Groundwater Flow Modeling of the Arlington Basin to Evaluate Management Strategies for Expansion of the Arlington Desalter Water Production

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Abstract Water supply reliability in Southern California is facing serious problems because of reduction in the availability of water from the State Water Project and Colorado River, drought, and growing concerns about environmental restoration. Groundwater sources supply more than fifty-five percent of domestic demands in the Western Riverside County. Western Municipal Water District is planning to increase water supply reliability by expanding the Arlington Desalter production which requires additional groundwater pumping from the Arlington Basin. Western was concerned that increasing groundwater pumping will cause excessive decline in groundwater levels, leading to decreased yields at existing Desalter wells. Three-dimensional groundwater flow model was developed for the Arlington Basin to investigate different water management strategies. Five groundwater management scenarios were run for a 30-year time period. The five model runs were used to determine the feasibility of the Arlington aquifer system to supply groundwater to the Arlington Desalter over the 30-year life of the facility. Model simulation results showed that long-term groundwater pumping from the existing Desalter wells is not sustainable without artificial recharge. However two of the modeling scenarios which incorporated a combination of artificial recharge and new production wells, were shown to meet the increased Desalter yield requirements as well as minimize adverse impacts.

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1 Introduction

Water supply reliability in Southern California is affected by a variety of factors such as a reduction in the availability of water from the State Water Project and the Colorado River, multi-year drought, limited local water resources, growing concerns about environmental restoration (e.g., the Sacramento-San Joaquin Delta), and water quality issues. In addition, vulnerabilities in regional and statewide infrastructure could increase due to major seismic events. For example, an earthquake could cause massive levee failures or salt water intrusion into the Bay-Delta, reducing or even shutting down the exportation of water for months, if not years (Harder 2006). In the future, the main driving forces for the declining water supply in Southern Californian will be increase in water demand (due to population growth and industrial expansion), water pollution from industries and agriculture, growing urbanization, and climate change. The growth of urban societies through-out the world is predicated to increase up to 60% in the year 2030 (Gholami et al. 2010). Population growth in California is expected to increase by approximately eleven million residents over the next 25 years, with half of that growth occurring in the warmer inland areas of Southern California (Hanak and Davis 2006).

Global estimates indicate that the average annual groundwater production for the world is approximately 775 km^3 which represents about one-sixth of the total freshwater abstraction (Qureshi et al. 2010). In Western Riverside County, the major water supplies are groundwater and imported water, which account for approximately ninety-five percent of domestic demands, with surface water sources accounting to only one percent. Recycled water is used for landscaping, irrigation, and augmenting surface lakes, and accounts for approximately three percent of the total water demand. Groundwater sources supply more than fifty-five percent of domestic demands in the County. Developing local water sources (including brackish groundwater recovery) is important to increase water supply reliability for Western Riverside County as population growth will substantially increase future water demands.

2 Background and History

The Arlington Groundwater Basin (Basin) is within Western Municipal Water District's service area, (Western Riverside County, California, USA). The Basin resides in the Santa Ana River (SAR) watershed. The groundwater basins in the SAR watershed are defined by the California Regional Water Quality Control Board's (RWQCB) basin plan amendment for TDS/Nitrogen management (RWQCB Santa Ana Region 2004). The RWQCB has established water quality basin plan objectives for Total Dissolved Solids (TDS) and nitrate-nitrogen for management zones within the SAR Watershed, including the Arlington Groundwater management zone. The Arlington Basin is located in a semi-arid region characterized by dry and hot summers and precipitation during the months of October through April. This climate results in significantly higher water demands in the summer than in the winter. Average monthly maximum and minimum temperatures are 26.2 and 10.5 centigrade, respectively, and average annual reference evapotranspiration is approx-

imately 141.0 cm (Western 2010). The long-term average annual precipitation for the period of 1880–2008 for Station 179 of the Riverside County Flood Control and Water Conservation District is 26.3 cm. The Basin covers approximately 60 square kilometers; composed of 68% urban area, 13% undeveloped land, 17% irrigated irrigation agriculture, and 2% irrigated parks (Western 2010). Significant early groundwater development in the Arlington Basin started with the growth of the citrus industry.

Land use changed following World War II as urbanization replaced most of the citrus groves with residential, commercial, and industrial development. The shift from agriculture to urban development resulted in changes in water demand patterns, water return flows to the basin, and water quality needs.

The Basin is a shallow alluvial-filled valley with estimated total groundwater storage capacity of 124.6 million cubic meters. The natural annual groundwater recharge is estimated at 10.5 million cubic meters (Western 2008). The groundwater is of poor quality, with Total Dissolved Solids (TDS) and nitrate-nitrogen concentrations of approximately 1,000 and 20 milligrams per liter, respectively. The Arlington Desalter Facility (Desalter) was originally constructed in the late 1980s for basin salt management and to reduce the subsurface outflow of poor quality groundwater from the Basin to the Temescal Basin (See Fig. 2). In 2004, the Desalter was approved by the California Department of Public Health (CDPH) as a drinkable water supply. The Desalter is a reverse-osmosis (RO) groundwater treatment facility. Groundwater is provided to the Desalter by five production wells (See Fig. 2). Three of those wells supply the RO process and the other two supply bypass water for blending with the RO permeate to produce drinking water. The brine concentrate is discharged into the Santa Ana Regional Interceptor pipeline operated by the Santa Ana Watershed Project Authority (SAWPA).

Today, the Arlington Basin provides water for private use as well as for Western's Arlington Desalter. Approximately1.2335 million cubic-meters per year come from private producers. Western has used the Arlington Basin Groundwater to supply the Arlington Desalter since late 2004, with an average of approximately 9.0 million cubic-meters per year. The groundwater productions from the Arlington Basin for 1970, 1980, 1990, 2000, and 2010 are 11.83, 3.23, 5.47, 12.59, and 9.24 million cubic-meters, respectively.

The Arlington Basin is uniquely situated with respect to various features and the surrounding environment. This is, in part, due to the fact that the Riverside Groundwater Basin located to the east is an adjudicated basin. Replenishment to the basin should occur if pumping is more than the safe yield. In addition, a significant amount of outflow from rising groundwater in the Arlington Basin discharge to surface at Hole Lake and the Arizona flood control channel. Furthermore, subsurface outflow from the Arlington Basin to the Temescal Basin (located to the west of the Basin, (See Fig. 2) has to be controlled to reduce impacts of poor quality water to the Temescal Basin. Lastly, because of its small capacity, operational problems might arise, such as dropping water levels below the pump bowls.

Western Municipal Water District (Western) developed an Integrated Regional Water Management Plan (IRWMP) for its service area to identify water management strategies that could improve water supply reliability by developing local water supplies, which would reduce the dependency on imported water (Western 2006). One of the IRWMP's management strategies is to expand the Desalter production of treated water from approximately 25,000 to up to 38,000 cubic-meters per day. This would occur in two phases: Phase 1 includes biological nitrate removal for the bypass groundwater, while Phase 2 includes brine concentrate minimization by using pellet softener treatment technology. Additional groundwater pumping is required for both phases.

Western is concerned that increasing groundwater pumping for the Desalter expansion will cause excessive decline of groundwater levels, leading to decreased yields at the existing Desalter production wells as well as potentially impacting other producers in the Basin. Currently, the groundwater levels in the Basin are declining by an average of approximately 0.31 meter per year due to increased pumping and a reduction in natural groundwater recharge (See Fig. 5). Three dimensional groundwater flow model is developed to investigate management alternatives for the Arlington Basin resources.

The primary objectives of this paper are to discuss development of the Arlington Groundwater Model and to evaluate different water management strategies for the expansion of the Arlington Desalter, ultimately aiming to ensure a reliable water supply.

3 Conceptual Model of the Arlington Aquifer

The Arlington Basin is bounded by the Sobrante de San Jacinto Mountains to the south, the La Sierra Hills to the north, a groundwater divide to the east and bedrock constriction to the west at the border between the Arlington and Temescal basins (See Figs. 1, 2 and 3). Inflow to the Arlington Basin is from deep percolation from precipitation and applied water (including agricultural and landscaping irrigation), subsurface inflow along the basin boundaries, and infiltration of flow within the unlined stream channels overlying the basin. Outflow from Arlington Basin are primarily municipal and private pumping, discharges at Hole Lake and Arizona channel (where shallow groundwater discharges to the ground surface, see Fig. 2), and subsurface to the Temescal Basin. The groundwater flow direction in the Arlington Basin moves from areas of recharge (in the surrounding highlands in the north and south) to the central portion of the basin, and then southwesterly into the Temescal Basin through the bedrock of the Arlington Narrow. In the northeastern portion of the basin, groundwater flows to the north toward Hole Lake (See Fig. 2).

