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Comprehensive Groundwater Balance Development to Characterize Selenium Loading to Surface Water Channels in Orange County, California

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Abstract: Selenium concentrations are elevated above water quality criteria in several tributaries of Newport Bay. A watershed-scale hydrogeologic study was performed to identify processes driving selenium transport in the former "Swamp of the Frogs" area (cities of Santa Ana, Irvine, and Tustin). The former Swamp of the Frogs area was a depositional environment that historically received regional surface water runoff and accumulated naturally occurring selenium-bearing sediments from the larger watershed. Development beginning in the early 20th century included surface water channel installation that lowered the water table and drained the wetland, mobilizing selenium. A comprehensive groundwater/surface water balance was conducted in order to constrain hydrologic processes that continue to drive selenium mobilization into the surface water channels. The groundwater budget included precipitation and irrigation percolation modeling and groundwater flow mapping from thousands of publicly-available groundwater level measurements. Groundwater balance results indicated that lateral groundwater flow from upgradient alluvial-fan recharge areas accounts for most of the groundwater input to the former wetland area with additional input supplied by deep percolation of precipitation within the former wetland area itself, deep percolation of irrigation, and sewer/water line leakage. Overlaying selenium concentration data from groundwater wells and surface water sampling locations confirmed that selenium concentrations are similar in groundwater and nearby groundwater-to-surface water discharge points (e.g., weepholes). Results supported a Best Management Practice (BMP) Strategic Plan developed in compliance with a regulatory order prescribing numeric limitations on groundwater-related discharges of selenium in the watershed.

Keywords: Monterey formation, selenium, groundwater balance, distributed parameter watershed model

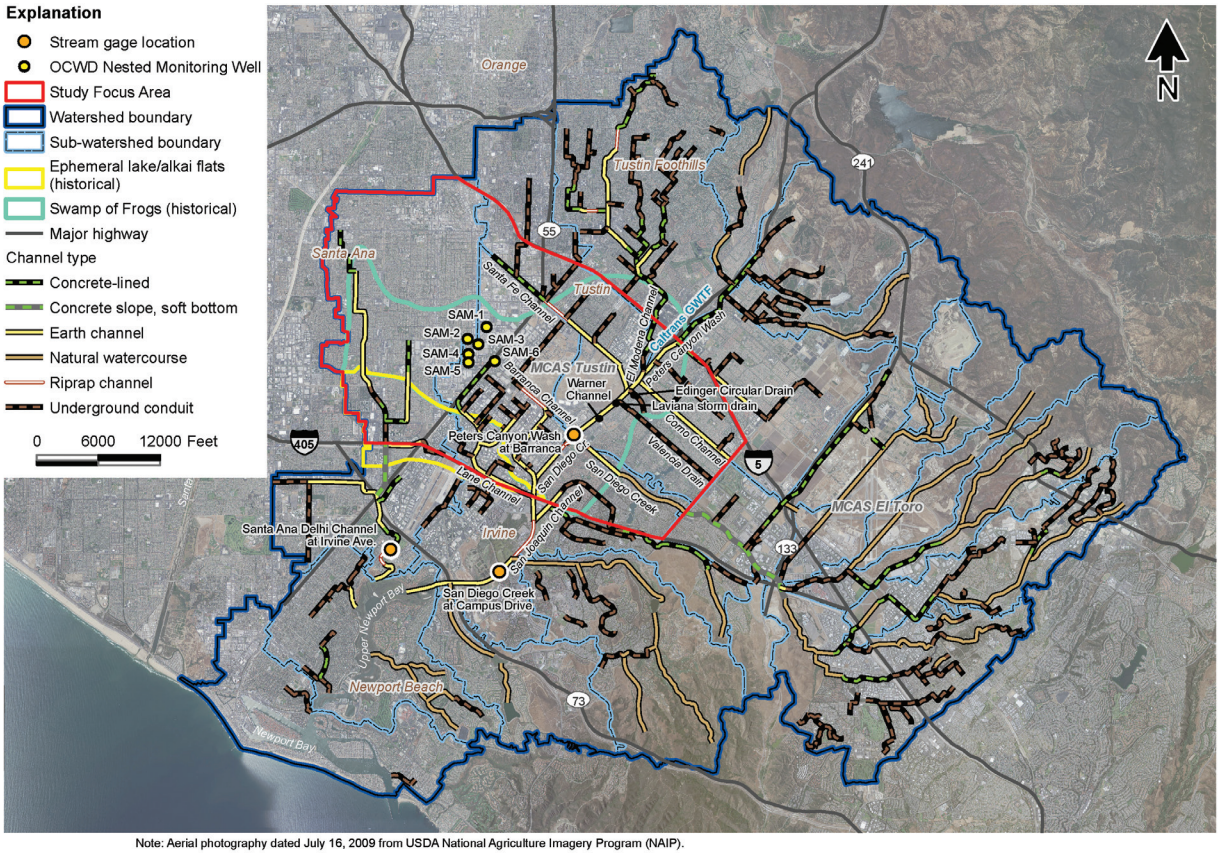
Agricultural and urban development has modified and destroyed wetland environments throughout the United States, often with unintended consequences (e.g., Winter 1988; Dahl 2011). One result of wetland drainage is oxygenation of previously anaerobic environments, which fundamentally alters aqueous redox-geochemistry and in some cases contaminant mobility (e.g., Borch et al. 2010). Selenium is an essential micronutrient in animals; however, it can have toxic effects at elevated concentrations (Hamilton 2004). In highly reducing anaerobic environments selenium occurs primarily as selenide (-II), which is tightly bound to sediments and relatively immobile. In aerobic systems selenium occurs primarily as the more oxidized selenate (Se[VI]), which is not tightly bound to sediments. Given these differences, in cases where selenium occurs, one consequence of wetland drainage is selenium mobilization into groundwater and surface waters.

Central Orange County, California was a wetland named "La Cienaga de las Ranas", or "Swamp of the Frogs," until urbanization of the area occurred in the early 20th century. The former wetland was a depositional environment, evaporative alkali salt flat, and groundwater discharge area (Meixner et al. 2004). The area received regional streamflow

and surface water runoff for millennia until urbanization starting around the turn of the 20th century led to significant hydrological changes. The wetland area was largely drained when land was developed for agricultural use. By the mid-20th century, with increased development, the entire wetland area was fully drained and surface water flow was captured by a network of interconnected surface water and flood control channels extending across central Orange County (Trimble 1998). The surface water channels exit the former wetland area as San Diego Creek on the east and Santa Ana Delhi Channel on the west, both of which flow south into Upper Newport Bay. Peters Canyon Wash is also a significant channel in the area that directs surface water flow from northern Tustin to the south through Irvine, and then merges with San Diego Creek (Figure 1).

This project focuses on the former wetland, ephemeral lake, and surrounding areas where selenium has been detected at elevated concentrations in surface water and includes areas primarily within the cities of Santa Ana, Irvine, and Tustin. Selenium concentrations elevated above applicable toxicity-standards have previously been observed in the surface water channels in this area (e.g., Hibbs and Lee 2000), which is of concern for fish, waterfowl, and other fauna. Selenium concentrations in surface water are often greater than the California Toxics Rule (CTR) chronic water quality criterion for selenium in surface water of 5 µg/L. Groundwater-related discharges have previously been recognized as a dominant source of selenium within the surface water channels (e.g., Hibbs and Lee 2000; Meixner et al. 2004; Hibbs et al. 2008).

Selenium occurrence has been determined to be likely due to marine geologic formations located in upgradient areas of the watershed that are naturally high in selenium content. The Monterey Formation in particular is well documented to contain elevated levels of selenium (USGS 2002). Over an extended time period, selenium-bearing sediments from these formations were eroded and deposited in the



Note: Aerial photography dated July 16, 2009 from USDA National Agriculture Imagery Program (NAIP).

