Task 3 Technical Memorandum Analytical Modeling of the Sacramento River

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

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ABSTRACT

Analytical modeling of the Sacramento River watershed was performed to determine the sources of pollutants to Delta drinking water intakes under present and projected future conditions. Salinity and organic carbon are two pollutants of primary concern in drinking water which are best controlled by ensuring high quality source water. The Watershed Analysis Risk Management Framework (WARMF) was applied to the Sacramento River watershed. Data was collected from 1921-2007 to drive the model and evaluate its calibration. It was calibrated for flow, temperature, total suspended sediment, electrical conductivity, and organic carbon. The calibrated model successfully predicted each parameter for various regions of the watershed with pollutant sources reflecting combinations of upstream inflows, natural nonpoint source load, agricultural areas, and urban areas. It was determined that upstream inflows and nonpoint source loads were the major sources of salinity in the Sacramento River at Freeport. The sources of organic carbon were more varied, with the four largest sources being nonpoint sources, upstream inflows, in-stream organic matter production, and point sources. The rice was the single largest source of pollutants among agricultural land uses because of the large amount of irrigation water used and sediment erosion in winter. The source and origin of salinity was analyzed. The correlation between total dissolved solids and electrical conductivity was poor in the Sacramento River watershed as a whole because the ratio between them varied with region and salinity concentration. Inorganic carbon was found to be a large component of TDS, especially when salinity is low. The management of salinity may need to take this into account since inorganic carbon originates as carbon dioxide in the atmosphere and occurs as a function of pH in surface waters instead of originating with pollutant loading. The calibrated model is suitable for use in evaluating future scenarios and watershed management practices to determine flow and pollutant loading to the Delta.

1 MODEL SETUP

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. 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. 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 recommended maximum of 500 mg/L. 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 this salinity 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 mg/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.

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.

Due to the expense of water filtration and chemical water purification, the protection of drinking water from these and other pollutants is done most cost-effectively by protection of the drinking water source. Protection of these sources involves assessment of the contribution of various sources to organic carbon and salinity concentrations at the intakes, and is best accomplished through numerical modeling.

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. 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). As part of these 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 (Shanz 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 were 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 to determine the sources of 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 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 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. Each of the tributaries to the Sacramento River were included in the model domain from the confluence with the Sacramento upstream to either the watershed divide or to one of eight reservoirs, as illustrated in Figure 1-1.