The Arlington groundwater Basin is an open system (i.e. groundwater flows into and out of the Basin), underflow flows out of the Arlington Basin to the Temescal Basin located to the west (See Fig. 2). Also, underflow from the Riverside Basin can flow into the Arlington Basin depending on the amount of groundwater pumping from the Basin. A flattened mound of groundwater exists and acts as a groundwater divide between the Arlington and Riverside basins (Eckis 1934). The Arlington Basin is a relatively shallow and narrow alluvial-filled valley that is incised into an elevated plateau of granitic bedrock of the Perris Block in the northern Peninsular Ranges (Morton 2004).

There are no mapped faults within the Arlington Basin that are attributable for the uplift of the surrounding hills. In addition, the granitic bedrock exposed in the south-central portion of the Arlington Basin does not act as an internal barrier to groundwater movement. In order to develop a conceptual model, four hydrogeological cross-sections were constructed across the Arlington Basin to identify water-bearing zones based on borehole lithology, geophysical borehole logs, well casing perforations, specific capacities, groundwater quality and groundwater thickness of levels (Western 2008). The cross-sections indicated an aquifer approximately 61.0 meter in the central portion of the Basin and as thick as 92.0 meter in the extreme northeast, and pinching-out to zero thickness along the northern and southern basin boundaries.

Based on the analysis of the cross-sections and the hydrogeological data, no evidence exists to support a multiple-layer aquifer system, that is no regional aquitard
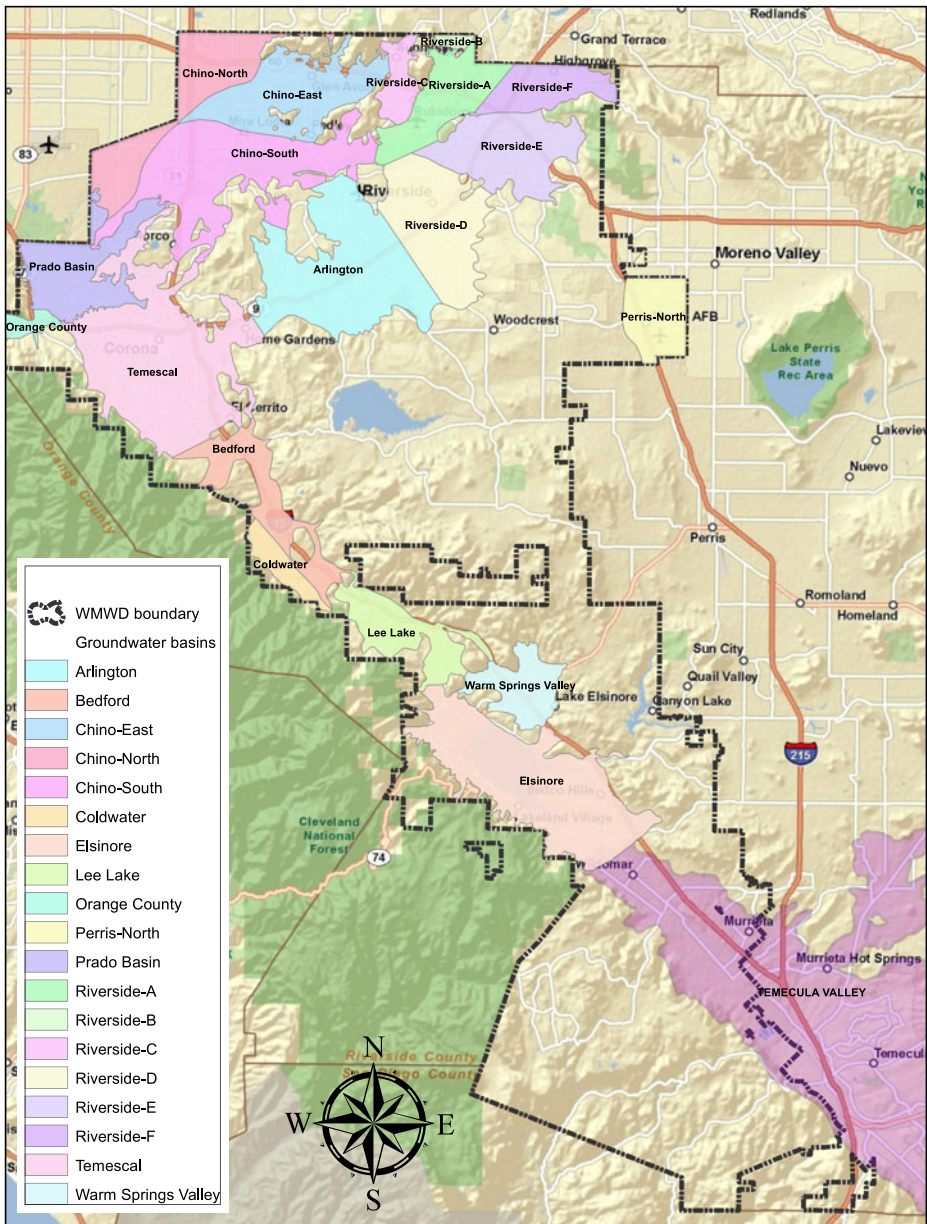
Fig. 1 Groundwater basins within the service area of Western Municipal Water District

exists to create continued confined aquifer conditions. The analyses of specific capacities of wells (screened for the entire basin saturated thickness) and changes in the water level data of production wells indicate that the aquifer system is unconfined to semi-confined. Therefore, Arlington Basin is assumed as a single unconfined aquifer (Western 2008). The hydraulic conductivities are highest along the central trough of the Bain where the water-bearing sediments are thickest, and lowest within the
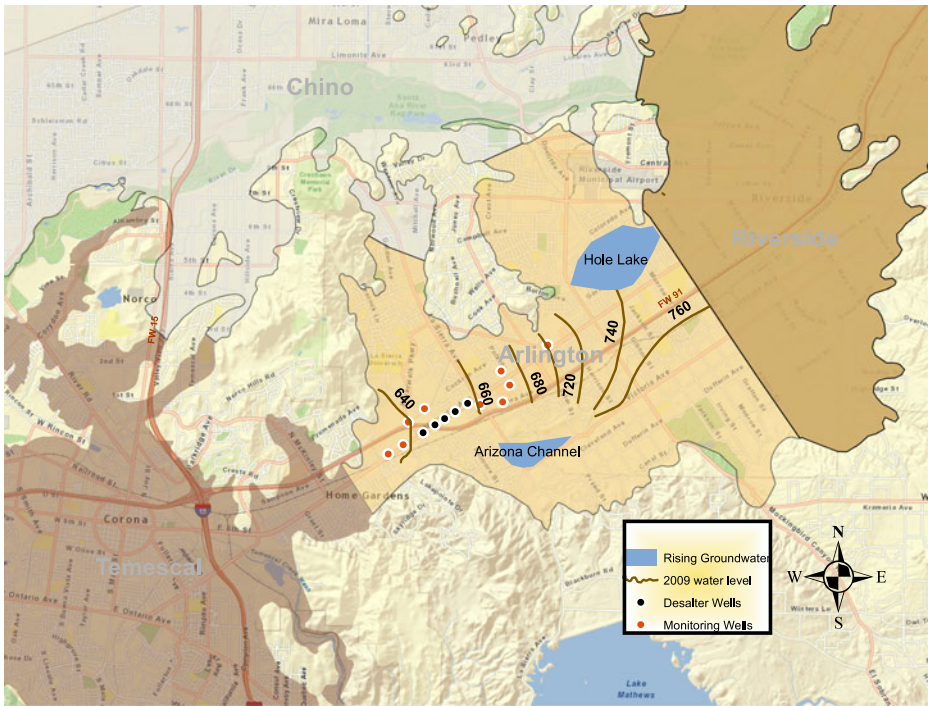
Fig. 2 Arlington desalter and monitoring wells

sediments on the northern and southern flanks of the Basin where the water-bearing sediments are thin.