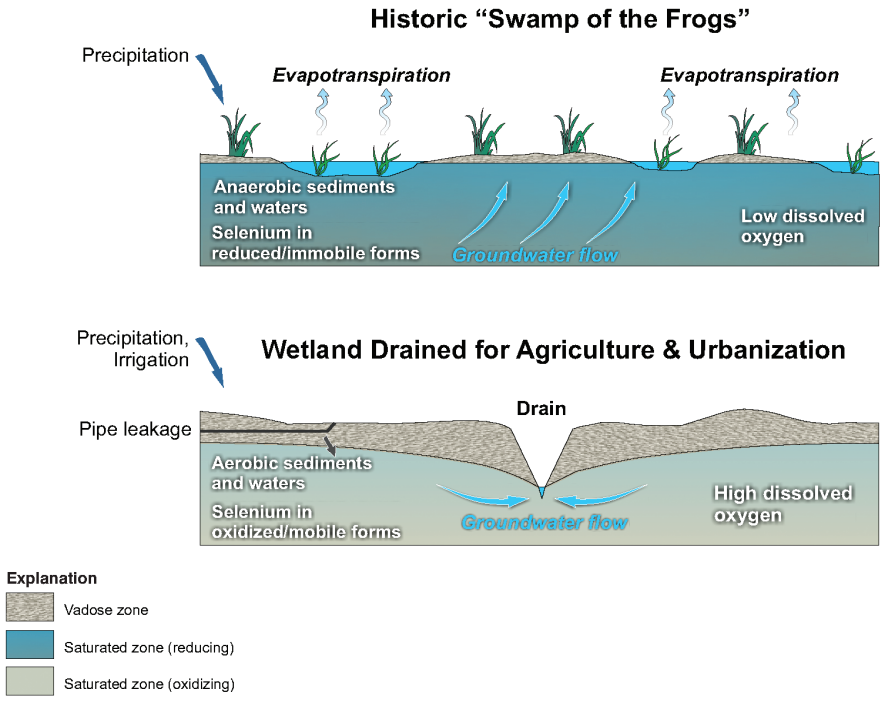
Figure 1. Project location and study focus area.

downslope wetland areas. In addition, selenium was leached by floodwaters and transported downslope via overland runoff to the wetland. The wetland areas were moderately to highly reducing anoxic environments, within which selenium would be reduced primarily to selenide (-II) (e.g., Meixner et al. 2004), and therefore was relatively immobile. Cyclic flooding and evaporation may have played a role in concentration of selenium deposits. Selenium may have been deposited preferentially on the edges of the wetland, where it would be first subject to immobilization by vegetation and anoxic sediments (Hibbs et al. 2008). Land use changes and channelization of the watershed in the 20th century fundamentally altered the redox geochemistry of the shallow groundwater. Lowering of the groundwater table introduced oxygen to previously hydric soils, which likely oxidized selenium to more mobile forms, including selenate (Se[VI]). Figure 2 presents a conceptual diagram of hydrologic processes and selenium transport in the historic "Swamp of the Frogs" and the same area following wetland drainage.

The Santa Ana Regional Water Quality Control Board (RWQCB) issued Order No. R8-2004-0021 (amended later by the Order R8-2007-0041) prescribing, in part, limitations on groundwater-related discharges of selenium in the watershed. Parallel to the effluent limitations, the RWQCB order allows for an alternative compliance approach, which led to the formation of the Nitrogen and Selenium Management Program (NSMP) Working Group to develop and implement a comprehensive Work Plan to address nitrogen and selenium loading. The Working Group consists of the County of Orange, Orange County Flood Control District (OCFCD), the watershed cities, individual dischargers, major land developers, water districts, RWQCB, and environmental groups.

The NSMP developed a draft Best Management Practice (BMP) Strategic Plan (NSMP 2011) based on the work products generated by many subtasks of the Work Plan. The BMP Strategic Plan recognized that a better understanding of groundwater in the watershed is necessary, and therefore proposed a phased approach for further watershed studies. The hydrogeologic characterization and water balance discussed in this report is an "Early Action Item" of the BMP Strategic Plan.

The present study supported policy recommendations regarding mitigation of selenium impacts by improving general understanding



Source: After Hibbs and Lee, 2000

Figure 2. Conceptual model of selenium deposition and remobilization in historic "Swamp of the Frogs."

of present-day drivers for continued selenium mobilization to the surface water channels. An understanding of selenium loading and drivers of selenium mobilization is necessary for effective mitigation planning. Pertinent questions posed by stakeholders and regulators that the water-balance study sought to address included the following:

1. What are the sources of water that cause perennial dry-weather flow in the surface water channels within the study area?
2. To what extent does over-irrigation contribute to dry-weather flow and selenium mobilization?
3. How can we expect selenium mobilization to vary in wet and dry precipitation years?
4. Where are selenium "hot-spots" in groundwater and surface-water that could be targeted for remedial action?
5. Are previous estimates of selenium loading to the surface-water channels consistent with the quantitative water balance and available groundwater selenium sampling data?

Methods

This study focuses on estimating the groundwater balance for the former wetland areas based on available data and hydrogeologic analyses. The analysis starts with estimating the magnitude of groundwater inputs and outputs for the surficial unconfined aquifer (Shallow Aquifer) within the bounds of the study focus area, which is 31 square miles and is shown on Figure 1. The thickness of the Shallow Aquifer was based on hydrogeologic interpretation conducted by the Orange County Water District (OCWD) and included in their regional groundwater model (OCWD 2012a). OCWD stratigraphic data are the most comprehensive available data source for aquifer thickness and are based on review of regional geologic reports, and hydrogeologic interpretation of lithologic logs, geophysical logs, depth-specific water level data, and water quality data.

This study analyzes water years 2005 through 2011 (i.e., October 1, 2004 through September 30, 2011). This timeframe was chosen to focus on recent conditions, while also covering a period with a range of climatic conditions and a statistical profile similar to the historical record. The average annual precipitation over the time period 2005 to 2011 (13.30 inches, as measured at Santa Ana Fire Station) is similar to the average of 1917 to 2011 (13.26 inches), while the median is slightly lower (9.81 and 11.67 inches, respectively). Water years 2005 and 2011 represent relatively wet periods (28.8 and 19.4 inches rainfall, respectively), while water year 2007 represents a relatively dry period (2.77 inches rainfall).

Groundwater inputs for the study area include deep percolation of precipitation and irrigation water (P_p, P_i), lateral groundwater inflow from upgradient portions of the Newport Bay watershed (GW_i), and deep percolation of water leaking from sewer and water lines (S). Groundwater outputs include production discharged to the sanitary sewer (E_r), production discharged to storm drains/ surface water channels (E_d), lateral groundwater outflow to downgradient areas (GW_o), vertical flux of groundwater downwards out of the Shallow Aquifer into deeper aquifer units (V), and passive discharge to surface water channels, storm drains, and subdrains (SW_o), through weeps, seeps, springs, and via the channel bottom. Mathematically, the net groundwater balance, or change in groundwater in storage within the study area, (ΔGWs), is represented by the following equation:

$$\Delta GW_s = [P_p + P_i + GW_i + S] - [E_r + E_d + GW_o + V + SW_o] \quad \text{(Equation 1)}$$

The annual average magnitude of each of the parameters listed on the right side of Equation 1 was estimated using standard hydrologic methods or obtained from literature references, as detailed in the following sections. The groundwater balance was estimated individually for each water year during the study time period (2005 through 2011), as well as on an average basis for the entire study time period. It was assumed that for each water year of our analysis, the sum of all groundwater inputs should approximately equal the sum of all groundwater outputs. This approach assumes that the annual change in groundwater storage within the study area (ΔGW_s) is zero, which is reasonable based on the observation of only minor and temporary changes in groundwater levels as measured in study area groundwater wells (Figure 3).

