ULARA

WATER-QUALITY MODELING FOR THE ULARA SALT AND NUTRIENT MANAGEMENT PLAN

DRAFT TECHNICAL MEMORANDUM NO. 5

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EXECUTIVE SUMMARY AND CONCLUSIONS

A spreadsheet mixing model was developed to simulate groundwater quality in the seven Upper Los Angeles River Area subareas to estimate future effects of implementing management measures identified in the Salt and Nutrient Management Plan (SNMP), and to help understand the potential effects on groundwater quality related to the use of recycled water within ULARA. The mixing model simulated total dissolved solids (TDS), chloride and nitrogen concentrations over a 29-year period using annual time steps. The model tracked flow, concentration and mass concurrently so that all flows and loads entering and leaving the groundwater system could be accounted for. The mixing model approach provides quantitative estimates of future concentrations and concentration trends, which is essential information for comparing the relative effectiveness of alternative water-quality management measures and for determining the number of measures needed to achieve water quality objectives. The modeling approach also reveals discrepancies and gaps in available data, which represent sources of uncertainty in the analysis and also suggest priorities for future monitoring programs.

Estimates of model inputs were derived from many sources, including Watermaster annual reports and databases, local water and wastewater agencies, Los Angeles Department of Water and Power's (LADWP) groundwater flow model, and new estimates of groundwater storage and tributary inflows. Several sets of historical water quality data were reviewed to estimate initial concentrations for modeling and to identify lingering effects of prior land use and hydrologic conditions. Input data were not all mutually compatible, which necessitated selecting among data sets, averaging, and calibration of the mixing model. The model was calibrated to observed concentration trends during 2002-2012 (referred to as the "baseline period" in other Technical Memoranda prepared for the ULARA SNMP).

To evaluate the effects of SNMP implementation, future scenarios were simulated representing 1) future baseline conditions, 2) future baseline plus planned SNMP tertiary recycled water use for irrigation and groundwater recharge (GWR), 3) future baseline plus SNMP tertiary recycled water irrigation and GWR plus stormwater recharge, and 4) future baseline plus SNMP tertiary recycled water irrigation and advanced-treated water GWR plus stormwater recharge. Estimates of future centralized and distributed stormwater recharge were based on the Los Angeles Department of Water and Power Stormwater Capture Master Plan (Geosyntec Consultants, 2015) and the Greater Los Angeles Regional Integrated Regional Water Management Plan (Leadership Committee, 2014). Future simulations were conducted for the 2016-2044 period.

The data analysis and modeling results support the following conclusions:

- Measured and simulated concentrations were variable among subareas, as are the Basin Plan Objectives (BPO). Thus, the amount of assimilative capacity was as dependent on the BPO as on the ambient water quality.
- Many subareas have existing water quality trends unrelated to recycled water use, such as increasing TDS and chloride concentrations in the Eagle Rock Basin. These can result from the effects of irrigation, historical land uses, and changes in groundwater flow directions that mobilize poor-quality water.

- Historical groundwater quality data are sparse and clustered in space and time. Where sampling coverage was extensive, the spatial variability of TDS, chloride and nitrogen concentrations within subareas was often high.
- Groundwater salinity is relatively high along the southern edges of the San Fernando West and San Fernando East subareas, which appears to correlate with subsurface inflow from marine sedimentary rocks adjacent to the basin and with pre-development groundwater flow patterns.
- Recycled water use is proposed for four of the seven ULARA subareas (Los Angeles River Narrows, San Fernando East, San Fernando West and Verdugo). In those areas, use of recycled water for irrigation raised the simulated concentration trends for TDS and chloride over the simulation period.
- Nitrogen trends were downward over the simulation period under baseline and all SNMP scenarios in all subareas except Tujunga. The exception in that subarea could result from the relatively high density of onsite wastewater disposal systems.
- Increased stormwater recharge (centralized and distributed) consistently lowered concentration trends of TDS and chloride over the simulation period. In some cases, simulated trends with full SNMP implementation were even lower than baseline trends, which means the stormwater recharge more than offset the effects of recycled water use.
- As of 2044, concentrations and trends were acceptable for all constituents in all subareas except the Los Angeles River Narrows (NAR), where there was a small shift toward increasing concentrations during 2016-2044. This result appears to stem from the relatively high intensity of recycled water use and low intensity of stormwater recharge contemplated by the SNMP in that subarea.
- The NAR results appear acceptable for the near future, particularly considering additional stormwater recharge likely to be implemented independently pursuant to the Enhanced Watershed Management Program adopted by the Los Angeles Regional Water Quality Control Board in April 2016 (not incorporated into model).

1. INTRODUCTION

The purpose of this technical memorandum (TM) is to quantitatively estimate the effects of future recycled water use and related water management activities on groundwater quality patterns and trends in the Upper Los Angeles River Area (ULARA). A mixing model approach was selected as appropriate for this level of planning analysis. A mixing model was developed to simulate three water-quality parameters expected to be affected by recycled water: total dissolved solids (TDS), chloride and nitrogen. In terms of spatial and temporal detail, the model was intended to indicate long-term trends in average concentrations over seven broad regions within ULARA. Seven subareas were defined by the Los Angeles Regional Water Quality Control Board (RWQCB-LA) in the Basin Plan (1994), and are described in TM-2: Eagle Rock (EAG), Narrows (NAR), San Fernando-East (SFE), San Fernando-West (SFW), Sylmar (SYL), Tujunga (TUJ) and Verdugo (VER). Note that EAG, SYL, and VER are considered separate groundwater basins, whereas NAR, SFE and SFW, and TUJ are sub-regions within the San Fernando Basin. A map of these seven subareas is shown in **Figure 1**.

Details of the mixing model structure and input are presented below. The objective for model calibration was to reproduce the dominant observed historical trends in TDS, chloride and nitrogen concentrations in each subarea, recognizing that trends are often quite variable from well to well. The objective for simulating future scenarios was to superimpose the effects of increased stormwater recharge and recycled water use for irrigation and recharge to determine whether they would collectively result in sustainable long-term water quality and achieve BPOs.

2. HISTORICAL WATER-QUALITY PATTERNS AND TRENDS

Water quality data from multiple sources and various historical periods were evaluated to characterize water quality patterns and long-term trends. The data sets and analysis are presented in **Appendix A**. In general, historical water quality data are sparse and clustered in space and time. Accordingly, spatial patterns in water quality evident in data sets with a broad geographic distribution of data points were combined with averages from data sets for other dates to obtain the best possible estimates of groundwater quality in each subarea as of 2002, which was the start of the mixing model calibration period. Also, the historical data were evaluated for trends. Because average groundwater residence time is on the order of decades to centuries, ambient water quality typically evolves slowly. Thus, trends from 1931-1932 to 2002-2012 were tabulated to inform model calibration.

3. MIXING MODEL CONCEPTS

A spreadsheet model was developed to simulate and quantify potential effects on groundwater quality of the recycled water and stormwater elements of the SNMP. The model is based on a mixing-model concept in which all sources and sinks of each water-quality constituent are tabulated for a specified increment of time in a defined region of the groundwater system. The advantages of the mixing model approach are that it requires quantitative consistency among flows and mass loads in all parts of the basin and at all times. The process of developing a mixing model often reveals inconsistencies among data sets, which points to areas that need additional attention. It also reveals data gaps that must be filled by means of reasonable assumptions in order to achieve a complete model. The modeling approach is the best means of integrating all available data to better understand the groundwater flow and water quality system, and it also provides a quantitative tool for comparing alternative management measures that could be implemented in the future.

Outputs (sinks) of the solute are subtracted from inputs (sources) to obtain the net change in solute mass in the groundwater region, and the change in mass is assumed to mix uniformly and completely throughout the region during the time increment. In this case, the regions are the seven SNMP subareas and the time increment is one year. The model is presently configured to simulate 29 consecutive years. This number resulted from an initial planning horizon to 2030. For the calibration simulation, the first 11 years corresponded to 2002-2012 (and subsequent years were disregarded). For future simulations, the 29 years were set to correspond to 2016-2044.

The model simulates three constituents, one at a time: TDS, chloride and nitrogen. Nitrogen is simulated instead of nitrate to simplify the accounting for nitrification, denitrification and variable composition of fertilizers. The 45 milligrams per liter (mg/L) Basin Plan Objective (BPO) for nitrate (as NO_3) is equivalent to an objective of 10 mg/L for nitrogen (as N). TDS and chloride are treated as conservative solutes, whereas nitrogen is subject to losses due to plant uptake, mineralization and denitrification. There is a total of 21 combinations of subarea (7) and constituent (3), which the spreadsheet model processes as a batch by means of a macro.

The model simulates water flow, solute concentration and solute mass concurrently. This facilitates the calculations for loads not associated with their own flow (such as aquifer dissolution or fertilizer application) and flows not associated with a solute (plant evapotranspiration). Conservation of mass is applied to water as well as to the solute.

An important assumption for this modeling effort is that the water budget in each subarea will be balanced over the long-term, which is a reasonable assumption for sustainable groundwater management. Most of the flows are estimated as average annual values and are based primarily on data compiled from the annual ULARA Watermaster Reports for the baseline data period. If the sum of inflows were consistently larger or smaller than the sum of outflows during the simulation period, a subarea would chronically gain or lose water. This would not be consistent with the goal of sustainable groundwater management. Because individual inflows and outflows were estimated separately for each subarea using separate data sources, total inflows often did not match total outflows during the simulation period. This was particularly true for future conditions, when projected flows obtained from a regional groundwater model developed by the Los Angeles Department of Water and Power differed substantially from historical flows estimated from data. To maintain the water balance for mixing model purposes, outflows (pumping and/or groundwater outflow to adjacent regions) were adjusted so that total outflows equaled total inflows. This was important not only to be consistent with sustainability but to provide a consistent basis for comparing alternative management scenarios.

Each subarea is simulated separately, but inflows from upgradient subareas are updated iteratively to reflect the current flow and solute balances in those regions. For example, SFE receives inflows from SFW, SYL, TUJ and VER. Updating was accomplished by running the spreadsheet macro 2-3 times in succession, and applying simulated concentrations from the previous iteration to groundwater inflows in the current iteration.

The diagram in **Figure 2** shows sources and sinks of salts and nutrients at a regional scale. Inputs of water and solute include subsurface inflow from tributary watershed areas, percolation from streams and spreading basins, and dissolution of aquifer minerals. Outputs include pumping by wells, groundwater seepage into the Los Angeles River, evapotranspiration by riparian vegetation, and subsurface outflow to adjacent subareas. Additional details related to urban hydrology are shown in **Figure 3**. These include pipe leaks (water and sewer), runoff from connected and disconnected impervious areas, and infiltration of rainfall and applied irrigation water past the root zone. Details of each source and sink are described in the following sections and in **Appendix B**.

4. MIXING MODEL SOFTWARE

The mixing model consists of a Microsoft Excel workbook with a master sheet where calculations are performed and results stored and displayed. Three separate data blocks contain 29 rows each corresponding to the 29 years of simulation. The columns of each data block represent individual inflows and outflows. The top data block tracks water flow and volume, the middle data block tracks solute concentration, and the bottom data block tracks solute mass. For some inputs, concentration is calculated from flow and mass and for others mass is calculated from flow and concentration. Flows that involve simulated groundwater concentrations use the simulated concentrations from the preceding year to avoid circular formulas or the need for complex iterative calculations. Two dropdown lists allow the user to select the subarea and solute for the current simulation, and all values automatically update when a new subarea-solute combination is selected.

Numerous additional workbook sheets store data for individual solute and flow inputs and outputs. They each contain data blocks dimensioned to 29 rows (years) by 21 columns (subarea-solute combinations). Formulas in the master sheet look up the values for the current year and subarea-solute combination. Each sheet has separate data blocks for flow, concentration and mass, structured identically to the master sheet. Supporting data and calculations are also included in each sheet.

A macro automatically processes the 21 subarea-solute combinations and stores the simulated groundwater concentrations for plotting and subsequent analysis.

5. OVERVIEW OF SIMULATED SCENARIOS

One historical calibration and four future scenarios were simulated using the mixing model. The calibration period was 2002-2012 (referred to as the “baseline period” in TM-2), which was implemented in the spreadsheet model as the first 11 years of a 29-year simulation. The remaining years were not used in evaluating model performance. The future scenarios were all simulated using the 2016-2044 time period. Although the planning horizon for SNMP compliance extends only to 2025, the longer period allows more time for the effects of projects implemented near the end of the compliance period to approach equilibrium, and conveniently uses the full 29-year simulation capacity currently included in the Excel workbook. The four future scenarios are:

1. Future Baseline Scenario. This scenario continues existing conditions and includes planned supplemental water capture at the spreading basins. Annual stormwater percolation at the spreading basins increases in steps from 21,500 acre-feet per year (AFY) in 2016 to 41,600 in 2035 and beyond, consistent with the LADWP groundwater model[1]. Percolation of imported water at the spreading basins was assumed to be 7,425 AFY each year, also consistent with the groundwater model. No new recycled water or stormwater irrigation or percolation projects are included. This scenario served as the reference condition for evaluating effects of SNMP implementation.
2. Tertiary Recycled Water Irrigation and GWR. This scenario includes only the recycled-water elements of the SNMP and was done so the effects of recycled water and stormwater elements could be assessed independently. The scenario assumes tertiary recycled water is used for irrigation and spreading basin recharge (GWR).
3. Tertiary Recycled Water Plus Stormwater. This scenario simulates tertiary recycled water irrigation and GWR plus stormwater recharge projects included in the SNMP. These include stormwater recharge at the large spreading basins plus distributed stormwater recharge via parcel-scale and neighborhood-scale infiltration facilities described in the Stormwater Capture Master Plan. This scenario includes all SNMP elements.
4. Advanced-Treated Recycled Water. This scenario also includes all SNMP elements, but with the advanced-treated water option for GWR at spreading basins.

Details and results for each simulation are presented in the following sections.

6. CALIBRATION AND FUTURE BASELINE SIMULATIONS

Many of the flows, concentrations and mass loads used in the mixing model were documented in TM-2 for historical conditions and in TM-3 for future scenarios. Where those data were used in the mixing model without modification, the description here simply references the prior TMs. **Table 1** is an index of data sources for all flows, mass loads and concentrations used in the model. Each of the water and mass budget items included in the mixing model is discussed below.

The calibration simulation simulated the years 2002-2012 using annual time steps.

[1] For comparison, stormwater recharge was highly variable from year to year during 2002-2012 and averaged 29,800 AFY.

6.1. INITIAL CONCENTRATIONS AND GROUNDWATER MIXING VOLUMES

Historical water quality data are too sparse to precisely define ambient groundwater quality in each subarea as of 2002, which was the start of the calibration period. For all subareas except SFW and TUJ, the median value from the 2002-2012 data set was selected as reasonable (see bottom of **Table A-1**). Data for that time period for SFW were geographically biased due to clustering. Instead, the average of the 1931-1932 and 1987-2014 median values was used. For TUJ, there are no recent data and the 1931-1932 median concentrations for chloride and nitrogen appeared to possibly be low outliers. The median concentrations during 1950-1980 were used as the best available estimate for 2002 concentrations.

Median concentrations were used instead of average concentrations to minimize the effect of outliers or skewed temporal or geographic concentration distributions. In most instances, median concentrations were similar to average concentrations. Furthermore, sensitivity tests of the mixing model demonstrated that using average rather than median values as initial concentrations did not substantially alter the simulated trends or change any conclusions (see **Section 7** "Sensitivity Analysis").

Initial concentrations for future scenarios were obtained by continuing the calibration simulation an additional three years, from 2012 to 2015. Simulated concentrations in 2015 were used as the initial concentrations for all future scenarios.

Estimates of the volume of aquifer accessed by wells in each subarea were developed in TM-2 based on contoured elevation surfaces for the water table and for the deepest section of perforated casing in active wells. The amount of groundwater in storage was estimated by multiplying the aquifer volume by the effective porosity, which represents the pore volume between mineral grains that is actively involved in groundwater flow and storage. A value of 0.20 (dimensionless fraction of total volume) was used for all subareas. Total porosity is typically higher (0.30-0.40) but includes small relatively isolated pores not actively involved in groundwater flow and storage. The selected value is closer to the expected range for specific yield (0.02-0.20 for silts to clean sands and gravels [Freeze and Cherry, 1979]), which is the volume of water drained by gravity from aquifer pores over a relatively short time span (days to weeks) in response to a drop in the water table. Solutes can mix into small pores that do not drain by gravity, so effective porosity is commonly estimated to be in the 0.20-0.30 range. Selecting a low value is conservative for the mixing model because it tends to accelerate any long-term changes in simulated water quality. The groundwater mixing volumes ranged from 86,000 acre-feet (AF) for the EAG subarea to 12,310,000 AF for the SFE subarea.

6.2. INFLOWS AND MASS LOADS

6.2.1. Background Mass Load

Some constituent mass inputs are either small or relatively unaffected by changes in land and water use. The solute mass for each of these inputs was assumed to be constant and approximately the same under historical conditions as recent and future conditions. These mass inputs are referred to here as "background mass load". Mass inputs included in this category were aquifer dissolution, atmospheric deposition, rainfall deep percolation and subsurface inflow from hill and mountain areas. The latter two mass inputs are associated with their own water inflows. Subsurface inflow from hill and mountain areas was assumed to remain the same as under historical conditions. In contrast, the volume of rainfall recharge was modified to reflect stormwater management under various simulated scenarios, but the solute mass associated with that recharge was assumed to remain unchanged. In other words, the same annual mass of solutes is assumed to be picked up by rain water percolating downward through the soil and vadose zone even if the flow rate becomes larger or smaller. However, solutes washed off of impervious surfaces that become dissolved into rainfall infiltration are added separately.

This background mass load concept implicitly assumes that dissolution of soil and aquifer minerals is a kinetically limited chemical process rather than an equilibrium process. When pumping is introduced into a groundwater basin, vertical and horizontal groundwater flows typically become much faster and decrease average groundwater residence times. Kinetically limited dissolution will put approximately the same mass of solute into solution over a given period of time, regardless of the flow rate. This has been found to be generally true for silicate minerals (Zhu, 2005; Hereford and others, 2007).

For the mixing model, background mass load was estimated by calibrating a simplified mixing model to observed concentrations in 1931-1932. Groundwater quality at that time reflected primarily pre-development conditions. For each subarea, a single concentration was assumed for rainfall recharge and subsurface inflow from hill and mountain areas, and that value was adjusted until the simulated flow-weighted average recharge concentration equaled the ambient measured groundwater concentration. Flows associated with rainfall recharge, stream percolation and subsurface inflow from hill and mountain areas were estimated using rainfall-runoff analysis methods. Stream water quality was estimated from 1931-1932 data. Details of the approach and inputs are provided in **Appendix B**. The result was that all seven subareas could be calibrated to historical groundwater concentrations with reasonably consistent values of TDS (750-865 mg/L). The corresponding solute masses for the inflows grouped as background mass load were then added as constant, fixed mass loads during the 2002-2012 calibration period. These inflows and loads were assumed to remain unchanged over time, so the same values were used for all future scenarios. The Watermaster is currently updating estimates of surface and subsurface inflow from watershed areas tributary to ULARA groundwater basins, but that work is not yet complete.

6.2.2. Rainfall and Irrigation Deep Percolation

Groundwater recharge from rain falling on pervious soils was estimated by multiplying a one-dimensional average annual rainfall recharge rate by the area of pervious soils in each subarea. The one-dimensional recharge rate was calculated using a regression equation applied to data from numerous semiarid regions around the world. The data and method are described in **Appendix B**. Average annual rainfall ranges from about 16 inches per year (in/yr) in SFW to 23 in/yr in VER, and the corresponding estimates of recharge range from 1.5 to 2.5 in/yr. The estimate for VER was increased to 4.0 in/yr during mixing model calibration in order to more closely balance recharge and pumping. The rate was assumed to be the same for irrigated and non-irrigated soils. In practice, rainfall recharge tends to be higher on irrigated soils than non-irrigated soils because less cumulative infiltration during the rainy season is needed to raise soil moisture to the point that significant amounts of deep percolation occur. However, no correction for this phenomenon was included in the mixing model.

The percentage of land surface that is pervious (not buildings or pavement) was assumed to be 40 percent in all subareas. This estimate was based on published averages for various lot sizes in the United States (Pilgrim and Cordery, 1993) and on the use of a planimeter to measure selected one-block samples in the ULARA subareas using high-resolution aerial photographs. Urban development density is fairly uniform across all of the subareas. The average annual rainfall recharge volumes calculated from these areas and recharge rates ranged from 48 AFY in EAG to 2,780 AFY in SFW. This base rate of rainfall recharge on pervious soils was assumed to occur in all years (historical and future) under existing and SNMP conditions.

The fate of rain falling onto impervious surfaces depends on stormwater management practices, which were an important element of the mixing model analysis. Impervious area can be subdivided into "connected" and "disconnected" subtotals representing surfaces from which runoff flows to curbs, gutters and storm drains versus surfaces where runoff flows to adjacent pervious soils. Common examples of the latter include runoff from downspouts, sidewalks and driveways onto lawns and gardens. Total impervious area was estimated from literature values and air photo interpretation as described above. The connected fraction of impervious area was estimated by comparing rainfall and runoff in two local, gaged watersheds: Burbank West Storm Drain (Los Angeles County Department of Public Works Gage E285) and Verdugo Wash at Estelle Avenue (Gage F252). These were selected because neither has reservoirs or diversions upstream of the gage. Daily rainfall was obtained from the Brand Park gage located in Verdugo Hills between the two watersheds. Daily rainfall and stream flow were compared for several small, early-season storms (<1 inch) in water years 2011 and 2012. Those events were unlikely to have substantial flow contributions from pervious surface runoff. The analysis indicated that about 55 percent of total land area was covered by connected impervious surface, and by difference about 5 percent of total land area was disconnected impervious surfaces. These percentages were assumed to be the same for all seven subareas.

All runoff from disconnected impervious surfaces was assumed to become groundwater recharge. This runoff essentially amplifies the amount of rain falling on the receiving pervious soil. Over the course of a winter, multiple rain events would quickly fill the soil moisture profile to capacity and pass all additional infiltration through the root zone to become deep percolation (groundwater recharge). Losses to evapotranspiration are also relatively low in winter, so this assumption is hydrologically reasonable. The resulting estimates of average annual recharge from disconnected impervious area runoff were similar in magnitude to the amount of rainfall recharge on pervious soils, ranging from 58 AFY in EAG to 3,620 AFY in SFW. This component of recharge is modified by "low-impact development" stormwater management measures, which essentially convert connected impervious area to disconnected impervious area.

The mass of TDS, chloride and nitrogen derived from soil and aquifer dissolution was assumed to be constant and part of the background mass load of rainfall recharge described earlier. Solutes in impervious surface runoff that are recharged by SNMP stormwater management measures are additional solute loads in rainfall recharge.

Irrigation generates groundwater recharge because some of the applied water percolates past the root zone. Irrigation efficiency is the ratio of water actually transpired by the plant to the amount of water applied, averaged over the irrigated plot. Studies of urban residential irrigation have found that overall efficiencies are commonly 50-60 percent (Baum and others, 2005; Xiao and others, 2007; Kumar and others, 2009). There are two principal components of inefficiency, and they impact groundwater differently. The first component consists of deep percolation beneath the root zone, which happens because water application rates, root depths and soil characteristics are not uniform throughout each irrigated area. For example, sprinkler spray heads that water a circle do not apply water uniformly over the entire area of the circle. Furthermore, the circular patterns of multiple sprinklers typically overlap to ensure full coverage of the entire plot. Because of this small-scale spatial variability, the amount of water applied in some parts of the irrigated area exceeds the water requirement of the vegetation and/or the ability of the soil to retain the water. In those locations, applied water percolates past the root zone and becomes groundwater recharge. In the mixing model, 15 percent of applied water is assumed to percolate beneath the root zone.

The second component of inefficiency is sprinkler overspray onto adjacent sidewalks, streets and driveways. In the mixing model, overspray losses are assumed to account for 25 percent of applied water, consistent with the total inefficiency and relative proportion of overspray and deep percolation inefficiency reported in prior studies (Baum and others, 2005; Kumar and others, 2009). The mineral content of the overspray runoff water is also assumed to leave the system because this loss typically flows to gutters and storm drains.

The salt content of applied water is evaporatively concentrated during irrigation. When plants transpire water through their leaves, it is essentially pure water. Plant roots actively exclude most of the TDS and chloride contained in the applied water. Thus, irrigation inevitably increases the salinity of water in the root zone. Salinity would increase to the point of plant toxicity if the salts were not flushed from the root zone by rainfall and deep percolation of some of the applied irrigation water. Although root zone salinity can fluctuate seasonally, it is reasonable to assume that it remains constant over periods of years. In the mixing model, all the TDS and chloride contained in the irrigation water that reaches the target vegetation (75 percent of total applied water) is assumed to become dissolved into the deep percolation flow that contributes to groundwater recharge (15 percent of total applied water). Because of this evaporative concentration process, the TDS and chloride concentrations in irrigation deep percolation are commonly on the order of five times greater than in the water used for irrigation (75%/15% = 5).

Nitrogen behaves differently from TDS and chloride in irrigated settings because plants actively take it up as an essential nutrient. The uptake and loss rates described below for fertilizer nitrogen are also applied to nitrogen in the irrigation water (5 percent reaches groundwater).

Because of the relatively large amount of irrigated area and the evaporative concentration of salts during the irrigation process, irrigation noticeably increases groundwater salinity throughout the ULARA basins.

For the future baseline simulation, irrigation water use was assumed to remain the same percentage of total water delivered, which is projected to decrease over time due to conservation efforts as documented in TM-3. The quality of delivered water depends primarily on the mix of imported supplies, which can vary substantially from year to year. The future mix cannot be predicted with certainty, so for the mixing model, water supplied by each purveyor in all future years was assumed to equal the median concentrations of TDS, chloride and nitrogen during 2002-2012 (the baseline period). These data were derived from consumer confidence report data each of the purveyors provide to their customers on an annual basis; the derivation is described in TM-2.

6.2.3. Fertilizer

Most of the nitrogen in fertilizer is taken up by the vegetation to which it was applied. However, most of the nitrogen in fertilizer mineralizes to nitrate, which is highly soluble and easily leached from the root zone by rainfall or excess applied irrigation water.

The first step in estimating the nitrogen load to groundwater from fertilizer was to estimate the amount of irrigated area in the SNMP subareas. Two methods were used, and they produced similar results. The first method was based on water use. Water purveyors in ULARA estimate that about 45 percent of delivered water is used outdoors (averaged among the purveyors). This equals 122,000 AFY (average for 2002-2012). Additionally, about 3,000 AFY of recycled water is used for irrigation. The total annual volume of irrigation water was divided by the estimated annual irrigation requirement for warm-season grass (3.5 feet per year) to obtain an estimate of 35,700 irrigated acres, which equals 28 percent of the total area of the SNMP subareas. This method implicitly assumes that all irrigated vegetation receives the amount of water required for turf irrigation. The second method was based on zoning and aerial photography. Areas of various residential, commercial and industrial land use categories were tabulated from a GIS map of zoning. Each category was multiplied by a percent irrigated factor obtained from aerial photo inspection and other sources (Steinert, 2016). This produced an estimate that, on average, 25 percent of each SNMP subarea is irrigated.

Irrigated areas were assumed to all receive 45 pounds per acre per year of nitrogen via fertilizer applications, which is the national average for residential lawns (U.C. Davis, 2012). Estimates of the fraction of applied nitrogen that percolates past the lawn root zone range from 2-20 percent of applied nitrogen. A value of 5 percent is used in the mixing model. Fertilizer leaching also adds TDS to groundwater. Assuming the fertilizer formula is ammonium nitrate, 129 pounds per acre of TDS is applied to the soil. In the case of ammonium nitrate (NH_4NO_3), all of the molecule can be taken up by plants, so 5 percent of the applied amount is also assumed to leach past the root zone. Leached fertilizer is added as a mass to deep percolation flows deriving from rainfall and applied irrigation water. Leached fertilizer accounts for less than 0.5 percent of total TDS inputs to groundwater and 3-14 percent of total nitrogen inputs, depending on subarea.

6.2.4. Water and Sewer Pipe Leaks

Water and sewer pipes in urban areas leak to some extent, creating a source of recharge to the underlying groundwater system. Conversely, sewer pipes can also gain flow from infiltration of groundwater where the water table is high. Leaks are often small and difficult to detect. Municipal water distribution systems are typically better studied and maintained because of the economic value of the leaked water and because leak detection is a best management practice for water conservation. A detailed study of water production and consumption data from 17 California municipal water purveyors found leakage losses ranging from 4 to 22 percent of production, with an average of about 7 percent (Water Systems Optimization, Inc., 2009). Another study monitored water use at numerous individual residences in ten medium to large California water systems using data loggers, and it found an average leak rate of 18 percent of the delivered volume (Aquacraft, 2011). A U.S. Environmental Protection Agency (USEPA) study found that "unaccounted for water" (which includes incidental unmetered uses in addition to leaks) in the range of 10 to 20 percent of total volume delivered is normal (Lahlou, 2001). For the mixing model, a water pipe leak rate equal to 7 percent of annual delivered volume was assumed for all water balance subareas.

Not all water pipe leakage becomes groundwater recharge. Because leaks generate soil moisture year-round at a slow, steady rate, it is very likely that substantial amounts of the water are intercepted by tree roots, where trees are present. For the mixing model, trees were assumed to intercept about one-third of the annual leakage, bringing the net recharge to groundwater down to 5 percent of annual water delivered.

Sewer pipes also leak, and a leakage rate equal to half the water pipe leak rate was assumed. This estimate reflects a subjective balance of factors that favor a higher leak rate (less active maintenance than water distribution systems, and pipe joint spreading due to tree root invasion) with factors that favor a lower rate (sewer pipes are mostly not pressurized, and leaks probably self-seal to some extent due to clogging by solids and biofilms). Thus, 2.5 percent of annual sewer flow was assumed to become groundwater recharge, after allowing for uptake of leaked water by trees. Sewer flow was estimated to equal indoor water use (55 percent of annual delivered water) minus the small fraction (2 percent) that is consumed during indoor use (Mitchell and others, 2001).

Applying these percentages to water deliveries and wastewater generation in the SNMP subareas produces estimates of 14,000 AFY and 3,800 AFY of groundwater recharge from water pipe leaks and sewer pipe leaks, respectively. The recharge per acre varies by a factor of about three among the subareas due to variations in water deliveries per acre. The lowest per-acre recharge from pipe leaks was in TUJ and the highest was in EAG.