4 Groundwater Flow Numerical Model Construction

The finite-difference groundwater modeling program (MODFLOW) developed by USGS (Harbaugh et al. 2000) was used for simulating the three-dimensional groundwater flow of the Arlington Basin. The MODFLOW—program was chosen as it is widely used and widely supported for use in the public and private sectors (Liu et al. 2010; Xu et al. 2011)

The model grid consists of 146 rows, 212 columns, and one layer. In the horizontal direction, each cell has a dimension of 50.0 X 50.0 meters. The grid cells are designated as "inactive" outside the model domain and as "active" inside the model domain. There are a total of 11,428 active cells. The discretization of time is a critical step in the model development because the model results are sensitive to time step of the model. Time discretization in MODFLOW 2000 includes stress periods and time steps. The transient stress period of the Arlington model is one year, based primarily on the availability of annual pumping data and annual urban water supply data, but the groundwater flow equation was solved by MODFLOW for 12 time steps in each stress period.

The R4 Model was used to calculate groundwater recharge from precipitation and applied water (Wildermuth 2002). Recharge from precipitation includes surface runoff and
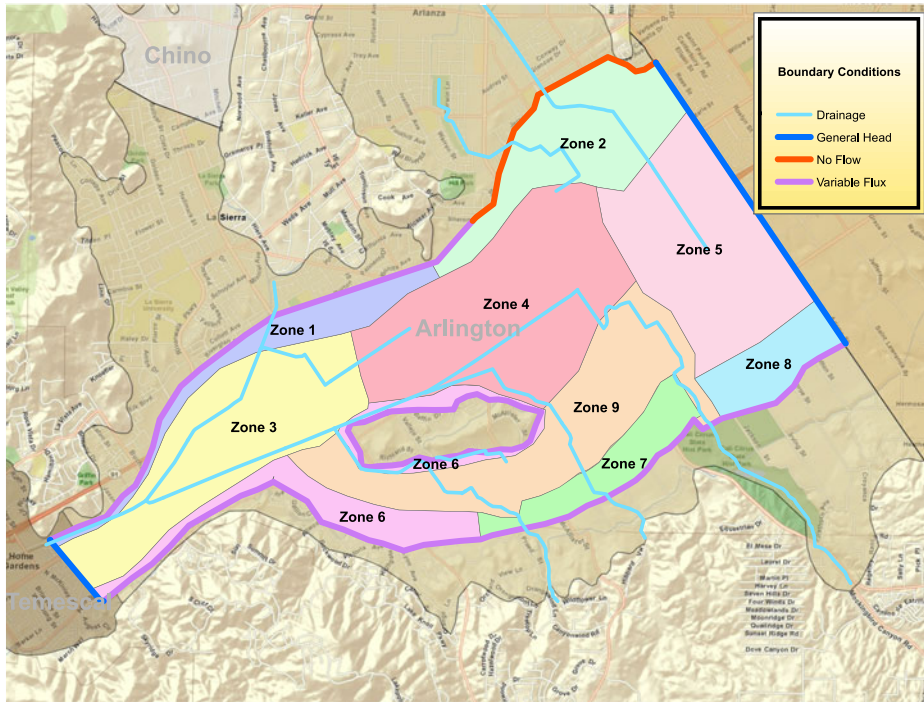
Fig. 3 Aquifer property zonation and model boundary conditions

areal recharge. Applied water includes agricultural irrigation, landscaping irrigation, and lakes/ponds. The information required for the R4 Model includes data for agricultural and landscaping irrigation, precipitation, weather and evapotranspiration, and soil.

5 Hydraulic Properties

The Arlington Basin is an alluvial groundwater basin in the Santa Ana River watershed which is bounded on the north and south by consolidated bedrock. During periods of flooding, alluvium was deposited in the stream channels as well as on the flood plains, where coarse-grained sediments are deposited along the stream channels and fine-grained sediments are deposited on the flood plains. The analysis of specific capacity at wells as determined by pumping test indicated that the hydraulic conductivity of aquifer in the Arlington Basin is higher in the coarse-grained, well-sorted alluvium in the central portion of the basin than in the finer-grained, poorly-sorted alluvium along the flanks of the basin. Specific capacity can be used to estimate the transmissivity at a well using the the empirical formula: $(Q/S)=(T/1500)$, where Q is the yield of the well; S is the drawdown in the well; and T is the transmissivity at the well (Driscoll 1986). The hydraulic conductivity at the well can be estimated from transmissivity using equation: $K=T/D$, where K is the hydraulic conductivity at the well and D is the thickness of the saturated sediment.

The initial hydraulic-property zonation (See Fig. 3) of the model is developed based on the estimated transmissivities which indicate higher hydraulic conductivity along the

center and low conductivity along the south and north boundary of the model area. The range of the initial hydraulic conductivity values is between 2.0 and 30.0 meter per day.

Specific Yield (SY) is the volume of water released from storage per unit surface area of aquifer per unit decline in the watertable. A thickness-weighted, average specific yield was calculated at each borehole in Arlington Basin, and these point values were imported to ArcGIS. Using a Kriging interpolation method available in the Geostatistical Analyst extension of ArcGIS, a specific yield raster was created to interpolate specific yield between the boreholes. This specific yield raster was used to populate the model grid cells within the model domain with initial values. The initial Specific Yield model zonation was first developed and adjusted during the calibration process (See Fig. 3).

6 Initial and Boundary Conditions

The initial heads for the transient calibration were computed assuming a steady-state condition for groundwater flow during the first stress period of 1966. The recharge values used in the steady-state simulation were computed by the R4 Model.

Figure 3 displays the boundary conditions of the model. A no flow boundary condition was specified for the base of the aquifer within the model domain. Along the north and south boundary of the model, variable flux is specified for locations where the main aquifer receives subsurface inflow from the saturated sediments that flank the surrounding bedrock hills. A no-flow boundary condition was assumed along an area of shallow bedrock, and along an area that separates the groundwater flow systems of Hole Lake area from the main Arlington Basin. A general head boundary was assumed along the east and west boundary of the model.

7 Model Calibration

Errors in model parameters and the conceptual model are the main sources of uncertainties in the simulated modeling results. The purpose of model calibration is to adjust model parameters so as to match field conditions, such as water levels at wells, with some acceptable criteria to minimize model errors.

The calibration process starts first by running the Arlington Numerical Model to check the water balance problems and possible errors that may happened during conversion process of the conceptual model to the numerical model. Second, the modeling results were checked to see whether the developed numerical model is capable of simulating the groundwater system's behavior, particularly for water levels at specific wells. The next step of the calibration process was to determine which model parameters should be calibrated. The model parameters include the hydraulic properties, boundary conditions, and other parameters. A pre-sensitivity analysis is conducted to examine the importance of model parameters before inverse modeling commence. Sensitivity analysis is the process of varying model input parameters over a reasonable range and observing the relative change in model response such as water levels. The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model parameters, so as to determine future data collection and investigation. Three model parameters with high sensitivity coefficients were identified during the pre-sensitivity step: horizontal hydraulic conductivity, specific yield, and general head boundary conductance at the Arlington Narrows. The sensitivity analysis of PEST demonstrated that the horizontal hydraulic conductivities in zones 4, 9, and 3 are very sensitive and important while horizontal conductivities in zone 1 and specific yield in zone 2 are the least important.

PEST Version 10 (Doherty 1994), inverse modeling computer program, was used for calibrating the Arlington Numerical Model. Hydraulic conductivity, specific yield, and general head boundary conductance at the Arlington Narrows were adjusted during the calibration process until a good fit between the hydraulic head of the model and field observation at wells was reached. The calibration period uses the hydrological base period of 1966–2004 because it includes more than two wet and dry cycles. A total of 511 water level measurements from different 10 wells are used in the model calibration which indicate a close match (See Fig. 4), with Residual Mean equals −0.076.

8 Water Management Strategies

Water demands for domestic and industrial uses within Western's service area increased due to population growth in the region. The availability of imported water from the State Water Project has decreased due to new regulations and multi-drought years. Recovering brackish groundwater of the Arlington Basin is important to increase water supplies for WMWD's service area and reduce dependency on imported water. Groundwater management may require coordination of the replenishment and withdrawal of water to achieve long-term sustainability for water supplies without detrimental effects on the other resources (Zagonari 2010). WMWD developed a number of potential management strategies for groundwater resources of the Arlington Basin and for improving the efficiency of the Arlington Desalter, with plans to expand the capacity of the facility from 25,000 of treated water to up to 38,000 cubic-meters per day. These strategies aim to achieve specific objectives, which are discussed in details in the following paragraphs to protect water quality and improve the sustainability and reliability of the Arlington Basin.