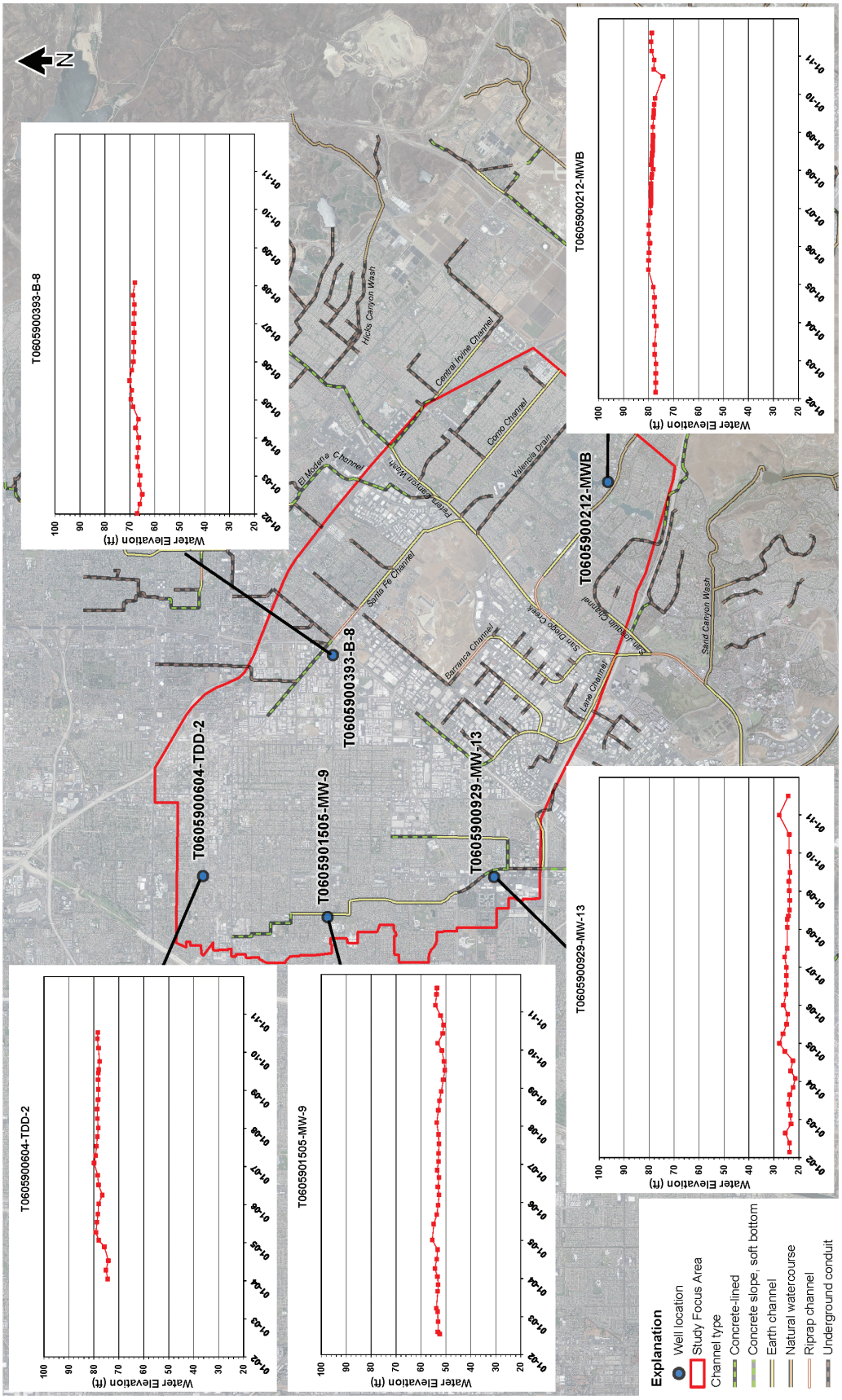


Figure 3. Time-series hydrographs for selected shallow wells.

Lateral Groundwater Inflow and Outflow

A groundwater potentiometric surface contour map was developed as a basis for quantifying groundwater inflow and outflow within the study area. Hundreds of active monitoring wells are screened in the Shallow Aquifer within the study area. The majority of these wells are associated with State-regulated groundwater remediation activities (e.g., dry-cleaner sites, industrial sites, gasoline stations), and quarterly water level and water quality data are largely publically available on-line from the State Water Resources Control Board (SWRCB) Geotracker website.

Depth-to-water and measuring-point elevation data from all available individual remediation sites within the study area were accessed from Geotracker. Typically, several monitoring wells are located at each Geotracker site. Data from a subset of the Geotracker sites located within the study area were excluded because measuring-point elevation values were anomalous, and apparently not based on a surveyed elevation benchmark. Following exclusion of these sites, 44 sites had depth-to-groundwater data available for inclusion in the database. Irvine Ranch Water District (IRWD) provided data for several additional shallow monitoring wells located east of Peters Canyon Wash.

The well data were filtered to include data only for wells with a shallow screen (less than or equal to fifty feet below ground surface), and with groundwater level data available during our study time period (water years 2005 to 2011). Approximately 148,000 individual well measurements were available that fit these criteria, and data were processed with a GIS-based computer program (Milbert and Zilkoski 2003), so that all water level data would be in a consistent vertical datum. Groundwater elevation was calculated for all the available data by subtracting the depth to water from the referenced measuring point elevation.

Many surface-water channels within the study area are recognized as gaining reaches (e.g., Meixner et al. 2004). Under non-storm flow conditions, the elevation of the top of the surface water column at any one location in a channel is therefore the same as the adjacent groundwater elevation at that location. Surveyed channel elevations for a 1.5 mile stretch of Peters Canyon Wash north of the confluence with San Diego Creek were provided by Orange County (OC) Watersheds. Surveyed surface-water elevation data were not available for the remainder of the study area, and this was recognized as a key data gap.

Average groundwater elevations for the study time period (October 2005 to October 2011) were determined for each Geotracker site within the study area (Figure 4). For sites with multiple individual monitoring wells, the site average values represent an average of all measurements made from all wells at that site. Data from nested monitoring wells indicate that groundwater elevations can vary vertically within the Shallow Aquifer. The calculated Geotracker site average groundwater levels therefore represent an average over the vertical screened interval of the monitoring wells used in each calculation (generally between the water table and fifty feet below ground surface (bgs)), a horizontal spatial average (across the horizontal extent of the site), and a temporal average over the study time period. The standard deviation of the values used to calculate averages for each site are plotted, and in most cases are relatively small (i.e., less than 10 percent of average groundwater elevation).

Lateral groundwater inflow was estimated based on Darcy's Law of groundwater flow:

$$Q = K \cdot i \cdot A \qquad \text{(Equation 2)}$$

where Q is groundwater discharge (L^3/T), K is hydraulic conductivity (L/T), i is the hydraulic gradient (L/L), and A is the cross-sectional area (L^2).

The groundwater elevation contour map (Figure 4) was used to estimate groundwater flow direction and the hydraulic gradient. Five "slice planes" were interpolated perpendicular to groundwater inflow flow direction at the upgradient edge of the study area (ENT-1 through ENT-5), and two slice planes were interpolated generally perpendicular to the groundwater direction at the downgradient boundary (EXT-1, EXT-2). Equation 2 was solved for each slice plane in order to estimate the lateral groundwater inflow and outflow.

For each segment, the cross-sectional area (A) is estimated as the product of the length of the slice plane and the vertical saturated thickness. The saturated thickness was determined from

the difference in the groundwater elevation and the elevation of the top of the aquitard unit that separates the Shallow Aquifer and underlying aquifer units. Aquitard elevation data were provided by OCWD (2012a). The hydraulic conductivity for each slice plane was initially based on hydraulic conductivity data for the study area also provided by OCWD (2012a). The hydraulic conductivity values of slice planes ENT-1, ENT-2, and ENT-3 were adjusted during finalization of the groundwater balance, as discussed below. The original values of 175 to 200 feet per day were adjusted to 93 feet per day.

Groundwater Recharge from Precipitation and Irrigation

Recharge from precipitation and irrigation was estimated using a soil-moisture balance model, the Distributed Parameter Watershed Model (DPWM), developed previously by Daniel B. Stephens & Associates, Inc. Application of the DPWM allows for quantitative estimates based on site-specific climatological, geologic, soils, land use, and vegetation factors. DPWM was developed based on the Mass Accounting System for Soil Infiltration and Flow (MASSIF) model developed by Sandia National Laboratories (2007). The DPWM is similar in concept to water balance models used by the USGS (e.g., Net Infiltration Model (INFIL) Hevesi et al. 2003). The model relies on the widely accepted United Nations FAO-56 procedure for computing actual evapotranspiration (AET) from the reference evapotranspiration (ET_0), which is estimated using the Penman-Monteith method (Allen et al. 1998, 2005). Water budget components accounted for in the DPWM model include precipitation, irrigation, bare soil evaporation, transpiration, runoff, run-on, soil water storage, and deep percolation (recharge).

