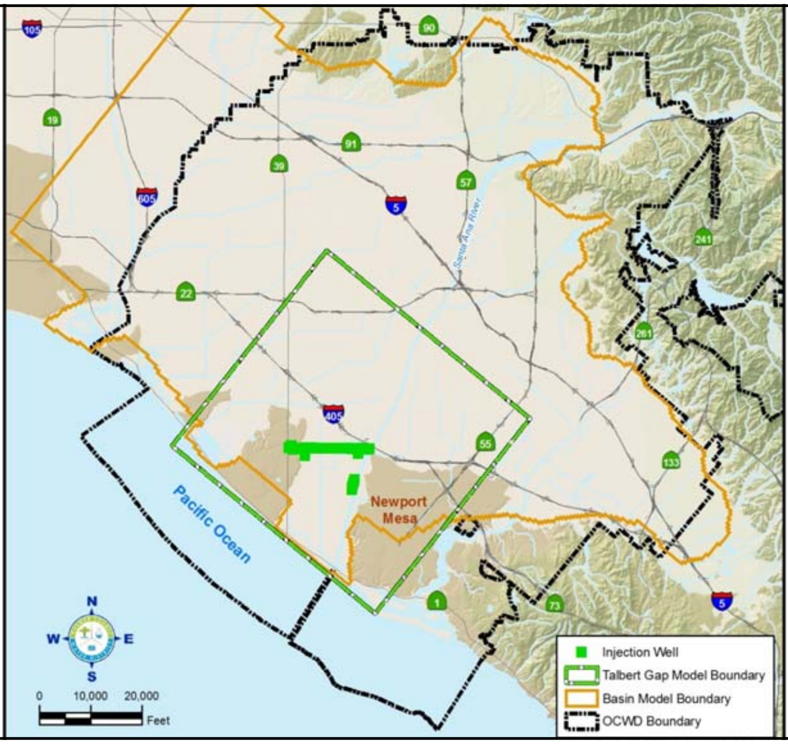


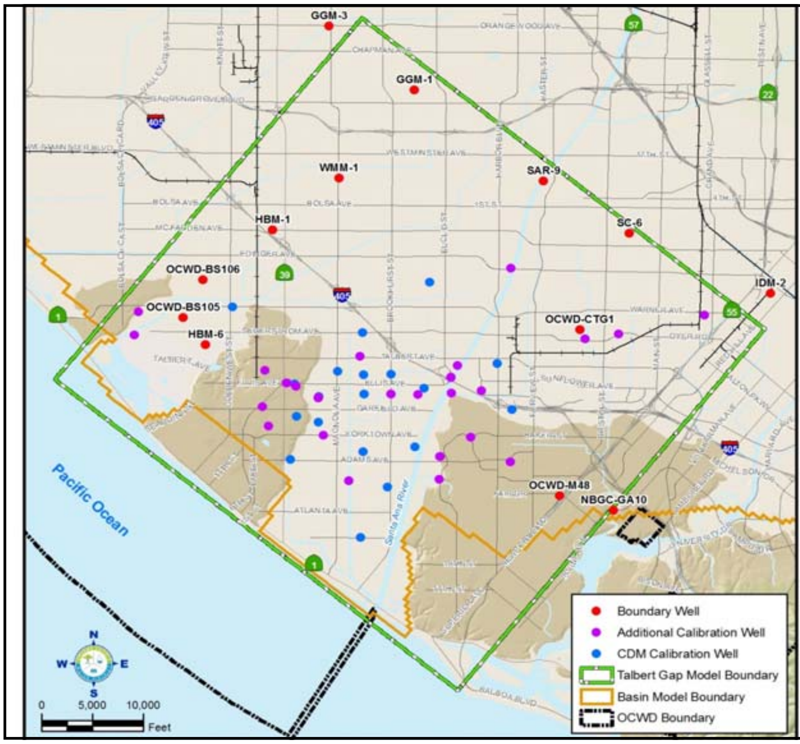
- Assess changes in local flowpaths and residence times due to recharge at La Palma
- Develop updated buffer area
- Verify modeling with intrinsic tracer

Ongoing Basin Model refinement activities:

- Increase to 5 layers (explicitly model aquitards)
- Extend calibration period to 2012
- Depending on calibration, reexamine layering based on new well logs and modify layers as appropriate

Talbert Barrier Model

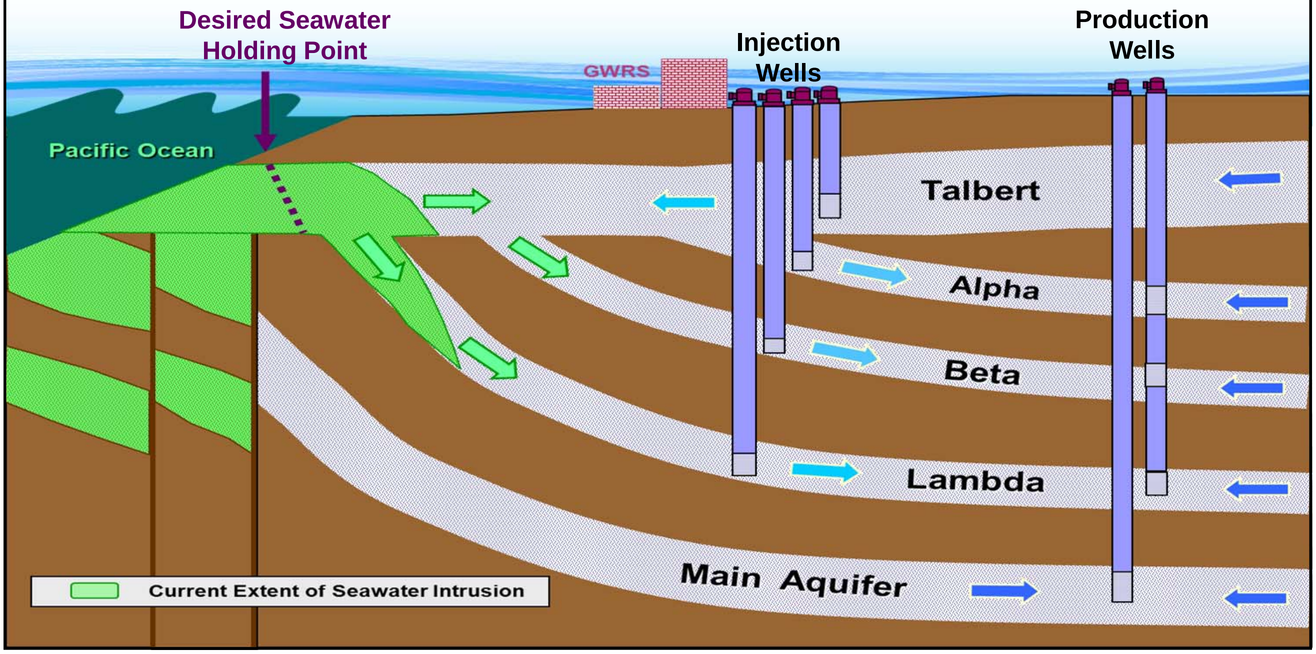


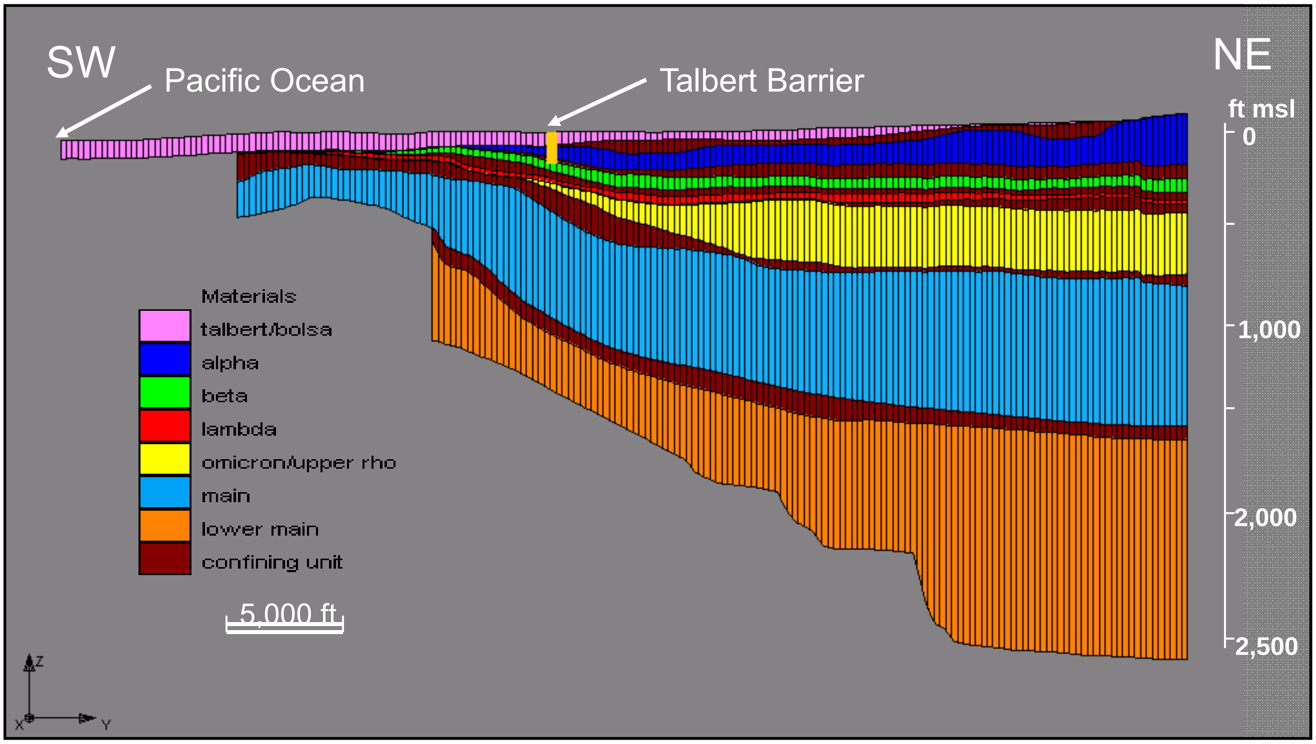


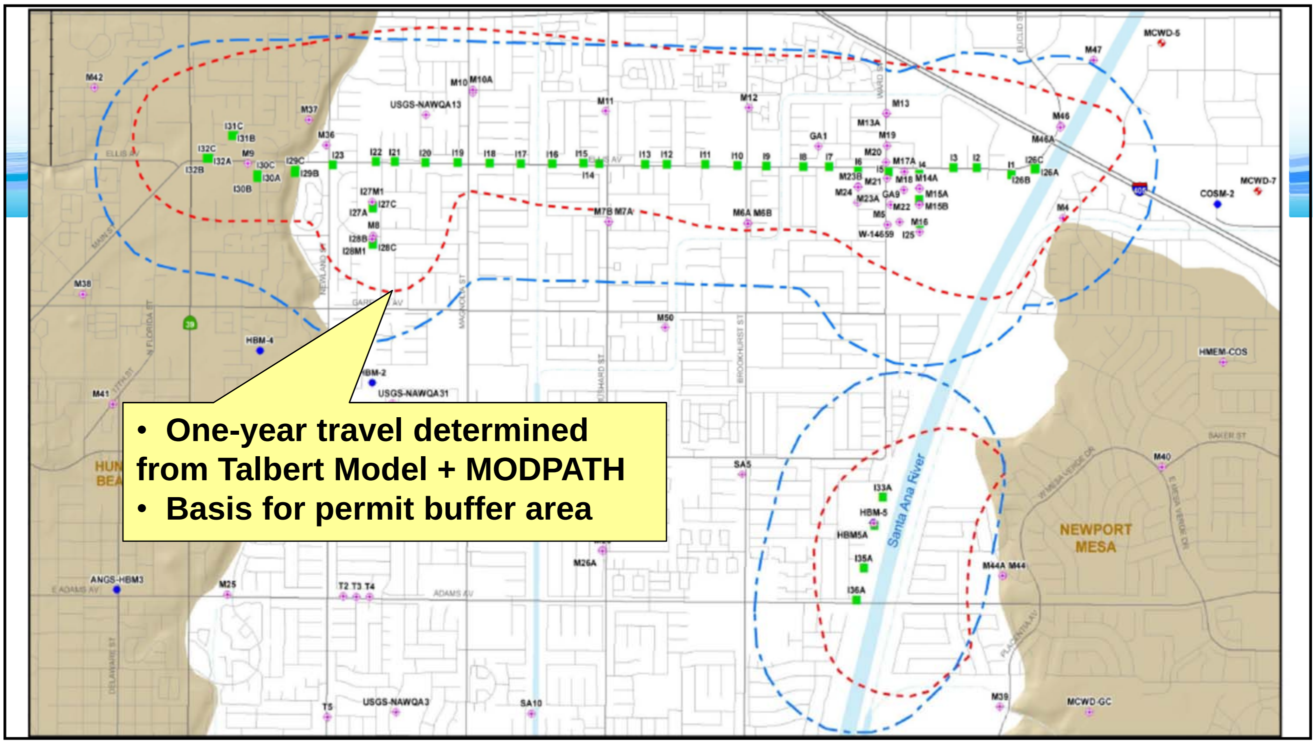
Talbert Model

- MODFLOW-based
- 13 layers
- 370,000 active grid cells
- Developed to more accurately simulate Talbert Barrier/Gap area with greater resolution
- Originally developed by CDM → now run and maintained by OCWD staff

Seawater can move into deeper aquifers through mergence zones.