First, expansion of the Arlington Desalter requires additional pumping of approximately 5.0 million-cubic-meter per year of groundwater from the Arlington Basin. The additional groundwater requires construction of new wells. Groundwater levels across the Arlington Basin and specifically at the existing Desalter production wells are declining by approximately 0.30 meters per year (See Fig. 5). The decline of groundwater levels is caused mainly by pumping of the existing Desalter production wells and by a reduction of natural recharges due to multi-year droughts and changes in land use.

Furthermore, the additional pumping from the Arlington Basin for the expansion of the Desalter will cause excessive drawdown of groundwater levels, leading to reduced yields at existing Desalter wells, reduced production at the Desalter, and impact to other producers within the Arlington and neighboring basins. Controlling groundwater drawdown at the existing Desalter production wells and across the Basin requires shifting of the current groundwater pumping at both existing Desalter wells and planned expansion wells in the eastern portion of the Basin. In addition, locations of the new production wells needs to be optimized to reduce impacts from additional pumping in the basin and neighboring basins.

Second, constructing new production wells in the eastern portion of the Arlington Basin may reduce groundwater resources in the Basin and potentially impact neighboring basins. Artificial recharge is needed to ensure sustainability of the groundwater supply to the Desalter, and to mitigate groundwater levels declines, and to minimize underflow from Riverside Basin. Locations of proposed artificial recharge sites should be selected to optimize capture of recharged water by new and existing Desalter wells, thus reducing potential liquefaction in high groundwater areas during earthquakes.

Water sources available for artificial recharge in the Arlington Basin include dry-weather flow from rising groundwater and urban runoff, stormwater runoff, and supplemental water
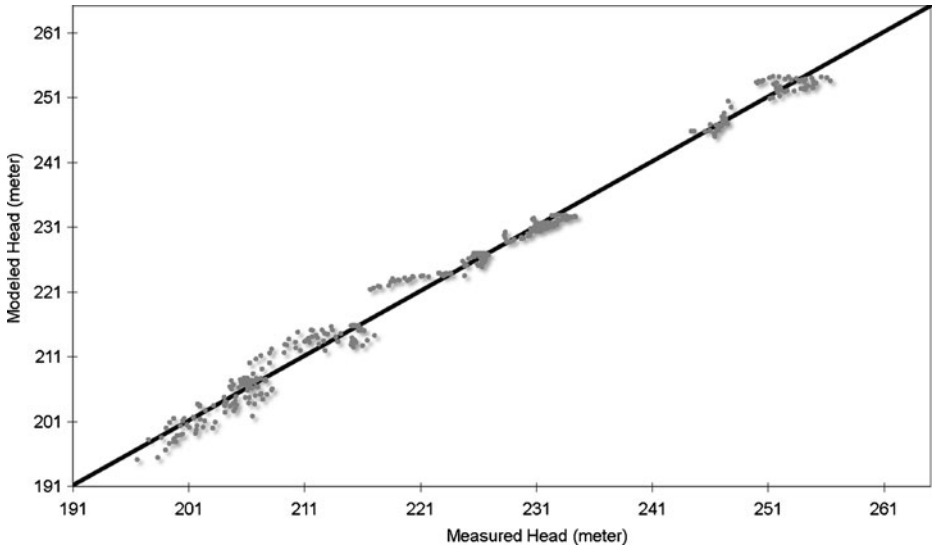
Fig. 4 Comparison of modeled and measured head for all calibration wells

from recycled water and/or imported water. There are two areas in the Arlington Basin where rising groundwater occurs: Hole Lake and the Arizona Flood Control channel (See Fig. 2). The capture and recharge of dry-weather flow and stormwater would not only increase the yield of the groundwater Basin but also benefit the Riverside County Flood
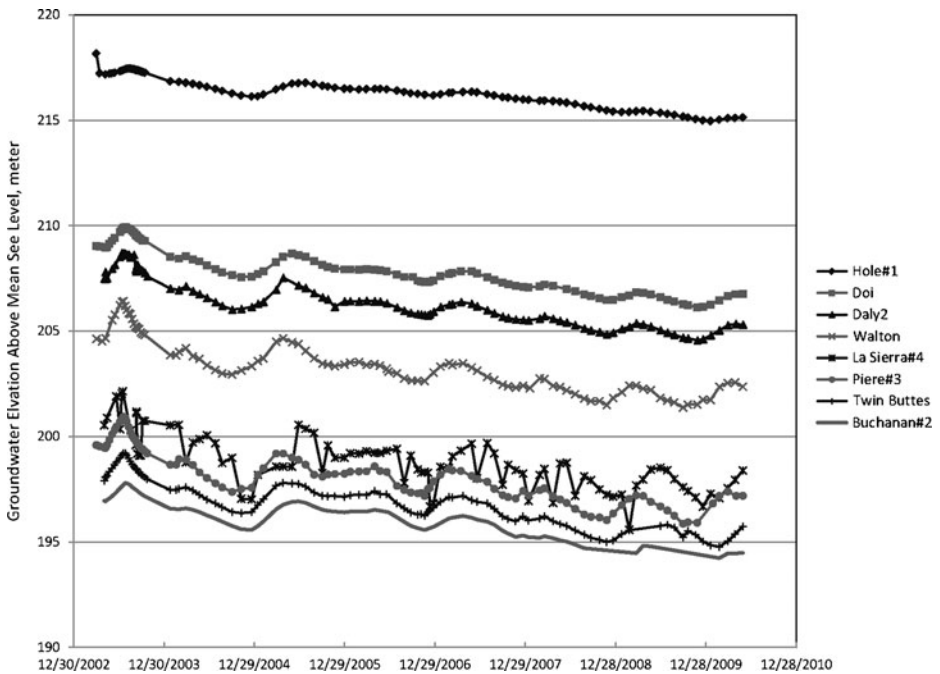

Fig. 5 Groundwater hydrographs at different locations for the Arlington Basin wells

Control and Water Conservation District (RCFC&WCD) and, in the case of capturing dry-weather flow, improve downstream water quality in the Santa Ana River and its tributaries.

Based on two sets of criteria, a GIS methodology was developed to identify potential areas that could be used for new production wells and artificial recharge. The potential well sites and recharge facilities were used to assist in the development of the management strategies. Four recharge sites were identified for the feasibility of the Arlington expansion: Magnolia, Metrolink, Monroe, and Victoria (See Figs. 8, 9 and 10).

9 Description of Groundwater Management Scenarios

The Arlington calibrated model was used to evaluate five water management scenarios for Arlington Basin for a 30-year time period (2004 through 2034). The objective of the modeling work is to determine the feasibility of the Arlington aquifer system to supply groundwater to the Arlington Desalter over the life of the facility (30 years) without causing undesirable impacts to the Arlington or neighboring basins by using artificial recharge and optimization of groundwater production. Table 1 displays two numbers for pumping and recharge for each of the management scenarios. These numbers are for phase 1 and phase 2 of the Desaltor expansion which starts in 2012 and 2017, respectively.

The objective of Management Scenario 1 (no project) is to evaluate aquifer sustainability for the Desalter expansion while only assuming groundwater production of 2004, with no additional pumping and artificial recharge (See Fig. 6). Current production was assumed to have 2004 conditions, which were 9.7 million cubic-meters per year of groundwater production and approximately 7.7 million cubic-meters per year of treated water. The overall treatment efficiency for the Desalter is approximately 80%.

Management Scenario 2 assumed construction of three new Desalter wells in the eastern portion of the Arlington Basin with no artificial recharge (See Fig. 7). It assumed the new Desalter wells would begin pumping in 2012 to reduce drawdown at the existing Desalter well field by 2.5 million cubic-meters per year. The operations at build out (2034) included 14.6 million cubic-meters per year of groundwater production, which yielded approximately 13.73 million cubic-meters per year of treated water, assuming the Desalter's overall treatment efficiency had been increased to approximately 94%. The objective of Management Scenario 2 was to evaluate the sustainability of the Arlington Basin for the Desalter expansion by pumping more than 50% of the groundwater needed to the Desalter expansion from the eastern portion of the basin, which is approximately 7.4 million cubic-meters per year—approximately 4.9 million cubic-meters per year necessary for the facility expansion of treated water and a shift of approximately 2.5 million cubic-meters per year that is currently produced from the existing Desalter wells—from the new proposed Desalter wells.

