Task 3 Technical Memorandum
Analytical Modeling of the Sacramento River

A Deliverable
for
California Urban Water Agencies (CUWA)
and the
Central Valley Drinking Water Policy Work Group

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Introduction

Background

The Sacramento-San Joaquin River Delta is a major source of drinking water for districts serving northern and southern California. The Delta receives inflows from the Sacramento River and San Joaquin River, as well as several smaller tributaries including the Calaveras, Cosumnes, and Mokelumne Rivers. Ocean water, transported through the Carquinez Straits on the incoming tide also mixes with the inland freshwater sources. Therefore, the water quality at the Delta drinking water intakes is dependent upon the pollutant loading from each of these sources and complex pathways by which these pollutants move through the Delta to drinking water intakes. Nutrients, salinity and organic carbon are of primary concern at drinking water intakes. There are limits on allowable salinity for drinking water to be suitable for human consumption. Nutrients stimulate algal growth resulting in taste and odor problems, water treatment challenges, and concern over algal toxins. Organic carbon is of interest due to harmful disinfection byproducts or DBPs, which can be generated during the water treatment process.

Salinity is defined as the quantity of salt dissolved in a given volume of water. While the concentration of dissolved salts in surface water tends to increase with increasing downstream distance, salinity of water samples collected at the Delta drinking water intakes can reach levels greater than the federal secondary maximum contaminant level of 500 mg/l and the CALFED Water Quality Program monthly average numeric target of 440 mg/l. (CALFED 2005). Concentrations in this range are approximately five times greater than concentrations found in the Sierra Nevada headwater streams where the Delta water originates. Significant sources of salinity between the headwater sources and the Delta intakes include seasonal seawater incursion, irrigated agricultural land drainage, and managed wetlands located in the Sacramento Valley and the Delta.

Concentration of salts through evapotranspiration, leaching of natural salts from valley soils, and agricultural chemical addition are the dominant processes involved in the generation of elevated salinity levels. Of the many chemical compounds contributing to salinity measurement, bromide compounds (present in sea water at around 65 µg/L) are the most problematic from a drinking water perspective. Bromate, a suspected human carcinogen, is a product of the reaction between ozone and bromide, and is therefore commonly found in water treated using ozonation processes. Drinking water suppliers that treat Delta water with ozone must take steps to ensure that bromate levels do not exceed the Maximum Contaminant Level (MCL) of 0.01 mg/l. Bromide also contributes to the formation of brominated trihalomethanes and haloacetic acids, compounds which are regulated in treated drinking water.

Total organic carbon (TOC) is a measure of the amount of carbon bound in organic compounds within a water sample. TOC is comprised of both dissolved and particulate fractions, and originates from a variety of natural and synthetic sources including the decay of plant and animal material, detergents, pesticides, and fertilizers. A recent study conducted by Jassby and Cloern (2000) suggests that tributary inputs of organic carbon are several times larger than the organic carbon loads generated via in-Delta primary productivity and agricultural drainage to the Delta. While organic carbon serves as the foundation of the food web and is therefore an essential component of a healthy aquatic ecosystem, dissolved organic carbon (DOC) in source waters has been identified as a constituent of concern in the Delta. DOC in source waters is problematic due a subset of the byproducts formed when the source water is treated with chlorine. Of the dozens of byproducts formed from the reaction of DOCs and chlorine, trihalomethanes and several haloacetic acids are currently regulated by the US EPA (1998). Organic carbon in source waters also has an adverse impact on treatment facilities that rely on ozone instead of chlorine for disinfection, as ozone dosage is positively correlated with TOC concentration.

Although current source water is of high enough quality to meet drinking water standards at most current water treatment facilities, changes in land use may degrade source water quality or drinking water standards may become more restrictive. Numerical modeling of the source water quality assesses the contribution of various sources toorganic carbon and salinity concentrations at the intakes. Numerical model is critical in evaluating the benefits of these hypothetical source protection scenarios.

Conceptual models have been developed of salinity (CALFED Bay-Delta Program 2007) and organic carbon (Roy 2006) for California's Central Valley and Sacramento-San Joaquin River Delta. The models were created to characterize the available data into tools which could be used to identify data gaps and monitor changes in water quality over time. Each model summarizes the sources of pollutants and how they reach the Delta drinking water intakes.

The salinity conceptual model identified four factors which affect salinity at drinking water intakes: inflows, water operations, watershed sources, and hydrodynamics. The volume of fresh river inflows is the largest of the four factors affecting salinity at the Delta drinking water intakes. Higher freshewater inflow decreases incoming salinity concentration and reduces ocean water incursion into the Delta. During low flow, the amount of reservoir releases, the implementation of flow barriers, and Delta pumping are primary drivers of Delta salinity. Salt is mobilized and concentrated by irrigation in the Central Valley watersheds. Lastly, the effect of all these inputs is regulated by the complex tidal hydrodynamics of the Bay and Delta.

The organic carbon conceptual model discusses various types of organic carbon and their transport to the Delta. Organic carbon can have terrestrial or aquatic origin, and this affects the chemical composition of the organic carbon and its bioavailability. Significant organic matter is produced within the Delta by phytoplankton and macrophytes. Terrestrial organic carbon originates from the decay of plant biomass. Loads were estimated from agricultural, urban, natural terrestrial, wetland, and point sources for Central Valley tributaries based on available monitoring data for wet and dry years. For both wet and dry years, agriculture was found to be the largest source of organic carbon in the San Joaquin River but natural terrestrial sources were the largest source in the Sacramento River.

In 2009, the WARMF surface water model was linked with groundwater modeling to track salt and nitrate for the Central Valley Salinity Coalition. Three pilot study areas were used: the Tule River basin of Tulare County, the east side of the San Joaquin River near Modesto, and Yolo County. The latter pilot study area was incorporated into the Sacramento River application of WARMF. The study determined fluxes of salt and nitrate between land, groundwater, and surface water under average, dry, and wet hydrologic conditions.

A considerable number of scientific studies have been conducted to investigate the causes of low DO in the Stockton Deep Water Ship Channel (DWSC). Although low dissolved oxygen is not a concern at the drinking water intakes, the causes of low dissolved oxygen in the DWSC including organic carbon and nutrients are concerns for drinking water. As part of these dissolved oxygen studies, much data has been collected and modeling has been performed to determine the sources and sinks of pollutants in the San Joaquin River and the Delta. The City of Stockton conducted monthly field sampling of DO, BOD, temperature, and chlorophyll-a in the San Joaquin River at nine stations. The data were used to calibrate the EPA Link-Node estuary model (Schanz and Chen 1993). The model was used to evaluate how the export pumping at Tracy would divert water from the upstream San Joaquin River through the Old River, which reduced the river inflow, increased the hydraulic residence time, and decreased DO in the DWSC (Chen and Tsai 1996). The model was also used to evaluate alternatives to increase DO in the DWSC and show that low DO conditions would persist even if the point source discharge from Stockton Regional Wastewater Treatment Plant was completely eliminated (Chen and Tsai 1997a and b). Low river inflow and high DO demanding substances from upstream would continue to cause low DO in the DWSC.

Jones and Stokes (1998) compared the seasonal variations of chlorophyll-a at Vernalis and DO concentration in the DWSC. High chlorophyll-a concentration was associated with a super saturation of DO at Vernalis and low DO in the DWSC. The algae grown in the upstream river appeared to have been transported downstream to DWSC, where the algae respired and decomposed to consume dissolved oxygen. In 1999, the San Joaquin River DO TMDL study was initiated to seek a watershed approach to solve the low DO problem for the DWSC.

CALFED funded a study to analyze field data collected by California Department of Water Resources. Analysis of data showed that ammonia was a significant DO sink, which could be derived in part from the ammonia discharge of Stockton Regional Wastewater Treatment Plant and in part from the decomposition of dying algae from the upstream (Lehman, Sevier, Giulianotti, and Johnson. 2004). The Link Node estuary model was improved and calibrated with the new data collected (Chen and Tsai 2002). The model was used to calculate the relative contribution of DO sinks to the DWSC (Chen and Tsai 2000). The oxygen consuming load from the upstream river was substantial. Foe, Gowdy, and McCarthy (2002) showed that the river load was primarily contributed by algae seeded by agriculture drains, which was then doubled by growth during the transport downstream to Vernalis. In 2003, CALFED funded a project for monitoring and investigations of the San Joaquin River and its tributaries. As part of this project, the WARMF watershed model was applied to the San Joaquin River to trace pollutants from their source to their sink at the DWSC.

In 2008, the California Urban Water Agencies (CUWA) obtained a grant from the State of California under Proposition 50. One aspect of the grant was to determine the sources of nutrients, salinity and organic carbon at Delta drinking water intakes. The approach taken was to pursue analytical modeling, as data deficiencies would limit the utility of conceptual or spreadsheet based models. Analytical modeling could provide a scientific basis for estimates of loading which varied by season and could be evaluated against measured data. The existing San Joaquin River model was upgraded and a new WARMF application for the Sacramento River was created to trace Delta drinking water pollutants back to their sources in the watershed.

Modeling Objective

The Central Valley Drinking Water Policy Work Group (Work Group) requires technical information to formulate a Drinking Water Policy for the Central Valley. Pollutants at drinking water intakes originate from a combination of urban, industrial, agricultural, and natural sources. To develop a drinking water policy, the sources of pollutants must be quantified to determine the impact at drinking water sources. It is important to understand these sources as they exist under current conditions and the effects of land use change and source management. The application of WARMF documented in this report integrates the pollutant sources into time series and summaries of pollutant loading for use by the DSM2 estuary model to determine how those pollutants move through the Delta to the drinking water intakes.

To meet the objectives of the Work Group, the modeling must accomplish the following:

1. Provide an integrated interpretation of the field data collected in the past and as part of ongoing efforts. The model predicts flow and water quality, based on known scientific principles of heat budget, mass balance, hydrology, hydrodynamics, chemical transformations, algal growth, and nutrient uptake. The predictions can be compared to the observed data to evaluate the performance of the model.

2. Provide summaries of pollutant sources under hydrologic conditions of concern.

3. Simulate the effect of changes to the watershed, such as land use change, source management, and alternate reservoir management.

4. Provide time series input of flow and water quality at the I Street Bridge in Sacramento, Yolo Bypass, and Delta east side tributaries for use by the DSM2 Delta model.

Model Domain

WARMF was set up to simulate the Sacramento River and its watershed that extends from the confluence with Morrison Creek upstream to Shasta Lake. The domain was extended to include the Putah Creek watershed as part of a separate project funded by the Central Valley Salinity Coalition. A third project, funded by the Metropolitan Water District of Southern California and the State Water Project Contractors, extended the domain further to include the land area located on the east side of the Sacramento River Delta between Morrison Creek and the Stanislaus River. Major tributaries in this area include the Cosumnes, Mokelumne, and Calaveras Rivers. The watershed area for each of the tributaries in the model domain extended from the confluence with the Sacramento River or Delta to either the watershed divide or to one of twelve reservoirs, as illustrated in Figure 1-1.

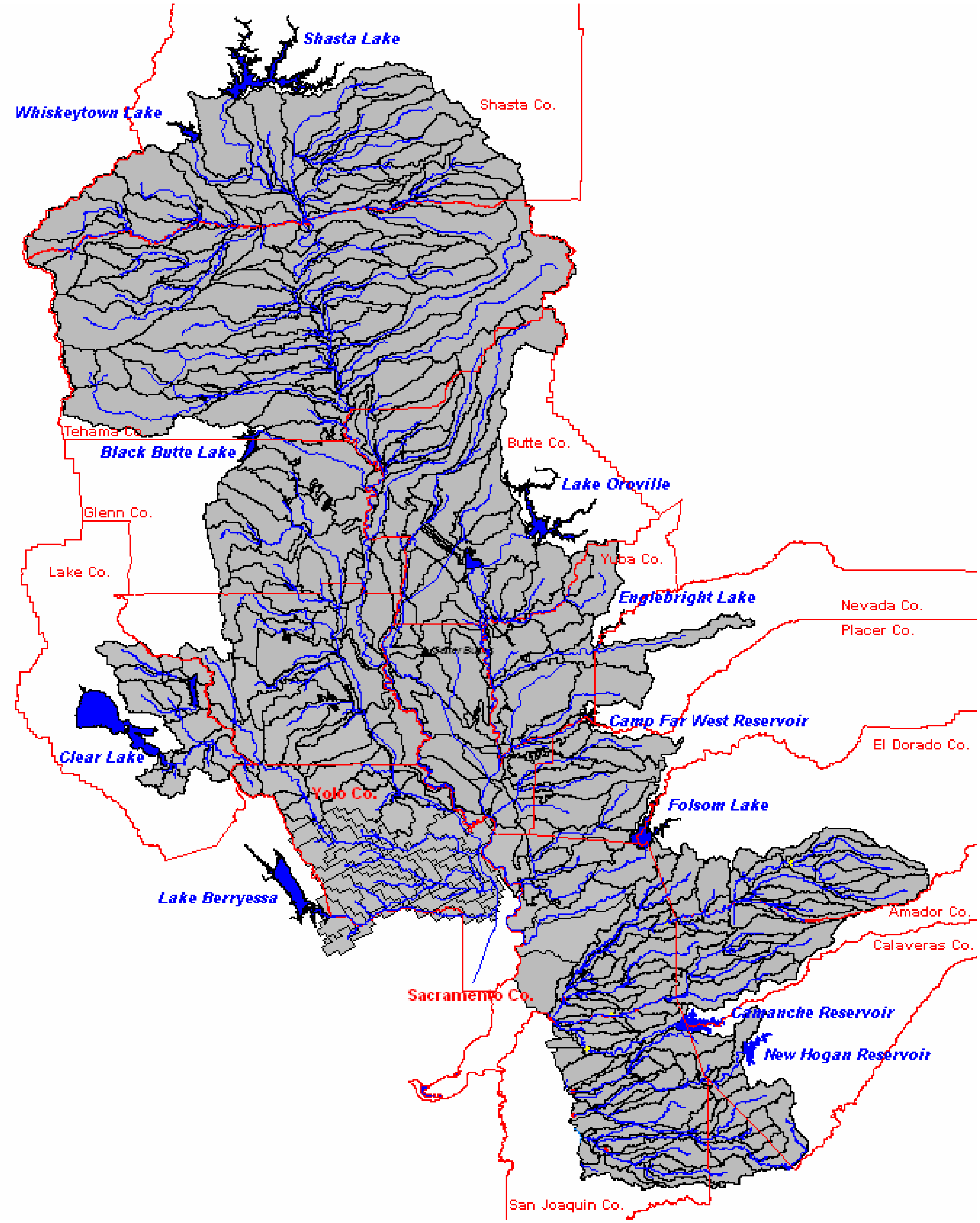

Figure 1-1 The Domain of WARMF Sacramento River Model.

The Sacramento River, its tributaries, and the streams draining directly to the Delta defined in Figure 1-1 were divided into 480 river segments and 479 land catchments. The model simulated natural storm water runoff, irrigation return flow, groundwater table fluctuations within each of the land catchments, and lateral groundwater flow from land catchments to their respective receiving river segments.

With this model set up, the boundary conditions were the Sacramento River at the Shasta Lake Dam, natural watershed divides, and eleven reservoirs located on tributaries to the Sacramento River and Delta between Shasta Lake and the Calaveras River. The reservoirs include Lake Oroville, Thermalito Afterbay, Englebright Lake, Camp Far West Reservoir, and Folsom Lake, on the east side of the Sacramento, Lake Berryessa, Clear Lake, Black Butte Lake, and Whiskeytown Lake on the west side, and Camanche and New Hogan Reservoirs draining Delta tributaries. For those boundary conditions, gaging station data provided measured inflows and water quality as inputs to the model. For the agricultural lands, the model inputs included daily diversions, location of water diversions, and areas upon which the irrigation water was applied. Based on the locations of diversions, the model used the water quality of the source water when applying that water as irrigation.

Hydrologic Simulation

WARMF simulates hydrology based on water balance and physics of flow. It begins with precipitation on the land surface. Precipitation and irrigation water can percolate into the soil. Within the soil, water first goes to increase the moisture in each soil layer up to field capacity. Above field capacity, water percolates down to the water table, where it flows laterally out of the land catchment according to Darcy's Law. Water on the soil or within the soil is subject to evapotranspiration, which is calculated based on temperature, humidity, and season. The amount of water entering and leaving each soil layer is tracked. If more water enters the soil than leaves it, the water table rises. If the water table reaches the surface, the soil is saturated and overland flow occurs. The overland flow is calculated by Manning's equation.

Rivers accept the subsurface and overland flow from catchments linked to them. They also receive point source discharges and flow from upstream river segments. Diversion flows are removed from river segments. The remaining water in the river is routed downstream using the kinematic wave algorithm. The channel geometry, Manning's roughness coefficient, and bed slope are used to calculate depth, velocity, and flow. The velocity is a measure of the travel time down the river, which in turn affects the water quality simulation. A thorough description of the processes simulated by WARMF is in the WARMF Technical Documentation (Chen, Herr, and Weintraub 2001).

Water Quality Simulation

The fundamental principle which guides WARMF simulation of water quality is heat and mass balance. Heat enters the soil in water from precipitation and irrigation. Heat is exchanged between catchments and the atmosphere based on the thermal conductivity of the soil. Heat in water leaving the catchments enters river segments, which combine the heat from multiple sources. As in catchments, there is thermal exchange between rivers and the atmosphere based on the difference in temperature between the water and the air. Radiative heating and cooling is also calculated for surface waters. Temperature is then calculated by heat balance throughout the model.

Chemical constituents enter the model domain from atmospheric deposition and from point source discharges. They can also enter the land surface in irrigation water and fertilizer application. Some chemicals are produced by the weathering of minerals in the soil. Chemical species move with water by percolation between soil layers, groundwater lateral flow to rivers, and surface runoff. Each soil layer is considered to be a mixed reactor, as is the land surface within each land use. Within the soil, cations are adsorbed to soil particles through the competitive exchange process. Anions and organic carbon are adsorbed to the soil using an adsorption isotherm. A dynamic equilibrium is maintained between dissolved and adsorbed phases of each ion. Reactions transform the dissolved chemical constituents within the soil. The dissolved oxygen concentration is tracked, and as D.O. goes to zero, anoxic reactions take place. When overland flow takes place, sediment is eroded from the catchment surface according to the modified universal soil loss equation. The sediment carries adsorbed ions (e.g. phosphate) with it to the river.

Rivers accept the water quality which comes with each source of flow. Each river segment is considered a completely mixed reactor. Ions form an equilibrium between dissolved and adsorbed to suspended sediment. Sediment can settle to the river bed and is scoured from the river bed when velocity is high enough. Chemical reactions are based on first order kinetics with their rate adjusted with a temperature correction. Algae are represented by three types: greens, blue-greens, and diatoms. Each has their own optimum growth rate, nutrient half-saturation concentrations, light saturation, optimum temperature, and temperature range for growth. At each time step, algal growth is a function of nutrient limitation, light limitation, and temperature limitation. Light penetration is a function of the algae, detritus, and total suspended sediment concentrations. Light intensity is integrated over the depth of the river segment.

Simulated Parameters

By default, WARMF simulates flow, temperature, and many chemical and physical parameters. Including a complete suite of parameters makes it possible to simulate important watershed transport and transformation processes including advection, adsorption equilibrium, settling, resuspension, biological processes, and oxic and anoxic chemical reactions. Salinity was calculated as TDS and EC by summing the concentrations of the major cations and anions. Organic carbon was subject to interactions with nutrients, dissolved oxygen, and temperature within the model. The array of hydrologic, chemical, and physical variables simulated in the Sacramento River watershed is shown in Table 1.1. Most parameters were used in model inputs and outputs. Some, like alkalinity and the “total” parameters at the bottom of the list, were only calculated from other parameters. Although fecal coliform is one of the parameters included in the model, proper model inputs have not been collected and simulated fecal coliform has not been calibrated against measured data.

Table 1.1 Parameters Simulated by WARMF for the Sacramento River Watershed

Parameter	Input	Calculated	Output
Flow	X	X	X
Depth		X	X
Velocity		X	X
Temperature	X	X	X
NOx	X		
SOx	X		
pH		X	X
Ammonia (as N)	X	X	X
Calcium	X	X	X
Magnesium	X	X	X
Potassium	X	X	X
Sodium	X	X	X
Sulfate	X	X	X
Nitrate (as N)	X	X	X
Chloride	X	X	X
Phosphate (as P)	X	X	X
Alkalinity		X	X
Inorganic Carbon	X	X	X
Fecal Coliform	X	X	X
BOD	X	X	X
Dissolved Oxygen	X	X	X
Blue-green Algae	X	X	X
Diatoms	X	X	X
Green Algae	X	X	X
Periphyton	X	X	X
Detritus	X	X	X
Clay	X	X	X
Silt	X	X	X
Sand	X	X	X
Total Suspended Sediment		X	X
Turbidity		X	X
Total Phosphorus		X	X
Total Kjeldahl Nitrogen		X	X
Total Nitrogen		X	X
Total Organic Carbon		X	X
Total Phytoplankton		X	X
Total Dissolved Solids (TDS)		X	X
Electrical Conductivity (EC)		X	X

Three species of algae were included in WARMF. The biomass concentrations of algae species were converted to chlorophyll and summed for total phytoplankton. Sediment was represented by sand, silt, and clay fractions in WARMF. Sand was considered bed load, while silt and clay were part of suspended load. Total Suspended Sediment was the sum of silt and clay. Total

Sediment included sand as well. Turbidity was calculated with a linear relationship to suspended sediment concentration. The ratio was determined by analysis of concurrent measured data.

Simulating Salinity

Although salinity is treated as a single pollutant, it is actually composed of many ions. The management of salinity may be affected by its composition. In natural waters generally and the Central Valley specifically, there are ten major ions which predominate as shown in Table 1.2. The equivalent weight is the molecular weight divided by the number of the charge. Five of the ions, ammonia through sodium, have a positive charge. Sulfate through phosphate have a negative charge. Inorganic carbon takes three forms which have a neutral or negative charge. Two other ions, hydrogen (H^+) and hydroxide (OH^-) determine the pH of the water, but generally contribute very little mass toward salinity.

Table 1.2 Major Ions in Sacramento Valley Waters

Ion	Chemical Symbol	Charge	Molecular Weight	Equivalent Weight
Ammonium*	NH_4^+	+1	18.04	18.04
Calcium	Ca^{2+}	+2	40.08	20.04
Magnesium	Mg^{2+}	+2	24.30	12.15
Potassium	K^+	+1	39.10	39.10
Sodium	Na^+	+1	22.99	22.99
Sulfate	SO_4^{2-}	-2	96.06	48.03
Nitrate	NO_3^-	-1	62.01	62.01
Chloride	Cl^-	-1	35.45	35.45
Phosphate	PO_4^{3-}	-3	94.97	31.66
Inorganic Carbon	H_2CO_3 HCO_3^- CO_3^{2-}	0 -1 -2	62.03 61.02 60.01	n/a 61.02 30.01

* Customarily referred to as "ammonia"

Salinity is measured directly as total dissolved solids (TDS). The analytical method used to measure total dissolved solids is to pass a sample through a filter, evaporate off the water, and determine the mass of the salts which precipitate out of solution. That mass is the ions which were in the water. Electrical conductivity (EC) is used as an analog for salinity because it is fast and inexpensive to measure and is often highly correlated with TDS. Electricity is conducted through water by ions, so EC is a measure of the concentration of ions in the water. Since different ions have different equivalent weights, the mass of the ions measured by EC depends on their composition. If the ratios of each ion relative to each other remain relatively constant spatially and temporally, there is a strong correlation between EC and TDS and a reliable ratio of EC/TDS.

To determine the proper ratio of EC/TDS, all of the water quality monitoring data collected throughout the watershed was screened for concurrent TDS and EC measurements. This data is encapsulated in Figure 1-2, which shows a ratio of 1.76 with a very high r-squared between EC and TDS.

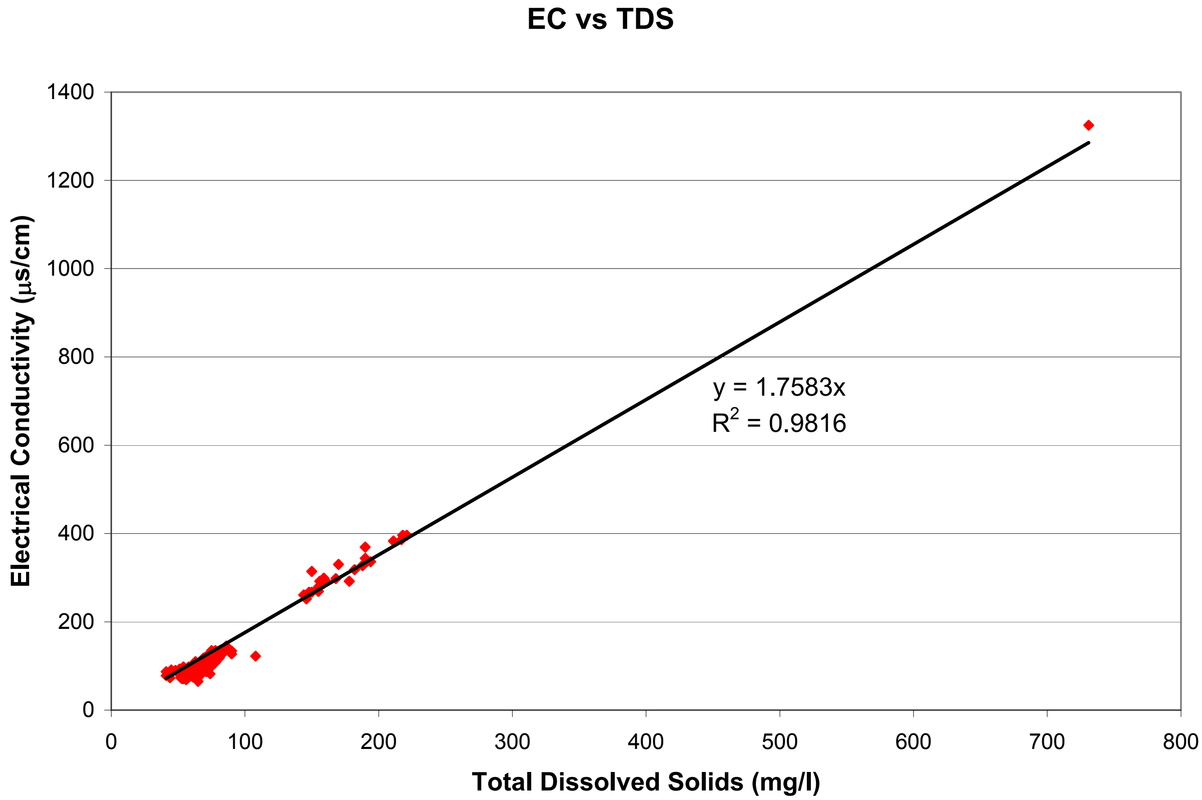

Figure 1-2 Correlation of All TDS and EC Measured Data

The cluster of points in the lower left corner of Figure 1-2, for TDS < 120 mg/l, represents the salinity typically found in most of the Sacramento River watershed, including the main stem of the Sacramento River. Figure 1-3 shows a blow-up of this part of the chart. The ratio between EC and TDS is 1.50 with a much lower correlation than for the entirety of the data. Since this level of salinity is typical for the watershed, WARMF calculates EC by multiplying TDS by 1.50. This could lead to underprediction of EC in areas of the model domain with higher salinity like Colusa Basin Drain. The relatively poor correlation at lower TDS concentrations means that 10-20% error is introduced which will propagate through to simulation results.

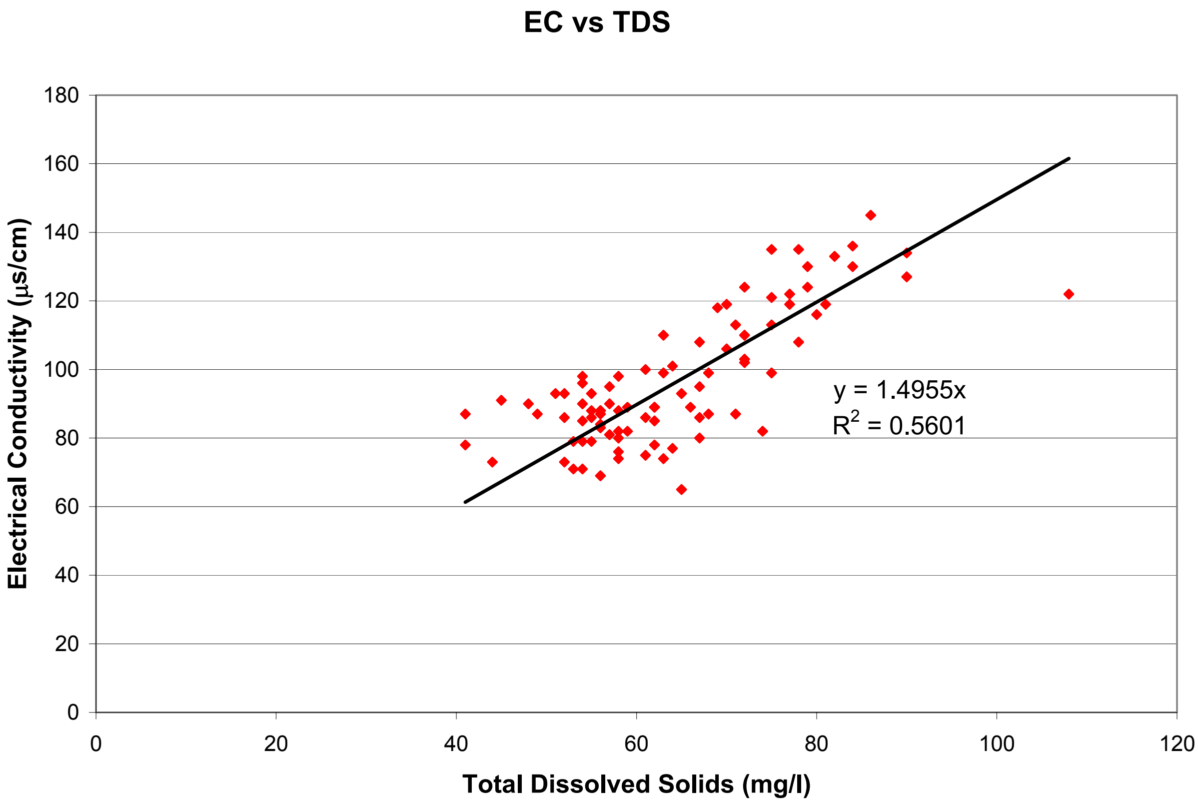

Figure 1-3 Correlation of TDS and EC Measured Data, TDS < 120 mg/l

Concurrent monitoring data of all the major ions was collected from the available data in the Sacramento River watershed. This is not a random sample over the watershed, but a compilation of available data. Ammonia and phosphate data were not available concurrently with the ions in the Yolo study area, but those ions were both much less than 1% of the total in the Modesto study area. Figure 1-4 shows the average percentages of each ion relative to the sum of all the ions for the Yolo Bypass drainage, the Colusa Basin Drain, and the remainder of the watershed. Note that the percentages of most ions are very different between the different subareas.

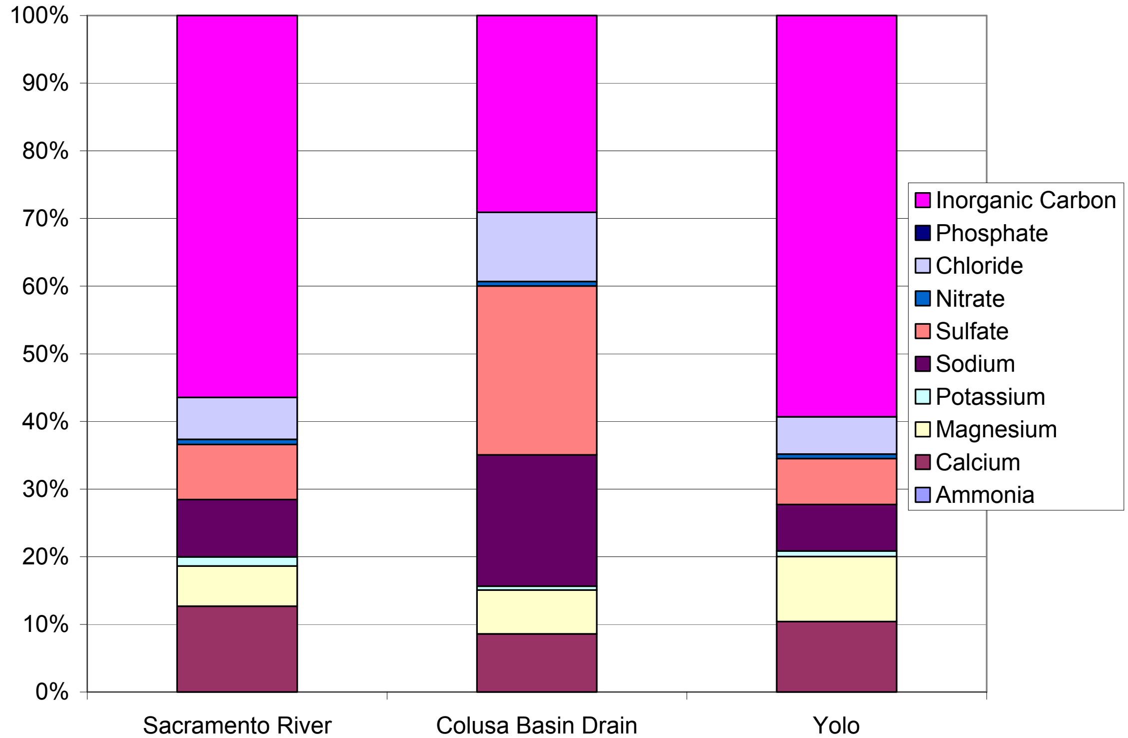

Figure 1-4 Composition of Total Dissolved Solids for the Sacramento River Watershed

The origins of the major ions are varied. Nutrients (ammonia, nitrate, and phosphate) come from waste discharges, fertilizers, atmospheric deposition, and decay of organic matter. Calcium, magnesium, potassium, sodium, sulfate, and chloride come from the weathering of minerals in the soil and atmospheric deposition. Sodium and chloride are also relatively abundant in municipal point source discharges. In the absence of carbonate minerals, inorganic carbon comes from the atmosphere.

Inorganic carbon forms complex equilibria between its various forms in aqueous solution, carbon dioxide in the atmosphere, and hydrogen ion in the water. Like oxygen, carbon dioxide dissolves in water. The equilibrium between dissolved carbon dioxide and atmospheric carbon dioxide is described by Henry's Law as shown in the equation below.

$$[CO_2(aq)] = K_H P_{CO_2}$$

$[CO_2(aq)]$ is the concentration of dissolved carbon dioxide in the water, K_H is the Henry's Law constant which is 0.039 moles/liter-atmosphere at 68 ^oF, and P_{CO2} is the partial pressure of carbon dioxide in the atmosphere. As of 2010, CO_2 is approximately 388 parts per million (ppm) in the atmosphere (0.000388 atmospheres partial pressure) and increasing at about 2 ppm per year (Earth System Research Laboratory 2010). As with dissolved oxygen, the aqueous dissolved carbon dioxide concentration can be greater than or less than what is predicted by Henry's Law, but it will seek out its equilibrium as water is exposed to the air. The equilibrium concentration of dissolved carbon dioxide is currently 1.51×10^{-5} moles/liter or 0.94 mg/l at 68 ^oF.

When carbon dioxide is dissolved in water, it combines with water to form carbonic acid, H_2CO_3. Carbonic acid forms acid-base pairs with bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. These reactions freely flow in both directions, as shown in the following linked chemical equations.

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$$

The dissociation/reassociation of carbonic acid and bicarbonate ion are governed by equilibrium constants relating the inorganic carbon species and hydrogen ion concentrations as shown below.

$$K_1 = \frac{[H^+][HCO_3^-]}{[H_2CO_3]}$$

$$K_2 = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]}$$

At 68 ^oF, K_1 is equal to $10^{-6.38}$ and K_2 is $10^{-10.38}$. Unlike the equilibrium between dissolved and atmospheric carbon dioxide, the equilibrium between inorganic carbon species occurs instantaneously. Given the relationships between atmospheric carbon dioxide, dissolved inorganic carbon species in the water, and hydrogen ions it is possible to calculate equilibrium inorganic carbon concentration as a function of pH as shown in Figure 1-5.

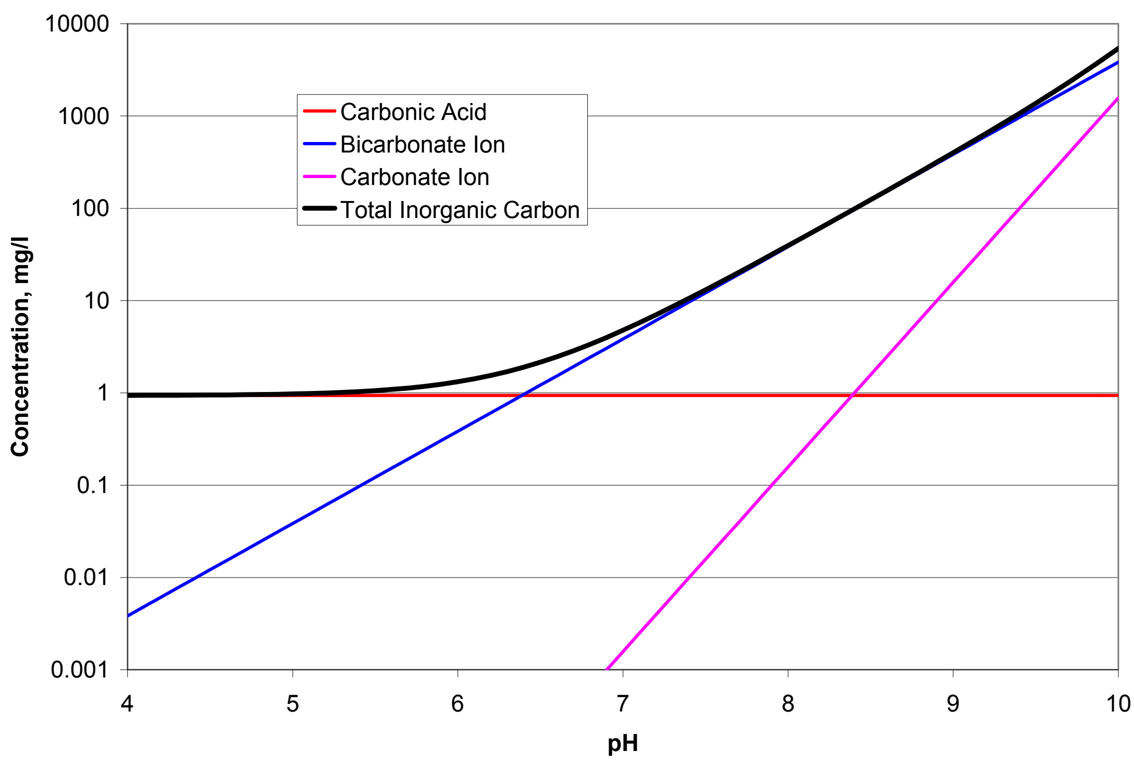

Figure 1-5 Equilibrium Total Inorganic Carbon Concentration with pH at 68 ^oF

Above a pH of about 7.5, the equilibrium inorganic carbon concentration increases by an order of magnitude for each pH point. 7.5 is a typical pH for the Sacramento River proper, although many tributaries have pH above 8, indicating the high sensitivity of inorganic carbon concentration to pH. Figure 1.4 shows that a substantial portion of salinity is inorganic carbon. It is common practice to assume that salinity is a conservative pollutant, but it is important to recognize that the inorganic carbon portion is not conservative and originates in the atmosphere as a function of pH.

Model Inputs

WARMF is a dynamic watershed model. It requires time series data and model coefficients which describe the physics of the watershed. All of the time series data are derived from measured data. Some of the model coefficients are known from data and thus are not subject to calibration. Other coefficients are only generally known and thus are adjusted to improve the match between model simulation results and measured in-stream flow and water quality data.

The time series used as model inputs are meteorology, air/rain chemistry, boundary inflows, diversions, and point sources. The values of each of these vary daily and drive the model simulations. Categories of time invariant model coefficients for which information is available includes fertilizer application, irrigation water distribution, geometric data (e.g. watershed slope and aspect), and land use. The values of the model coefficients do not change during the course of the simulation. The combination of the time series inputs and model coefficients is used to calculate the amount of water and concentrations of each chemical constituent throughout the watershed for each time step.

The daily values of driving variables are compiled and imported into the Data module of WARMF. During the simulation, the Data module automatically feeds these daily values to the model.

The following sections describe the measured input data for the Sacramento River Model.

Geometric Data

The Digital Elevation Model (DEM) data available from the EPA BASINS web site were imported to WARMF. WARMF used the DEM data to delineate the Sacramento River model domain into land catchments and river segments. WARMF also calculated the geometric dimensions and slope of land catchments and the length and slope of river segments. River segments were further divided manually to spatially align with observed hydrology and water chemistry locations, and to facilitate simulation of specific sub-basins of interest.

Land Use Data

The quantity, timing, and quality of surface water discharge are dependent upon the land use present within the watershed. Each land catchment simulated in the Sacramento River watershed model was assigned various land uses on its surface based on current land use data. The

Sacramento River watershed model was originally set up to simulate hydrologic and water quality processes based on the following land use categories: barren, commercial/industrial, confined feeding, coniferous, deciduous, fallow/non-irrigated farm, farm, grassland, marsh, mixed forest, orchard, pasture, residential, rice, scrub/shrub, and water.

Additional land use resolution was added to the model domain as part of this project. The current version of the Sacramento WARMF model employs 32 separate classes to describe land use within the model domain. The current land use classes include: Barren Land, Cotton, DairyPA, Deciduous Forest, Double Crop DLA, Evergreen Forest, Fallow, Farmsteads, Flowers and nursery, Grassland/Herbaceous, Lagoon, Marsh, Mixed Forest, Native Classes Unsegregated, Olives, citrus & subtropicals, Orchard, Other CAFOs, Other row crops, Paved areas, Perennial forages, Perennial Forages DLA, Rice, Sewage plant including ponds, Shrub/Scrub, Urban Commercial, Urban Industrial, Urban landscape, Urban residential, Vines, Warm season cereals/forages, Water, and Winter grains & safflower. The landuse analysis for this project was conducted by NewFields Agriculture and Environmental Resources (Newfields 2011). The products of this analysis include two ESRI Shapefiles, one depicting current and one depicting an estimate of 2030 landuse within the model domain. These shapefiles were provided to Systech and used as input for the current and future conditions scenarios described in an upcoming section of the report. The current condition shapefile was used to represent historical simulations as well. Using current land use for historical simulations can potentially introduce error, since urbanized area was less during historical time periods. The Source Contributions section of this report shows the magnitude of urban loading assuming current land use. The error introduced by using a current land use for historical runs is a fraction of the urban loading source contributions.

Meteorology Data

In WARMF, each land catchment was assigned the nearest available meteorology station with data of acceptable quality and quantity. Acceptable stations were identified through multiple steps of quality control and data processing.

All available data between 1921 and 2010 in the project region were collected from the California Irrigation Management Information System (CIMIS), the National Climatic Data Center (NCDC), California Data Exchange Center (CDEC), the University of California Integrated Pest Management Touchstone Network, and the PestCast network. The majority of the stations reported only daily precipitation and temperature, though a few stations also reported cloud cover, dew point temperature, wind speed, and air pressure. If cloud cover (CC) was unavailable it was estimated from precipitation (P), average temperature (T_{ave}) and dewpoint temperature (T_{dew}) as follows:

When there is precipitation:

2 cm/day < P	CC = 1
1 cm/day < P ≤ 2 cm/day	CC = 0.9
0 cm.day < P ≤ 1 cm/day	CC = 0.8

When there is no precipitation:

$(T_{ave} - T_{dew}) < 4\ ^{\circ}C$ CC = 0.6
$4\ ^{\circ}C \leq (T_{ave} - T_{dew}) < 6\ ^{\circ}C$ CC = 0.3
$6\ ^{\circ}C \leq (T_{ave} - T_{dew})$ CC = 0

A thorough quality check was performed on the collected meteorological data to remove suspicious or infeasible values, such as outliers and repeated days/months/years of data. Missing data at each station were then filled using data at a nearby station(s) and an adjustment factor to account for climatic variations between stations. To verify the climatic consistency of the final, filled station data, each station's mean characteristics (e.g. mean annual precipitation and mean annual temperature) were calculated and compared to the same values and locations in PRISM datasets. PRISM datasets are high resolution spatial climate datasets produced at Oregon State University using sophisticated geospatial methodologies to account for climatic variations between meteorological station locations. If the characteristics of the filled station data were different from those found at the station's location within the PRISM data, an adjustment was applied to ensure that the filled data was consistent with long term climatic trends at the location. If differences were extremely large, the station was removed from further use as input to WARMF. After this processing step, a total of 60 stations remained for use as input to WARMF. The stations and associated statistics are listed in Table 1.3 and their locations are shown in Figure 1-6.

Table 1.3 Meteorology Stations used for Input to WARMF

Station name	Mean Annual Precip., inches	Mean Annual Air Temp., ^{o}F
Acampo	17.6	60.0
Auburn Municipal	34.0	61.4
Browns Valley	30.3	61.6
Bryte	16.8	62.5
Camp Pardee	21.4	61.5
Chico	25.7	62.3
Clearlake	26.7	56.9
Colgate	40.8	61.6
Colusa (CIMIS)	15.9	61.0
Colusa (NCDC)	15.7	61.4
Cottonwood Creek	35.8	55.5
Cow Creek	45.7	55.5
De Sabla	66.8	55.3
Durham	22.0	61.1
Fair Oaks	22.5	61.8
Fiddletown Dexter	36.4	55.8
Folsom	22.5	61.8
Gerber	23.0	61.7
Grass Valley	52.8	55.3
Indian Valley	22.9	56.4
Lodi	17.0	60.0
Lodi West	12.8	57.9
Manteca	11.4	58.8
Manzanita Lake	41.6	44.6
Marysville	22.6	63.1
Meridian	23.4	60.5
Mineral	54.6	44.8
Mineral II	54.6	44.8

Station name	Mean Annual Precip., inches	Mean Annual Air Temp., ^{o}F
Nicolaus	18.2	62.4
Nicolaus II	18.7	62.2
Oakdale	11.4	58.5
Orland	21.1	61.9
Oroville	26.7	62.1
Oroville Dam	35.1	62.0
Pacific House	50.5	59.7
Paradise	53.8	60.1
Paskenta	25.2	61.9
Placerville	38.4	57.4
Placerville II	47.0	59.6
Plymouth	31.9	55.8
Red Bluff	23.0	62.8
Redding	38.2	62.5
Redding Airport	30.8	63.6
Redding II	38.2	62.5
Sacramento Exec Airport	19.2	61.9
Sacramento (NCDC)	18.1	62.3
Saddlecamp	29.6	54.4
Shingletown	49.2	52.0
Snow Mountain	66.1	45.5
Stockton	15.4	60.2
Stonyford	22.9	62.2
Stony Gorge	21.0	59.9
Sutter Hill	30.0	59.6
Tiger Creek	47.5	57.1
UCCE Sacramento	20.1	61.9
Upper Lake	45.6	56.6
Whiskeytown	62.2	60.6
Williams	15.8	61.8
Willows	18.8	61.4
Woodland	18.6	61.8

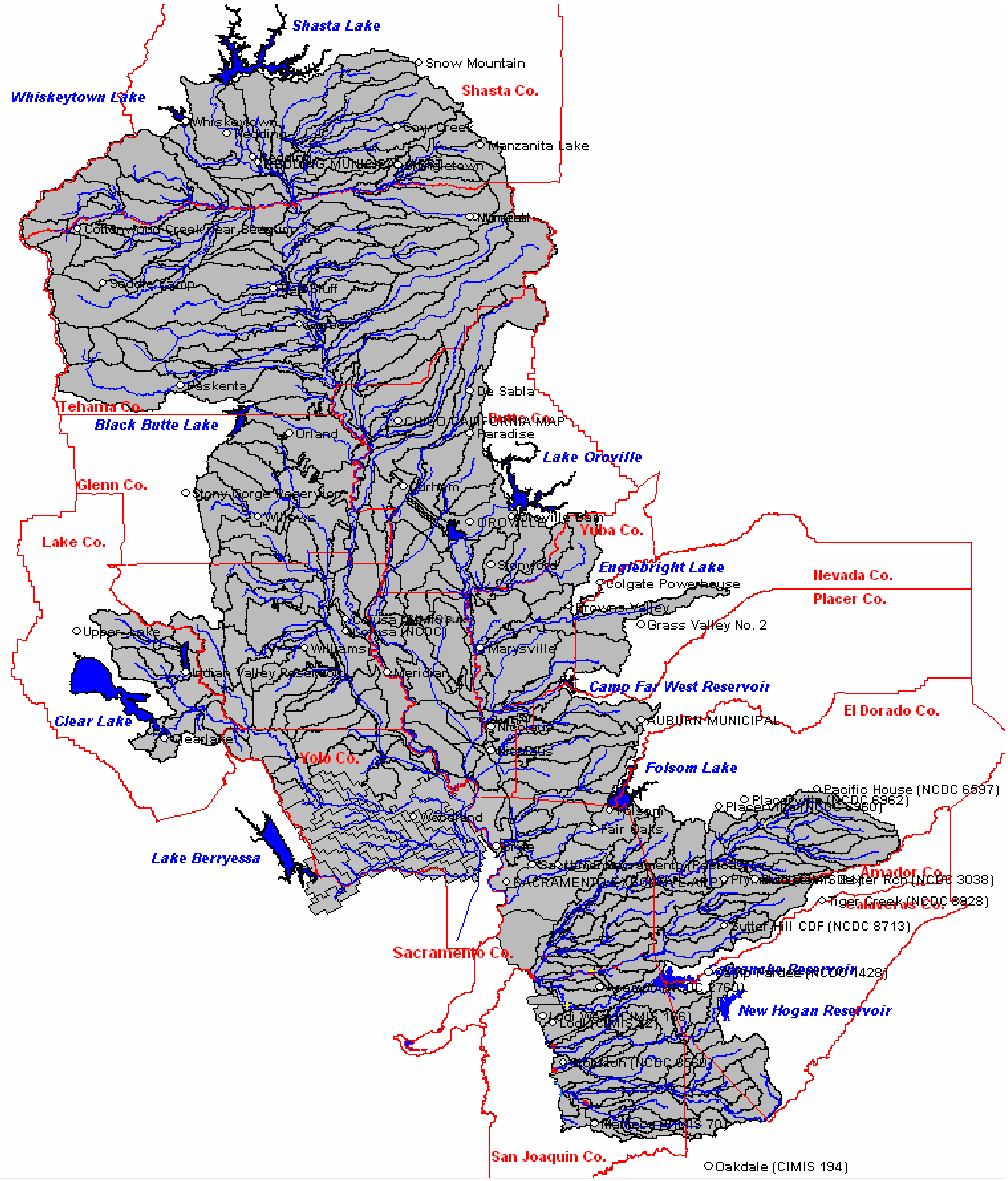

Figure 1-6 Locations of Meteorology Stations in the Sacramento River Watershed

Each land catchment area in WARMF was assigned the nearest of the final 60 stations. However, in many cases the nearest station was located outside of the catchment area and/or large climatic variations occurred within a single catchment area (e.g. due to large elevation changes creating climatic variations not captured by the station network). Therefore precipitation weighting factors and temperature lapse rates were calculated to ensure that the spatial averages of precipitation and temperature across the catchment area were maintained. Similar to the station data adjustment procedure described above, the precipitation weighting factors and temperature lapse rates were calculated using PRISM datasets. First, the spatial average of annual precipitation and temperature were determined from the PRISM data for each catchment area. These values were then compared to the point mean annual precipitation and temperature of each catchment's assigned meteorological station. Precipitation weights were determined as the ratio of the PRISM spatial average annual precipitation to the station point average annual precipitation. Thus for example if the station data underestimated the catchment's spatial average precipitation (e.g. if the station is location at a point of low elevation as compared to the rest of the catchment area), the ratio was greater than 1 and thus the station data was scaled up for that catchment to account for the difference. Temperature lapse rates were determined similarly, though as the difference (rather than ratio) between the PRISM spatial average temperature and the station point average temperature. Catchment temperature values were determined by subtracting the lapse rate from the station temperature data. Thus a negative lapse rate indicates that the overall catchment area is cooler than the assigned station's temperature values.

Air Quality and Rain Chemistry Data

Air quality data were used to calculate the dry deposition of atmospheric ammonia, nitrate, and other constituents to the land and canopy surfaces. Weekly air quality data were obtained from the US EPA's Clean Air Status and Trends Network (CASTNET) sites at Lassen Volcanic National Park and Yosemite National Park.