The quality of water leaking from water pipes is the average quality of delivered water, which was estimated as the flow-weighted blend of quality reported by the purveyors serving each SNMP subarea. Amounts delivered by each purveyor in each subarea during 2002-2012 were provided by the Watermaster. **Figure 4** shows annual variations in delivered water quality in each subarea during that period. The variations result from year-to-year changes in the proportions of imported water obtained from the Sacramento-San Joaquin Delta, Owens Valley, Colorado River and other external sources. For future simulations, the median values for 2002-2012 were used in every year. They are listed at the bottom of the figure.

The quality of sewer pipe leaks was similarly estimated as the effluent quality measured at wastewater treatment plants serving the subarea. Where more than one plant provides wastewater treatment service, a rough area-weighted average was calculated. **Table 2** lists the median TDS, chloride and nitrogen concentrations in effluent during 2002-2012 from the three wastewater treatment plants serving ULARA. Also shown are the estimated concentrations in leaks from sewer pipes in each subarea. These median values were applied throughout 2016-2044.

6.2.5. Septic Systems

Almost all buildings in the SNMP subareas are connected to sanitary sewers, but 7,700 buildings dispose of sanitary wastewater by means of an onsite wastewater system (see TM-2). About 80 percent of these are for single-family residences in SFE, SFW and TUJ. Water use and wastewater generation per connection were assumed to be the same for onsite wastewater system users as for users connected to the sanitary sewer system. All water entering the septic system was assumed to become groundwater recharge, with no reduction from plant evapotranspiration at the leach field. Total groundwater recharge from septic systems in the SNMP subareas was thus estimated to equal 2,790 AFY.

Septic effluent water quality was assumed to be the same as the sewer pipe leak quality described earlier, except additional losses were applied to nitrogen. Studies in other areas have shown that mineralization and denitrification processes each remove about 15 percent of the nitrogen in the effluent (Lowe, 2009; USEPA, 2002). These losses were applied to septic system recharge. The nitrogen concentration in septic system effluent was thus estimated to be 46-48 mg/L as N.

6.2.6. Hill and Mountain Surface Inflow

Surface runoff from hill and mountain areas (referred to as tributary watersheds in this TM) was assumed to be the same under current conditions as under predevelopment conditions because the watersheds remain largely undeveloped. Surface runoff under pre-development conditions was estimated by a regional regression of runoff per square mile of watershed as a function of annual rainfall, based on a number of reference gages. Details are presented in **Appendix B**. Although the amount of runoff entering the subareas may be similar to historical runoff, the amount of percolation within the regions has changed because most creeks and washes have been converted to engineered, concrete-lined flood conveyance channels. The lining greatly reduces channel percolation rates. However, many of the creeks and washes have debris basins, spreading basins or flood control reservoirs that impound water over a broader area than the natural channel and can locally increase stream percolation. Estimated average annual stream percolation for all SNMP subareas was approximately 15,500 AFY, or 65 percent of the predevelopment amount.

Water quality in tributary streams was assumed to be the same as under pre-development conditions (see **Appendix B**), because the watersheds are still relatively undeveloped.

For future scenarios, average annual flow and quality from stream recharge were assumed to remain the same as the 2002-2012 averages, except for recharge of stream flow at spreading basins.

6.2.7. Spreading Basins

Spreading basins are impoundments near or along creeks and washes that were designed to spread water over a broad area to increase percolation. There are five spreading basins in ULARA, all of which are in SFE (**Figure 1**): Branford, Hansen, Lopez, Pacoima and Tujunga. During 2002-2009, all the percolated water was storm runoff from the creek or wash next to the spreading basin. Beginning in 2010 LADWP and the City of Burbank also percolated imported water at the Pacoima and Tujunga spreading basins[2]. Two additional potential sources are simulated for the future: tertiary-treated recycled water and advanced-treated recycled water. **Figure 5** shows annual volumes of groundwater recharge from spreading basin percolation, with measured values for 2002-2014 and two alternative scenarios for 2014-2030. The projected values for all sources of spread water during 2016-2044 are from the Los Angeles Department of Water and Power groundwater model work and the SNMP planning process. Values for 2030 were assumed to continue through 2044. Water quality for each of the four sources of water is shown in **Table 2** and is based on average measured quality during 2002-2012 for Tujunga and Pacoima Creeks (natural flow), the quality of Metropolitan Water District of Southern California (MWD) wholesale water in San Fernando Valley (imported water), Donald C. Tillman Wastewater Reclamation Plant effluent (recycled water), and expected quality of advanced-treated recycled water. The water quality characteristics were assumed to be the same for all future scenarios.

6.2.8. Groundwater Flow between Subareas

Subsurface outflows and inflows between subareas depend on water level gradients and aquifer transmissivity at the boundary locations. The gradients change over time and from scenario to scenario. Estimates for 2002-2012 developed manually from water level contour maps are available from Watermaster annual reports. Estimates for 2014-2030 are available from the regional groundwater flow model developed by LADWP for a simulation that included most elements of the SNMP. The LADWP groundwater flow model extent does not include the EAG, SYL and VER subareas, and the groundwater flows it simulated among the other subareas were generally several times larger than the Watermaster estimates for flows during 2002-2012. The difference is due to differences in methodology and in other water balance items between the Watermaster tabulation and the LADWP model; subsurface flows do not change rapidly and should be about the same for both baseline and projected future periods. For the mixing model, the LADWP estimates were used in all historical and future scenarios for consistency. Specifically, the flows for 2014 from the LADWP groundwater model were also used in 2002-2013, and the flow for 2030 was used for 2031-2044. Imbalances in subarea water budgets that resulted from combining inputs derived from various sources and methods were resolved by adjustments to pumping, as described in the next section.

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[2] Prior to 1985, LADWP also percolated substantial amounts of imported water at the Headworks and Tujunga spreading basins.

The mixing model sets the quality of subsurface flow from one subarea to another equal to the simulated concentration in the source subarea for the previous year. Lagging the concentrations avoids circular references in the spreadsheet calculations and is consistent with the very gradual rate at which groundwater quality evolves.

6.3. OUTFLOWS

6.3.1. Groundwater Pumping

Initial estimates of groundwater pumping in each subarea were based on historical pumping recorded by the Watermaster for the 2002-2012 calibration simulation, as documented in TM-2. For future simulations, initial estimates were obtained from a simulation of some SNMP elements during 2014-2030 using the LADWP groundwater flow model (Jonny, 2016).

The initial pumping estimates were adjusted annually in each subarea for each mixing model simulation to achieve balanced subarea water budgets. To provide a consistent basis for comparing water quality concentrations and trends, it is important that all subareas have balanced water budgets in each simulation. Chronic increases or decreases in groundwater storage volumes during a simulation can noticeably affect simulated concentrations and are also inconsistent with sustainable groundwater management. Inflow and outflow data for the mixing model derived from multiple sources were not always consistent, and recharge volumes varied from one simulation to the next. Recharge was more precisely specified than outflows for each future simulation, so it was more practical to adjust outflows to achieve balanced water budgets. This was accomplished by a two-step process in which a subarea-constituent combination was simulated using the initial estimates of annual groundwater pumping. The resulting net storage change for each year was then added to (or subtracted from) the pumping estimate to achieve zero net storage change when the simulation was re-run. The adjustments were small enough that this procedure never resulted in negative pumping values.

Groundwater pumping and subsurface outflows are assigned the same concentration and have similar effects on simulated concentrations and trends. In terms of implementation, it was easier to adjust pumping than outflows because some subareas had groundwater outflow rates that were too small to absorb the initial budget imbalances. Also, pumping would logically change in response to the SNMP elements whereas subsurface flows would likely be less affected. For example, the projects in the SNMP would greatly increase recharge at spreading basins and from dispersed stormwater infiltration. It is assumed that local water purveyors will seek to recover that water by increasing the amount of groundwater pumping.

Annual groundwater pumping by subarea after adjustments to balance the water budgets are shown in **Figure 6** for the 2002-2012 calibration simulation and the 2016-2044 future baseline simulation. Roughly 80 percent of total pumping was in the SFE subarea under both scenarios. Pumping varied much more from year to year in the calibration simulation, reflecting actual historical variations in regional water supplies. Total pumping gradually increased during the future baseline scenario because that scenario included several planned increases in stormwater capture at the spreading basins.

Figure 7 shows the balanced average annual subarea water budgets for 2016-2025 for the future baseline scenario. These graphs reveal how the relative magnitudes of the inflow and outflow items vary dramatically from one subarea to the next.

6.3.2. Seepage to Los Angeles River

Some groundwater discharges into the lower, unlined reach of the Los Angeles River—and to a lesser extent Verdugo Wash—and leaves the San Fernando basin as surface outflow. This “rising groundwater” is estimated annually by the Watermaster. The LADWP groundwater flow model also simulates groundwater seepage (discharge) into the Los Angeles River and Verdugo Wash. The two estimates are very different in magnitude, location and variability. **Figure 8** compares the two estimates and presents the “blended” values used in the mixing model. The Watermaster values for 2002-2012 show groundwater discharge as occurring only in the VER and NAR subareas. It averaged about 6,400 AFY and fluctuated by approximately +/-60 percent from year to year. The groundwater model indicated groundwater discharge occurring in the SFW, SFE and NAR subareas. There was little simulated year-to-year variation, but total discharge decreased from 23,700 AFY to 14,700 AFY over the first 17 years of the simulation, partly in response to concurrent increases in groundwater pumping.

For the mixing model, the Watermaster and groundwater model flows were roughly averaged to an annual value of 9,400 AFY, and the proportional allocation of that discharge among SFW, SFE and NAR was assumed to be the same as in the LADWP groundwater model. For the calibration simulation, the average discharge was adjusted to reflect the percentage variability of the 2002-2012 Watermaster data. For the future baseline simulation, the average was used in all years. In practice, the outflows would respond to changes in pumping and recharge that would occur if the SNMP measures are implemented; but for the purposes of the mixing model the response was absorbed by changes in estimated pumping.

6.3.3. Riparian Evapotranspiration

Riparian vegetation is present adjacent to the Los Angeles River along the unlined reach in SFE and NAR. The water table is shallow where the river is gaining flow from groundwater discharge, and tree roots can extract water directly from the water table. The area of riparian tree canopy was obtained from vegetation maps developed for flood control and habitat restoration efforts (USACE, 2013). The 1,100 acres of canopy were found to be divided almost equally between SFE and NAR. Riparian use of groundwater was roughly estimated by subtracting average annual rainfall (16 inches) from average annual reference evapotranspiration (52 inches) and multiplying by canopy area. The resulting estimate of annual riparian use of groundwater was 3,400 AFY. This equaled 2 percent of total outflows from SFE during 2002-2012 and 15 percent of total outflows from NAR. Because riparian vegetation occurs almost exclusively along river reaches that are gaining seepage from groundwater, groundwater minerals not taken up by tree roots are carried into the river by the groundwater discharge. Thus, outflow to riparian evapotranspiration is assigned the ambient subarea water quality, as is done with all the other outflows.

6.4. Calibration Procedure and Results

6.4.1. Calibration Procedure

Model calibration attempted to match the predominant historical water quality trends observed in each area. A close match was not expected, given the large variability among wells in each subarea, the gross spatial averaging inherent in the mixing model, and differences among recent and older historical trends. Modest discrepancies between simulated and historical trends do not necessarily imply inaccuracy in evaluating the effects of SNMP elements. Those effects are evaluated based on comparisons among future simulations. Whatever errors or bias remain from the calibration process apply equally to all future simulations, such that the differences between the simulations can be more accurate than the absolute concentrations.

Variables adjusted during calibration included irrigation efficiency, the effect of channel lining on stream percolation, background mass loads, subsurface outflows from tributary watersheds, groundwater flows between subareas, average annual rainfall in the VER subarea, and the proportions of Pacoima Creek and Big Tujunga Creek percolation that occur in the SYL, TUJ and SFE subareas. The adjustments were generally small to avoid invalidating the data and assumptions used for the initial estimates, to maintain consistent assumptions across all subareas, and because relatively few adjustments uniformly improved model results for all subareas. The calibrated values are the ones described above under each water budget item.

6.4.2. Water Quality Concentrations and Trends

Time-concentration graphs showing simulated concentrations for the 21 constituent-subarea combinations during the 2002-2012 historical calibration period are shown in **Figure 9**. Insets on each graph list the historical trends based on measured data from 1932-2002 and 2002-2012 in milligrams per liter per decade. The 1932-2002 trends are the differences between the 2002 and 1932 average concentrations, divided by seven decades. The 2002-2012 trends are the Watermaster's description of the most common trend exhibited among individual wells in each subarea. The simulated trend is the difference between the initial concentration and the 2012 concentration in the calibration simulation. A comparison of historical trends estimated from water quality data with trends simulated by the mixing model reveals potential calibration errors.

Given the large spatial variation in historical concentrations and concentration trends among wells within individual subareas and the complete-mixing assumption incorporated in the mixing model, discrepancies between simulated and measured concentrations are to be expected. Some of the larger discrepancies were investigated to determine the possible causes.

Simulated nitrogen concentrations and trends during 2002-2012 were declining in all subareas except TUJ. The rising trend in simulated nitrogen in TUJ probably results from the large amount of loading from on-site wastewater systems, which is four times higher (on a per-acre basis) in TUJ than in the next-highest subarea.

A pattern evident in almost all subareas is a faster rate of increase (or lower rate of decrease) for chloride than for TDS. Most of the difference is probably real and results from the higher chloride-to-TDS ratio (Cl:TDS) in municipal water and wastewater than in historical ambient groundwater. **Figure 10** shows Cl:TDS for delivered water, tertiary-treated recycled water, groundwater in 2002 and simulated groundwater in 2012. Except in VER, Cl:TDS is higher in delivered water and recycled water than in groundwater, and the groundwater trend during 2002-2012 is an increase in Cl:TDS. This shift is logically the result of recharge from leaky pipes (water and sewer) and evaporatively-concentrated irrigation deep percolation, all of which preserve the relatively high Cl:TDS present in delivered water. Also, the Cl:TDS ratio of delivered water might have increased over the past few decades due to changes in sources of imported water. Because of these factors, the Cl:TDS of ambient groundwater would be expected to increase over time as it mixes with these sources of recharge and groundwater with ambient concentrations is pumped.

The one exception is the Cl:TDS in VER, where simulated Cl:TDS decreased during 2002-2012. A possible factor contributing to this anomaly is the relatively high use of groundwater for municipal supply: 55 percent of delivered water in VER versus much smaller percentages in the other subareas. However, the Cl:TDS is still slightly higher in delivered water than in 2002 groundwater, so a decrease in Cl:TDS would not be expected. Also, the subarea was sewered in 1984, and the declining trend could reflect gradual dilution of pre-1984 recharge from onsite wastewater disposal systems. Finally, it is also possible—as with all calibration results—that the 2002 groundwater quality was not representative of average ambient conditions due to sparse data.

Other notable discrepancies between measured and simulated water-quality trends include the relatively rapid increase in chloride in EAG. Recharge and salt loading in this region is dominated by irrigation deep percolation and leaky pipes, so a relatively rapid increase in the Cl:TDS ratio would be expected. Also, the historical ambient water quality is defined by a single well that might not have been representative of ambient groundwater quality throughout the region

Another discrepancy is the rapid decline in simulated nitrogen in SYL and NAR, where the measured trends were stable or increasing. This might be simply a timing issue as groundwater in all subareas gradually responds to the historical transition from a period of relatively high nitrogen loading from agriculture and septic systems to the current pattern of negligible agriculture and piped wastewater disposal. The 1932-2002 nitrogen trends were upward in all regions, whereas the simulated 2002-2012 trends were downward (except for the increase in TUJ discussed earlier). No calibration adjustments were made to the SYL and NAR nitrogen simulations.

6.4.3. Assimilative Capacity as of 2012

The dashed black line on each graph in **Figure 9** indicates the BPO for that constituent and subarea. A comparison of simulated concentrations with the BPOs indicates regions where concentrations or concentration trends are a concern for management. Assimilative capacity is defined as the difference between the BPO and ambient concentration, if the ambient concentration is below the BPO. If the ambient concentration is above the BPO, there is no assimilative capacity. The concept of assimilative capacity is that increases in concentrations of TDS, chloride or nitrogen can be acceptable if beneficial uses are not impaired. A guideline in the 2009 Recycled Water Policy recommends that Regional Water Quality Control Boards approve SNMPs with new recycled water projects that consume less than 10 percent of the initial assimilative capacity during the planning period (20 percent if multiple projects are planned). In addition to this criterion, mixing model results were evaluated with respect to concentration trends. Concentrations that are low but rising could become a problem in the future. Conversely, concentrations that are high but declining for a given scenario are less of a concern than concentrations that are high and stable or rising. In some subareas, one or more of the three constituents is already above the BPO. This could indicate historical loading unrelated to recycled water use, or possibly the use of non-representative water-quality data at the time the BPOs were originally established.

TDS and chloride concentrations were below the BPO in 2002 but trends were increasing in NAR, SFE, SYL and TUJ. In SFW and VER, the TDS concentration began above the BPO, while the chloride concentration began below it. Trends were upward for both constituents in VER but for chloride only in SFW. Finally, in EAG both concentrations began above the BPO and trends were increasing slightly to moderately.

Simulated concentrations and assimilative capacities in 2015 are shown for each subarea and constituent on the left side of **Table 3**. As of 2015, EAG, SFW, TUJ and VER had no assimilative capacity for TDS. Assimilative capacities for TDS in NAR, SFE and SYL ranged from 88 mg/L to 234 mg/L. For chloride, EAG had no assimilative capacity. In the other subareas, the assimilative capacity for chloride ranged from 5 mg/L to 65 mg/L. The substantial variation in assimilative capacities among the subareas is not solely due to differences in hydrogeology and loading. Some of it results from differences in BPOs among the subareas. For example, TUJ has a TDS BPO of only 400 mg/L, compared with 600-900 mg/L for the other subareas. The simulated TDS concentration in TUJ would be below the BPO in all the other subareas.

All subareas had assimilative capacity for nitrogen in 2015, due in part to the declining trends simulated in most subareas during the calibration period. The assimilative capacities for nitrogen were large fractions of the BPO (10 mg/L): 4.0 mg/L to 6.3 mg/L.

6.5. FUTURE BASELINE SIMULATION RESULTS

Simulated concentrations and assimilative capacities in 2025 for the future baseline scenario are also shown in the center-left part of **Table 3**. Assimilative capacity for TDS in NAR, SFE and SYL decreased from 2015 to 2025 due to increasing trends in concentrations. In the remaining subareas there was no assimilative capacity to begin with, and in three of those concentrations were increasing. Assimilative capacity for chloride decreased in the six subareas that had capacity in 2002, due to increasing trends in concentrations. Assimilative capacity was eliminated by 2025 in TUJ because the simulated concentration rose above the BPO. Assimilative capacity for nitrogen increased due to declining concentration trends in every subarea except TUJ, where the concentration trend was increasing.

The percentage change in assimilative capacity can be misleading as an indicator of water quality concerns. In many cases, large percentage changes occur when the initial concentration is near the BPO and initial assimilative capacity is consequently small. The same change in concentration (in mg/L) would be a small percentage of assimilative capacity if the initial concentration were lower or the BPO were higher. To provide a more comprehensive view of potential water quality concerns, data in **Table 3** were evaluated with respect to three criteria that represent potential water-quality concerns:

- Assimilative capacity decreased by more than 10 percent from 2015 to 2025, as discussed above (purple shading),
- The simulated concentration exceeded the BPO in 2015 and the annual trend was positive in 2025 and/or 2044 (blue shading), and
- The concentration trend became more positive or switched from negative to positive during 2025-2044 (orange shading).

Cell values in the table that exceed one of these thresholds are highlighted with colors that indicate which threshold was exceeded. For the future baseline scenario, the number of subareas that lost more than 10 percent of their assimilative capacity from 2015 to 2025 were two for TDS, four for chloride and one for nitrogen. High concentrations with increasing trends occurred in EAG (TDS and chloride) and TUJ (TDS only). The final criterion—upward curvature in the concentration trends (became more positive)—was triggered for chloride in NAR but not in any other subarea.

Time series plots of simulated concentrations for the future baseline scenario are included in the plots of results for the SNMP scenarios, discussed below.

7. SENSITIVITY ANALYSIS

The sensitivity of mixing model output to changes in model input was tested for several variables expected to strongly influence results. Variables were tested one at a time, and simulated concentrations were compared with results of the calibration-baseline simulation. The size of each adjustment roughly corresponded to the degree of uncertainty in each input variable. The results of eight tests are shown in **Table 4**. The variables that had the biggest effects relative to their ranges of uncertainty were irrigation efficiency, disconnected impervious area, pipe leaks and initial concentration. The first three of these are variables that could potentially be influenced by management measures.

8. SIMULATION OF SNMP

The SNMP includes several management measures, or elements, that would affect groundwater quality: direct use of recycled water for irrigation; groundwater recharge with recycled water; and groundwater recharge with stormwater. In general, the tertiary-treated recycled water elements tend to increase groundwater salinity, whereas stormwater recharge and advanced-treated recycled water tend to decrease it. Data and assumptions for incorporating these elements are described below, followed by a discussion of simulation results.

8.1. SNMP ELEMENTS

8.1.1. Element 1: Increased Recycled Water Use for Irrigation

The SNMP incorporates planning assumptions contained in the 2014 Greater Los Angeles County Integrated Regional Water Management Plan (IRWMP). These include projections of recycled water use for irrigation of large turf areas in NAR, SFE and SFW. Irrigation use of recycled water would gradually increase to 11,900 AFY above projected baseline usage by 2030, as shown in **Figure 11**. Recycled water is also presently used in VER, but the amount remains the same in the GLAC IRWMP projections.

For the mixing model, recycled water was assumed to replace an equal amount of potable supply water currently used for irrigation. Therefore, the volume of recharge from irrigation return flow does not change, but the quality does. The TDS, chloride and nitrogen concentrations in tertiary-treated recycled water were assumed to be the same as in the existing effluent from local wastewater treatment plants, all of which treat to a tertiary level. Values for each subarea that uses recycled water were calculated as a service-area-weighted average quality of the Tillman, Burbank and Los Angeles-Glendale wastewater treatment plant effluent concentrations. In the case of nitrogen, the same loss percentages to plant uptake and denitrification were applied as for fertilizer applications (5 percent of applied nitrogen remains in the water percolating down from the root zone to the water table).

8.1.2. Element 2: Recycled Water Percolation at Spreading Basins

Two types of recycled water are under consideration for percolating at the Pacoima and Hansen spreading basins: tertiary-treated recycled water (RW) and advanced water treatment (AWT) recycled water. For the RW option, percolation volumes would begin at 5,000 AFY in 2017 and increase to 19,000 AFY in 2020, 28,000 AFY in 2024 and 30,000 AFY in 2030, as documented in TM-3. With respect to TDS, chloride and nitrogen, this water is assumed to be the same as existing wastewater treatment plant effluent. For the AWT option, 30,000 AFY of AWT water would be percolated at Pacoima and Hansen spreading basins beginning in 2024. Advanced treatment includes reverse osmosis, which would decrease the solute concentrations in this water to 22 mg/L of TDS, 3.6 mg/L of chloride and 1.1 mg/L of nitrogen (TM-4).

8.1.3. Element 3: Increased Dispersed Stormwater Recharge

Dispersed stormwater recharge refers to all methods of infiltrating stormwater other than percolation at the five major spreading basins along Pacoima Creek and Big Tujunga Wash. It includes site-scale, “low-impact development” measures (downspout disconnection, grading of landscaped areas to pond and infiltrate rainfall, bio-swales in parking lots, etc.), street-scale measures (“green street” improvements such as stormwater percolation swales instead of curb-and-gutter, dry wells, porous pavement, etc.), and neighborhood-scale projects (grading parks, schools, utility corridors and other open-space areas to retain and infiltrate stormwater runoff from adjacent small urban watershed areas).

The SNMP includes implementation of two existing plans for increasing dispersed stormwater recharge: the IRWMP and the City of Los Angeles Stormwater Capture Master Plan (SCMP). The latter plan applies only to areas within the Los Angeles city limits, which excludes Burbank, Glendale, La Cañada Flintridge and San Fernando. The latter covers parts of eastern and northern SFE, northern NAR and most of VER. The two plans differ slightly in nomenclature, but essentially include the same types of dispersed stormwater recharge measures. Therefore, the two plans overlap in concept and are not additive. The SCMP describes two levels of implementation: “conservative” and “aggressive”. Preliminary tests with the mixing model indicated that the aggressive option would be needed to adequately offset the water quality effects of recycled water use. The SCMP-aggressive option is considerably more ambitious in its degree of implementation than IRWMP, and for the mixing model it was assumed to be implemented (instead of IRWMP) throughout City of Los Angeles lands. In the remaining parts of the SNMP subareas, the IRWMP was assumed to be implemented. In both cases, recharge from dispersed stormwater recharge was pro-rated on a uniform per-acre basis to the applicable SNMP areas. **Figure 12** shows the estimated average annual amounts of dispersed stormwater recharge in each subarea, broken down by IRWMP (non-City) and SCMP (City). Both plans were assumed to be implemented gradually over the first 10 years of the future simulation. At full implementation, SCMP projects would contribute 25,300 AFY of dispersed stormwater recharge and the IRWMP areas would contribute an additional 570 AFY.

8.2. Simulation Results: SNMP Implementation

SNMP implementation was simulated in two steps to show the separate effects of SNMP elements. The first step included only direct use of tertiary-treated recycled water for irrigation and for percolation at the spreading basins. The second step added dispersed stormwater recharge. Percolation of AWT water at the spreading basins was simulated separately, as described in Section 8.2.3 “Effects of Advanced-Treated Water Recharge at Spreading Basins”.

8.2.1. Effects of Tertiary-Treated Recycled Water Use and Percolation Only

The first step included direct use and percolation of tertiary-treated recycled water (the recycled-water-only or RW-only scenario). Centralized stormwater percolation at the spreading basins was carried forward from the baseline simulation (it was proposed in the IRWMP and also in the SCMP). The results of the RW-only scenario are shown in **Figure 13**, which presents simulated concentrations during 2016-2044 for all twenty-one subarea-constituent combinations. For comparison, each graph also shows simulated concentrations for the baseline scenario. Under the SNMP, recycled water use for irrigation would increase only in NAR, SFE and SFW[3], and percolation would occur only in SFE. Consequently, simulated concentrations in the remaining subareas were identical to baseline concentrations. In NAR, SFE and SFW there was a gradual increase in the simulated concentrations of TDS, chloride and nitrogen. This is the expected result, given that the concentrations of all three constituents are substantially higher in tertiary-treated recycled water than in potable delivered water (by 244-285 mg/L for TDS, 65-72 mg/L for chloride and 3.8-4.8 mg/L for nitrogen). The amount of departure from the baseline simulation depended partly on the amount of recycled water used, as a percentage of total water use.

[3] A small amount (256 AFY) of recycled water is used for irrigation in VER, but that amount would not increase under the future scenarios.

The smallest increase was in SFW, where TDS increased by 8.5 mg/L by 2025, chloride increased by 1.9 mg/L and nitrogen increased by 0.1 mg/L. The largest increases were in NAR, where TDS, chloride and nitrogen increased by 31.9 mg/L, 8.9 mg/L and 0.4 mg/L by 2025, respectively. The increasing trends continued through 2044.

8.2.2. Combined Effects of All SNMP Elements

The second step in simulating the effects of SNMP implementation was to add dispersed stormwater recharge. Simulated concentrations for all twenty-one subarea-constituent combinations are shown in **Figure 14**. The concentration curves for the baseline and RW-only simulations are also shown for comparison. Dispersed stormwater recharge lowered the concentration trends relative to the RW-only scenario and in some cases, also relative to the baseline scenario. In EAG, for example, the baseline and RW-only trends for TDS and chloride were identical (because no recycled water use is proposed) and increasing over time. Dispersed stormwater recharge lowered the trends to level or declining. In SFE, the TDS trend was lowered back to the baseline trend, and the chloride trend about halfway back from the RW-only trend to the baseline trend. The effect of dispersed stormwater recharge was relatively large in SFW; simulated trends were substantially lower than the baseline and RW-only trends. In both SFE and SFW the TDS and chloride trends with dispersed stormwater recharge were declining or essentially level by 2044. In SYL and TUJ—where additional use of recycled water is not proposed in the SNMP—dispersed stormwater recharge reduced or eliminated the increasing TDS and chloride trends of the baseline scenario. Even the increasing nitrate trend in TUJ was reduced to a level trend.

Eight subarea-constituent combinations still triggered one of the three thresholds of concern (described in Section 6.5) even with dispersed stormwater recharge. However, the exceedances were relatively small. To put the results in perspective, the simulated concentrations and trends in 2044 were evaluated to determine whether they were: 1) lower than the baseline scenario, 2) lower than the BPO or 3) increasing by less than 0.2 mg/L per year (0.05 mg/L/yr for nitrogen). Six of the eight subarea-constituent combinations had at least two of these three favorable characteristics.

NAR was the only subarea with possible future water quality concerns based on the simulations. The effect of dispersed stormwater recharge was relatively small in NAR because both IRWMP and SCMP-aggressive assumptions would implement less than one-sixth as much dispersed stormwater recharge on a per-acre basis as in the other subareas. Conversely, the effect of recycled water irrigation was relatively large, with NAR receiving 3-10 times more recycled water use per subarea acre than in SFE, SFW and VER. The simulated TDS and nitrogen trends gradually shifted from roughly level to increasing during the 2016-2044 simulation period. The chloride trend became more steeply increasing. These trends are probably acceptable for the near future because even at the end of the simulation, concentrations were half or less of the BPO for all three constituents. Given the relatively low concentrations and the uncertainties inherent in the mixing model, an adaptive management approach is reasonable. If ongoing monitoring confirms that the future trends are increasing, there is plenty of opportunity to implement additional dispersed stormwater recharge or other salinity reduction measures (see TM-4). Relevant to this point, a third regional stormwater management plan was developed that contemplates even larger amounts of recharge in NAR. The Enhanced Watershed Management Program (EWMP) for the Upper Los Angeles River Watershed (Black and Veatch, 2016) was prepared for the LARWQCB, which adopted the program on April 20, 2016. The EWMP would achieve about 5,100 AFY of stormwater recharge in NAR, or forty times more than proposed with the IRWMP and SCMP-aggressive projects. Test simulations using the EWMP recharge projections (not described herein) produced declining concentrations for TDS, chloride and nitrogen at the end of the simulation period.