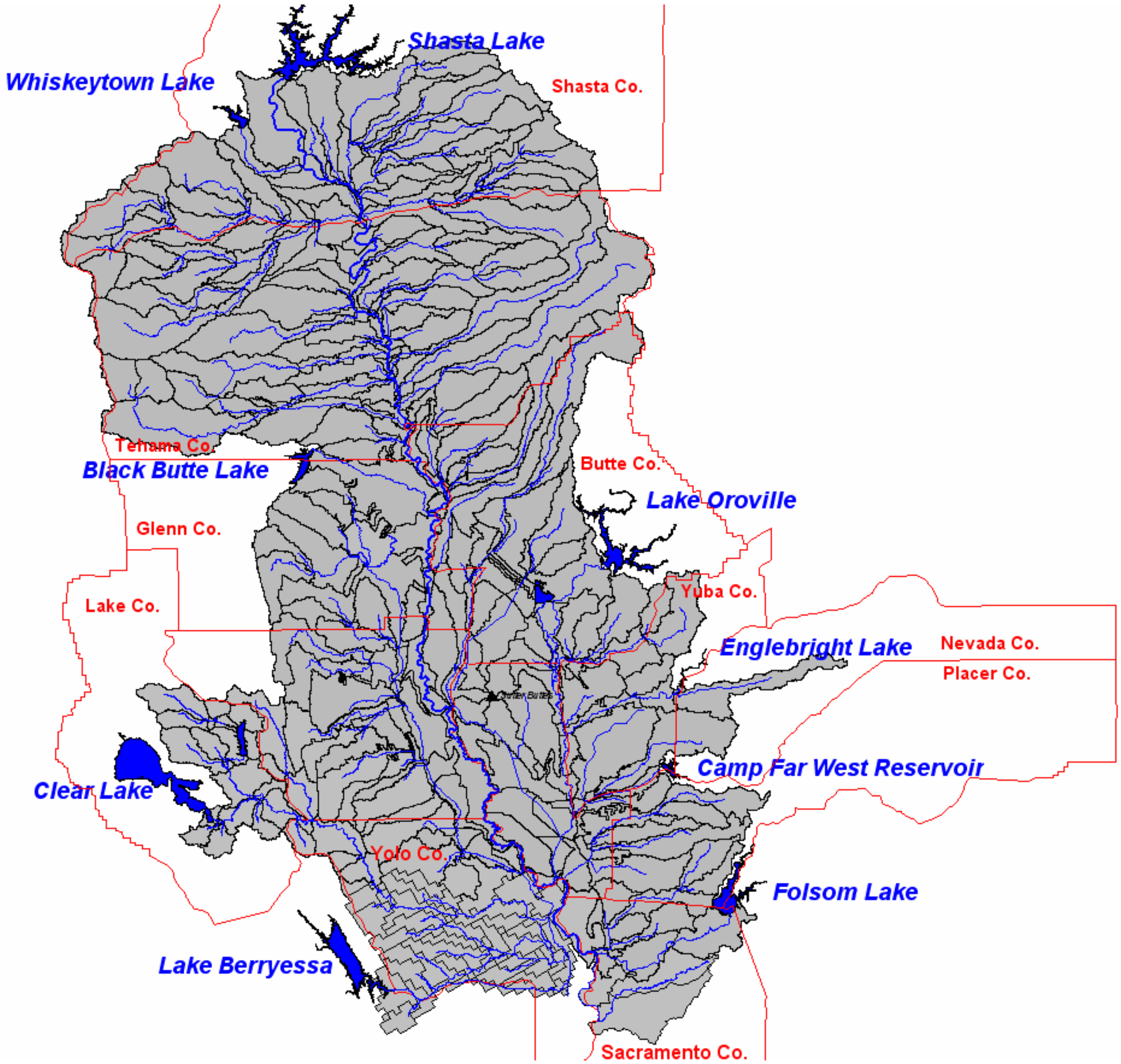

Figure 1-1 The Domain of WARMF Sacramento River Model.

The Sacramento River and its tributaries within the watershed defined in Figure 1-1 were divided into 351 river segments and 353 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 eight reservoirs located on tributaries to the Sacramento between Shasta Lake and Morrison Creek. The reservoirs include Lake Oroville, Englebright Lake, Camp Far West Reservoir, and Folsom Lake, on the east side of the Sacramento, and Lake Berryessa, Clear Lake, Black Butte Lake, and Whiskeytown Lake on the west side. 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 overland. 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.

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

Parameter	Input	Calculated	Output
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
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.

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.