Rain chemistry data was used to calculate wet deposition falling onto each of the land catchments. Data for rain chemistry were compiled from five National Atmospheric Deposition Program (NADP) sites in the vicinity of the Sacramento River drainage basin: Hopland, Sagehen Creek, Davis, Lassen Volcanic National Park and Yosemite National Park. Data from these stations were entered on a weekly basis for input to the WARMF model. The locations of the five sites in relation to the WARMF model domain are depicted in Figure 1-7.

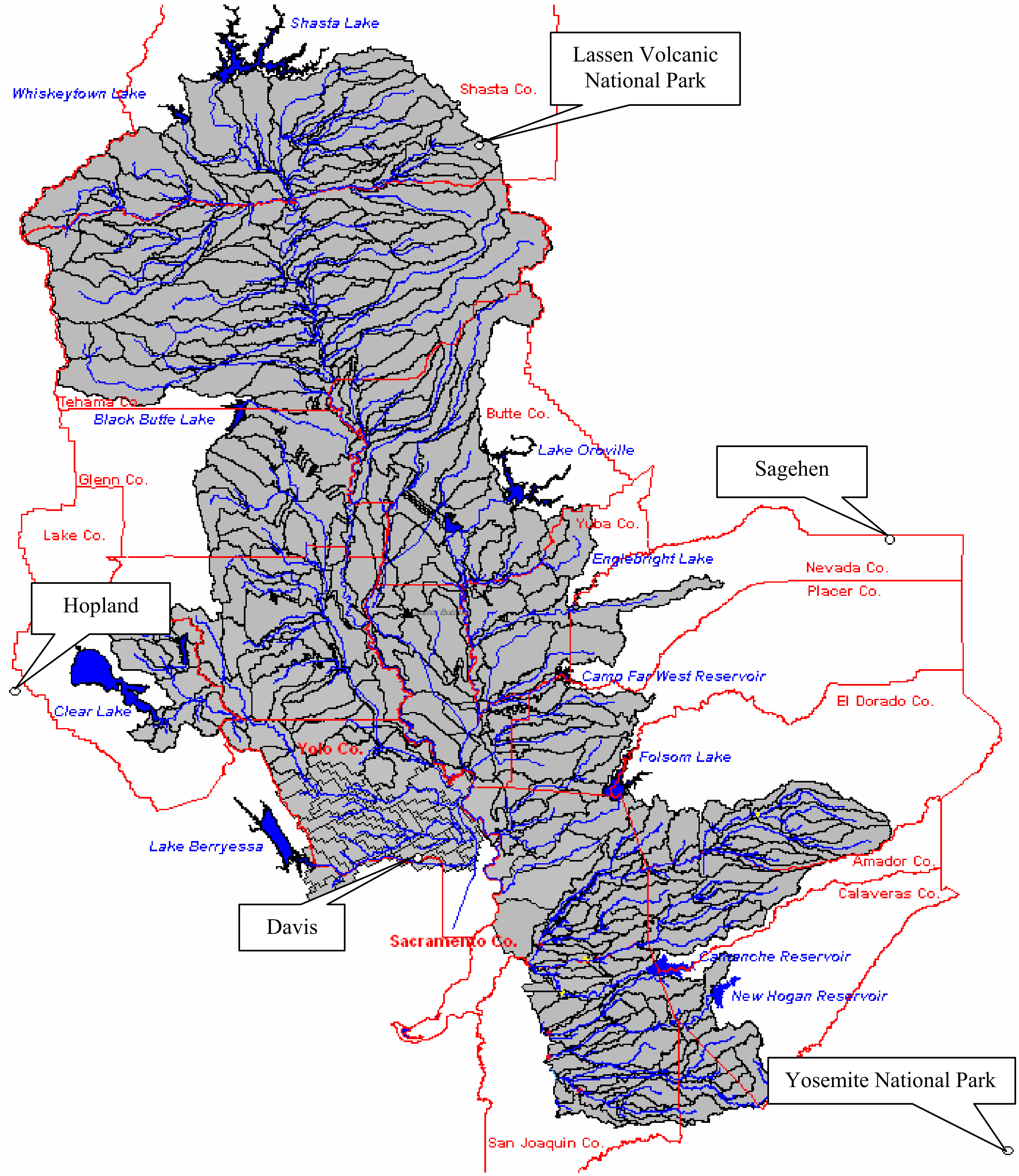

Figure 1-7 Air quality and precipitation chemistry data collection locations in the vicinity of the Sacramento River WARMF model domain.

Boundary River Inflows

Boundary river inflows were external inputs to the WARMF model. These inputs were treated like "point sources", with time series data defining the quantity and quality of water flowing across (from outside to inside) the modeled watershed boundary. Table 1.4 lists the boundary river inflows and their associated data sources. All twelve inflows are located just below major reservoirs, including the Sacramento River below Shasta Lake in the north, four west side tributaries (Clear Creek below Whiskeytown Lake, Stony Creek below Black Butte Lake, Cache Creek below Clear Lake, and Putah Creek below Lake Berryessa) and seven east side tributaries (Feather River below Lake Oroville, Feather River below Thermalito Afterbay, Yuba River below Englebright Lake, Bear River below Camp Far West Reservoir, American River below Folsom Lake, Mokelumne River Below Camanche Reservoir, and the Calaveras River below New Hogan Reservoir).

All available data for daily flow, temperature, and water quality constituent concentrations at the boundary river inflows were collected for the modeling period (1921-2010). Data availability varied greatly between the twelve inflows and also between the various constituents at each station. In all cases, daily flow data were available to create continuous time series for the latter half (1970-2010) of the modeling period. However, in many cases flow data were unavailable for some portion of the early part of the modeling period (before 1970). In those cases, flow was either taken from a nearby downstream station or was assumed to be zero.

Temperature and water quality data were much sparser than flow data and rarely available on a daily basis. Two steps were carried out to fill the data in order to generate a complete daily time series. First, nearby downstream stations were used to fill as much missing data as possible at the primary water quality station(s) near the inflow location. Second, default daily values were determined for an average year based on all of the available observations for each constituent. To do so, monthly average concentrations were first calculated using all of the observations that existed for each month. If no observations were ever collected in a particular month, that month's value was interpolated from the surrounding months. If no data were available for any months for a particular constituent, the monthly averages were estimated from another boundary river inflow of likely similar water quality characteristics (as noted below Table 1.4). The resulting monthly average concentrations were assigned to the 15th of each month and values in between were interpolated (i.e. between the 15th of a given month and the 15th of the prior or following month) to determine the default concentration for each day of the year. If observations were missing for a period of 90 days or longer, the default values were used to fill that portion of the time series. To prevent sharp changes in the resulting time series, a blending algorithm was used to gradually shift chemical concentrations from the last observed value to the default values. For missing periods shorter than 90 days, time series values were interpolated between observations.

For periods of the time series when the daily default values were used (i.e. missing periods greater than 90-days), additional adjustments were applied when possible to further improve the estimates. Specifically, if electrical conductivity (EC) measurements were available, the default ion concentrations were scaled up or down in equal proportions so that their sum multiplied by 1.5 was equal to the EC observations (since the sum of ions is the total dissolved solids (TDS), which multiplied by 1.5 is roughly equal to EC in µs/cm). If measurements of alkalinity were also available, additional adjustment factors for cations and anions were calculated in order to simultaneously match the measured values of EC and alkalinity.

Table 1.4 Data Sources for Boundary River Inflows

Upstream Boundary	Source(s) of Flow Data	Sources of Water Quality Data
Sacramento River at Shasta Dam	Sacramento River at Keswick (USGS 11370500)	Sacramento River at Keswick (USGS 11370500, Bur. Rec. RSA568, CDEC KWK, DWR A2101000)
Clear Creek at Whiskeytown Dam	Clear Creek near Igo (USGS 11372000)	Clear Creek above Paige Bar (DWR) Clear Creek near Igo (USGS 11372000, CDEC IGO) Clear Creek near Mouth [1] (DWR) Sacramento River at Keswick [2] (same stations as listed above)
Stony Creek at Black Butte Dam	Stony Creek below Black Butte Dam (USGS 11388000, CDEC BLB)	Stony Creek below Black Butte Dam (DWR, USACE, BDAT, USGS 11388000) Sacramento River at Keswick [3] (same stations as listed above)
Cache Creek below Clear Lake	Cache Creek below Lower Lake (USGS 11451000)	Cache Creek near Lower Lake (CAWRCB A8135000) Cache Creek NF nr Lower Lake [4] (USGS 11451500, CAWRCB A8205000) Cache Creek nr Rumsey [4] (USGS 11451760)
Putah Creek below Lake Berryessa	Putah Creek near Winters, CA (USGS 11454000)	Putah Creek near Winters, CA (USGS 11454000)
Feather River at Oroville Dam	Feather at Oroville (USGS 11407000)	Feather at Oroville (USGS 11407000, CAWRCB A0519100) Feather nr Gridley [5] (DWR, CDEC GRL, CAWRCB A0516500, USGS 11407150) Bear River near Wheatland [6] (USGS 11424000)
Feather River below Thermalito Afterbay	Thermalito Afterbay release to Feather R (USGS 11406920)	Thermalito Afterbay at Feather R (CAWRCB TA001000) Feather at Oroville [7] (USGS 11407000, CAWRCB A0519100)
Yuba River at Englebright Dam	Yuba R below Englebright Dam nr Smartville (USGS 11418000)	Yuba R Below Englebright Dam nr Smartville (USGS 11418000, CDEC YRS) Yuba R below Dry Creek [8] (USGS 11421500, CAWRCB A0615000)
Bear River at Camp Far West Dam	Bear River near Wheatland (USGS 11424000)	Bear River near Wheatland (USGS 11424000) Bear River at Mouth [9] (DWR, CAWRCB A0651201) Feather at Oroville [10] (USGS 11407000, CAWRCB A0519100)
American River at Folsom Dam	American R at Fair Oaks (USGS 11446500)	American R at Folsom (EPA STORET A7111601 & A7R84271087, USGS 11446200) American R near Fair Oaks [11] (CAWRCB A0718000 & WB00SCRM198, USGS 11446400 & 11446500)
Mokelumne River at	Mokelumne R below	Mokelumne R below Camanche Dam

Upstream Boundary	Source(s) of Flow Data	Sources of Water Quality Data
Camanche Dam	Camanche Dam (USGS 11323500)	(USGS 11323500, CADWR - SWAMP Site 531SJC512, East Bay Municipal Utility District - MSElliott) Camanche Reservoir (East Bay Municipal Utility District - CAMD)
Calaveras River at New Hogan Dam	Calaveras River below New Hogan Dam (CDEC NHG, USGS 11308900, USGS 11309500)	Calaveras R below New Hogan Dam (EPA STORET B2530000 & 405) New Hogan Reservoir (EPA STORET B2R80910485, B2R80920481 & 403)

1 Downstream station used to fill water quality data where primary stations were missing.
2 No data was available on Clear Creek for organic carbon, dissolved oxygen, suspended sediment or BOD. Default daily values for these constituents were derived from average concentrations at Sacramento at Keswick.
3 No data was available on Stony Creek for BOD. Default daily values for this constituent were derived from average concentrations at Sacramento at Keswick.
4 Downstream stations used to fill water quality data if data at primary station(s) were missing.
5 Downstream stations used to fill water quality data if data at primary station(s) were missing.
6 No data was available on Feather River for organic carbon. Default daily values for this constituent were derived from average concentrations in the Bear River near Wheatland.
7 Only temperature data was available for Thermalito Afterbay. All other water quality constituent data were taken from the upstream station, Feather River at Oroville.
8 Downstream stations used to fill water quality data if data at primary station(s) were missing.
9 Downstream stations used to fill water quality data if data at primary station(s) were missing.
10 No data was available on Bear River for inorganic carbon. Default daily values for this constituent were derived from average concentrations in the Feather River at Oroville.
11 Downstream stations used to fill water quality data if data at primary station(s) were missing.

Point Source Discharge Data

A large number of point source discharges exist in the Sacramento Watershed. The locations for 107 point source discharges to rivers and tributaries inside the model domain were identified and defined in the WARMF model. However, flow and/or water quality data were available for only 21 of the 107 locations. The remaining 86 point source discharges were defined in the model with flow and concentrations of zero in case data becomes available at a later date. The station names, locations and mean annual flows of the 21 point source discharges with data are listed in Table 1.5. The most significant of the point source discharges (The Sacramento Regional Wastewater Treatment Plant) was filled with estimates to obtain a complete record for the modeling period of 1921-2010. Information about current population and population growth since 1921 were used to scale values of typical wastewater treatment plant effluent to estimate discharge for the Sacramento wastewater treatment plant. This underestimates loading for the time period before the wastewater underwent secondary treatment. The 86 stations with no data are listed in Table 1.6.

Table 1.5 Point Source Discharges with Data

Name	NPDES	County	Lat	Long	Mean Annual Flow (cfs)
ANDERSON WPCP	CA0077704	Shasta	40.47	-122.28	2.4
CLEAR CREEK WWTP	CA0079731	Shasta	40.50	-122.37	12.6
COTTONWOOD WWTP	CA0081507	Shasta	40.40	-122.25	0.2
REDDING, CITY OF	CA0082589	Shasta	40.47	-122.29	4.3
SHASTA LAKE WWTP WQC	CA0079511	Shasta	40.66	-122.39	1.98
CORNING WWTP	CA0004995	Tehama	39.91	-122.12	1.26
MOLDED PULP MILL ISW	CA0004821	Tehama	40.17	-122.23	2.4
RED BLUFF CITY	CA0078891	Tehama	40.16	-122.22	1.8
WILLOWS WWTP	CA0078034	Glenn	39.50	-122.19	1.35
COLUSA WWTP	CA0078999	Colusa	39.25	-122.06	0.8
MAXWELL PUD	CA0079987	Colusa	39.28	-122.19	0.02
SC-Oroville WWTP	CA0079235	Butte	39.49	-121.56	4.8
CHICO WWTP	CA0079081	Butte	39.68	-121.93	11.7
CITY OF LIVE OAK WWTP	CA0079022	Sutter	39.26	-121.68	0.85
YUBA CITY WWTP	CA0079260	Sutter	39.11	-121.61	8.9
BEALE AIR FORCE BASE	CA0110299	Yuba	39.13	-121.39	0
LINDA CO. WATER DISRICT WATER POLLUTION CONTROL PLANT	CA0079651	Yuba	39.10	-121.58	1.86
OLIVEHURST PUD WWTP	CA0077836	Yuba	38.89	-121.11	3.5
NEVADA CITY WWTP	CA0079901	Nevada	39.26	-121.03	0.8
AUBURN WWTP	CA0077712	Placer	38.89	-121.10	2.2
LINCOLN	CA0084476	Placer	38.90	-121.34	5.4
PLACER COUNTY SMD 1 WWTP	CA0079316	Placer	38.96	-121.11	2.9
PLACER CO DFS	CA0079367	Placer	38.80	-121.13	2.6
PLEASANT GROVE WWTP	CA0084573	Placer	38.79	-121.38	11.8
ROSEVILLE WWTP CITY OF	CA0079502	Placer	38.74	-121.29	16.6
CITY OF SACRAMENTO COMBINED WWTP	CA0079111	Sacramento	38.52	-121.50	612
SACRAMENTO REGIONAL SANITATION DIST.	CA0077682	Sacramento	38.45	-121.46	243
CACHE CREEK INDIAN BINGO	CAU000541	Yolo	38.73	-122.14	0.3
CITY OF WOODLAND WWCF	CA0077950	Yolo	38.66	-121.87	8.8
CITY OF DAVIS STP	CA0079049	Yolo	38.59	-121.67	10.2
UNIVERSITY OF CALIFORNIA DAVIS	CA0077895	Yolo	38.54	-121.75	2.9
WEST SACRAMENTO WWTP	CA0079171	Yolo	38.56	-121.52	8.7

Table 1.6 Point Source Discharges with No Data

Name	NPDES	County	Lat	Long
AC POWDER COATING	CAP000111	Shasta	40.44	-122.29
BELLA VISTA WTP	CA0080799	Shasta	40.60	-122.35
CALARAN SAWMILL	CAU000089	Shasta	40.57	-122.37
CALAVERAS CEMENT COMPANY	CA0081191	Shasta	40.73	-122.32
CALIFORNIA OIL RECYCLERS INC	CAU000084	Shasta	40.52	-122.38
CLEAR CREEK WTP	CA0083828	Shasta	40.60	-122.54
COLEMAN FISH HATCHERY	CA0004201	Shasta	40.40	-122.18
FOOTHILL HIGH SCHOOL CSW WQC	CAU000394	Shasta	40.59	-122.40
INDUSTRIAL OPTICS	CAP000113	Shasta	40.45	-122.30
MILLSEAT FACILITY	CA0082279	Shasta	40.48	-121.86
MOUNTAIN GATE QUARRY	CA0084140	Shasta	40.73	-122.31
SEWAGE DISPOSAL PONDS	CAU000193	Shasta	40.71	-122.34
SHASTA LAKE WTF	CA0004693	Shasta	40.71	-122.41
SHEA CONSTRUCTION	CA0083097	Shasta	40.73	-122.32
SIERRA PACIFIC-ANDERSON	CA0082066	Shasta	40.47	-122.32
SIERRA PACIFIC-SHASTA LAKE	CA0081400	Shasta	40.68	-122.38
TARGET T615	CAU000083	Shasta	40.59	-122.35
US BUREAU OF REC	CA0084298	Shasta	40.69	-122.39
VOORWOOD CO	CAP000112	Shasta	40.45	-122.29
WHEELABRATOR SHASTA	CA0081957	Shasta	40.43	-122.28
WILLIAM HOBLIN	CAU000220	Shasta	40.61	-122.28
BELL-CARTER FOODS INC	CA0081639	Tehama	39.93	-122.18
DALES FACILITY	CA0080381	Tehama	40.37	-122.02
DARRAH SPRINGS HATCHERY	CA0004561	Tehama	40.41	-121.98
MEADOWBROOK FACILITY	CA0080373	Tehama	40.18	-122.24
MT LASSEN TROUT FARMS	CA0082104	Tehama	40.32	-121.97
TEHAMA COUNTY OF	CAU000168	Tehama	40.18	-122.24
WOODSON BRIDGE ESTATES	CAU000201	Tehama	39.91	-122.11
BALDWIN CONTRACTING	CAU001022	Glenn	39.78	-122.20
CITY OF ORLAND WTP	CAU000444	Glenn	39.75	-122.19
BIGGS, CITY OF	CA0078930	Butte	39.41	-121.72
FEATHER RIVER HATCHERY	CA0004570	Butte	39.52	-121.55
GRIDLEY PIT STOP	CAU000223	Butte	39.35	-121.69
NORTH STATE RENDERING	CAU000192	Butte	39.59	-121.69
NORTH YUBA WD	CA0084824	Butte	39.51	-121.27
OROVILLE WYANDOTTE ID	CA0083143	Butte	39.51	-121.46
PID WTP	CA0083488	Butte	39.81	-121.58
THERMALITO ANNEX HATCHERY	CA0082350	Butte	39.49	-121.69
CALPINE SUTTER ENERGY CENTER	CA0081566	Sutter	39.11	-121.69
LAKE WILDWOOD WWTP	CA0077828	Nevada	39.23	-121.22
ADVANCED METAL FINISHING LLC	CAP000103	Placer	38.95	-121.08
CARPENTER ADVANCED CERAMICS	CAP000108	Placer	38.95	-121.08
CERONIX	CAP000107	Placer	38.95	-121.08
COHERENT INC AUBURN GROUP	CAP000104	Placer	38.95	-121.08
CUSTOM POWDER COATING	CAP000102	Placer	38.95	-121.09
FORMICA CORPORATION	CA0004057	Placer	38.82	-121.31
SA NO28, ZONE NO6	CA0079341	Placer	38.98	-121.37
SIERRA PLATING	CAP000105	Placer	38.95	-121.10
UNION PACIFIC ROSEVILLE	CAU000049	Placer	38.73	-121.31
UNITED AUBURN INDIAN COMMUNITY	CA0084697	Placer	38.84	-121.31

Name	NPDES	County	Lat	Long
VIAN ENTERPRISES	CAP000106	Placer	38.93	-121.09
A C & W - GW TREATMENT	CA0083992	Sacramento	38.57	-121.30
AEROJET GENERAL CORPORATION	CA0004111	Sacramento	38.61	-121.20
ALTA PLATING INCORPORATED	CAP000027	Sacramento	38.57	-121.49
ASIAN AUTO RECYCLING	CAU000678	Sacramento	38.57	-121.26
BLOMBERG WINDOW SYSTEMS	CAP000026	Sacramento	38.51	-121.50
CAPITAL AUTO PARTS/TOWING	CAU000663	Sacramento	38.69	-121.41
EURO STARS DISMANTLING INC.	CAU000689	Sacramento	38.58	-121.26
EXTREME AUTO DISMANTLING	CAU000680	Sacramento	38.58	-121.26
GSV AUTO DISMANTLERS	CAU000682	Sacramento	38.58	-121.26
K & G AUTO DISMANTLER	CAU000683	Sacramento	38.57	-121.26
NIMBUS HATCHERY	CA0004774	Sacramento	38.63	-121.22
OFFICE OF STATE PUBLISHING	CA0078875	Sacramento	38.59	-121.49
RANCHO AUTO AUCTION	CAU000685	Sacramento	38.56	-121.25
RUEBEN E LEE RESTAURANT	CAU000042	Sacramento	38.60	-121.42
SACRAMENTO FACILITY	CA0082961	Sacramento	38.53	-121.39
SACRAMENTO IU	CAP000094	Sacramento	38.58	-121.49
SEVEN UP BOTTLING CO OF SAN FRANCISCO	CAU000584	Sacramento	38.62	-121.43
SILGAN CAN COMPANY	CAP000093	Sacramento	38.51	-121.47
STATE OF CALIFORNIA GENERAL SERVICES	CA0078581	Sacramento	38.57	-121.50
MCCLELLAN AIR FORCE BASE CA	CA0081850	Sacramento	38.66	-121.40
ZAPAD	CAU000672	Sacramento	38.58	-121.49
CHOPAN AUTO DISMANTLING	CAU000665	Yolo	38.58	-121.55
DAN'S MISSION TOWING	CAU000666	Yolo	38.58	-121.55
GENESIS AUTO DISMANTLER	CAU000667	Yolo	38.58	-121.55

Fertilizer Application Data

WARMF allows for monthly land application loading inputs for each land use. Land application represents any loading to the land surface which does not come from the atmosphere. It includes fertilizer in agricultural and urban land uses and disposal of animal waste from dairies and other confined feeding operations. The application rates used were estimated by NewFields Agriculture and Environmental Resources based on agricultural practices in the Sacramento River watershed. A detailed explanation of the methods used to estimate land application rates will be provided by NewFields in a separate document. The nitrogen and phosphorus application rates used in WARMF are shown in Table 1.7.

Table 1.7 Land Application Rates

Land Use	Ammonia Application Rate lb N/acre/yr	Nitrate Application Rate lb N/acre/yr	Sulfate Application Rate lb/acre/yr	Phosphate Application Rate lb P/acre/yr	Application Months
Barren land					
Cotton	215		727	7	4-10
DairyPA		120	5	6	5-9
Deciduous Forest					
Double Crop DLA	474	25	1462	50	3-9
Evergreen Forest					
Fallow					
Farmsteads	27	7	69		5-9
Flowers and nursery	119	119		7	2-9
Grassland / Herbaceous					
Lagoon	684		745	186	1-12
Marsh					
Mixed Forest					
Native Classes, Unsegregated					
Olives, citrus & subtropicals	317		1076	7	3-10
Orchard	239		809	7	4-10
Other CAFOs	245	236	95	22	1-12
Other row crops	194	21	580	7	5-9
Paved areas					
Perennial forages	119		399	7	3-11
Perennial Forages DLA	580	30	1787	61	3-11
Rice	110		378	23	4-6
Sewage plant incl. ponds					
Shrub/Scrub					
Urban Commercial	12	3	21	6	4-10
Urban Industrial	6	2	5	6	4-10
Urban landscape	157	39	393	6	3-11
Urban residential	56	14	134	6	3-11
Vines	105	27	259	7	4-9
Warm season cereals/forages	30		101	7	4-8
Water					
Winter grains & safflower	20		67	7	3-5

Irrigation Water Distribution

Irrigation from 56 federal, state and private water districts was simulated in the WARMF Sacramento River model. Where the district boundaries overlapped the land catchment boundaries, irrigation water was applied to the land in the model. The irrigation waters were diverted from various sources shown in Table 1.8. Many additional smaller diversions, often for individual farms, were also included in the model.

Table 1.8 Sources of Irrigation Water

Irrigation District Name	Water Source
4-M W.D.	Sacramento River upstream of Hamilton City
Anderson-Cottonwood I.D.	Sacramento River upstream of Bend Bridge
Arbuckle P.U.D.	Cottonwood Creek, Middle Fork
Biggs-West Gridley W.D.	Sutter-Butte Main Canal
Browns Valley I.D.	Yuba river
Camp Far West I.D.	Bear River
Capay Rancho W.D.	Pine Creek
Colusa County W.D.	Sacramento River upstream of Hamilton City
Colusa Properties	Sacramento River upstream of Verona
Cordua Irrigation District	Yuba River
Cortina W.D.	Sacramento River upstream of Hamilton City
Davis W.D. (Tc)	Sacramento River upstream of Hamilton City
Deseret Farms Of California	Sacramento River upstream of Hamilton City
Dunnigan W.D.	Sacramento River upstream of Hamilton City
El Dorado I.D.	Carson Creek, Sly Park Creek
Galt I.D.	Laguna Creek
Glenn Colusa I.D.	Sacramento River upstream of Hamilton City
Glenn Valley W.D.	Sacramento River upstream of Hamilton City
Glide W.D.	Sacramento River upstream of Hamilton City
Holthouse W.D.	Sacramento River upstream of Hamilton City
Jackson Valley I.D.	Jackson Creek
Kanawha W.D.	Sacramento River upstream of Hamilton City
Kirkwood W.D.	Sacramento River upstream of Hamilton City
Knights Landing Service Dist.	Sacramento River upstream of Verona
La Grande W.D.	Sacramento River upstream of Hamilton City
M And T Chico Ranch Inc.	Sacramento River upstream of Hamilton City
Maxwell I.D.	Sacramento River upstream of Hamilton City, Sacramento River upstream of Verona, Colusa Basin Drainage Canal
Meridian Farms Water Co.	Sacramento River upstream of Verona
Myers-Marsh M.W.C.	Sacramento River upstream of Hamilton City
Natomas Central M.W.D.	Sacramento River upstream of Verona
Nevada I.D.	Yuba River, Bear River
Newhall Land & Farming Co.	Sacramento River upstream of Verona
North Delta Water Agency	Putah Creek
North San Joaquin W.C.D.	Mokelumne River
Oji Brothers Farm, Inc.	Sacramento River upstream of Verona
Olive Percy Davis (Davis Ranches)	Colusa Basin Drainage Canal, Sacramento River upstream of Verona
Omochumne-Hartnell W.D.	Cosumnes River, Deer Creek
Orland-Artois W.D.	Sacramento River upstream of Hamilton City
Paradise Irrigation District	Little Butte Creek
Pelger M.W.C.	Sacramento River upstream of Verona
Pleasant Grove-Verona M.W.C.	Sacramento River upstream of Verona
Princeton-Codora-Glenn I.D.	Sacramento River upstream of Verona, Willow Creek
Provident I.D.	Sacramento River upstream of Hamilton City, Sacramento River upstream of Verona,

Irrigation District Name	Water Source
	Willow Creek
Putah South Canal	Putah Creek
Reclamation District 1004	Sacramento River upstream of Verona
Reclamation District 108	Sacramento River upstream of Verona
River Garden Farms Co.	Sacramento River upstream of Verona
Roberts Ditch Co.	Sacramento River upstream of Verona
Sutter Mutual Water Company	Sacramento River upstream of Verona
The Oji's	Sacramento River upstream of Verona
Thermalito Irrigation District	Feather River
Tisdale I. & D.C.	Sacramento River upstream of Verona
Tisdale I. & D.C. Service Area	Sacramento River upstream of Verona
Westside W.D.	Sacramento River upstream of Hamilton City
Woodbridge I.D.	Mokelumne River
Yolo County FC & WCD	Cache Creek

The locations of all water diversions from the Sacramento River and its tributaries are shown with white dots in Figure 1-8. The timing of irrigation withdrawals was determined based on the best available data for each of the diversions included in the WARMF Sacramento River simulation. During time periods when measured diversion data exist (see Table 1.9), water withdrawals were simulated using these data. During other periods, irrigation withdrawals were estimated by calculating monthly averages from the existing data then populating the diversion file with this information. Diversion water withdrawal data were unavailable for many of the diversions simulated. These diversions were simulated using the permitted withdrawal quantities, distributed throughout the year according to a distribution of monthly water withdrawals synthesized from timing information from other diversion locations with available data.

Each of the irrigation diversions included in the model were simulated dynamically by WARMF. For each diversion, WARMF diverts the quantity of irrigation water from their respective diversion point(s), and applies the water to specified land use types contained within each of the land catchments intersecting the irrigation district boundary. The chemical composition of the diverted water is defined by the WARMF simulation of the river segment from which each is taken.

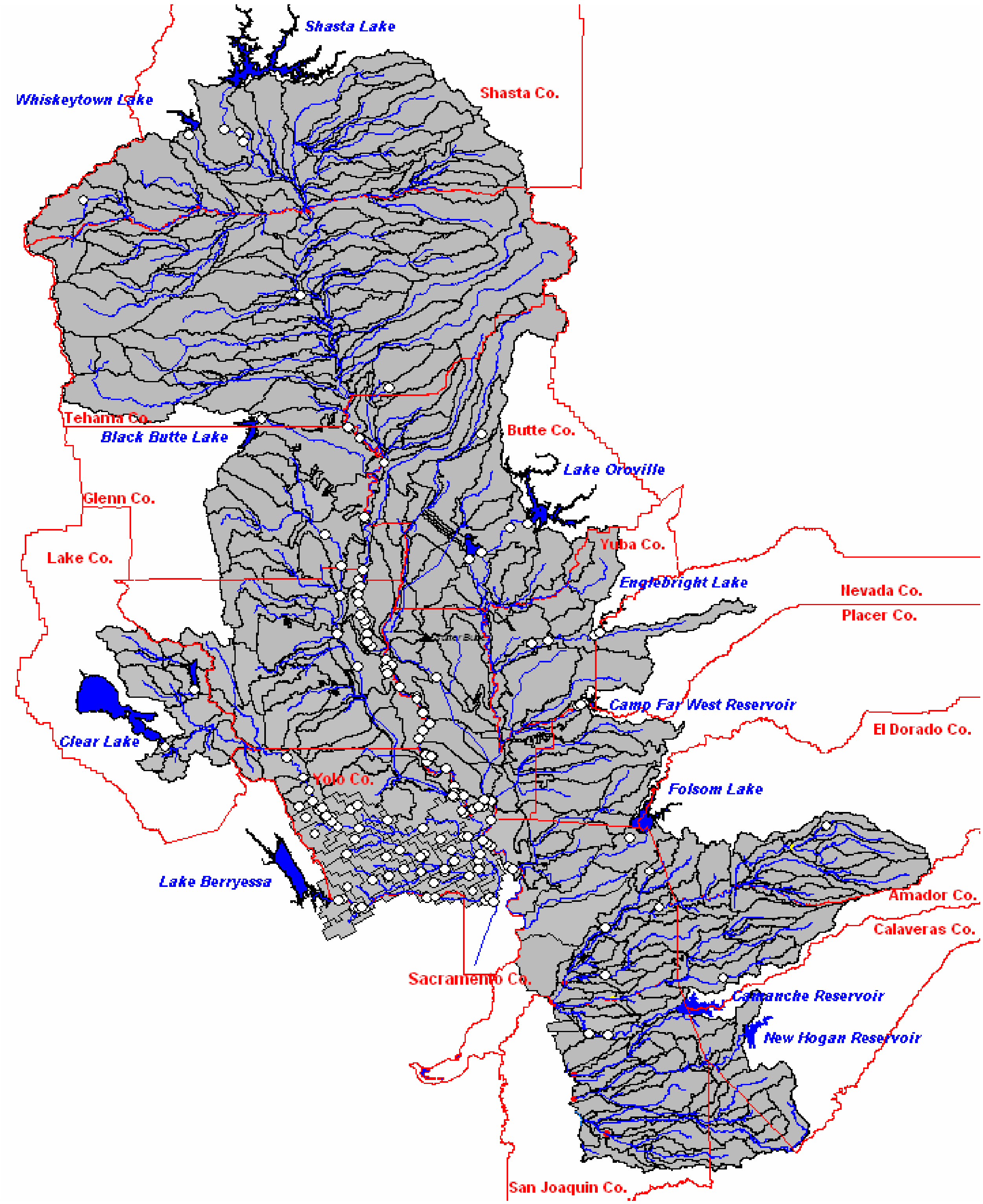

Figure 1-8 Locations (as indicated by the white dots) of water diversions from the Sacramento River and its tributaries.

Table 1.9 Diversions of Irrigation Water in the WARMF Sacramento River model domain.

Diversion	Data Available	Average Diversion Flow (ft^3/sec)
4-M W.D.	Calculated from Demand	2.9
Anderson-Cottonwood I.D.	Jan 1991 - Sept 2008	134.1
Arbuckle P.U.D.	Nov 1997 - Apr 2007	23.3
Biggs-West Gridley W.D.	Calculated from Annual Permit	222.5
Browns Valley I.D.	Calculated from Demand	17.8
Camp Far West I.D.	Calculated from Annual Permit	25.5
Capay Rancho W.D.	Calculated from Demand	0.8
Colusa County W.D.	Calculated from Demand	76.2
Colusa Properties	Calculated from Annual Permit	2.8
Cordua Irrigation District	Oct 1987 - Oct 1991	135.2
Cortina W.D.	Calculated from Demand	1.4
Davis W.D. (Tc)	Calculated from Annual Permit	2.8
Deseret Farms Of California	Calculated from Demand	1.7
Dunnigan W.D.	Calculated from Demand	18.1
El Dorado I.D.	Calculated from Demand	40
Galt I.D.	Calculated from Demand	14.6
Glenn Colusa I.D.	Jan 1993 - Dec 2007	870.3
Glenn Valley W.D.	Calculated from Demand	1.1
Glide W.D.	Calculated from Demand	18.8
Holthouse W.D.	Calculated from Demand	2.1
Jackson Valley I.D.	Calculated from Demand	14.6
Kanawha W.D.	Jan 1993 - Dec 2007	40.1
Kirkwood W.D.	Calculated from Demand	1.0
Knights Landing Service Dist.	Jan 2007 - Dec 2007	1.2
La Grande W.D.	Calculated from Demand	6.9
M And T Chico Ranch Inc.	Calculated from Demand	12.4
Maxwell I.D.	Jan 1993 - Dec 2007	70.6
Meridian Farms Water Co.	Calculated from Demand	32.8
Myers-Marsh M.W.C.	Jan 1993 - Dec 2007	0.4
Natomas Central M.W.D.	Calculated from Demand	110.5
Nevada I.D.	Calculated from permitted withdrawal	102.2
Newhall Land & Farming Co.	Jan 1993 - Dec 1993	50.2
North Delta Water Agency	Calculated from Demand	2.8
North San Joaquin W.C.D.	Calculated from Demand	27.6
Oji Brothers Farm, Inc.	Jan 1993 - Dec 2007	10.0
Olive Percy Davis	Jan 1993 - Dec 2004	66.4
Omochumne-Hartnell W.D.	Calculated from Demand	72.9
Orland-Artois W.D.	Calculated from Demand	71.4
Paradise Irrigation District	Calculated from permitted withdrawal	25.3
Pelger M.W.C.	Calculated from Demand	7.0
Pleasant Grove-Verona M.W.C.	Calculated from Demand	21.8
Princeton-Codora-Glenn I.D.	Jan 1993 - Dec 2007	96.7
Provident I.D.	Jan 1993 - Dec 2007	189.9
Putah South Canal	Oct 1994 – Sep 2008	252.3
Reclamation District 1004	Calculated from Demand	80.1

Diversion	Data Available	Average Diversion Flow (ft^3/sec)
Reclamation District 108	Calculated from Demand	192.0
River Garden Farms Co.	Jan 1993 - Dec 2007	31.0
Roberts Ditch Co.	Calculated from Demand	4.3
Sutter Mutual Water Company	Jan 1993 - Dec 2007	266.7
The Oji`S	Calculated from Demand	3.0
Thermalito Irrigation District	Calculated from permitted withdrawal	22.7
Tisdale I. & D.C.	Calculated from Demand	9.3
Westside W.D.	Calculated from Demand	44.7
Woodbridge I.D.	Apr 1926 – Sep 2009	116.4
Yolo County FC & WCD	Jan 1975 - Sep 2008	215.3

The quantity of irrigation water applied within each land catchment was calculated using a geographic information system (GIS). In the GIS, an intersection between layers representing the WARMF catchments and the irrigation district boundaries was created. The resulting layer was then employed to query a land use dataset to determine the land use distribution within each irrigation district present within each of the WARMF catchments. The calculated areas of each irrigated land use were used to estimate the demand for irrigation water within each of the WARMF catchments. Irrigation requirements for various land uses (provided by NewFields) are shown in Table 1.10.

Table 1.10 Applied Water Rates (feet/year)

Land Use Class	CIMIS Evapotranspiration Zone[1]						
	8	10	11	12	13	14	15
Cotton	3.4	3.2	N/A	4.2	N/A	4.3	4.6
Double Crop DLA	N/A	N/A	N/A	4.6	N/A	4.2	4.5
Farmsteads	4.0	3.4	4.4	5.3	4.1	5.4	6.0
Flowers and nursery	1.9	N/A	N/A	2.6	2.0	2.7	3.0
Olives, citrus, and subtropicals	1.9	N/A	2.2	2.6	2.0	2.7	3.0
Orchard	2.8	2.5	3.2	3.7	3.1	3.8	4.0
Other row crops	3.2	3.0	N/A	3.7	3.6	3.9	4.0
Perennial forages	3.7	3.1	4.1	4.9	3.8	5.0	5.6
Perennial forages DLA	N/A	N/A	N/A	4.9	N/A	5.0	5.6
Rice	3.4	N/A	N/A	3.9	3.8	4.1	4.2
Urban commercial	2.2	1.8	2.4	2.9	2.3	2.9	3.2
Urban industrial	2.2	1.8	2.4	2.9	2.3	2.9	3.2
Urban landscape and open space	3.5	2.9	3.8	4.6	3.6	4.7	5.2
Urban residential	4.0	3.4	4.4	5.3	4.1	5.4	6.0
Vines	1.7	1.5	1.9	2.2	1.8	2.3	2.5
Warm season cereals and forages	3.1	2.9	3.3	3.6	3.4	3.7	3.9
Winter grains and safflower	0.6	0.2	0.6	1.2	0.3	1.2	1.6

[1]Values of N/A represent combinations of land use class and evapotranspiration zone that do not exist within the WARMF model domain

In the Cache and Putah Creek watersheds in Yolo County, a detailed linkage between WARMF and the CVHM groundwater model was used to integrate groundwater usage with irrigation. In these watersheds, pumped groundwater was used in addition to surface water withdrawals to satisfy the irrigation water quantity requirements. In several cases elsewhere in the Sacramento River watershed, the demand for irrigation water calculated based on the number of cultivated acres within the irrigation district boundary exceeded the supply of irrigation water. Irrigation withdrawals were increased to meet the water demands of the cultivated land within the irrigation district boundary. These cases are identified in Table 1.9, where "calculated from demand" is entered in the data available column.

2 MODEL CALIBRATION

Procedure

Given meteorological and operational data, the Sacramento River Model made predictions for stream flow and water quality at various river segments. At locations where monitoring data was collected, the model predictions should match the measured stream flow and water quality. Initially, some model coefficients, such as physical properties of the watershed, are known. Other coefficients are left at default or typical literature values. The initial predictions made did not necessarily match the observed values very well. Model calibration was performed by adjusting model coefficients within reasonable ranges to improve the match between model predictions and observed data.

The model predictions and observed data were compared graphically. In the graph, the time series of model predictions were plotted in a curve on top of measured data. If the observed values fell on top of the curve, the match could be determined as good or poor by visual inspection.

The model predictions and observed data were also compared statistically. The differences between the predicted and observed values are errors. The magnitudes of the errors were calculated in the statistical terms of relative error, absolute error, root mean square error, and correlation coefficient. The relative (E_r) and absolute (E_a) errors are the primary statistics used in model calibration and are described as follows:

$$E_r = \frac{\sum (simulated - observed)}{n}$$

$$E_a = \frac{\sum | simulated - observed |}{n}$$

The error of each instance where there are both simulation results and observed data is the simulated minus the observed. The relative error cancels out errors greater than and less than observed and is thus a measure of model accuracy or bias. The absolute error measures model precision. Both can be expressed as a percent by dividing by the average observed value.

Both graphical and statistical comparisons were made with WARMF. WARMF has a scenario manager, where each scenario is a set of model input coefficients and corresponding simulation results. Scenario 1 may be used to represent a set of model coefficients used in the simulation. Scenario 2 may be used to represent a second set of modified model coefficients used in the simulation. After the simulations are complete, WARMF can plot the observed data as well as the model predictions for both scenarios on the same graph. By visual inspection, it is relatively easy to see whether the changes to model coefficients improve the match.

Likewise, WARMF calculates the values of various error terms for the model predictions. The comparison of the numerical values of errors for two scenarios can lead the user to adjust the model coefficients in the right way to reduce the errors.

Model calibration followed a logical sequence. Hydrological calibration was performed first, because an accurate flow simulation is a pre-requisite for accurate water quality simulation. The calibrations for temperature and conservative substances were performed before the calibration of nutrients (phosphate, ammonia, and nitrate), algae and dissolved oxygen concentrations.

Only a few model coefficients were adjusted for each calibration. For hydrological calibration, the boundary river inflows were checked for their accuracy as discussed in Chapter 1 of this report. Evapotranspiration coefficients, soil thickness, field capacity, saturated moisture, and hydraulic conductivity were then adjusted so that the simulated runoff from catchments could account for flow in headwater tributaries and thus for increases in flow between the monitoring stations along the mainstem of the Sacramento. For water quality calibration, coefficients used for model calibration include reaction rates, initial concentrations in the soil, and properties of each land use such as productivity. If the model does not match observed data after adjusting model coefficients, an investigation may find another cause of the mismatch, such as a diversion or point source missing from the model.

Model Coefficients

There are thousands of model coefficients in the Sacramento River WARMF model, including chemical reaction rates, soil depths and hydraulic conductivities, soil mineral compositions, temperature correction factors (to dynamically adjust rates for temperature changes), and many others. Some apply throughout the watershed (referred to as "system coefficients"), some apply to individual land uses, and other coefficients apply to individual catchments and river segments. Many of the coefficients do not have a significant impact on simulation results and therefore could be safely left at default literature values unless there was location-specific information to enter. Coefficients to which the model is more sensitive had to be calibrated. WARMF contains default values of those parameters, which were used as the initial values for the model. These initial values were adjusted during the model calibration process in order to better match the simulations of stream flow and water quality with observations. The model coefficients that were calibrated are described in more detail in the following sections.

System Coefficients

The system coefficients (i.e. those that apply to the entire system) can be viewed by double-clicking on the white space on the WARMF map. For the Sacramento River model, evaporation-related coefficients were calibrated while other system coefficients relating to hydrology, such as snow melt rates, were left at default values. Table 2.1 lists the evaporation coefficients, along with the typical ranges within which the coefficients vary. The last column is the value used for the Sacramento River calibration.

Table 2.1 Calibrated System Coefficients

Coefficient	Units	Description	Range	Value
Evaporation Magnitude	None	Multiplier of potential evapotranspiration calculated from temperature, humidity, and latitude	0.6 – 1.4	1
Evaporation Skewness	None	Seasonal adjustment of evapotranspiration calculations	0.6 – 1.4	1

There are a number of model system coefficients which have values for each land use. These coefficients define how the different land uses receive anthropogenic model inputs such as irrigation and respond to natural model inputs such as atmospheric deposition. These coefficients are accessed in WARMF the same way as the coefficients above, by double-clicking in the white space on the WARMF map. These were set based on literature values and agricultural practice. The land use coefficients are under the land use tab of the ensuing dialog box. The model is sensitive to the coefficients shown in Table 2.2.

Table 2.2 Calibrated System Land Use Coefficients

	Impervious Fraction	Cropping Factor	Productivity	Leaf Area Index
Units	None	none	kg/m2/yr	none
Description	Portion of each land use which is paved	"C" factor of Universal Soil Loss Equation[1]	Net creation of vegetation	Ratio of leaf area to land area[1]
Range	0 - 1	0 - 1	0 – 2.02	0-14
Barren land	0	1	0	0
Cotton	0	0.5	0.06	1.0
DairyPA	0	0.5	0	1.0
Deciduous Forest	0	0.0055	0.8	1.0
Double Crop DLA	0	0.5	3.14	1.0
Evergreen Forest	0	0.01	0.8	13.0
Fallow	0	0.1	0.1	1.5
Farmsteads	0.10	0.2	0.27	0.4
Flowers and nursery	0	0.5	2.02	1.0
Grassland/Herbaceous	0	0.075	0.1	1.5
Lagoon	0	0	0	0
Marsh	0	0	0.8	1.5
Mixed Forest	0	0.01	0.8	7.0
Native Classes Unsegregated	0	0.01	0.3	1.0
Olives, citrus & subtropicals	0	0.1	2.02	1.0
Orchard	0	0.1	0.67	1.0
Other CAFOs	0.15	1	0	0
Other row crops	0	0.5	1.34	1.0
Paved areas	1.00	0	0	0
Perennial forages	0	0.1	1.57	1.5
Perennial Forages DLA	0	0.5	1.57	1.0
Rice	0	0.01	0.90	1.0
Sewage plant incl. ponds	0.95	0	0	0
Shrub/Scrub	0	0.075	0.3	1.5
Urban Commercial	0.80	0.5	0.22	1.0
Urban Industrial	0.90	0.5	0.22	1.0
Urban landscape	0.20	0	0.27	0
Urban residential	0.15	0.125	0.27	0.4
Vines	0	0.1	0.40	1.0
Warm season cereals/forages	0	0.5	2.02	1.0
Water	0	0	0	0
Winter grains & safflower	0	0.5	1.12	1.0

[1] These coefficients vary by month. Coefficients for May are shown for illustrative purposes.

Catchment Coefficients

Catchment coefficients are the coefficients that apply to individual catchments throughout the modeled watershed area. These coefficients are important for simulating shallow groundwater flow and nonpoint source load. They can be set to different values for each catchment if they have different properties or lumped together with the same values. The coefficients for each individual catchment can be viewed and edited in WARMF by double-clicking on a catchment.

The catchment area, slope, and aspect were calculated from digital elevation models and are not subject to calibration. Meteorology coefficients were calculated based on meteorology station data and high resolution gridded climate data (PRISM data) as described in Chapter 1. In a few cases where it was evident that the total volume of rainfall was consistently too high or too low, the meteorology coefficients were further adjusted during the calibration process. Land uses were calculated by overlaying a land use shapefile with catchment boundaries. Fertilization and irrigation were estimated from agricultural practice as shown in Table 1.7 and Table 1.10. The remaining coefficients that require calibration are primarily soil properties and chemical reaction rates.

Calibration of the soil properties (listed in Table 2.3) is essential to adequately match the simulated with the observed quantity and timing of streamflow. Three soil layers were used in the Sacramento River application. These layers represent the shallow groundwater that interacts with surface waters, which is the focus of watershed modeling. Deep groundwater, which does not interact significantly with surface waters, is not included in the model. The Sacramento River WARMF application includes 479 individual catchments. However, observed streamflow data was not available at the outlet of every catchment. Therefore streamflow calibration was performed only where observed data was available. In particular, calibration efforts were focused on headwater tributaries where local area runoff is the sole source of streamflow and the impacts of soil coefficient adjustments are greatest. In catchments further downstream or below a reservoir, inflow to the catchment is much larger than local shallow groundwater runoff. Thus the effects of coefficient adjustments are diluted. In cases where multiple catchments were located upstream of a tributary streamflow station, the soil coefficients of all upstream catchments were assigned the same values and calibrated together.

Table 2.3 Calibrated Catchment Soil Coefficients

Coefficient	Units	Range
Layer 1 thickness	cm	> 0
Layer 2 thickness	cm	> 0
Layer 3 thickness	cm	> 0
Layer 1 field capacity	none	0.1-0.3
Layer 2 field capacity	none	0.1-0.3
Layer 3 field capacity	none	0.1-0.3
Layer 1 saturation moisture content	cm	0.2-0.5
Layer 2 saturation moisture content	cm	0.2-0.5
Layer 3 saturation moisture content	cm	0.2-0.5
Layer 1 initial moisture content	none	0.1-0.5
Layer 2 initial moisture content	none	0.1-0.5
Layer 3 initial moisture content	none	0.1-0.5
Layer 1 Horizontal hydraulic conductivity	cm/d	20-20000
Layer 2 Horizontal hydraulic conductivity	cm/d	20-20000
Layer 3 Horizontal hydraulic conductivity	cm/d	20-20000
Layer 1 Vertical hydraulic conductivity	cm/d	20-20000
Layer 2 Vertical hydraulic conductivity	cm/d	20-20000
Layer 3 Vertical hydraulic conductivity	cm/d	20-20000
Layer 1 Root distribution (fraction) reaching the layer	none	0.0 - 1.0
Layer 2 Root distribution (fraction) reaching the layer	none	0.0 - 1.0
Layer 3 Root distribution (fraction) reaching the layer	none	0.0 - 1.0

Reaction rates are important coefficients for water quality simulations. The reaction rates of most significance for the Sacramento River model are shown in Table 2.4. These rates are dynamically adjusted during the simulation based on changes in temperature. Reactions only occur under the proper dissolved oxygen concentration, for example nitrification under oxic conditions and denitrification when dissolved oxygen is near zero.

Table 2.4 Important Catchment Reaction Rate Coefficients

Reaction Rate	Units	Range	Value
BOD Decay	1/d	0.05-0.5	0.1
Organic Carbon Decay	1/d	0-0.1	0.001
Nitrification	1/d	0-0.1	0.001
Denitrification	1/d	0-0.1	0.1
Sulfate Reduction	1/d	0-0.5	0.05

The other important parameters for calibrating the water quality of the shallow groundwater include the initial concentrations of each chemical constituent in each soil layer of each catchment (Table 2.5). The initial concentrations weren't calibrated, but were set based on a balance over the course of the simulation. The initial concentrations were set individually for each catchment and soil layer to match the ending concentrations of the simulation under the assumption that the actual soil chemistry in the Sacramento Valley is in relative equilibrium rather than undergoing a trend of increasing or decreasing concentration.

Table 2.5 Catchment Initial Soil Pore Water Concentrations

Constituent	Units	Values
Ammonia	mg/l as N	0.02-2
Calcium	mg/l	10-60
Magnesium	mg/l	4-60
Potassium	mg/l	0.5-5
Sodium	mg/l	2.5-230
Sulfate	mg/l	1-330
Nitrate	mg/l as N	0.01-8
Chloride	mg/l	0.1-130
Phosphate	μg/l as P	100-1000
Organic Carbon	mg/l	1-8
Dissolved Oxygen	mg/l	0.1-8

River Coefficients

Physical data for river segments, including upstream and downstream elevations and lengths, are derived from digital elevation model data. Default stage-width curves and roughness coefficients (i.e. Manning's n) were used for each river segment since no travel time or survey data were available to populate these values. A Manning's n value of 0.04 was used as recommended by Rosgen (1996). Default values were also used for reaction rates and river bed scour coefficients. Table 2.6 shows the reaction rates.

Table 2.6 River Reaction Rate Coefficients

Reaction Rate	Units	Range	Value
BOD Decay	1/d	0.1-1	0.2
Organic Carbon Decay	1/d	0.01-0.1	0.07
Nitrification	1/d	0.01-1	0.5
Denitrification	1/d	0-1	0
Sulfate Reduction	1/d	0-0.5	0
Clay Settling	m/d	>0	0.000346
Silt Settling	m/d	>0	8.64
Sand Settling	m/d	>0	1036.8
Diatom Growth	1/d	0.2-0.5	3.2
Diatom Respiration	1/d	0.1-0.5	0.15
Diatom Mortality	1/d	0.1-0.5	0.05
Diatom Settling	m/d	0-1	0
Detritus Decay	1/d	0-1	0.2
Detritus Settling	m/d	0-1	0
Settled Detritus Decay	1/d	0-0.1	0.2

In addition to the settling rates shown above sediment transport in rivers is affected by scour from the river bed. Scour is controlled by the shear velocity of the water next to the river bed.