Management Scenarios 3 through 5 assumed construction of new Desalter wells and artificial recharge (See Figs. 8, 9 and 10). Management Scenario 3 included the construction of three new Desalter wells in addition to the existing Desalter wells, and four artificial recharge facilities; it assumed a two phase approach. Phase 1 would commence in 2012

Table 1 Groundwater production and recharge schedule for management scenarios in million cubic-meters

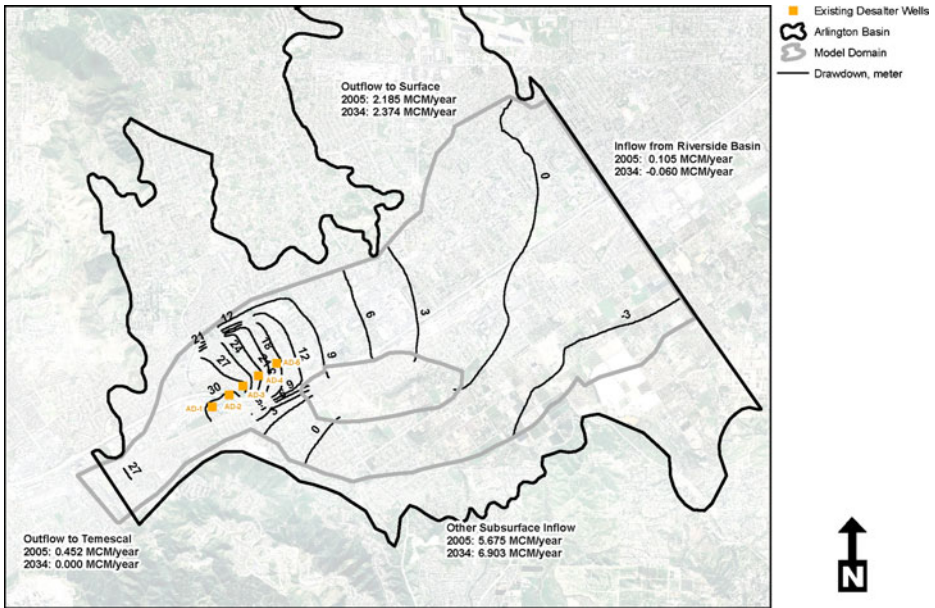| Management scenario no.	1	2	3	4	5
Total Pumping	(0/9.7)	(9.7/14.6)	(9.9/14.6)	(12.5/14.6)	(10.2/14.6)
Total Recharge	(0/0)	(0/0)	(2.5/4.9)	(2.5/3)	(2.5/4.9)

Fig. 6 Model simualtion results for management scenario 1 (Baseline)

with the objective of sustaining water levels at the existing Desalter wells at more than 3.0 meters above the screens with artificial recharge at the Magnolia and Metrolink sites. Phase 2 would begin in 2017 with the construction of three new Desalter wells and two additional recharge sites, Victoria and Monroe (See Fig. 8). The new well field in the eastern portion
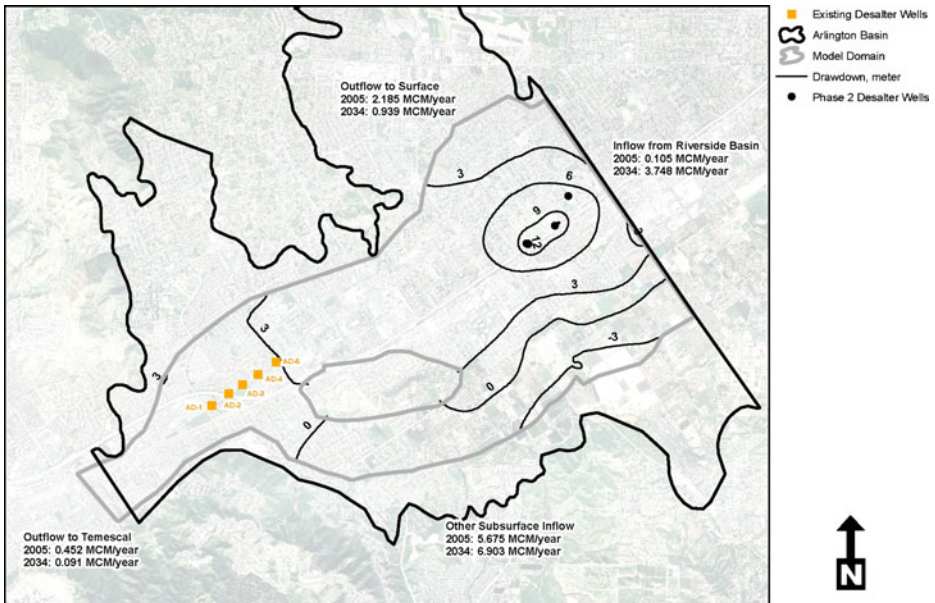

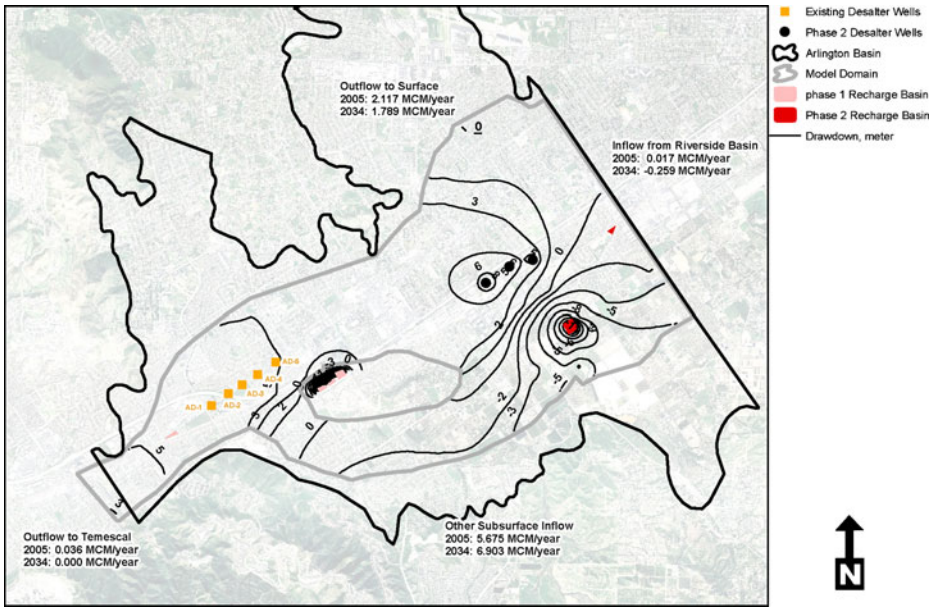**Fig. 7** Model simualtion results for management scenario 2

Fig. 8 Model simualtion results for management scenario 3

of the basin would increase groundwater production to 14.6 million cubic-meters per year from 9.9 million cubic-meters per year in Phase 1. The operations at build out (2034) would include 4.9 million cubic-meters per year of artificial recharge and 14.6 million cubic-meters per year of groundwater production, which would yield approximately 13.74 million
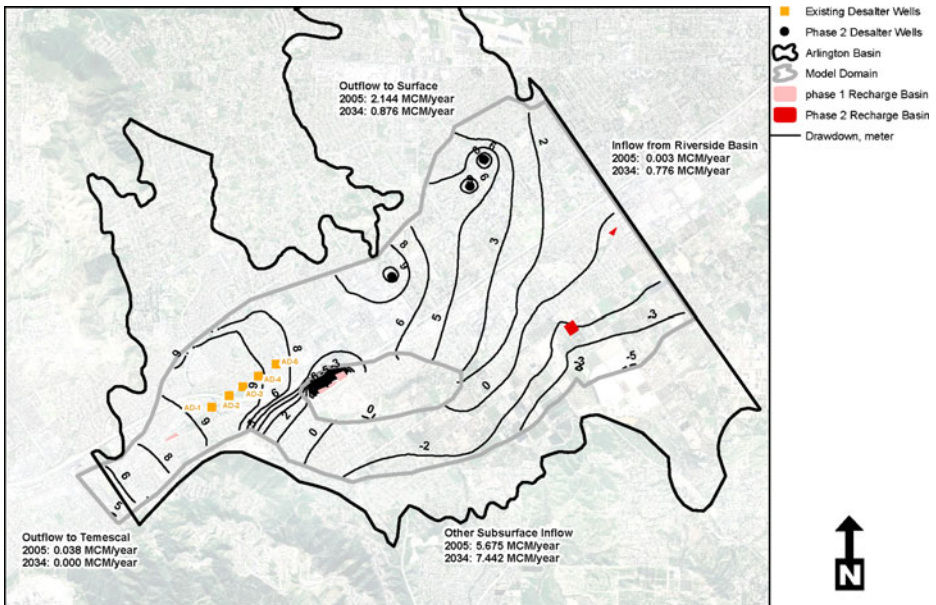