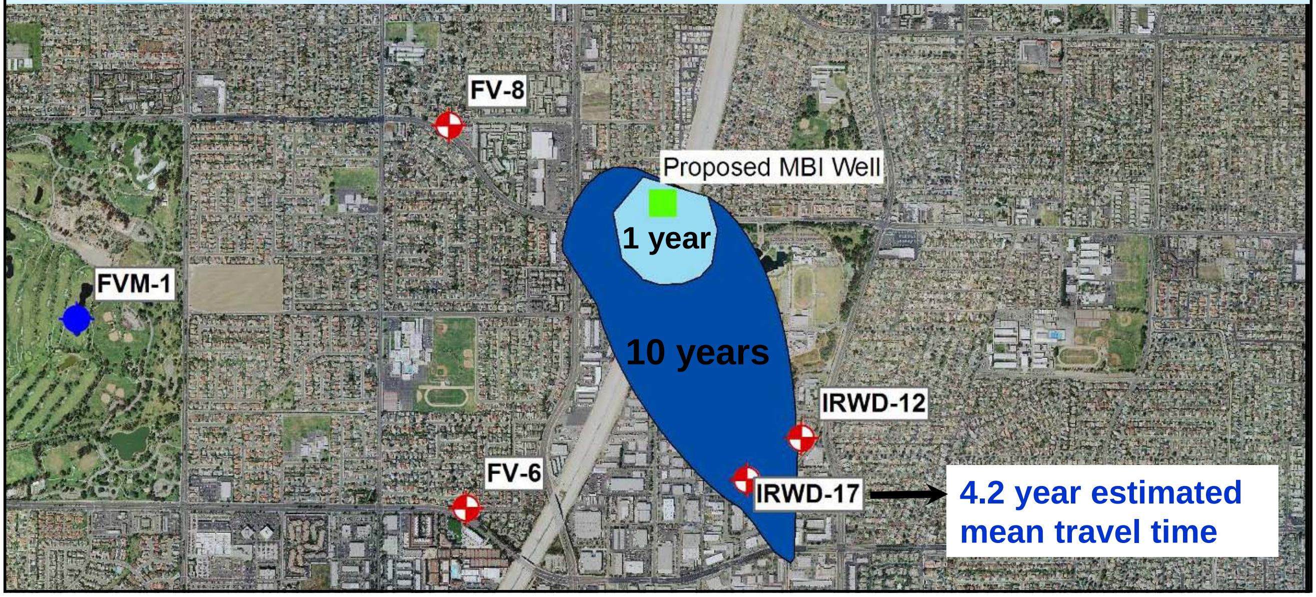






- One-year travel determined from Talbert Model + MODPATH
- Basis for permit buffer area

Talbert Model + MODPATH also used for travel time analysis for Demonstration Mid-Basin Injection Project planning & permitting



4.2 year estimated mean travel time

Ongoing Talbert Barrier Model activities:

- Extended calibration period to 2012
- Required substantial boundary condition interpolation (dynamic specified heads)
- Model to be used to analysis of potential barrier extension to the east beneath the Newport Mesa

Conclusions

- Basin Model and Talbert Model have been valuable tools for OCWD
- Models developed with oversight and assistance from outside experts
- Significant knowledge of basin hydrogeology has been gained via the model construction and calibration process
- Models have been selectively applied to GWRS for travel time assessments as appropriate
- New data and information is being added to extend calibration and refine models where necessary

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ORANGE COUNTY WATER DISTRICT

SINCE 1933

End of Presentation

Appendix B

Orange County Water District

Technical Memorandum

Date: August 6, 2013

To: NWRI GWRS Independent Advisory Panel

From: Li Li, Senior Hydrogeologist, P.G., C.Hg
Tim Sovich, Principal Engineer, P.E.

Subject: OCWD Groundwater Models Update

1 Introduction

The Orange County Water District (OCWD) basin-wide numerical groundwater flow model (Basin Model) was originally a three-layer transient model that was developed, calibrated, and utilized by OCWD staff as a predictive tool to more effectively manage the Basin and to determine the effects of potential future pumping and recharge projects. The model has proven to be a good representation of actual basin groundwater levels (OCWD, 2009).

The numerical model of the Talbert Barrier and surrounding vicinity (Talbert Model) was originally a seven-layer transient model that was developed in 1999 by Camp, Dresser & McKee, Inc. (CDM) for OCWD as part of the initial planning for the Groundwater Replenishment System to evaluate the expansion needs of the existing Talbert seawater intrusion injection barrier (CDM, 2000). In 2003, CDM further refined the Talbert Model to 13 layers and re-calibrated it (CDM, 2003).

This technical memorandum provides an overview of both models, an update on OCWD staff's effort in converting the Basin Model from 3 to 5 layers, and extending both the Basin Model and Talbert Model transient calibration periods several more years through June 2011 and June 2012, respectively.

2 OCWD Basin Model

2.1 Introduction

In general, a groundwater flow model contains two major components: the mathematical model and the conceptual model. The mathematical model is the computer program used to solve the complex system of equations that govern the flow of groundwater. The conceptual model is the hydrogeologic framework of the area being modeled, and is developed by gathering, analyzing, interpreting, and finally integrating the geologic and hydrologic data for a given area into a conceptual understanding of how the groundwater flow system looks and behaves.

For a properly-constructed model, the mathematical model needs to be appropriate for the level of detail inherent in the conceptual model. The modeled area must be divided into a mesh of grid cells – the smaller the grid cells, generally the more accurate the computations – assuming the hydrogeology can be reasonably defined at the grid cell level of detail. Based on all the input data, the model calculates a water level elevation for each and every grid cell of the modeled area at a given point in time. It should be noted that very simple groundwater flow problems can be solved analytically to achieve exact mathematical solutions. Therefore, the iterative numerical methods employed in approximating the groundwater flow equations in the modeling software can be validated by setting up a simplified hypothetical model run so that model output can be compared to the exact analytical solution. Such simplifying assumptions for which analytical solutions exist typically include steady-state conditions, homogeneous aquifer properties, symmetrical aquifer geometry, and simplified constant head and/or constant flux boundaries.

2.2 Model Extent and Code

The basin model encompasses the entire basin and extends approximately three miles west into the Central Basin of Los Angeles County rather than ending at the county line (Figure 1). Extending the model domain into Los Angeles County reduces the basin model's dependency on the westernmost model boundary, in which a time varying specified head condition is used. The Los Angeles/Orange county line is not a hydrogeologic boundary, i.e., groundwater freely flows through aquifers that have been correlated across the county line based on groundwater gradients in that area.

Coverage of the modeled area is accomplished with grid cells having horizontal dimensions of 500 feet by 500 feet (approximately 5.7 acres) and vertical dimensions ranging from approximately 50 to 1,800 feet, depending on the thickness of each model layer at that grid cell location. Basin aquifers and aquitards were grouped into three composite model layers thought sufficient to describe the three distinguishable flow systems referred to as the shallow, principal, and deep aquifer systems. The three model layers comprise a network of over 90,000 grid cells.

The two intervening aquitards between model layers 1 and 2 and between model layers 2 and 3 were represented in the model using a vertical leakance term rather than explicitly including them as individual model layers.

The widely-accepted computer program, "MODFLOW," developed by the USGS, was used as the base modeling code for the mathematical model (McDonald and Harbaugh, 1988). Analogous to an off-the-shelf spreadsheet program needing data to be functional, MODFLOW requires vast amounts of input data to define the hydrogeologic conditions in the conceptual model.

2.3 Model Input

The types of information that must be input in digital format (data files) for each grid cell in each model layer include the following:

- Aquifer top and bottom elevations
- Aquifer lateral boundary conditions (ocean, faults, mountains)
- Aquifer hydraulic conductivity and storage coefficient/specific yield
- Initial groundwater surface elevation contours
- Natural and artificial recharge rates (precipitation, percolation, and injection)
- Pumping rates for all production wells in the basin.

These model input data originate from well logs, aquifer pump tests, groundwater elevation measurements, hand-drawn contour maps, geologic cross sections, water budget spreadsheets, and other data stored in the OCWD Water Resources Management System (WRMS) database. The WRMS database includes all measured data needed to effectively manage and model the basin, including groundwater levels, groundwater quality, monthly pumping and injection volumes, and monthly recharge volumes for OCWD recharge facilities. Because MODFLOW requires the input data files in a specific format, staff developed a customized database and geographic information system (GIS) application to automate data compilation and formatting functions. These data pre-processing tasks form one of the key activities in the model development process.

Before a groundwater model can be reliably used as a predictive tool for simulating future conditions, the model must be calibrated to achieve an acceptable match between simulated and actual observed conditions. The basin model was first calibrated to steady-state conditions to numerically stabilize the simulations, to make rough adjustments to the water budget terms, and to generally match regional groundwater flow patterns. Also, the steady-state calibration helped to determine the sensitivity of simulated groundwater levels to changes in incidental recharge and aquifer parameters such as hydraulic conductivity. Steady-state calibration of the basin model is documented in more detail in the *OCWD Master Plan Report* (OCWD, 1999).

Typical transient model output consists of water level elevations at each grid cell that can be plotted as a contour map for one point in time or as a time-series graph at a single location. Post-processing of model results into usable graphics is performed using a combination of semi-automated GIS and database program applications.

Figure 2 presents a simplified schematic of the modeling process.

2.4 Model Development Process

Model construction and calibration were done by OCWD staff during the three-year period 1998-2000 but were built upon 12 years of effort by OCWD staff to collect, compile, digitize, and interpret hundreds of borehole geologic and geophysical logs, water level hydrographs, and water quality analyses. The process was composed of ten main tasks comprising over 120 subtasks. The major tasks are summarized below:

1. Finalize conceptual hydrogeologic model layers and program GIS/database applications to create properly formatted MODFLOW input data files. Over 40 geologic cross sections were used to form the basis of the vertical and lateral aquifer boundaries.

2. Define model layer boundaries. The top and bottom elevations of the three aquifer system layers and intervening aquitards were hand-contoured, digitized, and overlain on the model grid to populate the model input arrays with a top and bottom elevation for each layer at every grid cell location. Model layer thickness values were then calculated using the GIS.

3. Develop model layer hydraulic conductivity (K) grids. Estimates of K for each layer were based on (in order of importance): available aquifer test data, well specific capacity data, and lithologic data. In the absence of reliable aquifer test or specific capacity data for areas in layers 1 and 3, lithology-based K estimates were calculated by assigning literature values of K to each lithology type (e.g., sand, gravel, clay) within a model layer and then calculating an effective K value for the entire layer at that well location. Layer 2 had the most available aquifer test and specific capacity data. Therefore, a layer 2 transmissivity contour map was prepared and digitized, and the GIS was then used to calculate a K surface by dividing the transmissivity grid by the aquifer thickness grid. Initial values of K were adjusted during model calibration to achieve a better match of model results with known groundwater elevations.

4. Develop layer production factors for active production wells simulated in the model. Many production wells had long screened intervals that spanned at least two of the three model layers. Therefore, groundwater production for each of these wells had to be divided among each layer screened by use of layer production factors. These factors were calculated using both the relative length of screen within each model layer and the hydraulic conductivity of each layer. Well production was then multiplied by the layer factors for each individual well.