Above the critical shear velocity, scour is calculated in the form aV^b. For all river segments in the Sacramento River WARMF model, $a=1.0 \times 10^{-6}$ and b=1.3.

Adsorption coefficients control the partitioning between the dissolved phase of each constituent and the portion adsorbed to suspended sediment. For ammonia and phosphate, the adsorption isotherms were calculated using concurrent data of suspended sediment with ammonia, nitrate, and total nitrogen for the ammonia isotherm, and phosphate and total phosphorus for the phosphorous isotherm. Although calculated values varied greatly based on location and sample date, median values were determined (Table 2.7) and applied uniformly to all river segments. Default isotherms were used for all other constituents.

Table 2.7 Adsorption Isotherm Coefficients

Constituent	Units	Values
Ammonia	L/kg	1,400,000*
Calcium	L/kg	472.552
Magnesium	L/kg	404.556
Potassium	L/kg	197.971
Sodium	L/kg	20.7365
Sulfate	L/kg	16.2596
Nitrate	L/kg	0
Chloride	L/kg	0
Phosphate	L/kg	200,000*
Organic Carbon	L/kg	107.184
EC (Conservative)	L/kg	0

* Calculated from concurrent data, all others default values (no concurrent data was available)

Hydrologic Calibration

Hydrologic calibration is the process of adjusting the coefficients of the rainfall-runoff model within WARMF so that the simulations of streamflow match the observations as well as possible. There are three levels of hydrologic calibration: global, seasonal, and event. Global calibration is the process of matching the simulated annual volume of water passing a gage to the volume measured at the gage. In seasonal calibration, the simulated seasonal variation of streamflow is compared and adjusted to follow the same pattern on a measured hydrograph (i.e., a graph of streamflow rising and falling over time). The measured hydrograph typically has a period of high flow during the rainfall season and a recession to base flow during the dry season. Event calibration is the process of matching the simulated peak flows to the observed peaks during precipitation events.

There were 37 streamflow gaging stations on headwater tributaries within the Sacramento River WARMF model domain where simulated flow could be compared to observed data for model calibration. These 37 stations and the catchments calibrated using the data are listed below in Table 2.8.

Table 2.8 Tributary Streamflow Stations and Calibrated Catchments

Gaging Station	Tributary catchment	Years calibrated
Cow Creek near Millvale	Cow Creek	1997-2007
Cottonwood Creek Near Cottonwood	Cottonwood Creek	1997-2007
Battle Creek near Cottonwood	Battle Creek	1997-2007
Red Bank Creek near Red Bluff	Red Bank Creek	1959-1982
Elder Creek near Paskenta	Elder Creek	1997-2007
Paynes Creek near Red Bluff	Paynes Creek	1955-1966
Antelope Creek near Red Bluff	Antelope Creek	1975-1982
Mill Creek near Los Molinos	Mill Creek	1997-2007
Thomes Creek at Paskenta	Thomes Creek	1985-1996
Deer Creek near Vina	Deer Creek	1997-2007
Mud Creek near Chico	Mud Creek	1965-1974
Stony Creek near Hamilton	Stony Creek	1962-1973
Walker Creek at Artois	Walker Creek	1965-1981
Big Chico Creek near Chico	Chico Creek	1997-2007
South Fork Willow Creek near Fruto	S Fork Willow Creek	1963-1978
Butte Creek near Chico	Butte Creek	1997-2007
Stone Corral Creek near Sites	Stone Corral Creek	1970-1985
Bear Creek near Rumsey	Bear Creek	1998-2007
Cache Creek at Yolo	Cache Creek	1997-2007
Feather River below Shanghai Bend	Upper Feather River	1997-2007
Colusa Basin Drain near Colusa	Colusa Basin Drain	1998-2008
Yolo Bypass upstream of Willow Slough	Yolo Bypass	1976-1991
North Horncut Creek near Bangor	N Horncut Creek	1970-1981
South Horncut Creek near Bangor	S Horncut Creek	1975-1986
Deer Creek near Smartville	Deer Creek (Yuba)	1997-2007
Dry Creek near Wheatland	Dry Creek	1952-1962
Dry Creek at Vernon St Br at Roseville	Dry Creek	1997-2007
Arcade Creek near Del Paso Heights	Arcade Creek	1997-2007
Camp Creek near Somerset	Camp Creek	1954-2004
South Fork Cosumnes River near River Pines	Cosumnes River	1957-1980
North Fork Cosumnes River near El Dorado	Cosumnes River	1911-1987
Cosumnes River at Michigan Bar	Cosumnes River	1907-2010
Deer Creek near Sloughhouse	Deer Creek	1960-1977
Cosumnes River at McConnell	Cosumnes River	1941-1982
Dry Creek near Galt	Dry Creek	1926-1997
Mokelumne River at Woodbridge	Mokelumne River	1924-2009
Bear Creek near Lockeford	Bear Creek	1930-1985

The calibration was completed in January 2010 using the original more coarse land use representation of the watershed. The land use was updated in February 2011 using multiple updated sources of geographic information to delineate the watershed into 32 distinct land uses. Many coefficients which describe each land use, in particular agricultural properties, were updated at the same time. There was not time to recalibrate the watershed with the new land use. In cases where the land use and the coefficients that describe each land use changed significantly from the original values, the result is a change in simulation results which may be a poorer fit to the measured data than before the land use was changed.

The Colusa Basin Drain, west of the Sacramento River, is the receiving water for a mostly agricultural watershed. Its flow and water quality is highly dependent upon land use and parameters such as applied irrigation water rate. The change in land use coefficients caused a substantial decrease in simulated flow during the irrigation season as shown in Figure 2-1. These model input coefficients are considered to be "known" and thus not subject to adjustment in the calibration process. The original calibration is shown in blue and the new simulation results in red. With the old land use, the simulated flow averaged 125 cfs less than the observed. The simulation with the new land use averages 483 cfs less than observed. This is too large a discrepancy to be fixed through calibration, rather it calls into question the assumptions of the model. Two possibilities to improve the simulation are to increase the applied irrigation water from the amount shown in Table 1.10 or to assume that a substantial quantity of irrigation supply water is discharged into the Colusa Basin Drain unused.

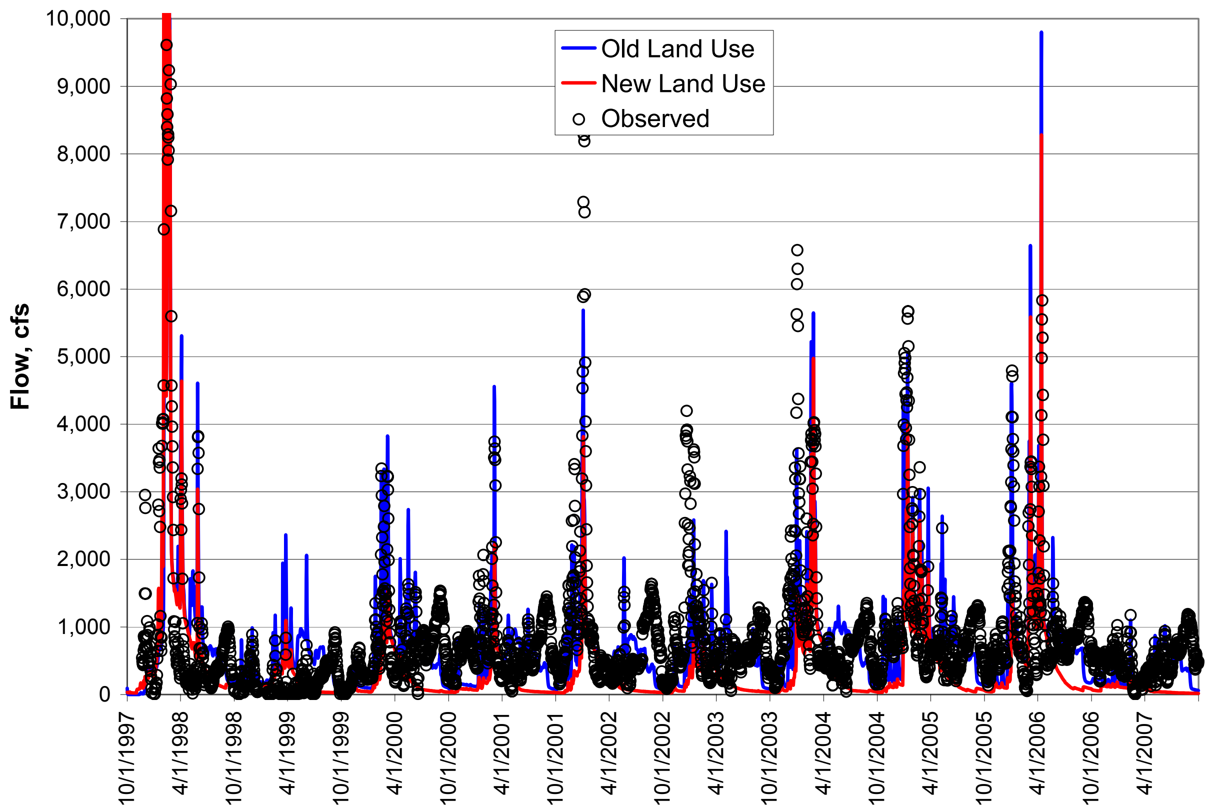

Figure 2-1 Simulated vs Observed Flow at Colusa Basin Drain at Colusa

Some representative calibration results from other Sacramento River tributaries are shown in Figure 2-2 through Figure 2-5 below. Simulation results are shown in blue lines and observed data in black circles. Ideally, the blue lines pass through all the black circles. However this is unlikely to occur due to a combination of model error, input data error, and streamflow measurement error. During the original calibration process, coefficients were adjusted so that large systematic differences were removed and an overall balance was achieved between positive and negative errors (i.e. simulations were not consistently too high or too low indicating that differences are due primarily to random errors in data rather than coefficient values).

In addition to visual inspection, statistical error measurements were used to evaluate how well the simulated matched the observed (under the assumption that the observations are error-free). The three primary statistics used were relative error, absolute error and R squared. Relative error is the average of the deviations between simulated and observed. Absolute error is the average of the absolute differences between model predictions and observations. R squared is the coefficient of determination or the square of the correlation coefficient. Relative error was the primary statistic used in calibration because a low relative error is indicative of a good water balance. Simulating the correct quantity of water is important in determining the sources of pollutants. In rivers with highly variable flow, the R squared statistic is higher with correct timing of peak flows. Since the primary concern for drinking water is in long-term pollutant load, timing of peaks is not a significant concern so R squared is not the best calibration measure. If the model were simulating exactly twice as much flow as observed, R squared would be very high but the calibration would be very poor because it would not have a water balance. Statistics for a selection of the calibrated watersheds are shown in Table 2.9 below. Because the objective of the project was to quickly produce an analytical model capable of predicting flow and water quality at the Delta model boundary control points, calibration efforts focused on these locations. Calibration of the tributary flows is coarse. Further calibration could be used to increase model accuracy in individual tributaries.

Figure 2-2 through Figure 2-5 illustrate the correlation between observed and simulated flow in a selection of tributaries to the Sacramento River. These locations were selected from the larger population of calibration locations to illustrate the diversity of hydrologic conditions that are present within the watershed. Cottonwood and Battle Creeks represent headwater catchments with different soils characteristics; Stone Corral Creek is representative of west side, drier, headwater catchments; Colusa Basin Drain is largely agricultural; Feather River at Olivehurst is dominated by upstream releases from Lake Oroville; and, Dry Creek at Roseville is representative of an urbanizing watershed.

In the figures below, calibration results as well as differences in hydrologic characteristics are evident between watersheds. In the mountainous headwaters (e.g. northern and eastern watersheds such as Cottonwood Creek and Battle Creek), a consistent pattern of significant seasonal runoff is evident and is generally well simulated by the model. In Cottonwood Creek baseflow drops to near zero but continues during the dry season, with few or no peaks. Battle Creek is hydrologically different from Cottonwood Creek. In Battle Creek, the level of baseflow during the dry season is higher than other similar watersheds. This is likely due to the volcanic terrain located within that watershed, which creates different patterns of water storage and release as compared to the others. In order to capture the higher level of baseflow in Battle Creek, different coefficients were used in the upper (high baseflow producing) sub-watersheds and the lower sub-watershed (versus using the same coefficients in all sub-watersheds as for the others). Peaks in these watersheds are generally well-simulated, with errors distributed between over and under-simulation. Errors are likely attributable in large part to error in model input caused by the sparse coverage of meteorology stations across the basin.

In the flatter, drier headwater watersheds (e.g. west and center of the valley such as Stone Corral Creek) the seasonal pattern of runoff is much less consistent from year to year with longer periods of low to zero baseflow. Drier watersheds are typically more difficult to simulate due to the larger impact of data errors, high spatial variability within the watershed, and the occurrence of complex hydrologic processes (e.g. Hortonian runoff). Figure 2-4 below demonstrates that the seasonal pattern of runoff is well captured but large errors occur in the simulation of peaks. These errors have a greater impact on the calibration statistics in these watersheds since the total volume of flow is lower (i.e. the ratio of error to mean flow is higher).

In watersheds downstream of major reservoirs (e.g. Feather River near Olivehurst), flow is dominated by reservoir outflow. The impact of runoff from the local watershed, and therefore the impact of coefficient adjustments, is much lower than in the headwater watersheds. Calibration statistics are generally very good in these watersheds reflecting the fact that the volume of streamflow is primarily reservoir outflow, which is a known quantity. The case is similar for other locations downstream of reservoirs within the watershed and, to a certain extent, for the mainstem of the Sacramento River since a large majority of streamflow in the river results from reservoir outflow from the eight major upstream reservoirs.

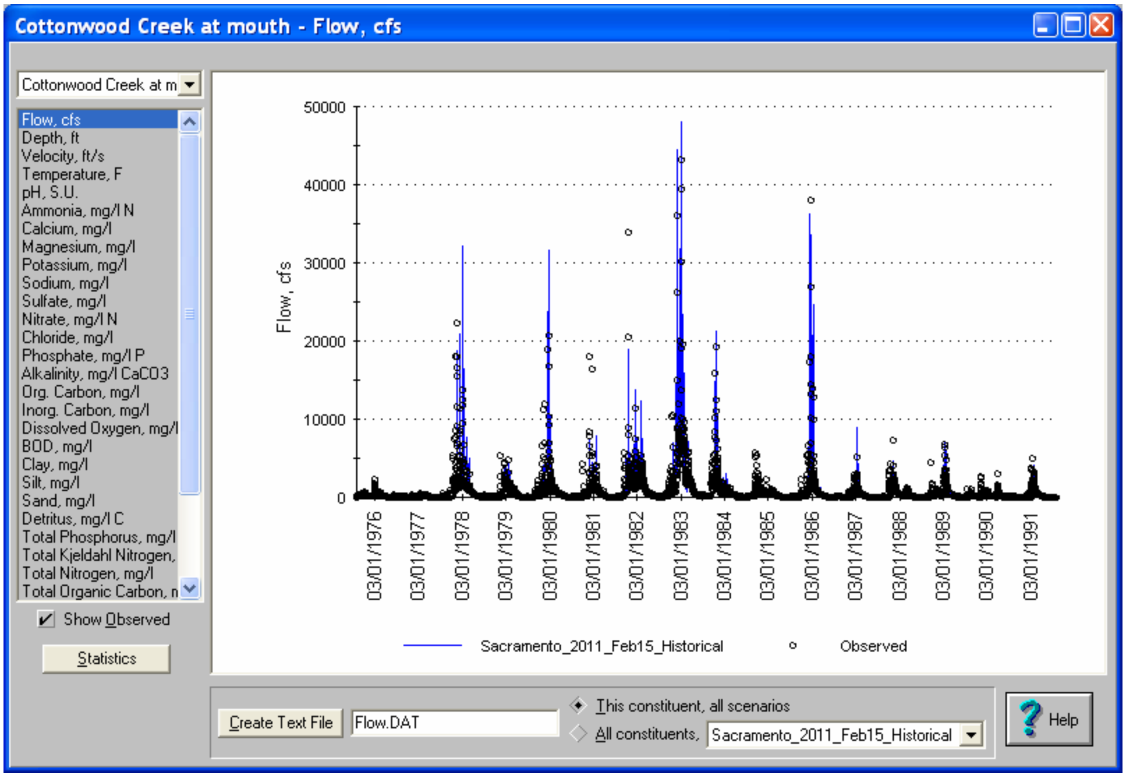

Figure 2-2 Simulated vs Observed Flow at Cottonwood Creek at Mouth

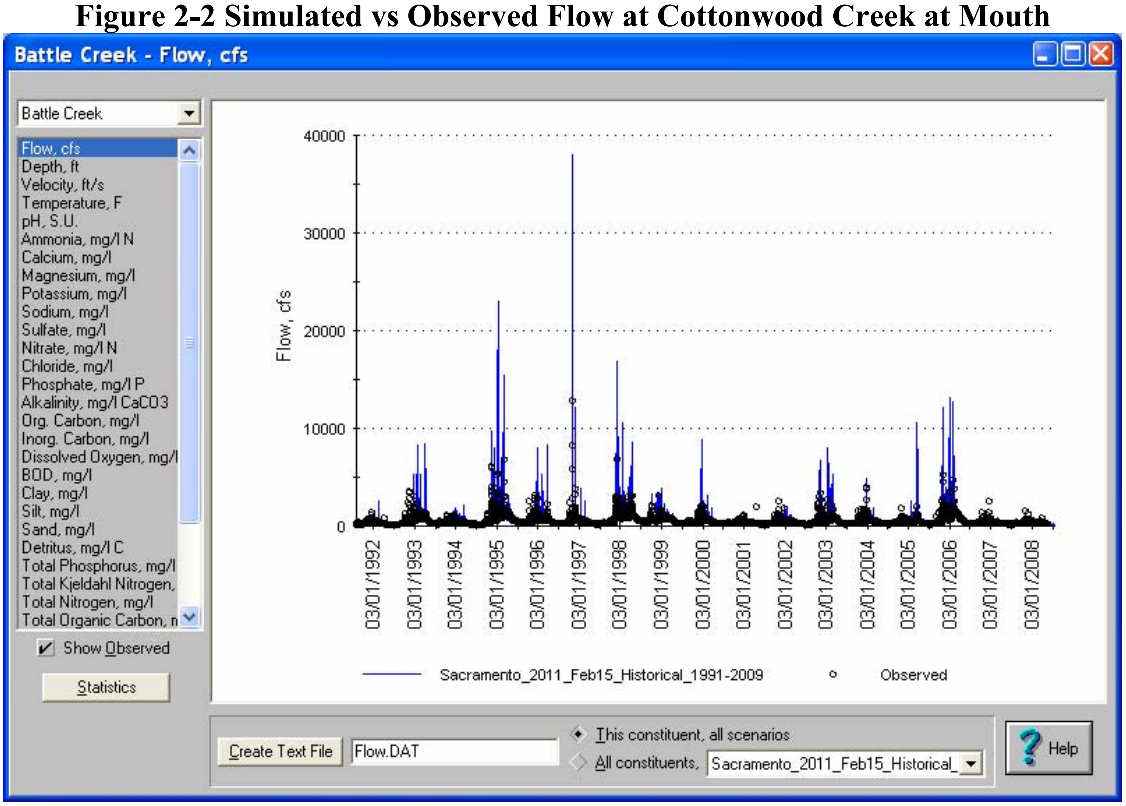

Figure 2-3 Simulated vs Observed Flow at Battle Creek

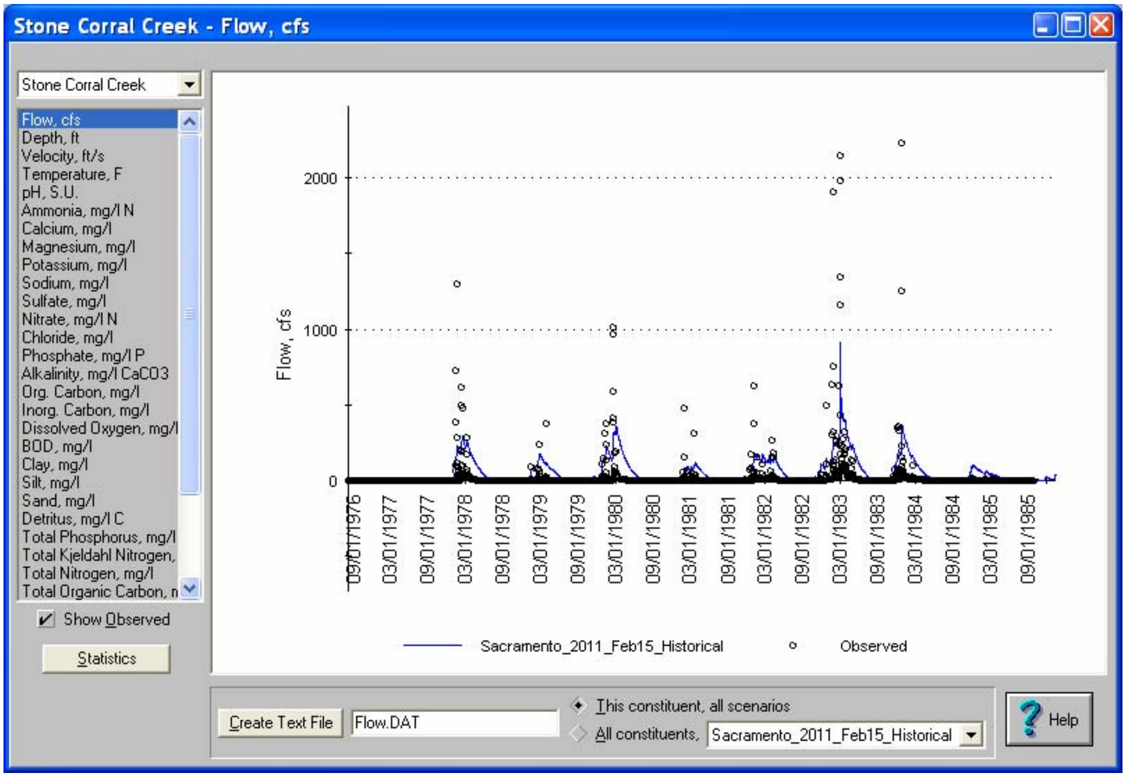

Figure 2-4 Simulated vs Observed Flow at Stone Corral Creek

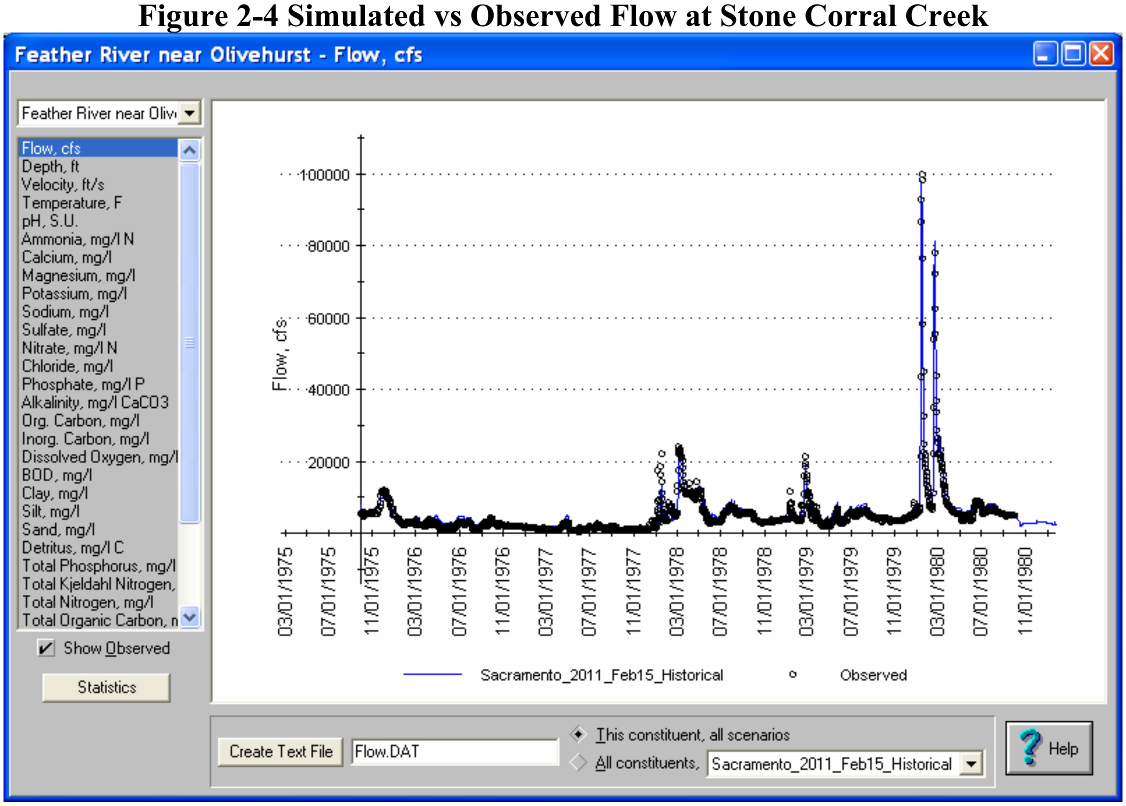

Figure 2-5 Simulated vs Observed Flow at Feather River near Olivehurst

Table 2.9 Flow Calibration Statistics for a Selection of Sacramento River Tributaries

Gaging Station	Calibration Time Period	% Relative Error	% Absolute Error	R squared
Cottonwood Creek Near Cottonwood	1976-1991	-0.7	49.2	0.776
Battle Creek near Cottonwood	1982-2008	16.4	53.7	0.651
Stone Corral Creek near Sites	1976-1985	88.3	115.6	0.142
Dry Creek at Roseville	1999 - 2008	-13.5	47.3	0.744
Feather River near Olivehurst	1975-1980	6.1	11.6	0.947

Hydrologic calibration of the locations corresponding to the Delta Model boundary control points was done after and using information learned from calibration of the upstream tributaries. The locations of the Delta model boundary control points were Sacramento River at Freeport and Yolo Bypass near Lisbon. Additional Delta model boundary control points were where the Cosumnes, Mokelumne, and Calaveras Rivers enter the Delta. Information about the calibration of these tributaries can be found in the final report for the Delta East Side Tributaries modeling work (Systech 2011). Calibration plots and statistics for the Cosumnes and Mokelumne Rivers are also provided in Appendix A for reference. The stations used to calibrate the WARMF model at the Delta Model boundary control points for this project are listed in Table 2.10, along with the date range of data used to calculate the model statistics.

Table 2.10 Hydrology calibration locations for the Delta Model boundary control points

Gaging Station	Calibration Time Period	% Relative Error	% Absolute Error	R squared
Sacramento River at Freeport	1951-2010	1.2	14.6	0.875
Yolo Bypass near Woodland	1951-2009	21.9	26.8	0.911

Calibration results for these stations are shown in Figure 2-6 through Figure A-2. Simulation results are shown in blue lines and observed data in black circles.

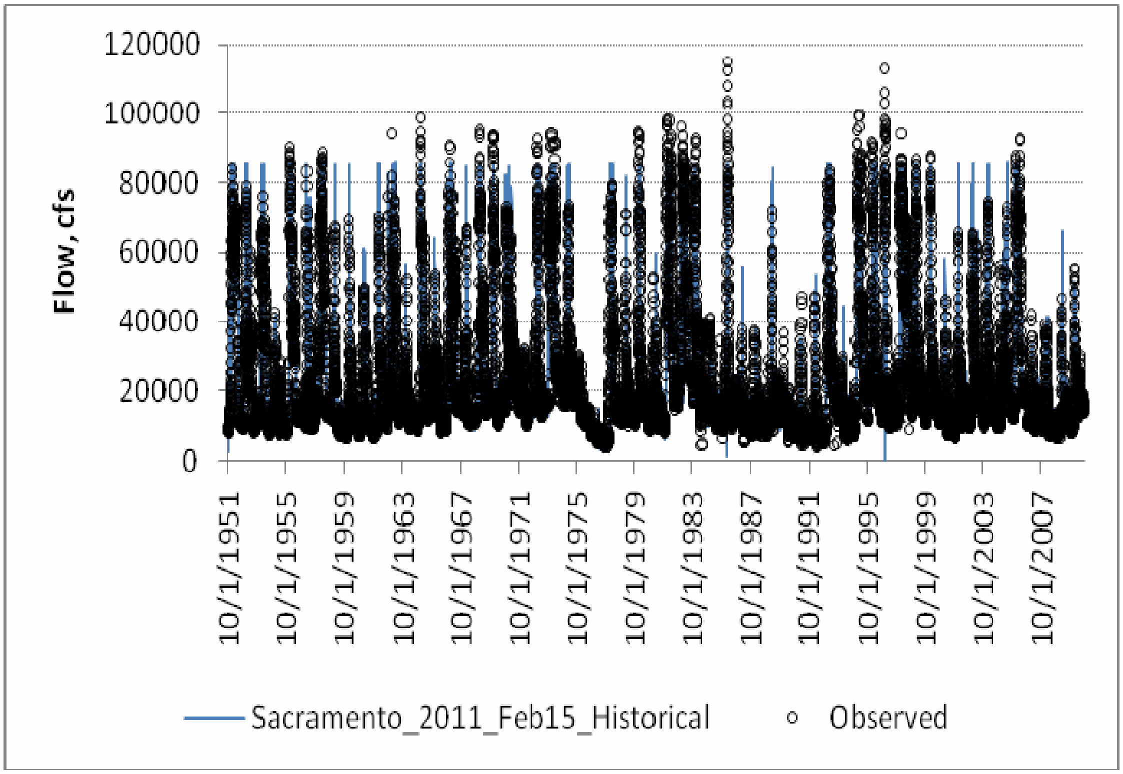

Figure 2-6 Simulated vs Observed Flow at Sacramento River at Freeport

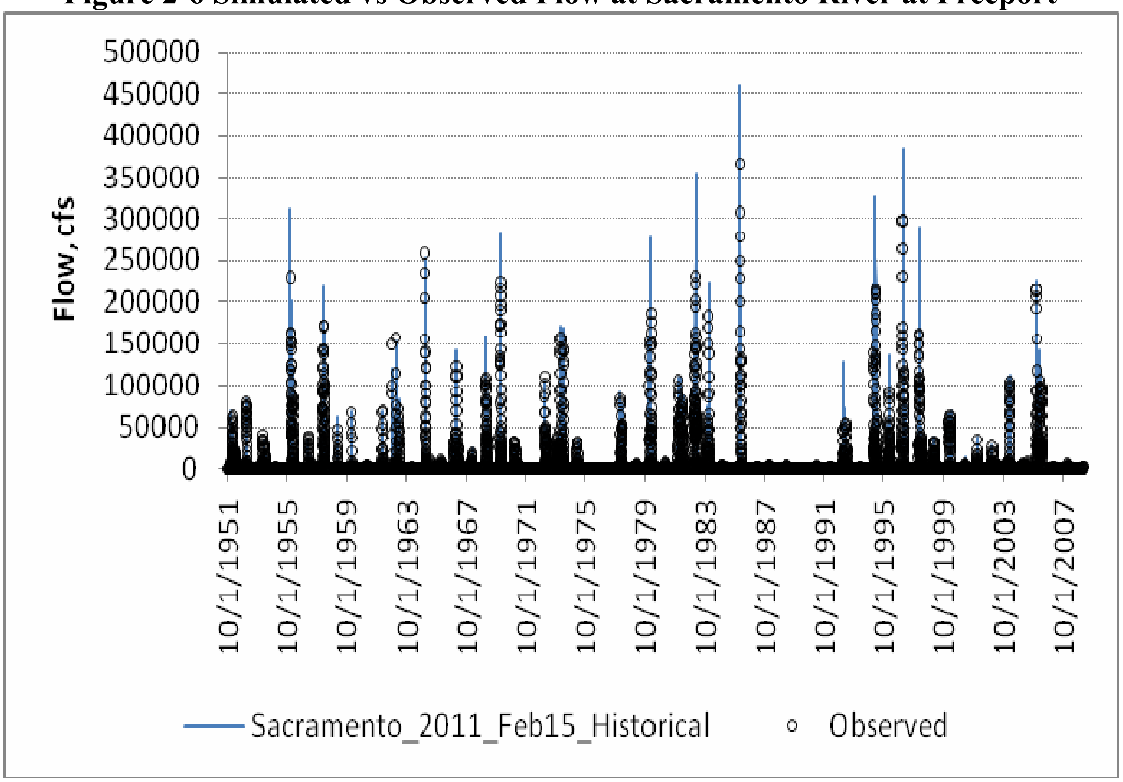

Figure 2-7 Simulated vs Observed Flow at Yolo Bypass near Woodland

Flow is simulated very well at each of the Delta Model boundary control points. Relative error at the Sacramento River at Freeport is 1%, indicating an extremely accurate water balance over the period of simulation. From an accuracy perspective, the Sacramento River at Freeport is likely to be the most important of the Delta Model boundary control points since the Sacramento contributes the overwhelming majority of the flow to the Delta. Relative error calculated at the Yolo Bypass location is significantly higher than at the other three Delta Model boundary control points. The high R-squared value indicates that there is a strong correlation between the simulated and observed discharge. Therefore, likely sources of error include spatial variability in precipitation to the Yolo Bypass watershed and/or a systematic error in the estimation of weir flow from the Sacramento River to the Yolo Bypass. Data for flows over the various flood control weirs on the Sacramento River (Moulton, Colusa, Tisdale, Fremont, and Sacramento) is sparse, especially for the first three. The model may simulating more flow in the Sacramento River proper instead of having that flow routed over the weirs to the Butte Sink and Sutter and Yolo Bypasses. Visual inspection of the WARMF results indicate that simulation of flow in the Yolo Bypass does appear to closely follow the observed data outside of the late winter / early spring flood season when the weirs are operating.

Water Quality Calibration

After the hydrologic calibration, water quality calibration was performed. As stated in the scope of work, the objective of this effort is to develop a watershed model capable of simulating organic carbon, total dissolved solids, nutrients, and electrical conductivity in the Sacramento River at the I-Street bridge in Sacramento and at points upstream. Given this objective the water quality calibration followed a certain order, reflecting the interdependence between water quality constituents (e.g. suspended sediment affects organic carbon). Generally, temperature and total suspended sediment were calibrated first, followed by major cations and anions. Following initial calibration of the water quality parameters, further adjustments were made to these constituents to calibrate the model to observed total dissolved solids (TDS) and electrical conductivity (EC) measurements.

There are observed water quality data for 133 locations in the current version of the Sacramento River WARMF model. The amount of data recorded at each of these locations ranges from an individual temperature sample to an extensive suite of physical and chemical parameters collected over multiple decades. Water quality collection sites with sparse data were included in the model because even a single sample can be useful in setting chemistry calibration parameters in the absence of more extensive data sets.

Of the 133 water quality stations in the WARMF model, 40 principal stations were used to set the majority of initial soil cation and anion concentrations and soil mineral content for each catchment, and to calibrate the WARMF Sacramento River simulation. These stations, along with the time periods during which in-stream water chemistry data were collected are listed in Table 2.11. Calibration was not specifically performed for all of the listed sites. Calibration results from a subset of these water quality data collection stations are presented in the following sections. These sites were selected from the larger set of stations based on their geographic location within the watershed, the number of samples collected for each of the parameters of interest, and to illustrate WARMF simulation capabilities under a variety of land use patterns (e.g. predominantly agricultural watersheds, upland tributaries, Sacramento mainstem sites, etc.).

The locations of the sites for which simulation results are presented are illustrated in Figure 2-8. Sites shown in bold are Delta Model interface locations.

Table 2.11 Water Quality Monitoring Stations

River	Location	Water Chemistry Data Collection Period(s)					
		Begin	**End**	**Begin**	**End**	**Begin**	**End**
American	at river mouth	1967	1969	1974	1983		
American	Sacramento	1960	1965	1974	1980	1995	1998
Battle Creek	Cottonwood	1956	1970				
Bear Creek	Rumsey	1960	1979	1992	2003		
Bear River	At river mouth	1958	1963	2002	2004	2008	2010
Big Chico Creek	At river mouth	1960	1979	2000	2004		
Cache Creek	Capay	1952	1976	1983	1986		
Cache Creek	Rumsey	1960	1981	1996	2001		
Clear Creek	at river mouth	1998	2010				
Colusa Drain	Highway 20	1960	1979				
Colusa Drain	Knights Landing	1996	2000				
Cottonwood Creek	upstream of South Fork	1982	1984				
Elder Creek	Gerber	1960	1966	1977	1979		
Elder Creek	Paskenta	1958	1970				
Feather River	Gridley	1964	1982	2003	2006		
Feather River	Nicolaus	1960	1966	1979	1980	1996	2000
Feather River	Shanghai Bend	1960	1966				
Lower Thomes Creek	At river mouth	1960	1966	1977	1980		
Mill Creek	At river mouth	1960	1979				
North Fork Cache Creek	Lower Lake	1951	1980	2000	2009		
North Fork Cottonwood Creek	At river mouth	1960	1966	1979	1979		
Red Bank Creek	At river mouth	1960	1966				
Sacramento	Bend Bridge	1978	1980	1989	2010		
Sacramento	above Colusa Basin Drain	1960	1980				
Sacramento	Freeport	1956	2010				
Sacramento	Fremont Weir	1951	1960	1977	1980	2000	2009
Sacramento	Grimes	1960	1963				
Sacramento	Hamilton City	1951	1980	1999	2000		
Sacramento	**Sacramento (I Street)**	**1951**	**1979**				
Sacramento	Verona	1969	1969	1996	1998	2008	2010
Upper Deer Creek	Vina	1995	2004				
Yuba	downstream of Dry Creek	1960	1980	1995	2004	2008	2010
Yuba	Smartville	1960	1966				
Cosumnes	Michigan Bar	1951	1980	2001	2006		
Cosumnes	**Twin Cities Rd.**	**1998**	**2006**				
Mokelumne	**Mouth**	**2000**	**2005**	**2008**	**2010**		
Mokelumne	Elliott	1999	2005				
Bear Creek	Mouth	2000	2007				
Calaveras	**Mouth**	**2004**	**2004**	**2008**	**2010**		
French Camp Slough	Airport Way	1960	1966	2000	2006		

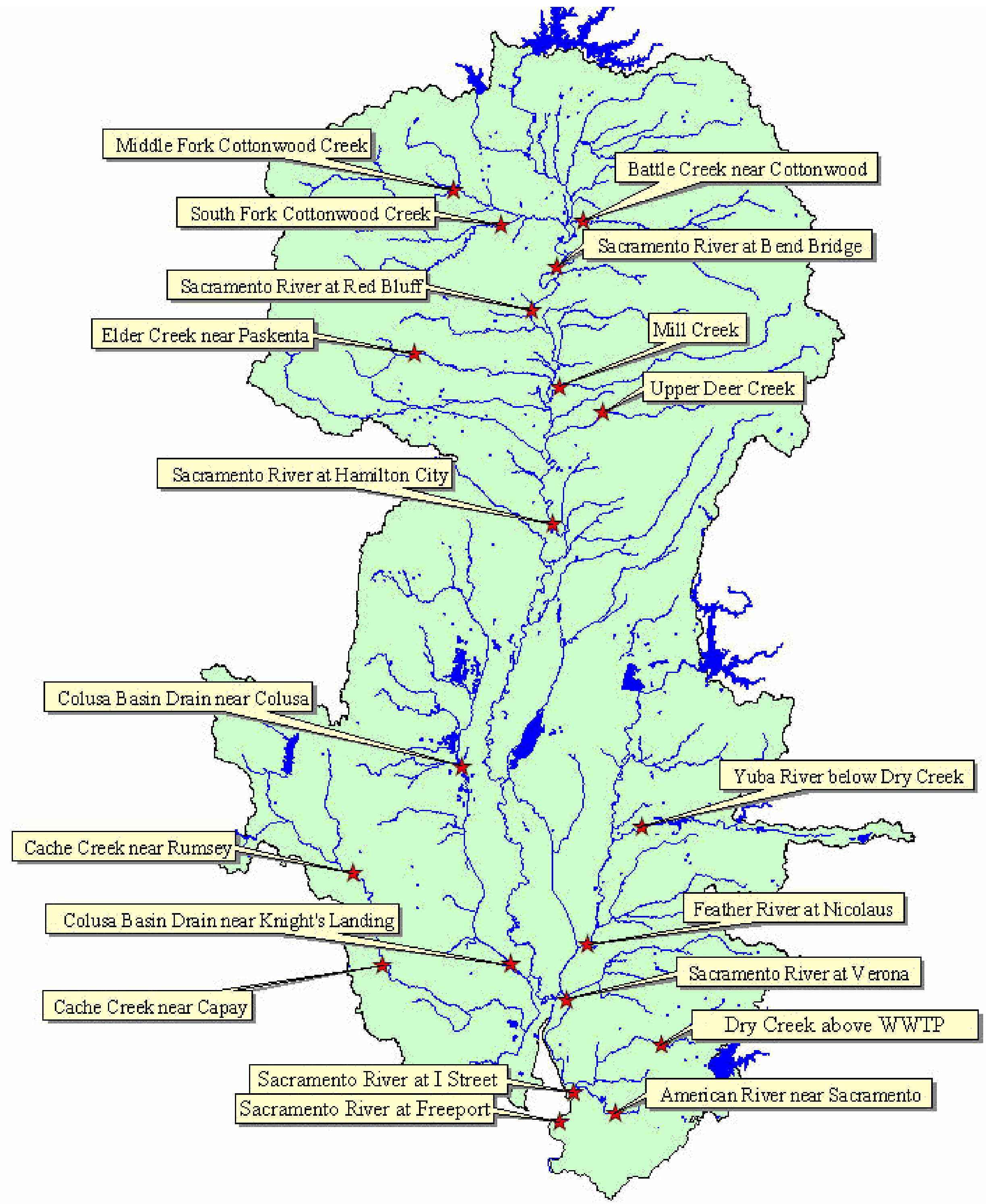

Figure 2-8 Locations of Water Quality Monitoring Stations

The following sections describe the calibration results for the water quality parameters of interest at the sites illustrated in Figure 2-8. For each water quality parameter, the simulated results (blue lines) and observed data (black circles) are compared from the most upstream station to the most downstream station. Additional water quality calibration results for the Putah Creek and Cache Creek drainages are in the CV-SALTS pilot study final report (Larry Walker & Associates 2010). Water quality calibration for the tributaries on the east side of the Delta, including the Cosumnes River, Dry Creek, Mokelumne River, and Calaveras River, is shown in the final report for the Delta East Side Tributaries expansion of the Sacramento River WARMF application (Systech 2011(b)).

Water Temperature

Differences between observed and simulated water temperatures were analyzed at seven locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Red Bluff, Mill Creek, Upper Deer Creek, Sacramento River at Hamilton City, Sacramento River at Verona, and Sacramento River at Freeport.

Figure 2-9 through Figure 2-15 show the time series of simulated and observed water temperature at various stations along the Sacramento River. The model is shown to follow the observed seasonal variations of water temperature during the time periods during which temperature data were collected.

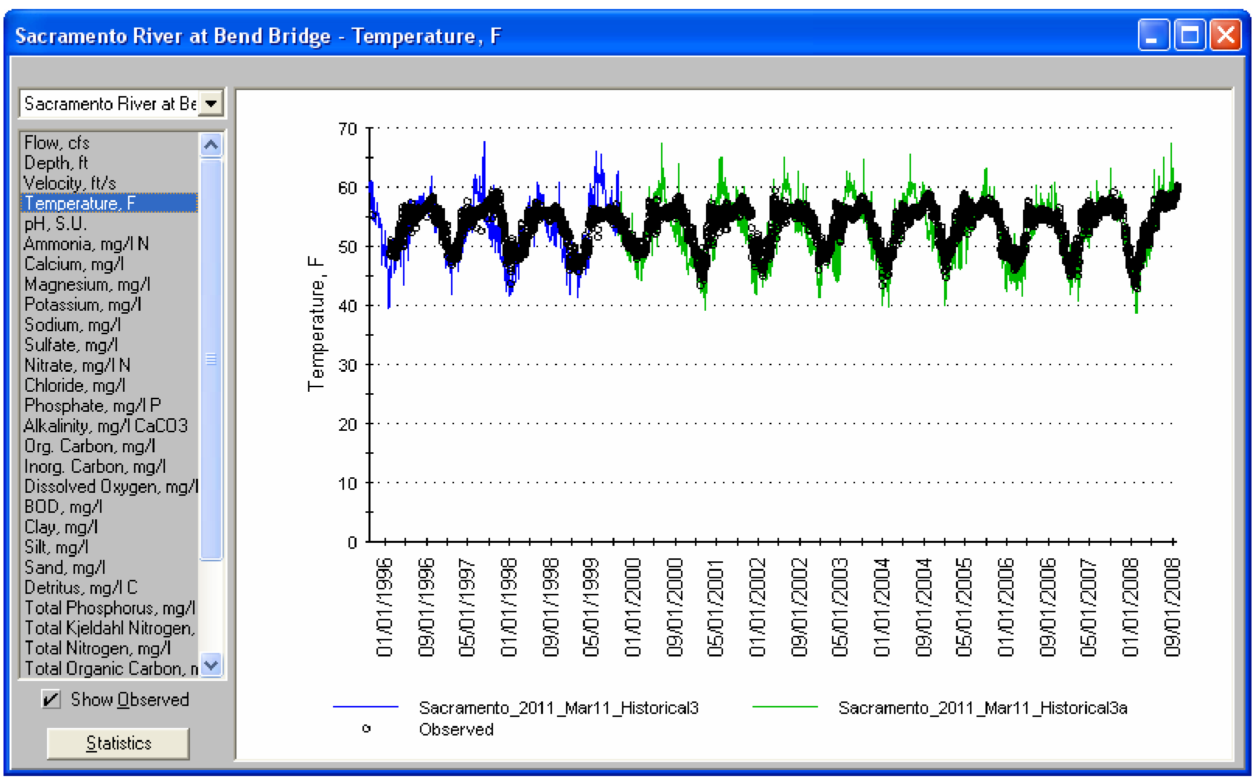

Figure 2-9 Simulated and observed temperature at Sacramento River at Bend Bridge

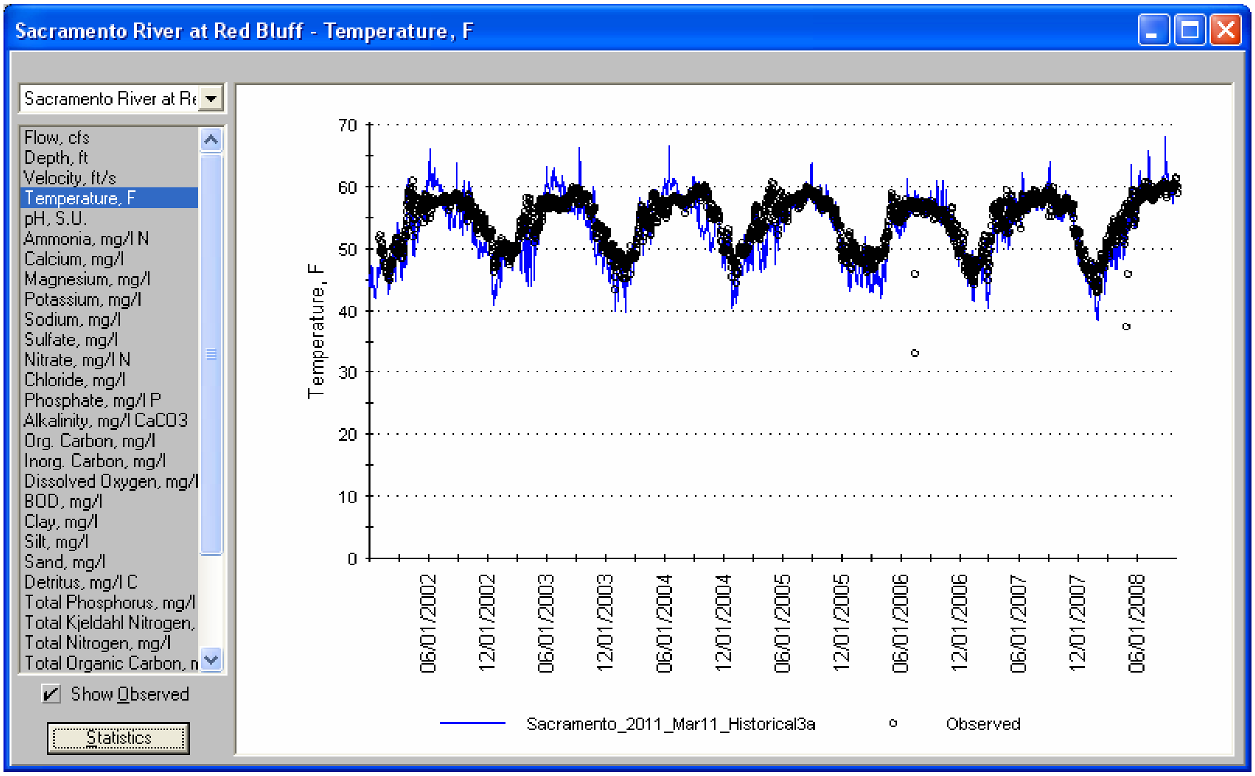

Figure 2-10 Simulated and observed temperature at Sacramento River at Red Bluff

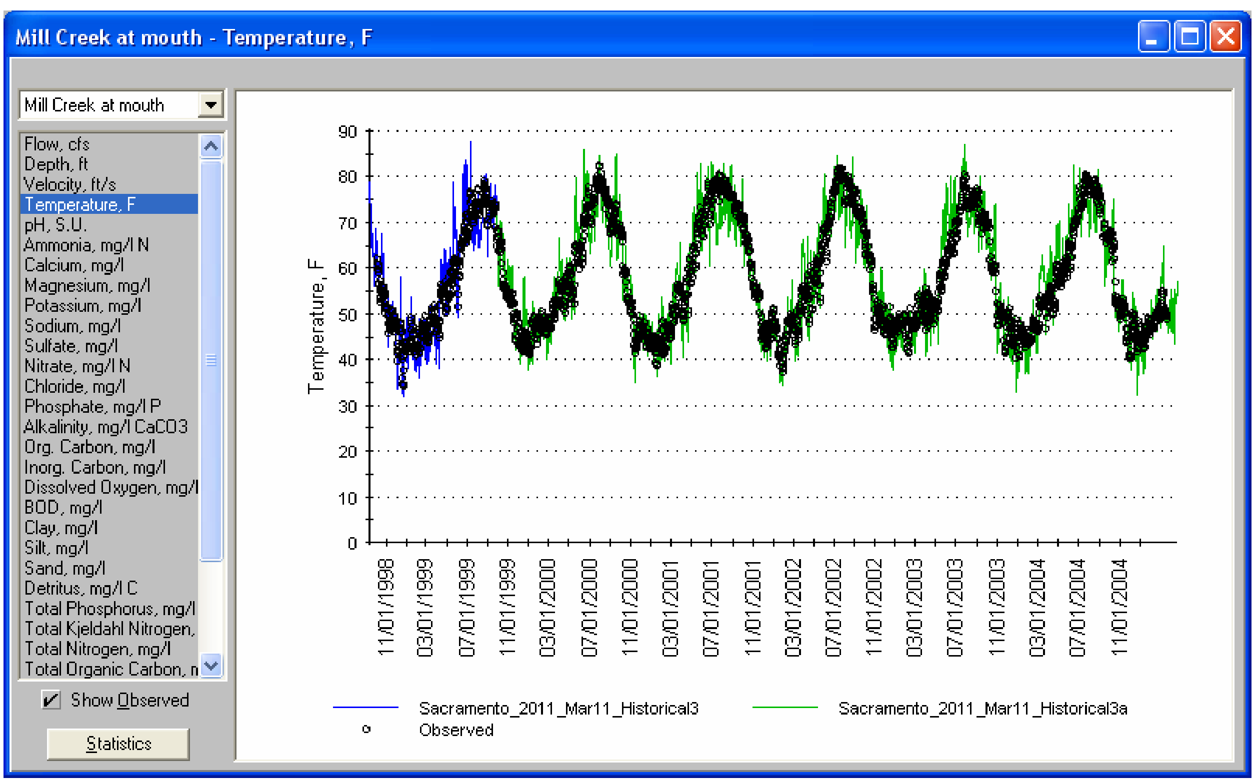

Figure 2-11 Simulated and observed temperature at Mill Creek

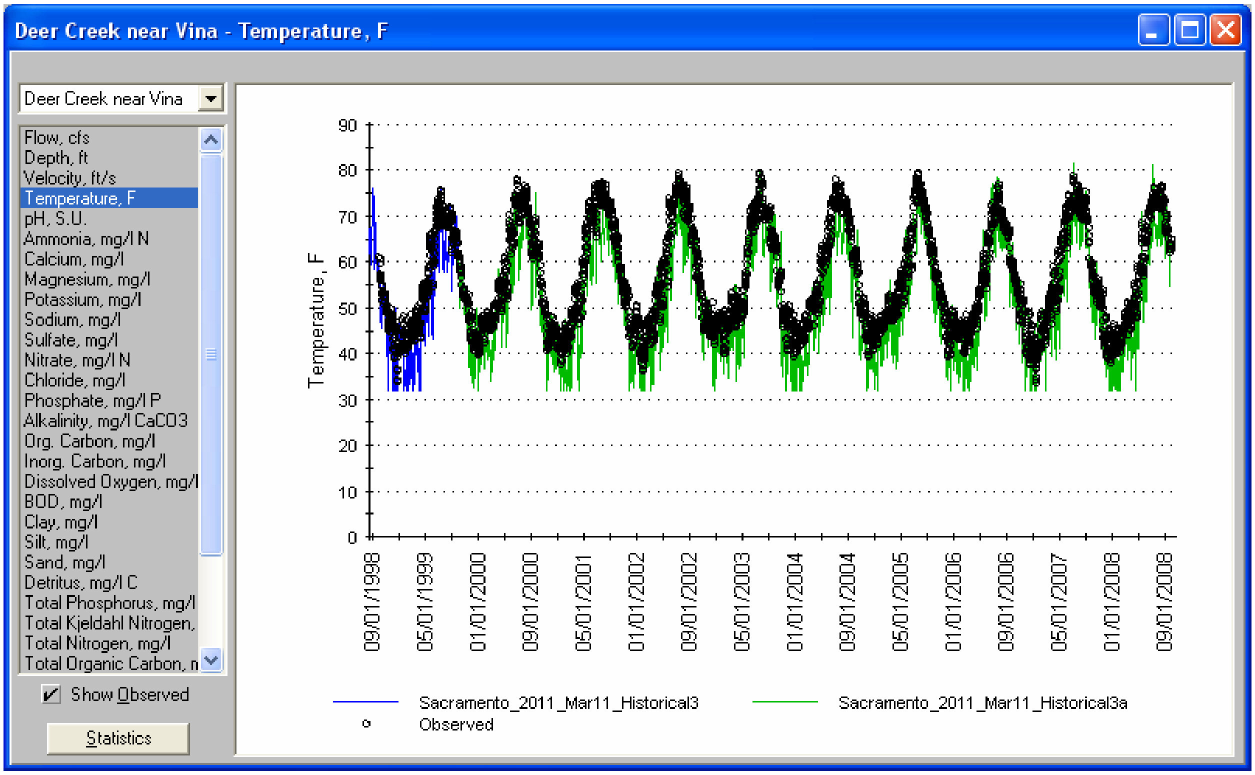

Figure 2-12 Simulated and observed temperature at upper Deer Creek

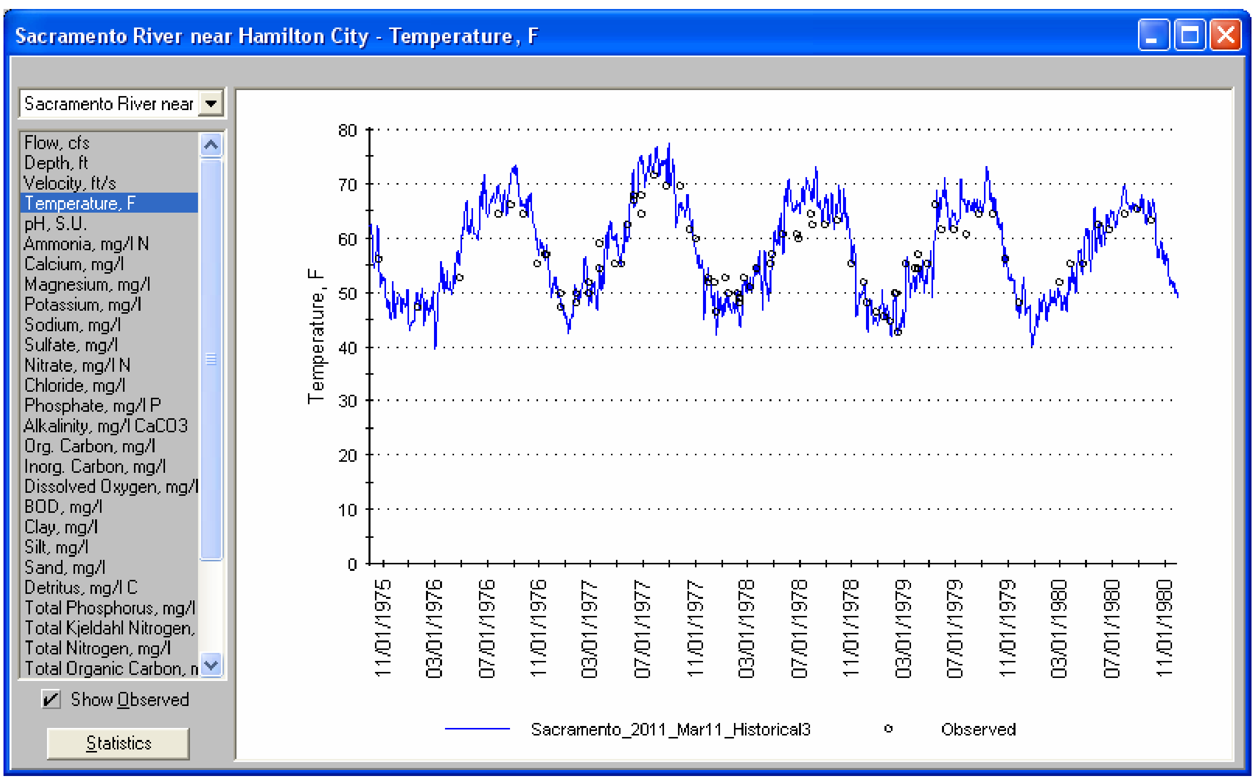

Figure 2-13 Simulated and observed temperature at Sacramento River at Hamilton City