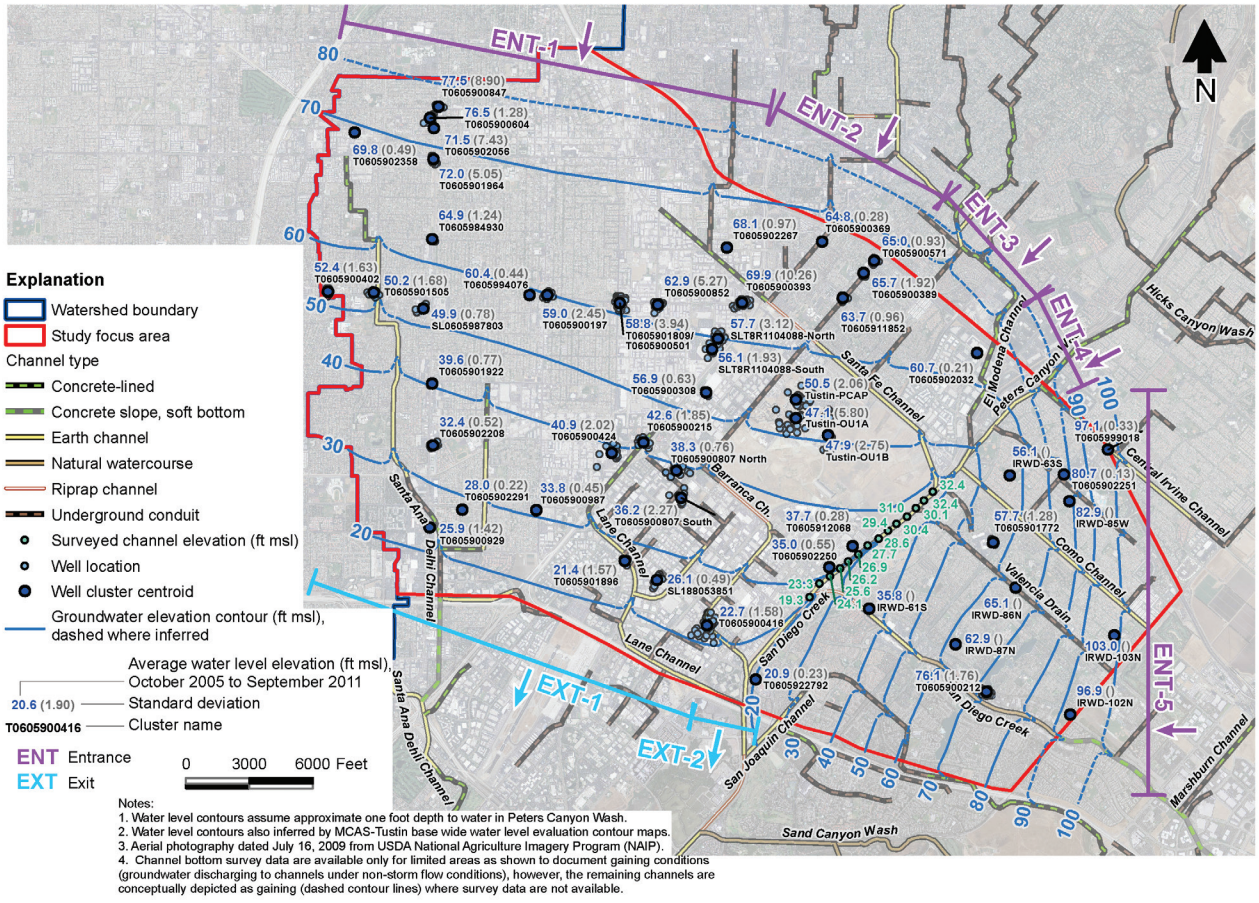


Figure 4. Groundwater elevation of the Shallow Aquifer.

The DPWM model domain covers the study area and entire upgradient watershed, and consists of uniform grid cells 295 feet (90 meters) on a side. The model was run for the complete study time period, water years 2005–2011, using a daily time-step routine. Model data were collected from weather stations, site-specific literature sources, and general literature sources, and/or were estimated from other properties. Key model parameters and data sources are summarized in Table 1.

Routing of precipitation within the study area is significantly impacted by urbanization, including covering of the land surface with impervious surfaces (i.e., pavement, asphalt, rooftop). The presence of impervious surfaces is generally understood to increase runoff and concomitantly decrease infiltration and deep percolation to groundwater. For the purpose of DPWM modeling, a "percent impervious surface" was assigned to each model grid cell (Homer et

Table 1. Key parameters used in Distributed Parameter Watershed Model (DPWM).

DPWM Parameter	Data Source	Notes/Methods
Precipitation Rate [L/T]	CIMIS; PRISM	• Based on hourly precipitation data from local gage Irvine #75 • Extrapolated over entire model area using PRISM
Irrigation Rate [L/T]	Irvine Ranch Water District (IRWD)	• 2,800 gal/ac-d = 37.7 in/yr for vegetated areas of developed cells • Median of Irvine Ranch Water District estimated irrigation requirements for developed areas • CA DWR estimates for agricultural areas (minor) • Monthly irrigation rates calculated from annual averages using monthly fraction of reference ET for CIMIS Zone 16
Soil Hydraulic Conductivity [L/T], Depth [L]	Soil Survey Geographic (SSURGO) Database (USDA NRCS)	• Unmodified for vegetated areas of developed land uses
Soil "Field Capacity" [-]	SSURGO, ROSETTA	• Soil properties related to water retention (i.e., van Genuchten parameters) estimated using ROSETTA based on SSURGO soil property data, model calculates "field capacity"
"Impervious" Surfaces Properties	USGS NLCD GIS data for impervious surfaces (2006); Literature survey (see following slide)	• Fraction impervious land surface from 2006 USGS National Land Cover Dataset (NLCD) • Hydraulic conductivity from literature survey (1·10-7 m/s =0.03 ft/d) • Meant to be generally representative of urban pavements with cracks
Rooting Depth for Grass/Turf [L]	Wu 1985 (Univ. of CA Cooperative Extension)	• "Middle" value for various grass species

al. 2015). The impervious surface portion of each cell in the DPWM model received no irrigation, contained no vegetation, and accepted all runoff from surrounding areas of the cell. Furthermore, runoff on impervious surfaces within each cell was routed directly to the impervious surface portion of the next downgradient cell, and so-on, until reaching the closest mapped surface water channel. DPWM routing of water therefore approximately represented storm flow to storm water drains and then to surface water channels. Because all runoff is routed from one impervious surface to the next when present, "focused recharge" (e.g., from building roofs to vegetated areas via downspouts) is not accounted for. Model results may therefore underestimate the amount of recharge from precipitation as influenced by focused recharge.

A literature review was conducted in order to evaluate the value of hydraulic conductivity assigned to the impervious surfaces section of each model grid cell. Previous studies included double-ring infiltrometer experiments on pavements and asphalts (Wiles and Sharp 2008), weighing lysimeter experiments of infiltration through fresh-laid asphalt (Raimier et al. 2004), laboratory permeameter testing on new asphalt cores (Huang et al. 1999), and previous urban watershed/climate modeling (Dupont et al. 2006). Based on this review, a hydraulic conductivity value of $1 \cdot 10^{-5}$ cm/s (0.028 feet per day) was assigned to the impervious surfaces within the model domain.

Sewer and Water Line Exfiltration/Infiltration

IRWD and the City of Santa Ana provided sewer and water line data used to estimate the amount of pipe exfiltration (loss). Exfiltration was estimated as a percentage of total consumption using a 5 percent loss estimate from Sharp (2010). Pipe infiltration may also occur, which would be considered a groundwater outflow component. Pipe infiltration is particularly relevant when considering sewer lines located beneath the water table, as reportedly occurs within the study area. However, specific data regarding pipe exfiltration and infiltration are currently not available. According to IRWD, sewer pipelines in the IRWD service area range from a minimum of 7 feet deep (below grade) to over 30 feet deep. Many of these pipelines are below shallow groundwater, making them subject to the risk of infiltration, not exfiltration (IRWD 2012). Given the range of groundwater depths (5 to 46 feet bgs) and the range of sewer line depths (7 to 30 feet bgs) in the study area, infiltration from sewer lines in the IRWD was assumed, in the absence of other data, as 2.5 percent loss, which is half of the 5 percent loss assumed by Sharp (2010).