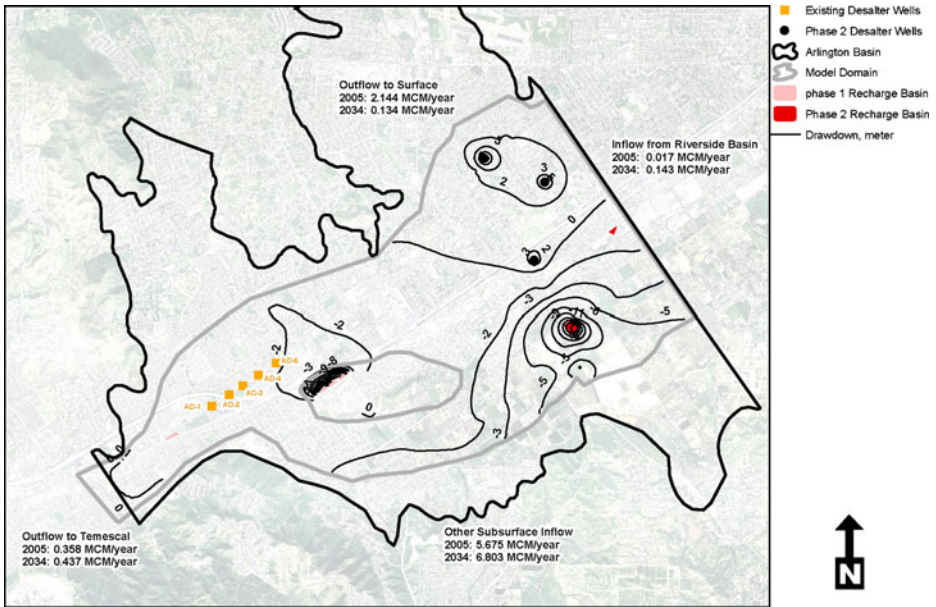**Fig. 9** Model simualtion results for management scenario 4

Fig. 10 Model simualtion results for management scenario 5

cubic-meters per year of treated water, assuming that the Desalter's overall treatment efficiency would be increase to approximately 94%. The objective of the Management Scenario 3 was to evaluate the sustainability of the Arlington Basin for the Desalter expansion by including 4.9 million cubic-meters per year of artificial recharge at four sites and pumping approximately 34% (5.0 million cubic-meters per year) of groundwater needed for the Desalter expansion from the eastern portion of the basin.

Management Scenario 4 includes the construction of three new Desalter wells and three artificial recharge facilities at the Metrolink, Magnolia, and Monroe sites. The artificial recharge at the Metrolink and Magnolia sites would commences in 2012, while the new Desalter wells and artificial recharge at the Monroe site would commence in 2017 (See Table 1). The new Desalter wells would increase groundwater production to 14.6 million cubic-meters per year and would include a shift of 2.82 million cubic-meters per year from the existing Desalter wells (Phase 1) to the new Desalter wells. Figure 9 shows the facilities associated with Management Scenario 4. The operations at build out (2034) would include approximately 3.0 million cubic-meters per year of artificial recharge and 14.6 million cubic-meters per year of groundwater production, which would yield approximately 13.72 million cubic-meters per year of treated water, assuming that the Desalter's overall treatment efficiency would increase to approximately 94%. The objective of the Management Scenario 4 was to evaluate the sustainability of the Arlington Basin for the Desalter expansion by including 3.0 million cubic-meters per year of artificial recharge at three sites (Metrolink, Magnolia and Monroe) and pumping approximately 34% (5.0 million cubic-meters per year) of the groundwater needed for the Desalter expansion from the eastern portion of the basin. The locations of the new production wells were in the northeast of the basin to capture surface outflow from rising groundwater and artificial recharge from the Monroe recharge site (See Fig. 9).

Management Scenario 5 includes the construction of the three Desalter wells and four artificial recharge facilities. It assumed a two phase approach. Phase 1 would commence in

2012 with the objective of sustaining water levels at the existing Desalter wells at more than 3.0 meters above the screens with artificial recharge at the Magnolia and Metrolink sites. In 2017, three new Desalter wells and two additional recharge sites (Victoria and Monroe) were initiated as part of Phase 2 (See Fig. 10). The new well field in the northeastern portion of the basin would increase production from 10.2 million cubic-meters per year in Phase 1 to 14.6 million cubic-meters per year and attempted to reduce outflow from rising groundwater in the Hole Lake area. The operations at build out (2034) would include 4.9 million cubic-meters per year of artificial recharge and 14.6 million cubic-meters per year of groundwater production, which would yield approximately 13.72 million cubic-meters per year of treated water, assuming the Desalter's overall treatment efficiency would be increased to approximately 94%. The objective of Management Scenario 5 was to evaluate the sustainability of the Arlington Basin for the Desalter expansion by including 4.9 million cubic-meters per year of artificial recharge at four sites and pumping approximately 33% (4.75 million cubic-meters per year) of groundwater needed for the Desalter expansion from the eastern portion of the basin.

10 Management Scenarios Model Results

Figures 11, 12, 13, 14 and 15 show simulated water levels at the existing Desalter wells for all management scenarios.

Table 2 shows the annual cumulative storage loss during the simulation (2005–2034) for all management scenarios.
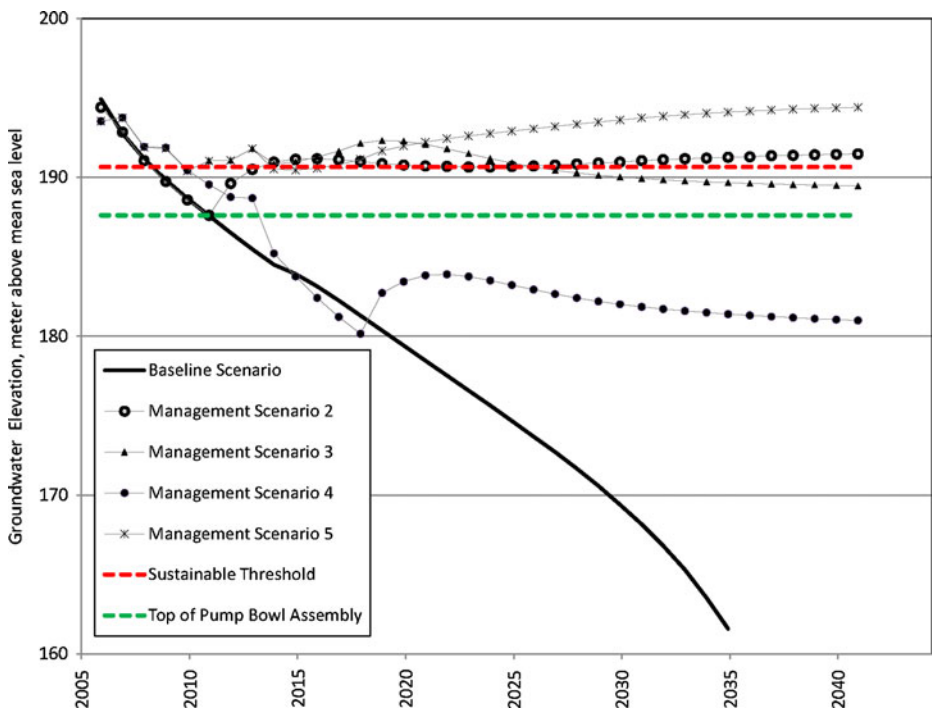