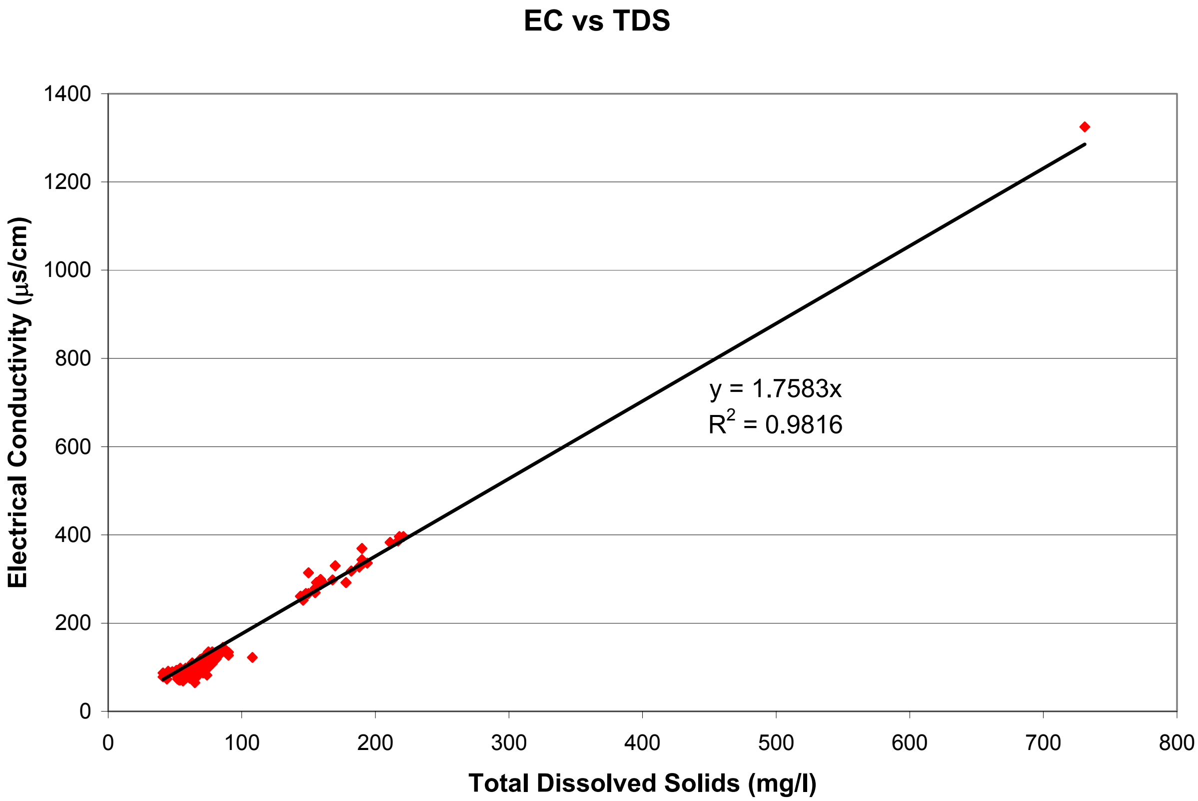

Figure 1-2 Correlation of All TDS and EC Measured Data

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 Drain. The relatively poor correlation at lower TDS concentrations means that 10-20% error is introduced which will propagate through to simulation results.