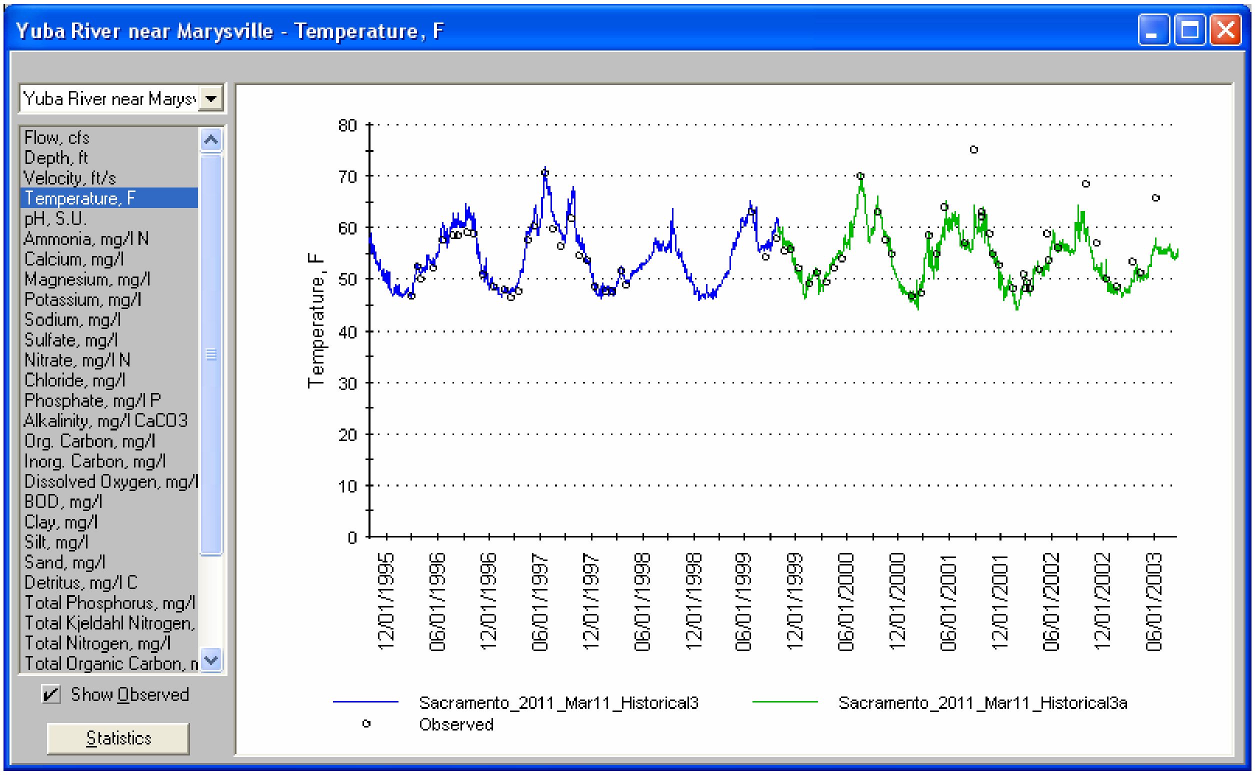

Figure 2-14 Simulated and observed temperature at Yuba River at Marysville

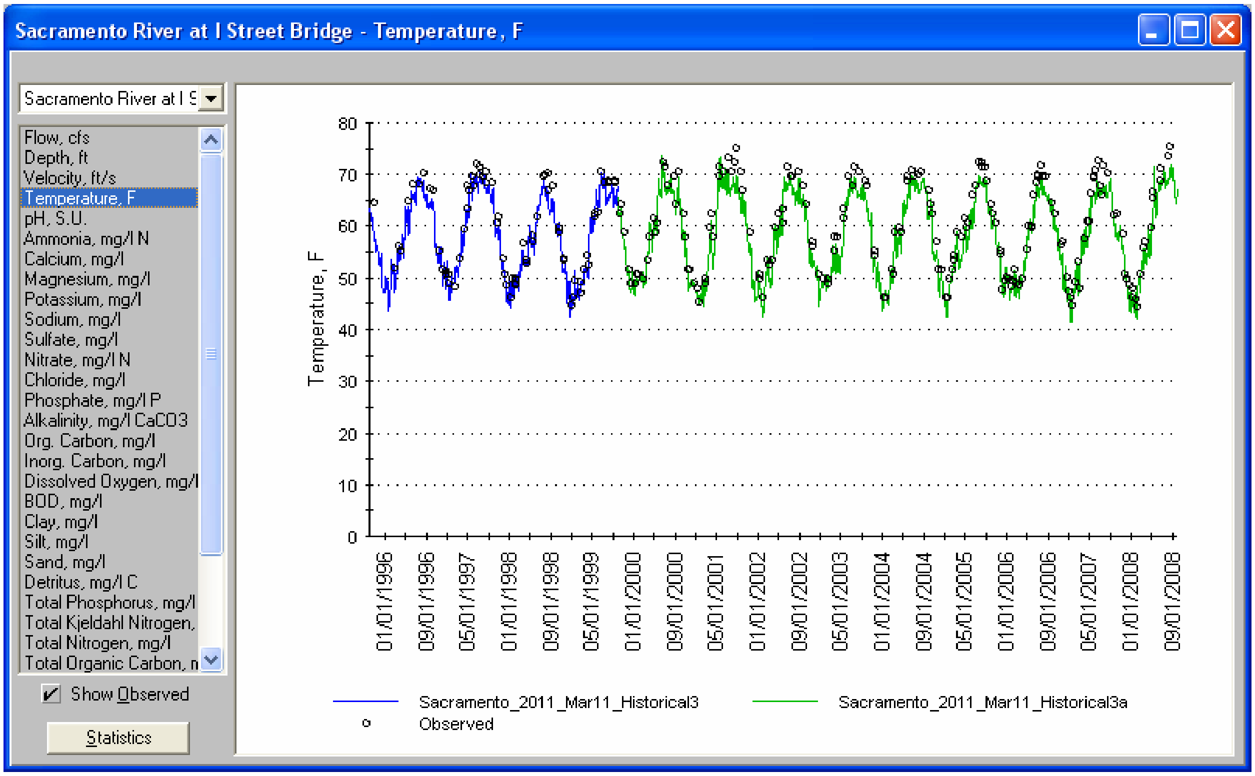

Figure 2-15 Simulated and observed temperature at Sacramento River at I Street

Table 2.12 provides a summary of model errors for various stations, assuming that the observed data are accurate. The goal of calibration was is to minimize the relative and absolute errors.

Table 2.12 Statistics of Temperature Calibration

Monitoring Station	Relative Error, ^{o}F	Absolute Error, ^{o}F
Sacramento River at Bend Bridge	-0.73	2.35
Sacramento River at Red Bluff	-1.24	2.32
Mill Creek	+0.23	3.36
Upper Deer Creek	-4.39	4.91
Sacramento River at Hamilton City	0.32	2.76
Yuba River at Marysville	-0.21	1.92
Sacramento River at Freeport	-2.12	2.21

The simulated temperature generally shows more variation than the observed data, implying that the model is simulating too much heat transfer between the water and the air. The observed and simulated temperature at Upper Deer Creek (Figure 2-12) show simulated temperature dropping to freezing in winter but measured data usually did not drop below 39 ^{o}F. Adjusting stream parameters that affect thermal inputs to the stream channel (e.g. stream cross-section, catchment temperature lapse rate, etc.) would likely improve the simulation results there. The model is underestimating the temperature in the Sacramento River at Freeport. Adjustments to river heat transfer coefficients and use of improved river cross-section data could probably improve the model performance.

Total Suspended Sediment

Although suspended sediment simulation is not directly an objective of the modeling, sediment is an import mode of transport and sequestration for organic carbon, nutrients, and many of the constituent ions which make up salinity. Differences between observed and simulated total suspended sediment were analyzed at three locations on the Sacramento River. Figure 2-16 through Figure 2-18 show the simulated and observed time series of total suspended sediment at these stations. The graphs focus on the time periods over which total suspended sediment data was collected, which in some cases was the 1970's.

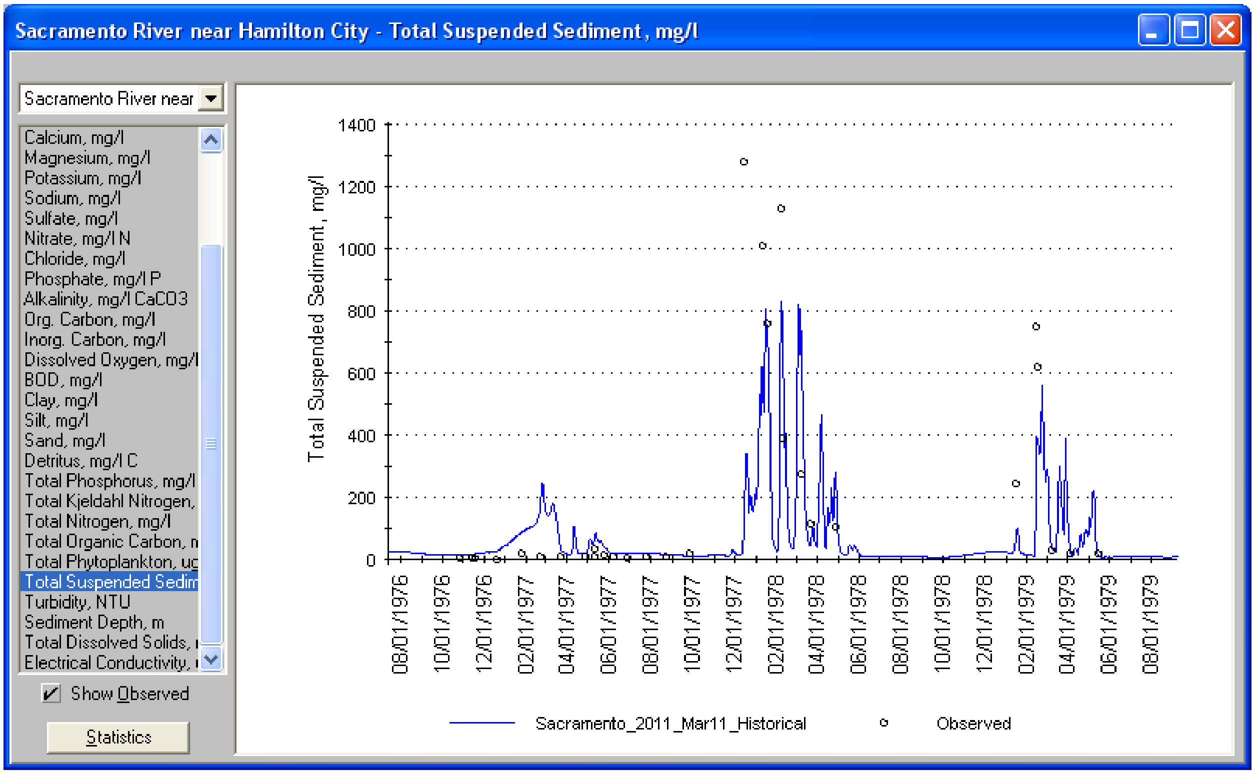

Figure 2-16 Simulated and observed total suspended sediment at Sacramento River at Hamilton City

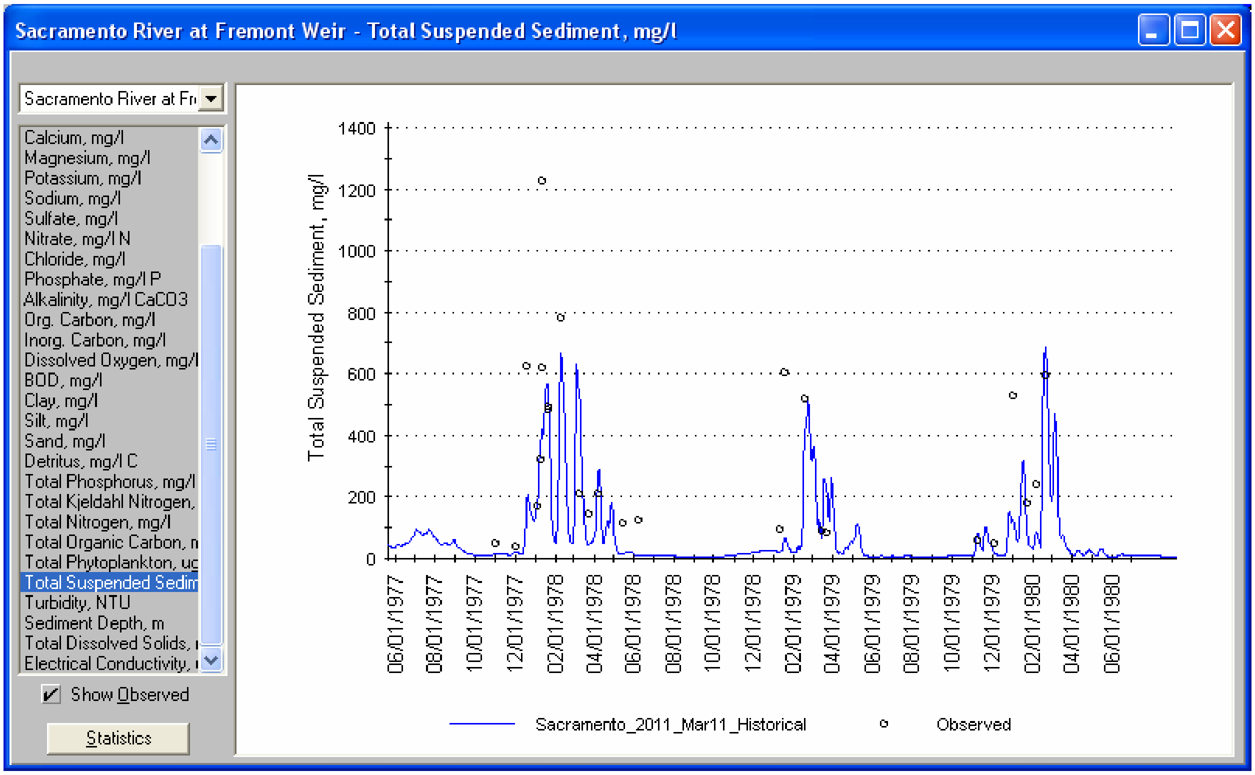

Figure 2-17 Simulated and observed total suspended sediment at Sacramento River at Fremont Weir

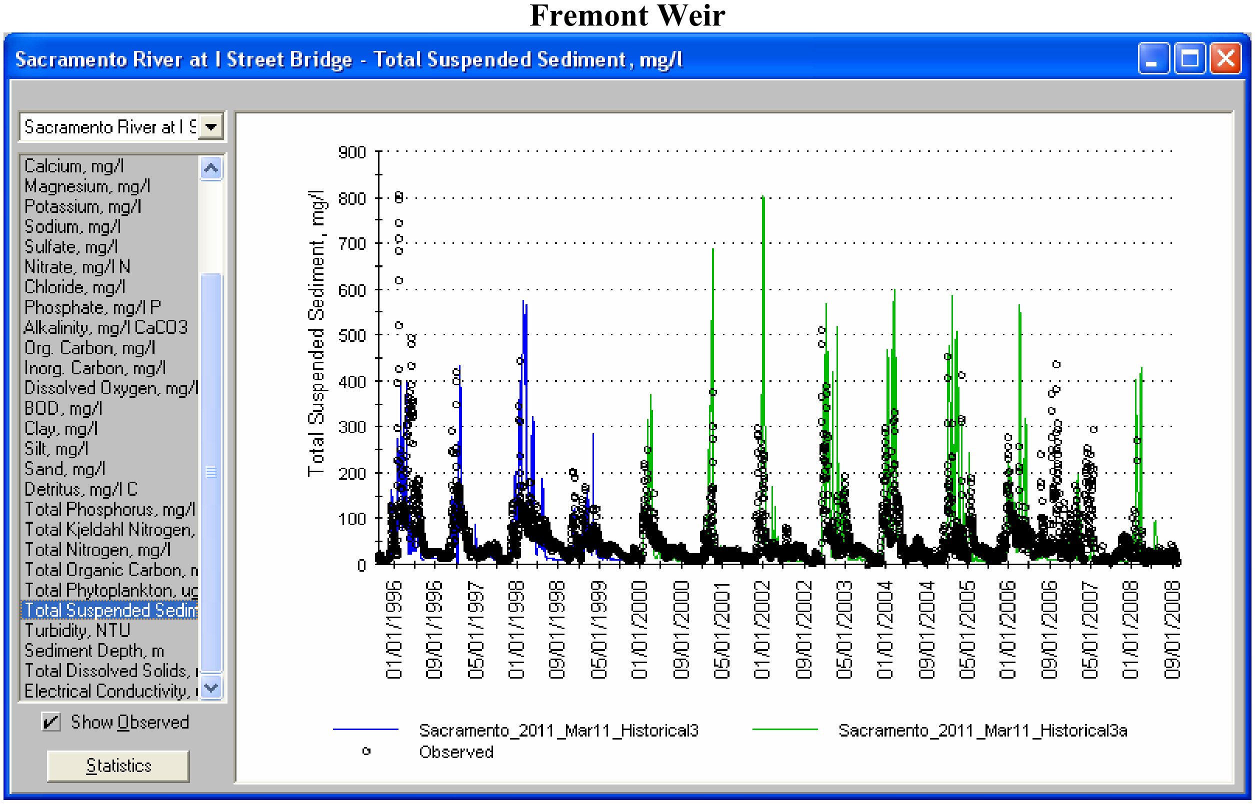

Figure 2-18 Simulated and observed total suspended sediment at Sacramento R. at I Street

Table 2.13 provides a summary of model errors for total suspended sediment. The calculations assume that these observed data are accurate. The goal of calibration is to keep relative error less than 10% and minimize absolute errors. Additional Delta model boundary control points were where the Cosumnes, Mokelumne, and Calaveras Rivers enter the Delta. Information about the calibration of these tributaries (for turbidity) can be found in the final report for the Delta East Side Tributaries modeling work (Systech 2011). Calibration plots and statistics for the Cosumnes and Mokelumne Rivers are also provided in Appendix A for reference.

Table 2.13 Model Errors of Total Suspended Sediment

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Hamilton City	-19%	63%
Sacramento River at Fremont Weir	-34%	54%
Sacramento River at Freeport	+7%	83%

At Hamilton City and Fremont Weir, the model simulations on average do not predict as much suspended sediment as was measured during peak events. The daily suspended sediment data collected by the US Geological Survey at Freeport provides a valuable method of evaluating the timing of high sediment events. The simulations did well predicting the timing and magnitude of high sediment events in winter. The measured data includes high sediment events of unknown source during low flow in 2006 and 2007. Since the simulations produce high sediment from overland flow and from river bed scour at high velocity, WARMF is not able to simulate high sediment concentration at low flow. Absolute error is high at all stations because of the difficulty predicting the magnitude of peak sediment concentrations and because of the low flow sediment peaks at Freeport.

Electrical Conductivity

Electrical conductivity is used as a measure of salinity because it is inexpensive to measure and is often well-correlated to total dissolved solids. As shown in Figure 1-2 and Figure 1-3, however, the correlation becomes weaker at the low salinity levels seen in much of the Sacramento River watershed. Although this introduces error into the measured data, the calibration analysis assumes that the measured electrical conductivity is accurate. Differences between observed and simulated electrical conductivity were analyzed at seven locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Hamilton City, Mill Creek, Yuba River below Dry Creek, Colusa Basin Drain near Knights Landing, Feather River at Nicolaus, Sacramento River at Verona, and Sacramento River at Freeport.

Figure 2-19 through Figure 2-25 show the simulated and observed time series of electrical conductivity at various stations within the Sacramento River WARMF model domain. The time series are focused on the time periods for which there is observed data.

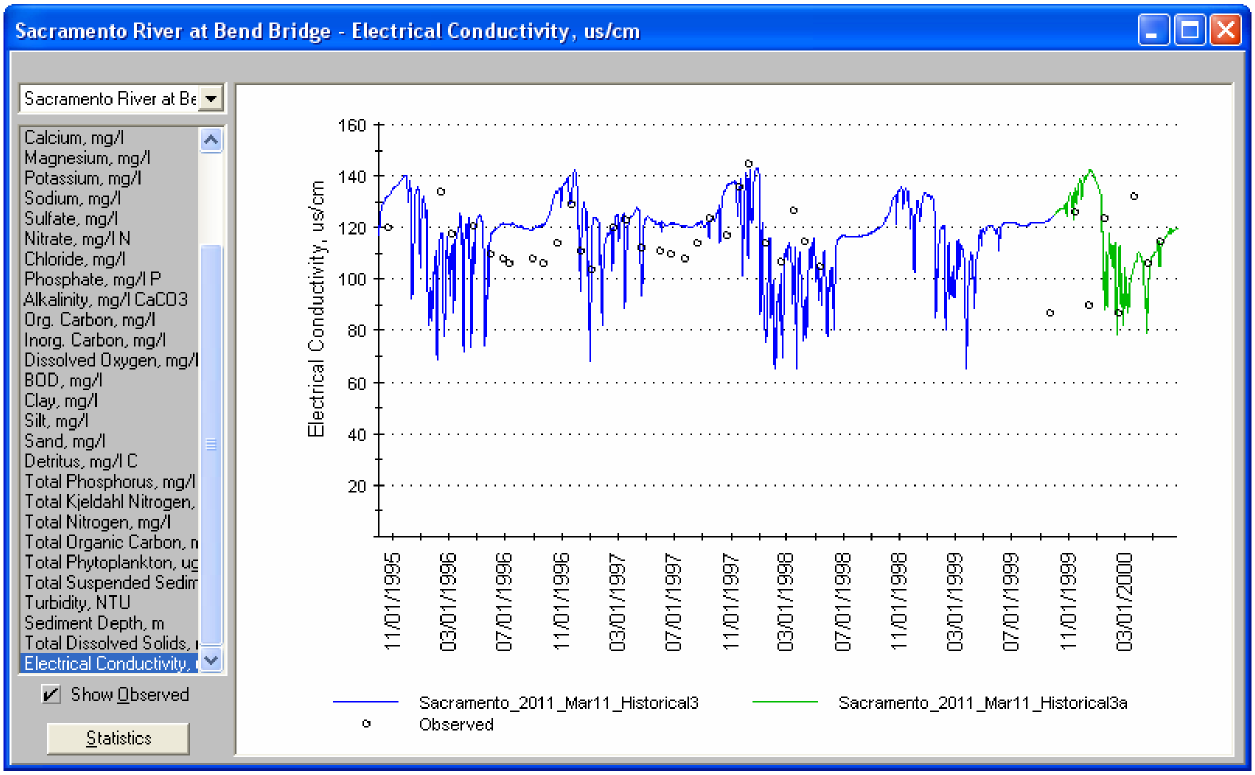

Figure 2-19 Simulated and observed electrical conductivity at Sacramento River at Bend Bridge

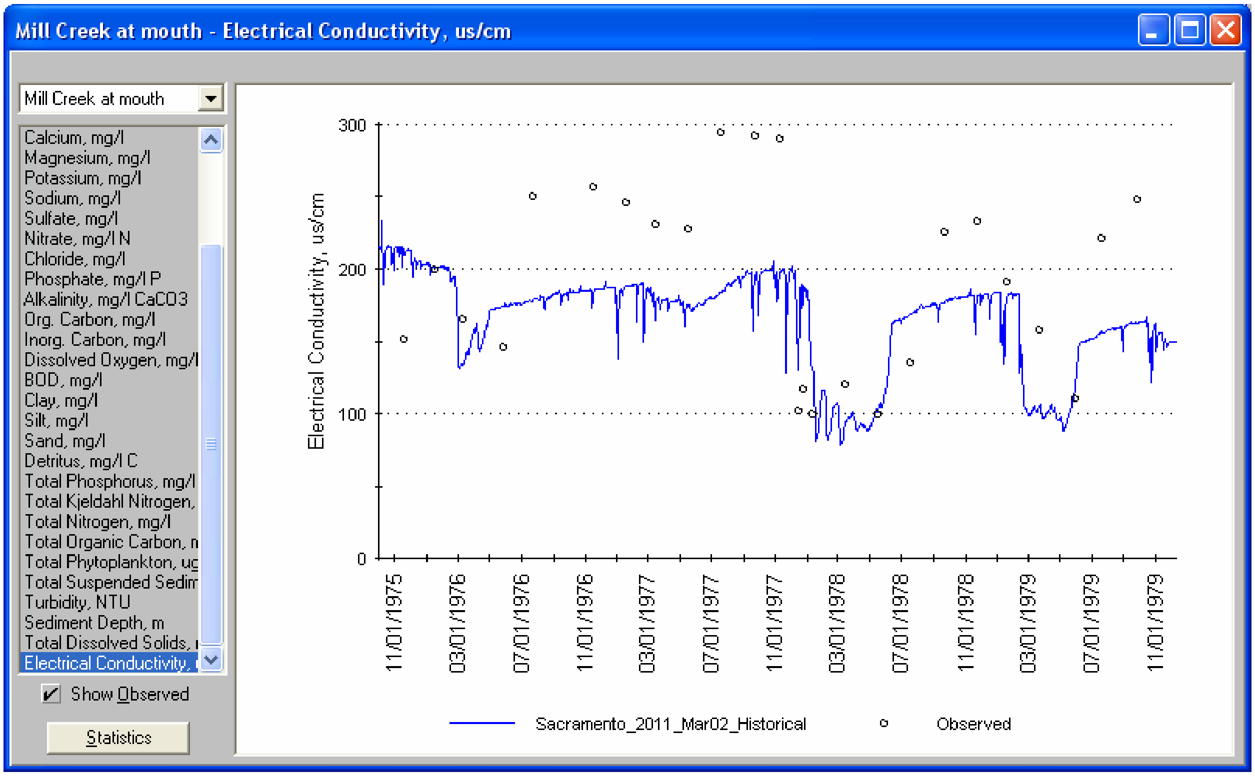

Figure 2-20 Simulated and observed electrical conductivity at Mill Creek.

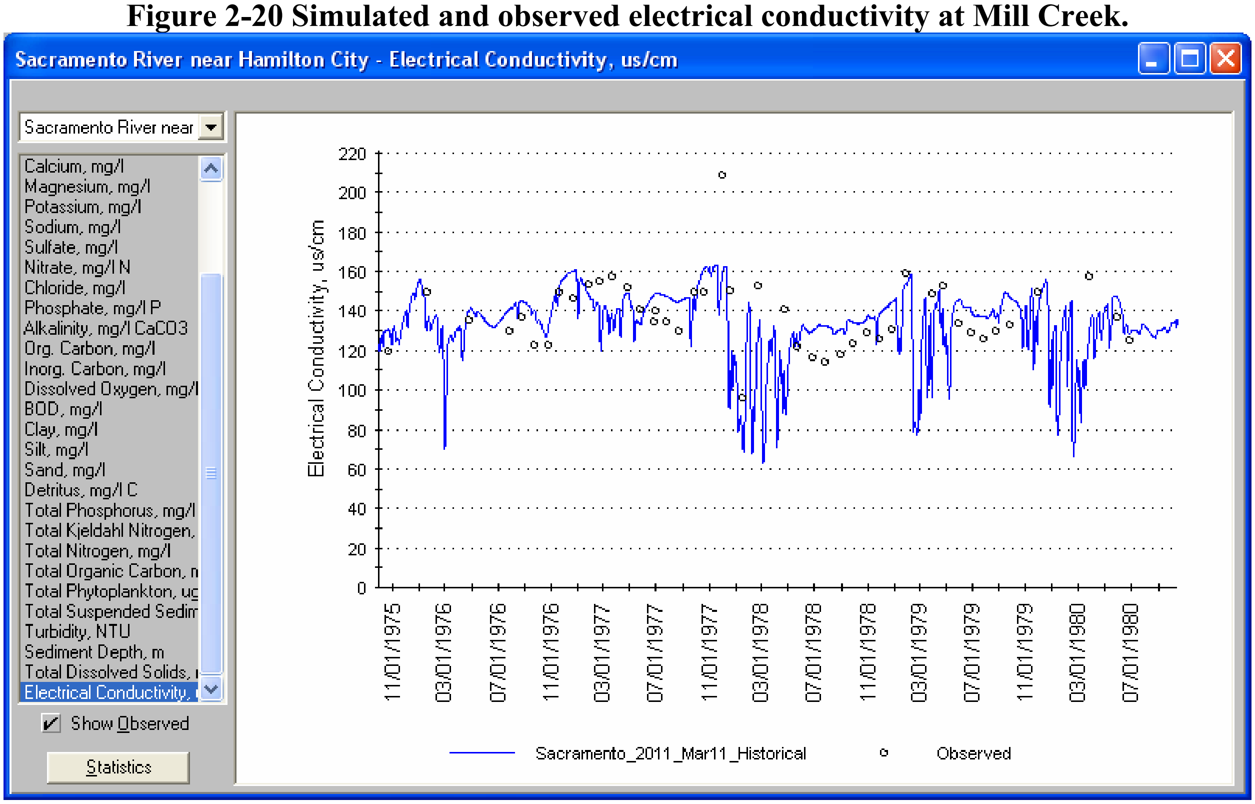

Figure 2-21 Simulated and observed electrical conductivity at Sacramento River at Hamilton City

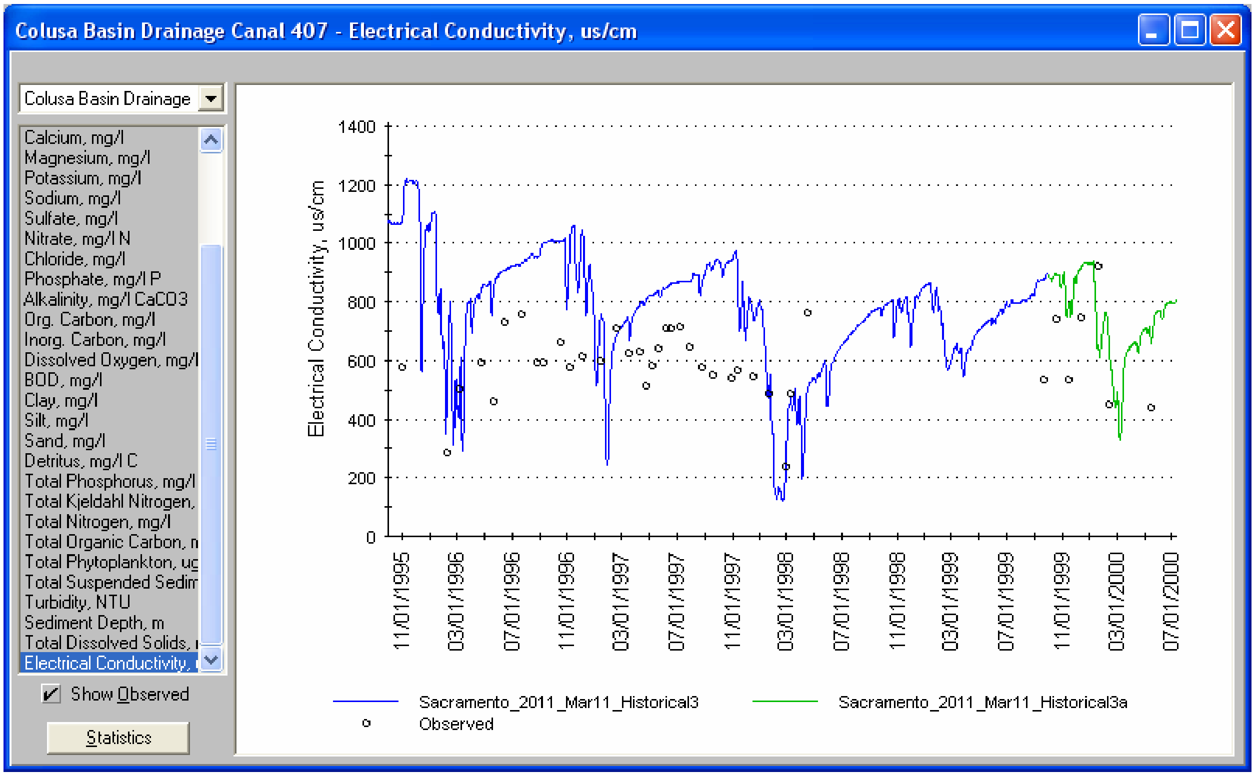

Figure 2-22 Simulated and observed electrical conductivity at Colusa Basin Drain near Knights Landing

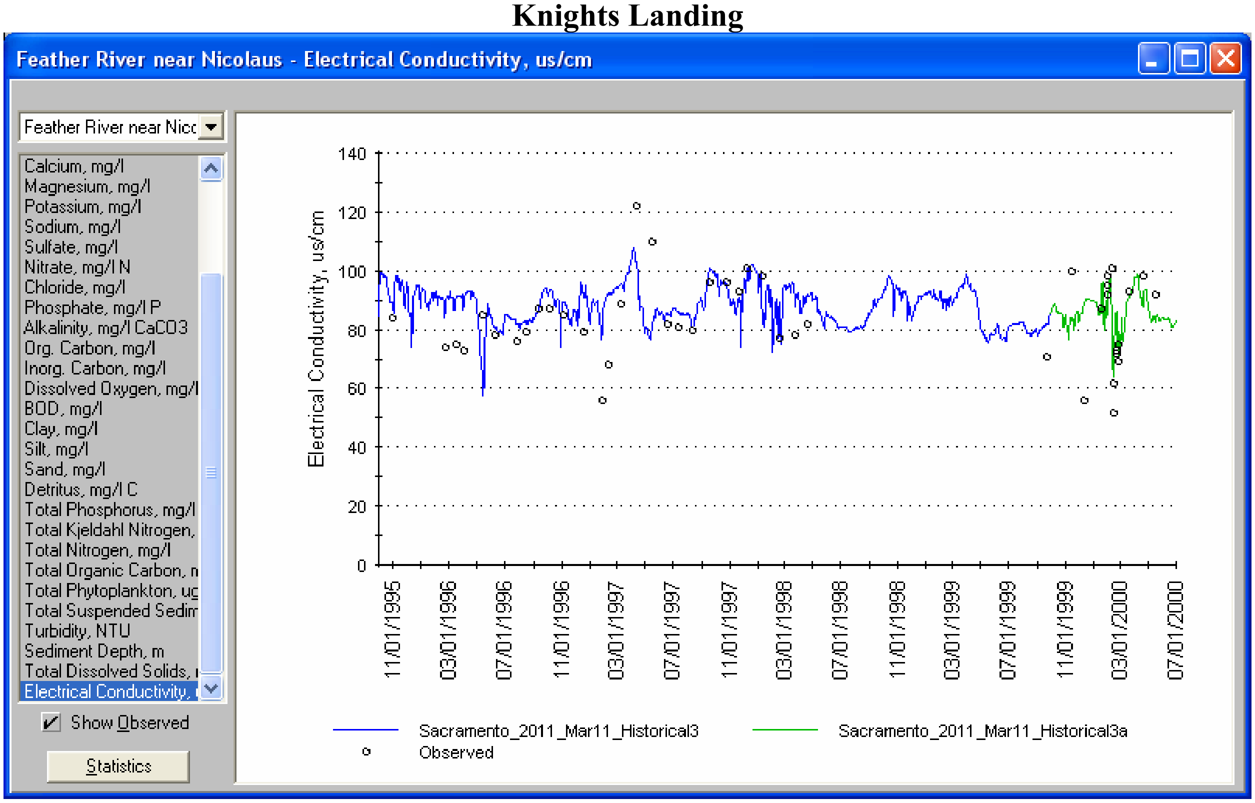

Figure 2-23 Simulated and observed electrical conductivity at Feather River at Nicolaus

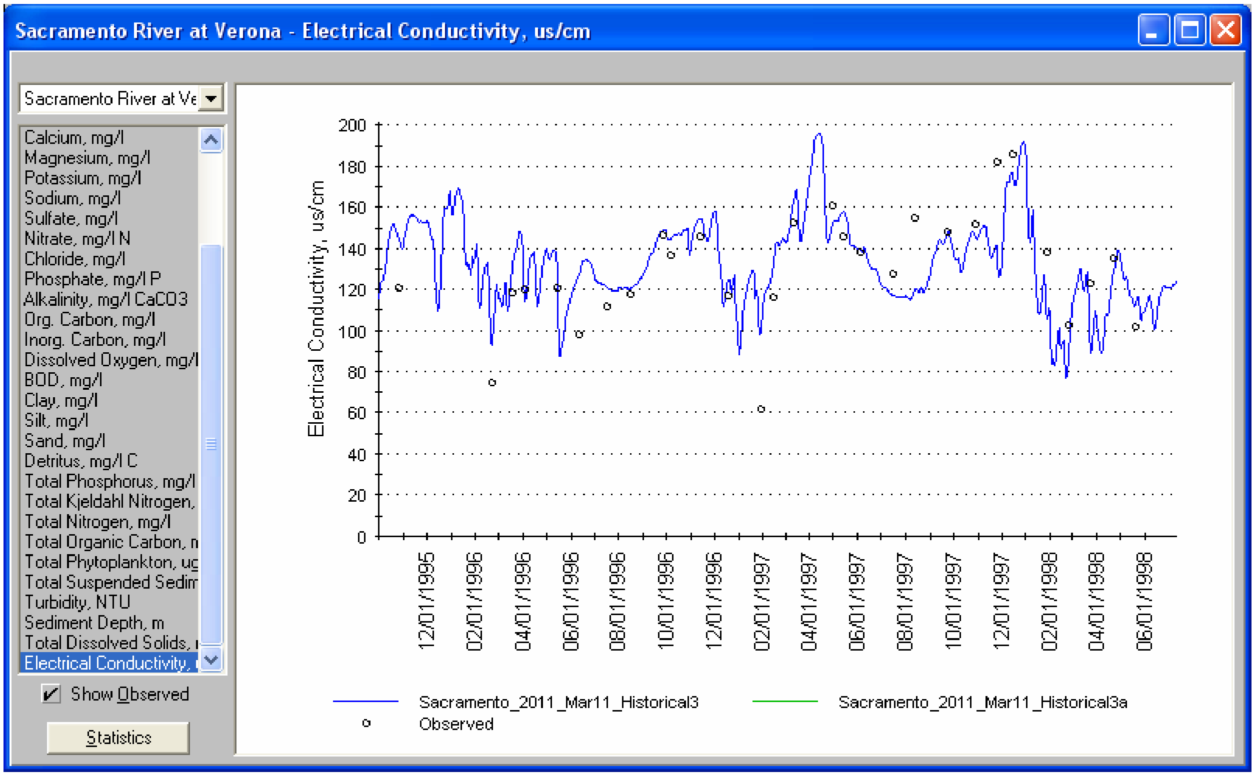

Figure 2-24 Simulated and observed electrical conductivity at Sacramento River at Verona

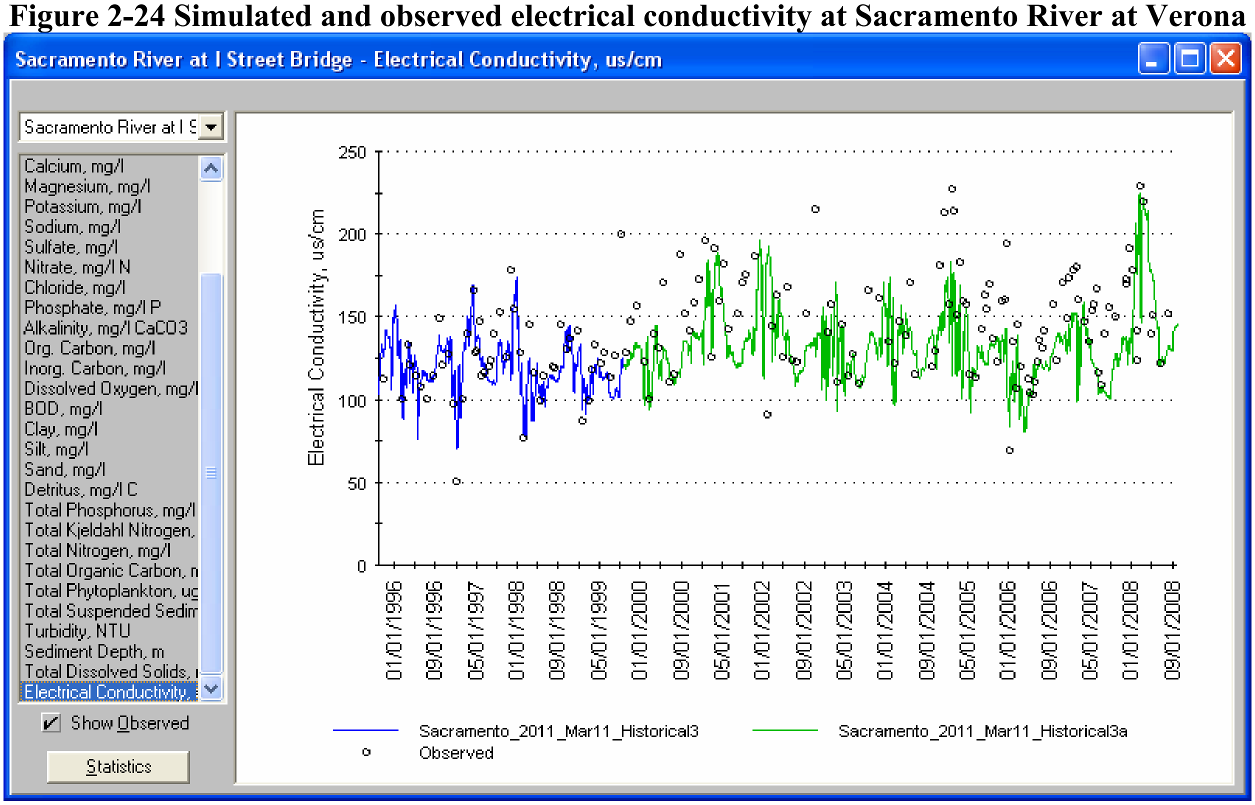

Figure 2-25 Simulated and observed electrical conductivity at Sacramento R. at I Street

Table 2.14 shows the model errors for electrical conductivity at various monitoring stations within the Sacramento River WARMF model domain. The goal of calibration was relative error less than 10% and absolute error less than 20%. Relative error was low on the main stem of the Sacramento River as far downstream as Verona and in the Feather River. The model underpredicted electrical conductivity in Mill Creek. The large error in the Colusa Basin Drain is caused by the flow error requiring reassessment of model inputs described in the hydrology calibration section of this report. Although the concentration is higher than observed, the simulated loading is actually less than observed because of the underprediction of flow. The simulated electrical conductivity was somewhat less than observed at the Sacramento River at Freeport station. This could be caused by the same agricultural assumptions which caused the model error in Colusa Basin Drain or it could be the result of sea water intrusion. EC calibration was not a priority of the Delta east side tributaries modeling project, but coarse adjustment of model parameters was performed for the Cosumnes, Mokelumne, and Calaveras Rivers so that the simulated EC would be reasonable in comparison with measured data.

Table 2.14 Model Errors of Electrical Conductivity

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	-1%	13%
Mill Creek	-16%	26%
Sacramento River at Hamilton City	-2%	11%
Colusa Basin Drain near Knights Landing	+32%	39%
Feather River at Nicolaus	+2%	12%
Sacramento River at Verona	+0%	11%
Sacramento River at Freeport	-9%	14%

Organic Carbon

Differences between observed and simulated organic carbon were analyzed at six locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Hamilton City, Colusa Basin Drain near Knights Landing, Feather River at Nicolaus, Sacramento River at Verona, Dry Creek near Roseville, and Sacramento River near Freeport. Evaluating the simulation results at these locations lets us determine model performance simulating organic carbon from different combinations of sources: upstream inflows, natural landscape, agricultural areas, and urban areas.

Figure 2-26 through Figure 2-32 show the simulated and observed time series of dissolved organic carbon at various stations within the Sacramento River WARMF model domain. Each graph is focused on the time periods for which there is observed data at each location.

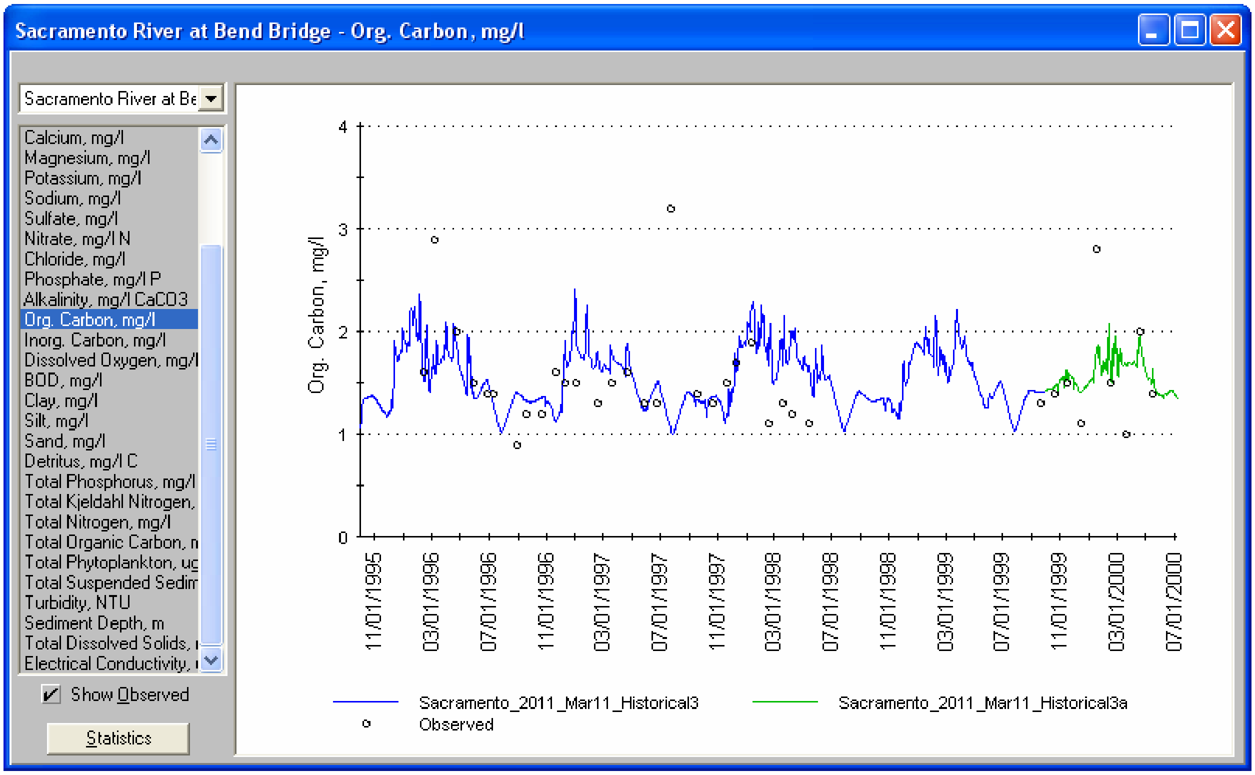

Figure 2-26 Simulated and observed organic carbon at Sacramento River at Bend Bridge.