Vertical Groundwater Outflow

The Shallow Aquifer is underlain by an aquitard unit that appears to be continuous throughout the study area, which is in turn underlain by regional aquifer units collectively referred to as the Principal Aquifer. Groundwater flow between the Shallow Aquifer and the Principal Aquifer is governed by differences in hydraulic head between the two units, and is restricted by the low hydraulic conductivity of the interlaying aquitard.

Vertical groundwater flow between the Shallow and Principal Aquifers was estimated based on calculation of the difference in groundwater elevation between the two units. Groundwater levels were generally higher in the Shallow Aquifer compared to the Principal Aquifer, indicating downwards vertical flow. The vertical groundwater flow (Q_v, L^3/T) can be calculated from:

$$Q_v = K_v \cdot i_v \cdot A_v \qquad \text{(Equation 3)}$$

where K_v is the vertical hydraulic conductivity, A_v is the cross-sectional area of vertical flow, and i_v is the vertical hydraulic gradient. Groundwater elevation contour maps of the Principal Aquifer are available from OCWD for each year of the study time period, and cover the entire extent of the study area and surrounding watershed (OCWD 2012b). GIS methods were used to interpolate the difference in groundwater levels in the Shallow and Principal Aquifer throughout the study area for each year, using the yearly OCWD maps for the Principal Aquifer, and the groundwater elevation contour map generated herein (Figure 3) for the Shallow Aquifer.

The study area was discretized into approximately 5,000 cells with dimensions of 416 feet by 417 feet. The vertical gradient

was calculated for each cell as the difference in hydraulic head between the Shallow and Principal Aquifer divided by the representative distance between the two units (500 feet). The vertical hydraulic conductivity was assumed to be $2.8 \cdot 10^{-3}$ feet per day ($1 \cdot 10^{-6}$ cm per second), which is representative of the fine-grained aquitard unit (e.g., Freeze and Cherry 1979).

Shallow Groundwater Production

Groundwater production from the Shallow Aquifer within the study area is limited to remediation and dewatering projects. Remediation systems and some dewatering facilities discharge water to the sanitary sewer system, while other dewatering facilities discharge either to storm drains, which flow into the surface water channels, or directly into the surface water channels themselves. Available data regarding groundwater production rates were compiled from available sources, including the City of Irvine, CalTrans, Nitrogen and Selenium Management Program (NSMP 2009), Geotracker, and Enviro Compliance Solutions Inc. (ECS 2012).

Passive Groundwater Discharge to Surface Water Channels

Groundwater flow to surface water channels in the study area is through direct discharge from dewatering projects, and passive discharge through weeps, seeps, springs, and the channel bottom. Direct monitoring data available to estimate passive groundwater discharge to surface water channels are limited. For example, although there are several surface water gages throughout the watershed, only one permanent surface water gage is located within the study area (Peters Canyon Wash at Barranca, Figure 1).

Passive groundwater discharge to surface water channels was first evaluated by analysis of available downstream surface water gage data. Daily streamflow records were analyzed to estimate the groundwater discharge (baseflow) component of the streamflow hydrograph. The surface water channels exit the study area as San Diego Creek to the east and Santa Ana Delhi Channel to the west. Streamflow gages are located on each surface water channel downstream of the study area (Figure 1), and streamflow data were provided by OC Watersheds. Baseflow in the surface water channels of the study area includes passive groundwater discharge (SW_o), and discharge by dewatering projects (E_d).

Daily streamflow records from the gages for San Diego Creek at Campus Drive and Santa Ana Delhi Channel at Irvine Avenue during the study time period were processed with digital filtering methods to estimate the baseflow component of the surface water flow hydrograph (Lim et al. 2005).

Passive groundwater discharge to surface water channels was estimated as the difference in the sum of groundwater inputs and the sum of remaining groundwater outputs. Equation 1 is rearranged to the following in order to solve for passive groundwater discharge:

$$SW_o = [P_p + P_i + GW_i + S] - [E_r + E_d + GW_o + V] \quad \text{(Equation 4)}$$

The reasoning behind this approach is that for the final groundwater balance, the sum of all groundwater inputs should approximately equal the sum of all groundwater outputs. This assumes that the annual change in groundwater storage within the study area (ΔGW_s) is zero, a reasonable assumption based on the observation of only minor and temporary changes in groundwater levels (Figure 3). Equation 4 was solved for each water year during the study time period, and also on an average basis over all years; it was assumed based on available hydrograph data (Figure 3) that increases in groundwater inflow during wet years is offset by increased outflow (i.e., discharge) within the same water year. A limitation of applying Equation 4 is that errors from previous water-balance calculations are compounded in estimation of groundwater discharge to surface-water channels; therefore, an additional adjustment step was included as described below.

Stream hydrograph results were used to constrain estimates using the groundwater balance method. Values of the total groundwater discharge to surface channels ($SW_o + E_d$) were compared using the two methods. Initially, values of total groundwater discharge to the surface channels from the groundwater balance method were larger than values estimated using the stream hydrograph

method by an average of approximately 43 percent. To minimize the difference in estimated discharge rates using the two methods, the following adjustments were made.

A review of input parameters used in the groundwater balance revealed that hydraulic conductivity parameters used in the groundwater inflow estimation had a significant impact on the overall groundwater balance and were prone to uncertainty. The hydraulic conductivity corresponding to the groundwater "entering" slice planes 1, 2, and 3 (Figure 4) was decreased to lower the value of GW_i, which concomitantly decreased the estimated value of SW_o. The hydraulic conductivity values were decreased to minimize the difference in the average total groundwater discharge ($SW_o + E_d$) estimated using the water balance approach and the stream hydrograph analysis. Initial values of hydraulic conductivity for the region of the entering slice planes 1, 2, and 3 provided by OCWD ranged from 175 to 200 feet per day, and were adjusted to 93 feet per day using this calibration procedure. The value of 93 feet per day is considered reasonable, as it is representative of aquifer sand units (e.g., Freeze and Cherry 1979), and is similar in magnitude to the hydraulic conductivity of other areas of the study area provided by OCWD.

Selenium Data Compilation

NSMP (2009) compiled available selenium data in passive groundwater discharge points ("surfacing groundwater"), surface water, sediments, and biota. We sought to overlay the selenium sampling data collected from surface-water sampling points (NSMP 2009) with data collected from groundwater monitoring wells in order to evaluate similarity in groundwater and surface water selenium concentrations and selenium flux from groundwater to surface water. Selenium data from NSMP (2009) were complemented with selenium data from samples collected from groundwater monitoring wells. Geotracker sites were screened for the availability of selenium data, and additional reported data were compiled from Hibbs and Lee (2000), Meixner et al. (2004), MCAS-Tustin (ECS 2012), IRWD (2012), OCWD (2013), and from a previously developed database provided by OC Watersheds.

Results and Discussion

Groundwater Balance

On an average basis, the principal groundwater input component is lateral groundwater inflow (14,970 ac-ft/yr, or 80 percent of total average input) (Table 2 and Figure 5). The original source of groundwater inflow to the study area is predominantly recharge of precipitation in the alluvial fan head areas along the foothills in the upgradient areas of the watershed. This same water supply likely fed the "Swamp of Frogs" wetland prior to development of the surface water channels.