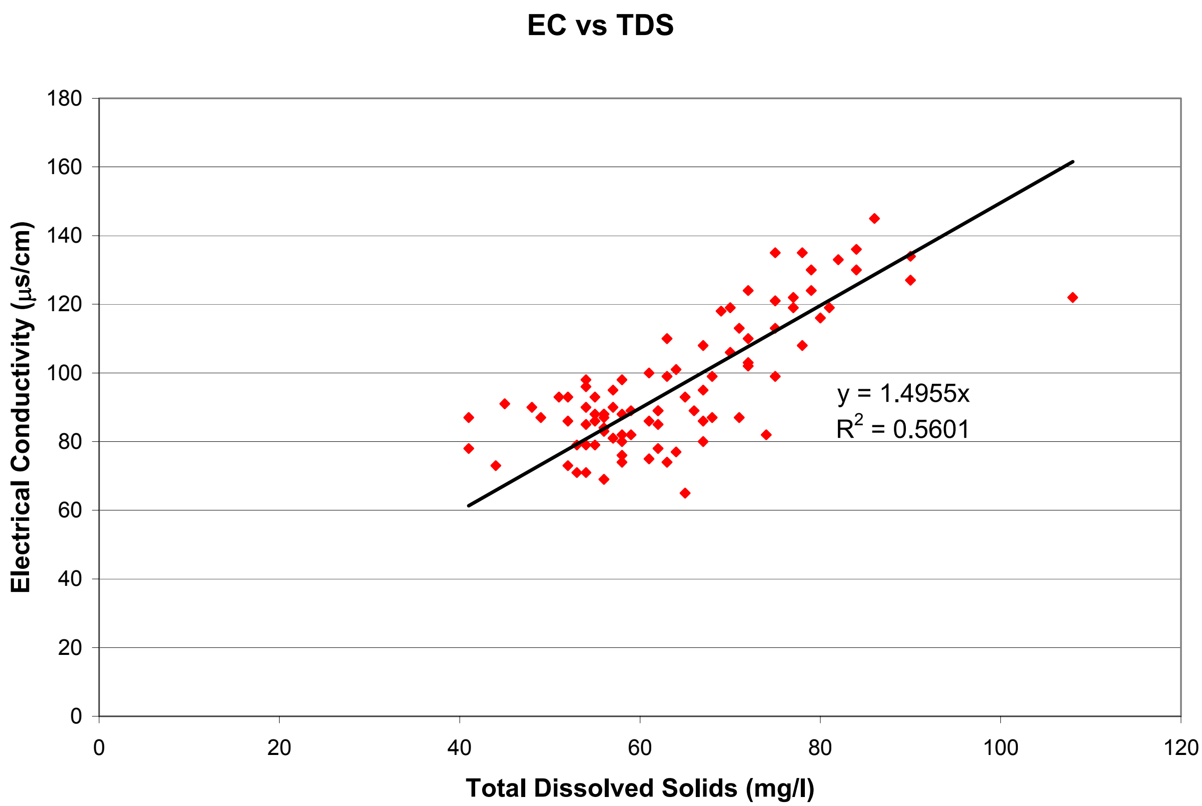

Figure 1-3 Correlation of TDS and EC Measured Data, TDS < 120 mg/l

Concurrent monitoring data of all the major ions was collected from the available data in the Sacramento River watershed. This is not a random samples 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.

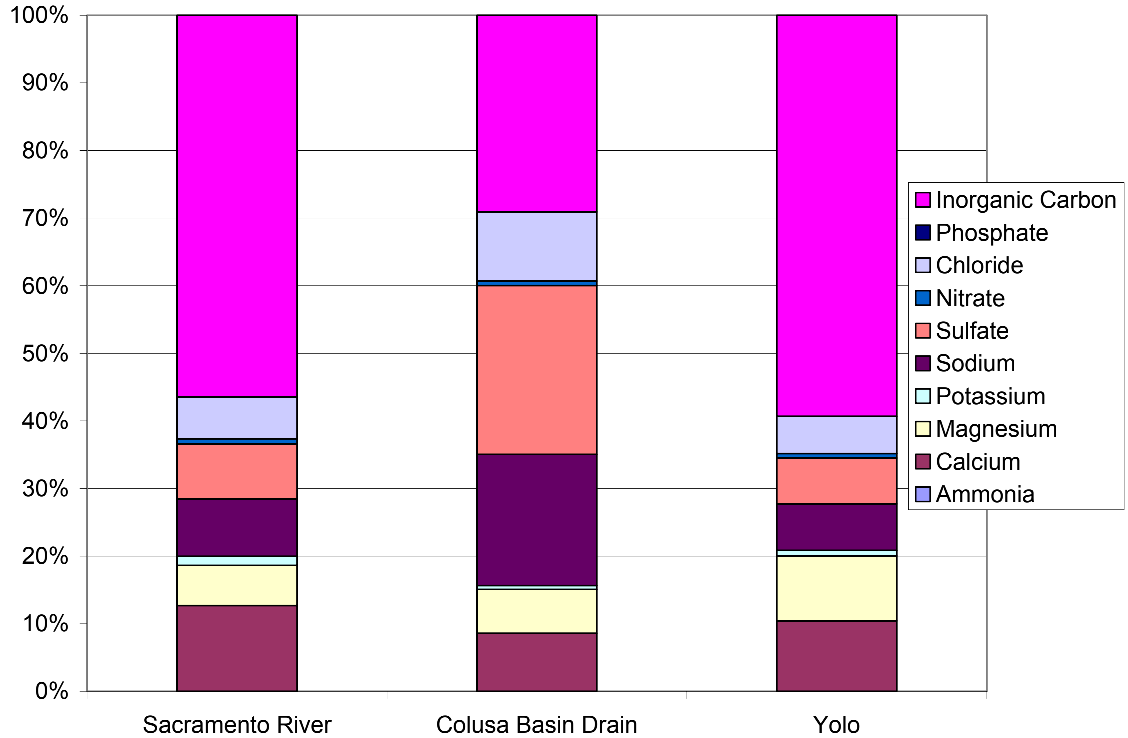

Figure 1-4 Composition of Total Dissolved Solids for the Sacramento River Watershed

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 x 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.

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

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 ion it is possible to calculate equilibrium inorganic carbon concentration as a function of pH as shown in Figure 1-5.