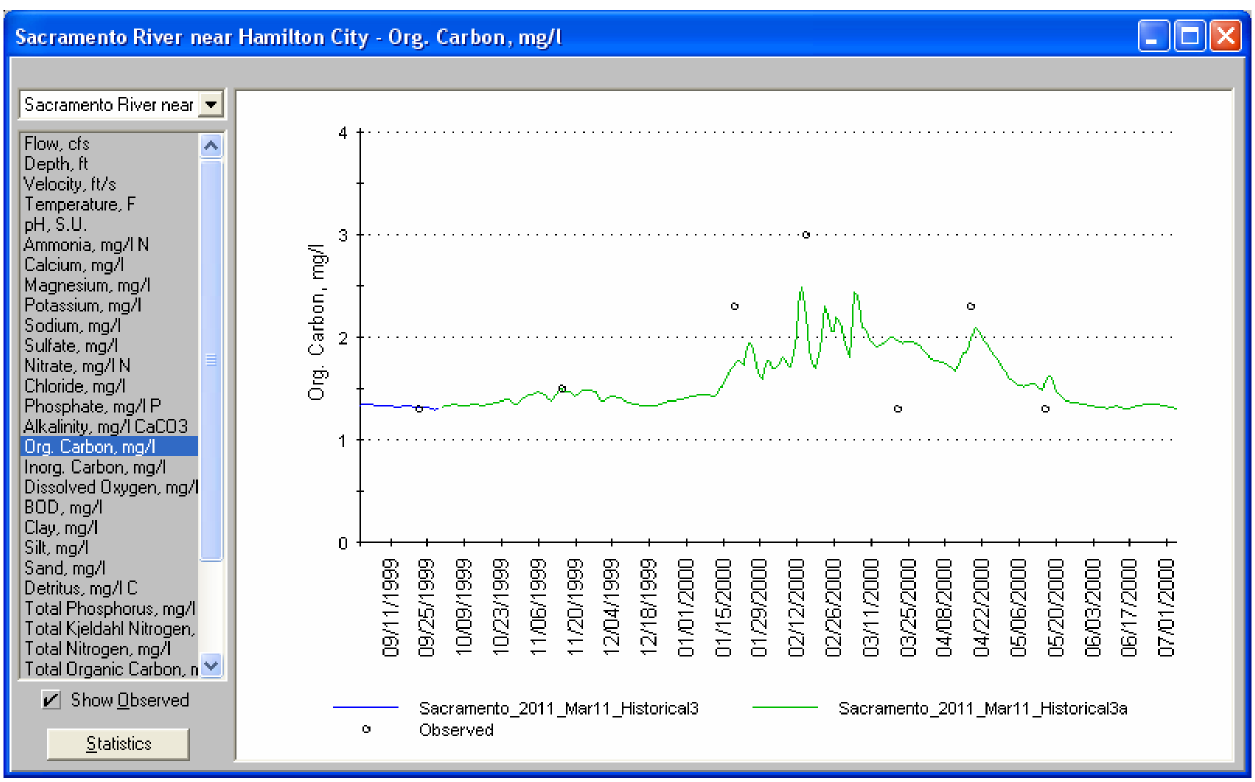

Figure 2-27 Simulated and observed organic carbon at Sacramento River at Hamilton City

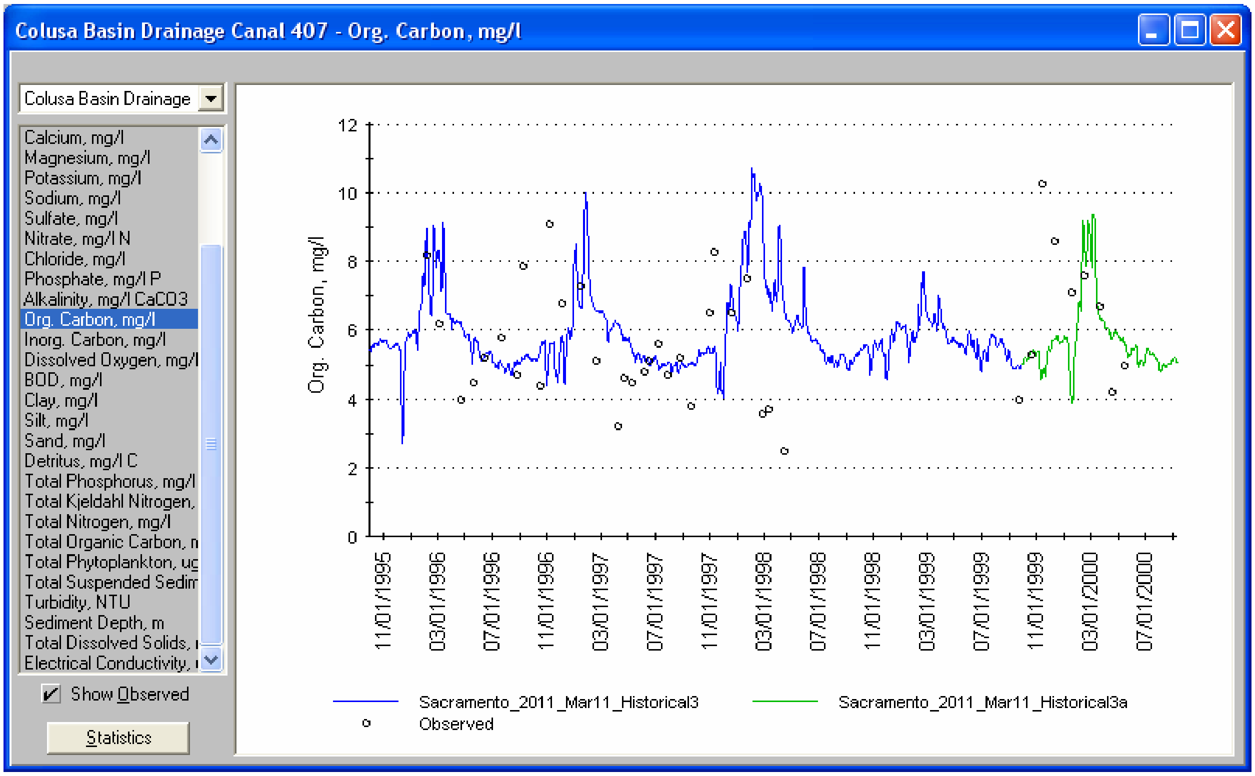

Figure 2-28 Simulated and observed organic carbon at Colusa Basin Drain near Knights Landing.

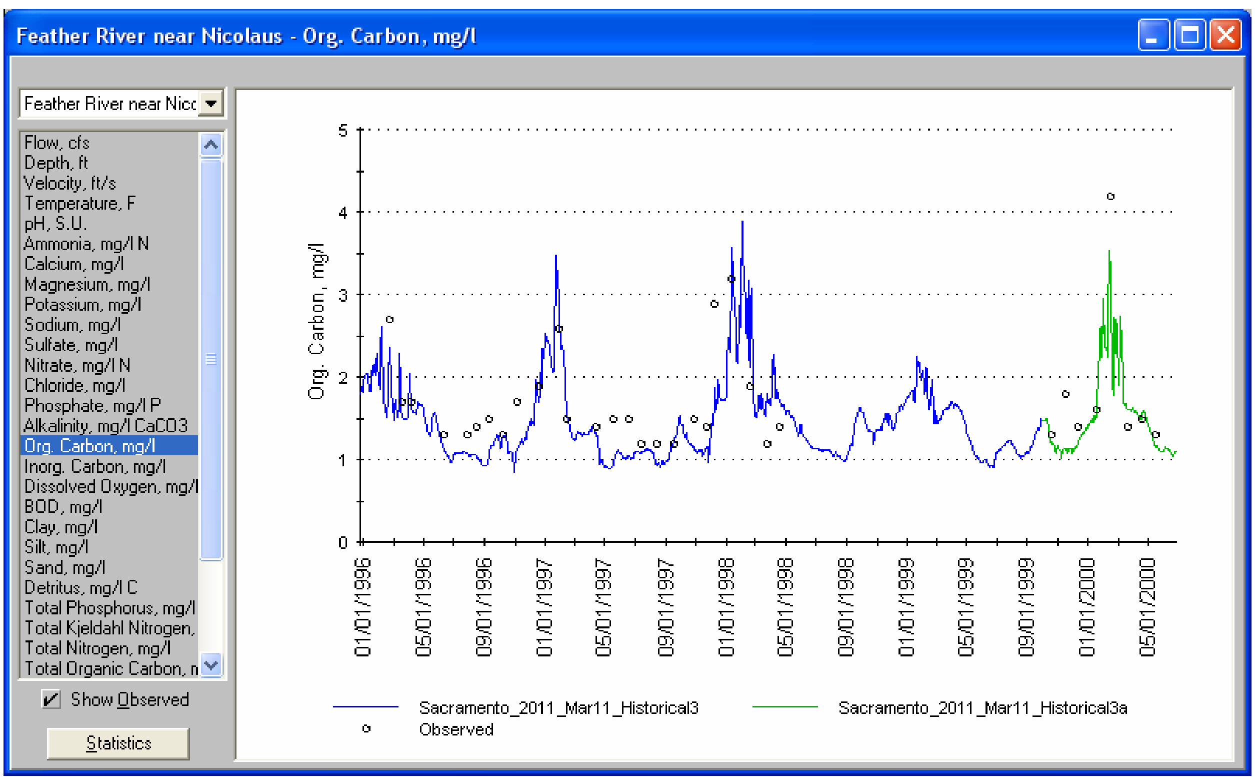

Figure 2-29 Simulated and observed organic carbon at Feather River at Nicolaus.

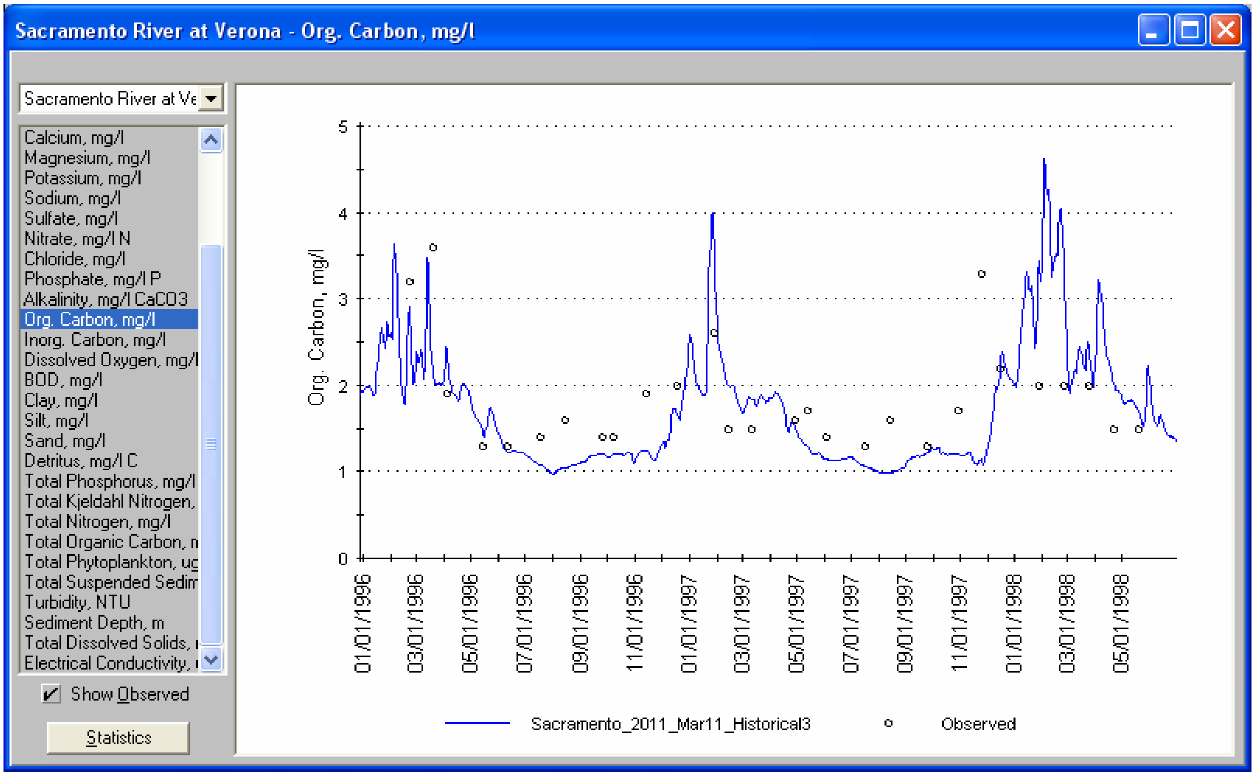

Figure 2-30 Simulated and observed organic carbon at Sacramento River at Verona

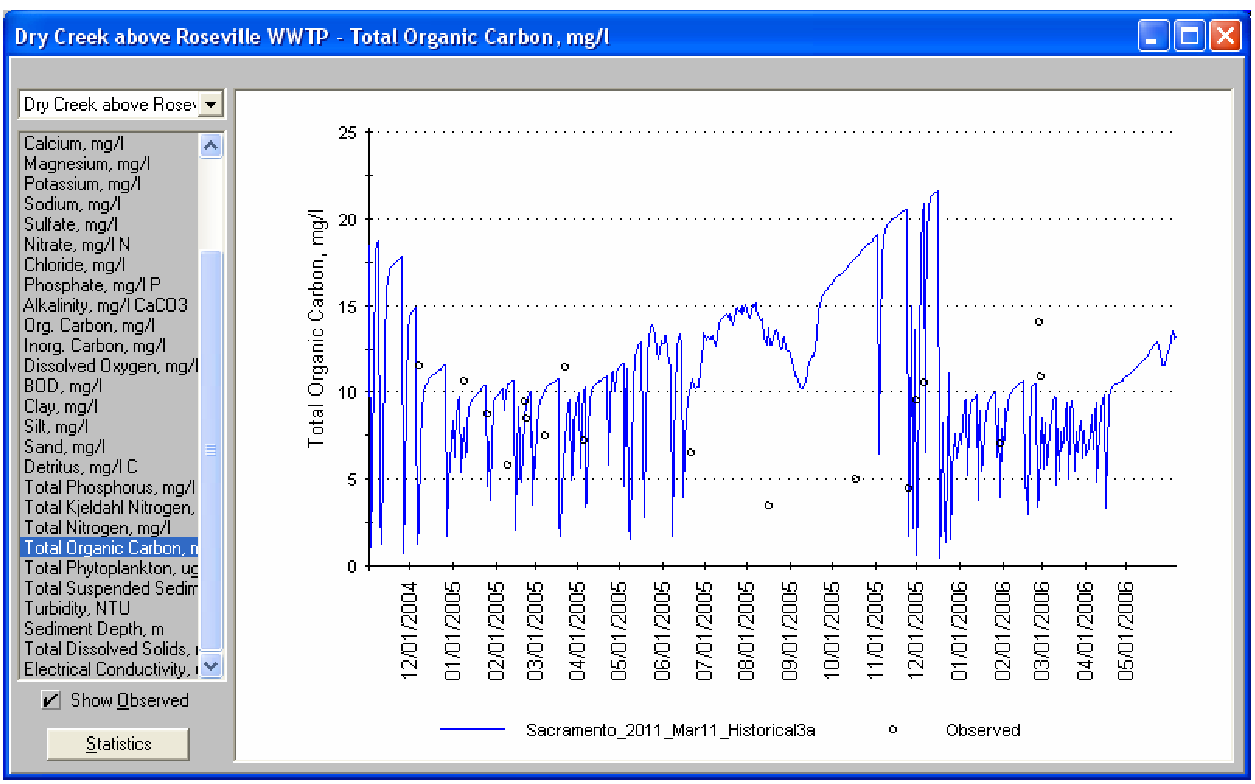

Figure 2-31 Simulated and observed organic carbon at Dry Creek above Roseville WWTP

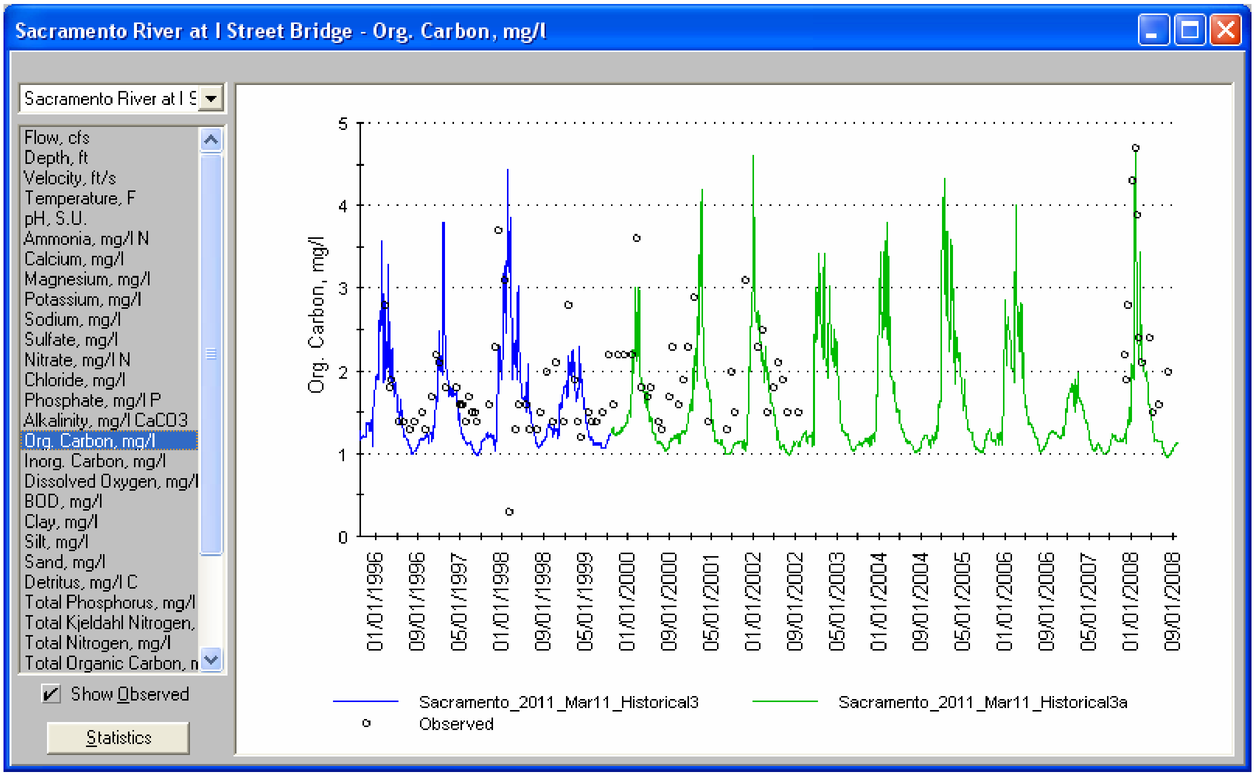

Figure 2-32 Simulated and observed organic carbon at Sacramento River at I Street

Table 2.15 shows the model errors for organic carbon at various monitoring stations within the Sacramento River WARMF model domain. The goal of calibration is less than 10% relative error and less than 20% absolute error. The WARMF simulation of organic carbon agrees well with the observed data in the upper watershed and in the urban Dry Creek watershed, but it underpredicts measured organic carbon in the Sacramento River near Freeport. The model's match to observed data in the Colusa Basin Drain is coincidental because the flow in the Drain does not match the simulated flow as discussed in the hydrology calibration section of this document. If the flow imbalance in the Colusa Basin Drain were fixed it would likely increase the amount of agricultural drainage throughout the watershed. With more simulated drainage, there would be more organic carbon loading from the agricultural lands. This additional loading would reduce the error in simulated organic carbon concentration at Freeport. Although the monitoring location on Dry Creek is upstream of the Roseville Dry Creek Wastewater Treatment Plant, it is downstream of the Placer County District 3 Wastewater Treatment Plant .The high absolute error at the Dry Creek site is caused by poor data from the Placer County discharge. The creek may be effluent dominated at this monitoring location in the summer. Additional Delta model boundary control points were where the Cosumnes, Mokelumne, and Calaveras Rivers enter the Delta. Information about the calibration of these tributaries can be found in the final report for the Delta East Side Tributaries modeling work (Systech 2011). Calibration plots and statistics for the Cosumnes and Mokelumne Rivers are also provided in Appendix A for reference.

Table 2.15 Model Errors of Organic Carbon

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	+3%	24%
Sacramento River at Hamilton City	-5%	19%
Colusa Basin Drain near Knights Landing	+5%	28%
Feather River at Nicolaus	-9%	19%
Sacramento River at Verona	-2%	30%
Dry Creek	+3%	64%
Sacramento River at Freeport	-18%	29%

Ammonia

Differences between observed and simulated ammonia were analyzed at six locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Hamilton City, Colusa Basin Drain near Knights Landing, Feather River at Nicolaus, Sacramento River at Verona, Dry Creek near Roseville, and Sacramento River at Freeport. Evaluating the simulation results at these locations lets us determine model performance simulating ammonia from different combinations of sources: upstream inflows, natural landscape, agricultural areas, and urban areas.

Figure 2-26 through Figure 2-32 show the simulated and observed time series of dissolved ammonia at various stations within the Sacramento River WARMF model domain. Each graph is focused on the time periods for which there is observed data at each location. Much of the measured data is actually below the detection limit of the sampling method and is shown as zero concentration. Because most of the measured ammonia concentration were at or near detection limit, the error in measured data is relatively large (generally 0.01-0.02 mg/l) compared to the scale of the Y axis.

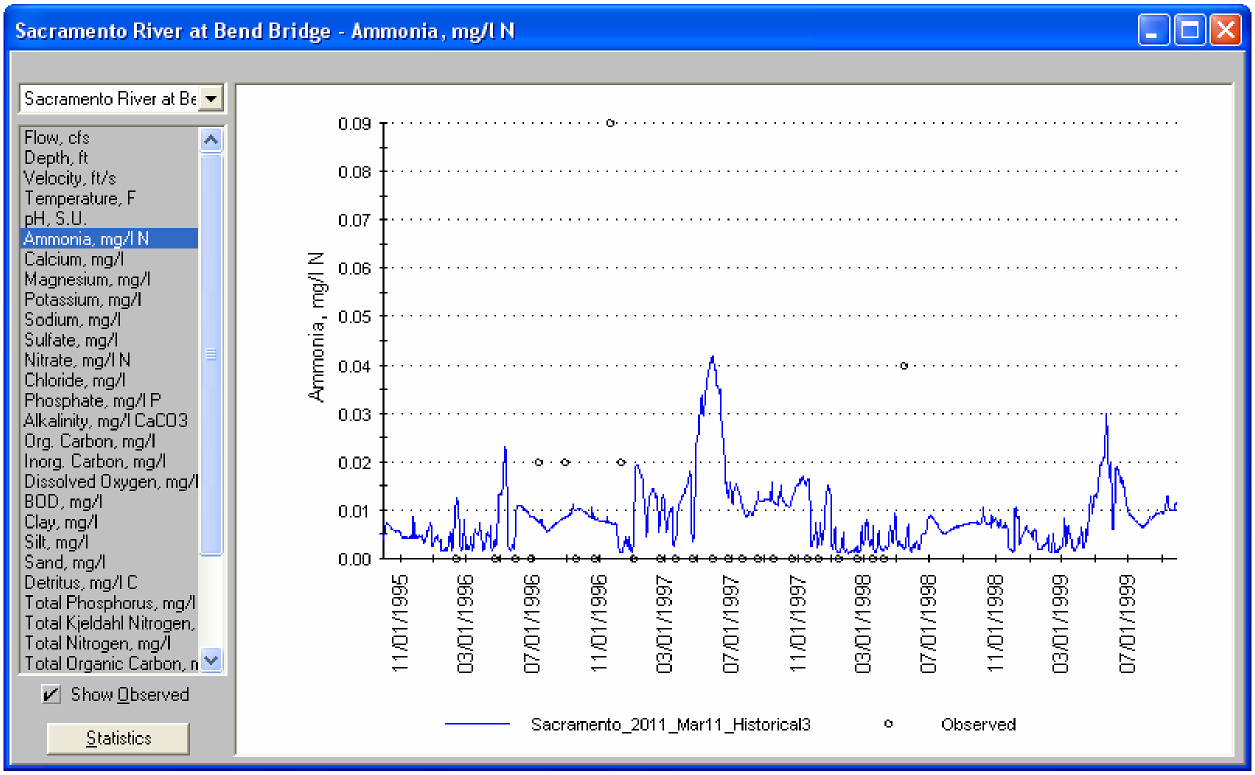

Figure 2-33 Simulated and observed ammonia at Sacramento River at Bend Bridge.

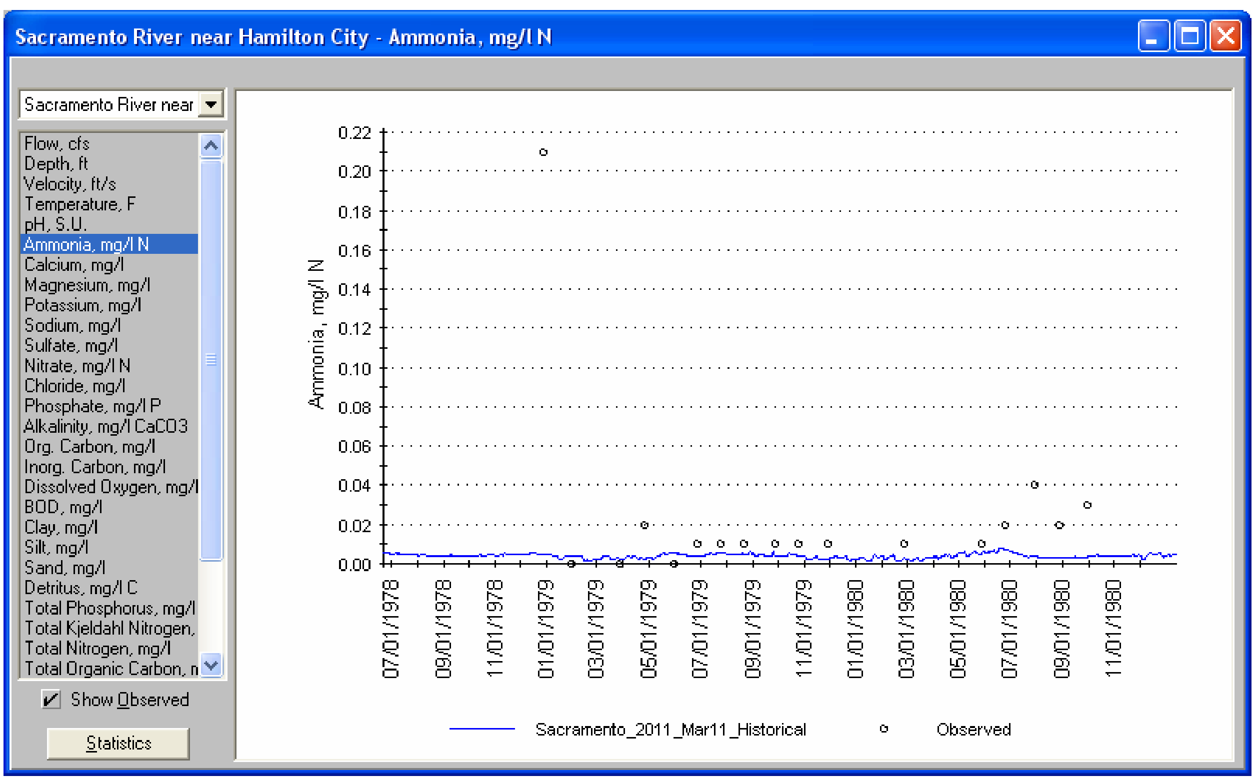

Figure 2-34 Simulated and observed ammonia at Sacramento River at Hamilton City

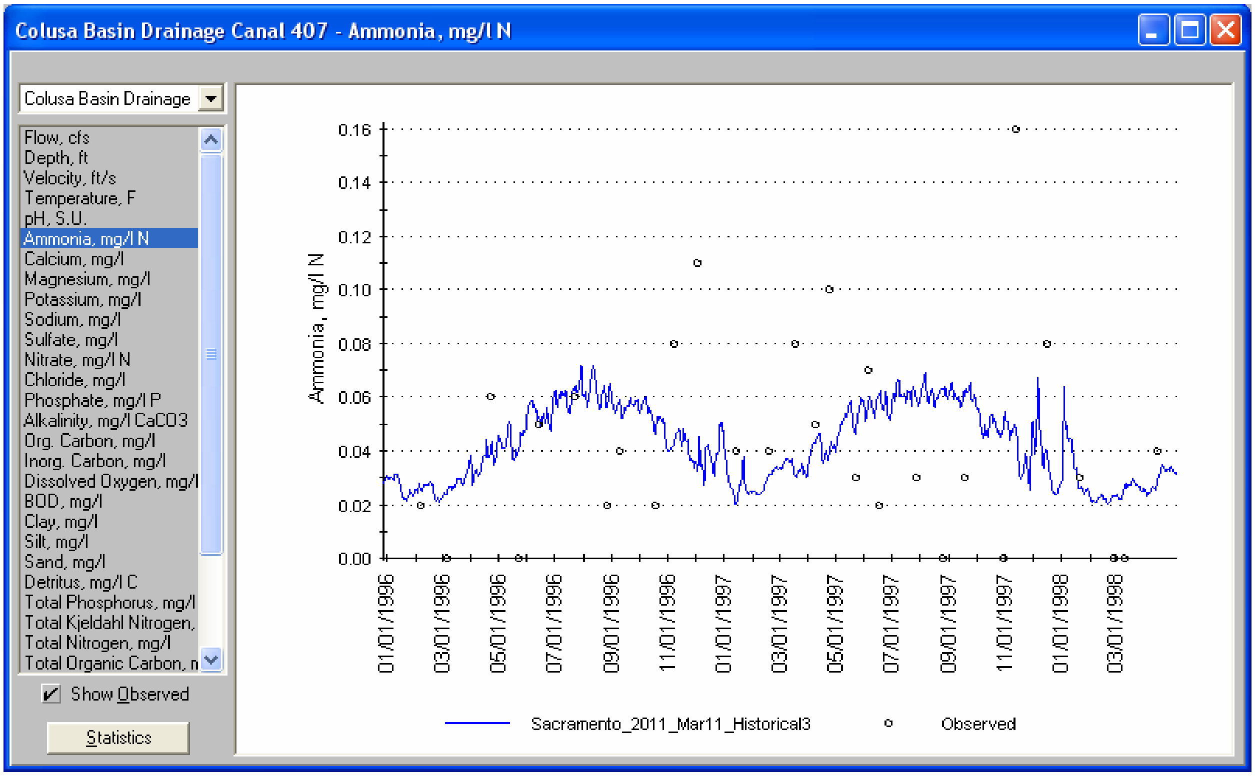

Figure 2-35 Simulated and observed ammonia at Colusa Basin Drain near Knights Landing.

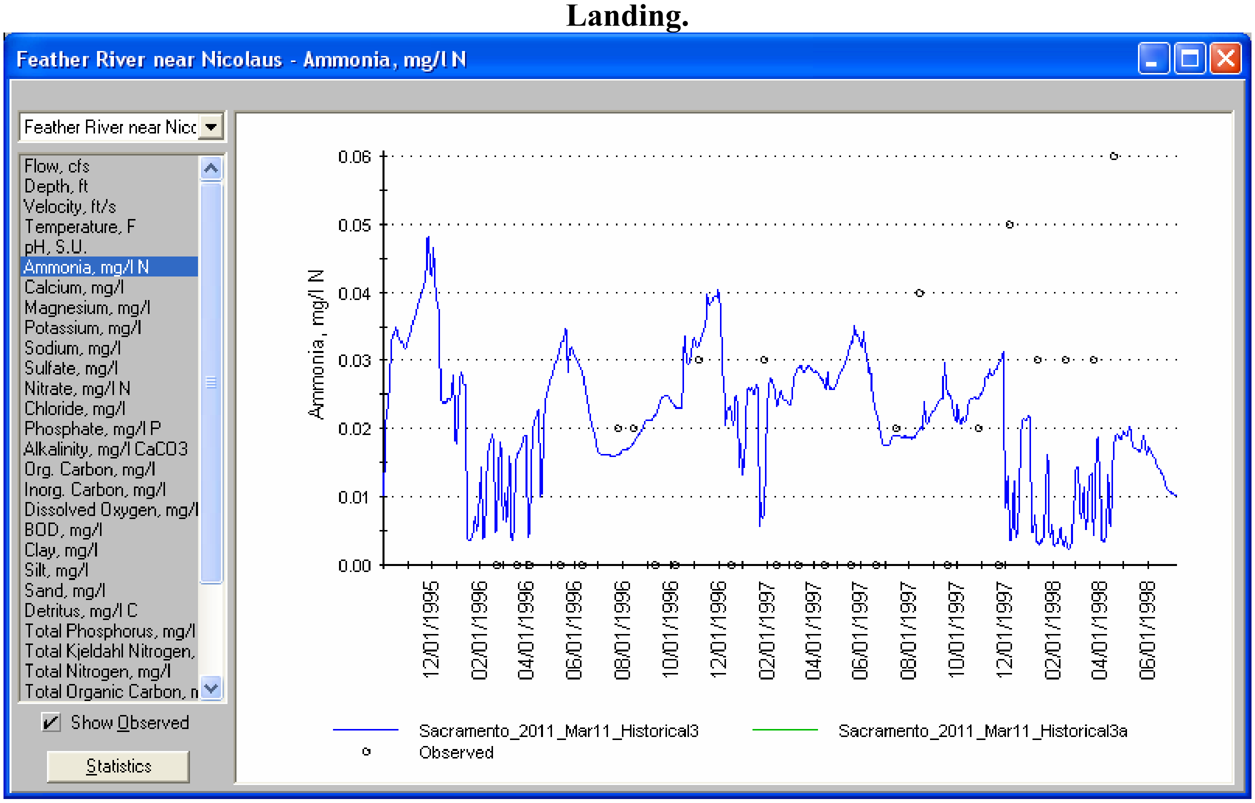

Figure 2-36 Simulated and observed ammonia at Feather River at Nicolaus.

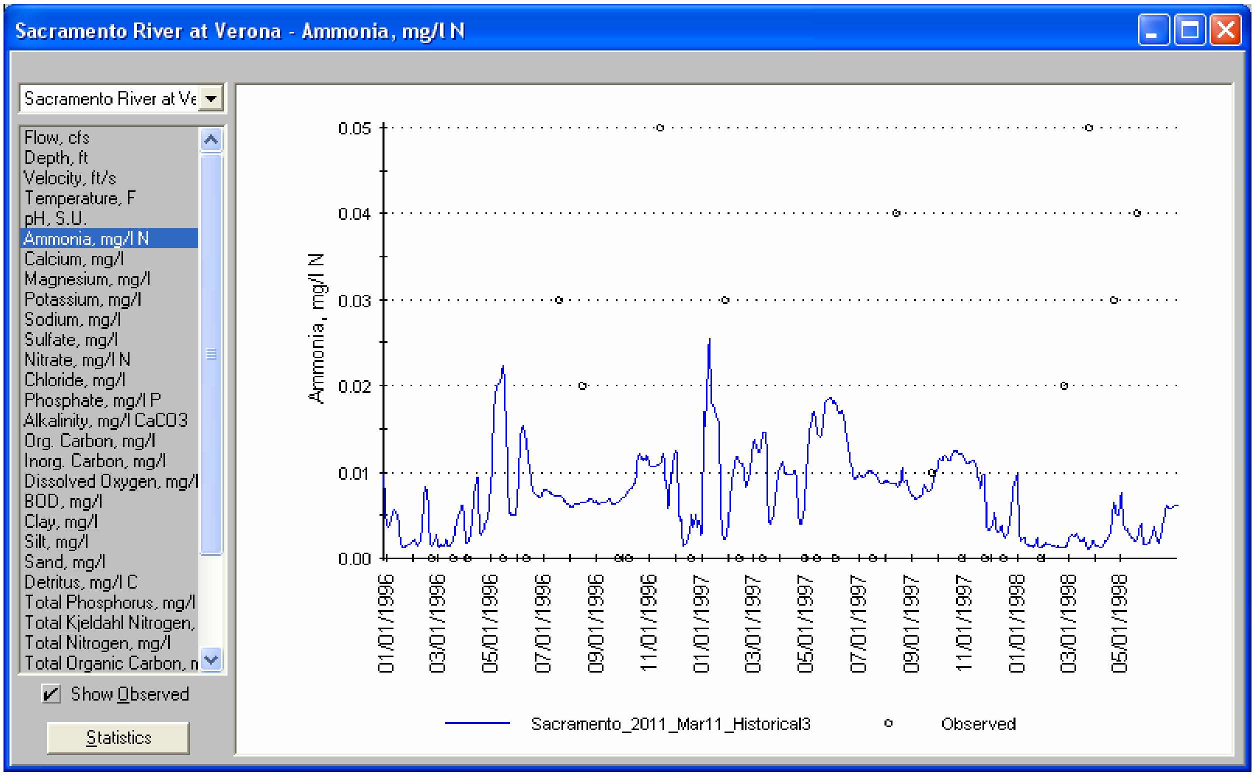

Figure 2-37 Simulated and observed ammonia at Sacramento River at Verona

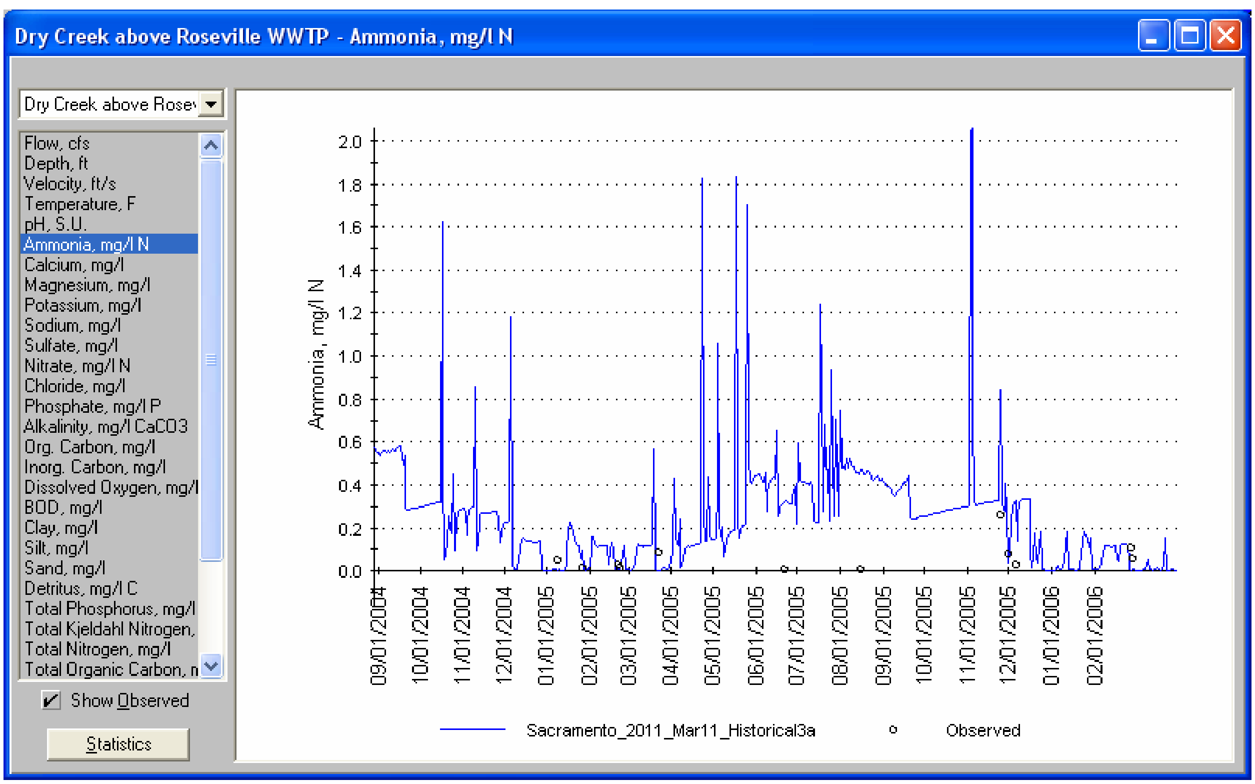

Figure 2-38 Simulated and observed ammonia at Dry Creek above Roseville WWTP

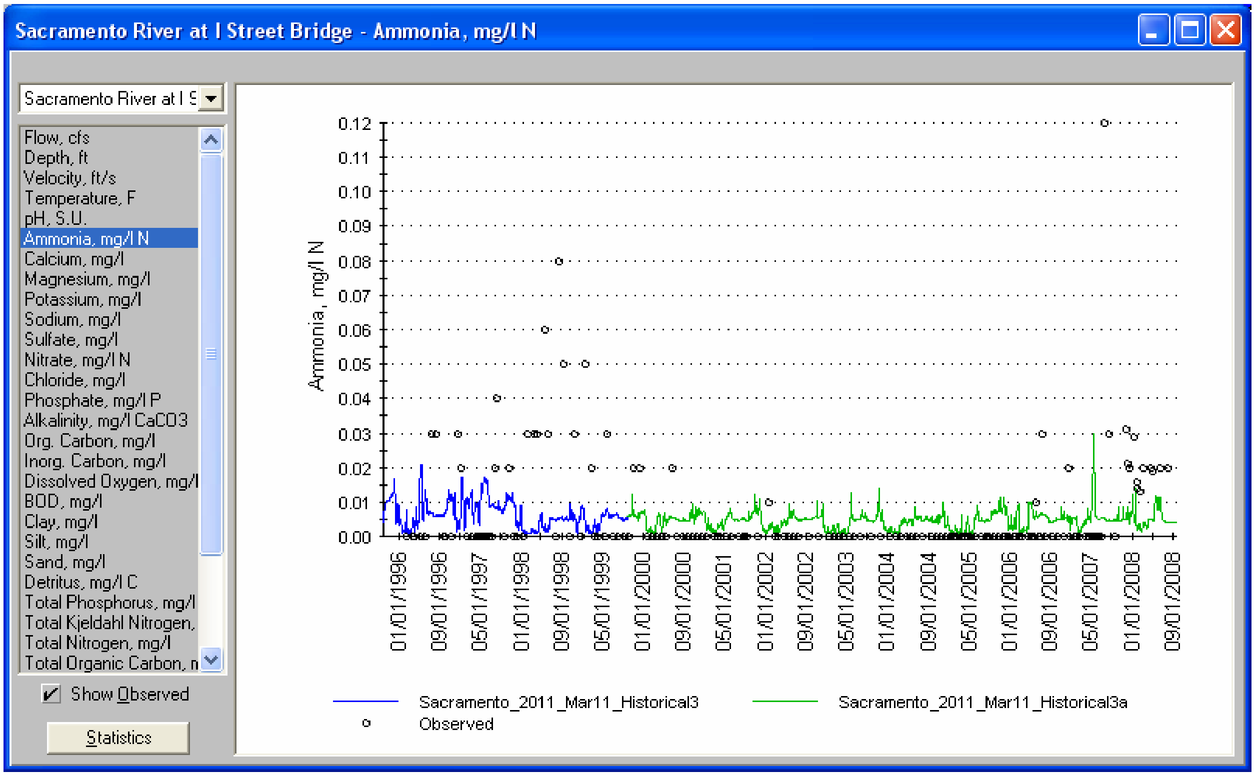

Figure 2-39 Simulated and observed ammonia at Sacramento River near Freeport

Table 2.16 shows the model errors for ammonia at various monitoring stations within the Sacramento River WARMF model domain. Because much of the data was below detection limit the errors are expressed in terms of concentration rather than percent. Ammonia measurements were generally to the nearest 0.01 or 0.02 mg/l. The only location with relative error greater than 0.02 mg/l was the urban location, Dry Creek near Roseville. Since there is a small (0.3 mgd) Placer County District 3 wastewater treatment plant discharge upstream with minimal data, it is not possible to match the observed data precisely. Although the error in Colusa Basin Drain is small, it may be coincidental. The ammonia concentration might be different if the flow balance there were corrected. WARMF is simulating an annual pattern of concentration not discernible in the measured data. This is likely a consequence of having relatively little agricultural drainage in the simulations. Ammonia calibration was not a priority of the Delta east side tributaries modeling project, but coarse adjustment of model parameters was performed for the Cosumnes, Mokelumne, and Calaveras Rivers so that the simulated ammonia would be reasonable in comparison with measured data.

Table 2.16 Model Errors of Ammonia

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	+0.00 mg/l	0.01 mg/l
Sacramento River at Hamilton City	-0.02 mg/l	0.02 mg/l
Colusa Basin Drain near Knights Landing	-0.00 mg/l	0.03 mg/l
Feather River at Nicolaus	+0.01 mg/l	0.02 mg/l
Sacramento River at Verona	-0.00 mg/l	0.02 mg/l
Dry Creek near Roseville	+0.13 mg/l	0.19 mg/l
Sacramento River at Freeport	-0.00 mg/l	0.01 mg/l

Nitrate

Differences between observed and simulated organic carbon were analyzed at six locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Hamilton City, Colusa Basin Drain near Knights Landing, Feather River at Nicolaus, Sacramento River at Verona, Dry Creek above the Roseville wastewater treatment plant, and Sacramento River at Freeport. Evaluating the simulation results at these locations lets us determine model performance simulating organic carbon from different combinations of sources: upstream inflows, natural landscape, agricultural areas, and urban areas.

Figure 2-26 through Figure 2-32 show the simulated and observed time series of nitrate at various stations within the Sacramento River WARMF model domain. Each graph is focused on the time periods for which there is observed data at each location.

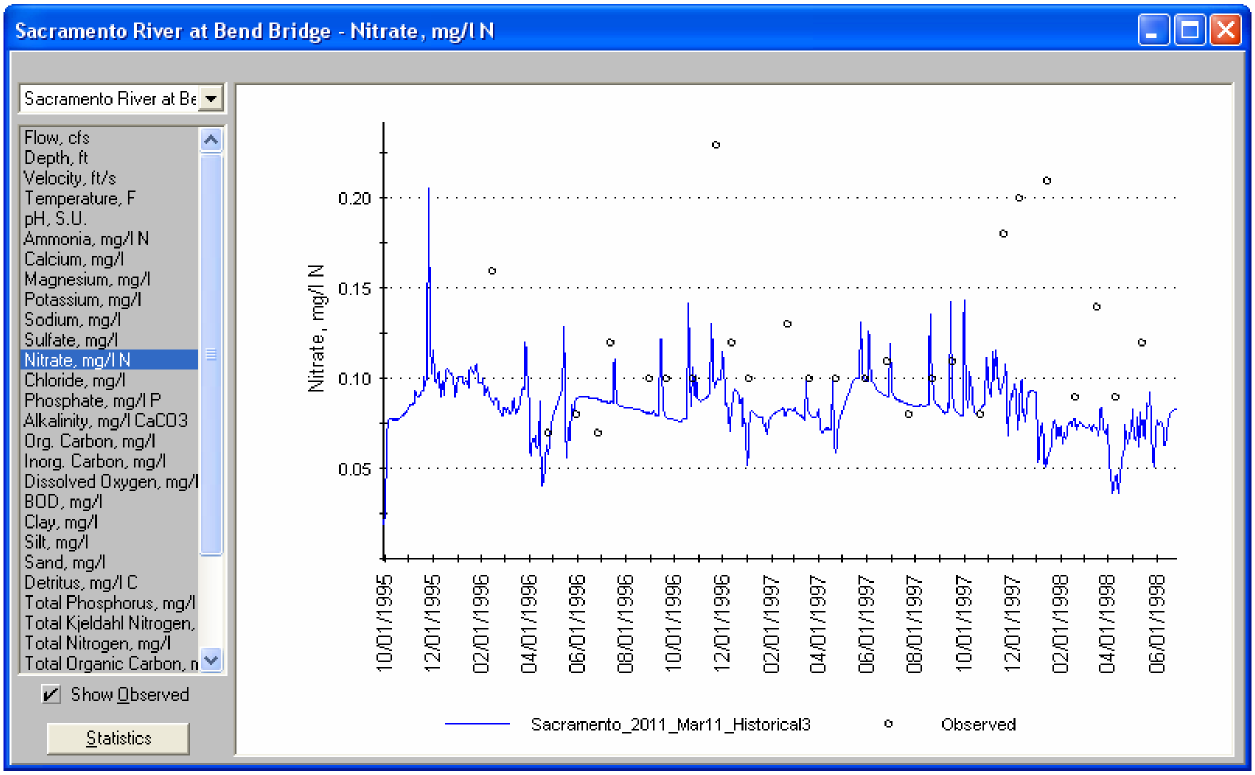

Figure 2-40 Simulated and observed nitrate at Sacramento River at Bend Bridge.

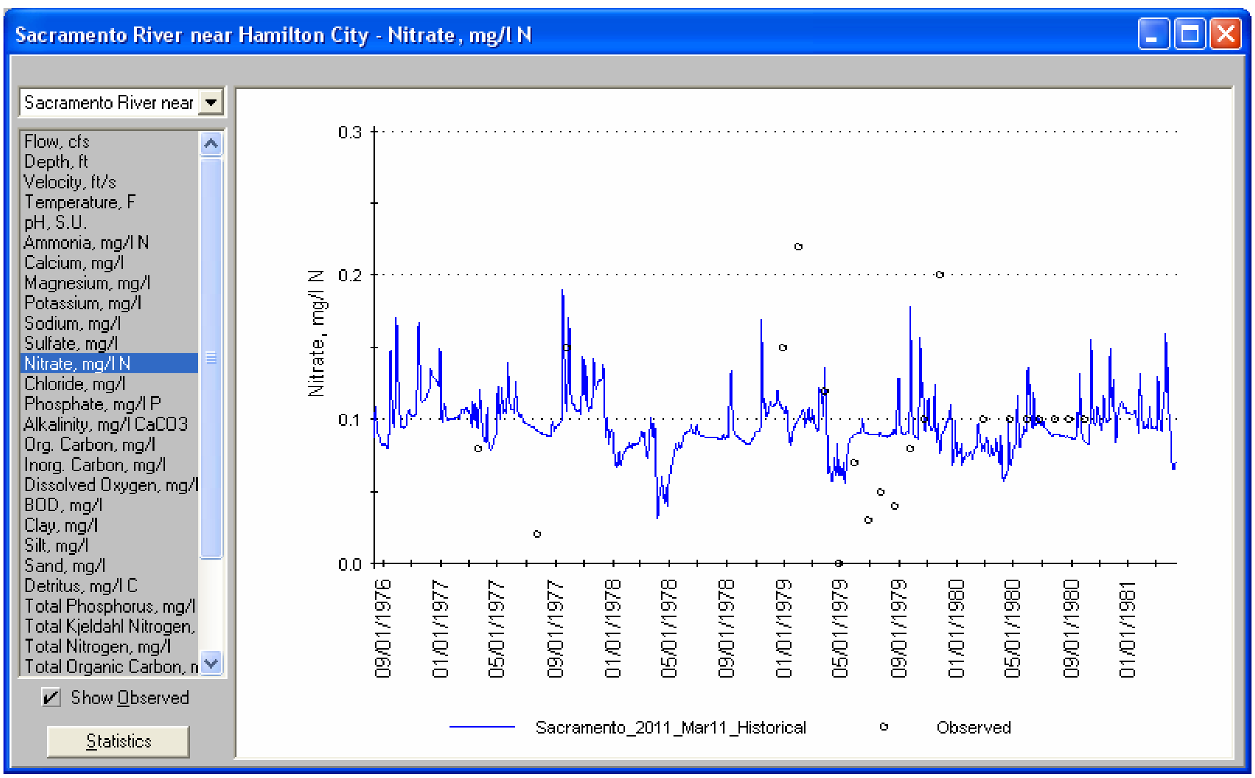

Figure 2-41 Simulated and observed nitrate at Sacramento River at Hamilton City

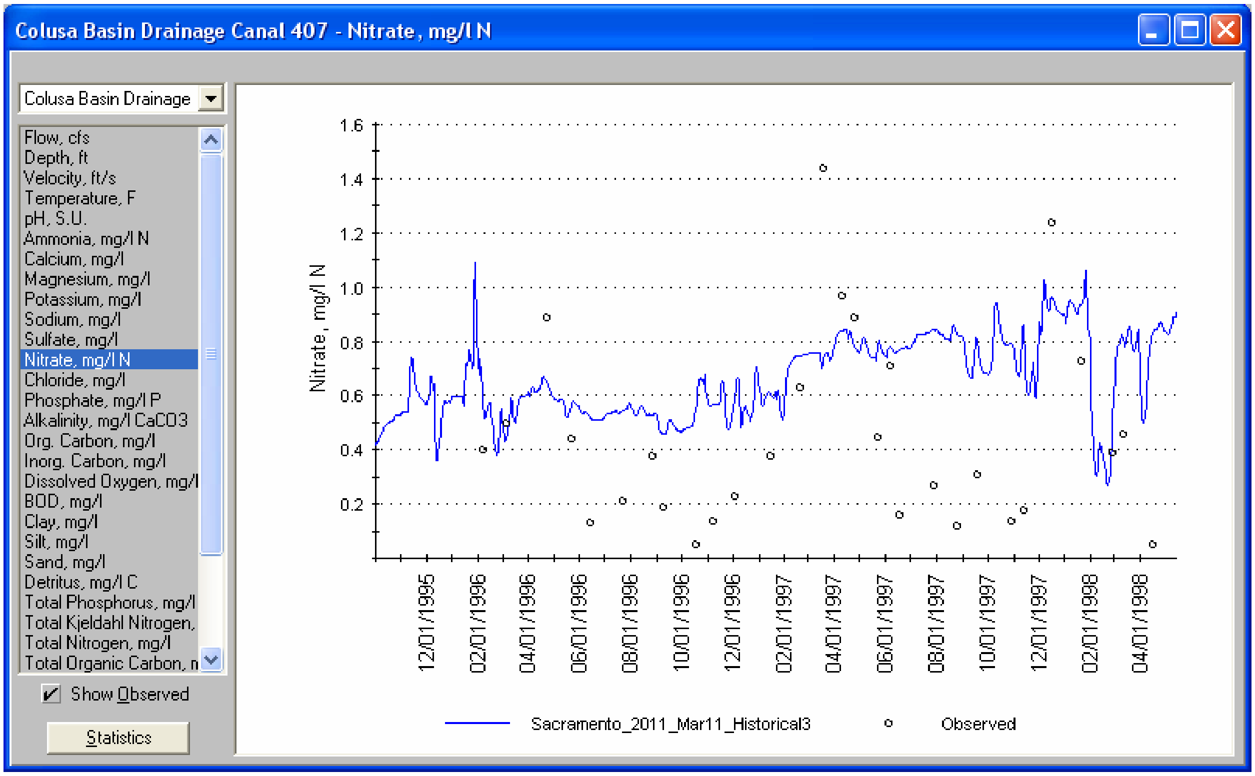

Figure 2-42 Simulated and observed nitrate at Colusa Basin Drain near Knights Landing.