8.2.3. Effects of Advanced-Treated Water Recharge at Spreading Basins

The SNMP includes the option of further reducing salt loads to the SFE subarea by using AWT to further treat the recycled water to be percolated at the spreading basins. AWT would decrease the TDS and chloride concentrations by a factor of 25-30 and the nitrogen concentration by a factor of five (**Table 2**). An additional mixing model simulation was completed in which tertiary-treated recycled water percolation at the spreading basins was replaced with advanced-treated recycled water. All other inputs were the same as for the step two simulation that included dispersed stormwater recharge. All spreading basin recharge is in SFE, and that proved to be the only subarea where concentrations were affected by the change. Although changes in simulated SFE concentrations would eventually affect simulated NAR concentrations because of groundwater flow from SFE to NAR, that effect had not become noticeable by the end of the simulation period. This is consistent with prior modeling of spreading basin recharge using LADWP's groundwater flow model. When increased spreading basin recharge was accompanied by increased pumping (to recover the additional water), both increases were observed within SFE and all the spreading basin recharge was captured by wellfields within SFE.

Simulated concentrations of TDS, chloride and nitrogen in SFE are shown in **Figure 15**. Simulation results for the baseline scenario and the SNMP scenario with tertiary-treated recycled water percolation at the spreading basins are also shown, for comparison. For TDS and nitrogen, the advanced-treated recycled water recharge accelerated the long-term declining trend in concentrations. For chloride, the AWT water changed a trend that had been rising and barely leveling off by 2044 to a consistently declining trend. By 2044, the AWT recycled water had decreased ambient groundwater concentrations relative to the tertiary-treated recycled water option by 76 mg/L for TDS, 18 mg/L for chloride and 0.7 mg/L for nitrogen.

9. REFERENCES CITED IN MAIN TEXT AND APPENDICES

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TABLES

Table 1. Index of Data Sources and Assumptions for Mixing Model Input

	Flow				Water Quality			
	Historical	Future 2016-2044			Historical	Future 2016-2044		
	2002-2012	Baseline	Tertiary Recycled Water	Tertiary Recycled Water + SCMP[1]	2002-2012	Baseline	Tertiary Recycled Water	Tertiary Recycled Water + SCMP[1]
Groundwater Recharge								
Rainfall deep percolation								
Pervious soils	§6.2.2	= 2012	= 2012	= 2012	§6.2.2	= 2012	= 2012	= 2012
Impervious areas	§6.2.2	= 2012	= 2012	= 2012	§6.2.2	= 2012	= 2012	= 2012
Irrigation deep percolation								
Municpal supply	§6.2.2	TM-3	TM-3	TM-3	§6.2.2	= 2012	= 2012	= 2012
Recycled water	§8.1.1	TM-3	TM-3	TM-3	§8.1.1	§8.1.1	= Baseline	= Baseline
Background mass load	§6.2.1	= 2012	= 2012	= 2012	§6.2.1	= 2012	= 2012	= 2012
Fertilizer	§6.2.3	= 2012	= 2012	= 2012	§6.2.3	= 2012	= 2012	= 2012
Pipe leaks								
Water	§6.2.4	§6.2.4	= Baseline	= Baseline	§6.2.4	= 2012	= 2012	= 2012
Sewer	§6.2.4	§6.2.4	= Baseline	= Baseline	§6.2.4	= 2012	= 2012	= 2012
On-site wastewater systems	TM-2	= 2012	= 2012	= 2012	§6.2.5	= 2012	= 2012	= 2012
Percolation from streams	§6.2.6	= 2012	= 2012	= 2012	§6.2.6	= 2012	= 2012	= 2012
Spreading basin percolation								
Natural stream flow	TM-2	TM-3	= Baseline	= Baseline	§6.2.7	= 2012	= 2012	= 2012
Imported water	TM-2	TM-3	TM-3	TM-3	§6.2.7	= 2012	= 2012	= 2012
Recycled water	TM-2	TM-3	TM-3	TM-3	§6.2.7	= 2012	= 2012	= 2012
Hill and mountain subsurface inflow	§6.2.1	= 2012	= 2012	= 2012	§6.2.1	= 2012	= 2012	= 2012
Groundwater Flow between Regions	§6.2.8	§6.2.8	= Baseline	= Baseline	§6.2.8	§6.2.8	§6.2.8	§6.2.8
Groundwater Discharge								
Wells	TM-2	§6.3.1	§6.3.1	§6.3.1	Water quality of all outflows equals current simulated ambient groundwater quality.			
Riparian vegetation ET	§6.3.3	= 2012	= 2012	= 2012				
Seepage into Los Angeles River	§6.3.2	§6.3.2	= Baseline	= Baseline				
Initial Concentrations	n.a.	n.a.	n.a.	n.a.	TM-2	=2015	=2015	=2015
Groundwater Storage	§6.3.1	§6.3.1	= Baseline	= Baseline	Equals simulated ambient groundwater quality			

§ = indicates report section in which information is located; SCMP = Los Angeles Department of Water and Power, Stormwater Capture Master Plan (2015)

ET = evapotranspiration

[1] Data sources for the advanced treated recycled water option are the same as for the tertiary-treated recycled water option except for flow and quality of recycled water percolation at the spreading basins (see text section 8.2.3).

Table 2. Water Quality of Wastewater Treatment Plant Effluent and Spreading Basin Recharge

Location	TDS (mg/L)	Chloride (mg/L)	Nitrogen (mg/L)
Wastewater Effluent Quality by Treatment Plant			
Donald C. Tillman	555	123	3.2
L.A. - Glendale	643	143	3.7
Burbank	636	125	5.2
Average Wastewater Effluent Quality by Subarea			
EAG	632	145	3.9
NAR	632	145	3.9
SFE	598	132	4.3
SFW	552	128	4.0
SYL	552	128	4.0
TUJ	552	128	4.0
VER	632	145	3.9
Spreading Basin Recharge Water Quality by Source			
Natural flow (stormwater)	253	13	0.1
Imported water	327	63	1.4
Tertiary-treated recycled water	555	123	3.2
Advanced-treated recycled water	22	4	1.1

Notes:

1. Wastewater treatment plant values are average concentrations in effluent measured during 2002-2012.
2. Values for subareas are area-weighted averages of the treatment plants with sewers in the subarea.

Table 3. Summary of Simulated Concentrations and Assimilative Capacities in 2015, 2025 and 2044

					Baseline Scenario					Baseline + Recycled Water Scenario					Baseline + Recycled Water + SCMP-Aggressive Scenario					Baseline + RW/AWT + SCMP-Aggressive Scenario				
SNMP Subarea	Water Quality Constituent	Basin Plan Objective (mg/L)	Concentration in 2015 (mg/L)	Assimilative Capacity in 2015 (mg/L)	Concentration in 2025 (mg/L)	Change in Concentration 2015 to 2025 (mg/L)	Change in Assimilative Capacity 2015 to 2025 (%)	Trend in 2025 (mg/L/yr)	Trend in 2044 (mg/L/yr)	Concentration in 2025 (mg/L)	Change in Concentration 2015 to 2025 (mg/L)	Change in Assimilative Capacity 2015 to 2025 (%)	Trend in 2025 (mg/L/yr)	Trend in 2044 (mg/L/yr)	Concentration in 2025 (mg/L)	Change in Concentration 2015 to 2025 (mg/L)	Change in Assimilative Capacity 2015 to 2025 (%)	Trend in 2025 (mg/L/yr)	Trend in 2044 (mg/L/yr)	Concentration in 2025 (mg/L)	Change in Concentration 2015 to 2025 (mg/L)	Change in Assimilative Capacity 2015 to 2025 (%)	Trend in 2025 (mg/L/yr)	Trend in 2044 (mg/L/yr)
EAG	**TDS**	800	858.9	None	867.3	8.4	N.A.	0.4	0.1	867.3	8.4	N.A.	0.4	0.1	839.0	-19.9	N.A.	-4.5	-2.2	839.0	-19.9	N.A.	-4.5	-2.2
NAR	**TDS**	900	666.2	234	694.0	27.8	-11.9%	1.4	0.8	725.9	59.7	-25.5%	4.0	1.8	701.3	35.1	-15.0%	2.0	1.2	699.7	33.6	-14.4%	1.4	0.0
SFE	**TDS**	600	511.8	88	522.7	10.9	-12.4%	0.3	-1.1	530.9	19.1	-21.6%	1.2	-0.6	508.8	-3.0	3.4%	-2.5	-2.0	495.1	-16.7	18.9%	-8.5	-3.6
SFW	**TDS**	800	838.6	None	812.8	-25.9	N.A.	-2.7	-1.8	821.3	-17.4	N.A.	-1.9	-1.1	767.1	-71.5	N.A.	-11.0	-5.4	767.1	-71.5	N.A.	-11.0	-5.4
SYL	**TDS**	600	402.2	198	410.8	8.7	-4.4%	0.4	0.1	410.8	8.7	-4.4%	0.4	0.1	393.3	-8.8	4.5%	-2.5	-0.7	393.3	-8.8	4.5%	-2.5	-0.7
TUJ	**TDS**	400	414.0	None	435.5	21.4	N.A.	1.5	1.0	435.5	21.4	N.A.	1.5	1.0	400.2	-13.9	N.A.	-4.5	-1.6	400.2	-13.9	N.A.	-4.5	-1.6
VER	**TDS**	600	748.7	None	773.1	24.4	N.A.	0.0	-0.3	773.4	24.7	N.A.	0.0	-0.3	766.6	17.8	N.A.	-1.1	-0.4	766.5	17.8	N.A.	-1.1	-0.4
EAG	**CL**	100	138.2	None	152.4	14.2	N.A.	1.2	0.6	152.4	14.2	N.A.	1.2	0.6	147.4	9.1	N.A.	0.3	0.1	147.4	9.1	N.A.	0.3	0.1
NAR	**CL**	150	85.0	65	90.9	5.9	-9.0%	0.3	0.4	99.8	14.8	-22.7%	0.9	0.8	97.8	12.7	-19.6%	0.7	0.6	97.0	12.0	-18.5%	0.5	0.4
SFE	**CL**	100	44.3	56	50.5	6.2	-11.1%	0.5	0.1	55.9	11.6	-20.8%	1.3	0.4	53.1	8.8	-15.8%	0.8	0.1	48.2	3.9	-6.9%	-0.4	-0.2
SFW	**CL**	100	72.5	27	82.1	9.5	-34.7%	0.9	0.6	84.0	11.4	-41.6%	1.0	0.7	78.9	6.3	-23.0%	0.1	0.1	78.9	6.3	-23.0%	0.1	0.1
SYL	**CL**	100	43.1	57	47.8	4.7	-8.3%	0.3	0.1	47.8	4.7	-8.3%	0.3	0.1	45.8	2.7	-4.8%	0.0	0.0	45.8	2.7	-4.8%	0.0	0.0
TUJ	**CL**	50	44.3	6	55.4	11.1	-100.0%	0.9	0.5	55.4	11.1	-100.0%	0.9	0.5	51.1	6.8	-100.0%	0.1	0.1	51.1	6.8	-100.0%	0.1	0.1
VER	**CL**	100	94.8	5	95.5	0.7	-12.8%	-0.3	-0.1	95.6	0.8	-14.8%	-0.3	-0.1	94.7	-0.1	2.0%	-0.5	-0.1	94.7	-0.1	2.2%	-0.5	-0.1
EAG	**N**	10.0	4.1	5.9	3.6	-0.5	8.6%	0.0	-0.02	3.6	-0.5	8.6%	0.0	0.0	3.6	-0.6	9.7%	-0.05	-0.02	3.6	-0.6	9.7%	-0.05	-0.02
NAR	**N**	10.0	5.2	4.8	4.7	-0.5	10.4%	0.0	-0.02	5.1	-0.1	2.1%	0.0	0.0	4.9	-0.3	6.0%	0.02	-0.01	4.9	-0.3	6.1%	0.01	-0.02
SFE	**N**	10.0	3.8	6.2	3.5	-0.3	5.3%	0.0	-0.03	3.5	-0.3	4.7%	0.0	0.0	3.3	-0.5	8.2%	-0.06	-0.03	3.3	-0.5	8.8%	-0.09	-0.04
SFW	**N**	10.0	5.4	4.6	5.1	-0.4	8.3%	0.0	-0.02	5.2	-0.3	6.3%	0.0	0.0	4.9	-0.5	11.6%	-0.06	-0.03	4.9	-0.5	11.6%	-0.06	-0.03
SYL	**N**	10.0	4.4	5.6	3.7	-0.7	12.0%	-0.1	-0.02	3.7	-0.7	12.0%	-0.1	0.0	3.6	-0.8	14.0%	-0.07	-0.02	3.6	-0.8	14.0%	-0.07	-0.02
TUJ	**N**	10.0	6.0	4.0	6.9	0.9	-22.8%	0.1	0.06	6.9	0.9	-22.8%	0.1	0.1	6.4	0.4	-10.8%	0.01	0.00	6.4	0.4	-10.8%	0.01	0.00
VER	**N**	10.0	3.7	6.3	2.8	-0.9	13.9%	0.0	-0.01	2.8	-0.9	13.9%	0.0	0.0	2.8	-0.9	14.1%	-0.05	-0.01	2.8	-0.9	14.1%	-0.05	-0.01

Notes:

TDS = total dissolved solids, CL = chloride, N = nitrogen, SCMP = Stormwater Capture Master Plan; mg/L = milligrams per liter; mg/L/yr = milligrams per liter per year; RW/AWT = tertiary-treated recycled water irrigation and advanced-treated recycled waer for percolation; N.A. = not applicable

= annual concentration trend becomes more positive or changes from negative to positive from 2025 to 2044

= concentration exceeded basin plan objective in 2015 and annual trend is positive in 2025 and/or 2044

= assimilative capacity decreases by more than 10% from 2015 to 2025

Table 4. Mixing Model Sensitivity Test Results

Variable	Change in Input	Largest Changes in Simulated Concentration in 2044			Comments
		Subarea	Constituent	Change (mg/L)	
Septic systems	Eliminate all	TUJ	TDS	-5	Negligible decreases in other regions.
		TUJ	Cl	-8	
		TUJ	N	-4	
Initial concentration	Increase or Decrease by 25%	SFW	TDS	+/- 120	Subreas with residence times of 45-91 years (VER, NAR and SYL): concentrations converged to reference simluation by 2044. Residence times 144-170 years (SFE, EAG, TUJ): 30-50% of initial change still remained at 2044. Residence time of 224 years (SFW): 60% of initial change remained in 2044.
		SFW	Cl	+/- 9	
		SFW	N	+/- 0.8	
Background mass load	Decrease by 50%	SYL	TDS	-35	Negligible change in SFE and TUJ
		VER	Cl	-10	
		NAR	N	-0.4	
Impervious area	Shift 10% of total area from non-irrigated to connected impervious	EAG	TDS	+5	Small effect because non-irrigated areas generate little recharge and connected impervious areas generate none.
		VER	Cl	+3	
		TUJ	N	+0.2	
Impervious area	Shift 10% of total area from connected to disconnected impervious	EAG SFW TUJ VER	TDS	-80	This is the type of change produced by Low Impact Development and Green Streets. The additional rainfall recharge is assumed to provide additional recharge water with no additional salts.
		EAG TUJ VER	Cl	-15	
		TUJ	N	-1	
Pipe leaks	Decrease water and sewer pipe leak rates:from 5 to 3% of annual flow for water; 2.5 to 1.5% for sewer	EAG	TDS	+60	Water pipe leaksalways decrease ambient concentrations while sewer pipe leaks cause a smaller decrease or in some cases an increase. Because the volume of water pipe leaks is roughly four times greater than sewer pipe leaks, the 40% reduction in both results in higher ambient concentrations.
		EAG	Cl	+8	
		TUJ	N	+0.3	
Irrigation efficiency	Decrease irrigation overspray and deep percolation each by 7.5% of applied water	EAG	TDS	+169	In the calibration simulation, minerals from 75% of the irrigation water beome concentrated into the 15% of applied water that percolates past the root zone. In the sensitivity test, minerals from 82.5% of the water become concentrated into 7.5% of the water, resulting in deep percolation twice as concentrated. VER, NAR and SFW also experienced large increases in simulated concentrations.
		EAG	Cl	+30	
		EAG	N	+0.6	
Groundwater storage volume	Increase or Decrease by 25%	VER	TDS	+/- 25	Decreasing the storage volume increases the slope of concentration trends. Biggest differences are at steepest parts of the concentration curves. As curves level out approaching equilibrium, effect of storage decreases to zero.
		EAG	Cl	+/- 10	
		VER	N	+/- 0.9	

Notes:
Sensitivity tests were done using the future baseline scenario as the reference condition.

FIGURES

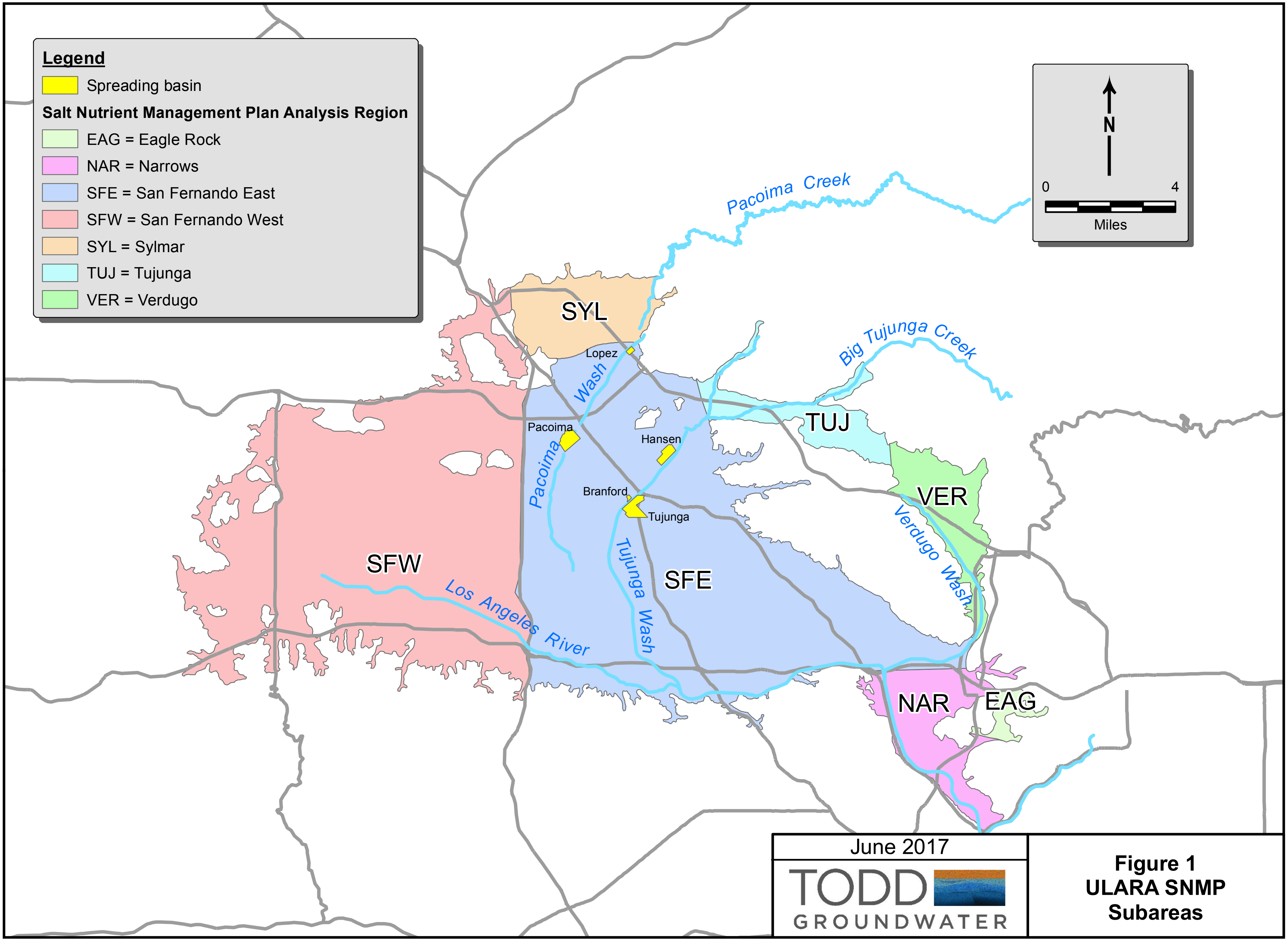
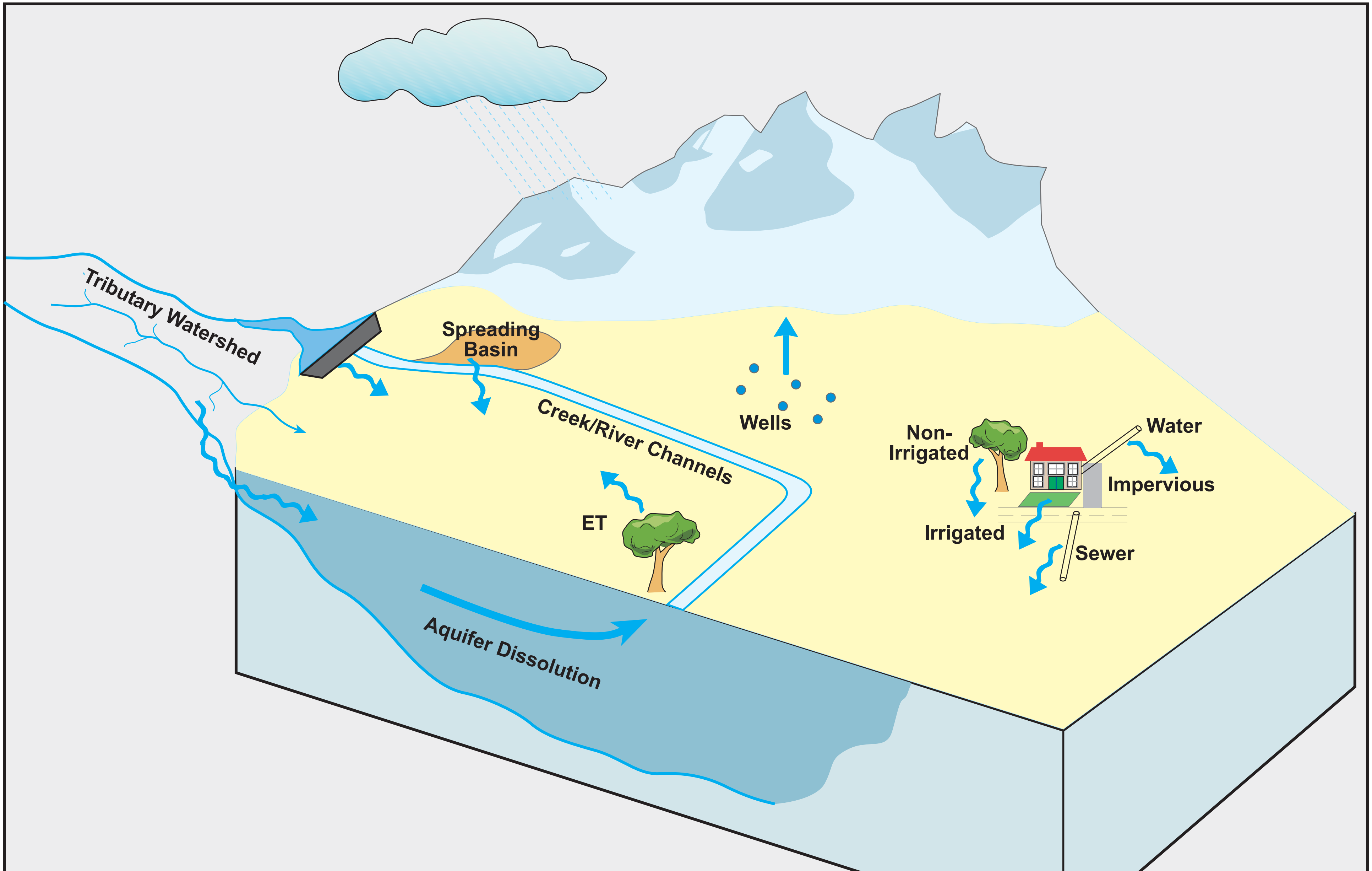


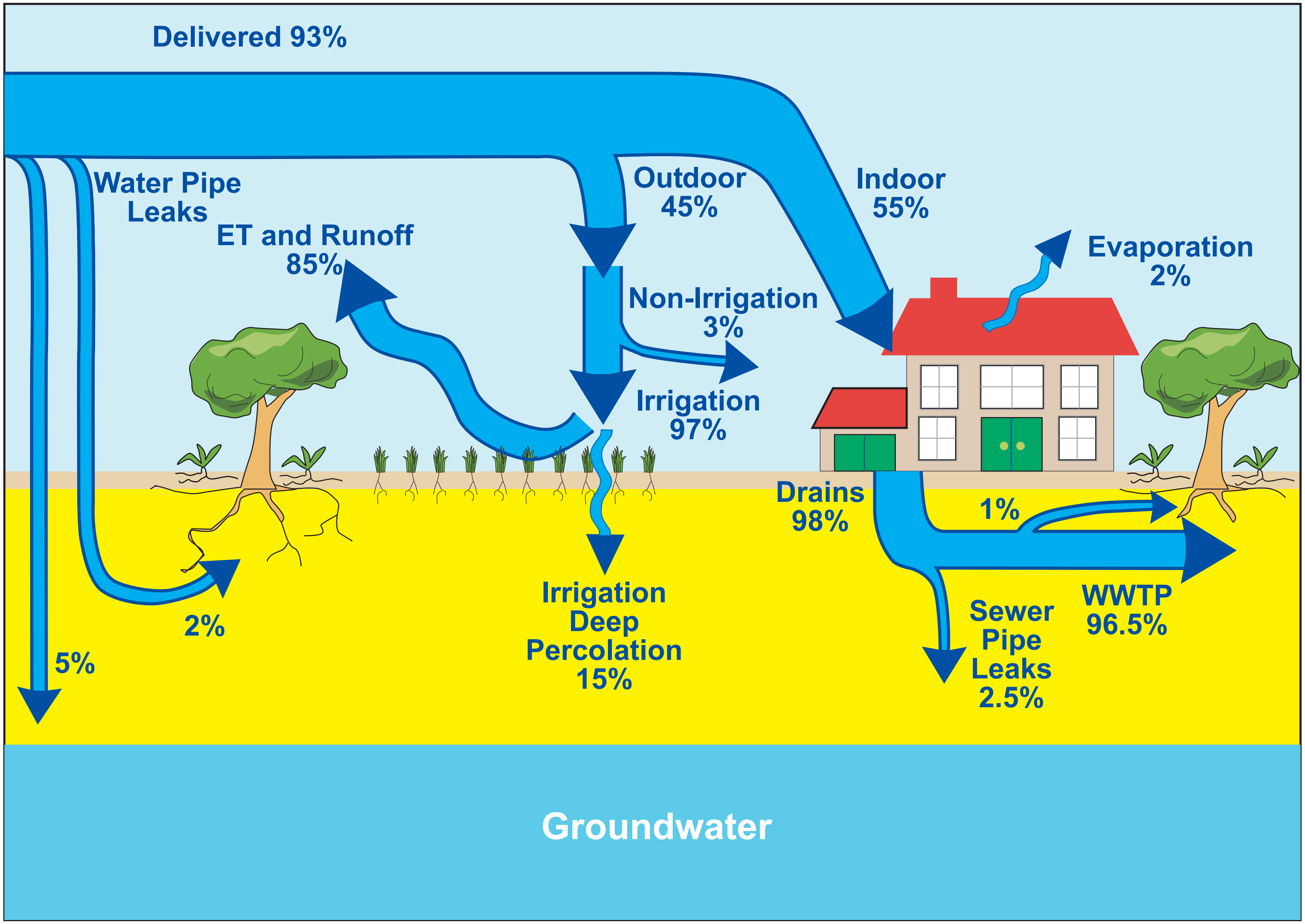
Figure 1
ULARA SNMP
Subareas



April 2017

TODD GROUNDWATER

Figure 2
Regional Diagram of Salt and Nutrient Sources

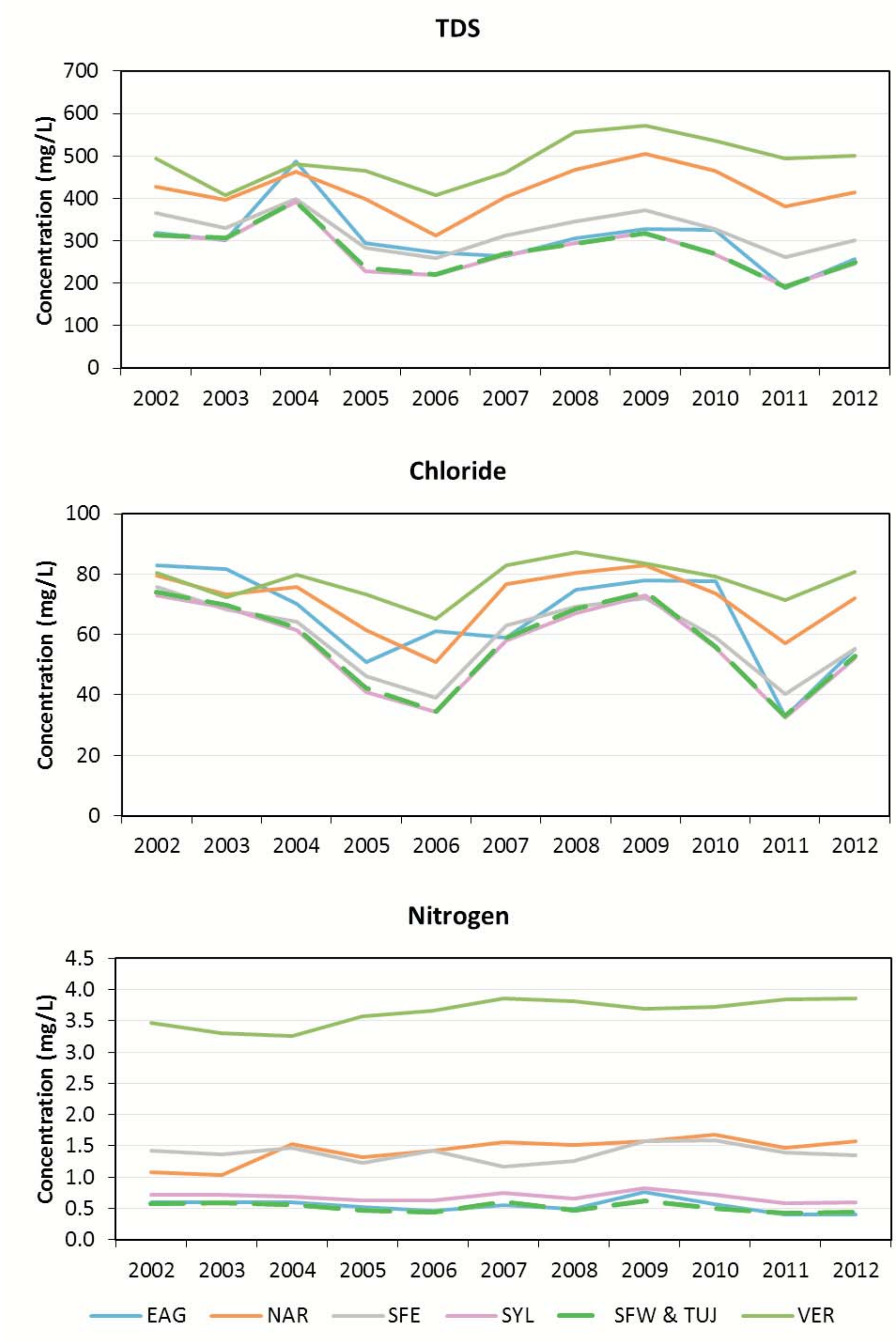


Numbers indicate percentage split of water flows.
ET - Evapotranspiration
WWTP - Wastewater treatment plan