The groundwater inflow estimate of 14,970 ac-ft/yr compares favorably to estimates of groundwater recharge in the upgradient areas of the watershed. OCWD (2009) estimates groundwater recharge from precipitation along the foothills of the Irvine Subbasin of 14,000 ac-ft/yr, and along the Tustin Hills of 6,000 ac-ft/yr, for a total of 20,000 ac-ft/yr in the areas of the watershed upgradient of the study area. DPWM model runs were conducted for the upgradient area of the watershed in order to validate the estimated groundwater inflow. Recharge estimates ranged from 14,400 to 17,700 ac-ft/yr, which generally agrees with the OCWD estimate of 20,000 ac-ft/yr, and the calculated groundwater inflow to the study area of 14,970 ac-ft/yr. Based on DPWM modeling, approximately 91 percent of the upgradient recharge was due to precipitation, while the remaining 9 percent was due to irrigation in the developed upgradient areas of the watershed.

The principal groundwater output component is passive discharge to surface water channels (12,157 ac-ft/yr, or 65 percent of average output). This is consistent with previous studies, including geochemical investigations demonstrating significant upwelling of groundwater into surface water channels (e.g., Hibbs and Lee 2000; Bechtel 2002; Meixner et al. 2004; Hibbs et al. 2008). For example, Hibbs et al. (2008) report 2006 field monitoring of discharge from four recently installed drains to Peters Canyon Wash. Geochemical signatures of the discharging water indicated it was likely dominated by groundwater flow. A combined discharge rate of 0.4 cubic feet per second (290 ac-ft/yr) was measured from these four drains alone.

Results are consistent with the general understanding that the study area is a groundwater convergence zone (former wetland) which is now drained by the surface channel network, in part, to maintain a lower water table. A strong groundwater convergence zone exists in the direct vicinity of Peters Canyon Wash and San Diego Creek south of its confluence with Peters Canyon Wash, with groundwater flowing into this area from several directions. The groundwater convergence zone is indicated by groundwater elevation contours that appear to "pinch in" around water elevations in the surface water channels (Figure 4). The mapped extent of confirmed groundwater convergence zones are limited by the availability of surveyed surface channel elevation data. If additional surface channel survey channel data were available, similar convergence zones would likely be confirmed along other stretches of the surface channels within the study area.

Comparatively wet and dry water years were evaluated in order to understand the water balance under varying climatic conditions. Over the study time period, the wettest water year is 2005 (Table 2), which is predicted to have a total groundwater input/output of 25,892 ac-ft/yr. In contrast, the driest year during the study time period was 2007, with a total groundwater input/output of 16,680 ac-ft/yr. Intermediate water years (2006, 2008, 2009, and 2010) exhibit a groundwater balance similar to the dry year 2007. These results are explained by the relatively minor recharge from precipitation and irrigation during all but the wettest years, as predicted by the DPWM modeling.

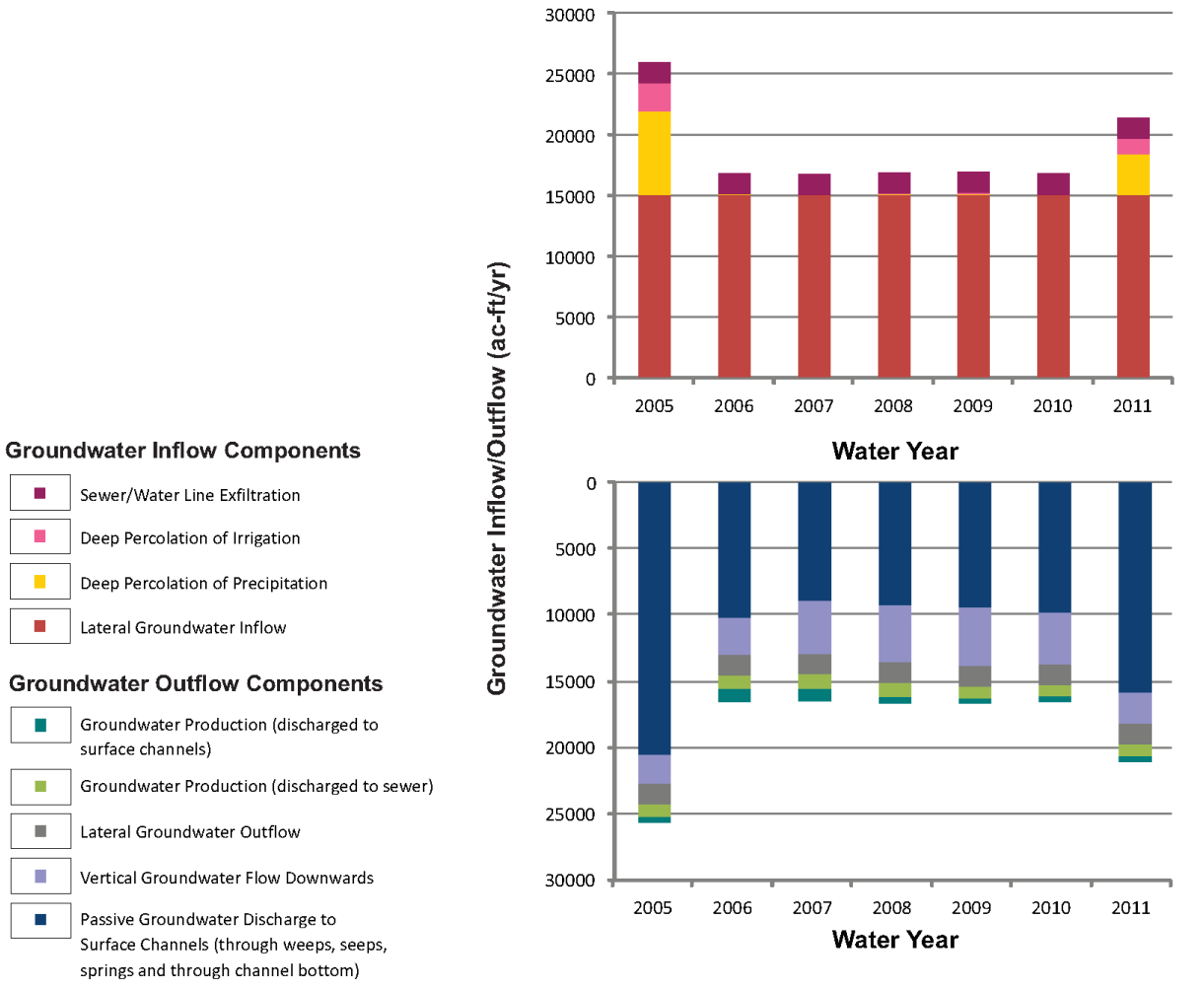


Figure 5. Water balance results.

Table 2. Water balance estimation results.

Category	Component (ac-ft/yr)	Water Year							Average	
		2005	2006	2007	2008	2009	2010	2011	ac-ft/yr	%[a]
Total Precipitation and Irrigation over Study Focus Area	Precipitation	46,214	11,852	2,156	11,370	11,336	8,878	32,497	17,757	-
	Irrigation (IRWD 2012)	21,526	21,526	21,526	21,526	21,526	21,526	21,526	21,526	-
Groundwater Inputs	Deep Percolation of Precipitation	6,893	49	0.4	68	74	29	3,334	1,492	8
	Deep Percolation of Irrigation	2,319	0.5	0.1	72	96	0.4	1,290	540	3
	Sewer/Water Line Exfiltration	1,709	1,709	1,709	1,709	1,709	1,709	1,709	1,709	9
	Lateral Groundwater Inflow	14,970	14,970	14,970	14,970	14,970	14,970	14,970	14,970	80
	Total Groundwater Input	25,892	16,729	16,680	16,819	16,849	16,709	21,303	18,712	-
Groundwater Outputs	Lateral Groundwater Outflow	1,556	1,556	1,556	1,556	1,556	1,556	1,556	1,556	8
	Vertical Groundwater Flow Downwards	2,208	2,812	4,071	4,363	4,461	3,976	2,416	3,473	19
	Groundwater Production (discharged to sewer)	943	1,046	1,119	1,095	866	860	904	976	5
	Groundwater Production (discharged to surface channels)	405	951	907	419	388	379	399	550	3
	Passive Groundwater Discharge to Surface Channels (through weeps, seeps, springs, and through channel bottom)	20,780	10,364	9,027	9,386	9,577	9,938	16,029	12,157	65
	Total Groundwater Output	25,892	16,729	16,680	16,819	16,849	16,709	21,303	18,712	-

[a]Percentage of total groundwater input or output, as applicable.