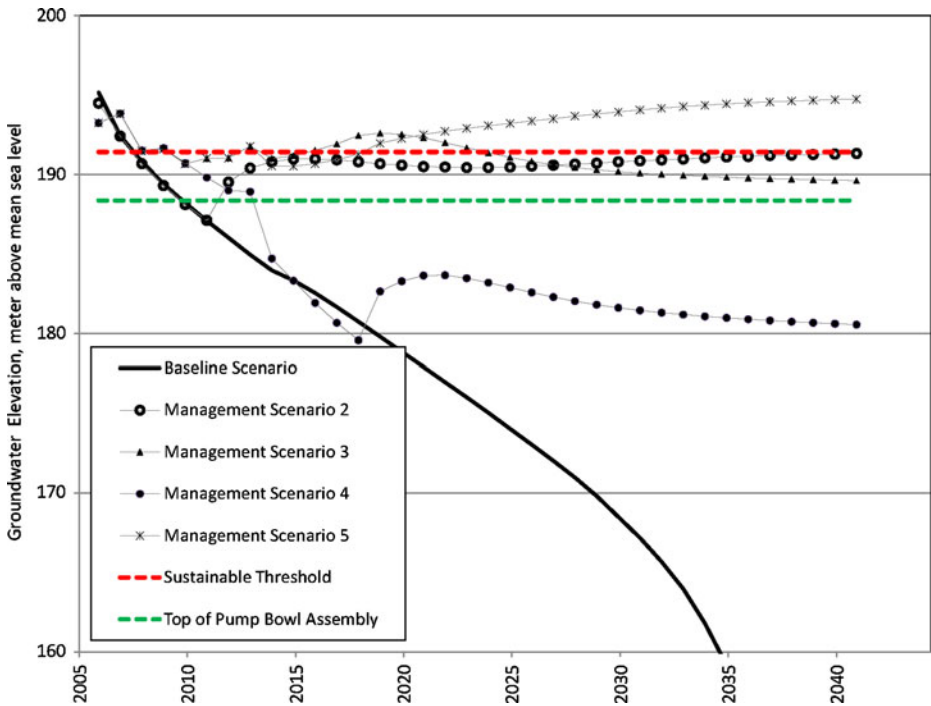Fig. 11 Simulated water levels at Arlington desalter well 1

Fig. 12 Simulated water levels at Arlington desalter well 2

The simulation results of the Baseline Scenario (Management Scenario 1) indicated that long-term pumping at the Arlington Desalter wells at 2004 rates was not sustainable because the maximum drawdown would be focused around the Desalter well field. A maximum drawdown of approximately 30.0 meters occurred within the cone of depression caused by the constant pumping at the Desalter well field. The simulated water levels were in constant decline during the simulation and dropped below the top of the pump bowl assemblies by 2011(See Figs. 11, 12, 13, 14 and 15). The drawdown around the Desalter well field did not increase subsurface inflow from the Riverside Basin, nor decrease surface outflow from rising groundwater, but reduced the groundwater storage in the basin. There was a continuous loss of groundwater from storage during the simulation—rapidly during the early years, but at a declining rate thereafter. The annual cumulative storage loss during the simulation was 16.52 million cubic-meters by the end of the baseline simulation (See Table 2).

The simulation results of Management Scenario 2 indicated that the aquifer system can support the increased pumping rates associated with the Desalter facility by locating new wells in the eastern portion of the basin and evenly distributing the pumping across the basin. Groundwater was lost from storage during the early years of the simulation but reached a relatively stable equilibrium by 2019. The accumulative groundwater storage loss was approximately 13.96 million cubic-meters, but annual storage losses tapered off to zero by 2019, indicating sustainable pumping rates at the Desalter well field. The basin yield increased in Management Scenario 2 mainly by inducing subsurface inflow from the Riverside Basin and decreasing the outflow of rising groundwater to Hole Lake. A maximum drawdown of approximately 12.0 meters occurred within the cone of depression caused by pumping at the new Desalter well field located east of the Arlington Basin (See
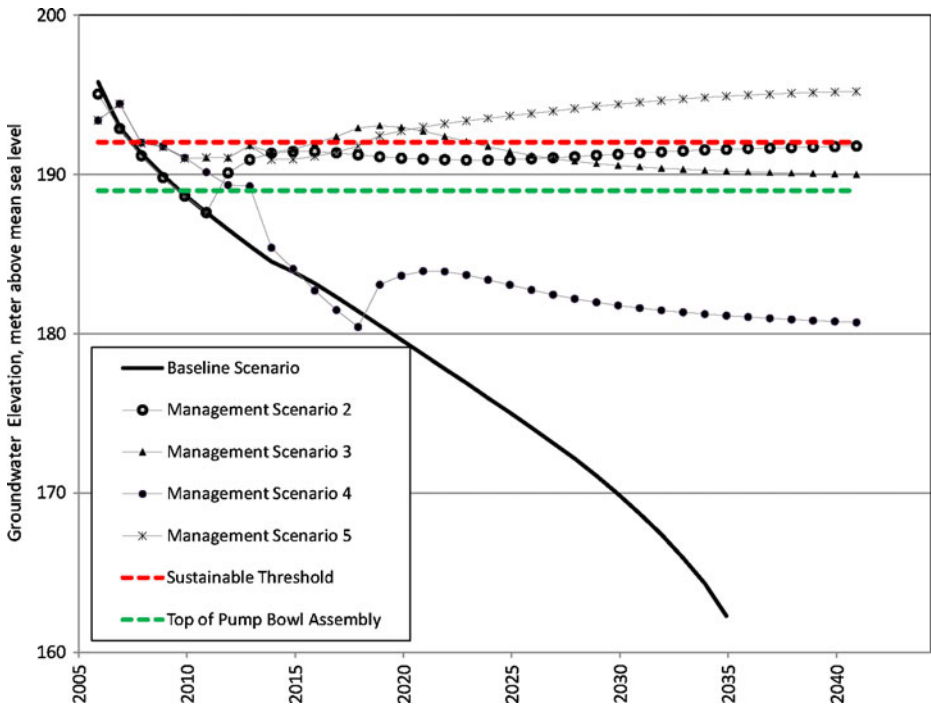
Fig. 13 Simulated water levels at Arlington desalter well 3

Fig. 12). This cone of depression extended further east of the Arlington Basin and caused subsurface inflow from the Riverside Basin that peaked at approximately 3.75 million cubic-meters per year by 2025 and continued each year thereafter. Drawdown around the Desalter new well field increased the yield of the groundwater basin by approximately 5.5 million cubic-meters per year by increasing subsurface inflow from the Riverside Basin, decreasing the outflow of rising groundwater, and eliminating subsurface outflow to the Temescal Basin. The simulated water levels at the existing Desalter well field were in decline until 2011 and then recovered by approximately 3.0 meters over the next 3 years. This recovery occurred because of the shift of approximately 2.5 million cubic-meters per year of groundwater production from the existing Desalter wells to the new Desalter wells in 2011, Table 1. Water levels at the existing Desalter wells remained relatively stable from 2014 until the end of the simulation, indicating sustainable pumping rates at these wells.

The simulation results of Management Scenario 3 indicated that the aquifer system relatively supported the increased pumping rates associated with the Desalter expansion, but only by constructing the artificial recharge basins and new wells in the eastern portion of the basin and evenly distributing pumping across the basin. Groundwater loss from storage occurred during Management Scenario 3. The cumulative loss was approximately 7.72 million cubic-meters by the end of the simulation year 2034 (See Table 2). A maximum drawdown of approximately 4.6 meters occurred within the cone of depression caused by constant pumping at the existing Desalter well field. The maximum drawdown within the cone of depression at the new Desalter well field was approximately 6.1 meters. Groundwater levels rose in the vicinity of the Metrolink and Victoria sites by approximately 11.0 and 9.0 meters, respectively. The simulated water levels were in decline until 2011, recovered by approximately 1.52 meters
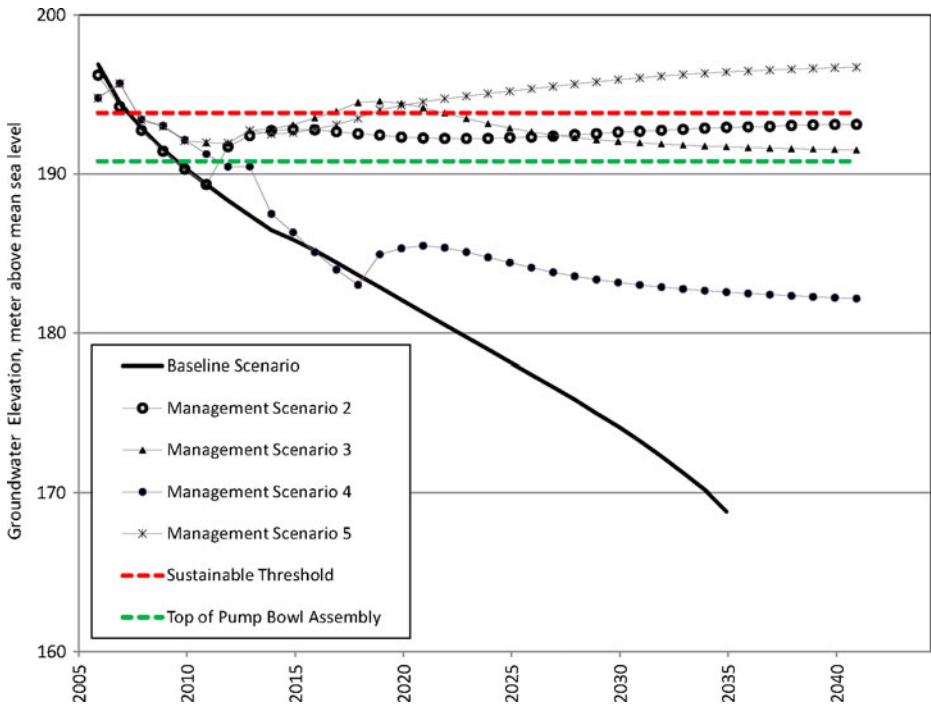
Fig. 14 Simulated water levels at Arlington desalter well 4

over the next few years, and then gradually declined again until they dipped below the sustainability threshold in 2025(See Figs. 11, 12, 13, 14 and 15). The recovery occurred due to the artificial recharge of approximately 2.53 million cubic-meters per year at the Magnolia and Metrolink sites. In the long run, water levels at the existing Desalter wells became relatively stable, indicating sustainable pumping rates at these wells.