June 2017

TODD GROUNDWATER

Figure 3
Parcel Scale Diagram of Salt and Nutrient Sources



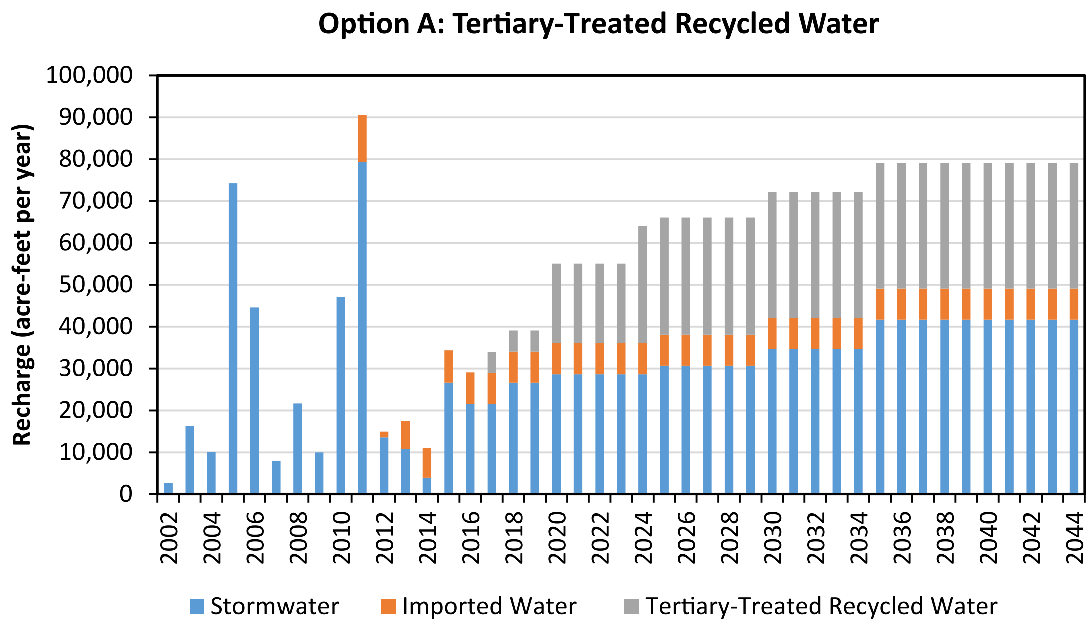
Median 2002-2012 Concentrations in mg/L Used for 2013-2030

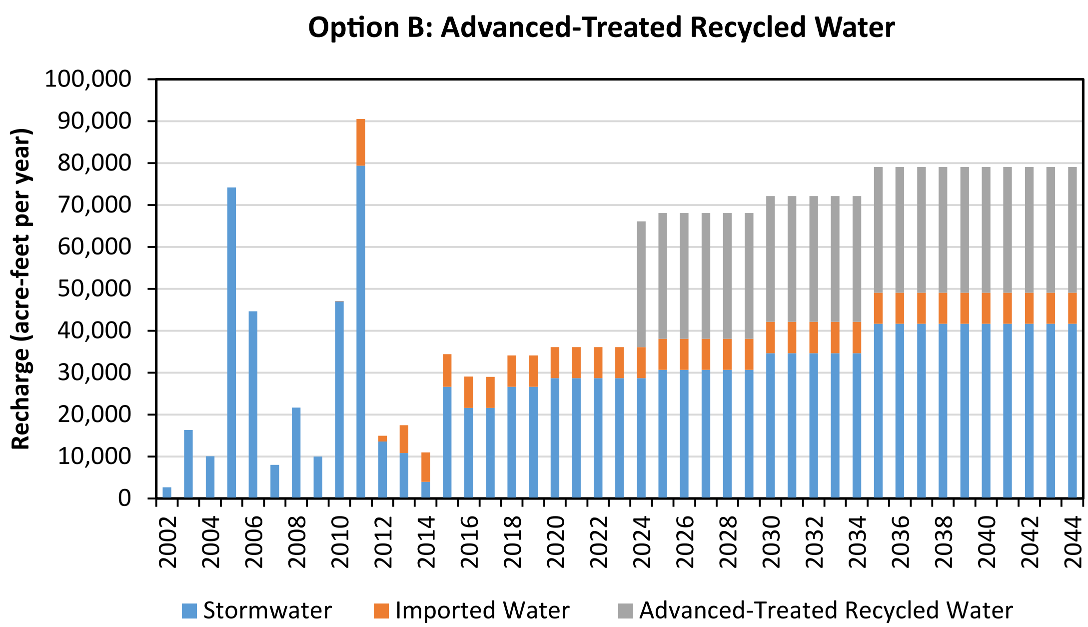
Constituent	EAG	NAR	SFE	SFW	SYL	TUJ	VER
TDS	301	414	327	270	269	270	494
Cl	70	74	63	59	58	59	80
N	0.55	1.51	1.39	0.50	0.68	0.50	3.7

April 2017

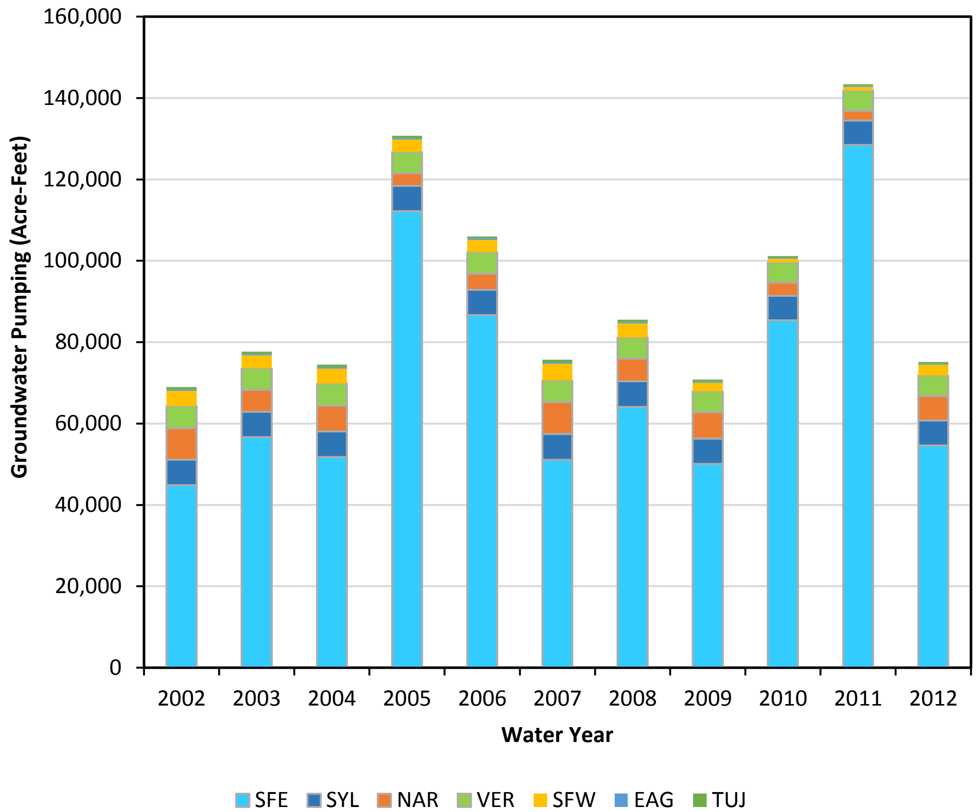
TODD GROUNDWATER

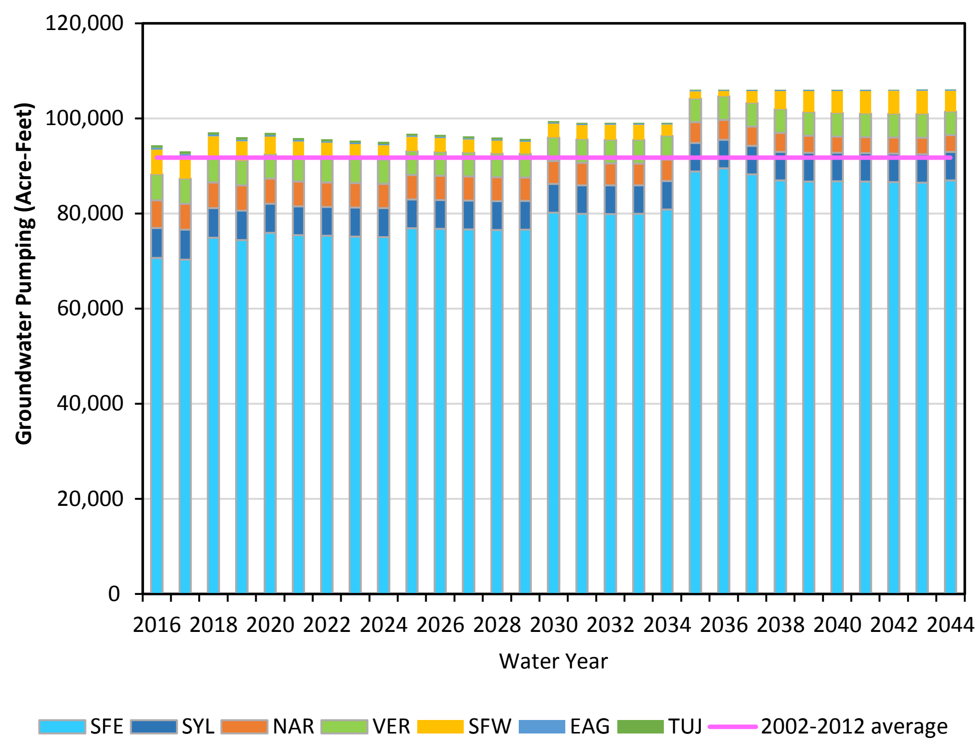
Figure 4
Measured and Projected Quality of Delivered Municipal Water





April 2017	**Figure 5**
TODD GROUNDWATER	**Sources of Recharge Water at Spreading Basins**

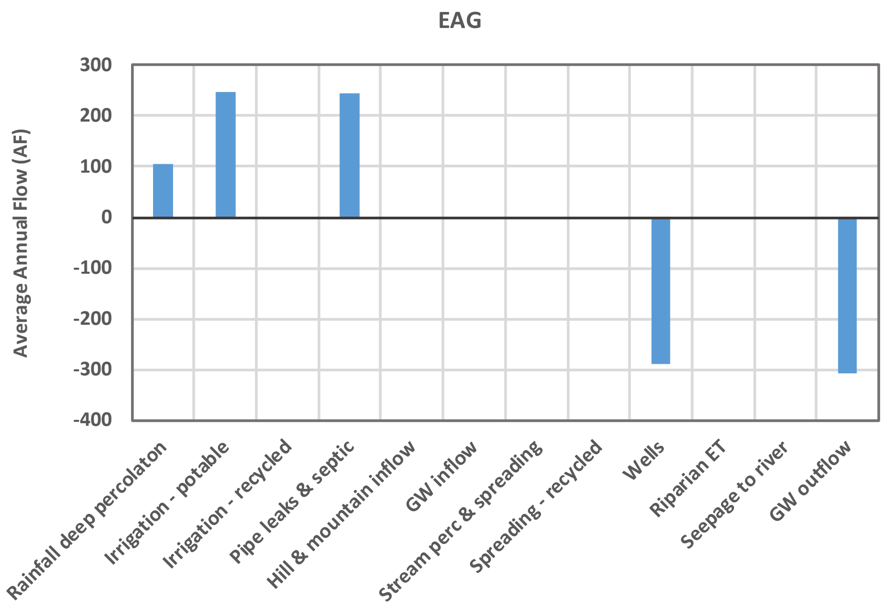


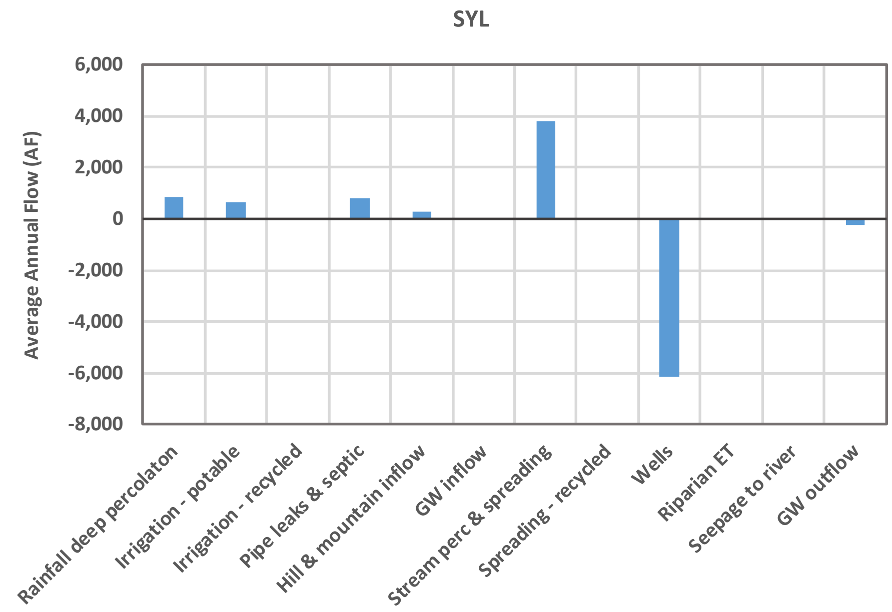


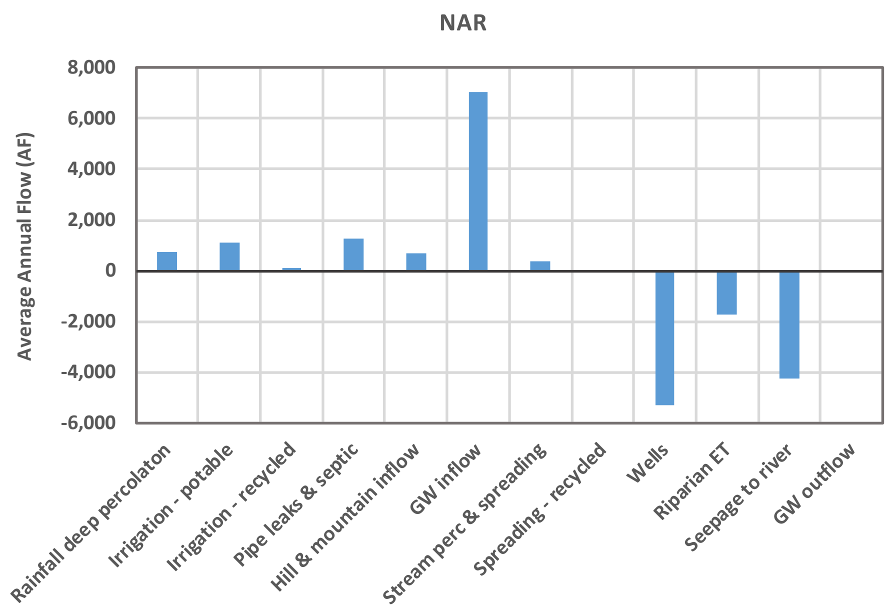
April 2017

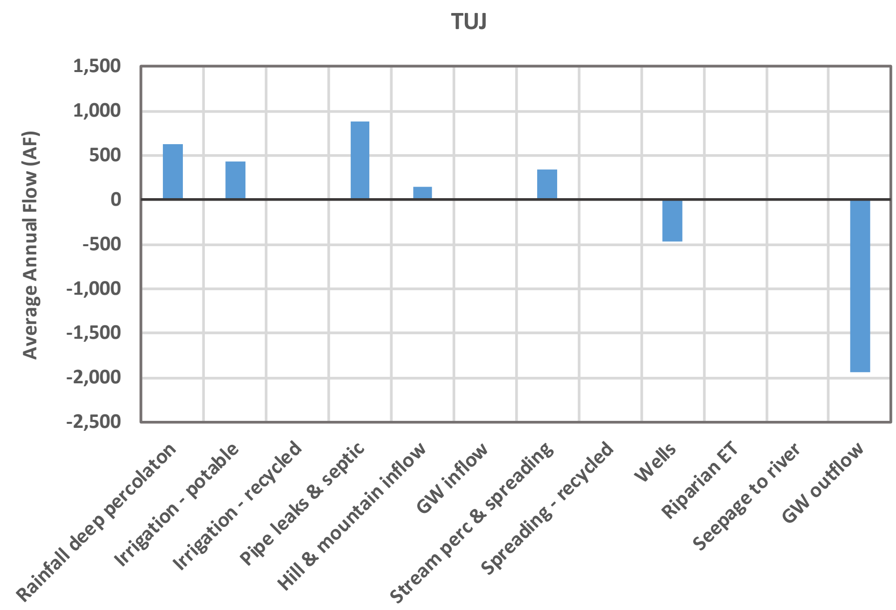
TODD GROUNDWATER

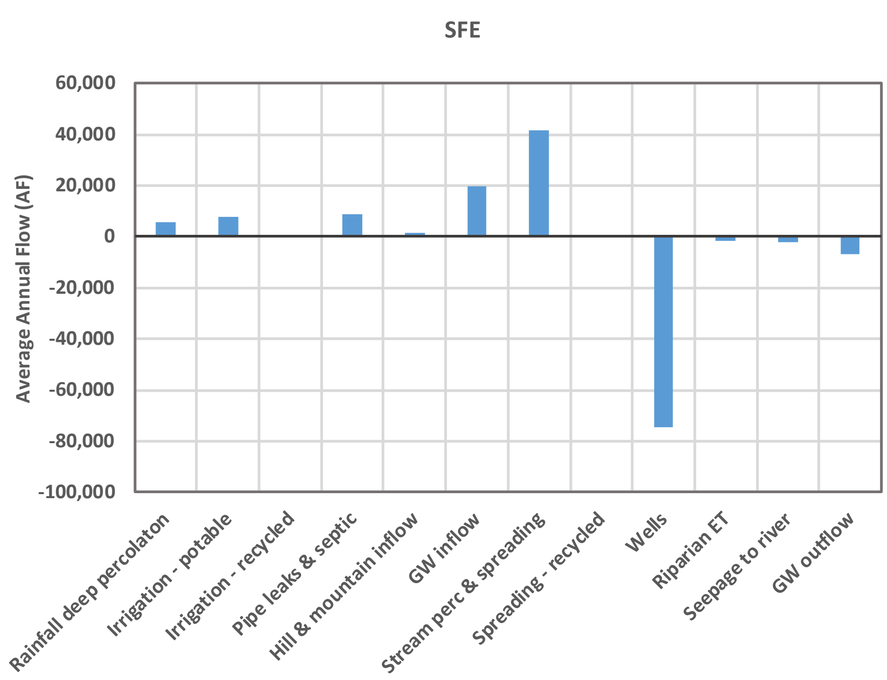
Figure 6
Annual Balanced Pumping for Calibration and Future Baseline Simulations

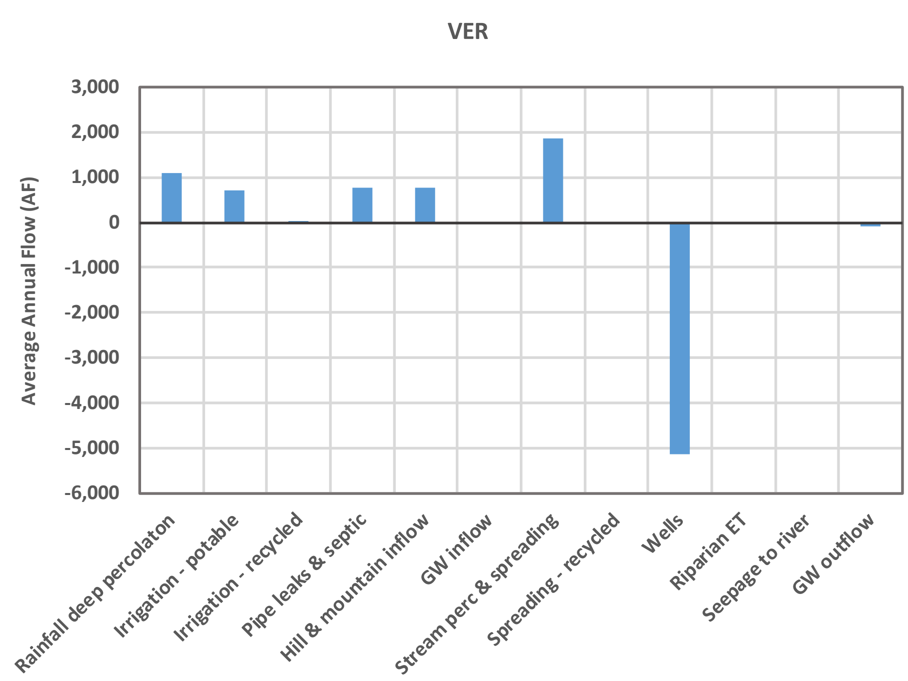


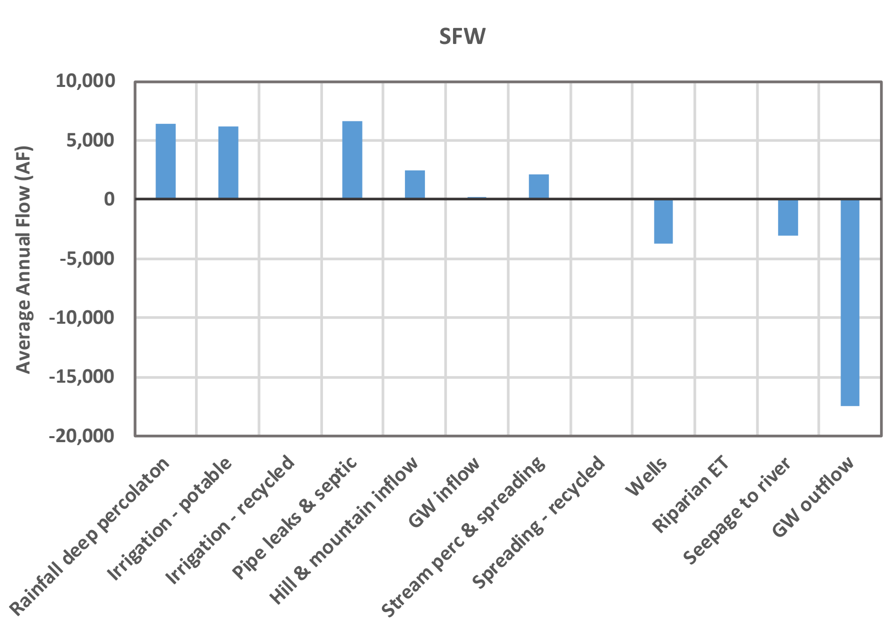




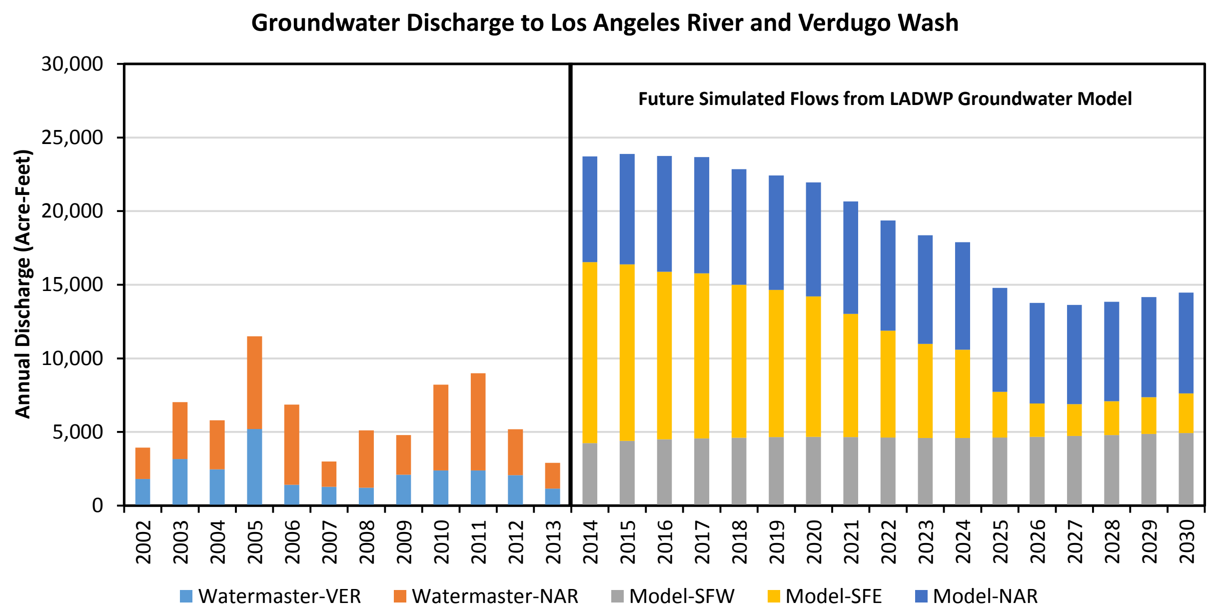


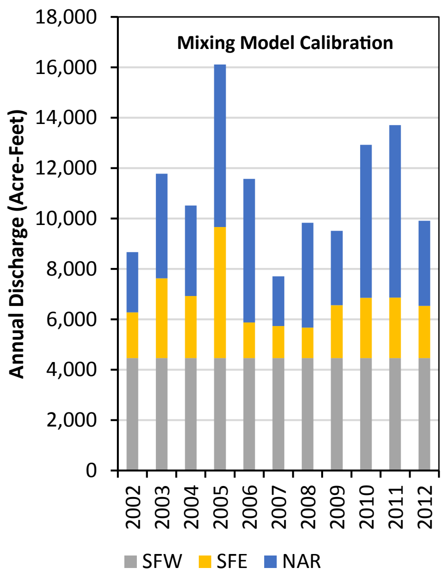






June 2017 TODD GROUNDWATER	**Figure 7** **Average Annual Water Balances, 2016 - 2025 for Future Baseline Scenario**





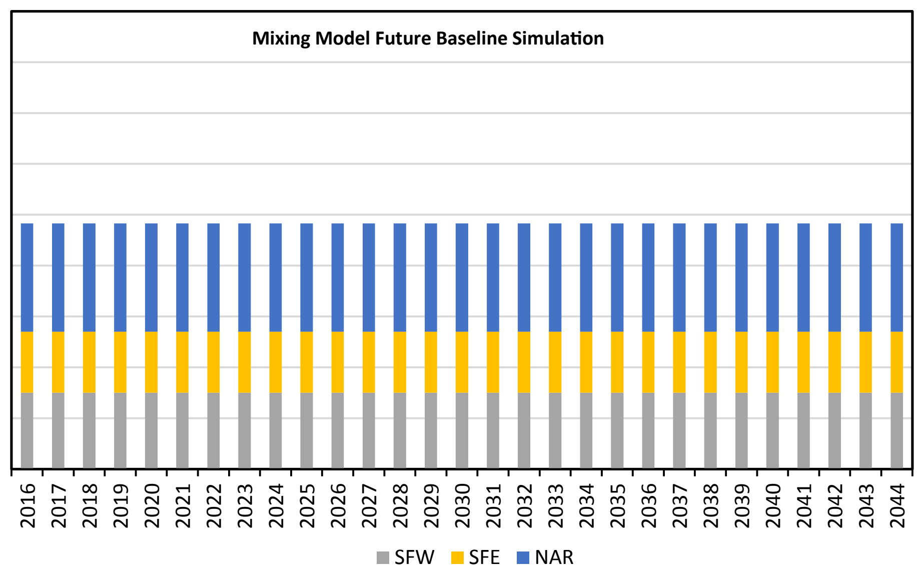


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Figure 8
Groundwater Seepage into Rivers and Creeks