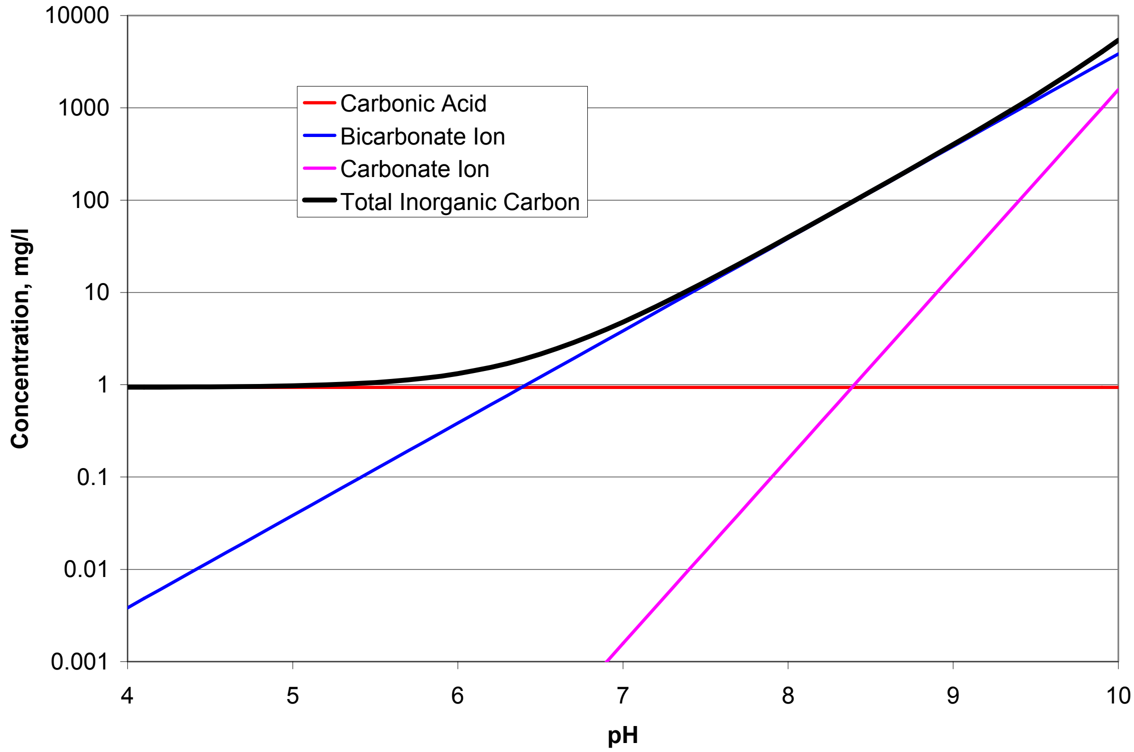

Figure 1-5 Equilibrium Total Inorganic Carbon Concentration with pH at 68 ^{o}F

Above a pH of about 7.5, the equilibrium inorganic carbon concentration increases by an order of magnitude for each pH point. The pH is generally around 8 in the Modesto and Yolo study areas, indicating the high sensitivity of inorganic carbon concentration to pH. Figure (5th from the top) 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 is 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, 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 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 resolution was added in the Cache Creek and Putah Creek watersheds when the model was used for the Central Valley Salinity Coalition. The additional land uses used in that area are cotton, flowers and nursery, olives / citrus / subtropical orchards, vines, perennial forages, warm season cereals and forages, winter grains & safflower, farmsteads, urban landscape, low impervious commercial / industrial, dairy facility, dairy lagoon, land constrained dairy land application, unconstrained dairy land application, resting dairy land application, sewage treatment plant, and paved areas. Outside of the Cache Creek and Putah Creek watersheds, the percentage of these additional land uses has been set to zero. The lands which are in those categories are placed in similar but more general classifications.