For example, if a well had a screened interval equally divided across layers 1 and 2, but the hydraulic conductivity of layer 1 was twice that of layer 2, then the calculated layer 1 and 2 production factors for that well would have been one-third and two-thirds, respectively, such that when multiplied by the total production for this well, the production assigned to layer 1 would have been twice that of layer 2. For the current three-layer model, approximately 25 percent of the production wells in the model were screened across more than one model layer. In this context, further vertical refinement of the model (more model layers) may better represent the aquifer architecture in certain areas but may also increase the uncertainty and potential error involved in the amount of groundwater production assigned to each model layer.

5. Develop basin model water budget input parameters, including groundwater production, artificial recharge, and unmeasured recharge. Groundwater production and artificial recharge volumes were applied to grid cells in which production wells or recharge facilities were located. The most uncertain component of the water budget – unmeasured or incidental recharge – was applied to the model as an average monthly volume based on estimates calculated annually for the OCWD Engineer's Report. Unmeasured recharge was distributed to cells throughout the model, but was mostly applied to cells along margins of the basin at the base of the hills and mountains. The underflow component of the incidental recharge represents the amount of groundwater flowing into and out of the model along open boundaries. Prescribed groundwater elevations were assigned to open boundaries along the northwest model boundary in Los Angeles County; the ocean at the Alamitos, Bolsa, and Talbert Gaps (Figure 1); the mouth of the Santa Ana Canyon; and the mouth of Santiago Creek Canyon (Figure 1). Groundwater elevations for the boundaries other than the ocean boundaries were based on historical groundwater elevation data from nearby wells. The model automatically calculated the dynamic or transient flow across these open boundaries as part of the overall water budget.

6. Develop model layer storage coefficients. Storage coefficient values for portions of model layers representing confined aquifer conditions were prepared based on available aquifer test data and were adjusted within reasonable limits based on calibration results.

7. Develop vertical leakance parameters between model layers. Vertical groundwater flow between aquifer systems in the basin is generally not directly measured, yet it is one of the critically-important factors in the model's ability to represent actual basin hydraulic processes. Using geologic cross sections and depth-specific water level and water quality data from the OCWD multi-depth monitoring well network, staff identified areas where vertical groundwater flow between the modeled aquifer systems is either likely to occur or be significantly impeded, depending on the relative abundance and continuity of lower-permeability aquitards between model layers. During model calibration, the

initial parameter estimates for vertical leakance were adjusted to achieve closer matches to known vertical groundwater gradients.

8. Develop groundwater contour maps for each model layer to be used for starting conditions and for visual comparison of water level patterns during calibration. Staff used observed water level data from multi-depth and other wells to prepare contour maps of each layer for November 1990 as a starting point for the calibration period. Care was taken to use wells screened within the appropriate vertical interval representing each model layer. The hand-drawn contour maps were then digitized and used as model input to represent starting conditions.

9. Perform transient calibration runs. The nine-year period of November 1990 to November 1999 was selected for transient calibration, as it represented the period corresponding to the most detailed set of groundwater elevation, production, and recharge data at that time. The transient calibration process and results are described in Section 2.2.

10. Perform various basin production and recharge scenarios using the calibrated model. Criteria for pumping and recharge, including proposed facility locations and volumes, were developed for each scenario and input for each model run.

2.5 Model Calibration

Calibration of the transient basin model involved a series of over 50 separate model runs for the 1990-99 period, using monthly flow and water level data. The time period selected for calibration represents a period during which basic data required for monthly transient calibration were essentially complete (compared to pre-1990 historical records). The calibration period spans at least one “wet/dry” rainfall cycle. Monthly water level data from almost 250 target locations were used to determine if the simulated water levels adequately matched observed water levels. As shown in Figure 3, the calibration target points were densely distributed throughout the basin and also covered all three model layers.

After each model run, a hydrograph of observed versus simulated water levels was created and reviewed for each calibration target point. In addition, a groundwater elevation contour map for each layer was also generated from the simulated data. The simulated groundwater contours for all three layers were compared to interpreted contours of observed data (November 1997) to assess closeness of fit and to qualitatively evaluate whether the simulated gradients and overall flow patterns were consistent with the conceptual hydrogeologic model. November 1997 was chosen for the observed versus simulated contour map comparison since these hand-drawn contour maps had already been created for the prior steady state calibration step. Furthermore, 1996-97 represented a somewhat typical year with approximately average rainfall.

Although November 1997 observed data were contoured for all three layers, the contour maps for layers 1 and 3 were somewhat more generalized than for layer 2 due to fewer available data points in these two layers.

Depending on the results of each transient calibration run, model input parameters were adjusted, including hydraulic conductivity, storage coefficient, boundary conditions, and recharge distribution. Implementation of time-varying head boundaries along the Orange/Los Angeles County line was found to be extremely useful in improving the calibration or fit between simulated and observed water levels in the northwestern portion of the model. Fifty calibration runs were required to reach an acceptable level of calibration (5-10% discrepancy) in which model-generated water levels reasonably matched observed water level elevations during the 9-year transient calibration period. Figure 4 shows examples of hydrographs of observed versus simulated water levels for three wells used as calibration targets.

Noteworthy findings of the model calibration process are summarized below:

- The model was most sensitive to adjustments to hydraulic conductivity and recharge distribution. In other words, minor variations in these input parameters caused significant changes in the model water level output.
- The model was less sensitive to changes in storage coefficient, requiring order-of-magnitude changes in this parameter to cause significant changes in simulated water levels, primarily affecting the amplitude of seasonal water level variations.
- The vast amount of observed historical water level data made it readily evident when the model was closely matching observed conditions.
- Incidental (unmeasured) recharge averaging approximately 65,000 AFY during the 1990-1999 period appeared to be reasonable, as the model was fairly sensitive to variations in this recharge amount.
- Groundwater outflow to Los Angeles County was estimated to range between 5,000 and 12,000 AFY between 1990 and 1999, most of this occurring in layers 1 and 3.
- Groundwater flow at the Talbert Gap was inland during the entire model calibration period, indicating moderate seawater intrusion conditions. Model-derived seawater inflow ranged from 500 to 2,700 AFY in the Talbert Gap and is consistent with observed chloride concentration trends over the 1990-99 period that have indicated seawater intrusion in this area.
- Model-derived groundwater inflow from the ocean at Bolsa Gap was only 100-200 AFY due to the Newport-Inglewood Fault zone, which offsets the Bolsa aquifer and significantly restricts the inland migration of saline water across the fault.
- Model adjustments (mainly hydraulic conductivity and recharge) in the Santiago Basin area in Orange significantly affected simulated water levels in the coastal areas.

- Model reductions to the hydraulic conductivity of layer 2 (Principal aquifer system) along the Peralta Hills Fault in Anaheim/Orange (Figure 1) had the desired effect of steepening the gradient and restricting groundwater flow across the fault into the Orange area. These simulation results were consistent with observed hydrogeologic data indicating that the Peralta Hills Fault acts as a partial groundwater barrier.
- Potential unmapped faults immediately downgradient from the Santiago Basins appear to restrict groundwater flow in the Principal aquifer system, as evidenced by observed steep gradients in that area, which were reproduced by the model. As with the Peralta Hills Fault, an approximate order-of-magnitude reduction in hydraulic conductivity along these suspected faults achieved the desired effect of reproducing observed water levels with the basin model.

2.6 Model Advisory Panel

The model development and calibration process was regularly presented to and reviewed by an external Model Advisory Panel. This technical panel consisted of four groundwater modeling experts who were familiar with the basin and highly qualified to provide insight and guidance during the model construction and calibration process. Twelve panel meetings were held between 1999 and 2002. The panel was tasked with providing written independent assessments of the strengths, weaknesses, and overall validity and usefulness of the model in evaluating various basin management alternatives. Key conclusions and findings of the panel regarding the transient model are summarized below.

1. Transient modeling has substantially improved the overall understanding of processes and conditions that determine how and why the basin reacts to pumping and recharge. This improved understanding, coupled with the model's ability to simulate existing and possible future facilities and alternative operations, significantly improves the District's potential ability to enhance and actively manage basin water resources.

2. Modeling has helped verify major elements of the basin conceptual model and has been instrumental in clarifying:

    - Variations in the annual water balance
    - Hydrostratigraphy of the basin
    - Horizontal flow between basin subareas
    - The potential degree of interconnection and magnitude of vertical flow between major aquifers
    - The potential hydraulic significance of the Peralta Hills Fault in the Anaheim Forebay

- Variations in aquifer hydraulic properties
- The relative significance of engineered versus natural recharge and groundwater outflow within the basin
- Numerous other hydrogeological conditions throughout the basin.

3. The ability of the model to simulate known and projected future conditions will evolve and improve as new data become available and updated calibration runs are completed.
4. Parameters used to set up the model appear to be within limits justified by known, estimated, and assumed subsurface conditions based upon available historic data.
5. Initial transient calibration completed using a nine-year calibration period (1990-1999) is considered adequate to confirm the initial validity of the model for use in evaluating a variety of potential future projects and conditions.
6. Areas of the basin that could benefit from future exploration, testing, monitoring, analysis and/or additional model calibration were identified.
7. The model is not intended nor considered appropriate for assessing detailed local impacts related to new recharge facilities or well fields. These impacts should be assessed using more detailed local sub-models and by conducting detailed field studies.
8. The model is not intended nor does it directly address issues related to availability of water for recharge, costs or institutional/regulatory constraints.
9. The model is not intended nor considered appropriate for analyzing land subsidence or solute transport.

One of the panel recommendations was that the basin model transient calibration period eventually be extended as new data for subsequent years becomes available.

2.7 Basin Model Update

2.7.1 Model Conversion from UNIX to PC

The original Basin Model was developed and used under a UNIX operating system environment in the late 1990s. With the emergence of Windows-based software developed specifically for numerical groundwater modeling, such as Groundwater Vistas, Groundwater Modeling System (GMS), and Visual Modflow, along with the evolution of higher efficiency personal computers (PCs), OCWD staff determined it would be more efficient to run the Basin Model on a PC platform and thus enabling the use of an off-the-shelf Graphical User Interface (GUI) for pre- and post-processing of model data. The chosen GUI was Groundwater Vistas (GV), due to the flexibility of the software, widespread use by other modelers, and the excellent technical support. Using GV has greatly reduced both pre- and post-processing efforts for OCWD staff thereby reducing the time required to set up model runs and to process the output results into a usable graphical format. Also, model run times have been reduced significantly on the PC as compared to the original UNIX system.

The existing Basin Model MODFLOW input files were first imported into GV and the Basin Model was then ran in GV on the PC. The resulting model-calculated groundwater elevations (heads) and water budget components were then compared with the original Basin Model results from the UNIX environment. The PC version was able to replicate the UNIX version without requiring any modifications or revisions. All of the following updates were performed on the PC version of the Basin Model using GV.

2.7.2 Model Conversion from Three to Five Layers

As discussed previously, the Basin Model originally used three layers to represent the three major aquifers in the basin; the two aquitards were represented implicitly using the MODFLOW leakance term. For the Basin Model update, OCWD staff determined that it was best to convert the aquitard layers from an implicit representation to explicitly including them in the model, which will reduce the efforts for pre-processing during calibration. Also, since modern PC processing speeds are much greater today than 10 years ago, adding these two additional aquitard layers to the model did not greatly increase simulation run times.

During the initial model development stage, the top and bottom elevations of the three aquifer system layers and intervening aquitards were hand-contoured, digitized, and overlain on the model grid to populate the model input arrays with a top and bottom elevation for each layer at every grid cell location. To explicitly represent the aquitards, these same elevations were used to define each of the two aquitard layers. In the aquifer mergence zones near the coast where erosional unconformities cause aquitards to effectively “pinch-out”, the aquitard layer thickness was nominally assigned as 1 foot.

The vertical hydraulic conductivity (Kz) values for the aquitards were previously generated as well during the initial model development stage to calculate the leakance term, therefore they were used directly in the five-layer model for the two aquitard layers. The ratio between the horizontal and vertical hydraulic conductivity was set as 1 to provide horizontal hydraulic conductivity (Kh) values for the two aquitard layers. Storativity values were also updated using the initially generated values for the aquitards.

Heterogeneous hydraulic conductivity and storativity values were represented as different zones rather than using a matrix representation in the GV model pre-processing environment. These zones facilitate changing these parameter values during model calibration.