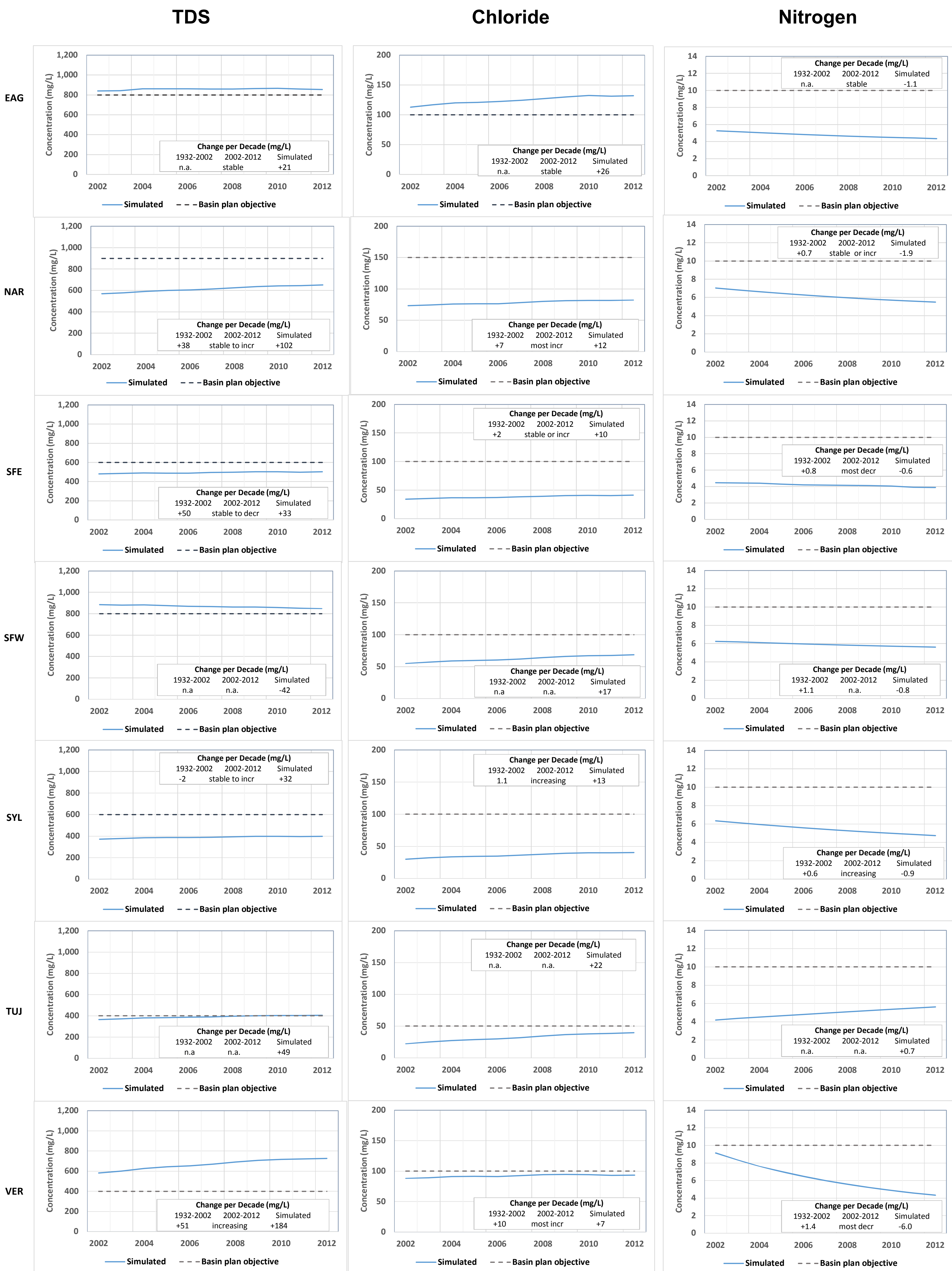

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Figure 9
Simulated Water Quality from 2002 - 2012 Calibration Simulation

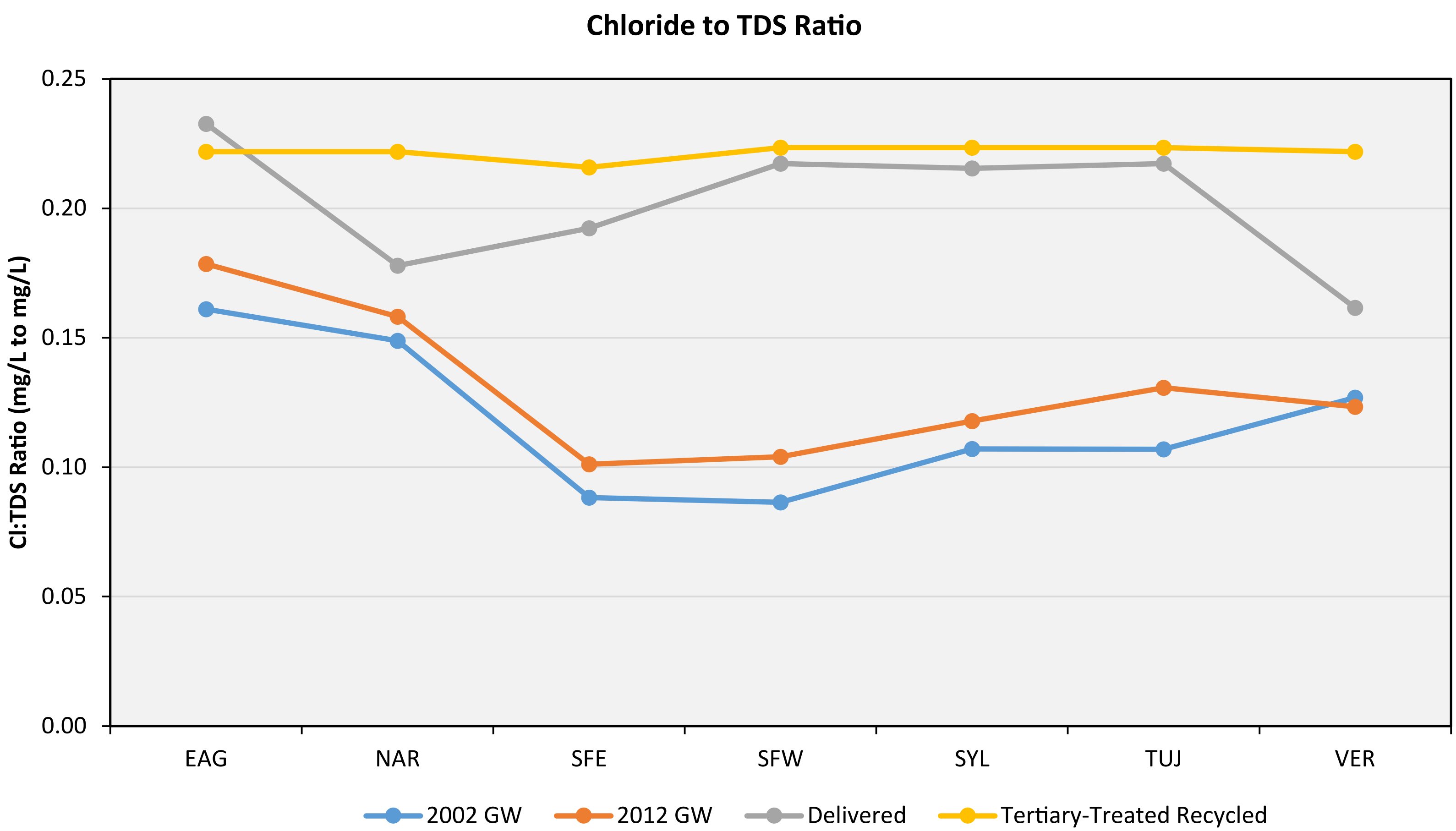

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Figure 10
Cl:TDS Ratios for Groundwater, Delivered Water and Recycled Water

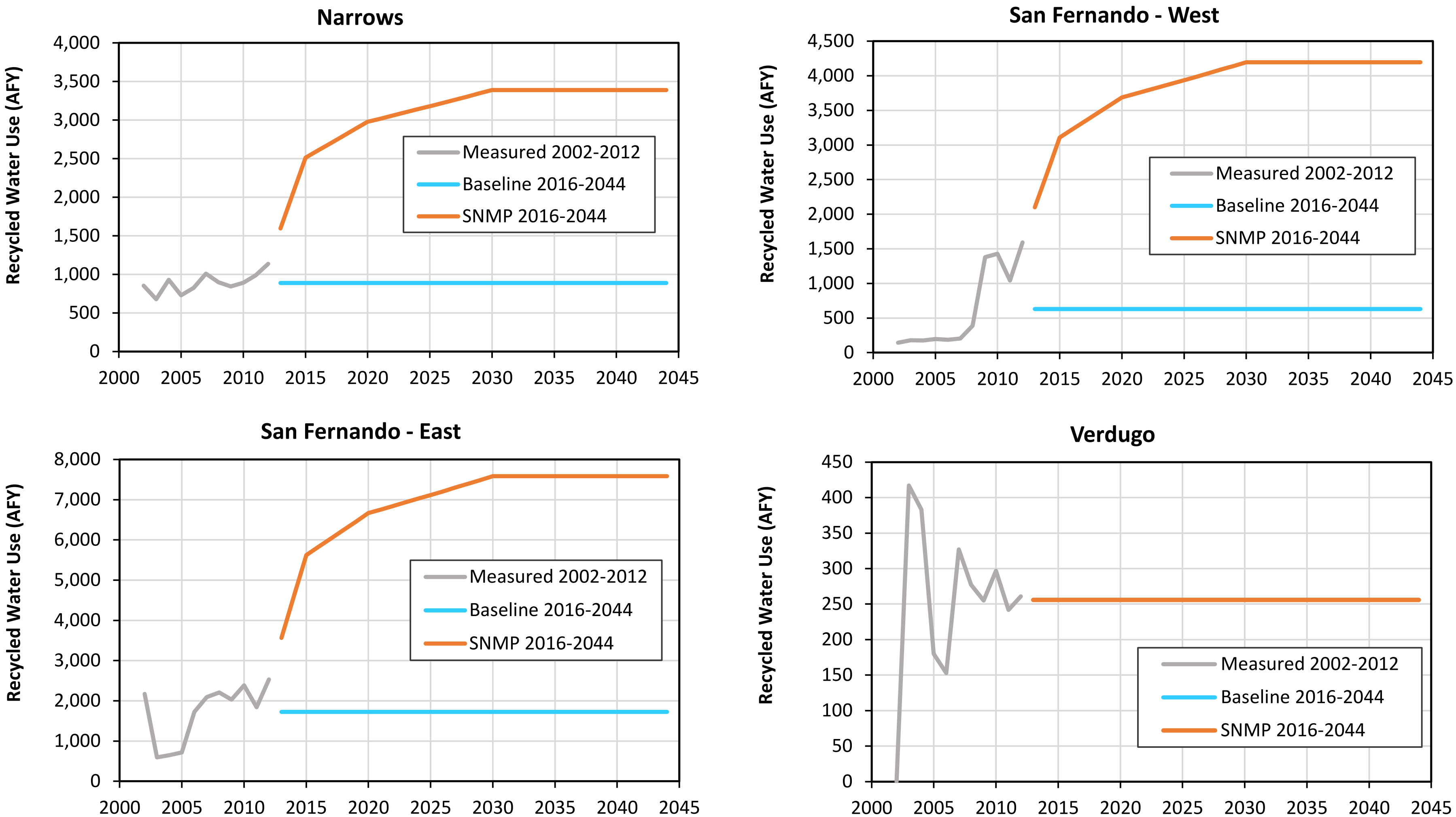

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Figure 11
Historical and Projected use of Recycled Water for Irrigation, 2002-2044

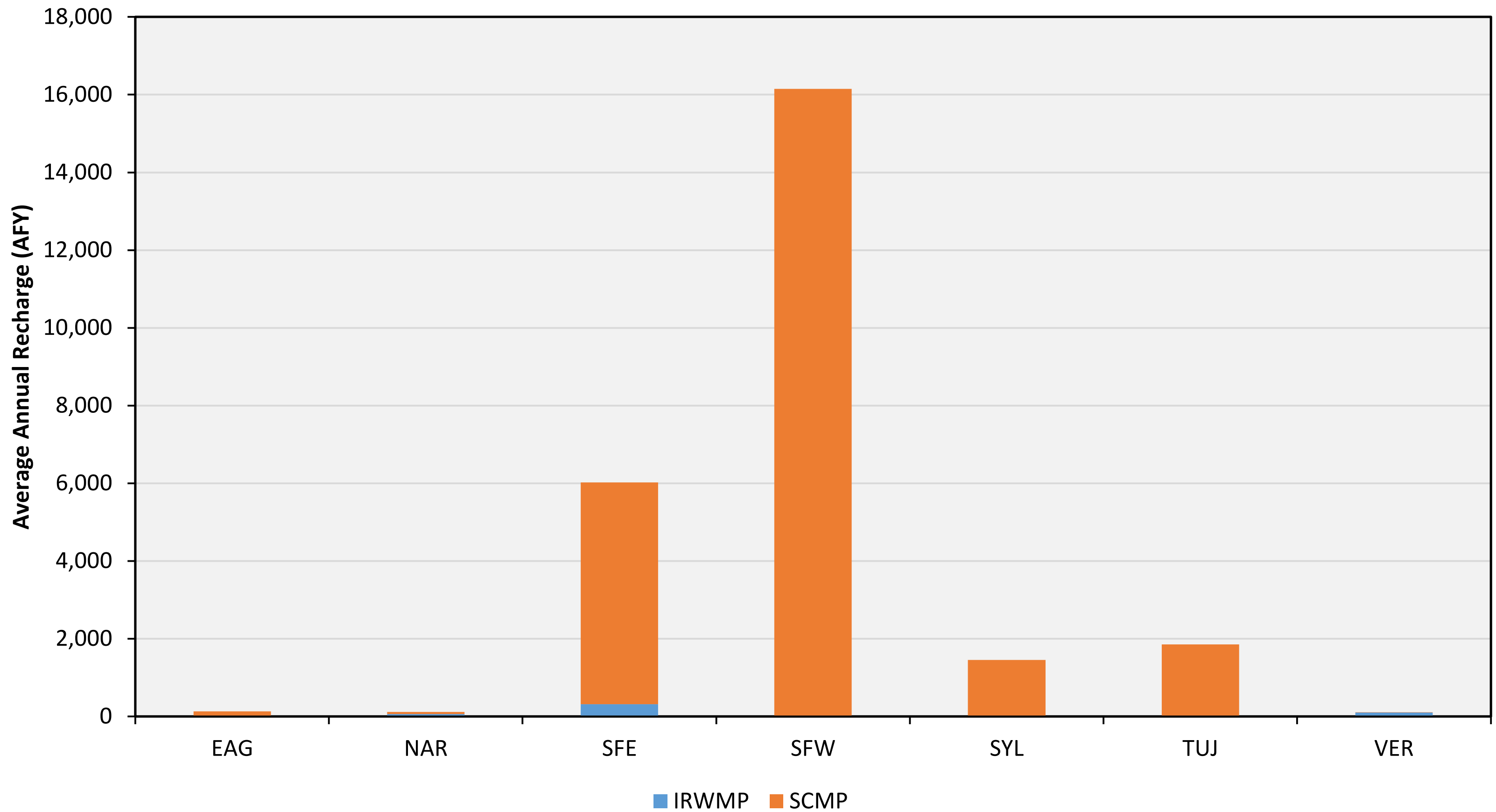

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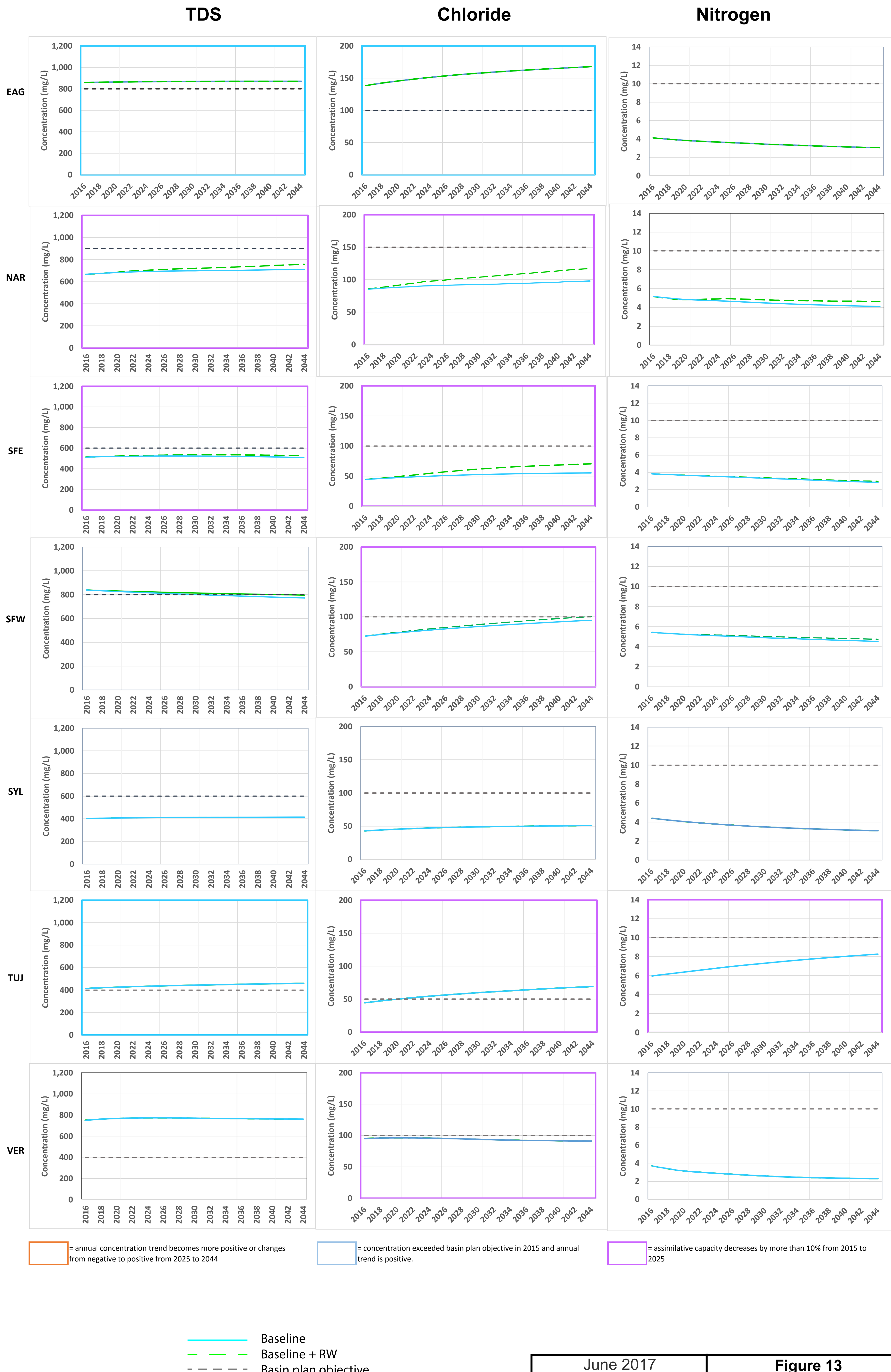
Figure 12
Dispersed Stormwater Recharge with SNMP Implementation



RW - tertiary-treated recycled water

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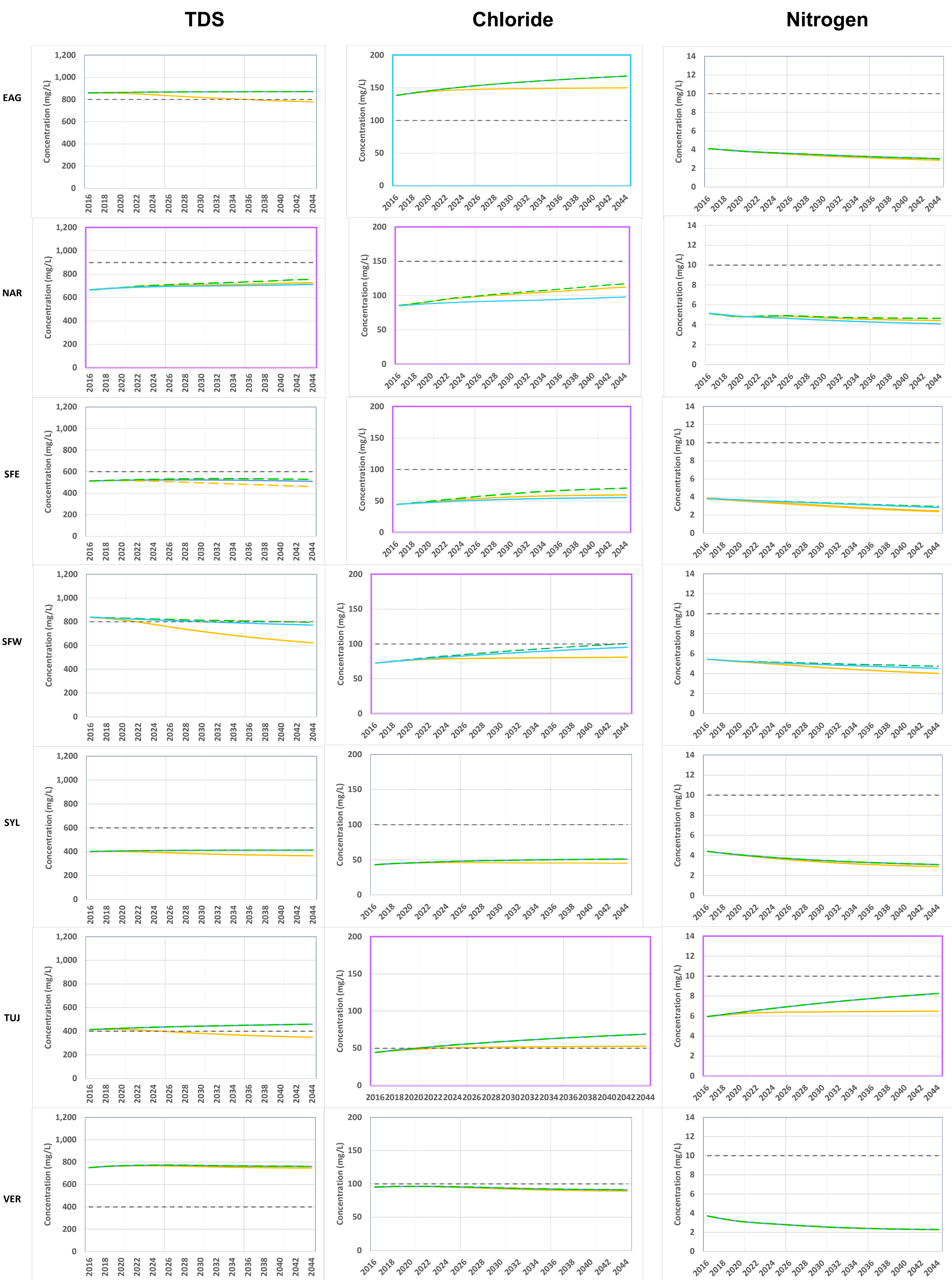
Figure 13
Simulation Results for the Baseline Plus RW Scenario



= annual concentration trend becomes more positive or changes from negative to positive from 2025 to 2044

= concentration exceeded basin plan objective in 2015 and annual trend is positive.

= assimilative capacity decreases by more than 10% from 2015 to 2025

Baseline
Baseline + RW
Basin plan objective
Baseline + RW + Aggressive SCMP

RW - tertiary-treated recycled water
SCMP - Stormwater Capture Master Plan

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Figure 14
Simulation Results for Full SNMP Implementation

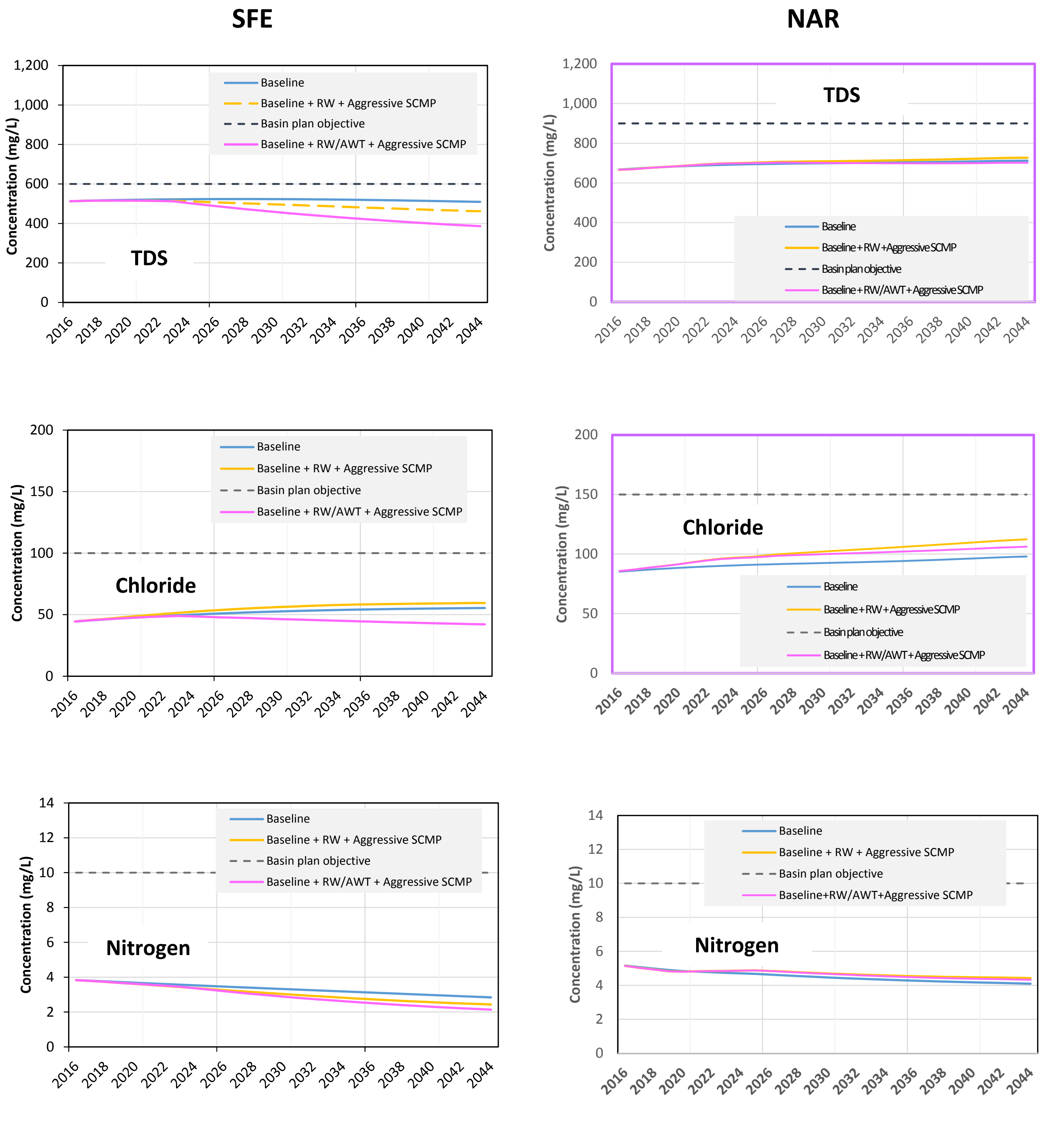

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Figure 15
Simulation Results in SFE and NAR for SNMP Implementation with AWT Option

APPENDIX A

Historical Water Quality Patterns and Trends

9.1. INTRODUCTION

TM-2 documented median concentrations of TDS, chloride and nitrogen in each subarea for 2002-2011 (the baseline period) and 1989-2015 (the “extended baseline” period). In order to obtain data for the SFW and TUJ subareas, TM-2 also used water quality data going back to 1950.

Groundwater quality evolves slowly in deep alluvial groundwater basins because average annual inflows and outflows are a small percentage of the total volume of groundwater in storage. For example, the water budgets and groundwater storage volumes developed for the modeling analysis indicate that the average residence time of groundwater in the seven subareas ranges from 45 years in VER to 219 years in SFW. Groundwater quality has a long memory, and current concentrations and trends reflect past decades and centuries of land and water use practices. For the purpose of detecting long-term patterns and trends relevant to the mixing model, additional historical water quality data were reviewed. Two advantages of using a longer analysis period are that older data sets sometimes had better spatial coverage than newer ones, and trends that might be obscured by local variability during the baseline period could be more obvious when viewed over substantially longer periods.

Available groundwater quality data are sometimes sparse and unevenly distributed in time and space. Estimates of average TDS, chloride and nitrogen concentrations for many of the subareas are spatially biased by clustering of data points in a small part of the subarea. Estimating long-term trends is hampered by the small number of years with data. Major data sources include tabulations of surface and groundwater quality measurements collected by the California Division of Water Resources in 1931-1932, a study of chloride sources entering the Los Angeles River (City of Los Angeles, 1993), and a compilation of water quality data for 1950-2015 from various state and federal databases by the ULARA Watermaster (TM-2). Additional interpretation of pre-development conditions was supported by an 1880 map of the San Fernando Valley (Hall, 1880). Median and average concentrations of TDS, chloride and nitrogen from each of those data sets are shown in **Table A-1**. With those data sources, the historical evolution of groundwater quality was broken into three periods described below.

9.2. PREDEVELOPMENT TO 1932

The 1931-1932 data reported in Bulletin 40 (California Division of Water Resources, 1933) have better spatial coverage than more recent data and are less influenced by prior land uses. **Figure A-1** shows maps of measured TDS, chloride and nitrate (as NO_3) from 1931-1932. This map reveals a spatial pattern of TDS that can be explained by geology and pre-development groundwater flow patterns. TDS in SFW tends to be highest along the southern edge of that region. **Figure A-2** shows a geologic map of the SNMP subareas and surrounding watersheds. Watersheds adjoining the eastern and northern regions are underlain by granitic rocks with low TDS and chloride. But the western and southwestern boundaries of SFW are bordered by Tertiary age marine rocks. Surface and subsurface inflow from those areas is higher in TDS and chloride, as noted in 1905 by Hamlin:

> “The western tributaries of Los Angeles River rise in Santa Susanna Mountains, which bound San Fernando Valley on the north, and in Santa Monica Mountains in the south. These streams are small, rarely reaching the eastern end of the valley. They flow over sandstones, shales, clays, etc. and are strongly impregnated with alkaline salts, in strong contrast to the pure water from the granitic range to the east.” (Hamlin, 1905)

Groundwater flow patterns under pre-development conditions forced the relatively saline water into a narrow band along the southern edges of SFW and SFE. Pre-development groundwater recharge was dominated by percolation from Pacoima and Big Tujunga Washes, resulting in predominantly north-to-south groundwater flow. **Figure A-3** shows a map of the San Fernando Valley in 1880 prepared by the

State Engineer (Hall, 1880). The prominence of the aforementioned washes and the sizes of their watersheds indicate that they contributed a lot of recharge. Groundwater discharge from the San Fernando Basin was to the Los Angeles River in the southeastern part of the basin. Also shown are inferred groundwater contour lines and flow directions consistent with this historical pattern of recharge and discharge. The predominantly north-to-south flow tended to push the high-TDS groundwater up against the south edge of the basin, from where it migrated east until it could discharge into the river.