The land use data employed in the Sacramento River WARMF model was assembled from two distinct data sets, shown in Figure 1-6 and Figure 1-7. One of the land use datasets used was downloaded from the California Department of Water Resources (http://www.landwateruse.water.ca.gov/basicdata/landuse/data_request/form.cfm, *accessed Sept. 18, 2008*). The dataset contains digitized polygons of land use within the central valley. Each polygon is assigned a land use designation: grain and hay crops, rice, field crops, pasture, truck nursery and berry crops, deciduous fruits and nuts, citrus and subtropical, livestock dairy poultry, urban residential, commercial, industrial, urban landscape, vacant, native vegetation, riparian vegetation, water surface, or barren. Produced by county between 1994 and 2004 the DWR land use dataset is the most detailed of the available products. However, the classification scheme used does not distinguish between native vegetation types. Therefore, in regions where the DWR data lacked sufficient detail, the National Land Cover Database (NLCD) was used to describe the land use cover type. The 2001 NLCD land cover layer for California was produced through a cooperative project conducted by the Multi-Resolution Land Characteristics (MRLC) Consortium. The NLCD is a medium-resolution (30-meter), remotely-sensed product which classifies land use into the following categories: Open Water, Developed, Open Space, Developed, Low Intensity, Developed, Medium Intensity, Developed, High Intensity, Barren Land (Rock/Sand/Clay), Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Grassland/Herbaceous, Pasture/Hay, Cultivated Crops, Woody Wetlands, Emergent Herbaceous Wetlands. A WARMF land use shapefile was created by merging these two data sources. WARMF calculated the land use distribution within each catchment by overlaying the land use shapefile with the boundaries of land catchments. The land use layer resulting from this analysis is shown in Figure 1-8.