2.7.3 Model Extension

Preliminary work to extend the Basin Model transient calibration through WY 2010-11 (i.e., through June 30, 2011) is currently in progress by OCWD modeling staff. The entire calibration period is from November 1990 through June 2011, which includes a wide range of basin storage conditions as well as a wide range in hydrology. For example, WY 2004-05 was a record-setting wet year and 2006-07 was a record-setting dry year.

1. Barrier Facilities and Injection

OCWD injection facilities for both the Alamitos and Talbert seawater intrusion injection barriers were included in the original Basin Model transient calibration (1990-99). However, since 1999, several new Talbert Barrier injection wells have gone on-line and were added to the updated five-layer Basin Model. In addition, original barrier well locations have been updated due to more accurate Global Positioning System (GPS) locations obtained over the last 10 years.

For the Talbert Barrier, per well monthly injection volumes were recorded and documented in OCWD's comprehensive water resource management database (WRMS) from July 2008 to present. Prior to July 2008, accurate per well injection totals were not recorded. Therefore, the original Basin Model evenly distributed total monthly Talbert Barrier injection across the entire barrier, with each original "legacy" injection well site having the same total monthly injection. At each injection site, the injection was distributed into the each of the appropriate aquifer layers. For the updated Basin Model prior to July 2008, the per well monthly injection volumes were estimated based on the total monthly injection volume and number of wells on-line as before . These injection estimates are currently being refined using more stringent criteria and rationale based on known timelines of when new wells came on-line and when certain wells were either on or off-line. After July 2008, since monthly injection volumes were measured and recorded in WRMS for each injection well casing, these values were used directly as model input.

For assignment of Alamitos Barrier injection in the updated Basin Model, per well monthly injection volumes directly from the WRMS database were used as before. These per well monthly volumes were not directly measured but rather were calculated by OCWD staff based on instantaneous weekly injection flow rate measurements taken by Los Angeles County Department of Public Works (LACDPW) staff operating the facilities.

2. Forebay Recharge Facilities

Monthly recharge volumes were recorded and documented in WRMS for 1990 to present and were based on observed percolation measurements by OCWD Forebay staff at the OCWD Field Headquarters in Anaheim. These monthly recharge values were used directly as model input for the individual spreading basins and facilities in both the original and updated Basin Model. Since the original Basin Model development, a couple new recharge basins have come on-line in recent years such as La Jolla Basin and Miraloma Basin, and have subsequently been included in the updated basin model.

Both the original and updated Basin Model included the same assumptions regarding the spatial distribution of Forebay facilities recharge. Vertically, all recharge was assigned to model layer 1. Laterally, facilities such as the Santa Ana River were subdivided in the model to vary the measured recharge of the entire 7-mile reach into sub-reaches to better represent field observations that portions of the river channel percolate better than other portions.

3. Groundwater Production and Dewatering

Monthly production data was extracted from the WRMS database and used in the model directly. Large system production wells account for greater than 95% of the pumping in the basin; for these wells, the only revision from the original model was to update with GPS locations, and the pumping from each well was automatically distributed to the appropriate layers based on the screened interval of each well entered into GV from WRMS. Previously, this vertical distribution of pumping was calculated outside of the model using the hydraulic conductivity and length of screen in each layer. The GV method also uses a similar algorithm but is incorporated internally as part of the integrated MODFLOW pre-processing. Precautions were taken on some wells by manually assigning the model layer(s) for production where the model layering did not appear to match with known screened intervals; such anomalous wells and/or model layering will be further evaluated during future model refinement.

For small system production wells, measured monthly per well production data does not exist; rather, only six-month billing totals were available. In the original Basin Model, total annual production from all small system wells was distributed evenly amongst each well, with a different value for model layer 1 wells as opposed to slightly deeper model layer 2 wells. A seasonal distribution was assumed in the original Basin Model equivalent to The Irvine Company (TIC) wells, which were predominantly agricultural similar to many of the small system wells. Over the last 10 years since development of the original Basin Model, monthly production has been calculated and entered in WRMS by assuming the six-month billing total for each well to be divided uniformly for all six months of that period. These calculated values retain the proper six-month total at each well and thus were used in the Basin Model update described herein.

Since 1999, representing the end of the original model's calibration period, there have been two documented local construction dewatering events within the model domain. The monthly dewatering volumes, representing both measured and estimated values, were incorporated into the Basin Model update as production in specific grid cells and stress periods and entirely within the shallow aquifer (model layer 1).

4. Unmeasured Recharge

The unmeasured or natural recharge in both the original and Basin Model included mountain front recharge and areal recharge. Mountain front recharge covered areas along Chino Hills, Peralta Hills, San Joaquin Hills, Santa Ana Mountains, and Tustin Hills. Also, recharge from the Coyote Hills area was included in the model, representing subsurface inflow from adjacent La Habra Basin in addition to surficial recharge along this mountain front. Areal recharge was separated into two areas: Forebay (unconfined) and Pressure (confined) areas.

In the Pressure area, the small amount of areal recharge represented downward leakage from the shallow Perched or Semi-Perched Zone (not modeled) rather than representing direct percolation of rainfall as in the Forebay area. Therefore, the pressure area recharge did not have seasonal or year to year variation in the model and was kept at the same amount and extended to June 2011 in the updated model. The mountain front recharge and Forebay areal recharge were assumed to be heavily influenced by rainfall; therefore the preliminary input for these parameters was based on reported rainfall data. These initial estimates will be further evaluated and refined during transient calibration, staying within prescribed limits based on OCWD's annually reported incidental recharge.

5. Specified Head Boundaries

The Pacific Ocean model boundaries in the coastal gaps where the shallow aquifer (model layer 1) is hydraulically connected to the ocean were kept as constant head boundaries set at the current approximate mean sea level condition and extended to June 2011.

A time-varying specified head boundary was used via the MODFLOW Time-Variant Specified Head (CHD1) Package (Leake and Prudic, 1991) for the Layer 1 model boundary upstream of the Santiago Basins area. The seasonal change in groundwater elevations in this area appears to be very minor and thus the small seasonal head changes originally assigned to this boundary do not have any noticeable impact on the simulated heads at nearby calibration wells. Therefore, in the updated Basin Model, this boundary was simplified to a constant head boundary without seasonal variations.

In both the original and updated Basin Model, the CHD1 package was employed along the LA county boundary with synthetic hydrographs developed from available water level data. Using additional groundwater elevation data from monitoring wells constructed after the original Basin Model development, the specified heads along this entire boundary are being refined, especially for the later years in the calibration period. The selected wells located near this boundary that were used for interpolating heads along this boundary are shown in Figure 3.

The water level data for these wells did not necessarily cover the entire modeling period and all three modeled aquifer layers; therefore, the following steps were required for interpolation:

A. Temporal interpolation. When water level data for a well in a specific aquifer did not cover all of the monthly stress periods, linear temporal interpolation was conducted to fill in the missing stress periods. Water level data from these wells were frequent enough to adequately illustrate the maximum and minimum water level each year and show seasonal variation. For these wells, linear interpolation was considered adequate to fill in a few missing monthly water level data.

B. Spatial interpolation from nearby well locations to active model boundary cell locations. Once the temporal interpolation (described in part A above) was completed, water levels were interpolated to all active model boundaries from the actual well locations used (Figure 3). First, the well locations were projected to the closest model cell along a flow line (June 2011) and the water levels of that cell were set equal to those of the well in that layer and all stress periods. Then, a one-dimensional (along the model boundary) interpolation was conducted for the active cells on the model boundary between the cells with the set water levels. Since the gradient along the boundary was not normally uniform, during interpolation, the contour map from June 2011 was used as a reference to calculate the gradient from well to well and then used as a factor for linear interpolation between that well and the grid cell. The contour map for June 2011 was chosen because it was the most current contour map available at the time of this update; it has not yet been shown whether or not using the June 2011 contour map was a better choice than using a standard linear interpolation. The boundary heads can be further refined during transient calibration as necessary.

6. Calibration Target Wells

Approximately 100 target or calibration wells were used in the original three-layer Basin Model. Several additional monitoring and production wells have been constructed in recent years since the original model development. Therefore, to ensure a thorough evaluation of the extended model period, especially for the more recent years, additional calibration wells were selected for the five-layer model, as shown in Figure 3. Hydrographs were created for each calibration well, comparing observed and simulated water levels (heads).

2.8 Future Model Refinement

Since the original Basin Model development in 1999-2000, many additional wells have been constructed within the model domain. The majority of these wells have lithology logs and geophysical logs that can be used to update and refine the basin-wide geological cross-sections that were used to define the original Basin Model layer elevations. The basin-wide cross-sections will be updated using the new well information, and the model layer elevations will subsequently be refined, targeting certain areas with known discrepancies that previously were lacking data, such as the LA county portion of the model and the Deep aquifer (model layer 5) in the Anaheim Forebay area. Further calibration of aquifer parameters may be necessary after layer revisions. The model will be extended to the most current water year at that time.

2.9 Applications of the Basin Model

Typical applications of the Basin Model include the estimate of the effects of potential future pumping and recharge projects on groundwater levels, storage, and the water budget. The storage coefficients determined during the original Basin Model calibration are also used via the District’s Geographic Information System (GIS) along with measured water level records stored in the WRMS database to make the annual change in groundwater storage estimate (OCWD, 2007).

Another recent application of the Basin Model was to estimate the effects of additional recharge from new Miraloma Basin on the GWRS subsurface retention time buffer area located in the Anaheim Forebay (OCWD, 2011). Miraloma Basin is located in the vicinity of Kraemer and Miller Basins (Figure 5). Kraemer and Miller Basins were the only surface recharge facilities originally permitted to recharge GWRS water (RWQCB, 2004). In accordance with the California Department of Public Health’s (CDPH) Draft Groundwater Replenishment Regulations at the time of the permit’s adoption, OCWD was required to develop a six-month buffer area downgradient of Kraemer and Miller Basins, inside which drinking water wells could not be constructed or operated. The original six-month buffer area was determined on the basis of a sulfur hexafluoride (SF_6) artificial tracer test conducted by Dr. Jordan Clark of University of California at Santa Barbara (UCSB) (Clark, 2009). OCWD subsequently acquired the Miraloma property and developed it into a recharge basin intended primarily for GWRS water recharge.

In order to determine the necessary modifications to the Anaheim Forebay GWRS buffer area, the existing tracer test-determined buffer area was used in conjunction with three-layer Basin Model simulations featuring MODPATH runs (OCWD, 2011). A six-month model baseline condition was established for all nearby recharge basins using the period January through June 2008 to coincide with the same local recharge conditions as during the UCSB SF_6 tracer test. However, the simulation was actually started in November 2007 to allow the numerical solution to stabilize for the first two months of the simulation prior to the six-month period of interest. In the baseline simulation, no recharge was considered for Miraloma Basin. In the second simulation, the same time period was used and all conditions were kept identical to the baseline run, except for adding approximately 87 acre-feet per day (afd) of recharge at the proposed Miraloma Basin for the six-month period. The 87 afd was considered to be a maximum recharge rate for a new recharge basin in this vicinity. Nearby La Jolla Basin, when new, had a maximum recharge rate of approximately 8 afd per acre of wetted recharge area. Therefore, assuming the same per acre maximum recharge rate for the proposed 11 acres of wetted area at Miraloma Basin equated to 87 afd. With GWRS recycled water recharged at adjacent Miller Basin, operational data indicated that the maximum recharge rate can be maintained for six months without significant decay. Therefore, the maximum assumed rate of 87 afd for the proposed Miraloma Basin was held constant for the entire six-month simulation period. Using the maximum expected recharge rate ensured that the model results represented a “worst-case” or furthest extent estimate of the 6-month buffer area.

After running the Basin Model for both scenarios (baseline and Miraloma recharge), a particle tracking analysis was conducted by running the computer code MODPATH (Pollock 1994) along with the two sets of Basin Model groundwater flow field results. The particles were placed in the Basin Model grid cells corresponding as closely as possible to the edges of Miller, Kraemer and Miraloma basins. The particles were released in January 2008 and forward tracked over the six-month period through June 2008. Based on the particle tracking results from the two simulations with and without the proposed Miraloma recharge, the percent change in the six-month travel distance was calculated for the individual particle flow paths emanating from Kraemer, Miller, and Miraloma basins. Then, the model-predicted percent change in six-month travel paths was applied to the existing Kraemer/Miller buffer area boundary. As such, the updated six-month buffer zone still incorporated the overall shape of the original buffer area based on the tracer test results, but also incorporated the model-predicted incremental change due to the proposed recharge at Miraloma Basin.