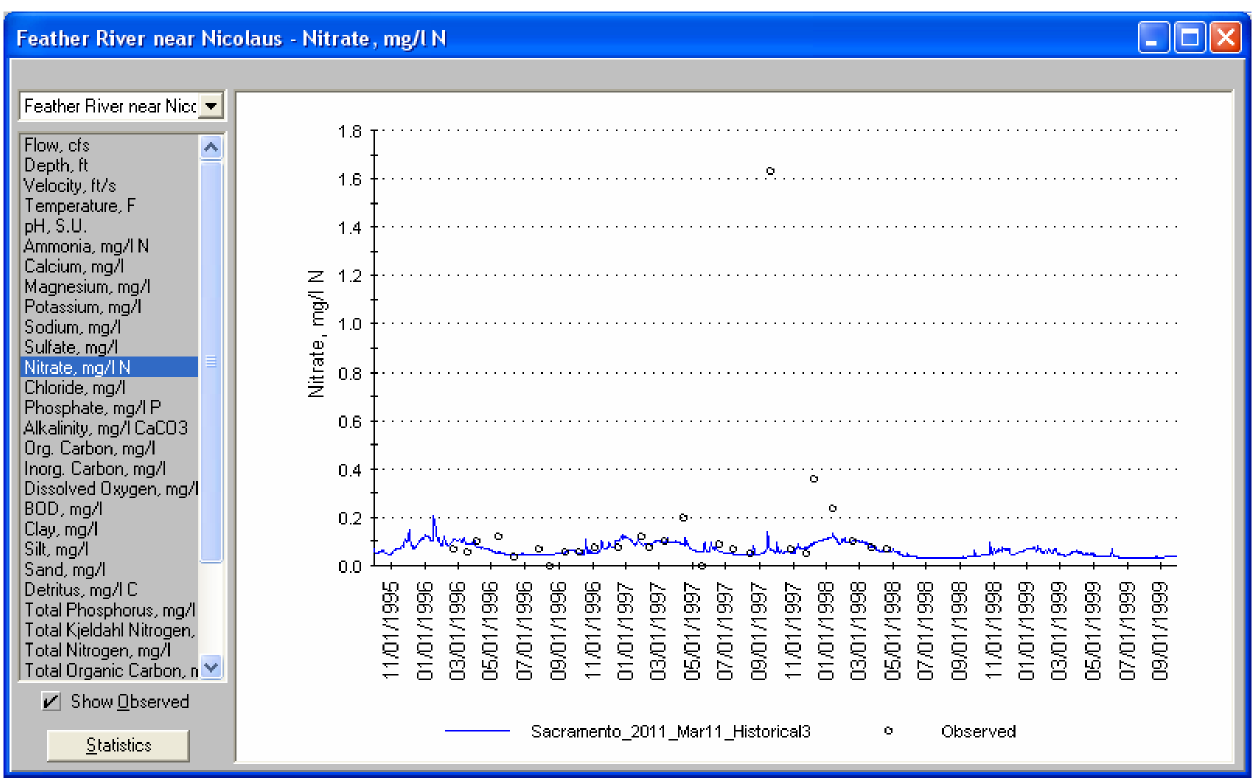

Figure 2-43 Simulated and observed nitrate at Feather River at Nicolaus.

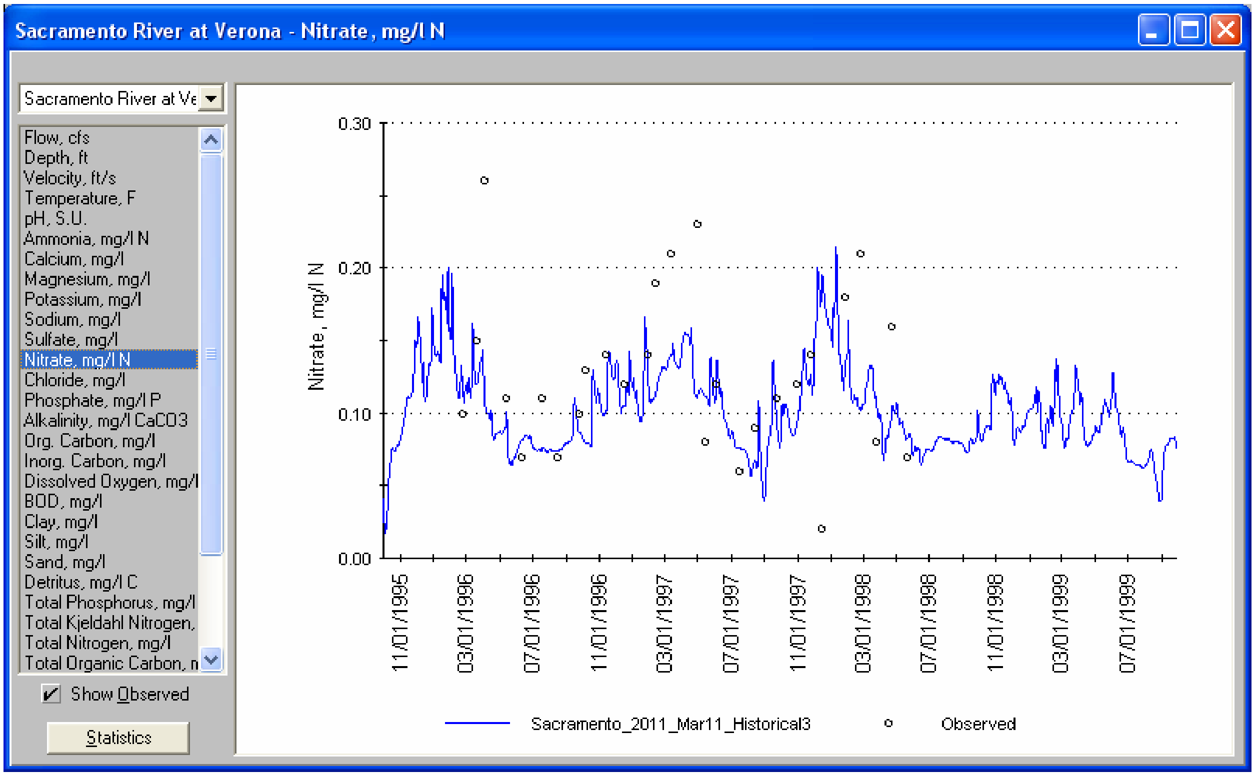

Figure 2-44 Simulated and observed nitrate at Sacramento River at Verona

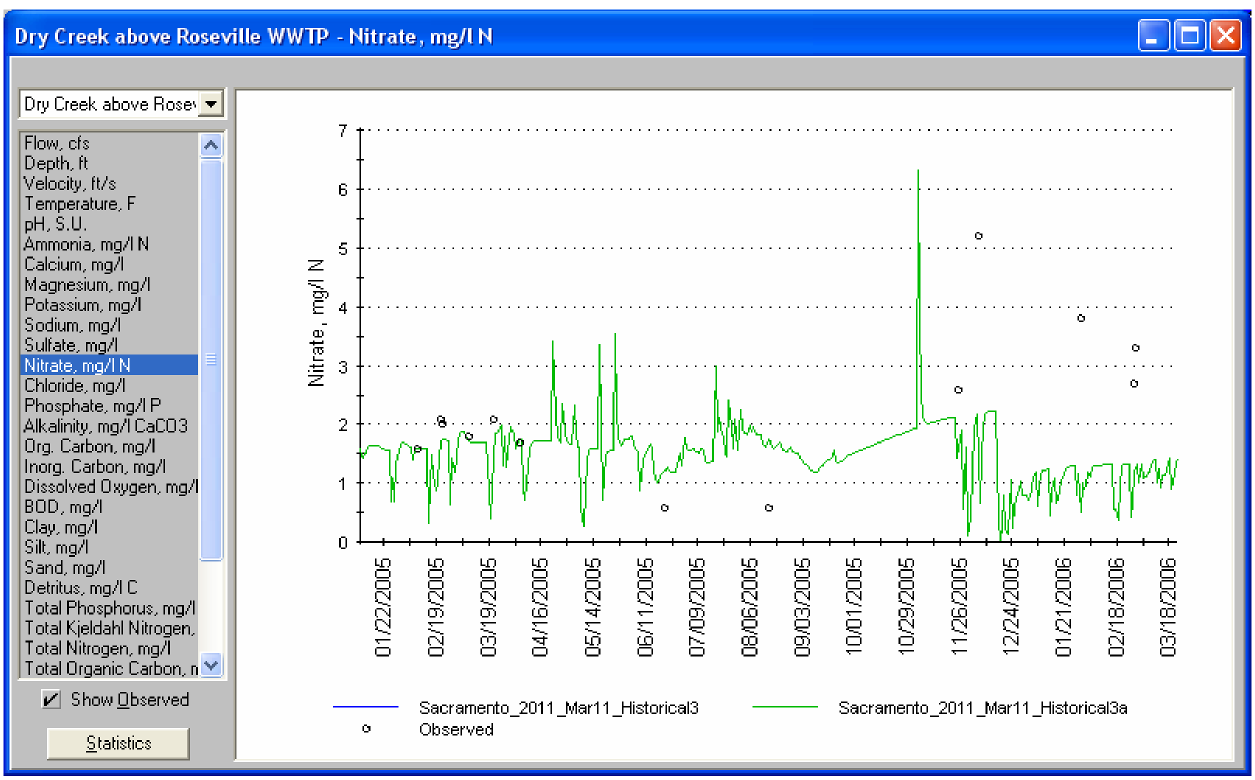

Figure 2-45 Simulated and observed nitrate at Dry Creek above Roseville WWTP

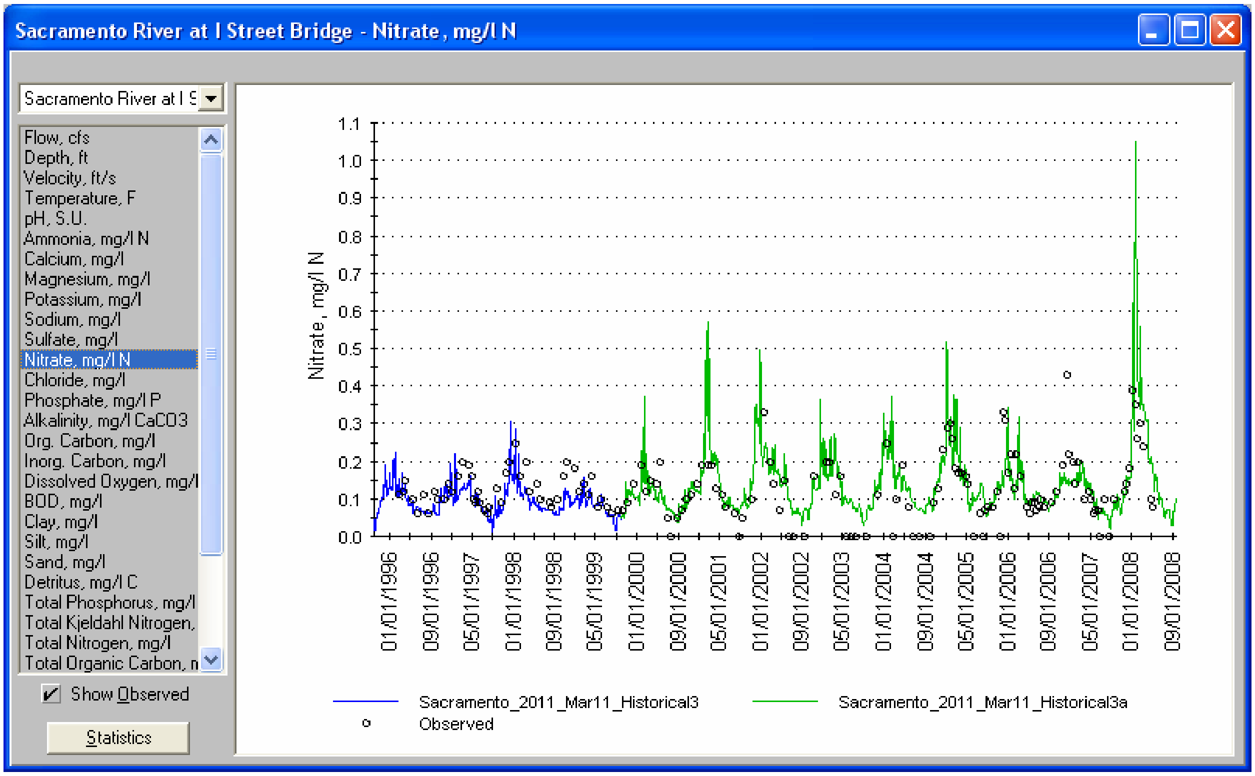

Figure 2-46 Simulated and observed nitrate at Sacramento River at Freeport

Table 2.17 shows the model errors for nitrate at various monitoring stations within the Sacramento River WARMF model domain. The goal of calibration is relative error less than 10% and absolute error less than 30%. The WARMF simulation of nitrate follows the seasonal pattern of high concentration in winter, low in summer very well but there are significant errors at each monitoring station. The nitrate simulation in the Colusa Basin Drain is controlled by the flow simulation, which is not accurate in summer with the current set of model input coefficients. If the flow in the Drain were made more reasonable, the nitrate simulation would improve with more agricultural returns. A precise calibration of Dry Creek near Roseville is not possible because there is little information about the discharge of the Placer County District 3 wastewater treatment plant. Nitrate calibration was not a priority of the Delta east side tributaries modeling project, but coarse adjustment of model parameters was performed for the Cosumnes, Mokelumne, and Calaveras Rivers so that the simulated nitrate would be reasonable in comparison with measured data.

Table 2.17 Model Errors of Nitrate

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	-31%	34%l
Sacramento River at Hamilton City	+2%	43%
Colusa Basin Drain near Knights Landing	+53%	77%
Feather River at Nicolaus*	-51%	63%
Sacramento River at Verona	-17%	35%
Dry Creek	-38%	50%
Sacramento River at Freeport	+5%	39%

* If outlier data point is discarded, relative error is -2% and absolute error is 16%.

Phosphorus

Differences between observed and simulated total phosphorus were analyzed at six locations within the WARMF Sacramento River model domain. From upstream to downstream, these locations include Sacramento River at Bend Bridge, Sacramento River at Hamilton City, Colusa Basin Drain near Knights Landing, Feather River at Nicolaus, Sacramento River at Verona, Dry Creek near Roseville, and Sacramento River at Freeport. Evaluating the simulation results at these locations lets us determine model performance from different combinations of sources: upstream inflows, natural landscape, agricultural areas, and urban areas.

Figure 2-26 through Figure 2-32 show the simulated and observed time series of dissolved organic carbon at various stations within the Sacramento River WARMF model domain. Each graph is focused on the time periods for which there is observed data at each location.

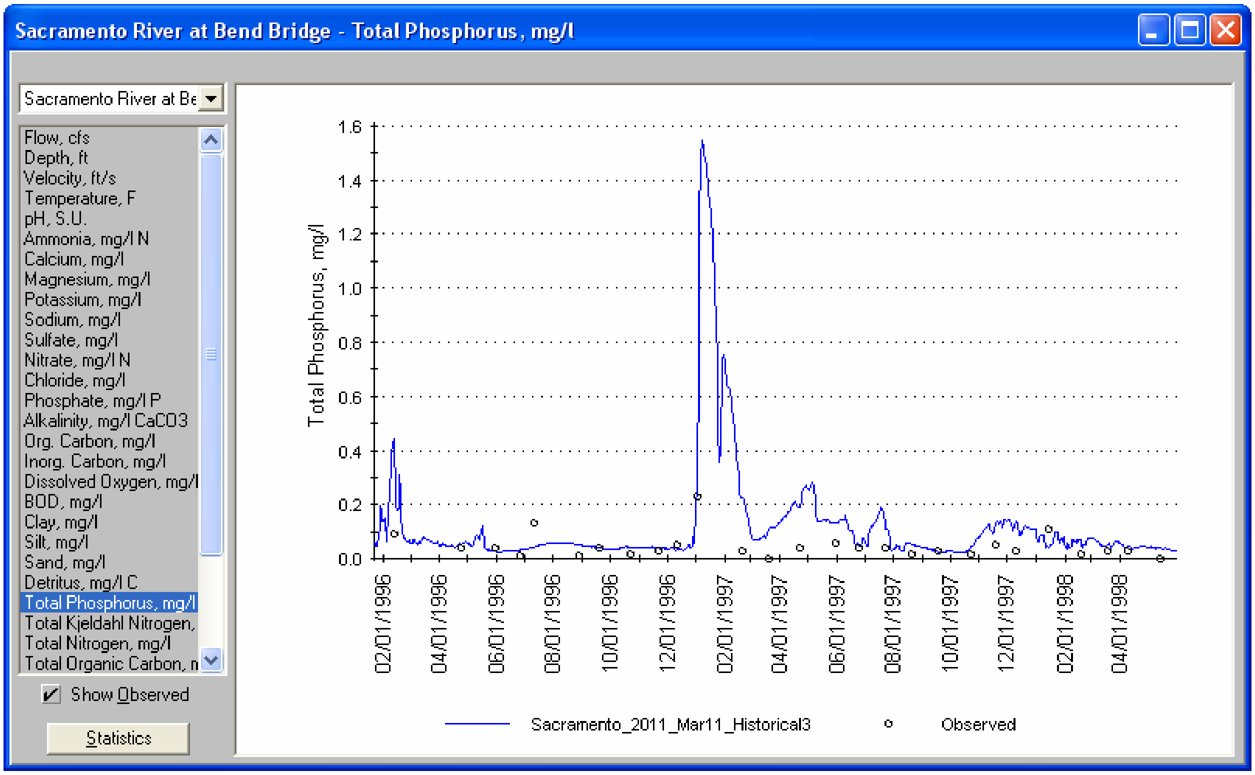

Figure 2-47 Simulated and observed total phosphorus at Sacramento River at Bend Bridge.

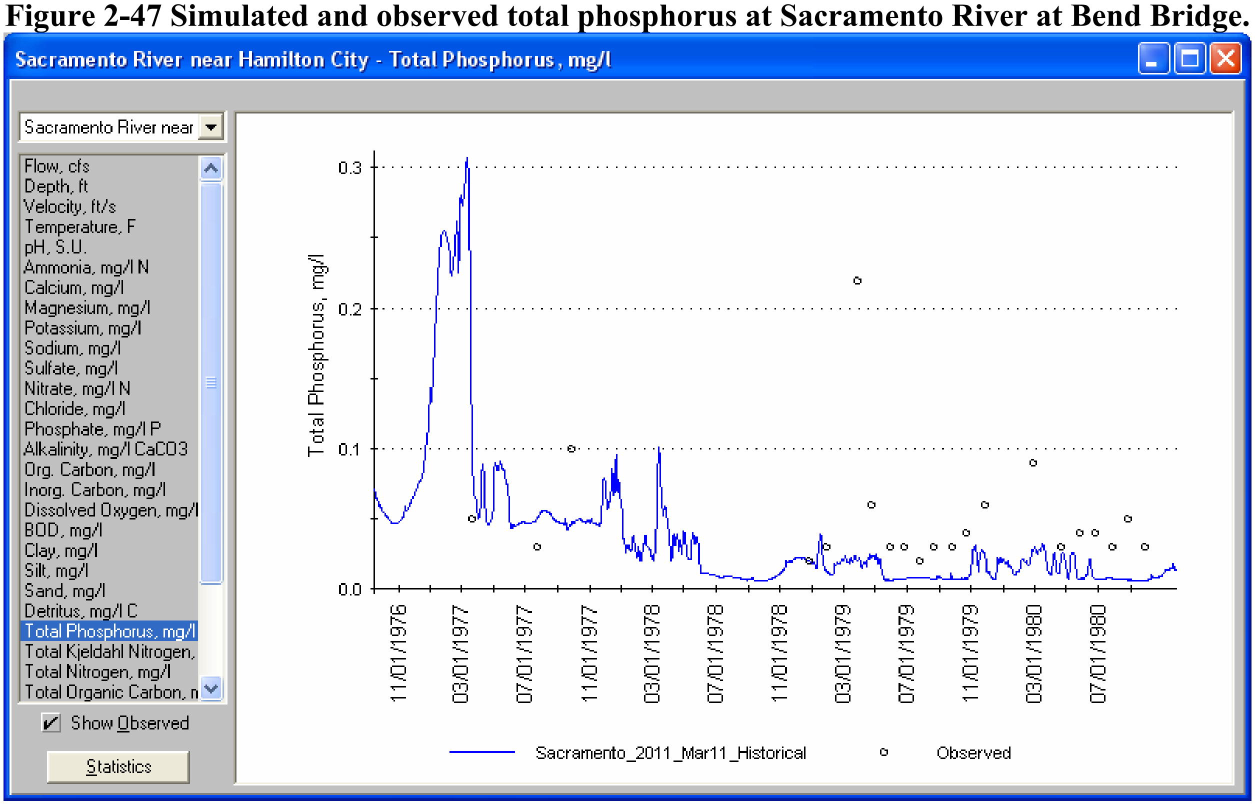

Figure 2-48 Simulated and observed total phosphorus at Sacramento River at Hamilton City

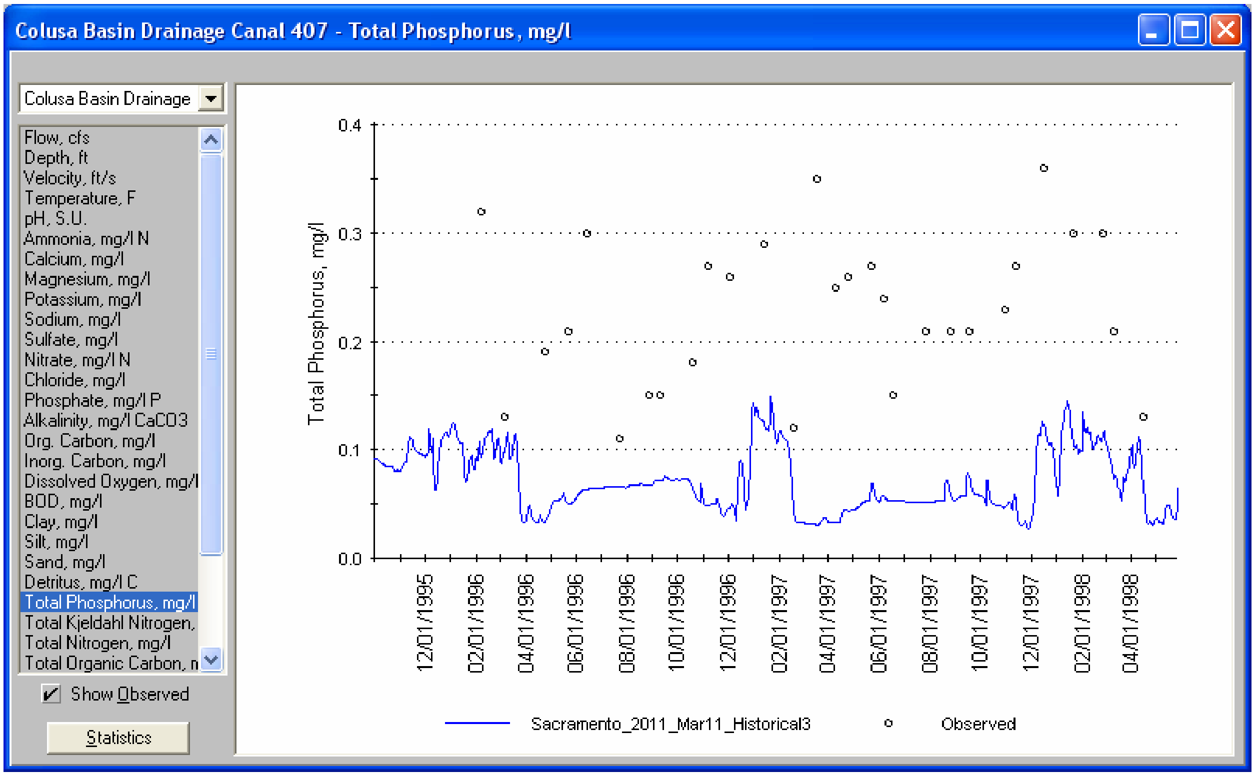

Figure 2-49 Simulated and observed total phosphorus at Colusa Basin Drain near Knights Landing.

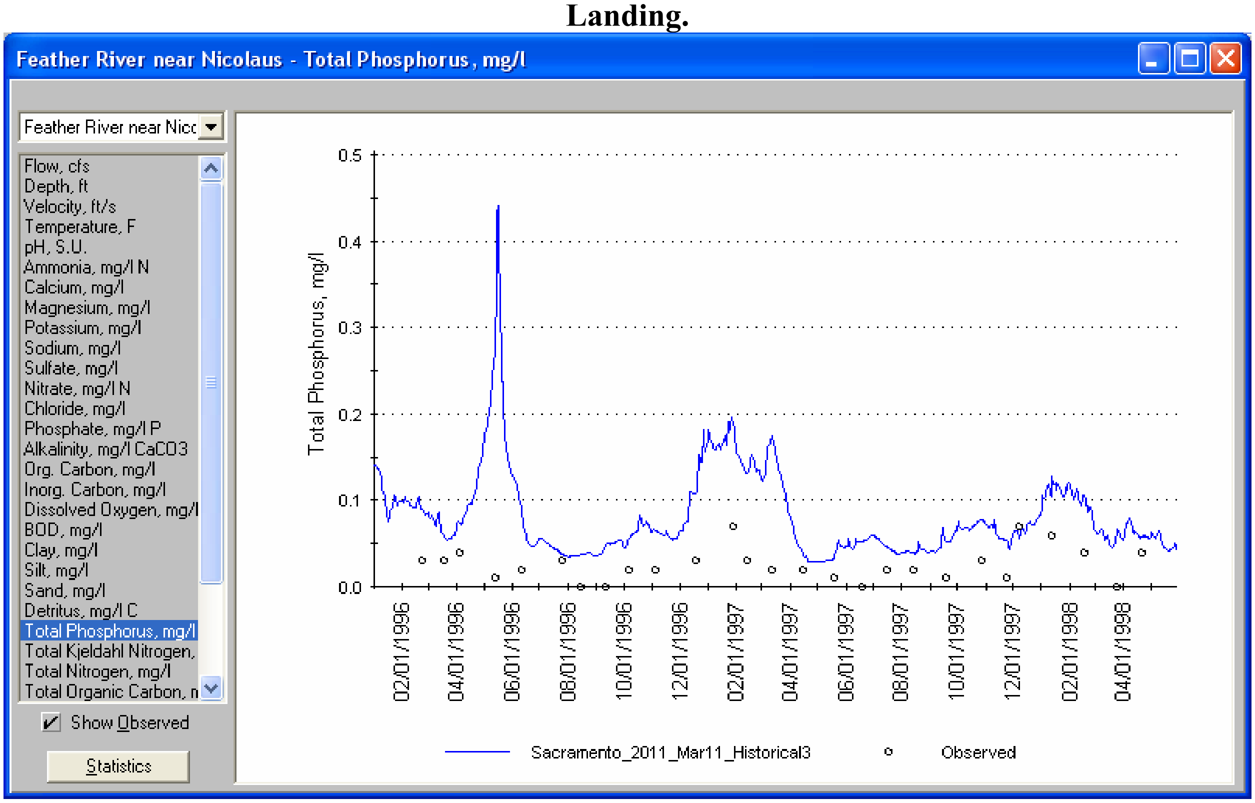

Figure 2-50 Simulated and observed total phosphorus at Feather River at Nicolaus.

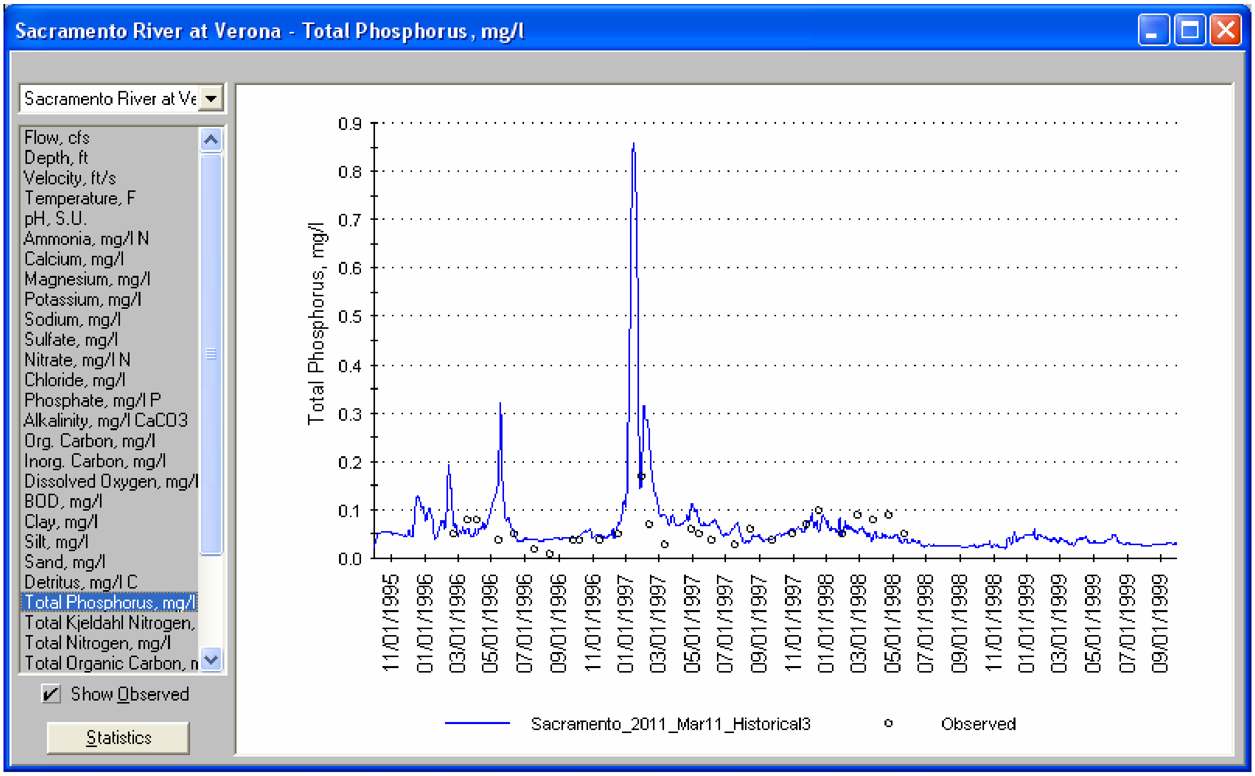

Figure 2-51 Simulated and observed total phosphorus at Sacramento River at Verona

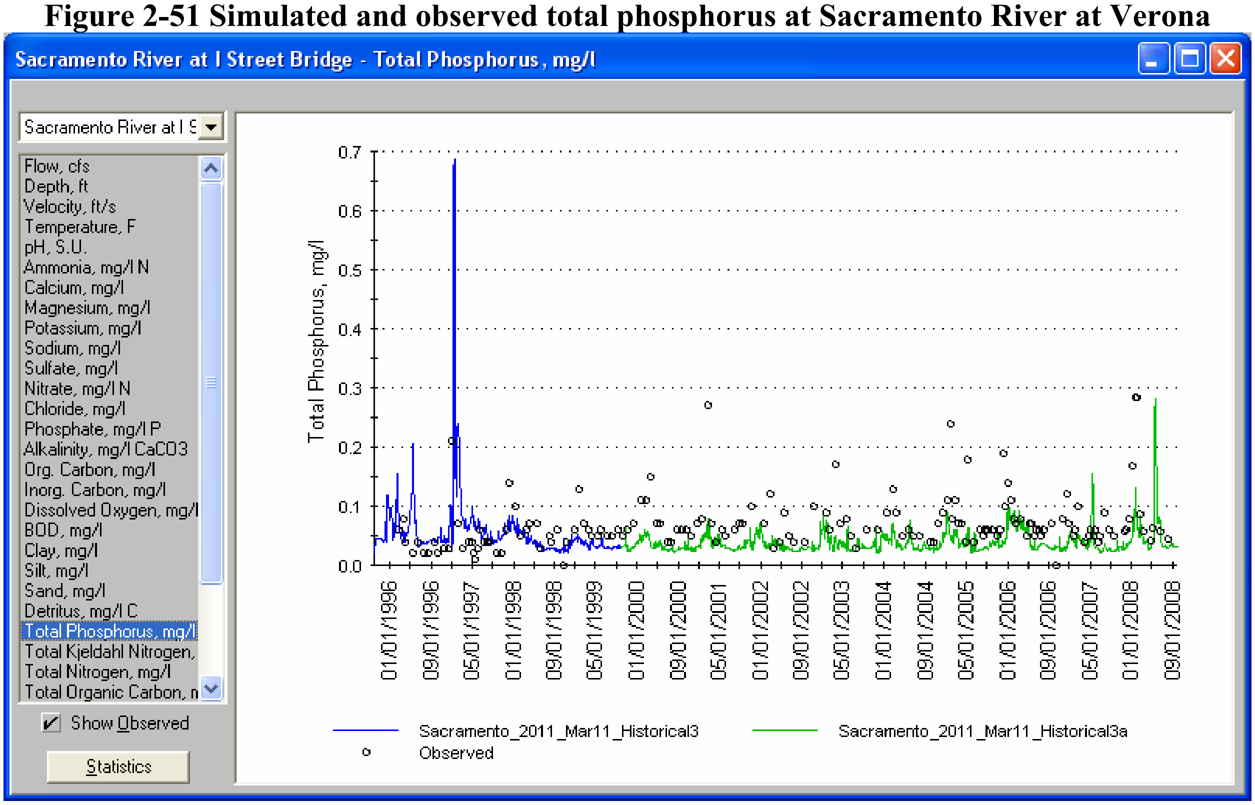

Figure 2-52 Simulated and observed total phosphorus at Sacramento River at Freeport

Table 2.18 shows the model errors for total phosphorus at various monitoring stations within the Sacramento River WARMF model domain. There are large errors between simulated and observed concentrations in both directions at all locations. The large simulated spike in concentration in early 1997 propagated from the Sacramento River boundary inflow at Keswick Reservoir. The error in Colusa Basin Drain is explained by the flow imbalance which results in too little nutrient rich water entering surface waters. Point sources are projected to be a major contributor of phosphate to the watershed, but there is little data to accurately characterize those sources. Phosphorus calibration was not a priority of the Delta east side tributaries modeling project, but coarse adjustment of model parameters was performed for the Cosumnes, Mokelumne, and Calaveras Rivers so that the simulated phosphorus would be reasonable in comparison with measured data.

Table 2.18 Model Errors of Total Phosphorus

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	+110%	141%
Sacramento River at Hamilton City	-60%	73%
Colusa Basin Drain near Knights Landing	-70%	70%
Feather River at Nicolaus	+229%	233%
Sacramento River at Verona	+19%	54%
Sacramento River at Freeport	-39%	55%

Summary

This report summarizes the calibration of the WARMF model to the Sacramento River as of March 2011. The primary goals of the modeling were to simulate salinity, nutrients, and organic carbon where the Sacramento River enters the Delta under present and future conditions and accurately determine the sources of the pollutants. The comparisons of predicted and observed values were made over many locations, time periods, and seasons to demonstrate that the model can predict the sources of pollutants between different land uses, regions, and hydrologic conditions. The matches between simulation results and observed data was within the goals of calibration at the Sacramento River at the I Street Bridge for flow, suspended sediment, electrical conductivity, and ammonia. The absolute error of nitrate was greater than 30%, simulated organic carbon was too low on average, and phosphorus simulation had large errors., The model is likely underestimating the pollutant load coming from agricultural areas. The inability to simulate summer flow in the Colusa Basin Drain is likely part of a systematic error requiring reassessment of the model input parameters, especially applied water rates. Simulated total phosphorus concentrations had relatively large errors which may have been caused by a lack of phosphorus discharge data for point sources. Although the model can be used for scenario analysis, it is important to remember the sources of error identified in the calibration process. Some of these errors cancel themselves out when running a comparative analysis of multiple scenarios. The simulated loading coming from agricultural areas is too low, so when looking at loading allocations the portion coming from agriculture is probably unrealistically conservative.

3 SOURCE CONTRIBUTION

Introduction

The streamflow and water quality predictions discussed in Chapter 2 are useful for understanding patterns of flow and pollutant concentrations at specific points in the watershed. The calibration is also an important first step in understanding the reliability of the model to predict pollutant loads. The calibrated model provides information about source contributions of waters and pollutants, providing greater understanding of watershed system behaviors, which is important for the formulation of management alternatives. Presented here are the sources and sinks of flow and key water quality constituents upstream of the Yolo Bypass at Lisbon and the Sacramento River at Morrison Creek. Morrison Creek is south of the City of Sacramento, downstream of Freeport and immediately downstream of the Sacramento Regional Wastewater Treatment Plant, which is included in this analysis.

Source of Water

Table 3.1 shows the average flows of source waters to the Model Domain (Sacramento River at Morrison Creek + Yolo Bypass) for the historical simulation period of 10/1/1975 to 9/30/1991. Total inflow from upstream reservoirs is 22,787 cfs, which is 72% of the total inflow to the model domain. The largest reservoir inflow by a large margin comes from Shasta Lake at 30% of total inflow. Local runoff (i.e., overland and shallow groundwater flow) accounts for 27% of the total inflow, while point source discharges account for about 1%. Total outflow is slightly less than inflow due to a small amount of evaporative losses and change in storage. About 14% of the flow in the Sacramento River and Yolo Bypass is diverted, with the remainder entering the Delta.

Table 3.1 Average Annual Flows of Source Waters to the Sacramento R. and Yolo Bypass

Source	Flow in cfs	Percent of Total
Inflows	**31,595**	**100%**
Reservoir Inflows	22,787	72%
Shasta Lake	*9,332*	30%
Whiskeytown Lake	*137*	0%
Black Butte Lake	*467*	1%
Clear Lake	*329*	1%
Lake Berryessa	*493*	2%
Lake Oroville	*981*	3%
Thermalito Afterbay (incl. Sutter Main Canal)	*4,926*	16%
Englebright Lake	*2,216*	7%
Camp Far West Reservoir	*406*	1%
Folsom Lake	*3,500*	11%
Point Source Discharges	327	1%
Runoff (Shallow Groundwater and Overland Flow)	8,481	27%
Outflows	**31,473**	**100%**
Diversions	4,317	14%
Total Flow out of the model domain (Sacramento at Morrison Creek + Yolo Bypass)	27,156	86%

Since both inflows and diversions are seasonal, the relative amount of source waters varies monthly. Figure 3-1 shows the average monthly contributions of each type of inflow (solid areas) and the flow removed by diversions (red line). Every month of the year, reservoir releases are the largest source of water to the river. From January through March, local runoff (shallow groundwater and overland flow) averages 75-80% as much flow as the boundary inflows. In summer, local runoff decreases and diversions become significant. Point sources are proportionately highest in October, when they contribute 2.4% of the total flow.

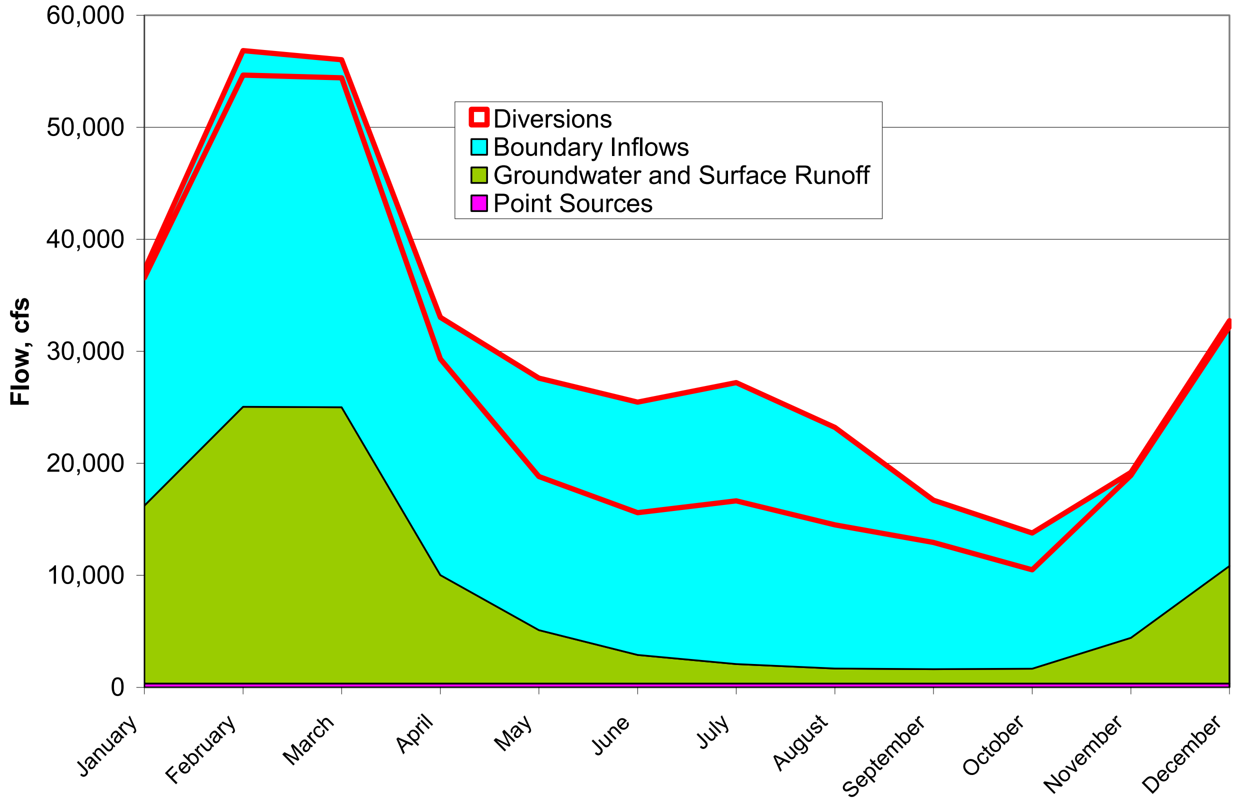

Figure 3-1 Average Monthly Source Waters of the Sacramento River at I Street Bridge

Sources of Suspended Sediment

Although sediment is not a constituent of concern in the Sacramento River watershed, adsorption to sediment is an important mechanism for the transport and removal of nutrients which adsorb to it. Table 3.2 summarizes the sources of suspended sediment load in the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for the 1976 through 1991 water years. Simulations indicate soil erosion from the land is the major contributor of total suspended sediment to the river but about 17% of the suspended sediment was scoured from the river bed. The solids discharged from wastewater treatment plants is considered detritus, not sediment, so there is no point source contribution to suspended sediment. About 63% of the suspended sediment was predicted to settle to the river bed with 7% entrained in diversions. The settling sediment was responsible for the removal of organic carbon, ammonia, and phosphorus shown in Table 3.5, Table 3.7, and Table 3.11.

Table 3.2 Sources and Sinks of Total Suspended Sediment, Sacramento R. and Yolo Bypass

Sources	**Total Suspended Sediment Load (tons/day)**	**Total Suspended Sediment Load (% of inputs/outputs)**
Inflows from Upstream	**773**	**2.22%**
Lake Shasta	260	0.75%
Lake Oroville + Thermalito Afterbay	295	0.85%
Englebright Lake	79	0.23%
Camp Far West Reservoir	22	0.06%
Folsom Lake	29	0.08%
Whiskeytown Reservoir	2	0.01%
Black Butte Lake	31	0.09%
Clear Lake	15	0.04%
Lake Berryessa	40	0.12%
Nonpoint Sources (Surface Runoff)	**28,009**	**80.60%**
Barren land	1206	3.47%
Cotton	91	0.26%
DairyPA	0	0.00%
Deciduous Forest	73	0.21%
Double Crop DLA	34	0.10%
Evergreen Forest	841	2.42%
Fallow	120	0.35%
Farmsteads	684	1.97%
Flowers and nursery	18	0.05%
Grassland/Herbaceous	6516	18.75%
Lagoon	0	0.00%
Marsh	0	0.00%
Mixed Forest	112	0.32%
Native Classes Unsegregated	0	0.00%
Olives, citrus & subtropicals	41	0.12%
Orchard	456	1.31%
Other CAFOs	15	0.04%
Other row crops	571	1.64%
Paved areas	0	0.00%
Perennial forages	663	1.91%
Perennial Forages DLA	0	0.00%
Rice	3882	11.17%
Sewage plant (not including discharge)	0	0.00%
Shrub/Scrub	9989	28.75%
Urban Commercial	124	0.36%
Urban Industrial	195	0.56%
Urban landscape	0	0.00%
Urban residential	335	0.96%
Vines	38	0.11%
Warm season cereals/forages	804	2.31%
Water	0	0.00%
Winter grains & safflower	1202	3.46%
Resuspension from River Bed	**5,967**	**17.17%**
Point Sources	**0**	**0.00%**
Sinks		
Settling to River Bed	**21,883**	**89.45%**
Diversions	**2,580**	**10.55%**
NET LOAD TO THE DELTA	**9,867**	

Figure 3-2 shows the relationship between loading and concentration of suspended sediment. Both concentration and load peaked each year during the high flow winter runoff season. Relatively little sediment was transported the rest of the year, including during irrigation season.

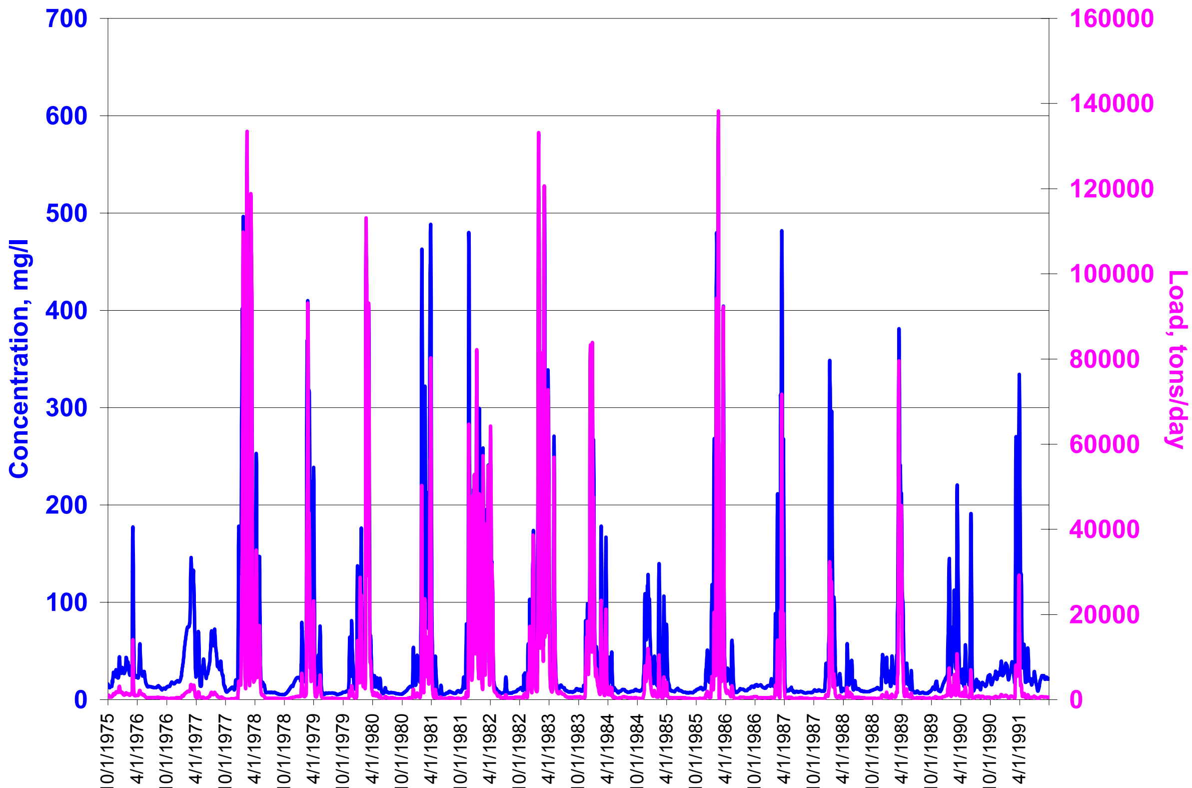

Figure 3-2 Total Suspended Sediment Load (pink line) vs. Concentration (blue line) at Sacramento River at Morrison Creek

Sources of Total Dissolved Solids

Table 3.3 summarizes the fluxes of TDS load in the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for water years 1976-1991. Inflows from upstream reservoirs accounted for 56% of the salt entering the Delta via the Sacramento River and Yolo Bypass. 38% of the salt load came from nonpoint source groundwater accretions and surface runoff within the watershed. Most of the remainder of the salt load came from point sources. Within the nonpoint source portion, 58% of the load comes from natural land cover areas. Figure 3-3 shows a pie chart of the major loading sources for visual reference. Since the model calibration likely underestimates the loading coming from agricultural areas, the actual percentages of salt loading from agricultural land uses are likely somewhat higher than what is listed. Diversions removed 16% of the TDS load and settling of ions adsorbed to sediment removed an additional 3%.