9.3. 1932 TO 2002

More recent studies of water quality patterns confirmed that groundwater salinity tends to be highest along the south edge of the SFW and SFE regions (City of Los Angeles, 1993). **Figure A-4** shows chloride trends for six wells in the SFW and SFE regions during 1930-1990. The highest concentrations were consistently at the southernmost well (1N/15W-25D1, shown in purple). The second-highest concentrations are at the southeastern corner of SFE, where the saline smear along the south edge of the basin has mixed with fresher groundwater arriving from the north (well 1N/13W-19B1, shown in green).

Groundwater quality as of 2002 was estimated as the median of measured concentrations during 1987-2014 that were compiled by the Watermaster from state and federal databases. A map showing the locations of 100 wells with TDS, chloride and nitrogen data is shown in **Figure A-5**. Sampling was clustered around production wells and areas with specific management issues, and broad areas had no samples at all. Overall, the data are more spatially clustered than the 1931-1932 data. A comparison of median concentrations in 1987-2014 with median concentrations in 1931-1932 revealed that concentrations of all three constituents increased in almost all subareas, and the exceptions can be traced to data limitations. **Figure A-6** compares the two data sets. Two regions had no data at all for either the beginning or ending dates (EAG, TUJ), so their trends could not be estimated. The anomalous decreasing trend for TDS and chloride in SFW almost certainly results from geographic sampling bias in the recent data: all the measurements were from a single cluster of wells that apparently were in a low-salinity part of SFW. The trends for SYL are also questionable, because TDS and chloride normally move in the same direction and in that subarea they had opposite trends. The remaining subareas exhibited consistent trends for all three constituents, and the ranges of those trends were used for mixing model calibration: increases of 38-52 mg/L per decade for TDS, 1-10 mg/L per decade for chloride, and 0.6-1.3 mg/L per decade for nitrogen.

9.4. 2002 TO 2012

The 70-year period from 1932 to 2002 reveals long-term trends more clearly than data from the most recent 10-year period. Nevertheless, SNMPs normally use the most recent decade to determine “existing” trends. A statistical analysis of trends during 2002-2012 and 1989-2015 was completed for TM-2, and a summary is shown in **Table A-2**. Sample sizes were mostly small—as few as one data point—so it was not possible to quantitatively evaluate trends by regression analysis. Even in regions with relatively abundant data (44 data points in SFE), there commonly was substantial disparity among trends for individual wells. This local variability underscores the difficulties and limitations of evaluating water quality impacts on the basis of broad spatial averages. Another limitation of the data set for 2002-2012 is that it contains no information for SFW or TUJ.

9.5. HISTORICAL DATA SUMMARY AND CONCLUSIONS

In addition to the historical statistics, **Table A-1** includes “best estimates” of median and average concentrations for 2002, which is the starting point for the mixing model calibration period. In most cases, data from the 2002-2012 data set were considered the best estimate. For SFW, the average of the 1931-1932 and 1987-2014 data sets was selected, to balance their respective temporal and geographic biases. For TUJ, the 1950-1980 values were used, which are the most recent data available and are based on a reasonable number of samples.

Several conclusions can be drawn from this review of historical water quality data that have ramifications for calibrating and interpreting the water quality model. First, groundwater quality is not uniform throughout individual SNMP subareas in contrast to the assumption of complete mixing in the water quality model. Estimating a median or average using sparse data—which is the case for almost all of the regions—is highly unreliable. Where data are more abundant, the variability in the data is large relative to the mean or median. This poses challenges for estimating assimilative capacity at a regional scale and for interpreting future changes in water quality at individual wells. Second, current water quality patterns reflect historical influences stretching back over decades to centuries. Water quality could continue to get worse for many years even after introducing measures that will eventually improve it. Finally, water quality trends can result from changes in groundwater flow directions even if there is no change in loading. For example, **Figure A-7** shows groundwater contours and flow directions for spring 2013 developed by the Watermaster (2014). Since 1880, when groundwater flow was predominantly north-to-south (**Figure A-3**), groundwater flow has become primarily west-to-east due to pumping in SFE and decreased recharge from the concrete-lined Pacoima and Big Tujunga Washes. Thus, it is likely that relatively saline groundwater along the south edge of the basin is now able to spread farther north as it migrates east. This could result in increasing trends in TDS and chloride unrelated to land use or salt loading of the basin.

TABLES

Table A-1. Summary of Historical Groundwater Quality Data

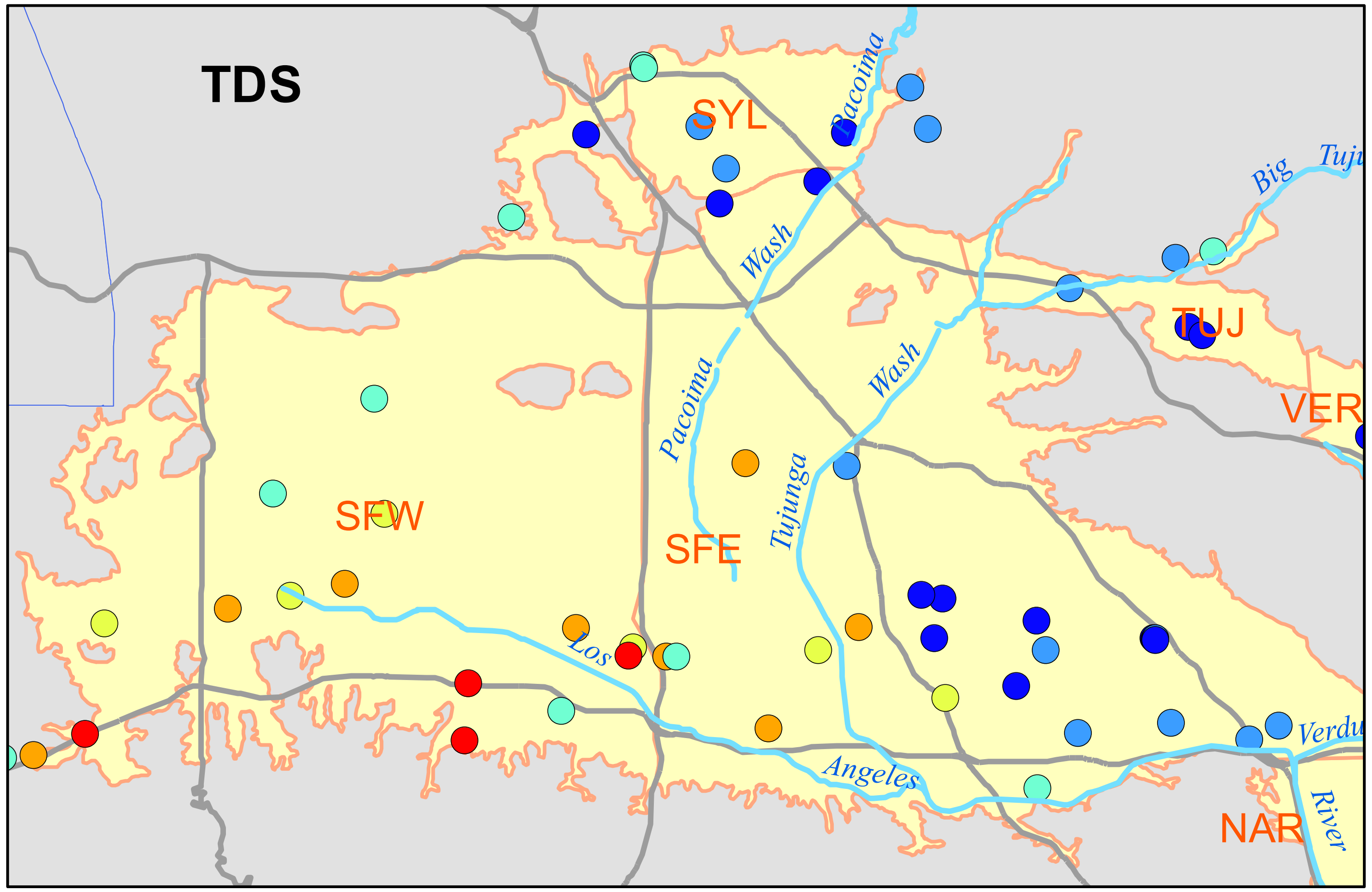
Basin/Subbasin	No. of Wells	TDS (mg/L)		Chloride (mg/L)		NO_3-N (mg/L)	
		Median	Average	Median	Average	Median	Average
1931-1932 Data from DWR Bulletin 40							
Eagle Rock	0	--	--	--	--	--	--
Narrows	1	272	272	21	21	2.5	2.5
SF-East	21	357	534	28	33	1.8	2.3
SF-West	20	1,068	1,277	72	104	2.5	3.0
Sylmar	8	378	403	22	22	2.0	2.8
Tujunga	4	434	401	14	13	0.5	0.5
Verdugo	4	179	180	9	9	1.2	1.2
GAMA Database (1950-1980)							
SF-West	18	1,063	1,096	52	64	4.2	3.8
Tujunga	10	359	445	19	23	4.0	5.7
All Years Compiled by Watermaster (1987-2014)							
Eagle Rock	1	838	836	106	80	5.2	5.1
Narrows	6	538	557	68	74	7.5	6.3
SF-East	68	372	526	18	35	3.8	5.7
SF-West	3	706	768	33	32	10.2	6.2
Sylmar	6	365	360	28	28	6.3	6.0
Tujunga	0	--	--	--	--	--	--
Verdugo	16	535	545	82	86	10.4	10.1
2002-2012 Data Compiled by Watermaster							
Eagle Rock	1	836	835	108	72	5.4	5.3
Narrows	6	554	568	71	72	7.3	6.3
SF-East	68	473	534	33	34	4.5	5.0
SF-West	3	--	--	--	--	--	--
Sylmar	6	367	375	28	28	6.6	6.3
Tujunga	0	--	--	--	--	--	--
Verdugo	16	550	564	86	88	10.0	9.4
Best Estimate for Natural (pre-development) Ambient Groundwater Quality							
Eagle Rock	n.a.	838	836	106	80	5.2	5.1
Narrows	n.a.	272	272	21	21	2.5	2.5
SF-East	n.a.	357	534	28	33	1.8	2.3
SF-West	n.a.	1,068	1,277	72	104	2.5	3.0
Sylmar	n.a.	378	403	22	22	2.0	2.8
Tujunga	n.a.	434	401	14	13	0.5	0.5
Verdugo	n.a.	179	180	9	9	1.2	1.2
Best Estimate for 2002 Ambient Groundwater Quality							
Eagle Rock	n.a.	836	835	108	72	5.4	5.3
Narrows	n.a.	554	568	71	72	7.3	6.3
SF-East	n.a.	473	534	33	34	4.5	5.0
SF-West	n.a.	887	1,023	53	68	6.3	4.6
Sylmar	n.a.	367	375	28	28	6.6	6.3
Tujunga	n.a.	359	445	19	23	4.0	5.7
Verdugo	n.a.	550	564	86	88	10.0	9.4

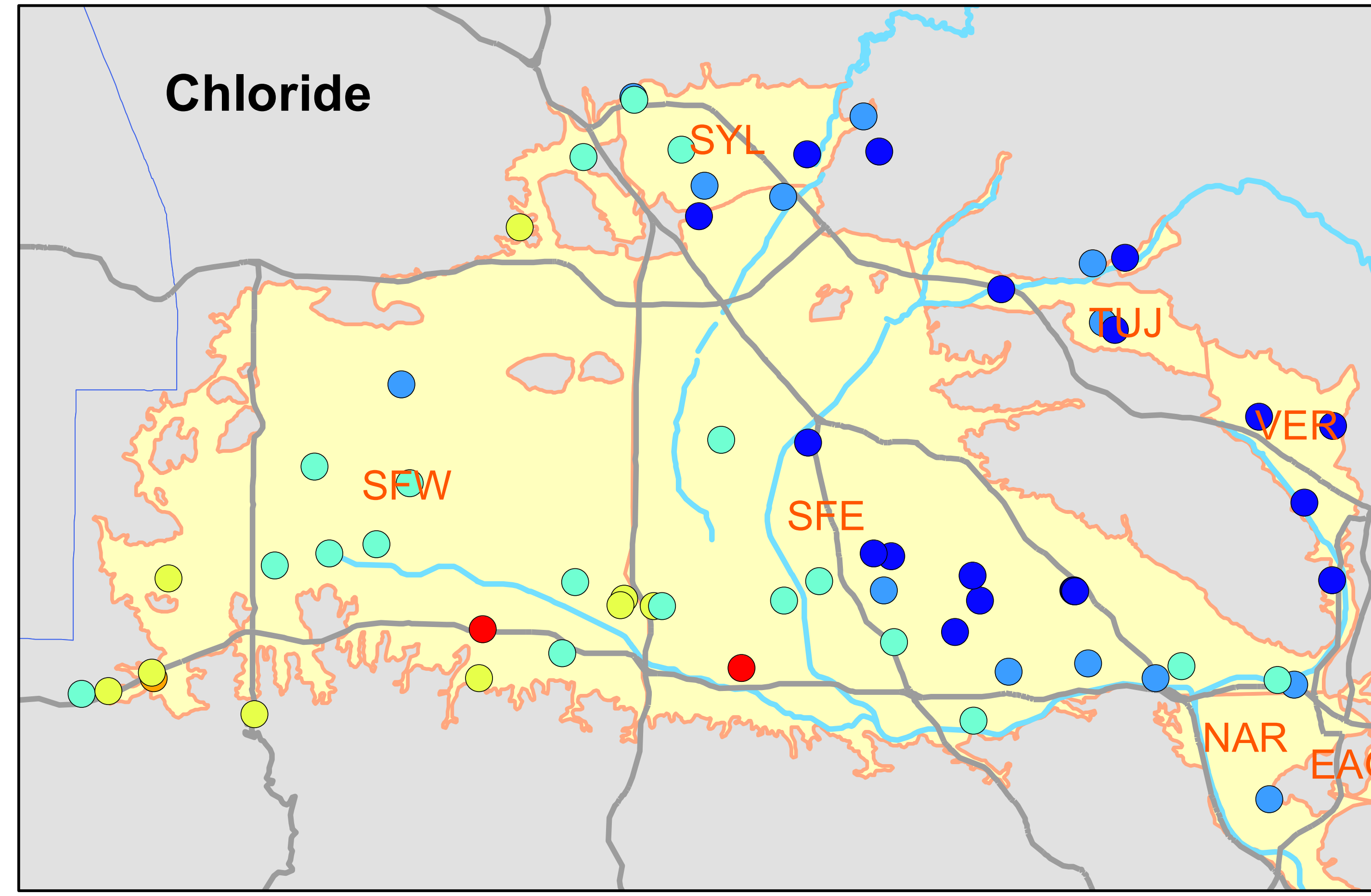
TDS = total dissolved solids; mg/L = milligrams per liter; NO_3-N = nitrate as nitrogen

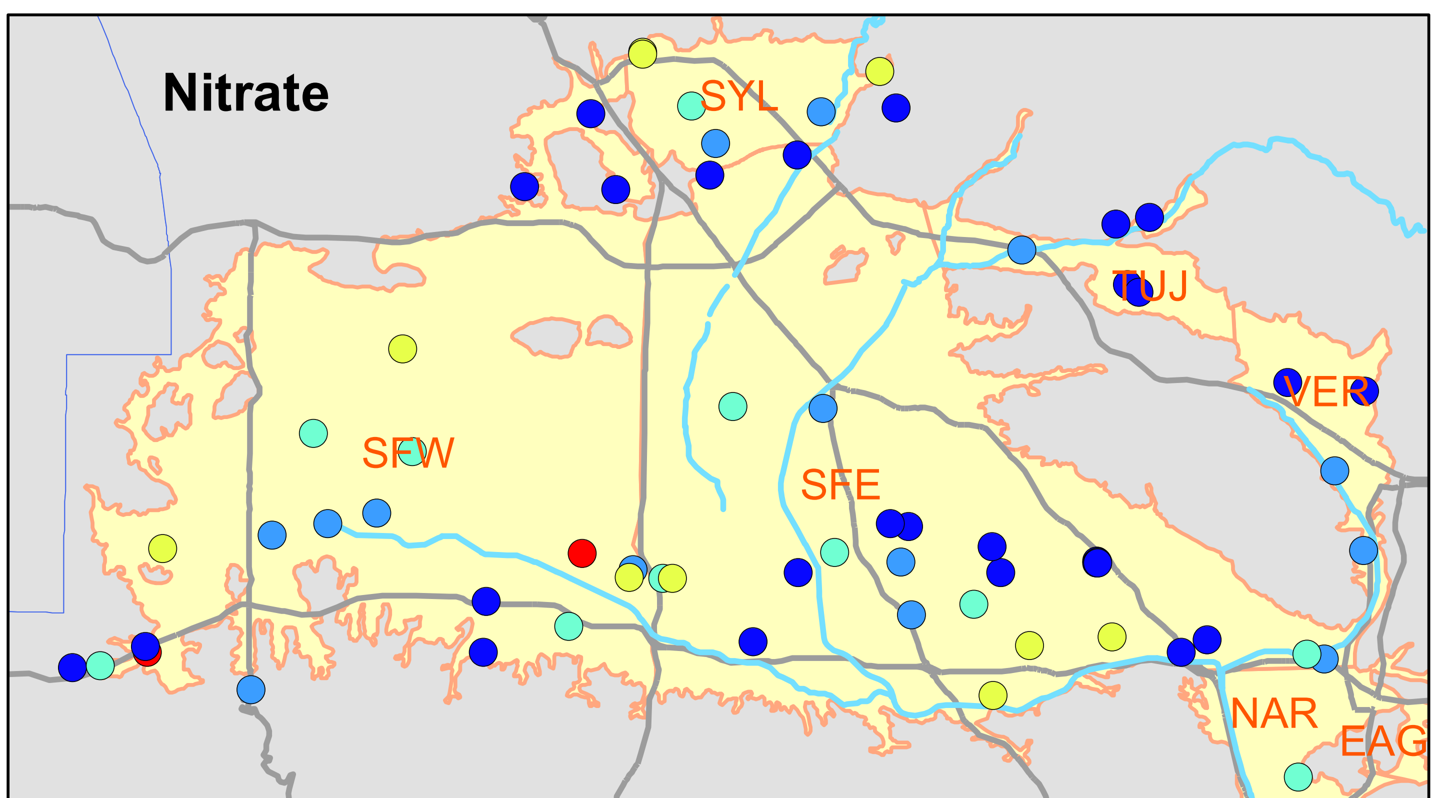
Table A-2. Summary of Recent Groundwater Quality Trends

Trend	Total Dissolved Solids				Chloride				Nitrate			
	1987-2014		2002-2012		1987-2014		2002-2012		1987-2014		2002-2012	
	No. of Wells	Percentage	No. of Wells	Percentage	No. of Wells	Percentage	No. of Wells	Percentage	No. of Wells	Percentage	No. of Wells	Percentage
	Eagle Rock											
Increasing	0	0%	--	--	0	0%	--	--	0	0%	--	--
Decreasing	0	0%	--	--	0	0%	--	--	0	0%	--	--
Stable	1	100%	--	--	1	100%	--	--	1	100%	--	--
	Narrows											
Increasing	2	25%	0	0%	6	75%	4	57%	1	13%	2	25%
Decreasing	0	0%	0	0%	0	0%	0	0%	4	50%	3	38%
Stable	6	75%	7	100%	2	25%	3	43%	3	38%	3	38%
	San Fernando - East											
Increasing	16	25%	6	12%	24	34%	13	25%	7	11%	8	11%
Decreasing	4	6%	5	10%	7	10%	3	6%	42	66%	42	59%
Stable	44	69%	38	78%	39	56%	35	69%	15	23%	21	30%
	San Fernando - West											
Increasing	--	--	--	--	--	--	--	--	--	--	--	--
Decreasing	--	--	--	--	--	--	--	--	--	--	--	--
Stable	--	--	--	--	--	--	--	--	--	--	--	--
	Sylmar											
Increasing	4	67%	0	0%	3	50%	4	100%	6	100%	6	100%
Decreasing	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
Stable	2	33%	4	100%	3	50%	0	0%	0	0%	0	0%
	Tujunga											
Increasing	--	--	--	--	--	--	--	--	--	--	--	--
Decreasing	--	--	--	--	--	--	--	--	--	--	--	--
Stable	--	--	--	--	--	--	--	--	--	--	--	--
	Verdugo											
Increasing	12	80%	5	36%	11	69%	7	50%	1	6%	2	11%
Decreasing	2	13%	1	7%	0	0%	0	0%	13	72%	12	67%
Stable	1	7%	8	57%	5	31%	7	50%	4	22%	4	22%

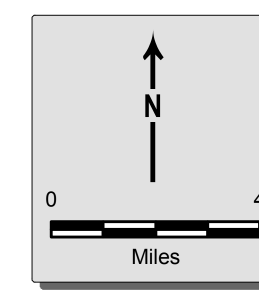
FIGURES







	TDS	Cloride	Nitrate
	1,500-2,000	120-150	40-50
	1,000-1,500	90-120	30-40
	750-1,000	60-90	20-30
	500-750	30-60	10-20
	250-500	15-30	5-10
	0-250	0-15	0-5



Median Concentration in Milligrams per Liter

April 2017

TODD GROUNDWATER

Figure A-1
Groundwater Quality
in 1931-1932

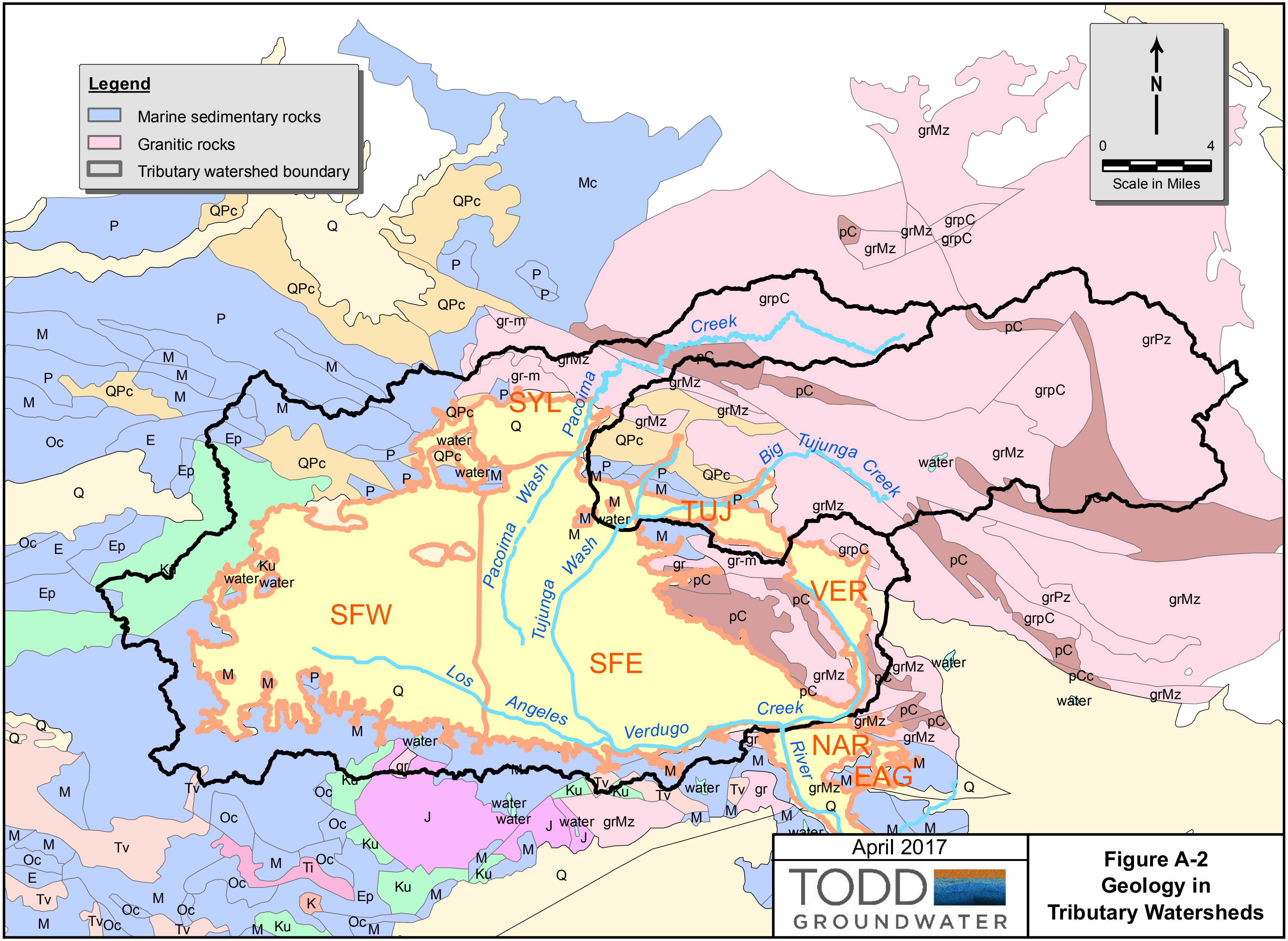


Figure A-2
Geology in Tributary Watersheds

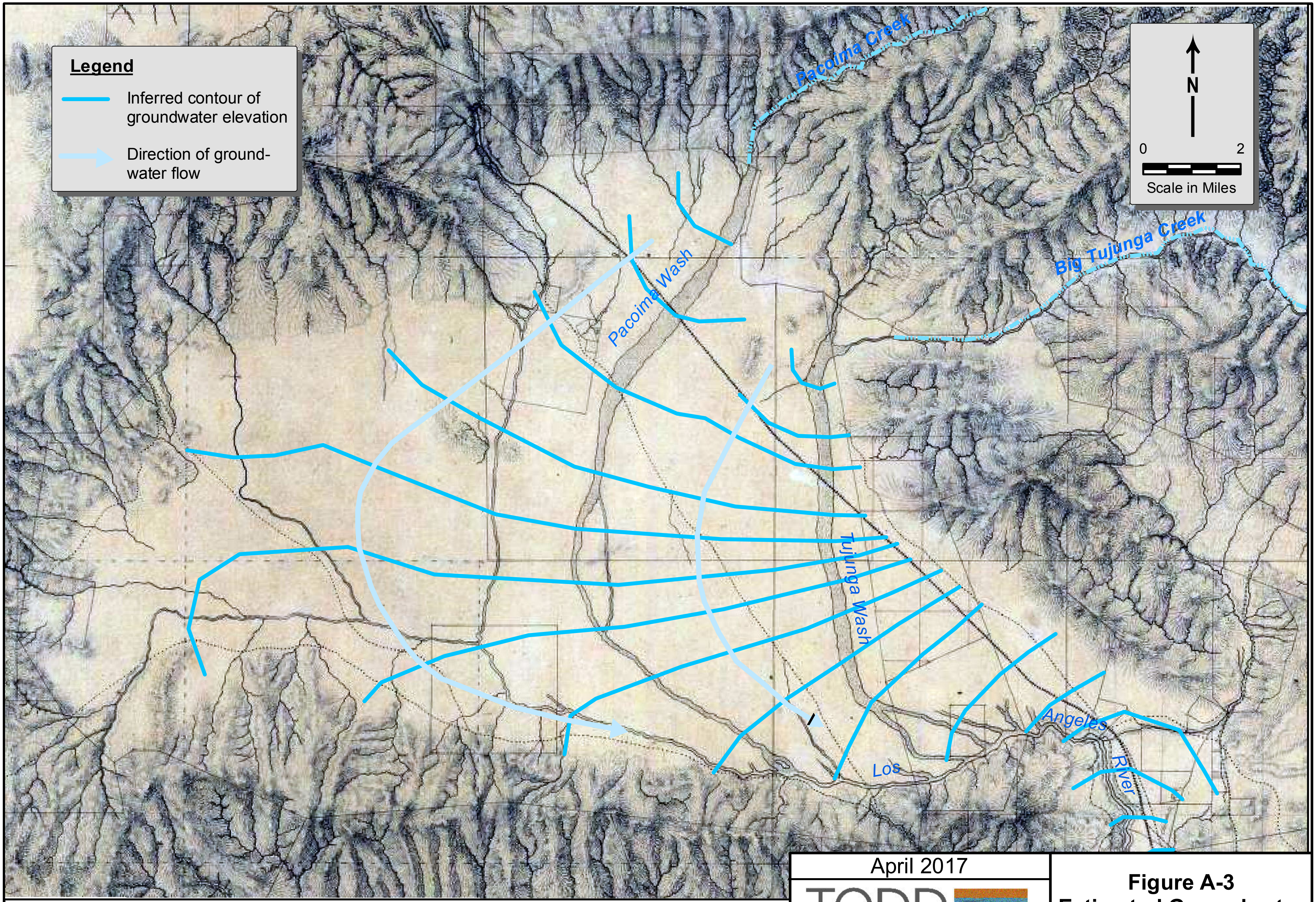


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Figure A-3
Estimated Groundwater Flow Conditions in 1880

Base map from Hall (1880)