Flow of water through the vadose zone may contribute to loading of selenium into the Shallow Aquifer (e.g., Meixner et al. 2004; Hibbs et al. 2008). The components of the water balance that flow through the vadose zone within the study area are therefore of particular interest, though they comprise only a small percentage of the overall water balance. These components include deep percolation of irrigation and precipitation, and exfiltration from sewer and water lines. During wet years, vertical flow through the vadose zone appears to be driven primarily by recharge from precipitation. Given the available data, the water balance calculations indicate that during dry and intermediate years, recharge from the vadose zone is driven primarily by sewer and water line exfiltration. However, higher quality data for irrigation inputs and sewer/water line infiltration/exfiltration are needed to better characterize recharge from the vadose zone.

Recharge from irrigation is significant only during wet years, and accounts for less vertical flow compared to recharge from precipitation. These observations are consistent with results reported by Meixner et al. (2004) and Hibbs et al. (2008) that groundwater within the study area in some instances exhibits an isotopic signature similar to local precipitation, while in other instances exhibits an isotopic signature consistent with mixing of local precipitation and imported water that may have leaked from sewer/water lines or percolated from irrigation.

A sensitivity analysis for the overall groundwater balance indicates that hydraulic conductivity is the most sensitive parameter in this analysis (Figure 6). Additional parameters evaluated included irrigation rate, groundwater pumping rate, and pipe exfiltration rate. The most significant parameter evaluated was the hydraulic conductivity of the upgradient areas of the study area (Entering Zones 1, 2, and 3 on Figure 4). As discussed above, the value of hydraulic conductivity for this area was constrained by comparing the overall calculated groundwater balance and stream baseflow. Irrigation rates used in the DPWM, groundwater pumping (discharged to sewer), and hydraulic conductivity of exiting zone 1 (Figure 4) have a relatively minor impact on the total groundwater flow balance.

Selenium Discharge Assessment

The geometric mean selenium concentration for each monitoring well site was plotted on a map with the surface-water sampling data near groundwater discharge points ("surfacing groundwater") data (Figure 7). Selenium concentrations in groundwater are elevated throughout the study area, with concentrations generally exceeding the CTR chronic water quality criteria for selenium in surface water of 5 µg/L, and in many areas exceeding the U.S. Environmental Protection Agency maximum contaminant level for groundwater of 50 µg/L. Overlaying the groundwater data from wells and the surfacing groundwater data confirms that selenium concentrations are similar in groundwater sampled from wells and nearby passive groundwater discharge points. Selenium "hot spots" (>40 µg/L) appear to be in the vicinity of Valencia Drain and Como Channel, MCAS-Tustin, and north of Lane Channel. The groundwater well data also reveals that elevated selenium levels (>10 µg/L) are observed outside of the boundary of the former Swamp of Frogs, along the northern and eastern boundaries of the study area.

NSMP (2009) includes a detailed assessment of selenium loading to surface water channels from various sources, including urban runoff, dewatering facilities, remediation projects, agricultural discharges, atmospheric deposition, open space, and passive groundwater discharge. NSMP (2009) estimates passive groundwater discharge to be the largest source of selenium in the San Diego Creek subwatershed, accounting for an average of 730 lbs/yr of the 1,060 lbs/yr total from all sources (69 percent).

We evaluated this estimate of selenium loading from groundwater to the surface water channels of the San Diego Creek subwatershed to assess if it is consistent with the water balance and selenium data evaluation. The following equation was used to back-calculate the selenium concentration in groundwater (C_{Se}) that would result in an average annual loading of 730 lbs/yr:

$$C_{Se} = \frac{F_{lb/y} \bullet (4.536 \bullet 10^{8})}{SW_{o} \bullet (1.233 \bullet 10^{6}) \bullet 0.4} \qquad \text{(Equation 5)}$$

where F is the reported loading rate in units of

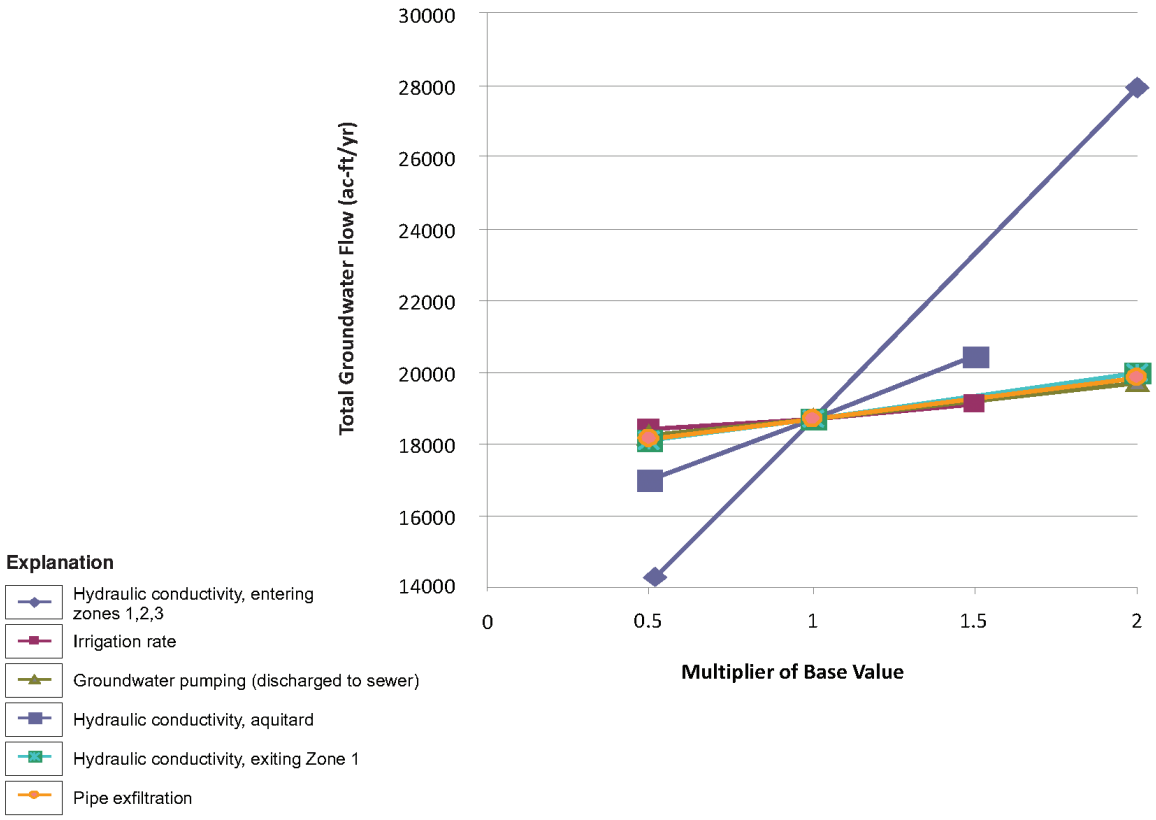


Figure 6. Sensitivity analysis, groundwater balance.

lbs/yr, $4.536 \cdot 10^8$ is a conversion factor from units of lbs to µg, SW_o is the average annual flow rate of passive groundwater discharge to the surface water channels in units of ac-ft/yr, $1.233 \cdot 10^6$ is a conversion factor from units of ac-ft to liters (L), and 0.40 is a factor for the mitigation of selenium concentrations within the surface water channels after discharge from groundwater, as reported by Meixner et al. (2004) and used in the NSMP (2009) calculations.

The value of SW_o for San Diego Creek and its tributaries was obtained from the groundwater balance (Table 2). The calculated value of C_{Se} for the San Diego Creek subwatershed is 56 µg/L, which appears reasonable based on available selenium concentration data in groundwater summarized in Figure 7. The NSMP (2009) estimated loading rates are generally consistent with the groundwater balance and selenium data assessment completed in this study.