Table 3.3 Sources and Sinks of Total Dissolved Solids to the Sacramento R. & Yolo Bypass

Sources	Load (tons/day)	% of Sources / Sinks)
Inflows from Upstream	**4,460**	**56.79%**
Lake Shasta	2,182	27.79%
Lake Oroville + Thermalito Afterbay	663	8.44%
Englebright Lake	335	4.27%
Camp Far West Reservoir	58	0.74%
Folsom Lake	409	5.21%
Whiskeytown Reservoir	23	0.29%
Black Butte Lake	267	3.40%
Clear Lake	170	2.16%
Lake Berryessa	353	4.50%
Nonpoint Sources	***3,033***	**38.62%**
Barren land	24	0.31%
Cotton	24	0.31%
DairyPA	0	0.00%
Deciduous Forest	68	0.87%
Double Crop DLA	12	0.15%
Evergreen Forest	428	5.45%
Fallow	11	0.14%
Farmsteads	45	0.57%
Flowers and nursery	1	0.01%
Grassland/Herbaceous	640	8.15%
Lagoon	0	0.00%
Marsh	43	0.55%
Mixed Forest	45	0.57%
Native Classes Unsegregated	0	0.00%
Olives, citrus & subtropicals	7	0.09%
Orchard	223	2.84%
Other CAFOs	1	0.01%
Other row crops	123	1.57%
Paved areas	3	0.04%
Perennial forages	124	1.58%
Perennial Forages DLA	0	0.00%
Rice	444	5.65%
Sewage plant (not including discharge)	0	0.00%
Shrub/Scrub	501	6.38%
Urban Commercial	1	0.01%
Urban Industrial	1	0.01%
Urban landscape	70	0.89%
Urban residential	59	0.75%
Vines	7	0.09%
Warm season cereals/forages	54	0.69%
Water	12	0.15%
Winter grains & safflower	62	0.79%
Resuspension from River Bed	**94**	**1.20%**
Reaction Product	**9**	**0.11%**
Point Sources	**257**	**3.27%**
Sinks		
Settling to River Bed	**268**	**17.82%**
Reaction Decay	**8**	**0.53%**
Diversions	**1,228**	**81.65%**
NET LOAD TO THE DELTA	**6,196**	

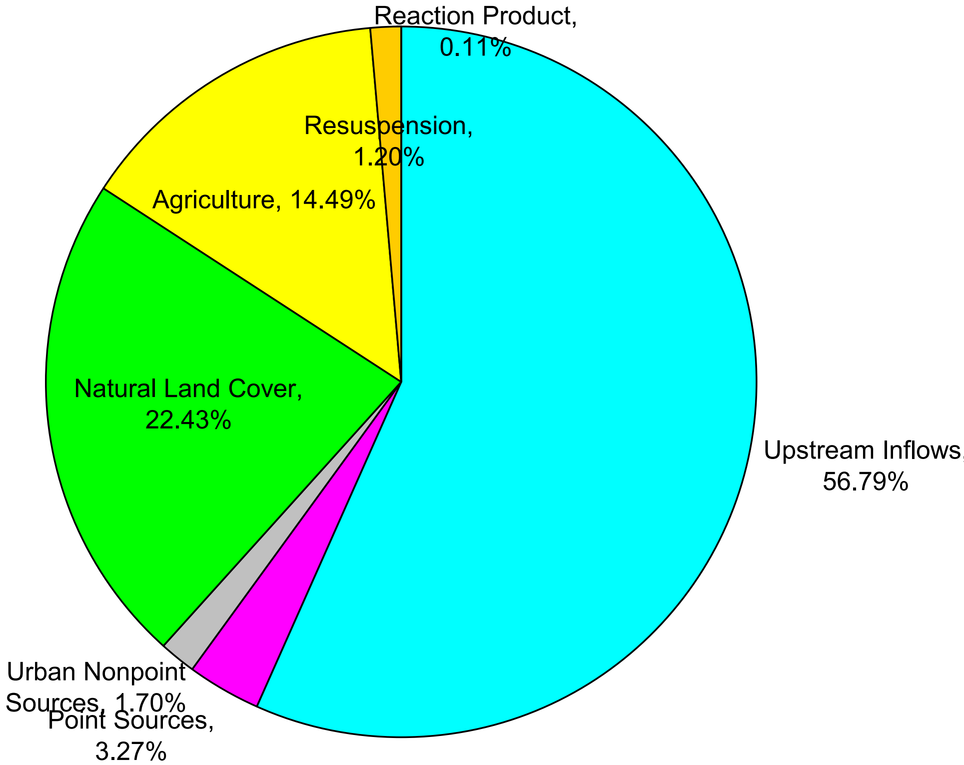

Figure 3-3 TDS Loading Sources of the Sacramento River and Yolo Bypass

Table 3.3 shows that the grassland/herbaceous land cover contributes more nonpoint source load of salt than any other land use. An important management consideration is the intensity of loading, or the loading rate for a given land area. Table 3.4 shows the loading produced by each land use. Note that this breakdown is only for the 38% nonpoint source load of the overall total dissolved solids loading. This corresponds to the yellow, green, and gray portions of Figure 3-3. Cotton is the land use which produces the highest loading per acre, but the acreage of Cotton in the Sacramento River watershed is small. Other land uses contributing relatively high amounts of salt include Double Crop Dairy Land Application, Rice, Vines, Barren Land, Other (non-dairy) Confined Animal Feeding Operations, and Orchards.

Table 3.4
Total Dissolved Solids Load from Groundwater Accretion / Surface Runoff by Land Area

Land Use	Load (lb/acre/year)
Barren land	458
Cotton	1695
DairyPA	0
Deciduous Forest	225
Double Crop DLA	946
Evergreen Forest	334
Fallow	112
Farmsteads	289
Flowers and nursery	241
Grassland/Herbaceous	291
Lagoon	0
Marsh	274
Mixed Forest	298
Native Classes Unsegregated	0
Olives, citrus & subtropicals	255
Orchard	443
Other CAFOs	446
Other row crops	828
Paved areas	101
Perennial forages	413
Perennial Forages DLA	0
Rice	573
Sewage plant incl. ponds	70
Shrub/Scrub	339
Urban Commercial	24
Urban Industrial	19
Urban landscape	318
Urban residential	205
Vines	486
Warm season cereals/forages	332
Water	104
Winter grains & safflower	279

Figure 3-4 shows the sources of salt within various regions of the watershed. Light blue shows boundary inflows, green shows nonpoint sources, and magenta is point sources. Each bar chart represents a different location on the maps. The chart in the north is the Sacramento River at Hamilton City, the large chart in the south is the Sacramento River at Morrison Creek, the chart in the southwest is the Yolo Bypass and the chart north of the Yolo Bypass is the Colusa Basin Drain. Two thirds of the salt at the Sacramento River at Hamilton City is from upstream inflows and almost all the remainder is from nonpoint sources. The Colusa Basin Drain has almost entirely nonpoint source load. 87% of the salt load in the Yolo Bypass comes from upstream inflows and inflows from flood control weirs on the Sacramento River. Nonpoint sources contribute 11% of the load to the Yolo Bypass and 3% is from point sources. The salt load at the Sacramento River at Morrison Creek is 56% from upstream inflows, 38% from nonpoint sources and 6% from point sources including the Sacramento Regional wastewater treatment plant.

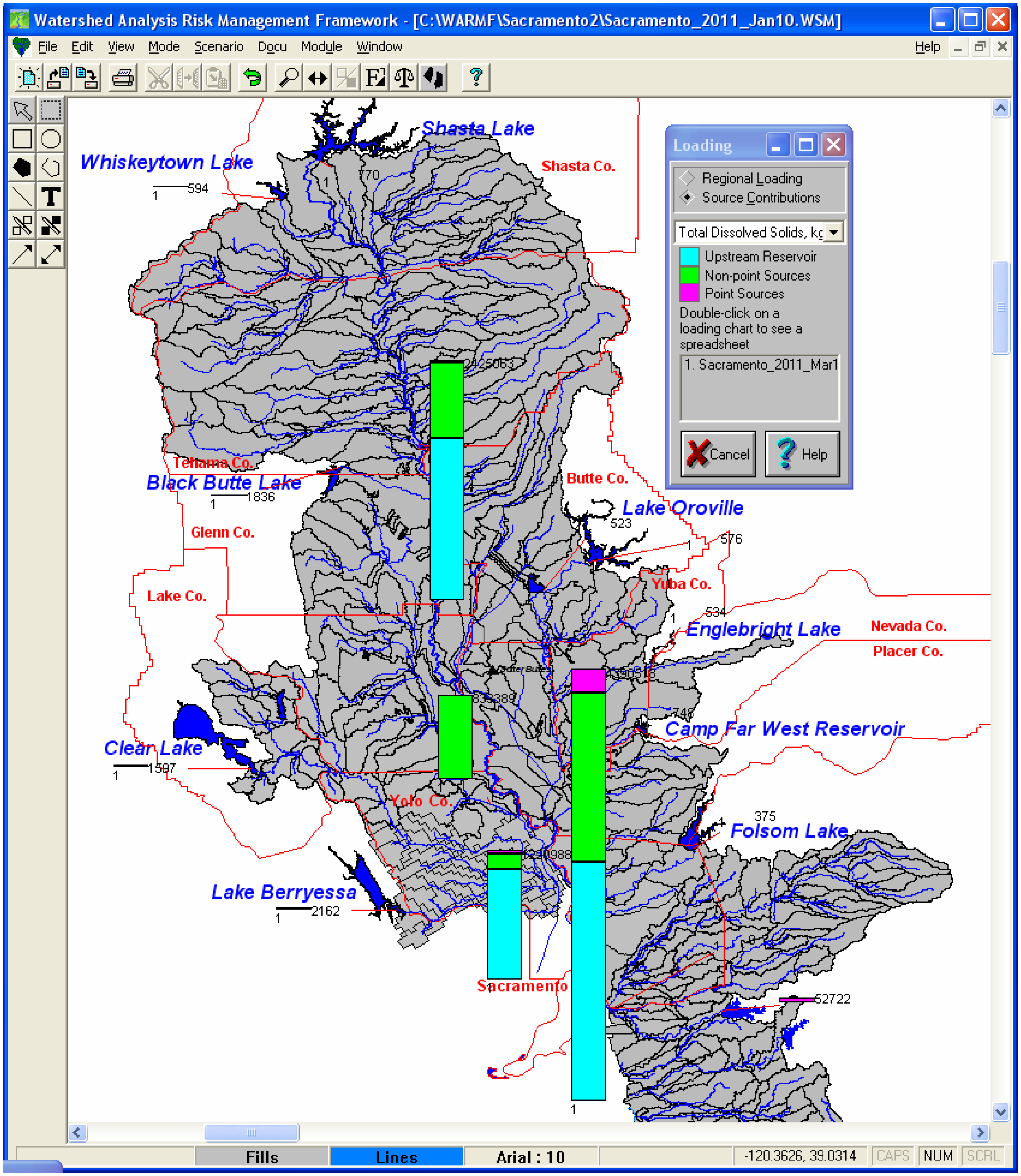

Figure 3-4 Source Contributions Loading of Total Dissolved Solids

Figure 3-5 shows the relationship between TDS load and TDS concentration at the Sacramento River at Morrison Creek. The concentration and load peaks occur together during the winter wet season and are at a minimum before the rainy season. Concentration is generally between 70 and 150 mg/l.

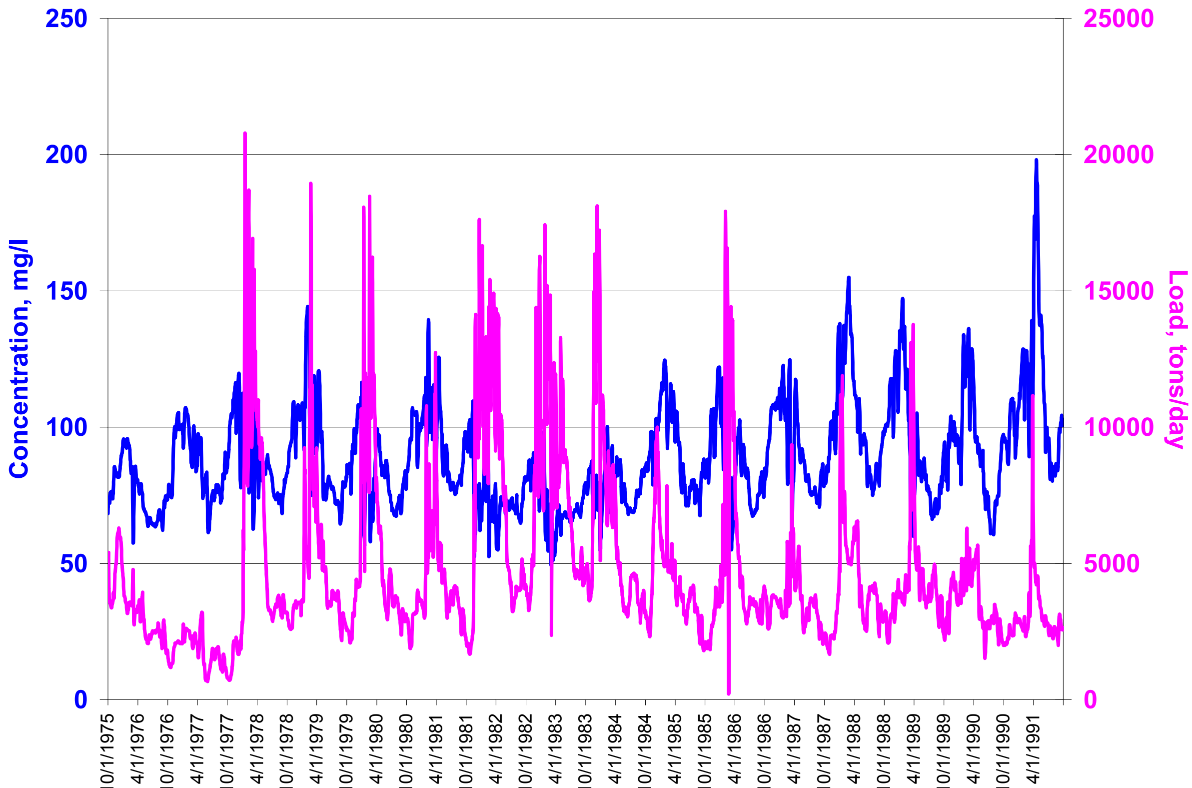

Figure 3-5 TDS Load (pink line) vs. TDS Concentration (blue line) at Sacramento River at Morrison Creek

Sources of Organic Carbon

Table 3.5 summarizes the sources of organic carbon load in the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for the 1976 through 1991 water years. 48% of the load came from nonpoint source groundwater accretion and surface runoff. The boundary river inflows contributed about 27% of the load, while point sources contributed 9% of the organic carbon loading. Organic carbon production and resuspension of river bed sediment accounted for 16% of the load. The nonpoint source load is broken down by land use. Natural land covers contributed half the nonpoint source load or 24% of the total. Rice is the largest single land use contributor to the organic carbon load, contributing about 41% of the nonpoint source portion of the load or 20% of the total. Only about 1% of nonpoint source load came from urban areas. Figure 3-6 shows the major loading sources in a visual format.

Table 3.5 Sources and Sinks of Organic Carbon

Sources	Load (tons/day)	Load (% of inputs/outputs)
Inflows from Upstream	**92.44**	**37.48%**
Lake Shasta	35.97	14.58%
Lake Oroville + Thermalito Afterbay	20.71	8.40%
Englebright Lake	7.36	2.98%
Camp Far West Reservoir	2.87	1.16%
Folsom Lake	16.05	6.51%
Whiskeytown Reservoir	0.66	0.27%
Black Butte Lake	3.24	1.31%
Clear Lake	2.59	1.05%
Lake Berryessa	2.99	1.21%
Nonpoint Sources	***122.28***	**49.58%**
Barren land	1.34	0.54%
Cotton	0.39	0.16%
DairyPA	0	0.00%
Deciduous Forest	2.8	1.14%
Double Crop DLA	0.2	0.08%
Evergreen Forest	18.43	7.47%
Fallow	0.91	0.37%
Farmsteads	1.66	0.67%
Flowers and nursery	0.03	0.01%
Grassland/Herbaceous	26.45	10.72%
Lagoon	0	0.00%
Marsh	1.7	0.69%
Mixed Forest	1.47	0.60%
Native Classes Unsegregated	0	0.00%
Olives, citrus & subtropicals	0.21	0.09%
Orchard	5.23	2.12%
Other CAFOs	0.02	0.01%
Other row crops	3.66	1.48%
Paved areas	0.18	0.07%
Perennial forages	3.49	1.42%
Perennial Forages DLA	0	0.00%
Rice	20.52	8.32%
Sewage plant (not including discharge)	0.01	0.00%
Shrub/Scrub	21.15	8.58%
Urban Commercial	0.22	0.09%
Urban Industrial	0.22	0.09%
Urban landscape	1.83	0.74%
Urban residential	2.38	0.96%
Vines	0.26	0.11%
Warm season cereals/forages	2.7	1.09%
Water	0.95	0.39%
Winter grains & safflower	3.89	1.58%
Resuspension from River Bed	**4.2**	**1.70%**
Reaction Product	**2.9**	**1.18%**
Point Sources	**24.82**	**10.06%**
Sinks		
Settling to River Bed	**24.14**	**26.67%**
Reaction Decay	**35.95**	**39.71%**
Diversions	**30.43**	**33.62%**
NET LOAD TO THE DELTA	**167.63**	

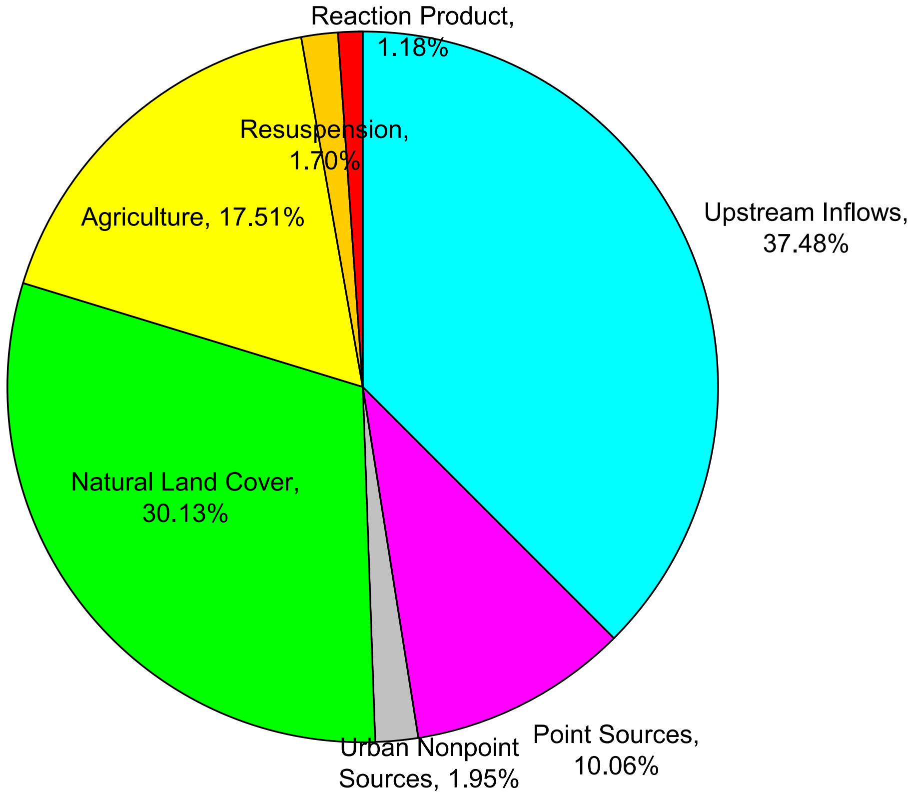

Figure 3-6 Organic Carbon Loading Sources of the Sacramento River and Yolo Bypass

Table 3.5 shows that the grassland/herbaceous, scrub/shrub, and rice land uses contribute considerably more nonpoint source load of organic carbon than other land uses. In general, a large amount of loading could be caused by a large amount of land area and/or a high intensity of loading per unit area. Table 3.6 shows the loading produced by each land use. Cotton, Barren Land, Rice, and Other Row Crops contributed the greatest amount of organic carbon relative to land area. Note that this breakdown is only for the portion of organic carbon loading shown in yellow, green, and gray in Figure 3-6.

Table 3.6 Organic Carbon Load from Nonpoint Sources by Land Area

Land Use	Load (lb/acre/year)
Barren land	26
Cotton	28
DairyPA	0
Deciduous Forest	9
Double Crop DLA	16
Evergreen Forest	14
Fallow	9
Farmsteads	11
Flowers and nursery	16
Grassland/Herbaceous	12
Lagoon	0
Marsh	11
Mixed Forest	11
Native Classes Unsegregated	0
Olives, citrus & subtropicals	8
Orchard	11
Other CAFOs	16
Other row crops	24
Paved areas	7
Perennial forages	12
Perennial Forages DLA	0
Rice	26
Sewage plant incl. ponds	6
Shrub/Scrub	15
Urban Commercial	4
Urban Industrial	6
Urban landscape	8
Urban residential	8
Vines	17
Warm season cereals/forages	17
Water	9
Winter grains & safflower	17

Figure 3-7 shows the sources of organic carbon at various locations within the watershed. Light blue shows boundary inflows, green shows nonpoint sources, and magenta is point sources. The bar chart in the north is the Sacramento River at Hamilton City. The largest bar chart in the south is the Sacramento River at Freeport. The other bar charts are for the Yolo Bypass and Colusa Basin Drain. Nonpoint sources were the largest contributors to organic carbon load at Hamilton City and in the Colusa Basin Drain, with 57% and nearly 100% of the load respectively. Nonpoint sources contributed 42% of the load in the Sacramento River at Hamilton City with point sources only about 1%. Inflows from reservoirs and flood control weirs account for 91% of the organic carbon in the Yolo Bypass, with most of the remainder being nonpoint source load. At the Sacramento River at Morrison Creek, upstream inflows and nonpoint sources were about 45% of the total load each with point sources being the remaining 11% of the load. The point source fraction is higher at the Delta interface than the overall proportion of load from the watershed because local discharges in the Sacramento area do not have as much time to decay or settle out compared to other organic carbon sources father upstream.

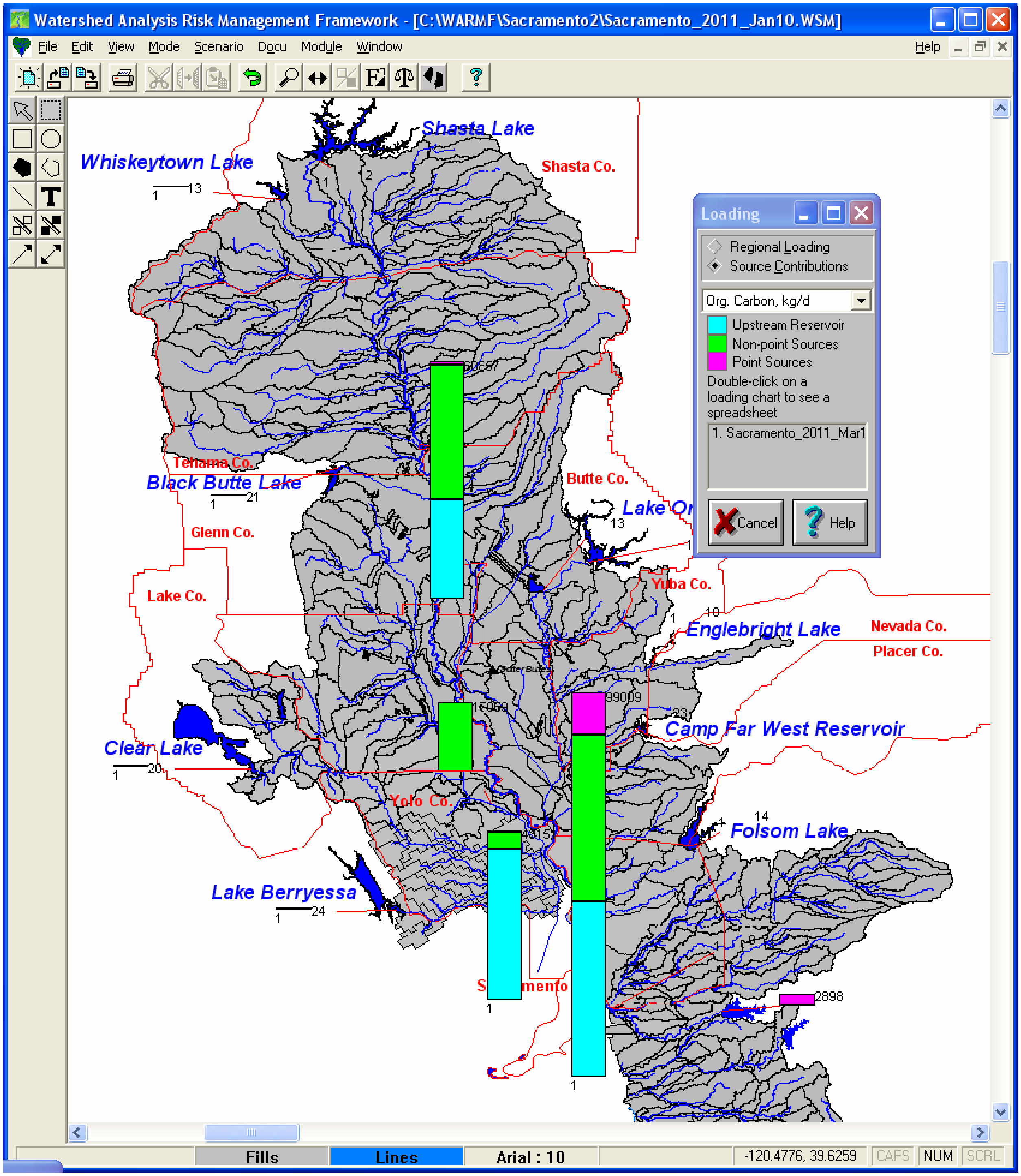

Figure 3-7 Source Contributions Loading of Organic Carbon

Figure 3-8 shows the relationship between total organic carbon load and concentration at the Sacramento River at Morrison Creek. There were generally high concentration peaks twice a year: during the winter runoff season and during the later part of the summer dry season. The highest load of the year coincided with the winter high concentration. Summer load was higher than in spring and fall.

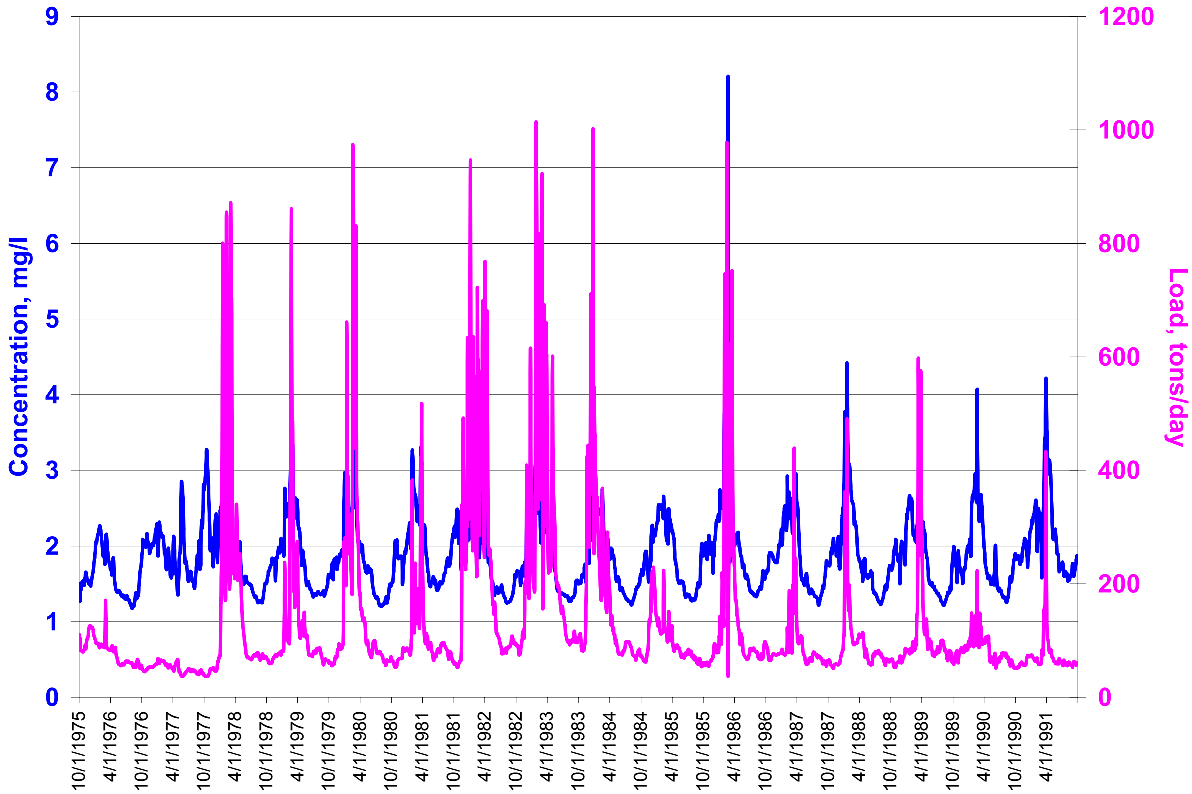

Figure 3-8 Organic Carbon Load (pink line) vs. Concentration (blue line) at Sacramento River at Morrison Creek

Sources of Ammonia

Table 3.7 summarizes the sources of ammonia load in the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for the 1976 through 1991 water years. 27% of the load came from nonpoint source groundwater accretion and surface runoff. The boundary river inflows contributed about 37% of the load, while point sources contributed 9% of the ammonia loading. Simulated ammonia underwent extensive transformations in-stream, with 23% of ammonia from sediment resuspension and 9% produced by decay of organic matter. 52% of the ammonia in the river settled out before reaching the Delta. The nonpoint source load is broken down by land use. Rice was by far the largest nonpoint source of ammonia, followed by Other Row Crop and Orchard land uses. Natural land covers delivered only about 6% of ammonia loading coming from the land. The information in Table 3.7 is summarized in visual format in Figure 3-9.

Table 3.7 Sources and Sinks of Ammonia

Sources	Load (tons N/day)	Load (% of inputs/outputs)
Inflows from Upstream	**25.63**	**33.89%**
Lake Shasta	8.65	11.44%
Lake Oroville + Thermalito Afterbay	8.26	10.92%
Englebright Lake	3.04	4.02%
Camp Far West Reservoir	0.80	1.06%
Folsom Lake	1.16	1.53%
Whiskeytown Reservoir	0.03	0.04%
Black Butte Lake	1.11	1.47%
Clear Lake	2.33	3.08%
Lake Berryessa	0.25	0.33%
Nonpoint Sources	**18.29**	**24.18%**
Barren land	0.04	0.05%
Cotton	0.18	0.24%
DairyPA	0.00	0.00%
Deciduous Forest	0.06	0.08%
Double Crop DLA	0.65	0.86%
Evergreen Forest	0.07	0.09%
Fallow	0.01	0.01%
Farmsteads	0.19	0.25%
Flowers and nursery	0.01	0.01%
Grassland/Herbaceous	0.55	0.73%
Lagoon	0.00	0.00%
Marsh	0.13	0.17%
Mixed Forest	0.01	0.01%
Native Classes Unsegregated	0.00	0.00%
Olives, citrus & subtropicals	0.72	0.95%
Orchard	2.44	3.23%
Other CAFOs	0.02	0.03%
Other row crops	2.51	3.32%
Paved areas	0.00	0.00%
Perennial forages	0.60	0.79%
Perennial Forages DLA	0.00	0.00%
Rice	8.01	10.59%
Sewage plant (not including discharge)	0.00	0.00%
Shrub/Scrub	0.26	0.34%
Urban Commercial	0.04	0.05%
Urban Industrial	0.02	0.03%
Urban landscape	0.85	1.12%
Urban residential	0.74	0.98%
Vines	0.04	0.05%
Warm season cereals/forages	0.12	0.16%
Water	0.00	0.00%
Winter grains & safflower	0.03	0.04%
Resuspension from River Bed	**15.66**	**20.71%**
Reaction Product	**6.30**	**8.33%**
Point Sources	**9.75**	**12.89%**
Sinks		
Settling to River Bed	**35.90**	**74.31%**
Reaction Decay	**2.96**	**6.13%**
Diversions	**9.45**	**19.56%**
NET LOAD TO THE DELTA	**33.89**	

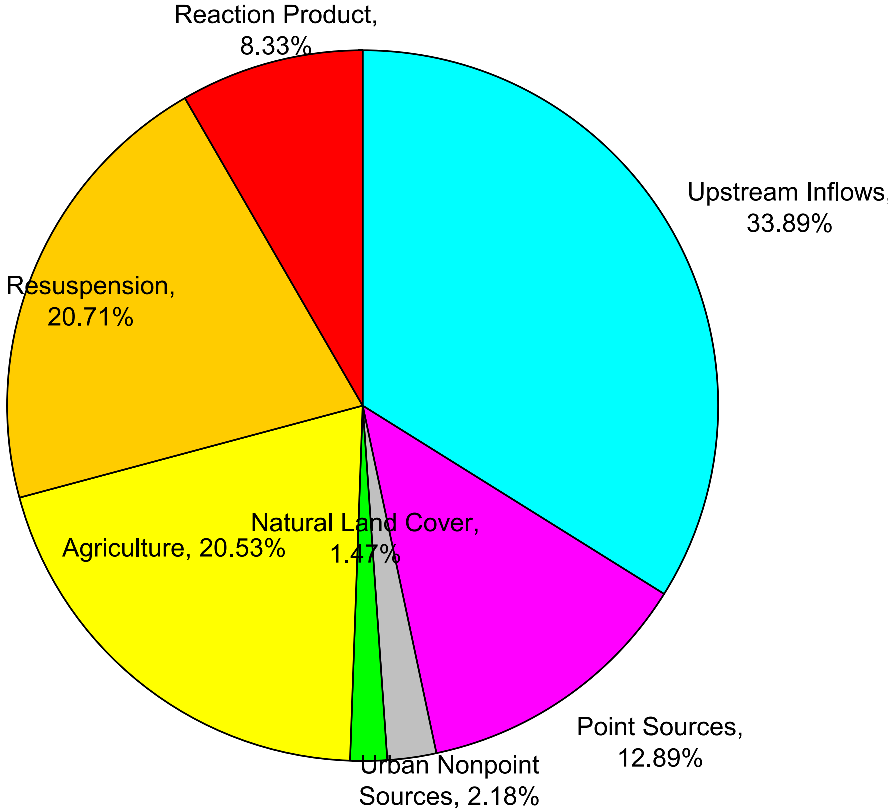

Figure 3-9 Ammonia Loading Sources of the Sacramento River and Yolo Bypass

Table 3.7 shows that the rice, other row crops, and orchards contribute considerably more nonpoint source load of ammonia than other land uses. Table 3.8 shows the loading produced by each land use per acre. Note that this breakdown is only for about one quarter of the overall ammonia loading (in yellow, green, and gray in Figure 3-9). The table shows dramatic differences in loading intensity by land use. Double Crop Dairy Land Application produces easily the highest loading per unit land area. Olives / Citrus / Subtropical, Other (non-dairy) Confined Animal Feeding Operations, Other Row Crops, Cotton, and Rice all contribute more than 10 lb/acre/year. Of these top intensity land uses, only Other Row Crops and Rice have large amounts of acreage in the watershed. No other land use loads more than 5 lb/acre/year to surface waters in the watershed.

Table 3.8 Ammonia Load from Nonpoint Sources by Land Area

Land Use	Ammonia Load (lb N/acre/year)
Barren land	0.84
Cotton	11.63
DairyPA	0.00
Deciduous Forest	0.19
Double Crop DLA	51.93
Evergreen Forest	0.05
Fallow	0.08
Farmsteads	1.21
Flowers and nursery	3.42
Grassland/Herbaceous	0.25
Lagoon	0.00
Marsh	0.82
Mixed Forest	0.10
Native Classes Unsegregated	0.00
Olives, citrus & subtropicals	27.07
Orchard	4.95
Other CAFOs	21.65
Other row crops	13.94
Paved areas	0.02
Perennial forages	1.91
Perennial Forages DLA	0.00
Rice	10.34
Sewage plant incl. ponds	0.02
Shrub/Scrub	0.20
Urban Commercial	0.62
Urban Industrial	0.45
Urban landscape	3.91
Urban residential	2.66
Vines	2.79
Warm season cereals/forages	0.72
Water	0.03
Winter grains & safflower	0.14

Figure 3-10 shows the sources of ammonia at various locations within the watershed. Light blue shows boundary inflows, green shows nonpoint sources, and magenta is point sources. The bar chart in the north is the Sacramento River at Hamilton City. The largest bar chart in the south is the Sacramento River at Freeport. The other bar charts are for the Yolo Bypass and Colusa Basin Drain. At Hamilton City, 78% of the ammonia comes from the upstream inflows at Lake Shasta and Whiskeytown Reservoir. Almost all the rest is nonpoint sources originating in the local watershed. Ammonia in the Colusa Basin Drain is essentially all from nonpoint source loading. Inflows from reservoirs and flood control weirs account for 93% of the ammonia in the Yolo Bypass, with most of the remainder being nonpoint source load. Point source load was less than 1% of the total in the Yolo Bypass. At the Sacramento River at Morrison Creek, 54% of the ammonia originated in upstream reservoirs. 33% of the load came from nonpoint source loading, and the remaining 13% was from point sources. The point source fraction is higher at the Delta interface than in the rest of the watershed because discharges in the Sacramento area do not have the same opportunity to settle out as those sources father upstream.

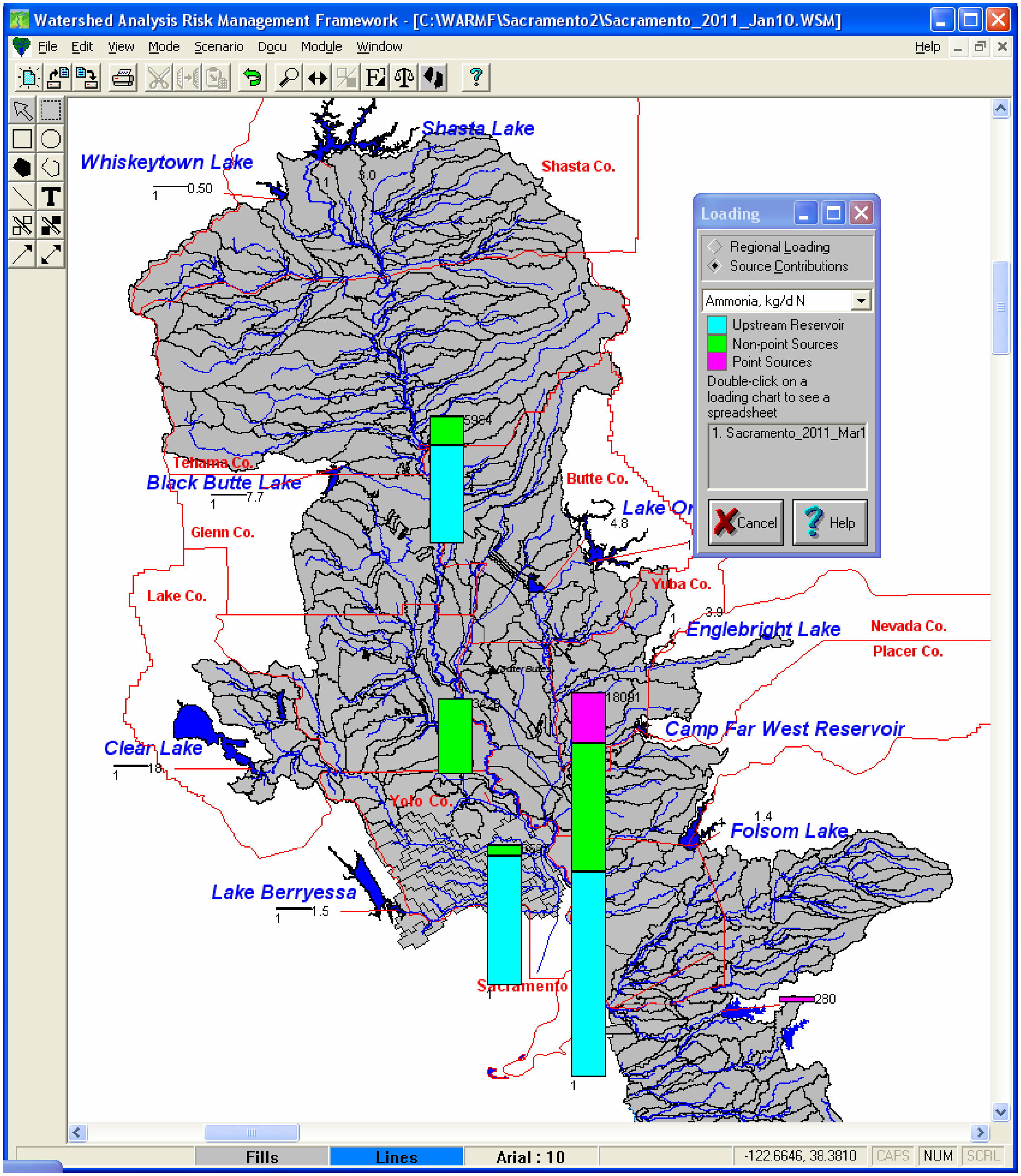

Figure 3-10 Source Contributions Loading of Ammonia

Figure 3-11 shows the relationship between ammonia load and concentration at the Sacramento River at Morrison Creek. The minimum ammonia concentration was generally in early spring during peak flow but there was not a strong seasonal pattern. The highest ammonia load of the year was generally in late spring.

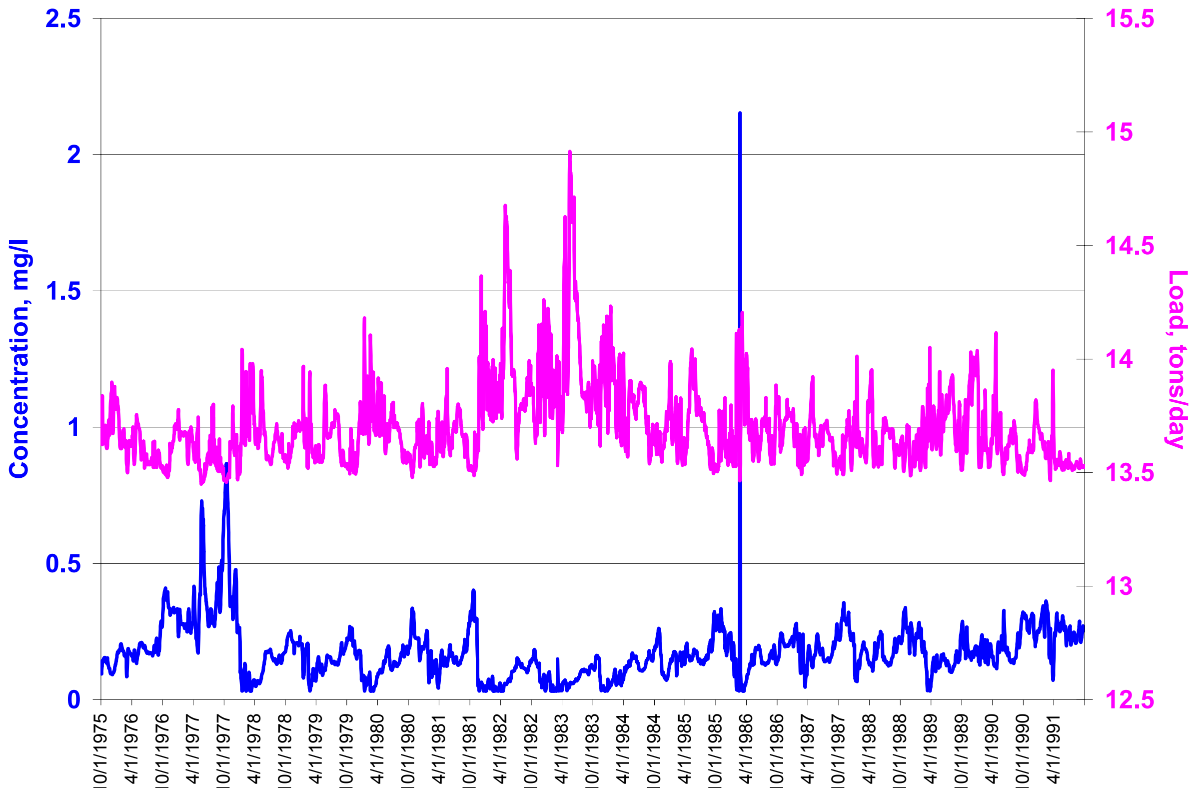

Figure 3-11 Ammonia Load (pink line) vs. Concentration (blue line) at Sacramento River at Morrison Creek

Sources of Nitrate

Table 3.9 summarizes the sources of nitrate load to the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for the 1976 through 1991 water years. 57% of the load came from nonpoint source groundwater accretion and surface runoff. The boundary river inflows contributed about 28% of the load, while point sources contributed 12% of the nitrate loading. Since nitrate does not readily adsorb to sediment particles, settling and resuspension are not important sources or sinks of nitrate. The most important land use sources are rice, other row crops, and orchards. Figure 3-12 shows the major loading sources in a visual format.

Table 3.9 Sources and Sinks of Nitrate

Sources	Load (tons/day)	Load (% of inputs/outputs)
Inflows from Upstream	**4.27**	**28.91%**
Lake Shasta	1.95	13.20%
Lake Oroville + Thermalito Afterbay	0.72	4.87%
Englebright Lake	0.21	1.42%
Camp Far West Reservoir	0.10	0.68%
Folsom Lake	0.78	5.28%
Whiskeytown Reservoir	0.01	0.07%
Black Butte Lake	0.18	1.22%
Clear Lake	0.13	0.88%
Lake Berryessa	0.19	1.29%
Nonpoint Sources	**8.65**	**58.56%**
Barren land	0.01	0.07%
Cotton	0.20	1.35%
DairyPA	0.00	0.00%
Deciduous Forest	0.07	0.47%
Double Crop DLA	0.19	1.29%
Evergreen Forest	0.43	2.91%
Fallow	0.03	0.20%
Farmsteads	0.11	0.74%
Flowers and nursery	0.02	0.14%
Grassland/Herbaceous	0.63	4.27%
Lagoon	0.00	0.00%
Marsh	0.04	0.27%
Mixed Forest	0.08	0.54%
Native Classes Unsegregated	0.00	0.00%
Olives, citrus & subtropicals	0.12	0.81%
Orchard	1.50	10.16%
Other CAFOs	0.04	0.27%
Other row crops	1.75	11.85%
Paved areas	0.00	0.00%
Perennial forages	0.24	1.62%
Perennial Forages DLA	0.00	0.00%
Rice	1.88	12.73%
Sewage plant (not including discharge)	0.00	0.00%
Shrub/Scrub	0.44	2.98%
Urban Commercial	0.01	0.07%
Urban Industrial	0.00	0.00%
Urban landscape	0.31	2.10%
Urban residential	0.29	1.96%
Vines	0.09	0.61%
Warm season cereals/forages	0.11	0.74%
Water	0.02	0.14%
Winter grains & safflower	0.03	0.20%
Resuspension from River Bed	**0.00**	**0.00%**
Reaction Product	**0.40**	**2.71%**
Point Sources	**1.45**	**9.82%**
Sinks		
Settling to River Bed	**0.00**	**0.00%**
Reaction Decay	**1.53**	**37.23%**
Diversions	**2.58**	**62.77%**
NET LOAD TO THE DELTA	**11.96**	

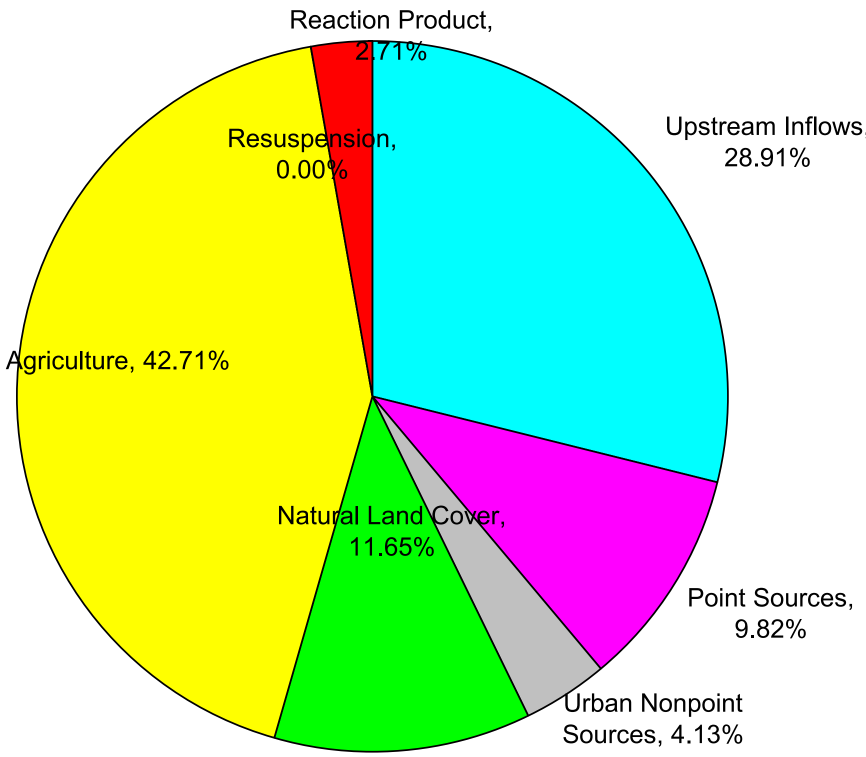

Figure 3-12 Nitrate Loading Sources of the Sacramento River and Yolo Bypass

Table 3.10 shows the loading intensity produced by each land use on a per area basis. The land uses which contribute the most loading per acre are Other (non-dairy) Confined Animal Feeding Operations, Double Crop Dairy Land Application, Cotton, and Flowers and Nursery, although none of these have a large amount of acreage in the watershed. Other row crops, vines, olives / citrus / subtropical, orchards, and rice were the other land uses contributing greater than 2 lb/acre/year. This analysis only applies to the nonpoint source sections (yellow, green, and gray) of Figure 3-12 above.

Table 3.10 Nitrate Load from Nonpoint Sources by Land Area

Land Use	Nitrate Load (lb N/acre/year)
Barren land	0.30
Cotton	13.33
DairyPA	0.00
Deciduous Forest	0.24
Double Crop DLA	15.35
Evergreen Forest	0.39
Fallow	0.28
Farmsteads	0.69
Flowers and nursery	11.81
Grassland/Herbaceous	0.31
Lagoon	0.00
Marsh	0.24
Mixed Forest	0.98
Native Classes Unsegregated	0.00
Olives, citrus & subtropicals	4.47
Orchard	3.06
Other CAFOs	37.16
Other row crops	9.93
Paved areas	0.14
Perennial forages	0.74
Perennial Forages DLA	0.00
Rice	2.41
Sewage plant incl. ponds	0.10
Shrub/Scrub	0.34
Urban Commercial	0.19
Urban Industrial	0.12
Urban landscape	1.42
Urban residential	1.01
Vines	6.22
Warm season cereals/forages	0.55
Water	0.21
Winter grains & safflower	0.12

Figure 3-13 shows the sources of nitrate at various locations within the watershed. Light blue shows boundary inflows, green shows nonpoint sources, and magenta is point sources. The bar chart in the north is the Sacramento River at Hamilton City. The largest bar chart in the south is the Sacramento River at Freeport. The other bar charts are for the Yolo Bypass and Colusa Basin Drain. At Hamilton City, 55% of the nitrate is from upstream inflows, 33% is from nonpoint sources, and 11% is from point sources. Nitrate in the Colusa Basin Drain is essentially all from nonpoint source loading. Inflows from reservoirs and flood control weirs account for 71% of the nitrate in the Yolo Bypass, with 18% nonpoint sources and 11% point sources. At the Sacramento River at Freeport, 61% of the nitrate is from nonpoint sources, 27% is from upstream inflows, and the remaining 12% is from point sources. These proportions of sources at the Delta boundary are approximately the same as all the nitrate loading sources in the watershed.