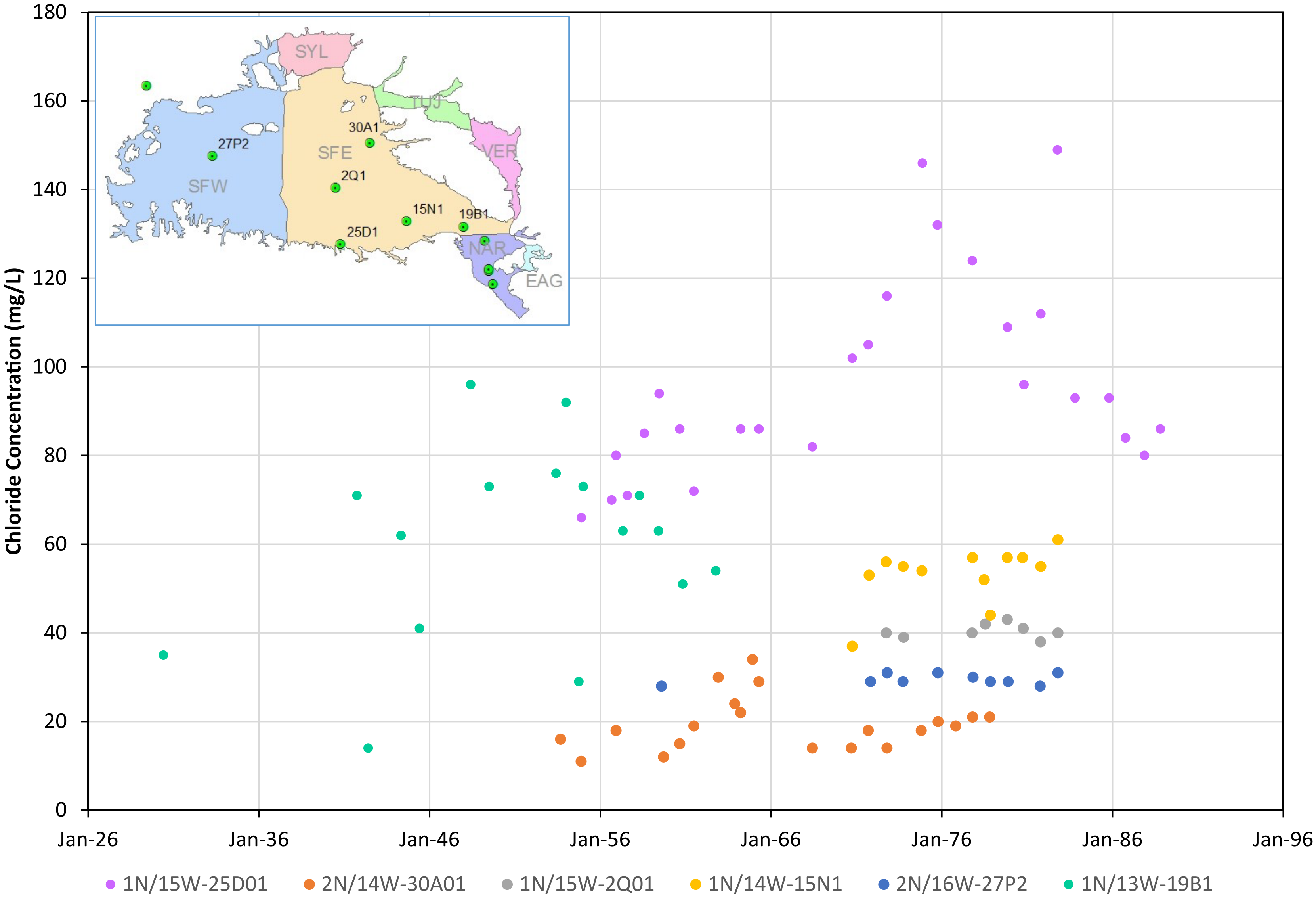

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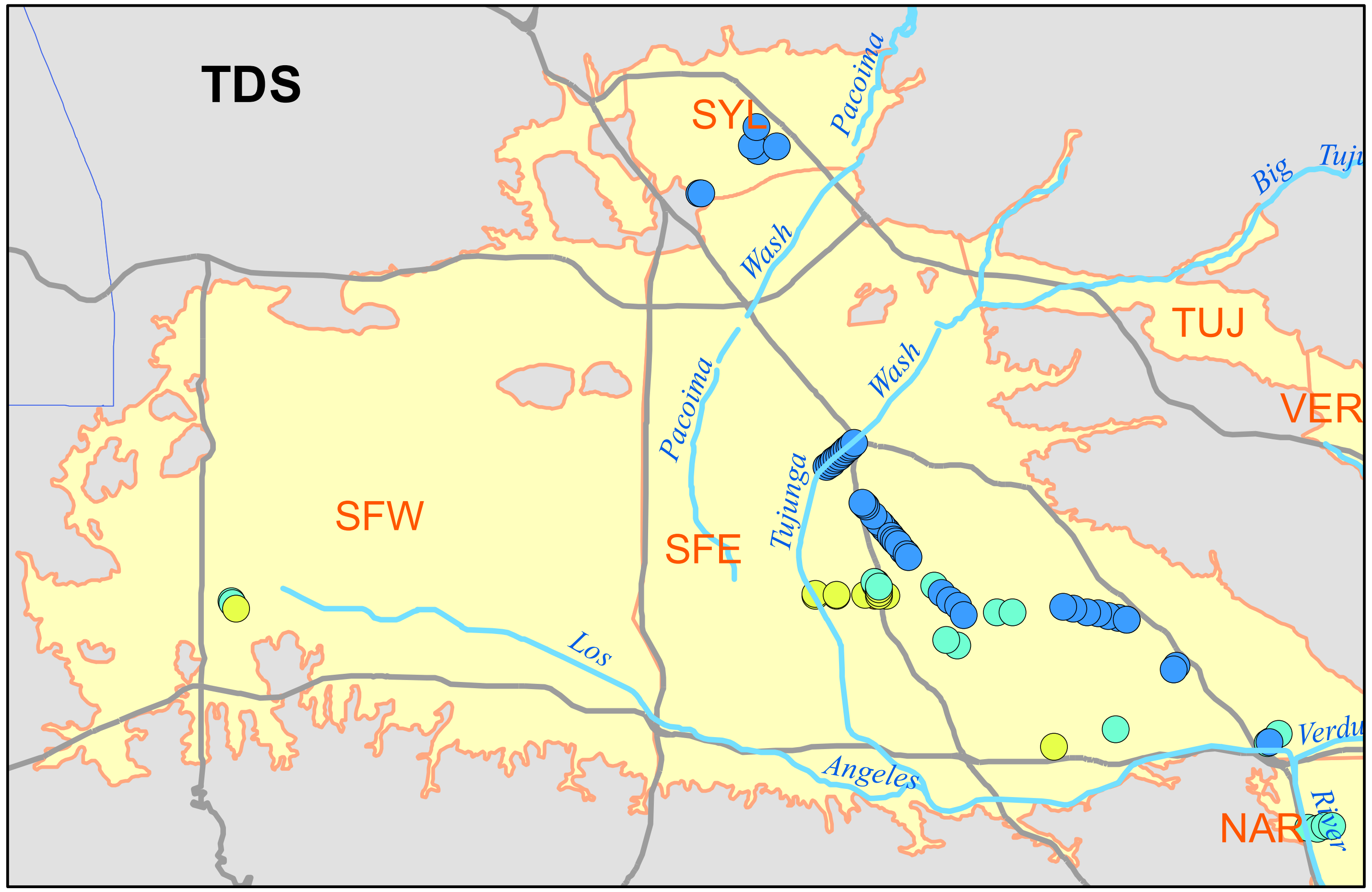
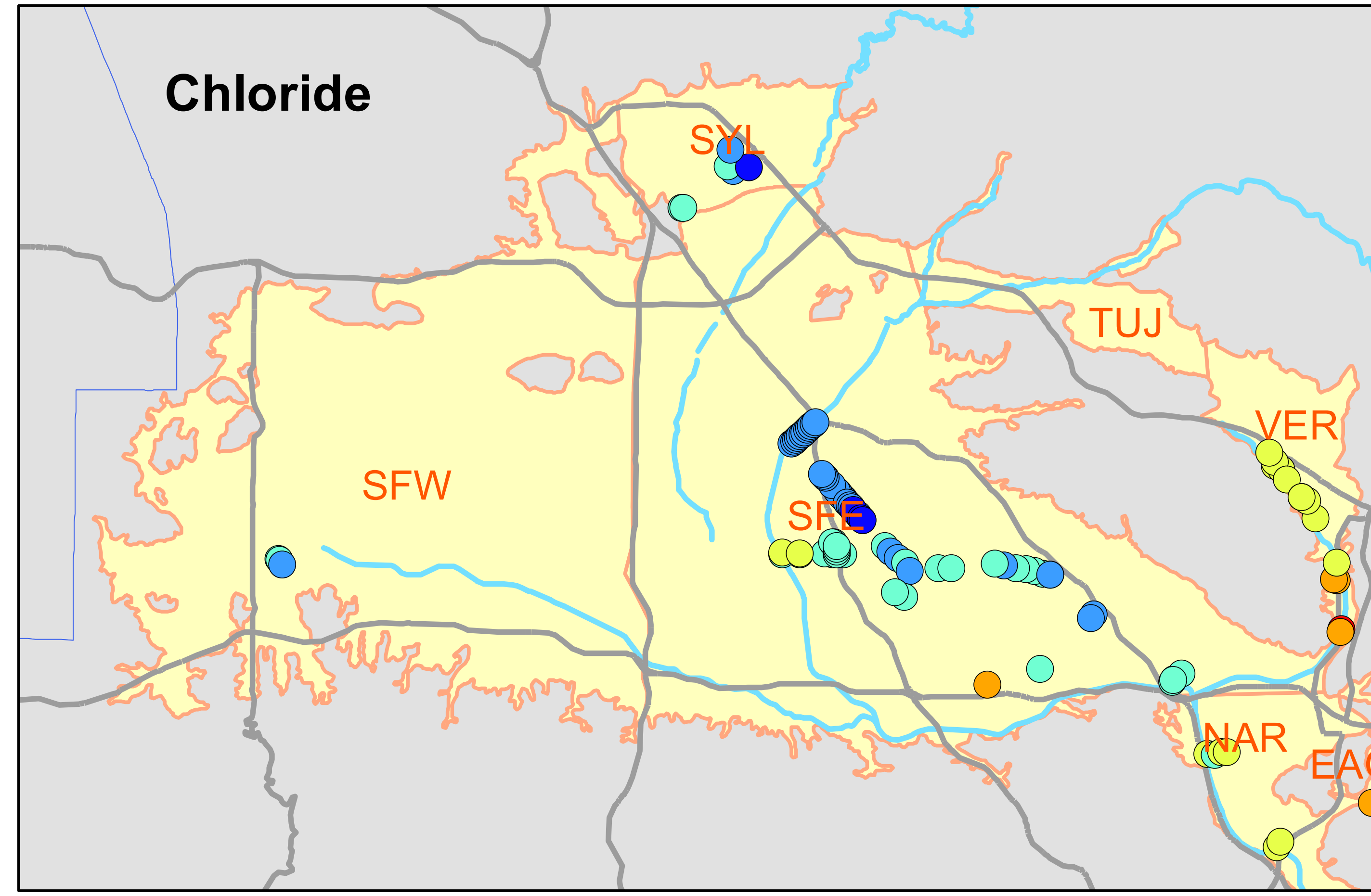
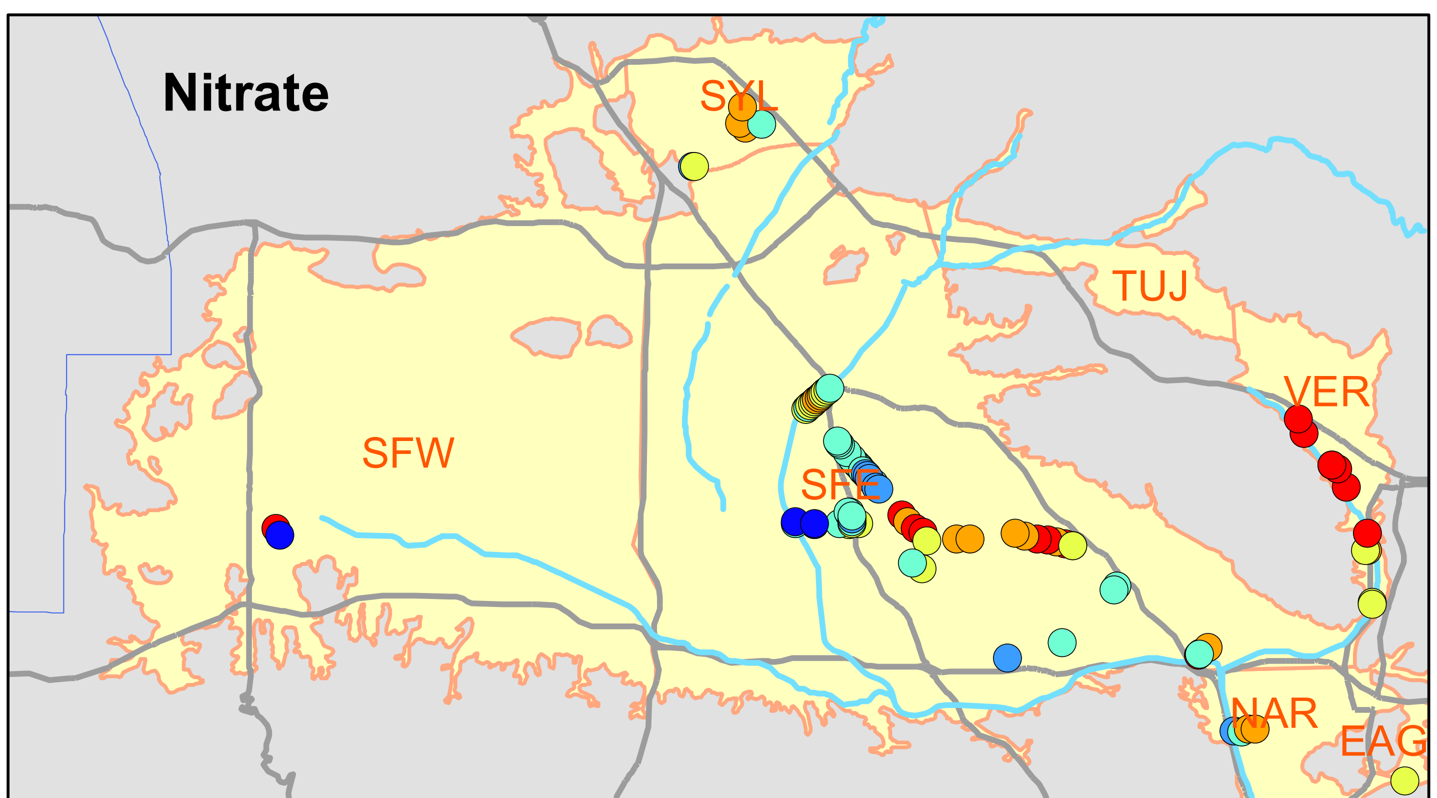
Figure A-4
Chloride Trends in Groundwater 1930 - 1990







	TDS	Cloride	Nitrate
● (red)	1,500-2,000	120-150	40-50
● (orange)	1,000-1,500	90-120	30-40
● (yellow)	750-1,000	60-90	20-30
● (light green)	500-750	30-60	10-20
● (light blue)	250-500	15-30	5-10
● (dark blue)	0-250	0-15	0-5

Median Concentration in Milligrams per Liter

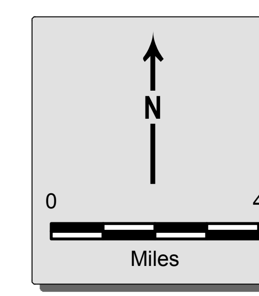


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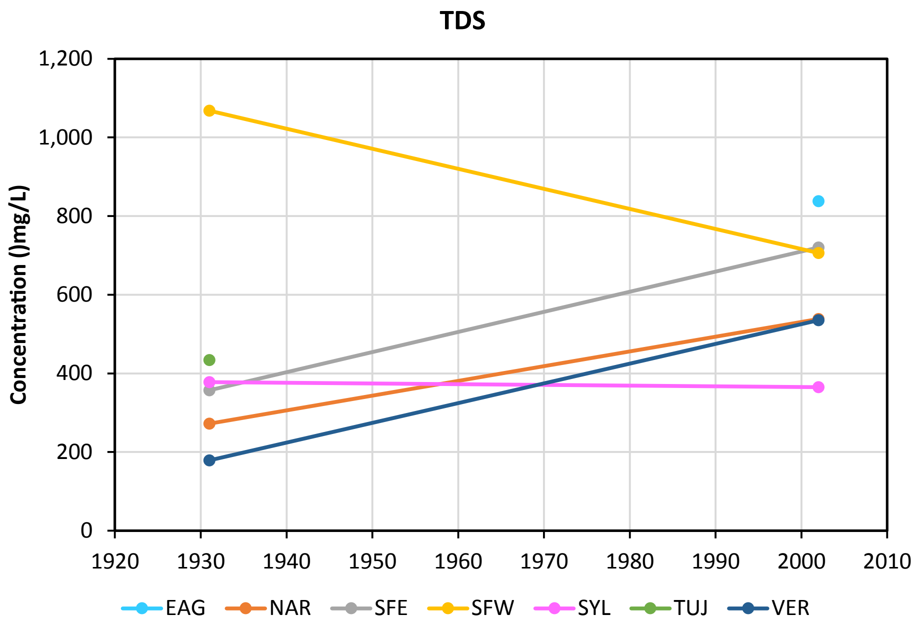
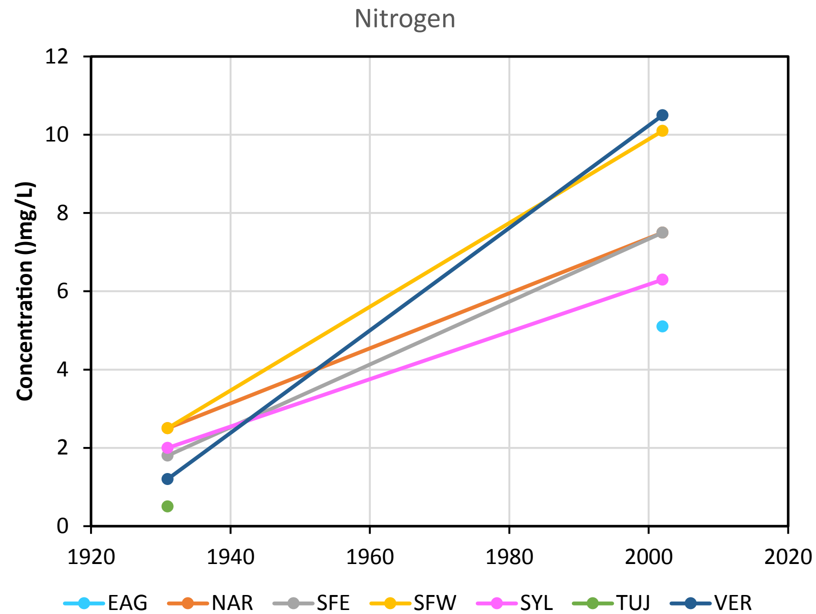
Figure A-5
Groundwater Quality in 1989-2015





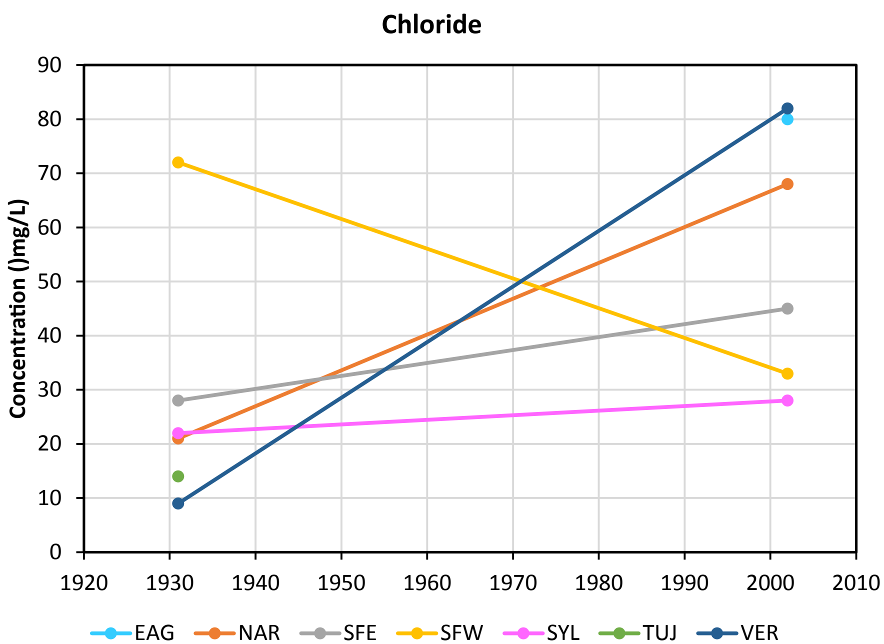


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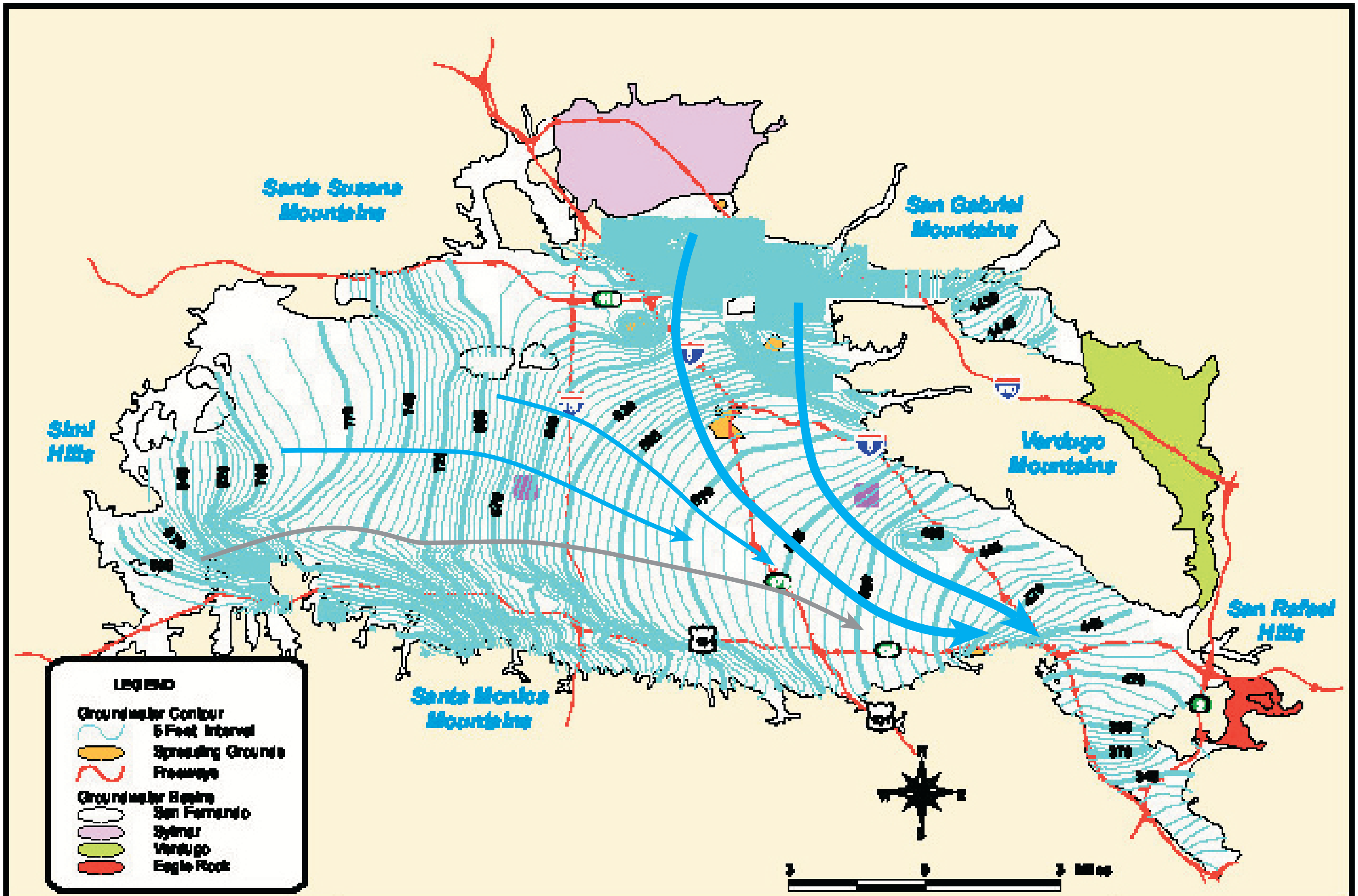
Figure A-6
Water Quality Trends
1932 - 2002



2012-13 Water Year ULARA Watermaster Report	Simulated Groundwater Elevation Contours Spring (April) 2013	PLATE 9

Source: Watermaster (2014)

April 2017

TODD GROUNDWATER

Figure A-7
Groundwater Elevation Contours Spring 2013

APPENDIX B

Background Mass Load Analysis

9.6. INTRODUCTION

Mass loads to groundwater from atmospheric deposition, aquifer dissolution, subsurface inflow from tributary watersheds and rainfall recharge are difficult to measure directly from data. Also, the first three of those loads would not be affected by recycled water use or other foreseeable groundwater management measures. The volume of rainfall recharge could vary substantially depending on stormwater management practices, but the amount of solute mass picked up by rainfall as it percolates through soils and the unsaturated zone was assumed to remain the same for all amounts of rainfall recharge. The same assumption was made for dissolution of aquifer minerals below the water table. These constant mass inputs reflect an assumption that dissolution of minerals is primarily limited by the kinetics of the dissolution process rather than by chemical equilibrium, consistent with field studies of silicate mineral dissolution in aquifers (Zhu, 2005; Hereford and others, 2007).

All of the components of background mass load were assumed to be constant in all years at a rate equal to the rate under pre-development conditions. Their combined total was estimated by applying a simplified mixing model to each SNMP subarea. The model included only flow and mass items present under pre-development conditions: subsurface inflow from tributary watersheds, rainfall recharge, stream percolation and groundwater inflow from upgradient regions. **Table B-1** shows the flow, concentration and mass of TDS, chloride and nitrogen for all sources of recharge in each SNMP subarea under pre-development conditions. The data and assumptions used to derive the estimates for individual recharge items are described below. All flows and concentrations were estimated from data except the concentrations assigned to rainfall recharge and subsurface inflow from tributary watersheds, where a single value was obtained by calibrating the model to observed groundwater concentrations in 1931-1932.

9.7. TRIBUTARY WATERSHED HYDROLOGY AND FLOW PATHS

Water flowing out of tributary watersheds into the subareas can conceptually be divided into three categories: peak flows that across the region during large storm events without percolating, smaller surface outflows that percolate into the subareas, and subsurface inflow to the subarea along the mountain front. Peak flows that cross over and leave the subarea were estimated by a statistical analysis of stream gage records from seven watersheds in the ULARA and greater Los Angeles region. Gages were selected that had a relatively long period of record prior to development of the watershed or regulation of flow by a dam. Where dams were present during the period of analysis, they were of small enough size not to significantly influence large peak flows. The gages are listed in **Table B-2**. A frequency threshold for peak flows that traveled across the ULARA subareas without percolating was obtained from historical anecdotal descriptions of the flow regime in the Los Angeles River near downtown Los Angeles. All surface inflows to the ULARA subareas percolated into the ground “except at time of flood” (Hall, 1888). For this analysis, that frequency was interpreted to be one day in two years, or an exceedance probability of 0.14 percent for daily flows. All streamflow from ULARA tributary watersheds that occurred at less than the threshold defining “flood” flows was assumed to percolate into the groundwater subareas.

Annual non-flood flow volume for the reference watersheds was divided by watershed area to obtain unit runoff volumes in acre-feet-per-year per square mile of drainage area (**Table B-2**). These values proved to be moderately correlated (r-squared = 0.59) with average annual rainfall in the watershed, as shown in **Figure B-1**. The regression equation ($y = 15.2x - 222$ AFY/mi^2) was applied to the tributary watersheds adjacent to each of the seven SNMP subareas to obtain estimates of groundwater recharge from stream percolation under pre-development conditions.

Concentrations of TDS, chloride and nitrogen in streams under pre-development conditions were estimated from surface water quality data collected in 1931-1932 (DWR, 1933). Specific conductance, chloride and nitrogen concentrations were sampled on 5-10 dates in the Los Angeles River (two locations), Pacoima Creek, Big Tujunga Creek, Big Tujunga Wash and Verdugo Creek. Flow was also measured, and the concentrations are plotted against flow in **Figure B-2** for low to moderate flows. The graphs show a common pattern of relatively high concentrations at low flows, decreasing asymptotically to a lower concentration at high flows due to dilution by rapid rainfall runoff during storm events. Low flows are more sustained than high flows, and flow-weighted averages for the purpose of mixing model calculations were assumed to be the concentrations near the transition point from low-flows (possibly influence by evaporation or groundwater inflow) to the asymptotic high-flow tail. Specific conductance was converted to TDS by linear regression of paired values for 43 wells measured on multiple dates during 1988-2015. The resulting equation was:

$$\textbf{TDS} = \textbf{0.750 (Specific Conductance)} - \textbf{75.7}$$

where TDS is in mg/L and specific conductance is in microsiemens per centimeter.

The 1931-1932 data set did not include any measurements of streams draining watersheds underlain by marine rocks adjacent to SFW. Concentrations were estimated by adjusting Pacoima Creek concentrations upward, partly on the basis of calibration to groundwater quality.

The third component of tributary watershed outflow is subsurface outflow directly into the ULARA subareas. This outflow was estimated as the average annual amount of rainfall recharge in the part of the watershed closest to the subarea boundary, where recharge would probably flow to the subarea rather than toward a stream channel within the tributary watershed.

Average annual rainfall recharge was estimated from a compilation of studies of rainfall recharge in semiarid regions around the world (Bedinger, 1987). A plot of average annual recharge versus average annual rainfall was prepared from those data and a non-linear regression equation was fitted to the data focusing on the 14 to 23 inch-per-year range applicable to ULARA and tributary watersheds. The data and regression curve are shown in **Figure B-3**.

A map of average annual rainfall in the subareas and tributary watersheds is included in TM-2 and shows contours ranging from 16 inches in San Fernando Valley to 30 inches along the crest of the San Gabriel Mountains. Applying the deep percolation regression equation to average annual rainfall in 25 tributary areas obtained annual recharge rates of 1.5 to 3.2 inches per year, as shown in **Table B-3**. These rates were adjusted upward in two of the watersheds during calibration of the pre-development model in order to obtain a closer match with observed water quality. Pacoima Wash and Tujunga Wash traverse two subareas. Based on calibration and channel length, recharge from Pacoima Wash percolation was divided equally between SYL and SFE. For Tujunga Wash, 4 percent of recharge was allocated to TUJ and 96 percent to SFE. Average annual percolation from streams flowing onto the subareas totaled 23,800 AFY under pre-development conditions.

The percentage of watershed area from which recharge flows directly to the adjoining SNMP subarea was estimated visually from maps, based on topography and stream channel location within the watershed. The percentages are also listed in **Table B-3**. Average annual subsurface inflow to the subareas totaled 5,900 AFY under pre-development conditions.

9.8. Rainfall Recharge

Pre-development rainfall recharge within the SNMP subareas was estimated by the same method used for the tributary watersheds. The one-dimensional recharge rate was calculated from average annual rainfall and multiplied by the entire surface area of the subarea.