The model results indicated that the groundwater flow directions in the study area will not change due to the proposed recharge except in the immediate vicinity of Miraloma Basin. Over the six-month period, the resultant MODPATH-predicted groundwater travel distance increases due to the proposed Miraloma recharge along the various flow paths (particle tracks) emanating from Kraemer, Miller, and Miraloma basins ranged from 0 to 10%. Accordingly, the previous 6-month buffer area was modified along its margins to account for the model-predicted changes using GIS software (Figure 5), overall, the updated buffer area extends a maximum of 10% further downgradient to the southwest. At Miraloma Basin, the updated buffer area extends further to the south since the previous buffer area did not include Miraloma or its local mounding effects.

Miraloma Basin went into service in July 2012 and immediately began receiving GWRS water for recharge. OCWD is in the process of acquiring and developing another new recharge basin, La Palma Basin, that is located approximately ¼-mile south of Kraemer and Miraloma Basin. Like Miraloma Basin, La Palma Basin is intended to recharge primarily GWRS water. As such, a similar modification to the GWRS retention time buffer area will be necessary, though new CDPH regulations allow for as little as two months retention time. OCWD has proposed using a similar buffer area modification procedure for La Palma Basin as was used and approved for Miraloma Basin.

3 Talbert Model

3.1 Existing Talbert Model

Between 1999 and 2000, OCWD contracted with Camp Dresser & McKee Inc. to develop a detailed groundwater flow model of the Talbert Gap (Figure 6) and surrounding area for the purpose of evaluating and estimating the amount and location of fresh water injection wells needed to control seawater intrusion under current and projected future basin conditions. The Talbert Gap modeling effort was undertaken as part of the design scope of work for Phase 1 of the GWR System, which included expansion of the existing Talbert Seawater Intrusion Barrier. The configuration and initial calibration of the Talbert Gap Model and further model refinement and calibration were documented by Camp Dresser & McKee Inc. (2000, 2003).

Consistent with the Basin Model Advisory Panel’s findings, OCWD determined that a more detailed model of the Talbert Gap was necessary to evaluate the local water level changes associated with various potential injection barrier alignments and flow rates. The Talbert model comprises an area of 85 square miles and uses the MODFLOW code (Harbaugh and McDonald, 1996) with 13 vertical layers and 509,000 grid cells (250 feet x 250 feet horizontal dimensions). Figures 6 and 7 show the model area and layering schematic, respectively. The original model (CDM, 2000) modeled the aquitards implicitly and had seven aquifer layers; subsequent refinement work by CDM modeled the aquitards explicitly for 13 vertical layers. The model layering generally follows the conceptual model of aquifer-aquitards developed in the 1960s for coastal Orange County by the California Department of Water Resources (DWR, 1966; DWR, 1968)

Key findings of the Talbert Gap model are summarized below.

- Depending on the amount of basin production, particularly near the Talbert Barrier, 30 million gallons per day (mgd) (approximately 34,000 afy) of injection will substantially raise water levels, yet may not be sufficient to fully prevent seawater intrusion in the Talbert Gap if groundwater production increases in the future. Additional injection wells beyond those planned for Phase 1 of the GWR System may be required.

- Under projected 2020 conditions, the future Talbert Barrier may require an annual average injection rate of up to 45 mgd based on the results of existing analyses. This estimated future injection requirement will be further evaluated as additional data are collected.

The Talbert model inland boundaries do not coincide with hydrologic or geologic features, e.g., recharge area, faults. Therefore, simulated water levels are highly influenced by the time-varying water levels specified along the boundaries. For future Talbert model predictive runs, the basin model should be used to generate water levels that can then be specified along the inland Talbert model boundaries.

- The Talbert model was less sensitive to adjustment of hydraulic conductivity and storage coefficient than the Basin Model, primarily because of the stronger influence of the specified-head boundaries in the Talbert model.

3.2 Model Extension

Preliminary work to extend the Talbert model transient calibration through WY 2011-12 (i.e., through June 30, 2012) is currently in progress by OCWD modeling staff. The entire calibration period is from November 1990 through June 2012, which includes a wide range of basin storage conditions as well as a wide range in hydrology.

1. Barrier Injection

   Injection volumes at Talbert seawater barrier wells were calculated based on the total monthly injection volume and number of injection wells online before July 2008. These calculations will be refined during model calibration. After July 2008, injection volumes were recorded and documented for each barrier well casing in WRMS, and therefore available for direct use in the model. Because of the high level of vertical refinement in the model (13 layers) and in the construction of the injection wells, injection volumes can typically be assigned to a single discrete layer. Where the injection interval covers more than one model layer, injection volumes are distributed automatically by GV based on the transmissivity of the layers targeted for injection at each injection well location.

2. Groundwater Production and Construction Dewatering

   Monthly production volumes were updated using the most current data from the WRMS database. Pumping for each well was automatically distributed to each layer in GV based on the screened intervals and transmissivity values.

   As was described in the Basin Model update section, two isolated construction dewatering events occurred within the model domain since the end of the original model calibration period. The dewatered volume was incorporated into the model as production in specific grid cells and stress periods in the Talbert aquifer (Layer 1).

3. Areal Recharge

   The Talbert model area is located within the pressure (confined) area of the Basin, where the recharge amount is not directly related to rainfall data.

Therefore, consistent with the previous original model and Basin Model, the areal recharge is kept constant throughout the model and all stress periods.

4. Specified Head Boundaries

The Talbert model utilizes the time-varying specified head boundary (CHD1 package in MODFLOW) on three sides of the model domain, and a constant head boundary at the ocean front in both the Talbert and Bolsa gaps in model layer 1. The inland time-varying head boundary was developed in the original model using a combination of Basin Model simulated heads and available observed water level data along the boundaries. Head values were assigned to all active model cells on the model boundary for each stress period and all seven aquifers (not aquitards).

Attempts have been made to use this method to generate the boundary condition for the extended calibration period. However, the results have not been satisfactory so far, partially because the basin model is still under revision with the more recently added years not fully calibrated yet, and the Basin Model update only extends to June 2011, which is one year less than the Talbert model extension.

With the availability of additional water level data from recently drilled wells and/or multi-port wells, only observed water level measurements near the inland model boundaries were used to create the synthetic hydrographs for populating CHD1 package input files. Spreadsheets were developed to temporally and spatially interpolate the observed heads to the active boundary cells for all stress periods and all layers using these selected wells. The methodology is similar to what was described in more detail above for the Basin Model update along the LA County specified head boundary.

In order to evaluate the boundary effect, the boundary heads for the original 108 monthly stress periods (Nov. 1990 – Oct. 1999) were not changed. The boundary update only applies to the extended stress periods (Nov. 1999 – Jun. 2012). However, during future calibration, boundary heads for the entire calibration period will be updated as necessary using all available water level observations near the inland boundaries.

The selected wells used along the boundary for interpolation for extending the calibration period are: GGM-1, WMM-1, SAR-9, HBM-1, HBM-6, SC-6, OCWD-BS105, OCWD-BS106, IDM-2, GGM-3, OCWD-M48, OCWD-CTG1, and NBGC-GA10 (Figure 8). The majority of these wells are either nested or multi-port monitoring wells. The Westbay multi-port monitoring wells provided the most extensive data in developing the lateral boundaries since the majority of the seven aquifer layers were covered by the various zones monitored at these sites. Some of the wells listed above were also used in the original calibration by CDM.

The water level data for these wells did not necessarily cover the entire modeling period and all seven aquifers; therefore, the interpolation required three steps:

A. Temporal interpolation. When observed water level data for a well in a specific aquifer did not cover all of the monthly stress periods, temporal interpolation was conducted as the first step. Linear interpolation was used to fill in the missing months.

B. Vertical interpolation. When a monitoring well did not have a measurement port in every aquifer layer, vertical interpolation of observed water level data from vertically adjacent aquifer zones above and below the desired aquifer was required. The difference in water levels between aquifers at nearby wells with similar geology and surrounding pumping conditions was applied to the well with the missing port, as long as water level data for at least one of the aquifers was available for all stress periods. This procedure was only used at a few locations, including GGM-1 for layer 5, OCWD-M48 for layers 5, 7 and 9, SC-6 for layer 9. Overall, each aquifer had adequate number of wells for a reasonable spatial interpolation. The easternmost boundary near the 55 Freeway had the least available observed data for developing the specified heads.

C. Lateral interpolation from the selected boundary well locations to all active boundary cells. Once the temporal and vertical interpolation was completed to define synthetic hydrographs for all layers for all stress periods at the selected locations, water levels were interpolated horizontally to all active model boundary cells. First, the selected well locations were projected to the closest model cell, adjusting the water levels of that cell based on the flow direction and gradient. Then a one-dimensional (along the model boundary) linear interpolation within each layer was conducted for the active cells on the model boundary between the cells with the assigned water levels.

5. Calibration Target Wells

In addition to the numerous calibration or target wells used in the original Talbert model, additional target wells were selected for the Talbert model extension, especially in the area where no wells were existed in the original model, mostly in the Newport Mesa area (Figure 6).

3.3 Future Model Refinement

As was discussed with the Basin Model Future Refinement, a better understanding of the Talbert Gap has been obtained since the original CDM work due to the several new monitoring wells that have been constructed since then. Talbert area geologic cross-sections originally developed by DWR (DWR, 1966) have been refined by OCWD staff, and the resulting refinements to the aquifer layering will be incorporated into the Talbert Model. In addition to model layer refinements, there are a few other issues that need to be addressed during model refinement, such as Talbert aquifer extent, fault representation, etc. Corresponding aquifer parameter adjustment may be needed for calibration.

3.4 Applications of the Talbert Model

In addition to helping to guide the planning, location, and hydraulic effectiveness of supplemental injection wells for the Talbert Barrier during pre-GWRS planning activities, the Talbert Model was also used to estimate the general flow paths and subsurface residence time of barrier injection water. Initial analyses were carried out using the original seven layer model coupled with the USGS particle tracking code MODPATH (Pollack, 1994). One-year subsurface retention time maps were created for all aquifers (OCWD, 2000) receiving injection water. The maximum horizontal extent/travel revealed through this analysis was the basis for the Talbert Barrier's recycled water retention buffer area (Figure 9), inside which new drinking water production wells are not allowed, as required by the original California Department of Public Health requirements contained within the original permit to operate GWRS (RWQCB, 2004; OCWD, 2005).

A similar travel time assessment was conducted later for the Demonstration Mid-Basin Injection (DMBI) Project using the 13-layer Talbert Model (DDBE, 2009; OCWD, 2011). The DMBI project involves the construction and testing of initial injection (one well, MBI- 1) and monitoring facilities (two wells, SAR-10 and SAR-11) to help assess the feasibility of injecting GWRS water into the Principal aquifer in the central portion of the Basin; the DMBI facilities are located approximately three miles north-northeast of the Talbert Barrier, along the Santa Ana River (Figure 10). In support of the project's CDPH regulatory permitting and California Environmental Quality Act (CEQA) compliance, the MODPATH code was used to determine preliminary estimates of subsurface travel time to the nearest drinking water wells, IRWD-12 and IRWD-17, from the MBI-1 site (Figure 11). The shortest mean transport time was estimated at 4.2 years for IRWD-12, well in excess of the minimum two months currently required by CDPH (CDPH, 2013).