Summary

The following summarizes results from the hydrogeologic characterization and water balance development:

- On average, approximately 80 percent of total groundwater input in the study area (18,712 ac-ft/yr) is due to lateral groundwater inflow (14,970 ac-ft/yr). The next largest recharge sources are sewer/water line exfiltration (9 percent or 1,709 ac-ft/yr), infiltrating precipitation (8 percent or 1,492 ac-ft/yr), and infiltrating irrigation (3 percent or 540 ac-ft/yr).
- On average, approximately 65 percent of total groundwater output in the study area (18,712 ac-ft/yr) is due to discharge to surface water channels (12,157 ac-ft/yr). The next largest sinks are vertical groundwater flow (19 percent or 3,473 ac-ft/yr), groundwater outflow (8 percent or 1,556 ac-ft/yr), and groundwater

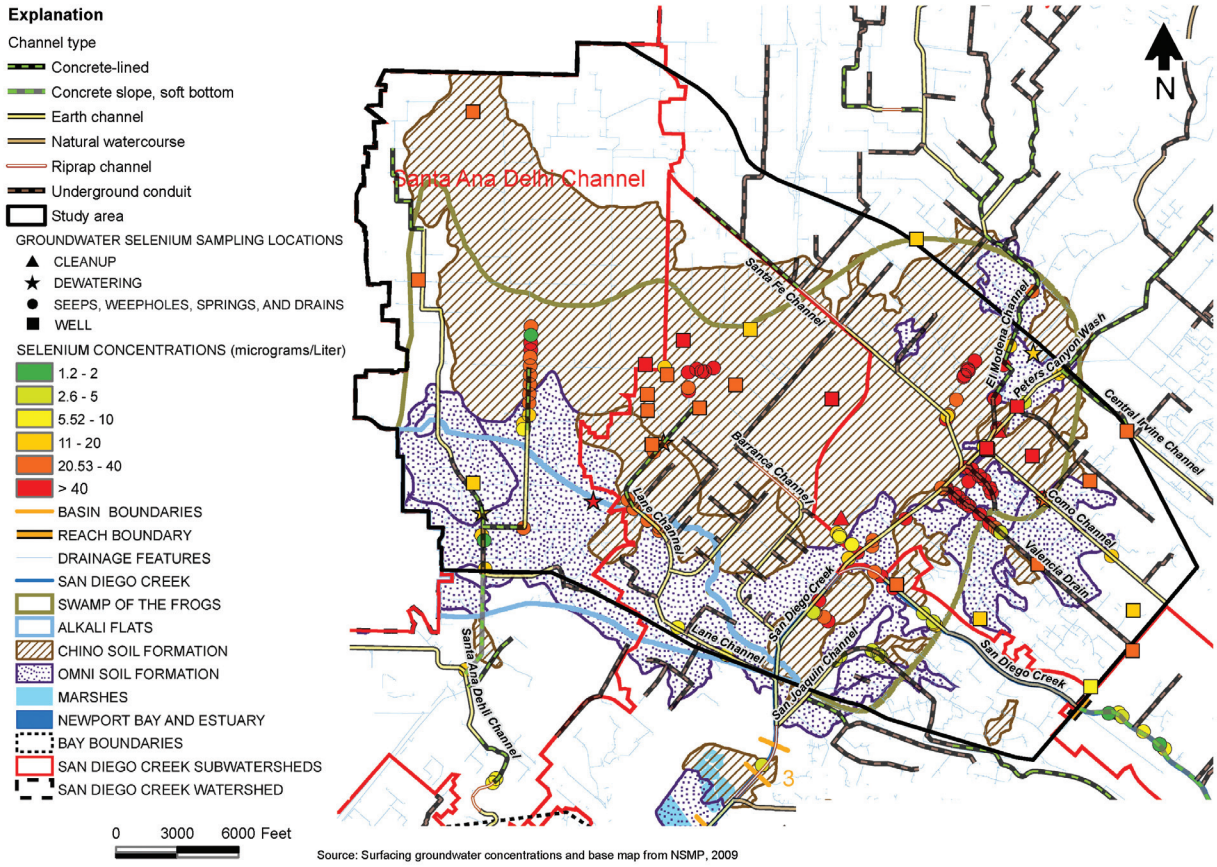


Figure 7. Selenium concentrations in groundwater and surfacing groundwater.

extraction from shallow wells (8 percent or 1,526 ac-ft/yr).

- In wet years (such as 2005), the relative contribution of the various groundwater sources changes to 58 percent lateral groundwater inflow, 27 percent infiltrating precipitation, 9 percent infiltrating irrigation, and 7 percent sewer/water line exfiltration. About 80 percent of the outflow is due to discharge to surface water channels (20,780 ac-ft/yr), 9 percent is due to vertical flow downwards, 6 percent is due to groundwater extraction, and 6 percent is due to lateral groundwater outflow.
- In relatively dry years (such as 2007), lateral groundwater inflow accounts for about 90 percent of the groundwater input. About 10 percent is due to sewer/water line exfiltration and less than 1 percent is due to infiltrating precipitation and/or irrigation. About 55 percent of the outflow is due to discharge to surface water channels (9,027 ac-ft/yr), 24 percent is due to vertical flow downwards, 12 percent is due to groundwater extraction, and 9 percent is due to lateral groundwater outflow.

The water balance was used to verify prior estimates of selenium discharge to the channels and assess proposed engineering solutions to control the discharge. The selenium discharge concentration calculated for the San Diego Creek subwatershed using the water balance is 56 µg/L, which appears reasonable based on available selenium concentration data in groundwater.

Conclusions

Results from our study improve conceptual understanding of the regional hydrologic system and drivers for continued selenium mobilization in the watershed. The majority of groundwater influx into the former wetland area is from groundwater underflow from upgradient portions of the larger watershed (Figure 4); this water originates

primarily as precipitation-related recharge in alluvial-fan head areas north and east of the former wetland area. This conceptual understanding of the local hydrologic system is consistent with the fact that this area was formerly a perennial wetland that was fed by groundwater underflow.

To a more limited extent, shallow groundwater occurs today due to deep percolation of precipitation, irrigation, and sewer/water-line leakage within the former wetland area. Over-irrigation in the former wetland area of residential/commercial turf is not a main driver for the presence of shallow groundwater or shallow groundwater-discharge to the surface water channels. However, selenium mobilization may occur from water percolation through the vadose zone within the former wetland area from deep percolation of precipitation and irrigation and sewer/water-line leakage. Vertical percolation through the vadose-zone in the former wetland area is considered to be significantly greater in wet years as compared to dry years (Figure 5).

Perennial groundwater discharge to the surface water channels occurs due to the presence of shallow groundwater and construction of the surface water channel network below the shallow groundwater table (and in certain instances continued surface-water channel lowering due to erosion). The presence of the surface-water channel network limits long-term increases in groundwater elevation and groundwater-in-storage within the former wetland area, as water readily drains into the surface water channels when groundwater levels rise (i.e., "the bath-tub overflow drain effect"; Figure 3). Groundwater discharge to the surface-water channels is therefore greatest in wet years (Figure 5); however, groundwater elevations do not change markedly from year-to-year.

Selenium hot-spots in groundwater have been identified in certain areas that are also known to be proximal to observed hot-spots within the surface-water network (Figure 7). These areas may be targeted for remedial actions, including surface-water diversion and/or treatment.

Several data gaps were identified during completion of the study, including (1) depth-discrete soil and sediment sampling data to delineate selenium impacts and source areas, and to distinguish vadose-zone leaching as a selenium source separate from leaching from saturated sediments; (2) hydraulic properties of impervious surfaces within the watershed to better constrain percolation estimates in these areas; (3) extensive and depth-discrete selenium groundwater sampling data from throughout the former wetland area have not been collected as part of a consistent and contemporaneous sampling program; (4) sewer/water line exfiltration/infiltration measurements are generally not available to constrain estimates of the importance of this source in the groundwater balance; (5) surface-water channel floor elevation data are lacking to compare to groundwater elevation data in identification of gaining surface water reaches; (6) few surface-water flow gages are available to estimate baseflow and related selenium discharge rates; and (7) local turf irrigation rates are generally not available.

Future work could be focused on additional data collection, including a soil and groundwater sampling program, sewer/water-line infiltration/exfiltration studies, irrigation practices surveys and local irrigation applied water measurements, and the development of feasibility studies that evaluate the merits and/or means of mitigating selenium concentrations in the watershed.

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