9.9. Groundwater Flow between Regions

Two of the subareas (SFE and NAR) receive groundwater inflow from other regions, and in three regions (SFE, SFW and NAR) there is groundwater discharge to the Los Angeles River. Groundwater flow between subareas and discharge to the Los Angeles River under pre-development conditions were estimated from the amounts of recharge in each subarea, with an assumption of zero long-term net change in groundwater storage. That is, total outflow was assumed to equal total recharge. In two cases, groundwater outflow had to be partitioned into two pathways. Based on the length and location of the river channel relative to regional boundaries and groundwater flow directions, 30 percent of groundwater outflow from SFW was assumed to discharge to the river and the remainder to flow into SFE. From SFE, 50 percent of outflow was estimated to be to the river and 50 percent to NAR. SFE also received all of the outflow from SYL and TUJ, and NAR received the outflow from VER and EAG.

The quality of groundwater inflow from an upgradient subarea was set equal to the median concentration measured in 1931-1932, with a few exceptions. Outflow from SFW to SFE was given the measured concentrations, whereas outflow to the Los Angeles River was given concentrations about 30 percent higher, consistent with the presence of higher groundwater salinity in the southern part of SFW where the river is located. Measured TDS and chloride concentrations in VER in 1931-1932 were anomalously low compared to other subareas, and those values proved to be incompatible with reasonable mixing-model assumptions. Accordingly, TDS was estimated from more recent data and chloride was estimated from the average chloride:TDS ratio of 1931-1932 data. NAR chloride and nitrogen concentrations for 1931-1932 also appeared anomalous compared to TDS and to values in SFE. The chloride concentration was instead estimated from the chloride:TDS ratio and nitrogen was estimated from adjoining regions.

9.10. Calibration of Pre-Development Conditions

Under predevelopment conditions, ambient water quality was assumed to equal median concentrations measured in 1931-1932, with a few exceptions for missing data or outlier values. These values are shown in the bottom line of each recharge mass balance table (**Table B-1**). Simulated ambient groundwater quality was assumed to equal the flow-weighted average concentration of each solute and is shown in the next-to-last row of each table. Some flows and concentrations were adjusted to obtain a match between simulated and measured ambient concentrations with reasonably consistent assumptions across all regions. These assumptions included, for example, that chloride-to-TDS ratios (Cl:TDS) should be fairly similar in all regions, as should the concentrations associated with rainfall recharge and subsurface inflow from tributary watersheds. Concentrations in groundwater should be lower than in surface water (at moderate streamflows not dominated by groundwater discharge). Calibration issues and adjustments for each subarea are described below.

The EAG region has no stream recharge or subsurface inflow. Subsurface outflow from hills to the east was assumed to flow to VER to help balance the modern water balance in that subarea. VER stream water quality values are shown in the **Table B-1** as placeholders. With no blending from other sources, concentrations of background mass load items (shown in brown) were necessarily equal to the ambient concentration in the one groundwater measurement.

Measured TDS and chloride in NAR was surprisingly low in 1931-1932: only about one-third the median concentrations during 1987-2014), and considerably lower than SFE concentrations (versus higher than SFE in 1987-2014). Also, a concentration of zero for the background mass load items would not be sufficient to lower simulated TDS down to the reported level from 1931-1932. Accordingly, predevelopment TDS in this region was assumed to equal median TDS from 1987-2014, and the chloride concentration was estimated by applying the empirical Cl:TDS ratio of 0.0549 to the TDS concentration. All groundwater outflow from VER was assumed to enter NAR, but only 50 percent of the outflow from SFE. The remaining SFE outflow was assumed to discharge into the Los Angeles River. In addition, 12 percent of the groundwater outflow from SFW was assumed to flow into NAR. This reflects the eastward-moving band of relatively saline groundwater along the south edge of the San Fernando Basin and an assumption that only part of that flow discharges into the Los Angeles River, while some of it continues east via the subsurface to NAR.

Stream recharge in SFE consisted of 96 percent of Big Tujunga Creek percolation, 100 percent of Little Tujunga Creek percolation and 50 percent of Pacoima Creek percolation. Surface water quality was a 70:30 weighted average of Big Tujunga and Pacoima concentrations measured in 1931-1932. It was not possible to calibrate to the median measured TDS concentration from 1931-1932 (357 mg/L) with the large inflow of relatively high TDS inflow from SFW and a reasonable value for background mass load TDS. In SFE, average TDS was much higher than median TDS (534 versus 357 mg/L), so a higher target concentration was reasonable. An intermediate value (481 mg/L) allowed calibration to be achieved with a reasonable TDS concentration for the background mass load items. In addition, outflow from SFW was partitioned into a lower TDS component (70 percent of total outflow, at 670 mg/L) mixing into SFE and a higher-TDS component (30 percent of total outflow, at 1,000 mg/L) near the southern edge flowing into the Los Angeles River and NAR.

For SFW, no data were available for stream water quality. Because the tributary watersheds contain Tertiary-age marine rocks, TDS and chloride concentrations are probably higher than for streams in the eastern watersheds. With little basis for quantitative adjustment, a TDS concentration of 325 mg/L (88 mg/L higher than streams in SFE), a chloride concentration of 30 mg/L (23 mg/L higher than SFE) and a nitrogen concentration of 0.2 mg/L (0.1 mg/L higher than SFE) were selected and were consistent with reasonable calibrated concentrations for background mass load items.

Recharge in SYL under pre-development conditions consisted only of stream percolation and the background mass load items (rainfall recharge and subsurface inflow from tributary watersheds). Half of Pacoima Creek percolation was assumed to be in SYL and it was assigned the median water quality values measured in 1931-1932. The calibrated TDS and chloride concentrations for background mass loads were the highest of all the subareas, but not by a large amount.

The TUJ subarea was assumed to receive only 4 percent of Big Tujunga Creek percolation. A small percentage was necessary to balance the modern water budget and is consistent with generally shallow depths to groundwater and hence rejected recharge (Johnny, 2016). With this relatively small contribution of stream recharge, the calibrated TDS concentration for background mass load items was the lowest of all the subareas (657 mg/L), but not by a large amount. The calibrated chloride concentration was the second-lowest among the subareas.

The VER region presented several calibration challenges. It was necessary to increase stream recharge and subsurface inflow from tributary watersheds in order to bring the modern water budget into balance, and those patterns were assumed to also be present under pre-development conditions. The historical water quality data are unusual and questionable in that groundwater TDS and chloride concentrations were lower than surface water concentrations and were also the lowest of all the subareas. Matching the reported concentrations for 1931-1932 required unrealistically low TDS and chloride concentrations. With no other variables available for adjustment, it was decided to assign the same TDS for background mass load as in TUJ and to estimate the corresponding chloride concentration from the empirical regional Cl:TDS ratio. This subarea remains uncalibrated for pre-development conditions, but it is not clear whether the discrepancy stems from the historical water quality data or from the model.

9.11. CONTEMPORARY BACKGROUND MASS LOADS

The mass loads of TDS, chloride and nitrogen associated with rainfall recharge and subsurface inflow from tributary watersheds were carried forward from the pre-development model to the 2002-2030 model. As explained earlier, those loads derive from atmospheric deposition and dissolution of soil and aquifer minerals, which are probably similar under contemporary conditions as under predevelopment conditions and also are not affected by use of recycled water or other associated water management activities. In the 2002-2030 model, those mass loads are dissolved into the net recharge from rainfall recharge.

TABLES

Table B-1. Background Mass Loads under Pre-Development Conditions

EAGLE ROCK BASIN									
	TDS			Chloride			Nitrogen		
Basin Inflows	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	0	274	0	0	12	0	0	0.5	0.0
Subsurface inflow from tributary watersheds	0	838	0	0	80	0	0	5.0	0.0
Rainfall recharge	119	838	136	119	80	13	119	5.0	0.8
Groundwater inflow from other subareas									
1	0		0	0		0	0		0.0
2	0		0	0		0	0		0.0
3	0		0	0		0	0		0.0
4	0		0	0		0	0		0.0
Total	119	838	136	119	80	13	119	5.0	0.8
Measured (1931)		838			80			5.0	

NARROWS SUBAREA									
	TDS			Chloride			Nitrogen		
Basin Inflows	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	349	249	118	349	11	5	349	1.9	0.9
Subsurface inflow from tributary watersheds	668	820	743	668	70	63	668	10.0	9.1
Rainfall recharge	848	820	944	848	70	81	848	10.0	11.5
Groundwater inflow from									
1 SFE - 50%	18,348	481	11,976	18,348	28	697	18,348	2.0	49.8
2 VER	3,992	535	2,898	3,992	35	190	3,992	0.2	0.8
3 SFW - 12%	1,577	1,000	2,140	1,577	90	193	1,577	3.0	6.4
4	0		0	0		0	0		0.0
Total	25,782	538	18,819	25,782	35	1,229	25,782	2.2	78.5
Measured (1931)		538			35			2.2	

Expected from regression

SAN FERNANDO - EAST									
	TDS			Chloride			Nitrogen		
Basin Inflows	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	13,878	237	4,471	13,878	9	169	13,878	0.1	1.3
Subsurface inflow from tributary watersheds	1,589	750	1,617	1,589	15	32	1,589	4.2	9.1
Rainfall recharge	6,334	750	6,446	6,334	15	129	6,334	4.2	36.1
Groundwater inflow from									
1 SFW - 70%	9,199	670	8,364	9,199	72	899	9,199	3.0	37.4
2 SYL	5,074	378	2,603	5,074	22	151	5,074	2.0	13.8
3 TUJ	622	434	366	622	14	12	622	1.0	0.8
4	0		0	0		0	0		0.0
Total	36,696	479	23,867	36,696	28	1,393	36,696	2.0	98.5
Measured (1931)		481			28			2.0	

SAN FERNANDO - WEST									
	TDS			Chloride			Nitrogen		
Basin Inflows	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	3,761	325	1,659	3,761	30	157	3,761	0.2	1.0
Subsurface inflow from tributary watersheds	2,441	808	2,677	2,441	88	292	2,441	4.1	13.6
Rainfall recharge	6,939	808	7,609	6,939	88	829	6,939	4.1	38.6
Groundwater inflow from									
1	0		0	0		0	0		0.0
2	0		0	0		0	0		0.0
3	0		0	0		0	0		0.0
4	0		0	0		0	0		0.0
Total	13,142	670	11,944	13,142	72	1,277	13,142	3.0	53.2
Measured (1931) - north		670			72			3.0	
Measured (1931) - south		1000			90			3	

SYLMAR BASIN									
Basin Inflows	TDS			Chloride			Nitrogen		
	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	3,858	224	1,174	3,858	9	47	3,858	0.2	1.2
Subsurface inflow from tributary watersheds	308	865	361	308	65	27	308	7.5	3.1
Rainfall recharge	908	865	1,065	908	65	80	908	7.5	9.2
Groundwater inflow from									
1	0		0	0		0	0		0.0
2	0		0	0		0	0		0.0
3	0		0	0		0	0		0.0
4	0		0	0		0	0		0.0
Total	5,074	378	2,601	5,074	22	154	5,074	2.0	13.6
Measured (1931)		378			22			2.0	

TUJUNGA SUBAREA									
Basin Inflows	TDS			Chloride			Nitrogen		
	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	335	243	111	335	9	4	335	0.0	0.0
Subsurface inflow from tributary watersheds	143	865	168	143	25	5	143	3.2	0.6
Rainfall recharge	143	865	168	143	25	5	143	3.2	0.6
Groundwater inflow from									
1	0		0	0		0	0		0.0
2	0		0	0		0	0		0.0
3	0		0	0		0	0		0.0
4	0		0	0		0	0		0.0
Total	622	530	447	622	16	14	622	1.5	1.2
Measured (1931)		434			14			1.0	

VERDUGO BASIN									
Basin Inflows	TDS			Chloride			Nitrogen		
	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr	AFY	mg/L	Tons/yr
Stream percolation	1,623	274	604	1,623	12	26	1,623	0.5	1.0
Subsurface inflow from tributary watersheds	759	845	870	759	62	64	759	0.0	0.0
Rainfall recharge	1,611	845	1,847	1,611	62	136	1,611	0.0	0.0
Groundwater inflow from									
1	0		0	0		0	0		0.0
2	0		0	0		0	0		0.0
3	0		0	0		0	0		0.0
4	0		0	0		0	0		0.0
Total	3,992	613	3,320	3,992	42	226	3,992	0.2	1.0
Measured (1931)		535			35			0.2	

AFY = acre-feet per year; mg/L = milligrams per liter; TDS = total dissolved solids

Concentration adjusted during calibration

Calculated background mass load

Table B-2. Peak Flow Thresholds and Runoff Volumes in Reference Watersheds

Stream Gage Name	Gage Number	Drainage Area (mi2)	Average Annual Rainfall (in)	Flow Exceeded 0.14% of Time (cfs)	Annual Discharge Less Than Exceedance Threshold	
					Volume (AFY)	Volume per Area (AFY/mi^2)
Mint Canyon Creek at Sierra Highway	F328B	28	12.5	60	259	0.740
Santa Anita Creek Below Santa Anita Dam	F119C	10.8	35.0	265	4,274	11.307
Verdugo Wash At Estelle Avenue	F252	26.8	25.0	684	7,101	10.599
Eaton Wash Below Eaton Wash Dam	F271	12.4	29.0	154	1,590	4.422
Pacoima Creek near San Fernando	11093000	28.3	28.5	480	7,006	8.686
Little Tujunga Creek near San Fernando	11096500	21.1	25.0	274	1,687	3.198
Big Tujunga creek below Hansen Dam	11097000	153	26.0	1,520	11,495	2.890

Notes: mi^2 = square miles; cfs = cubic feet per second; AFY = acre-feet per year

Table B-3. Estimated Groundwater Recharge from Rainfall and Streams under Pre-Development Conditions

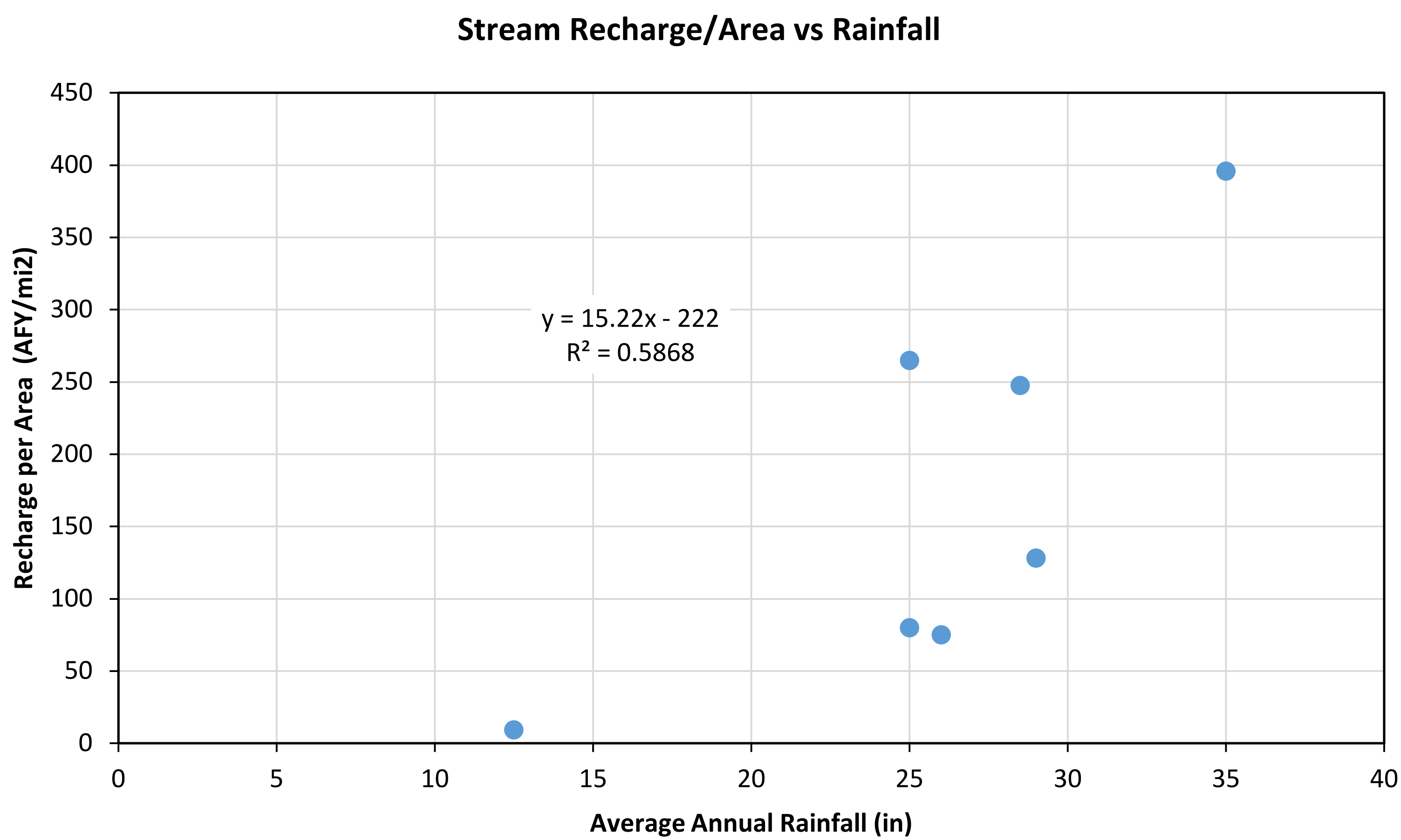
				Rainfall Recharge Flowing Subsurface to Basin				Stream Recharge	
Tributary Watershed	Tributary To	Area (mi^2)	Average Annual Rainfall (in)	Rainfall Recharge Rate (in/yr)[a]	Fraction of Watershed Flowing Subsurface to Basin	Contributing Area (mi^2)	Rainfall Recharge Volume (AFY)	Flow Exceeded 0.14% of time (cfs)	Flow Volume <=0.14% Exceedance (AFY)
Tributary Watersheds									
Unnamed hills between EAG and VER	VER	1.9	21.0	*3.5*	100%	1.9	350	--	0
Griffith Park	NAR	3.8	16.0	1.5	100%	3.8	308	--	0
San Raphael Hills	NAR	4.6	20.5	2.1	15%	0.7	76	--	349
Forest Lawn and Mt. Washington	NAR	3.4	16.5	1.6	100%	3.4	284	--	0
Santa Monica Mountains	SFE	10.2	20.5	2.1	100%	10.2	1,129	--	0
Verdugo Mountains	SFE	18.3	17.0	1.6	25%	4.6	398	--	504
Small hills in basin	SFE	0.4	17.5	1.7	100%	0.4	37	--	0
Lopez Canyon	SFE	0.4	18.0	1.7	40%	0.1	14	--	11
Kegel Canyon	SFE	2.6	18.0	1.7	5%	0.1	12	--	127
Big Tujunga Wash[b]	SFE	See information under TUJ subarea							8,046
Pacoima Creek[b]	SFE	See information under SYL subarea							3,503
Little Tujunga Wash	SFE	21.1	25.0	2.9	0%	0.0	0	274	1,687
Aliso and Limekiln Canyons	SFW	10.3	20.5	2.1	15%	1.5	172	--	789
Browns and Devil Canyons	SFW	17.2	21.0	2.2	0%	0.0	0	--	1,684
Bee Canyon and Bull Wash	SFW	9.8	19.0	1.9	10%	1.0	97	--	590
Small hills in basin	SFW	2.6	16.5	1.6	100%	2.6	222	--	0
Small hills in basin	SFW	2.0	18.0	1.7	100%	2.0	188	--	0
Bell Creek	SFW	23.8	17.0	1.6	20%	4.8	413	--	698
Santa Monica Mountains	SFW	15.5	17.0	1.6	100%	15.5	1,349	--	0
Loop Canyon to Grapevine Canyon	SYL	7.2	20.0	2.0	40%	2.9	308	--	355
Pacoima Creek[b]	SYL	28.3	28.5	3.8	0%	0.0	0	480	3,503
Verdugo Mountains	TUJ	1.4	19.0	1.9	100%	1.4	143	--	0
Big Tujunga Wash[b]	TUJ	153.0	26.0	3.2	0%	0.0	0	1,520	335
Verdugo Mountains	VER	6.2	20.0	2.0	20%	1.2	134	--	411
Blanchard Canyon to Hay Canyon	VER	8.6	25.5	*4.0*	15%	1.3	275	--	1,212
Subtotal Tributary Watersheds							5,907		23,805
Basins and Subareas									
Eagle Rock Basin	EAG	1.3	17.5	1.68	100%	1.3	119	--	0
Narrows Subarea	NAR	10.1	16.5	1.58	100%	10.1	848	--	0
San Fernando--East Subarea	SFE	75.2	16.5	1.58	100%	75.2	6,334	--	0
San Fernando--West Subarea	SFW	84.9	16	1.53	100%	84.9	6,939	--	0
Sylmar Basin	SYL	9.4	18.5	1.80	100%	9.4	908	--	0
Tujunga Subarea	TUJ	6.7	19.5	1.94	100%	6.7	143	--	0
Verdugo Basin	VER	7.6	23	*4.00*	100%	7.6	1,611	--	0
Subtotal In-Basin							16,903		0
Total Recharge							22,810		23,805

mi^2 = square miles; AFY = acre-feet per year; cfs = cubic feet per second

[a] Italic font indicates estimates from regression equation that were adjusted upward during model calibration.

[b] These major streams traverse two subareas. Stream recharge is divided between the subareas.

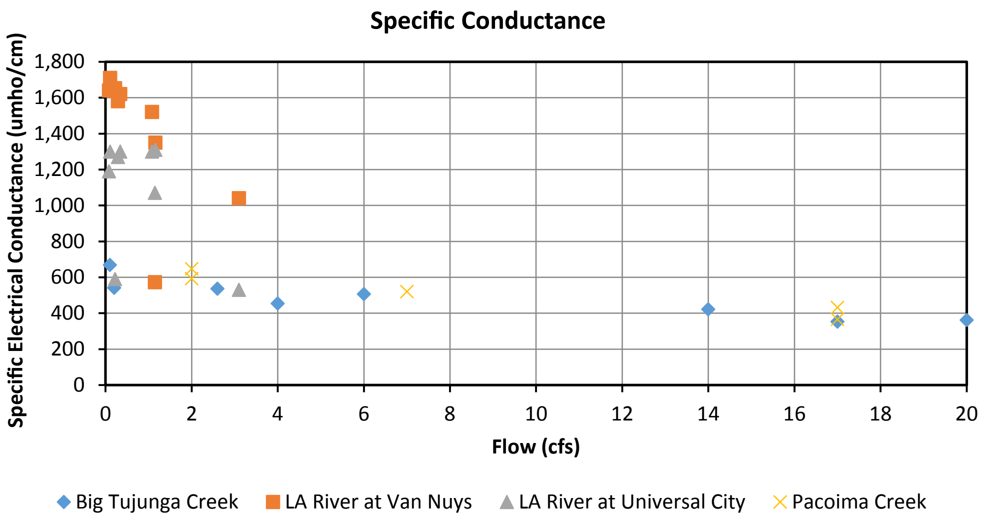
FIGURES

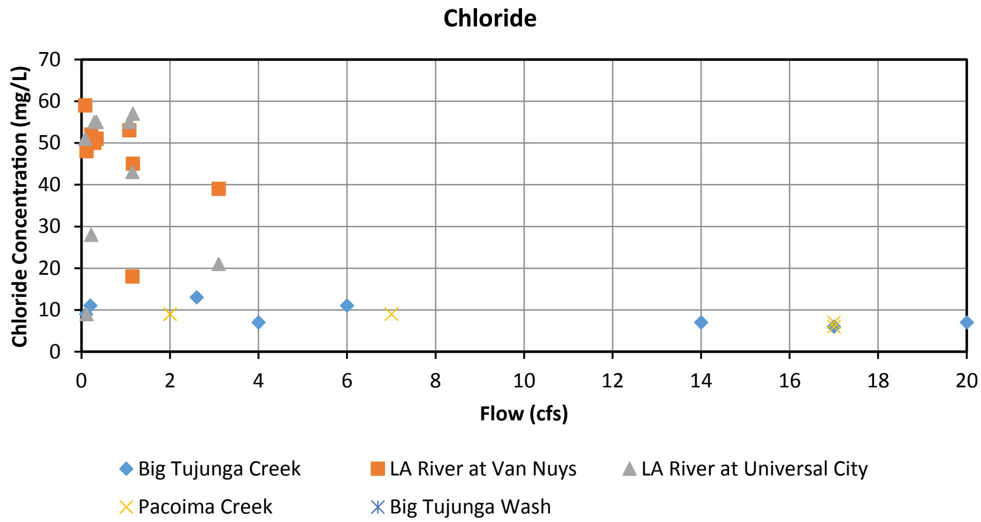


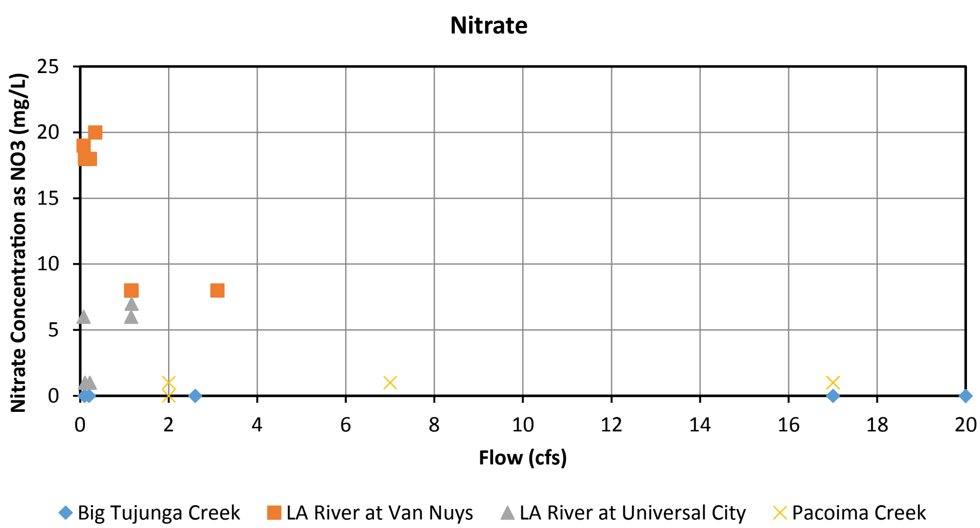
April 2017

TODD GROUNDWATER

Figure B-1
Rainfall Runoff Relationship



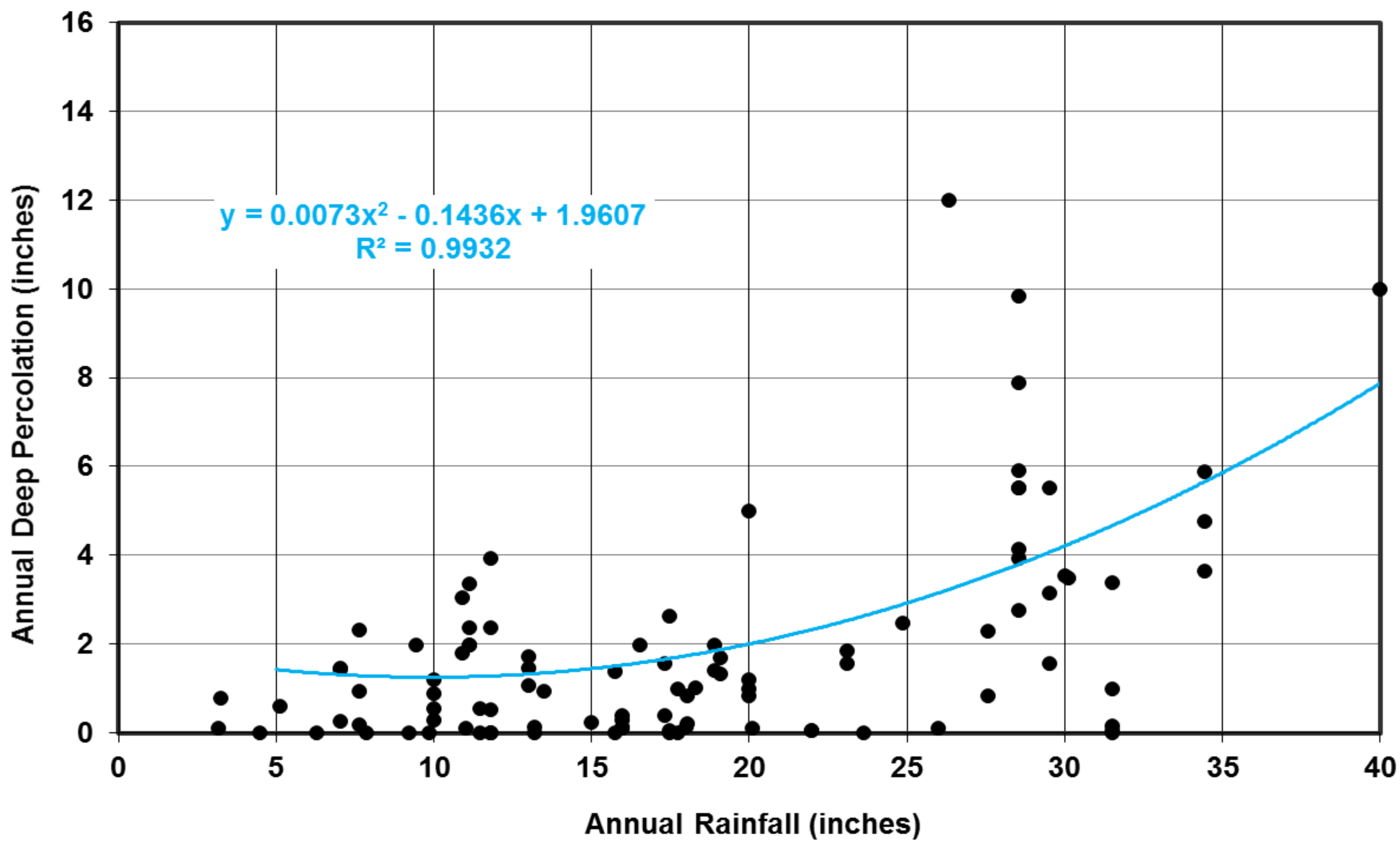




April 2017

TODD GROUNDWATER

Figure B-2
Stream Water Quality Versus Flow in 1931 - 1932



April 2017

TODD GROUNDWATER

Figure B-3
Relationship of Deep Percolation to Annual Rainfall