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Figure 1: Basin Model Extent

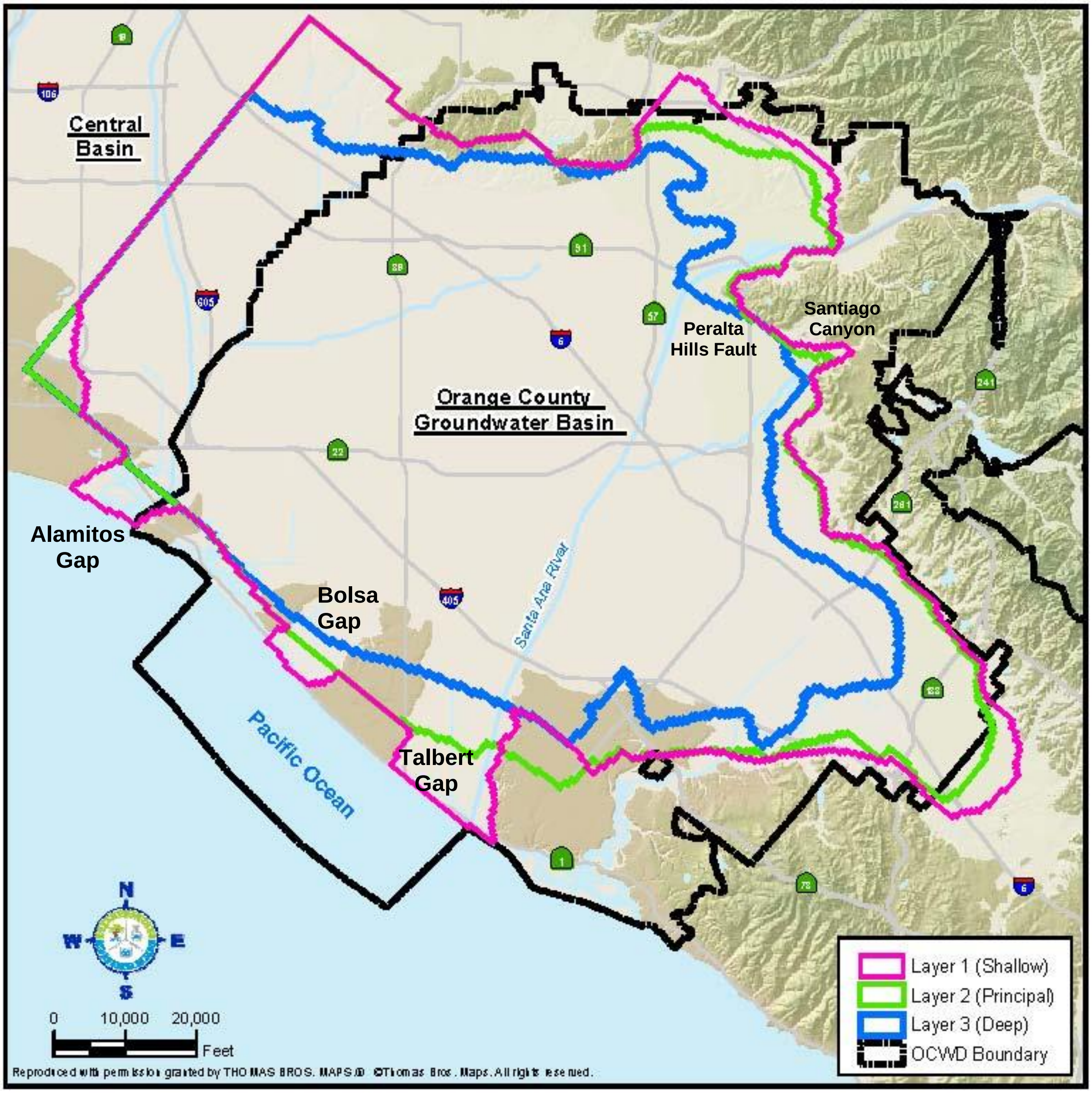

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Figure 2: Model Development Flowchart

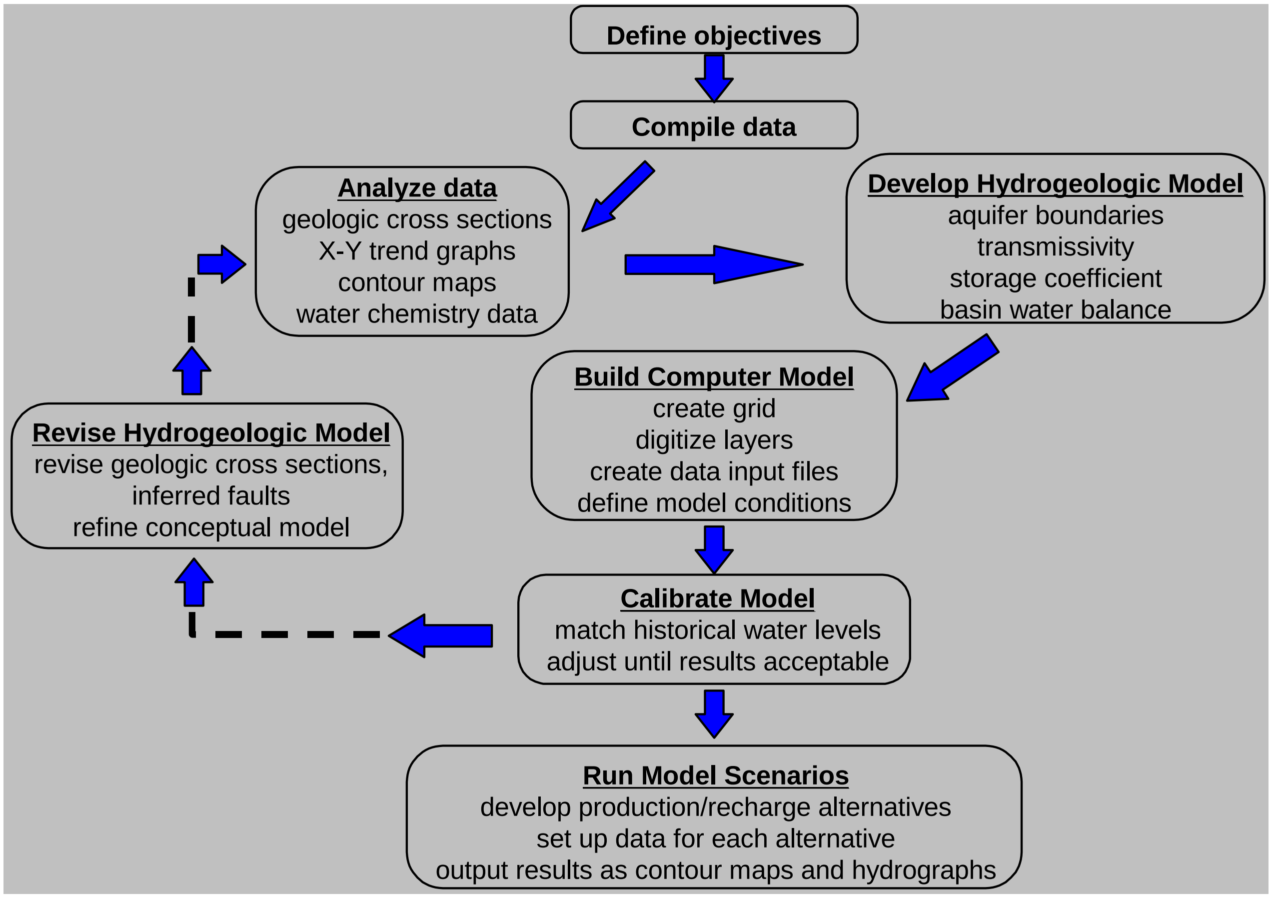


Figure 3: Basin Model Calibration Wells and Boundary Wells

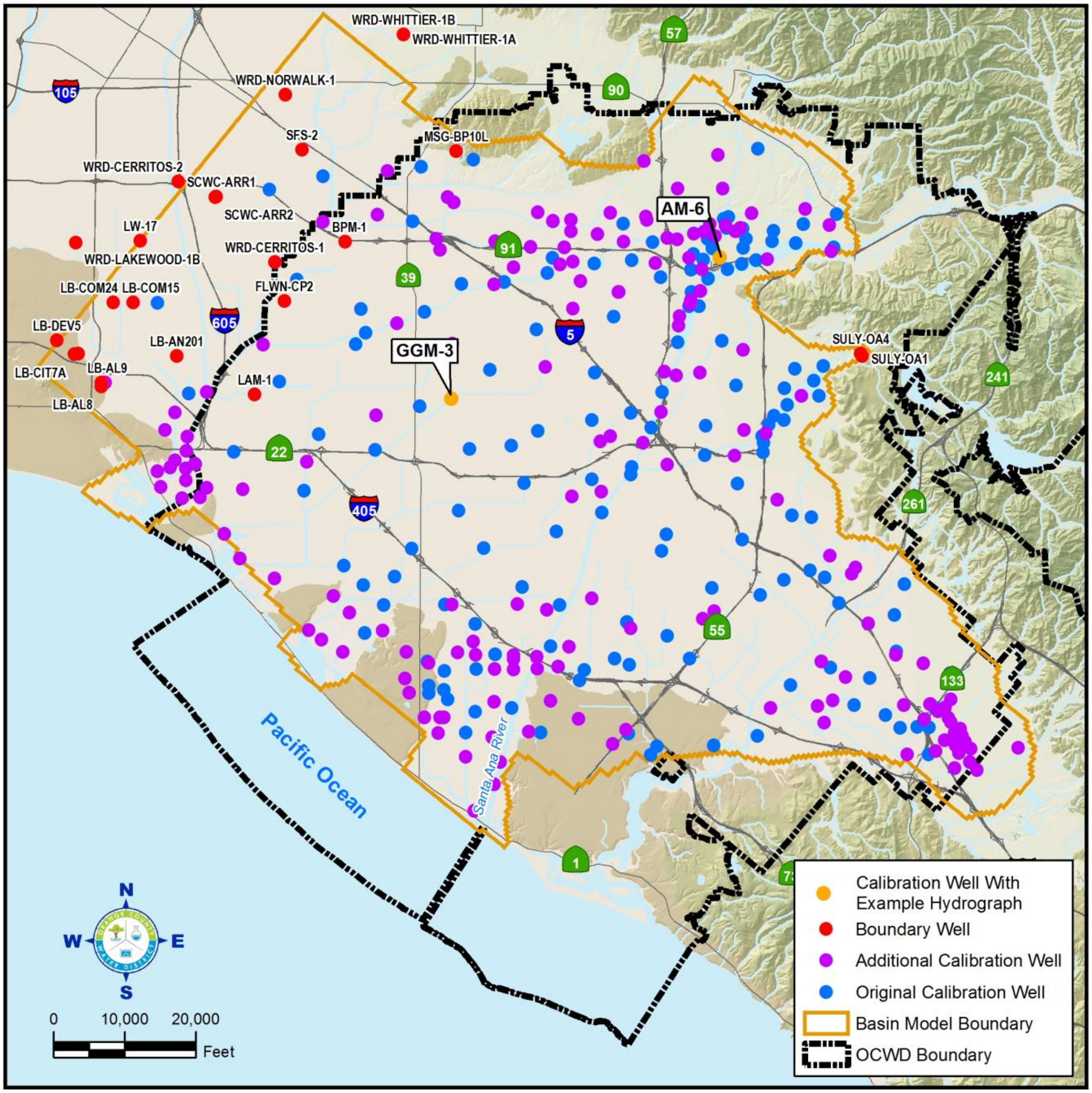
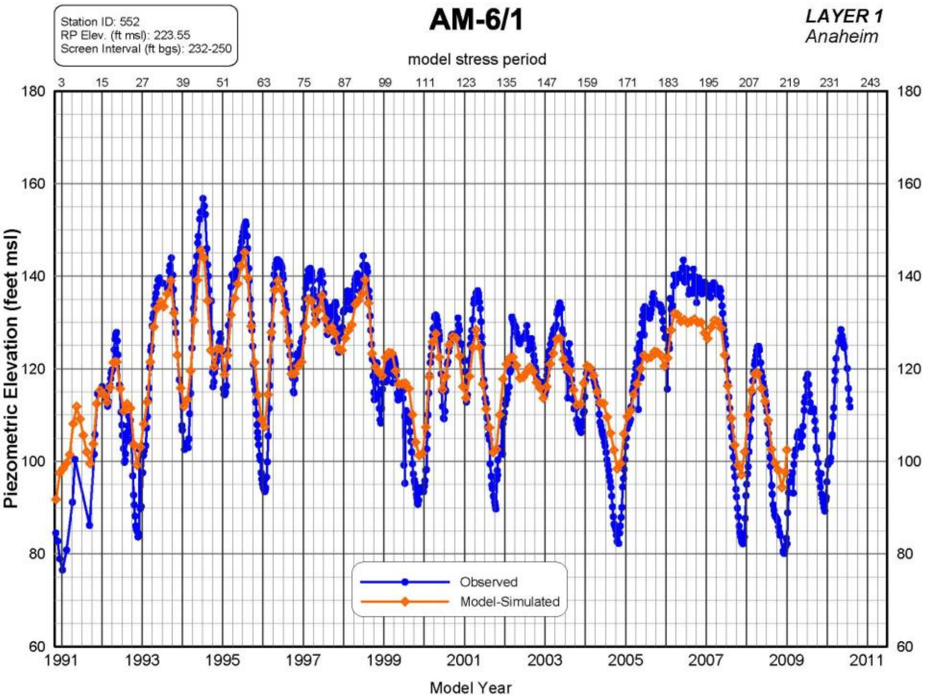