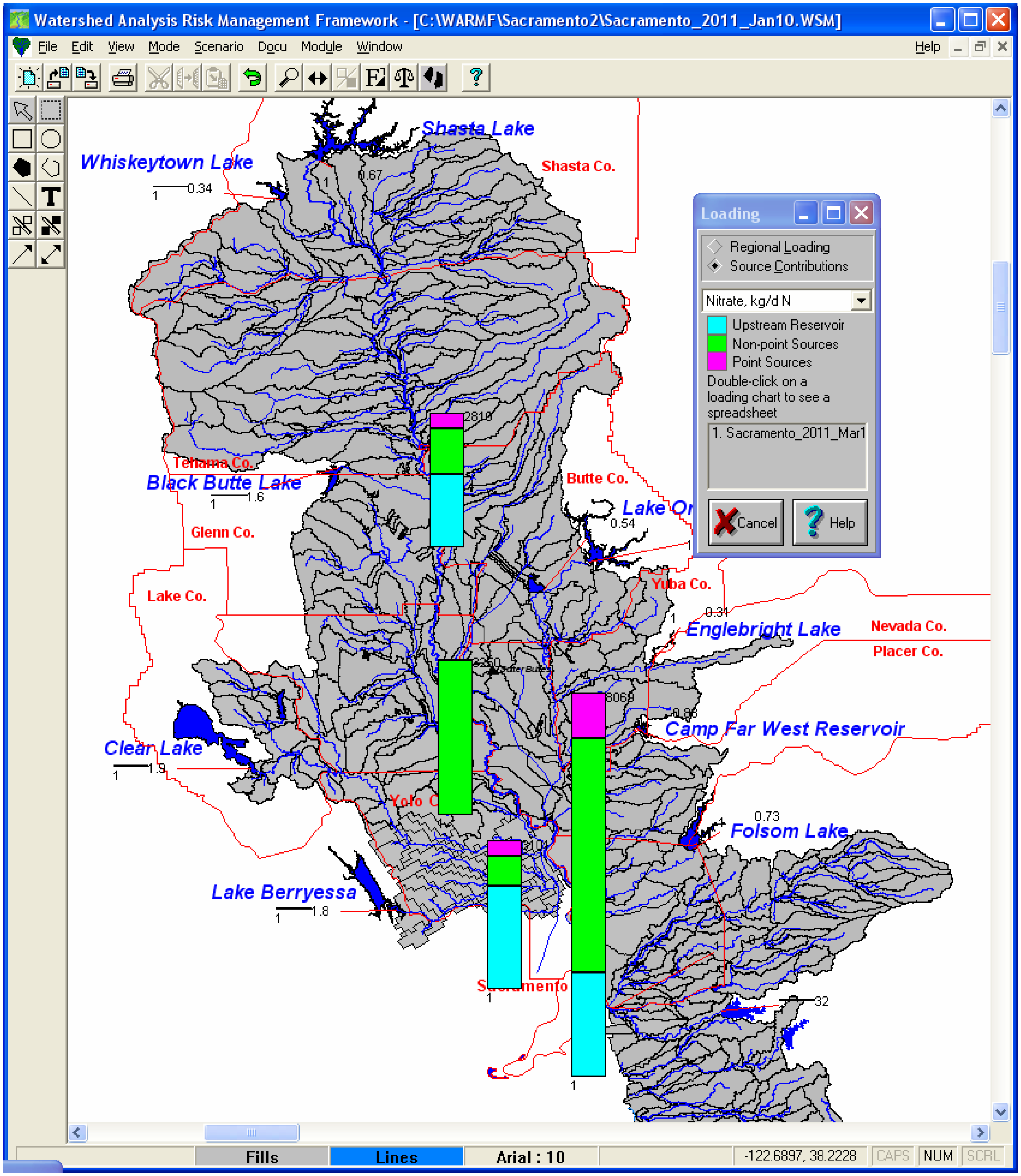

Figure 3-13 Source Contributions Loading of Nitrate

Figure 3-8 shows the relationship between nitrate load and concentration at the Sacramento River at Morrison Creek. Nitrate shows a very strong seasonal pattern of high concentration in winter and low in summer. Since this correlates to flow, the load has the same seasonal pattern.

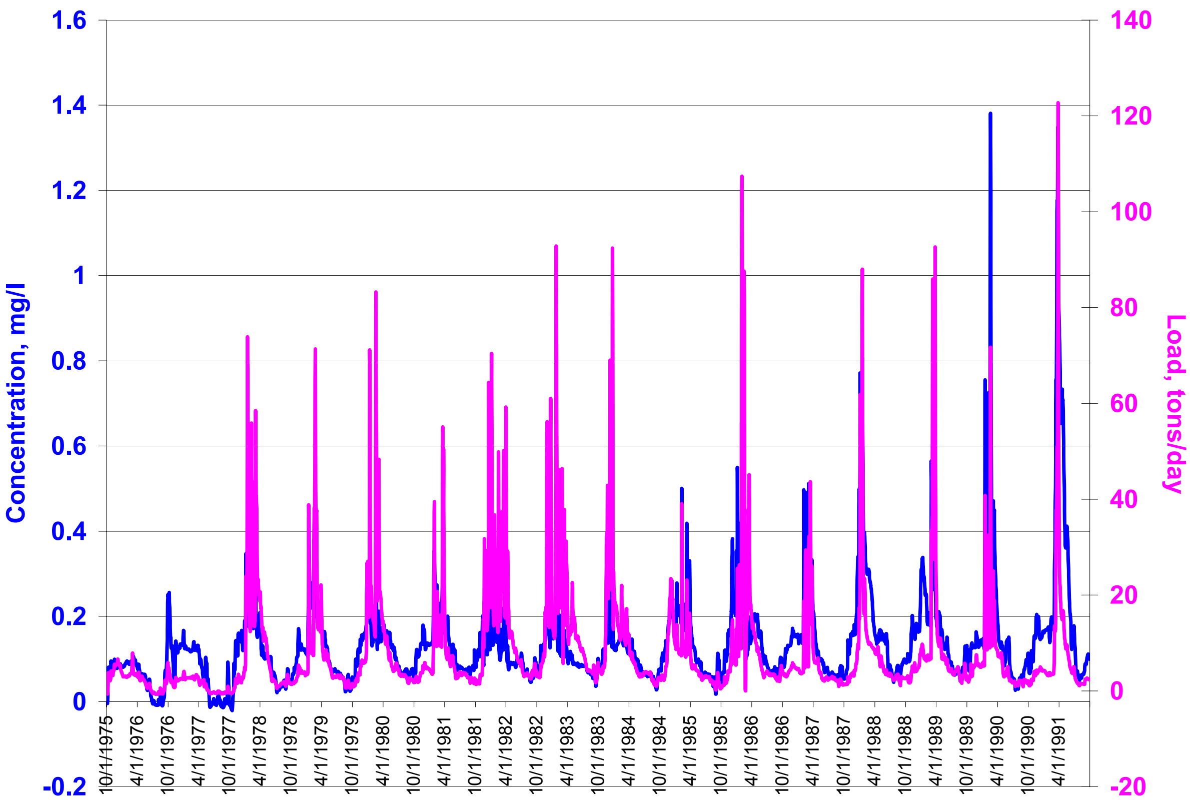

Figure 3-14 Nitrate Load (pink line) vs. Concentration (blue line) at Sacramento River at Morrison Creek

Sources of Phosphorus

Some caution should be taken in the following source analysis of phosphorus because the model is not well calibrated for phosphorus. Although there is an apparent systematic error resulting in too little simulated agricultural runoff, potential errors for other sources are not as clear. Table 3.11 summarizes the sources of total phosphorus to the Sacramento River upstream of Morrison Creek and Yolo Bypass upstream of Lisbon for the 1976 through 1991 water years. 25% of the load came from nonpoint source groundwater accretion and surface runoff. The boundary river inflows contributed about 36% of the load, while point sources contributed 14% of the phosphorus loading. Simulated in-stream processes were very important for phosphorus, with 21% of phosphorus coming from resuspension of river bed sediments but 50% of phosphorus settling out of the water column before reaching the Delta. Figure 3-15 shows the major loading sources in a visual format.

Table 3.11 Sources and Sinks of Phosphorus

Sources	Load (tons/day)	Load (% of inputs/outputs)
Inflows from Upstream	**3.07**	**36.55%**
Lake Shasta	1.19	14.17%
Lake Oroville + Thermalito Afterbay	0.84	10.00%
Englebright Lake	0.29	3.45%
Camp Far West Reservoir	0.11	1.31%
Folsom Lake	0.28	3.33%
Whiskeytown Reservoir	0.01	0.12%
Black Butte Lake	0.18	2.14%
Clear Lake	0.05	0.60%
Lake Berryessa	0.12	1.43%
Nonpoint Sources	**2.14**	**25.48%**
Barren land	0.02	0.24%
Cotton	0.01	0.12%
DairyPA	0.00	0.00%
Deciduous Forest	0.02	0.24%
Double Crop DLA	0.02	0.24%
Evergreen Forest	0.14	1.67%
Fallow	0.01	0.12%
Farmsteads	0.02	0.24%
Flowers and nursery	0.00	0.00%
Grassland/Herbaceous	0.24	2.86%
Lagoon	0.00	0.00%
Marsh	0.02	0.24%
Mixed Forest	0.01	0.12%
Native Classes Unsegregated	0.00	0.00%
Olives, citrus & subtropicals	0.00	0.00%
Orchard	0.10	1.19%
Other CAFOs	0.00	0.00%
Other row crops	0.05	0.60%
Paved areas	0.00	0.00%
Perennial forages	0.08	0.95%
Perennial Forages DLA	0.00	0.00%
Rice	0.92	10.95%
Sewage plant (not including discharge)	0.00	0.00%
Shrub/Scrub	0.19	2.26%
Urban Commercial	0.02	0.24%
Urban Industrial	0.01	0.12%
Urban landscape	0.04	0.48%
Urban residential	0.04	0.48%
Vines	0.00	0.00%
Warm season cereals/forages	0.06	0.71%
Water	0.01	0.12%
Winter grains & safflower	0.08	0.95%
Resuspension from River Bed	**1.77**	**21.07%**
Reaction Product	**0.36**	**4.29%**
Point Sources	**1.06**	**12.62%**
Sinks		
Settling to River Bed	**4.27**	**81.49%**
Reaction Decay	**0.34**	**6.49%**
Diversions	**0.63**	**12.02%**
NET LOAD TO THE DELTA	**3.32**	

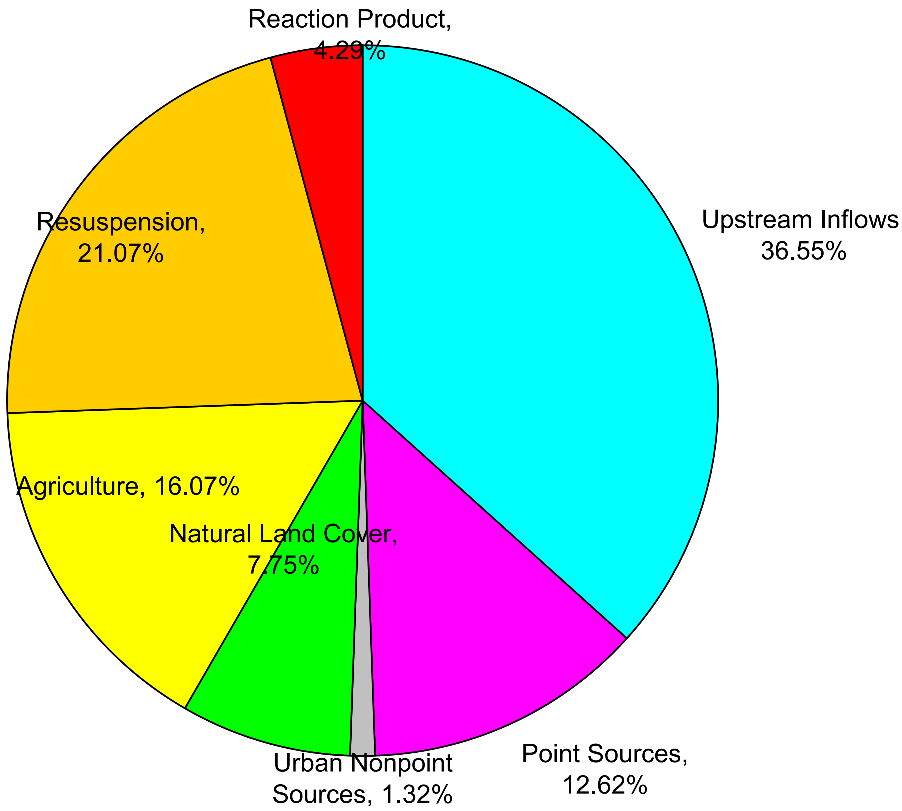

Figure 3-15 Phosphorus Loading Sources of the Sacramento River and Yolo Bypass

Table 3.11 shows that the rice contributes considerably more nonpoint source load of phosphorus than other land uses. Table 3.12 shows the loading intensity of each land use on a per unit area basis. This analysis includes just the quarter of Figure 3-15 in yellow, green, and gray comprising nonpoint sources coming from the land. Other (non-dairy) Confined Animal Feeding Operations, Double Crop Dairy Land Application, and rice land uses deliver the highest amount of phosphorus per land area to surface waters in the Sacramento River and Yolo Bypass watersheds.

Table 3.12 Phosphorus Load from Nonpoint Sources by Land Area

Land Use	Phosphate Load (lb/acre/year)
Barren land	0.72
Cotton	0.51
DairyPA	0.00
Deciduous Forest	0.08
Double Crop DLA	1.63
Evergreen Forest	0.11
Fallow	0.08
Farmsteads	0.12
Flowers and nursery	0.31
Grassland/Herbaceous	0.11
Lagoon	0.00
Marsh	0.14
Mixed Forest	0.11
Native Classes Unsegregated	0.00
Olives, citrus & subtropicals	0.07
Orchard	0.21
Other CAFOs	2.06
Other row crops	0.27
Paved areas	0.07
Perennial forages	0.27
Perennial Forages DLA	0.00
Rice	1.19
Sewage plant incl. ponds	0.04
Shrub/Scrub	0.18
Urban Commercial	0.32
Urban Industrial	0.39
Urban landscape	0.20
Urban residential	0.15
Vines	0.27
Warm season cereals/forages	0.33
Water	0.08
Winter grains & safflower	0.32

Figure 3-16 shows the sources of total phosphorus at various locations within the watershed. Light blue shows boundary inflows, green shows nonpoint sources, and magenta is point sources. The bar chart in the north is the Sacramento River at Hamilton City. The largest bar chart in the south is the Sacramento River at Freeport. The other bar charts are for the Yolo Bypass and Colusa Basin Drain. At Hamilton City, 72% of the phosphorus is from upstream inflows, 18% is from nonpoint sources, and 10% is from point sources. Phosphorus in the Colusa Basin Drain is essentially all from nonpoint source loading. Inflows from reservoirs and flood control weirs account for 86% of the phosphorus in the Yolo Bypass, with the rest split between point and nonpoint source load. At the Sacramento River at Morrison Creek, 50% of the phosphorus is from upstream inflows, 27% is from point sources, and the remaining 23% is from nonpoint sources. The proportion of point source phosphate is higher where the river enters the Delta because large discharges of phosphorus in the Sacramento area do not have the same opportunity to settle out of the water column as loading from father upstream in the watershed.

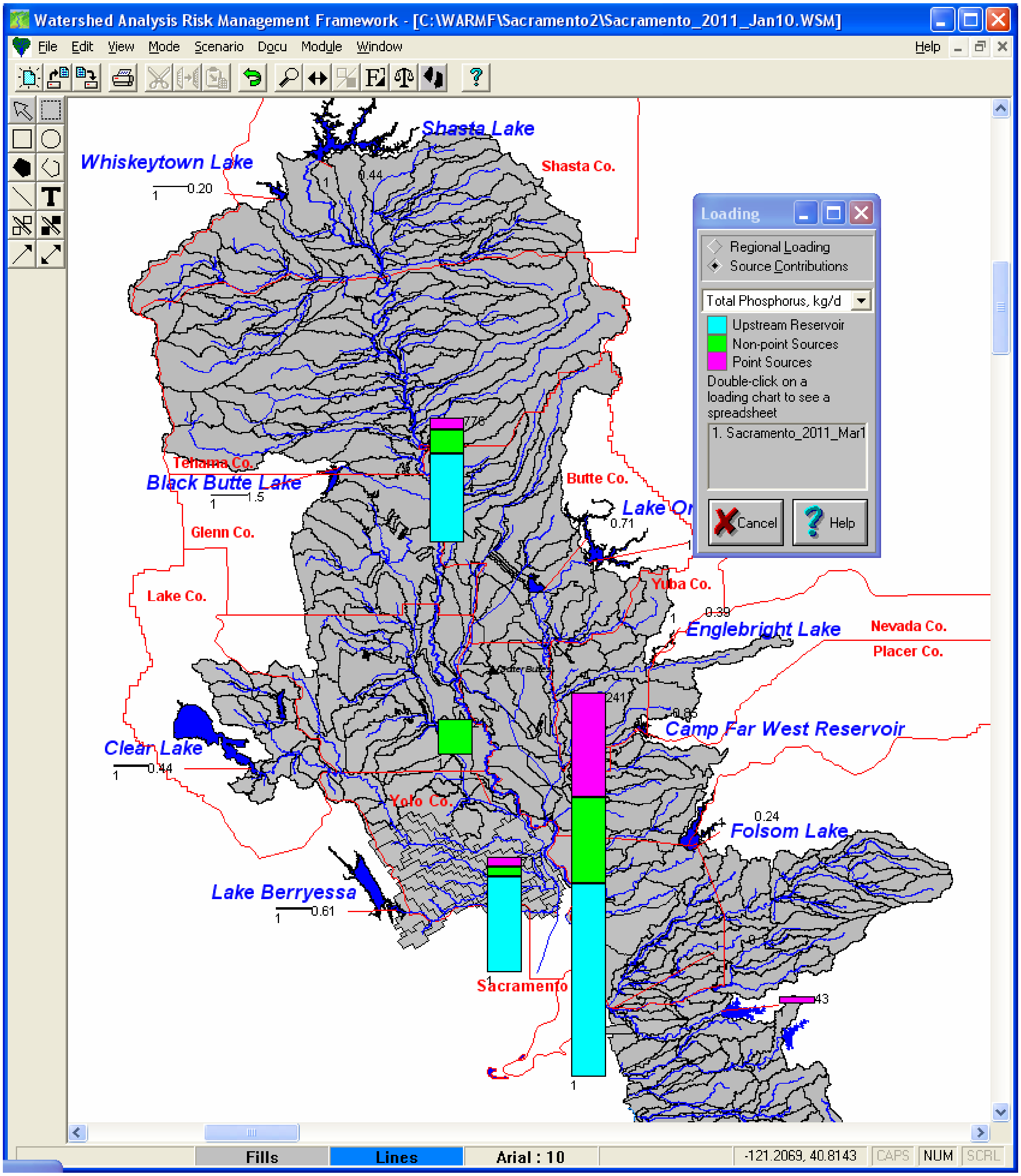

Figure 3-16 Source Contributions Loading of Phosphorus

Figure 3-17 shows the relationship between total phosphorus load and concentration at the Sacramento River at Morrison Creek. The highest phosphorus concentration and load occurred during winter. Note the significantly higher concentration in the dry years of 1976 and 1977 when point source discharge was a higher than normal percent of the load.

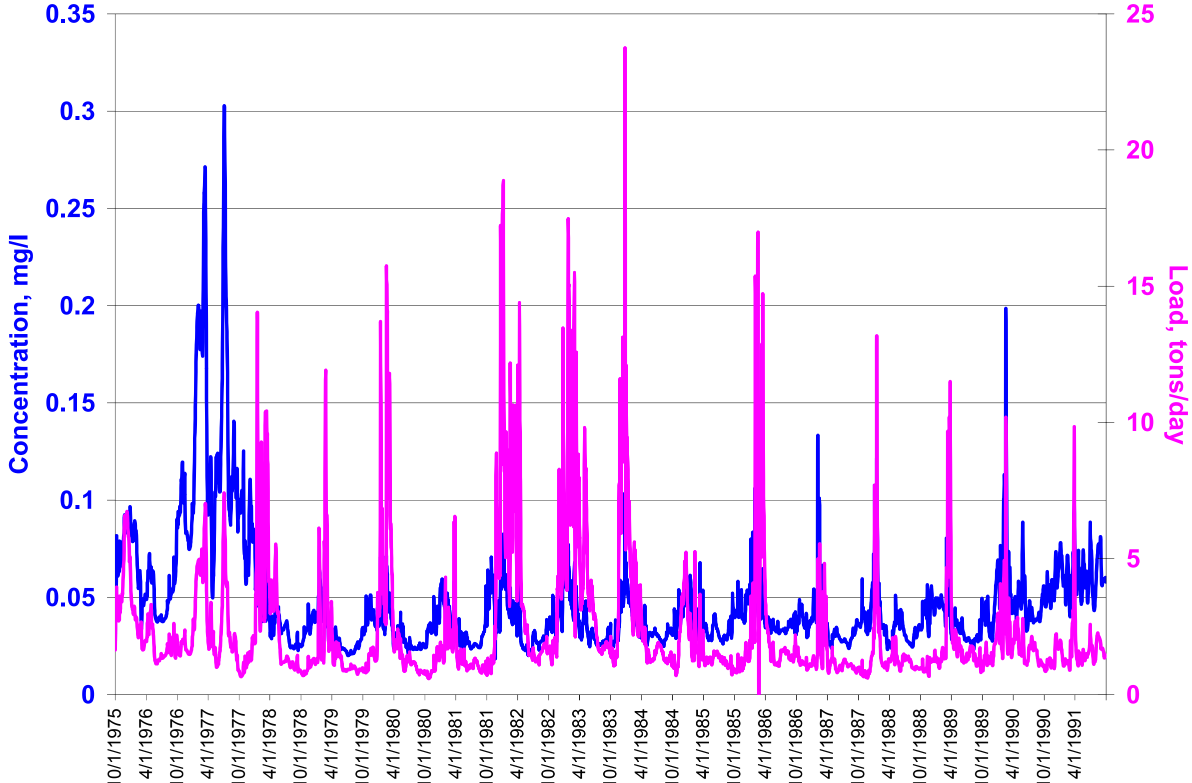

Figure 3-17 Phosphorus Load (pink line) vs. Concentration (blue line) at Sacramento River at Freeport

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Data was collected for the Sacramento River watershed back to October 1, 1921 for use in calibrating the model and linking to the CALSIM model. There was sufficient data to provide model inputs and to judge the calibration of model outputs. Measured flow and water quality from many historical time periods were used to calibrate the model using a coarse land use dataset. Calibration proceeded from upstream to downstream, focusing on the Sacramento River proper and major tributaries. This was done because the primary consideration for protection of Delta drinking water supplies is the flow and loading to the Delta, not within the Sacramento River watershed. The calibration strategy included sufficient resolution to identify the sources of pollutants within regions and land uses in the watershed.

The model's land use database was upgraded to include much greater resolution of land use classes. Detailed information on land use characteristics was also imported into the model. The model was not calibrated further after this upgrade. This resulted in significant differences between simulation results and observed data in some instances. The Colusa Basin Drain, a tributary with a largely agricultural watershed, shows much less simulated flow during the irrigation season than was observed at the gaging station near Highway 20. This error of simulating too little agricultural drainage caused simulation errors in electrical conductivity and organic carbon in the Colusa Basin Drain and to a lesser extent further downstream in the Sacramento River proper. Phosphorus simulation does a poor job of matching observed data. This is in part because the model was not recalibrated after the land use upgrade but also likely because phosphorus data from point sources is poor and point sources are an important source of phosphorus in the Sacramento River.

The composition of salinity was analyzed using measured data of the major cations, anions, and inorganic carbon. It found that total inorganic carbon was a significant component of total dissolved solids, particularly for low salinity waters like the Sacramento River. Since inorganic carbon originates in the atmosphere and its concentration is a function of pH in water exposed to air, it may be worthwhile to consider this when managing salinity as a whole. The correlation between electrical conductivity and total dissolved solids is weak for low salinity conditions seen in most of the Sacramento River watershed, so a data measurement error of plus or minus 10 to 20 percent should be assumed for electrical conductivity measurements.

The calibration of the WARMF model showed reasonable results for flow, temperature, total suspended sediment, organic carbon, salinity, and ammonia at most calibration locations. There were higher errors for nitrate, but this may be caused in part by outlier data. Phosphorus calibration was poor throughout the watershed. Flow calibration is within calibration goals for the Sacramento River, but not as strong for individual tributaries as a consequence of the calibration priorities for the project. The model simulations showed relative error under 10% for organic carbon at monitoring locations on the Sacramento River main stem and Feather River. There were significant errors in model simulation of flow and chemical constituents in the Colusa Basin Drain. These probably originate with an input applied water rate which is probably too low. It was not possible to significantly improve the model calibration while keeping the given applied water rates. Errors in simulating the Colusa Basin Drain and presumably other agricultural areas of the watershed propagate downstream and cause the model to simulate electrical conductivity 9% lower than observed and organic carbon 18% lower than observed in the Sacramento River at Freeport.

The sources of pollutants were analyzed with the calibrated model. The major categories of sources were point sources, urban runoff, agricultural drainage, and natural land cover. Simulated organic carbon, ammonia, and phosphorus showed important in-stream processes which shifted the source composition of each constituent toward those sources most prevalent in the lower watershed. Although both sediment scour and settling were important processes, the model simulated more settling which thus acted as a sink for adsorbed nutrients.

Although the model calibration can be improved upon, it can still be used to evaluate prospective watershed management scenarios. It is important to consider how model calibration error would affect evaluation of the results from those scenarios. For random calibration error, it is sufficient to allow for a certain level of uncertainty in simulation results. The apparent underprediction of agricultural loading, however, implies that the error for that component is likely to be in one direction. Some systematic errors cancel themselves out when comparing one scenario against another. This makes comparative analysis stronger than using the model to predict what the concentration of a constituent will be under a certain set of circumstances.

Recommendations

The model application process used relied upon extensive knowledge of agricultural processes to constrain the model. While this is very valuable information to incorporate into the model, there is uncertainty in this knowledge which can cause model error if used verbatim without additional calibration as it was in this case. The model can provide expert “knowledge” of watershed physical processes as a feedback mechanism to determine the right model parameters to use. It is recommended that continued modeling work allow for a range of possible values for model inputs which can then be adjusted through model calibration.

The applied water rates in particular are vital to correct simulation of agricultural areas and should be highest priority for adjustment to improve model performance. The fate of unused irrigation supply water should be ascertained since it may be an important component of total flow from agricultural areas. The Colusa Basin Drain should be calibrated for water quality and the agricultural coefficients determined through the calibration process (including applied water rate) should be applied throughout agricultural areas of the watershed.

Point source data should be collected when possible from the discharger or the Regional Water Quality Control Board. After updating point source data, additional work should be done calibrating the model’s simulation of phosphorus. Calibration of Sacramento River tributaries was coarse because it was not a priority of the project, but additional work calibrating the tributaries could improve the accuracy of the model's predictions of the sources of loading within the watershed. The Delta east side tributaries were calibrated for flow, turbidity, and organic carbon as part of a separate project, but other parameters of interest to the Central Valley Drinking Water Policy Work Group (salinity, ammonia, nitrate, phosphorus) were only coarsely adjusted. Calibration of these parameters could be done to improve and identify model performance for these parameters in the Cosumnes, Mokelumne, and Calaveras Rivers.

The analytical modeling process identified potential management concerns with managing salinity as a single conservative entity. Measurement of salinity with electrical conductivity provides an efficient way of collecting data, but care needs to be taken because the correlation between electrical conductivity and total dissolved solids becomes weak at low salinity. The inclusion of inorganic carbon in measurements of salinity may also be problematic from a management perspective. Inorganic carbon can be more than 50% of total dissolved solids, but salinity control measures will only reduce inorganic carbon concentration if they happen to reduce pH. Salinity control measures should take into account that only the portion of salinity other than inorganic carbon can be managed at the source.

If the management of salt were to benefit from separation of inorganic carbon from the rest of the ions which make up salinity, changes to monitoring and modeling methodologies would be important. This would include occasional analytical measurement of total dissolved solids to ensure consistent correlation with electrical conductivity and measurements of inorganic carbon (or the specific ions of concern). Modeling used for salinity management should be able to simulate the components correctly as opposed to simulating electrical conductivity as a single conservative substance.

Extensive monitoring of Steelhead Creek and Dry Creek in the Sacramento suburbs has been conducted for many years to learn about organic carbon loading from urban areas. Although this data is very valuable, especially in conjunction with a USGS flow gage near the Roseville wastewater treatment plant, limited discharge information from the Placer County District No. 3 wastewater treatment plant discharge farther upstream made it difficult to discern the nonpoint source loading signal from the urban area. Besides point source discharge, potential sources of organic carbon in urban areas could include animal waste, in-stream algae growth, decay products of plant matter washed into the stream, and decay of plant matter from the riparian zone. If continued study of urban organic carbon loading is pursued, it is recommended that the studies gather complete data from point sources. This would provide valuable information to constrain future modeling efforts.

Since its tributary watershed is heavily agricultural, monitoring the Colusa Basin Drain is a good method of learning about the quantity and quality of agricultural runoff. There is currently a flow gage operating in the Colusa Basin Drain at Highway 20 near Colusa. In the late 1990's, data was collected near the outlet of the Drain near Knights Landing. If more monitoring were done in the future, the location near Knights Landing would be a good choice. The in-stream monitoring should include concurrent measurements of nutrients, organic carbon, total dissolved solids, suspended sediment, and flow if possible. This would provide a strong basis for performing future modeling of the Colusa Basin Drain and by extension the rest of the core Sacramento Valley agricultural area.

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Appendix A

Delta East Side Tributaries Time Series Output

Flow

Simulated flow is shown in blue lines and observed data is in black circles in Figure A-1 and Figure A-2. Calibration statistics are shown in Table A.1. Refer to the final report for the Delta East Side Tributaries modeling work (Systech 2011) for discussion of the calibration of these tributaries.

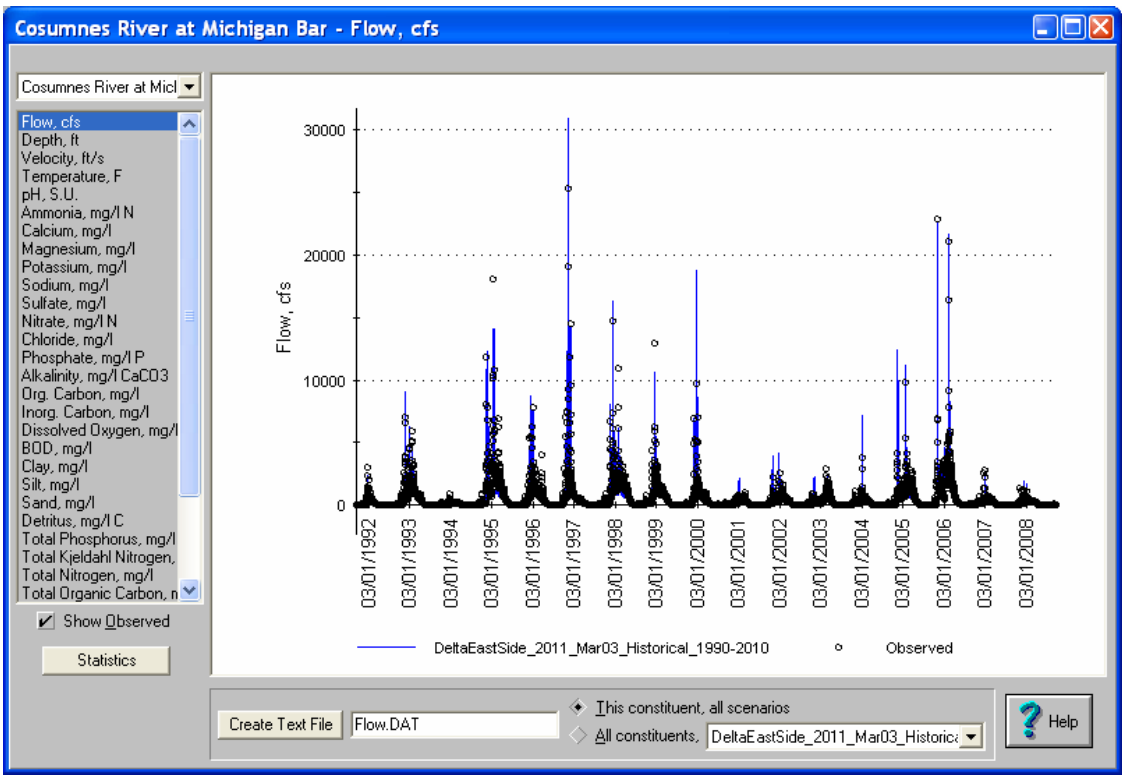

Figure A-1 Simulated vs Observed Flow at Cosumnes River at Michigan Bar

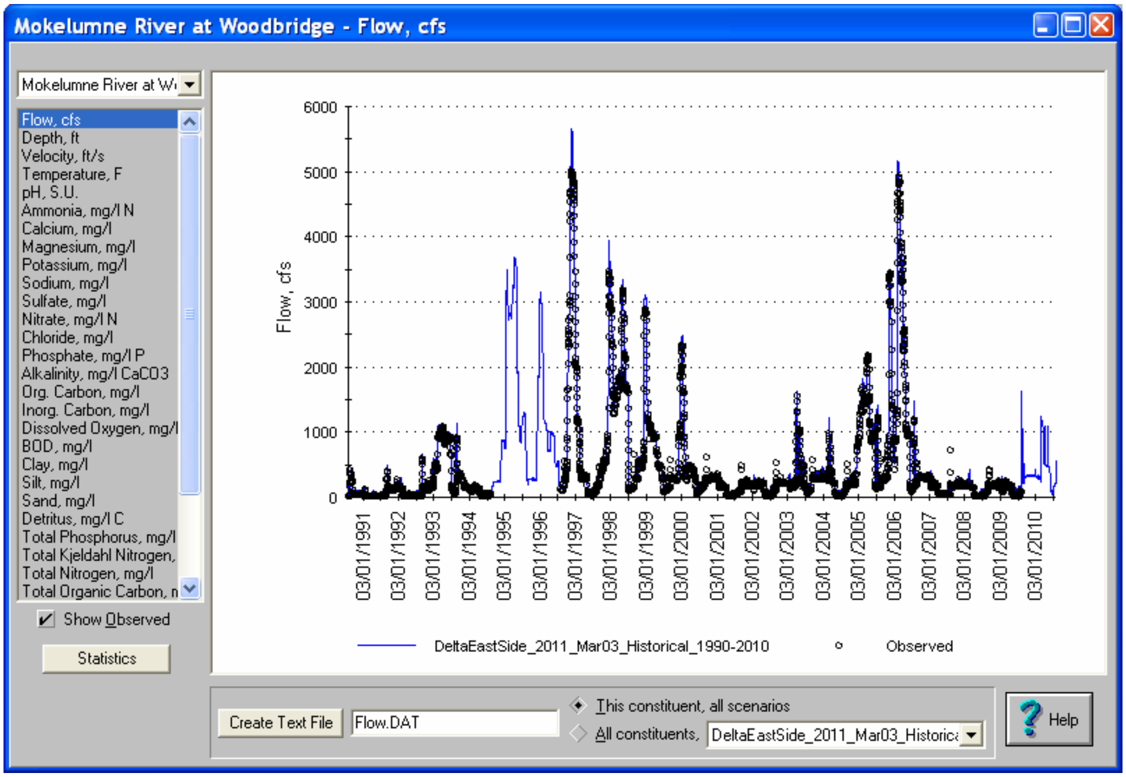

Figure A-2 Simulated vs Observed Flow at Mokelumne River at Woodbridge

Table A.1 Hydrology calibration statistics for the Delta Model boundary control points

Gaging Station	**Calibration Time Period**	**% Relative Error**	**% Absolute Error**	**R squared**
Cosumnes River at Michigan Bar	1990-2010	1.1	45.4	0.756
Mokelumne River at Woodbridge	1980-1990	9.6	10.7	0.993
Calaveras River	No flow data available for calibration			

Turbidity

For the Delta east side tributaries expansion of WARMF, turbidity in NTU was calculated as 0.5902 times the simulated total suspended sediment concentration in mg/l.. Simulated turbidity is shown in blue lines and observed data is in black circles in Figure A-3 through Figure A-5. Calibration statistics are shown in Table A.2. Refer to the final report for the Delta East Side Tributaries modeling work (Systech 2011) for discussion of the calibration of these tributaries.

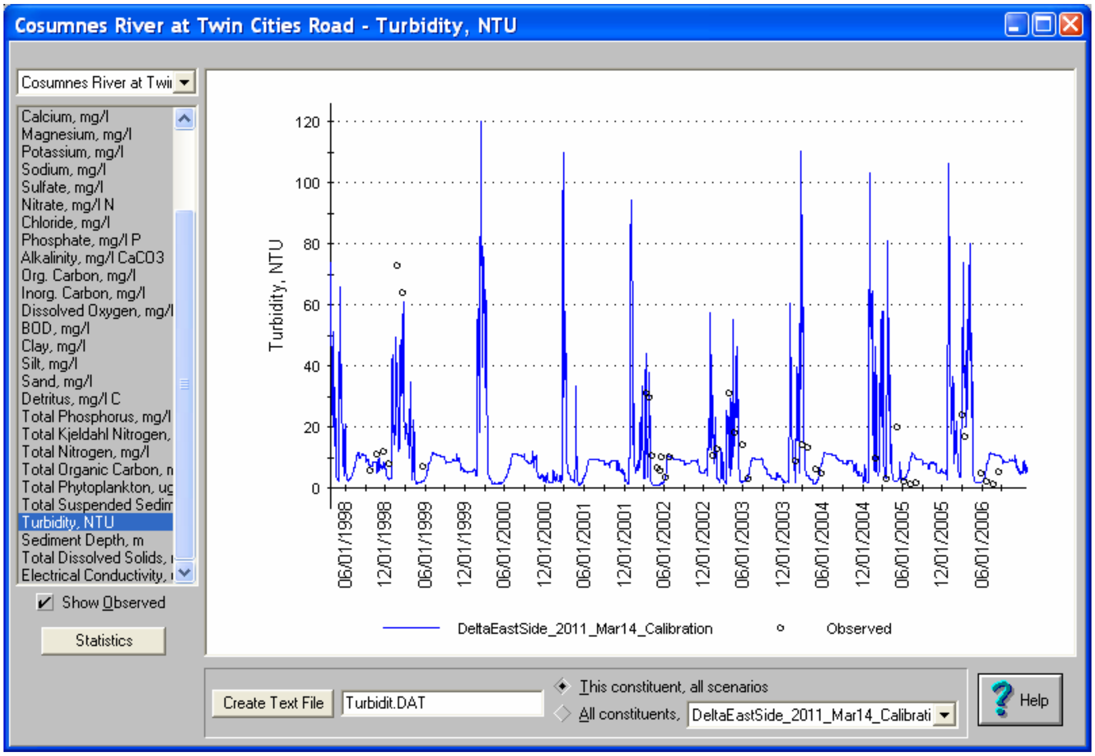

Figure A-3 Simulated vs Observed Turbidity at Cosumnes River at Twin Cities Road

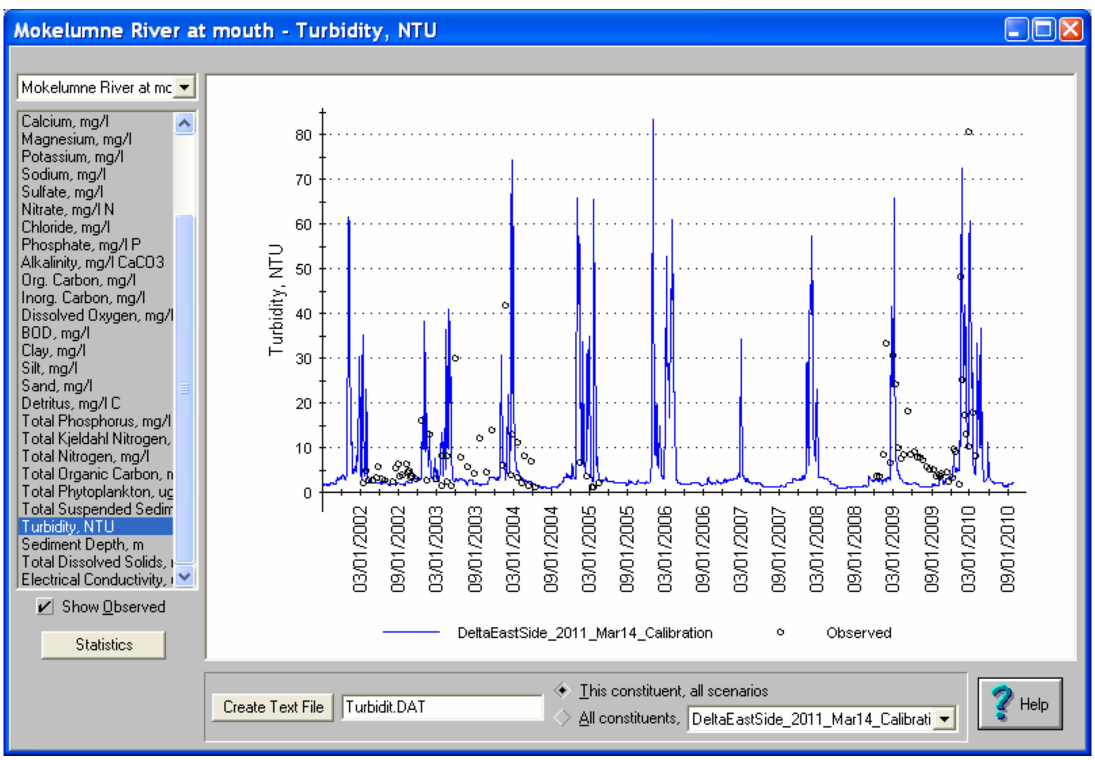

Figure A-4 Simulated vs Observed Turbidity at Mokelumne River at mouth

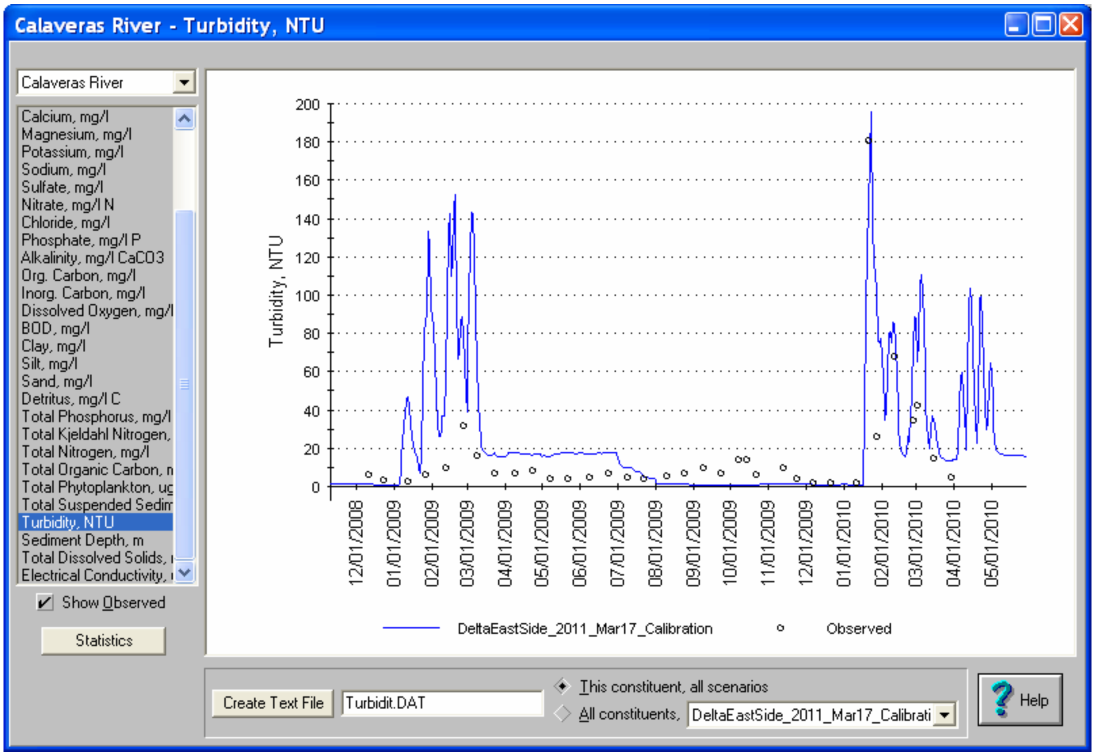

Figure A-5 Simulated vs Observed Turbidity at Calaveras River at mouth

Table A.2 Turbidity calibration statistics for the Delta Model boundary control points

Gaging Station	Calibration Time Period	% Relative Error	% Absolute Error	R squared
Cosumnes River at Twin Cities Road	1998-2006	-11.9	58.1	0.602
Mokelumne River at mouth	2002-2010	-13.9	97.4	0.393
Calaveras River at mouth	2008-2010	396.7	398.5	0.859

Organic Carbon

Simulated turbidity is shown in blue lines and observed data is in black circles in Figure A-3 through Figure A-5. Calibration statistics are shown in Table A.2. Refer to the final report for the Delta East Side Tributaries modeling work (Systech 2011) for discussion of the calibration of these tributaries.

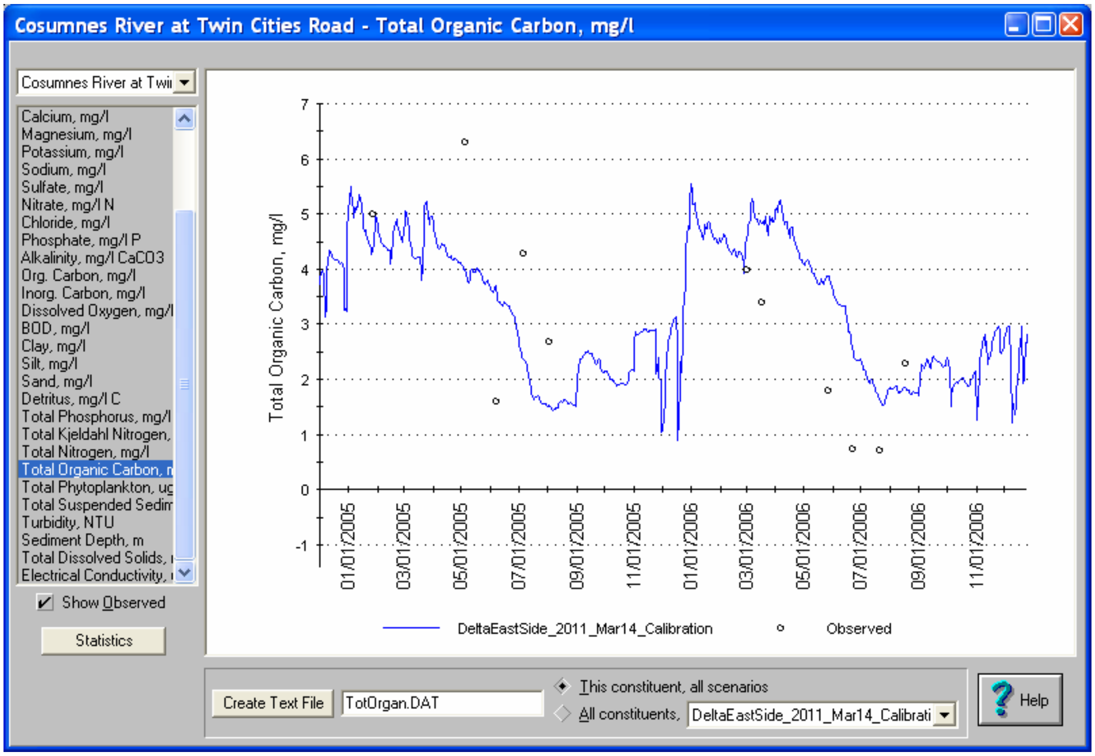

Figure A-6 Simulated vs Observed Total Organic Carbon at Cosumnes River at Twin Cities Road

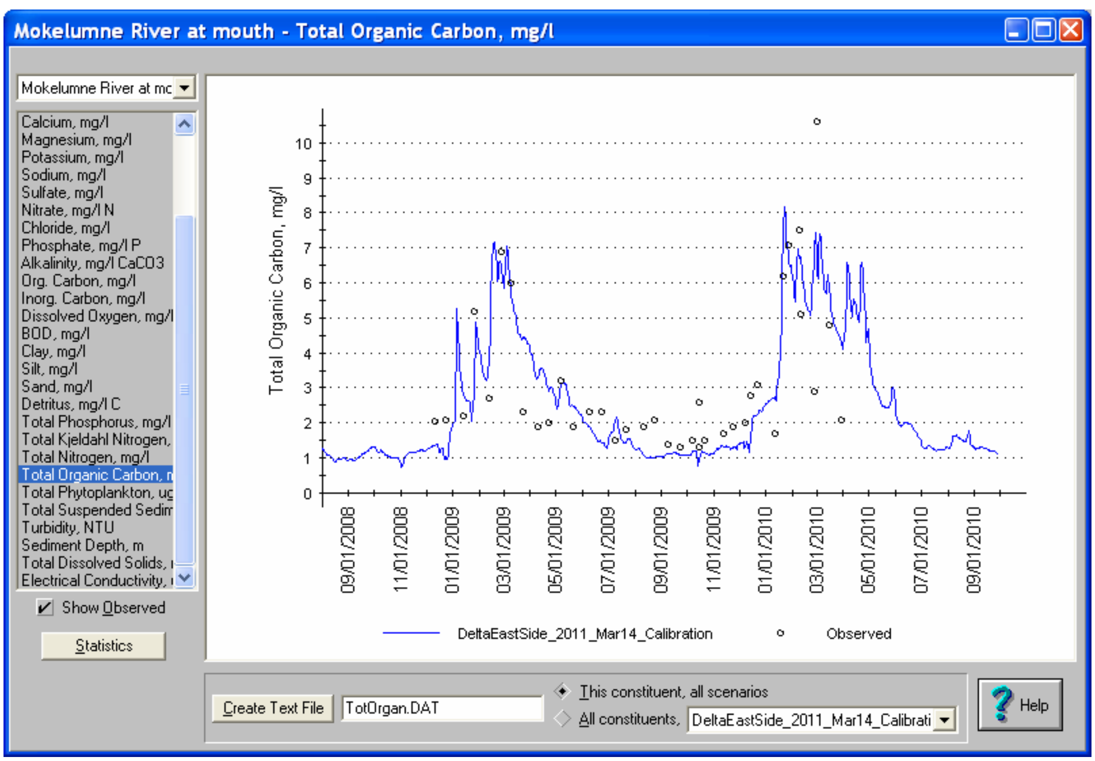

Figure A-7 Simulated vs Observed Total Organic Carbon at Mokelumne River at mouth

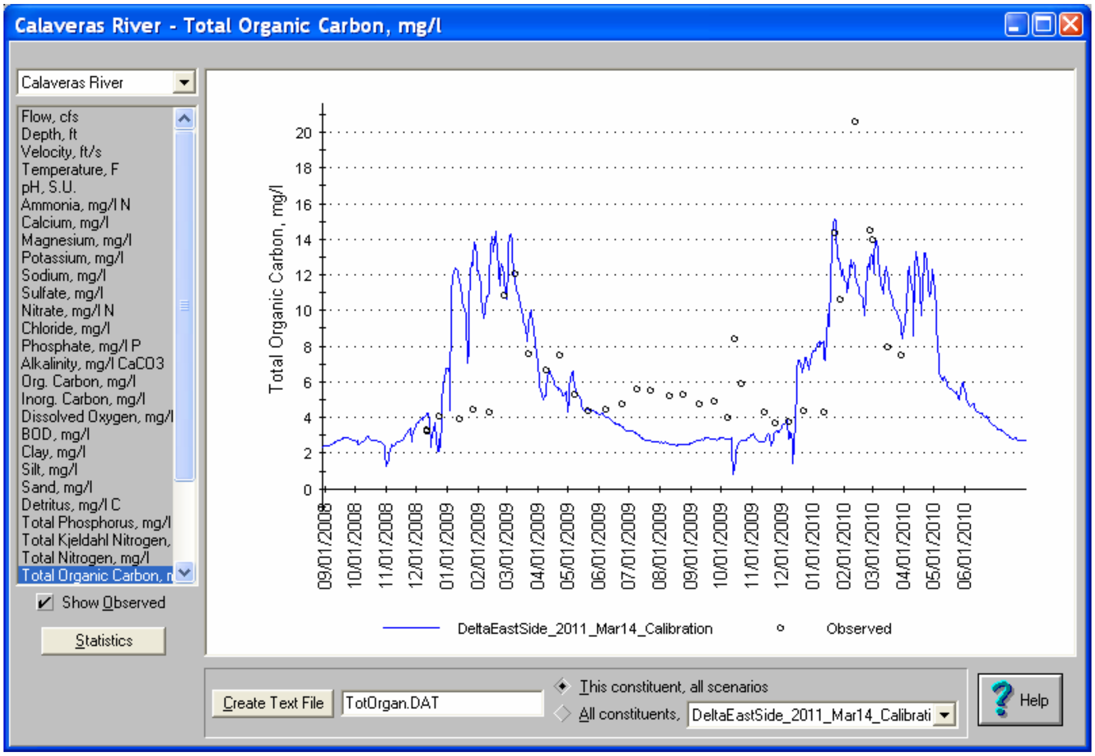

Figure A-8 Simulated vs Observed Total Organic Carbon at Calaveras River at mouth

Table A.3 Total Organic Carbon calibration statistics for the Delta Model boundary control points

Gaging Station	Calibration Time Period	% Relative Error	% Absolute Error	R squared
Cosumnes River at Twin Cities Road	2002	7.3	46.2	0.23
Mokelumne River at mouth	2009-2010	-1.8	40.8	0.67
Calaveras River at mouth	2008-2010	-3.8	60.2	0.42