The simulation results of Management 4 indicated that a maximum drawdown of approximately 9.0 meters occurred within the cone of depression caused by constant pumping at the existing Desalter well field. The development of this cone of depression eliminated groundwater outflow to the Temescal Basin by 2009. Groundwater was lost from storage during the first 15 years of Management Scenario 4 but rebounded in 2019 and then increased thereafter. The cumulative loss was approximately 3.28 million cubic-meters by the end of the simulation year 2034 (See Table 2). The simulated water levels declined during the simulation and dropped below the top of the pump bowl assemblies by 2014 (See Figs. 11, 12, 13, 14 and 15). The Management Scenario 4 results indicated that the Phase 1 pumping rate of 12.5 million cubic-meters per year (See Table 1) at the Arlington Desalter wells was not sustainable. Storage loss from the Arlington Basin was persistent, and maximum drawdown was focused around the existing Desalter well field.

The simulation results of Management Scenario 5 indicated that the aquifer system supported the increased pumping rates associated with the Desalter facility expansion to 38,000 million cubic-meters per day of treated water, but only by constructing new wells in the eastern portion of the basin and by evenly distributing pumping across the basin. Water levels around the existing Desalter wells increased by approximately 1.5 meters, and water levels around the new Desalter well field dropped by approximately 3–5 meters. Groundwater levels rose in the vicinities of the Metrolink and Victoria recharge sites by approximately 9.0 and 11.0 meters,
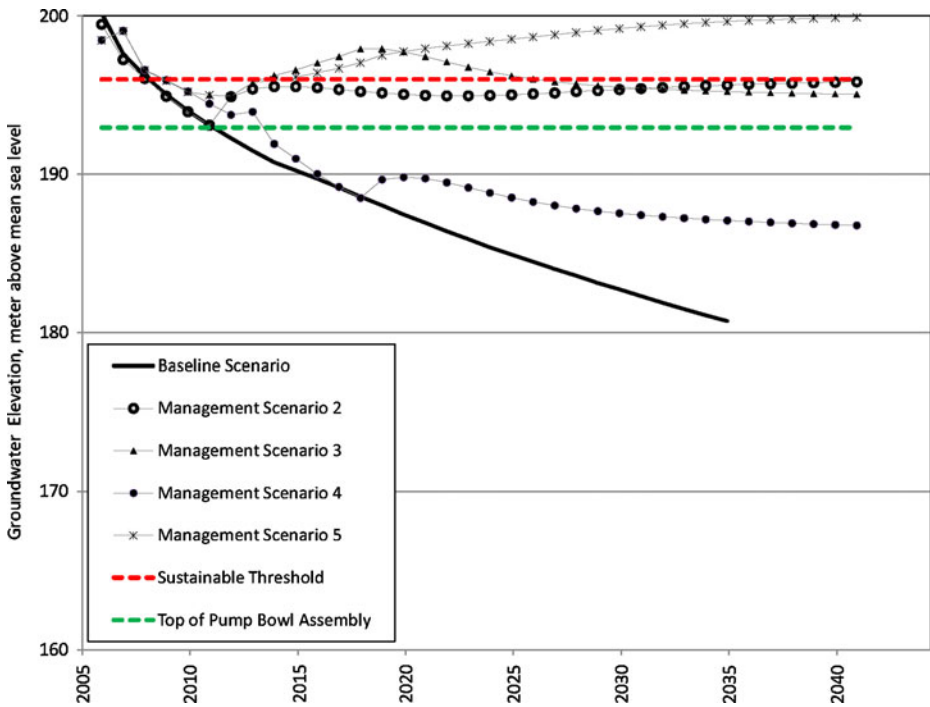
Fig. 15 Simulated water levels at Arlington desalter well 5

respectively. Groundwater storage increased during Management Scenario 5. Groundwater storage declined in early years and increased later on. The cumulative storage increase was approximately 2.28 million cubic-meters by the end of the simulation (2034), (See Table 2). The simulated water levels were in decline until 2010, then gradually recovered and stabilized until the end of the simulation. This recovery occurred due to the artificial recharge of approximately 2.53 million cubic-meters per year. Water levels at the existing Desalter wells remained relatively stable from 2014 to the end of the simulation, indicating sustainable pumping rates at these wells and at all wells across the basin, (See Figs. 11, 12, 13, 14 and 15).

11 Summary and Conclusions

A finite-difference three-dimensional numerical flow model was developed for the Arlington groundwater Basin. The Arlington Basin is a relatively shallow and narrow

Table 2 Cumulative storage change in groundwater for the management scenarios, million cubic-meters

Scenario no.	1	2	3	4	5
2005	−.08	−0.1	−0.56	−0.61	−0.56
2015	−10.36	−13.44	−1.09	−7.91	−1.95
2025	−14.12	−14.05	−6.32	−6.88	0.88
2034	−16.52	−13.96	−7.72	−3.28	2.28

alluvial-filled. The model input data include deep percolation from precipitation and applied water (including agricultural and landscaping irrigation), subsurface inflow along the basin boundaries, infiltration of flow within the unlined stream channels overlying the basin, and outflow primarily from municipal and private pumping. The numerical flow model was calibrated for the period from 1966–2004. The calibrated model was used to evaluate water management scenarios for the expansion of the Arlington Desalter. These scenarios include increasing groundwater pumping by construction new production wells only or construction or a combination of construction of new production wells and recharge basins. Five water management scenarios where evaluated by the calibrated model. The main conclusions of the water management modeling results are summarized below:

- Long-term groundwater pumping from the existing Desalter wells at 2004 rates (Baseline Scenario) is not sustainable. Storage loss from the Arlington Basin would be persistent, and maximum drawdown would be focused around the existing desalter well field. In the short term, this drawdown requires significant modifications to the existing desalter wells to lower pump bowl assemblies and sealing off upper portions of well screens, which could result in reduced production capacities at the wells and the desalter facility.
- The aquifer system can support the increased pumping rates necessary to expand the desalter to 38,000 cubic-meters per day of treated water by constructing new wells in the eastern portion of the Basin and evenly distributing pumping across the Basin (Management Scenario 2). The new groundwater yield to support the Desalter expansion would be derived primarily from underflow from Riverside Basin (≈ 3.75 million cubic-meters per year), reduced outflow of rising groundwater to Hole Lake (≈ 1.23 million cubic-meters per year), and reduced underflow to the Temescal Basin (≈ 0.4 million cubic-meters per year).
- A combination of artificial recharge and construction of new production wells can increase the yield of the Basin, minimize subsurface inflow from the Riverside Basin, reduce outflow from rising groundwater, and reduce outflow to the Temescal Basin (Management Scenarios 3 & 5). To reduce rising groundwater and to capture artificial recharge from sites located in the eastern and southeastern parts of the Basin, the best location for the new production wells is in the northeast portion of the Arlington Basin. To reduce drawdown near existing Desalter wells, the best location for the artificial recharge should be in the western portion of the Basin.
- Expanding the Arlington Desalter under any of the sustainable management scenarios (Management Scenarios 3 & 5) evaluated in this study will provide an additional source of approximately 4.84 million cubic-meters per year of highly reliable and potable water. The costs associated with producing this water will be cheaper than the costs associated with comparatively unreliable imported water from Metropolitan Water District of Southern California.
- The source waters available for artificial recharge in the Basin include dry-weather flow (i.e. rising groundwater and urban runoff), stormwater runoff, and supplemental water including recycled water and/or imported water. The capture and recharge of dry-weather flow and stormwater would not only increase the yield of the groundwater basin but also improve the quality of downstream water in the Santa Ana River.

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