Figure 4: Calibration Hydrographs for Monitoring Wells



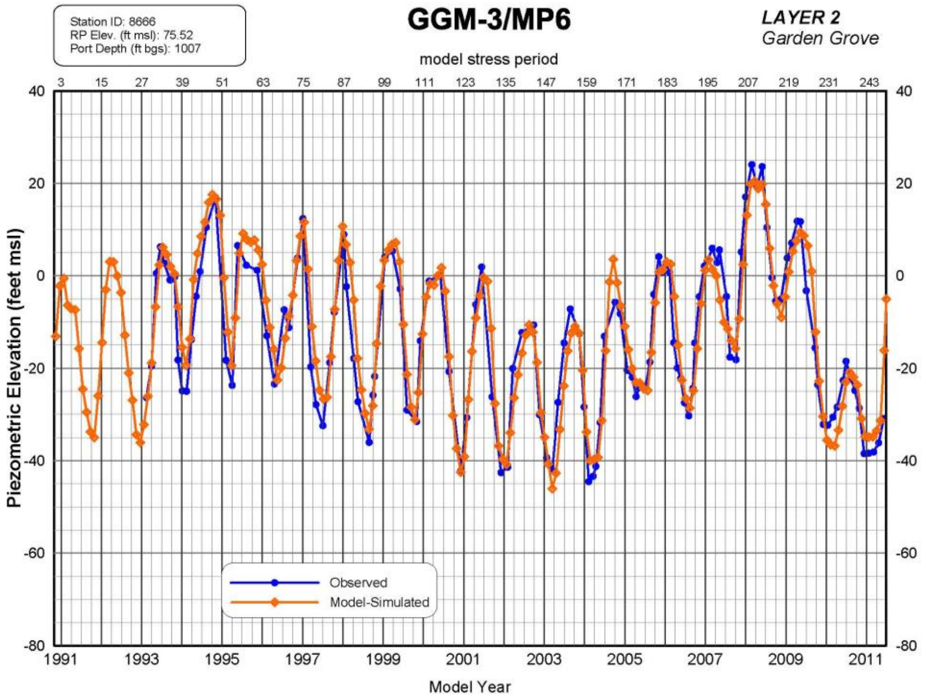


Figure 5: Miraloma Basin Location and Retention Time Buffer Area

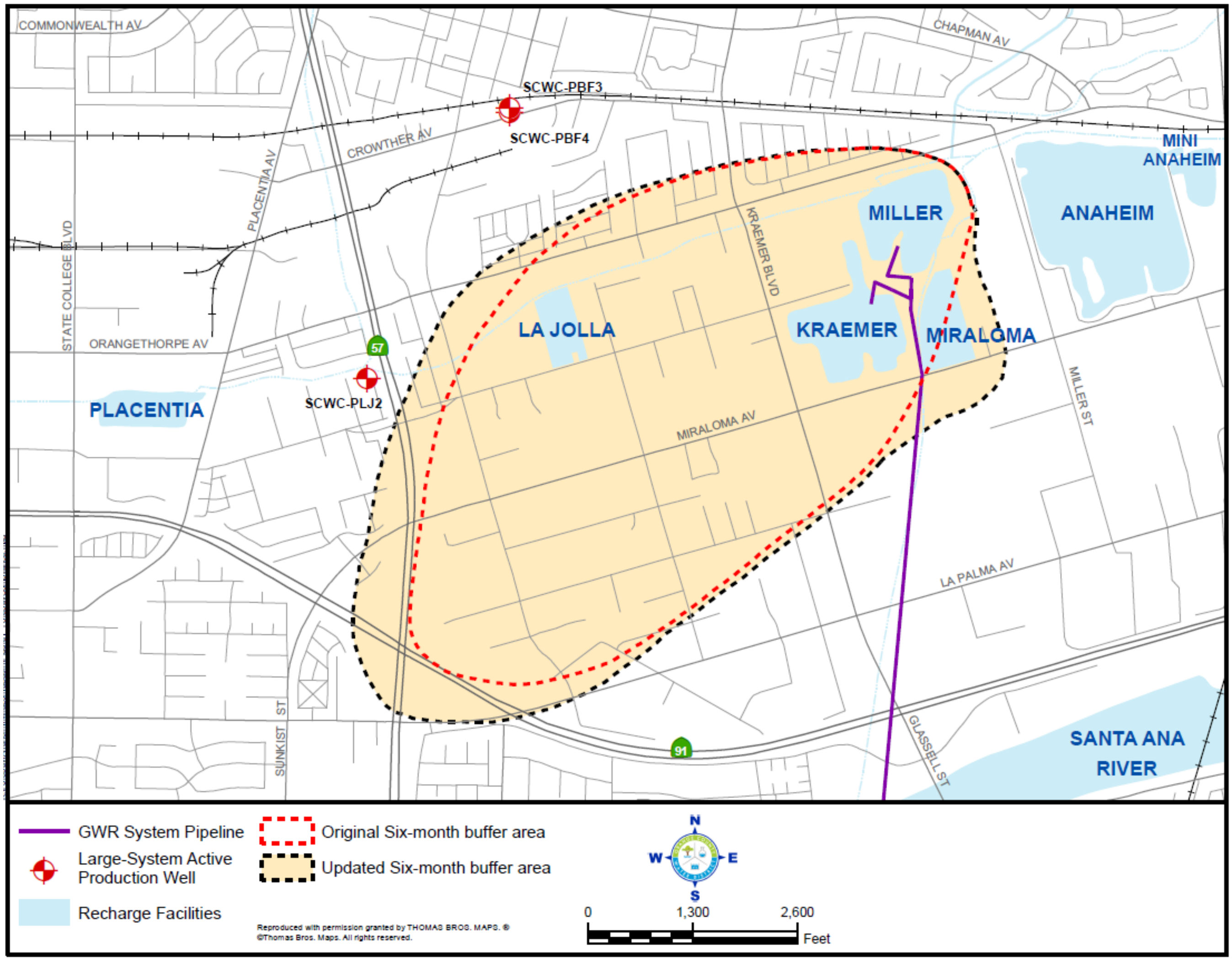


Figure 6: Talbert Gap Model and Basin Model Boundaries

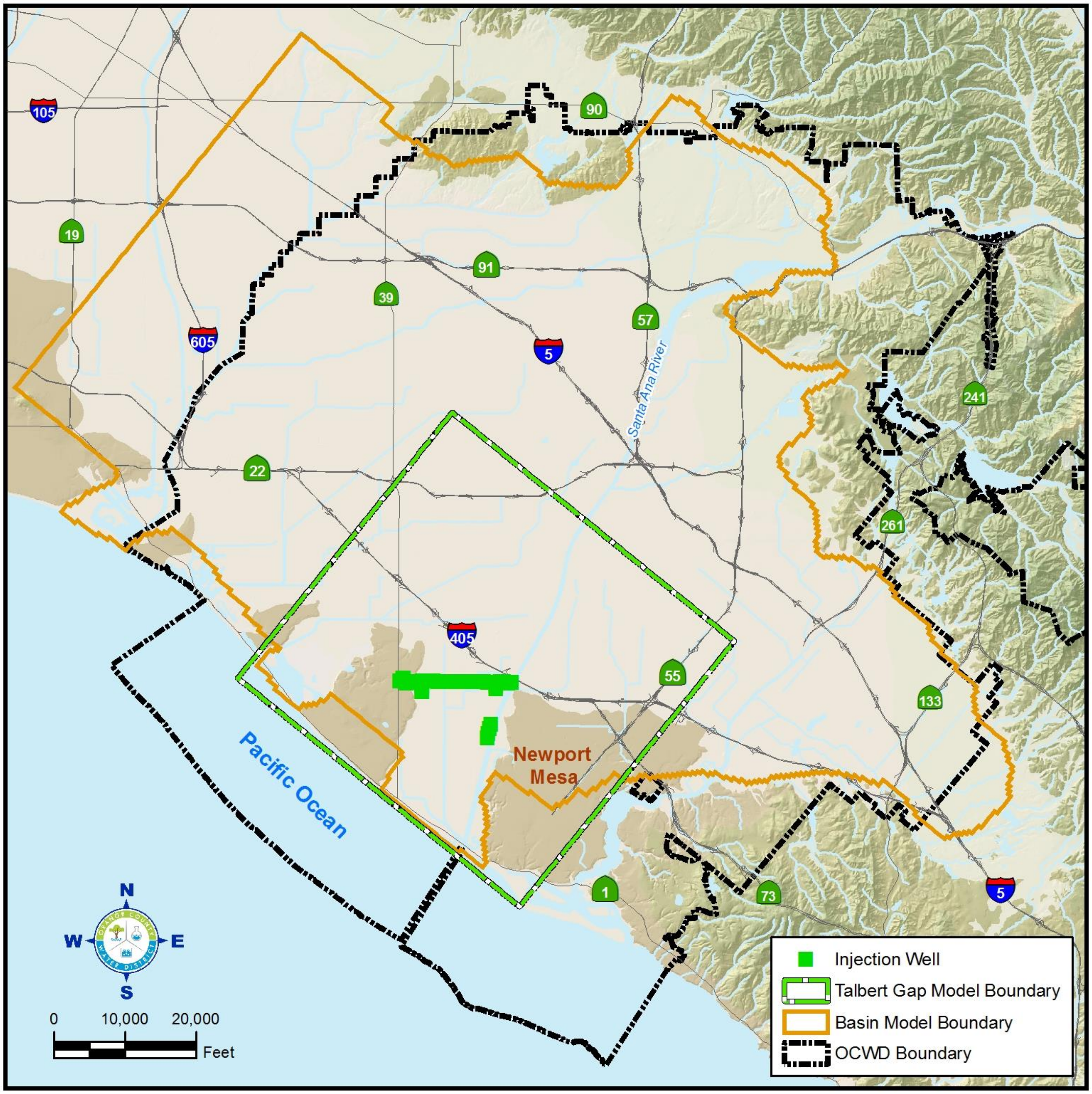


Figure 7: Talbert Model Aquifer Layering Schematic

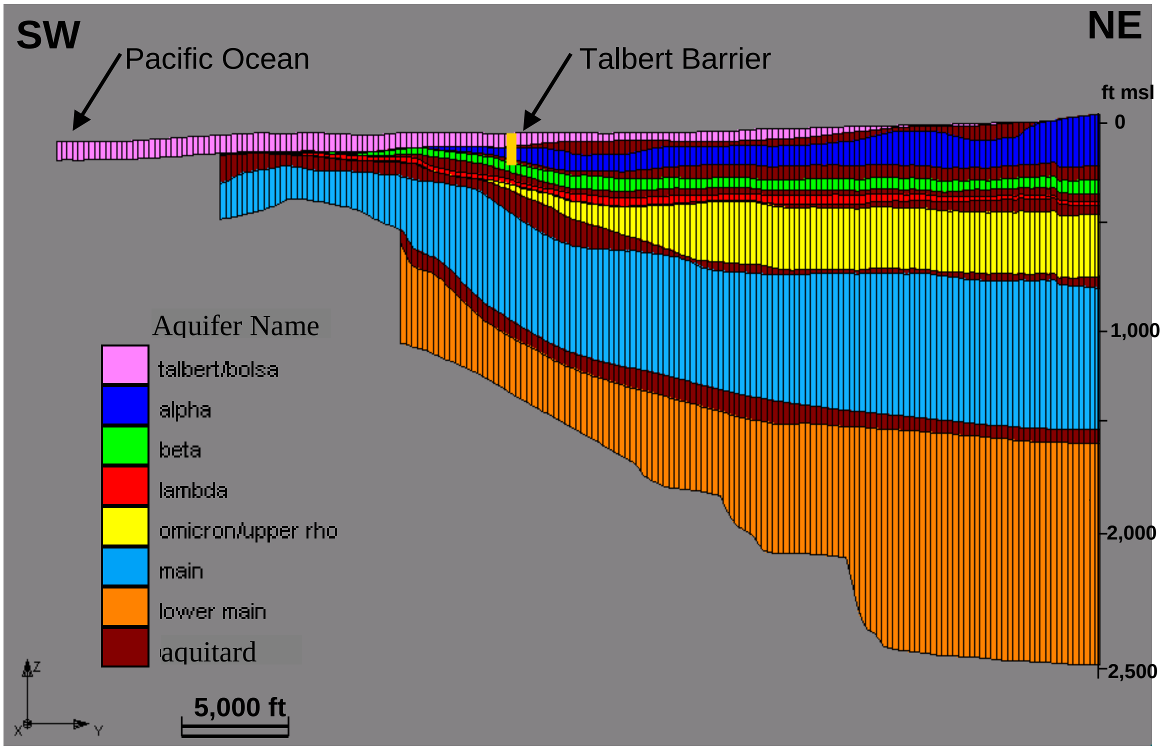


Figure 8: Talbert Model Calibration Wells and Boundary Wells

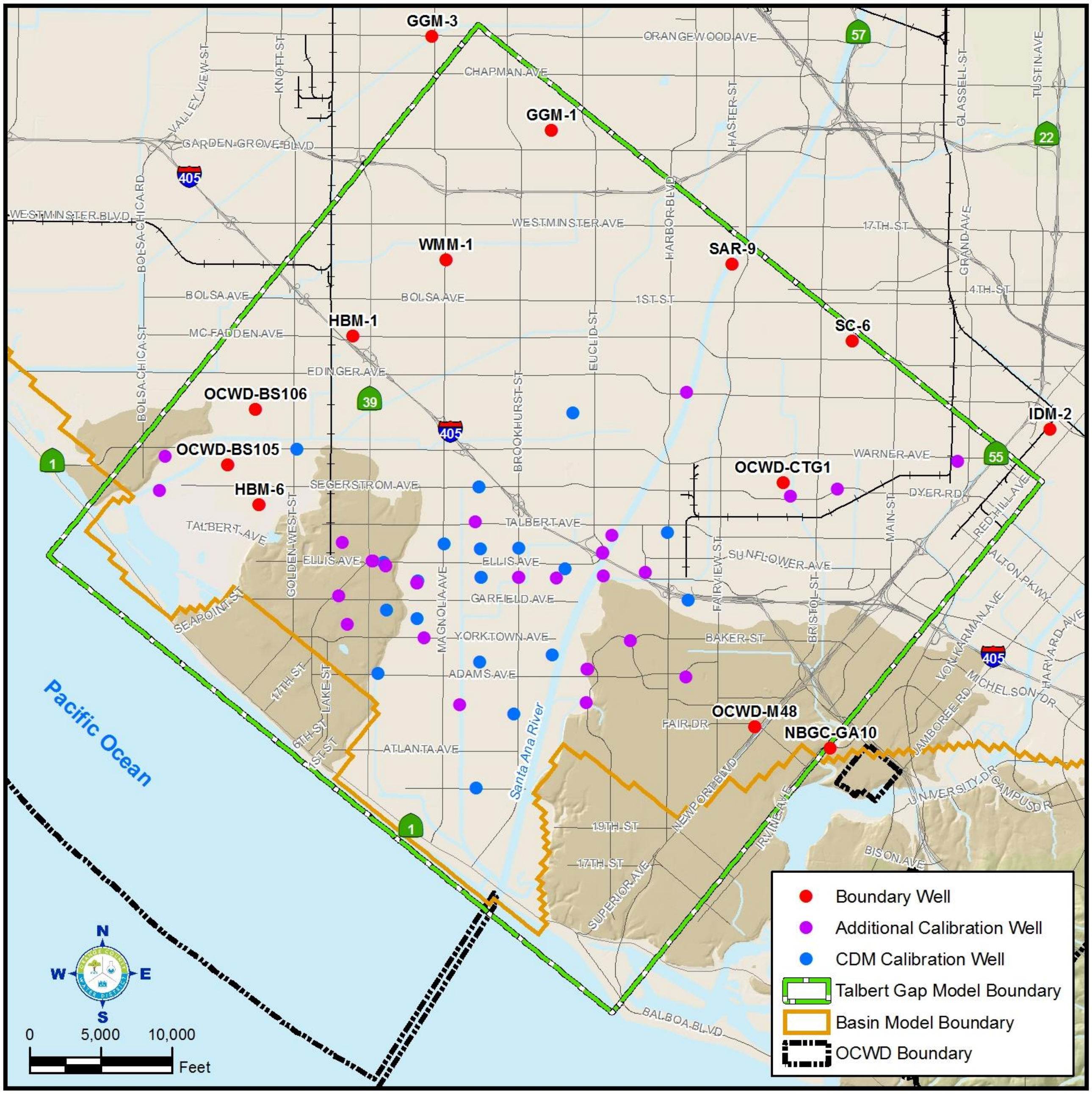


Figure 9: 2000-Foot and 1-Year Travel Zone at the Talbert Gap Barrier

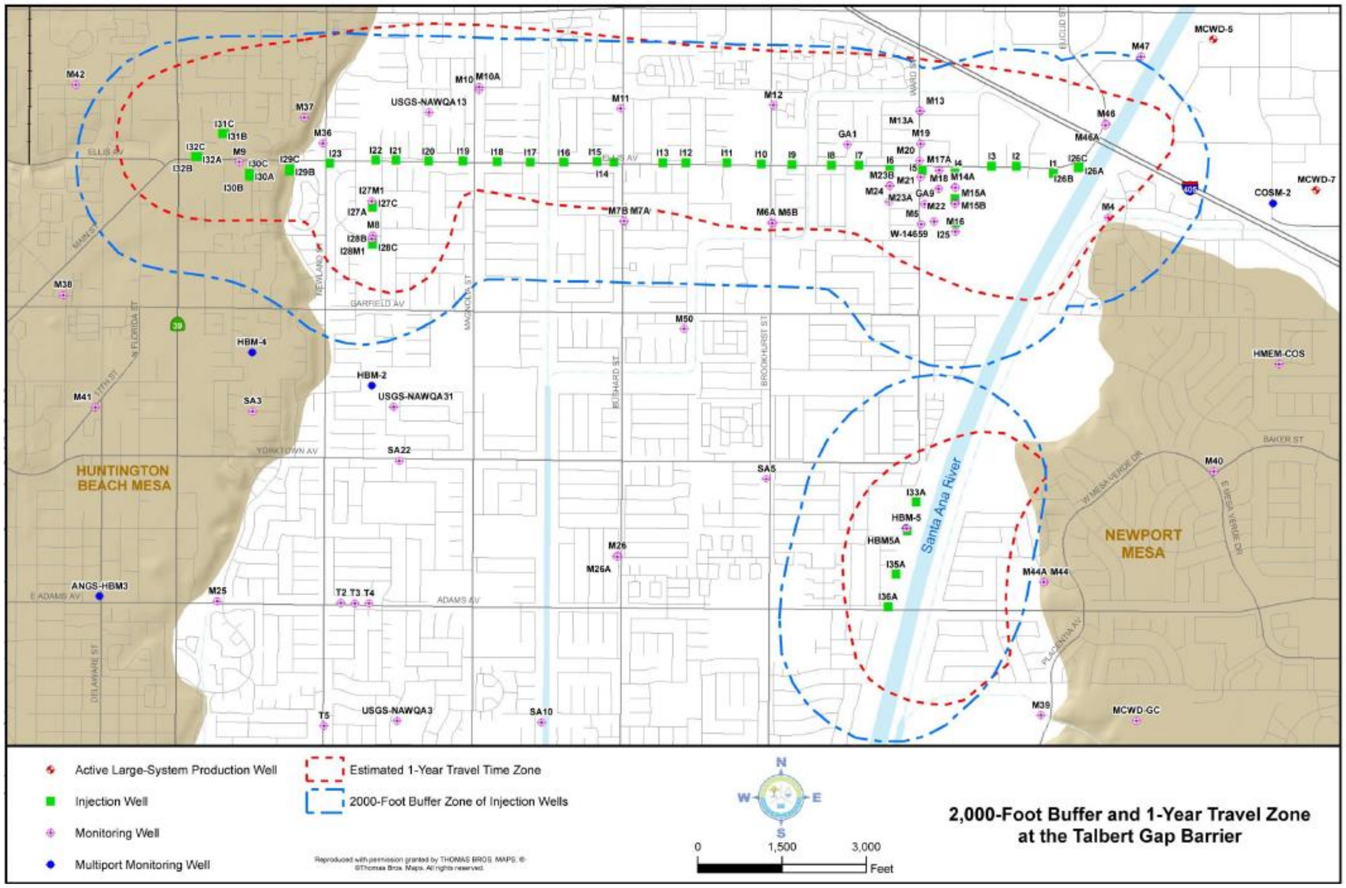
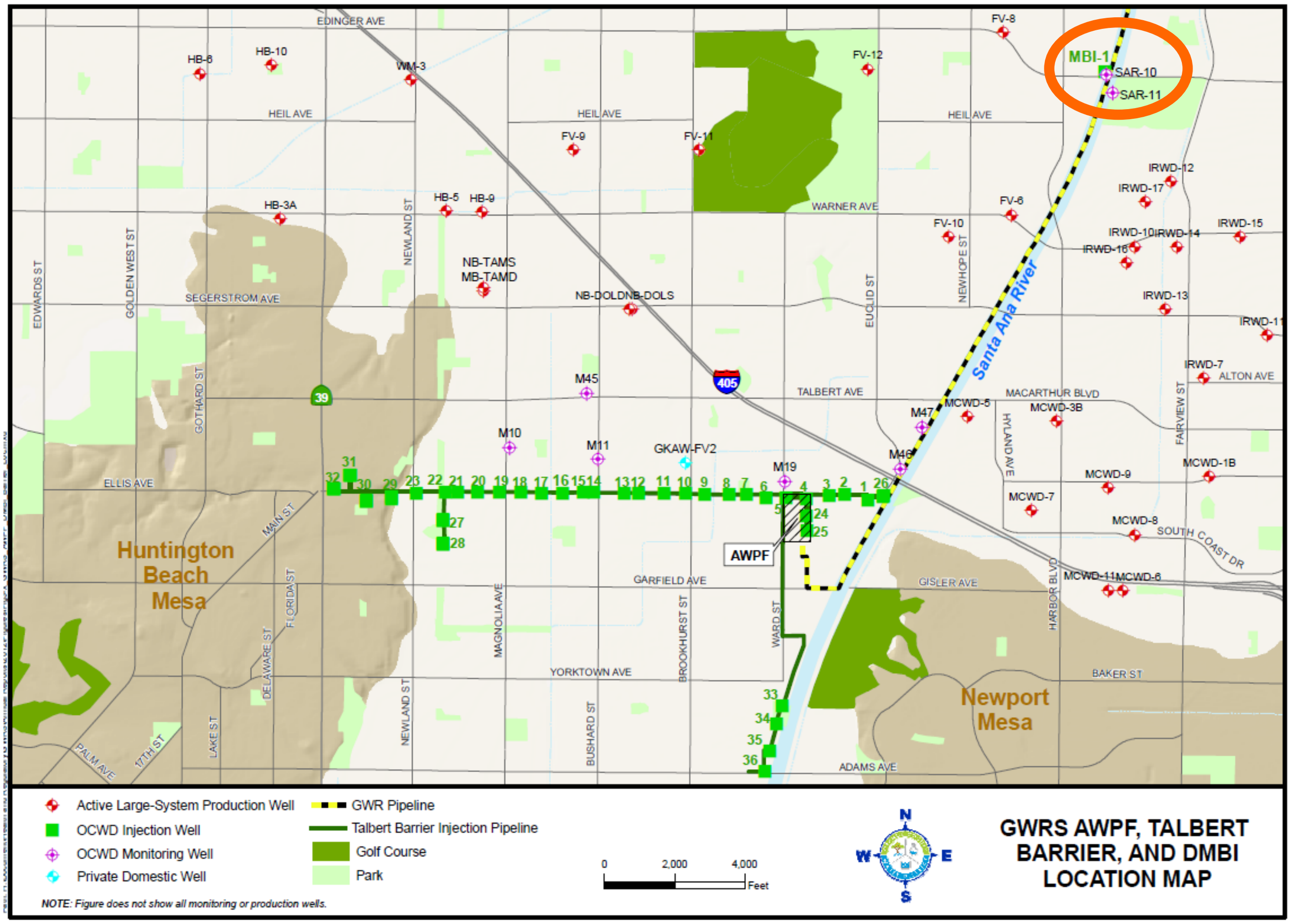


Figure 10: GWRS AWPF, Talbert Barrier, and DMBI Location Map



NOTE: Figure does not show all monitoring or production wells.

Figure 11: Demonstration Mid-Basin Injection Subsurface Retention Time Assessment