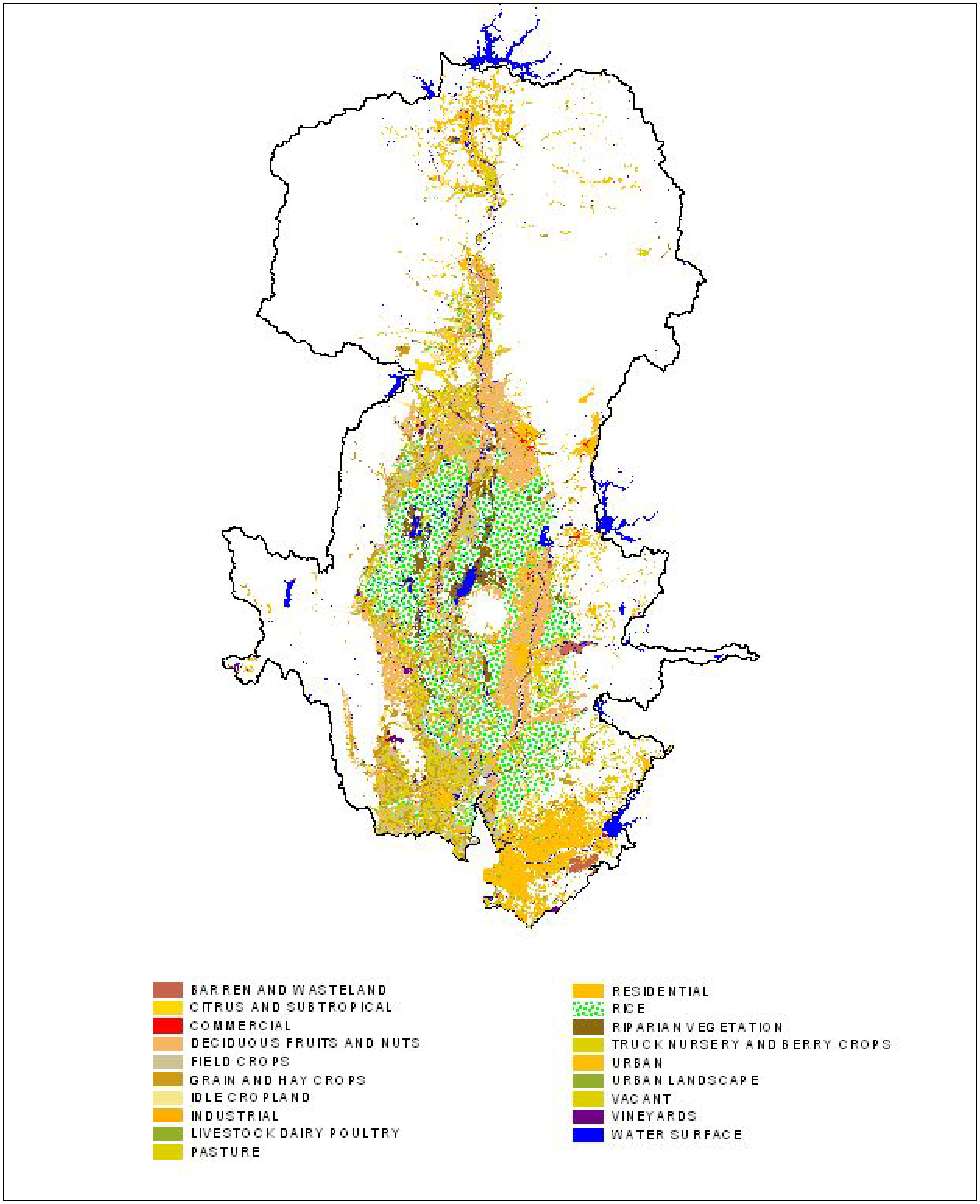

Figure 1-6 California Department of Water Resources land use data

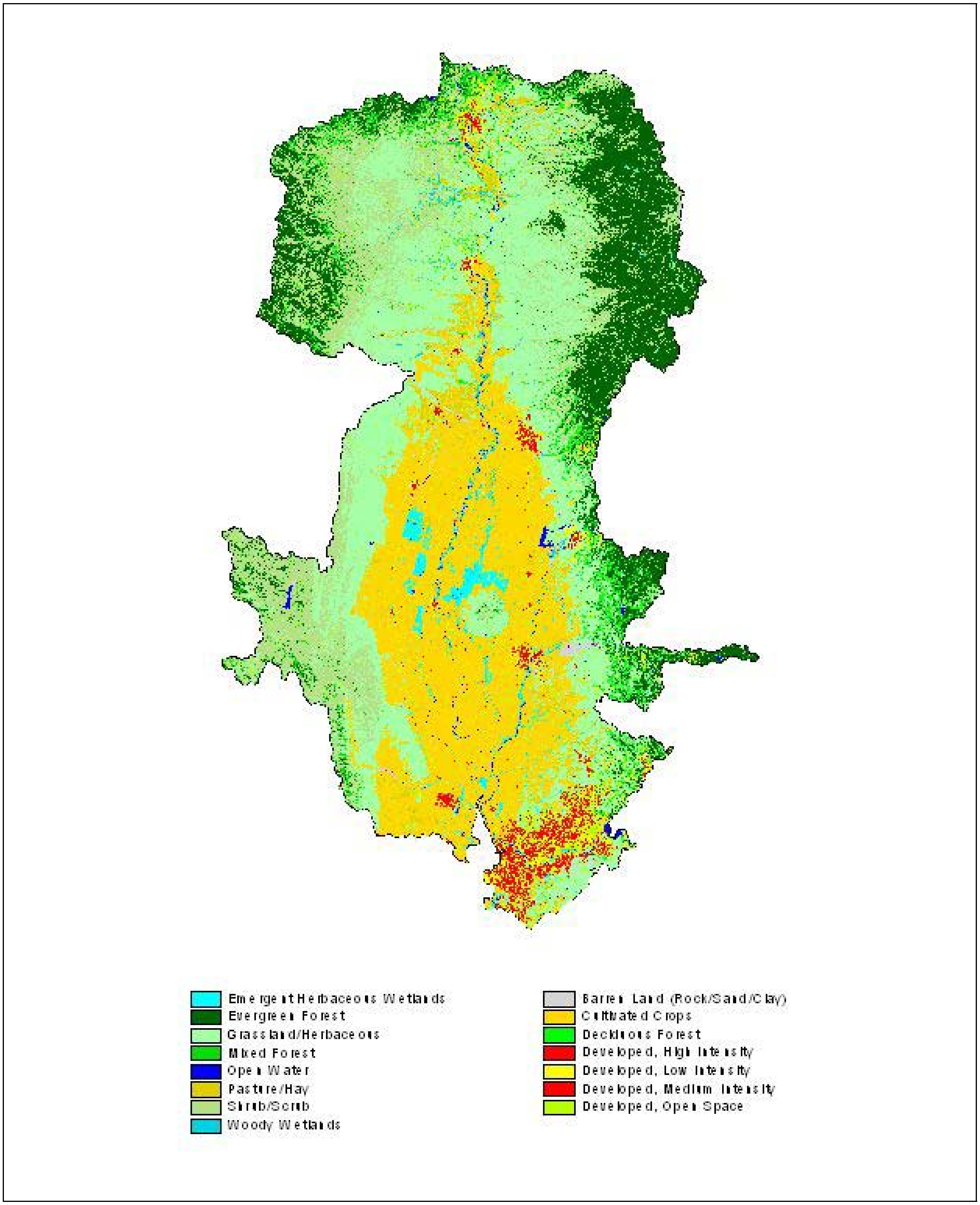

Figure 1-7 National Land Cover Database (NLCD) land use data

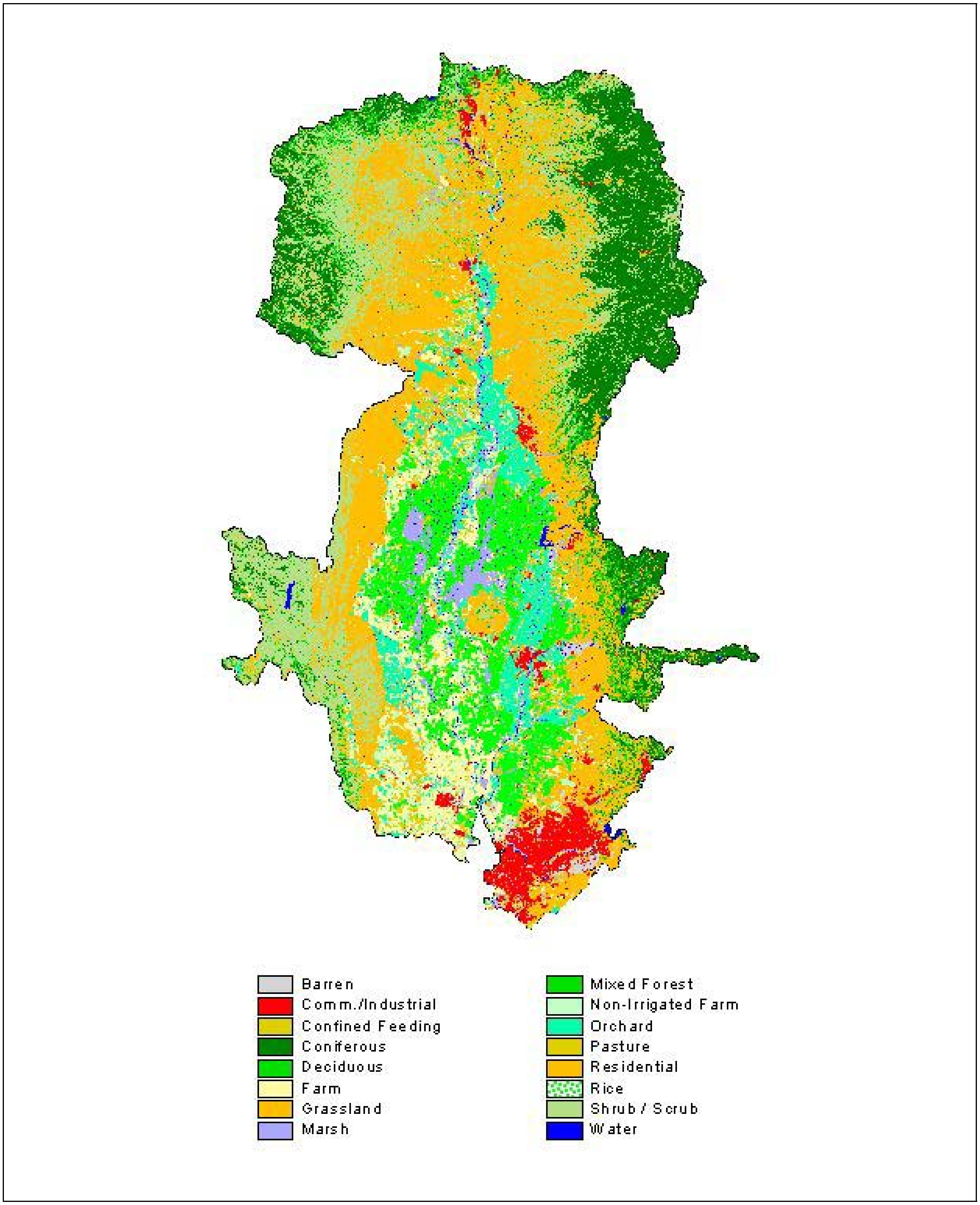

Figure 1-8 Land use data used in the Sacramento River WARMF model

A similar process was used to calculate land uses in the Cache Creek and Putah Creek watersheds combining DWR and NLCD land use databases. Additional resolution of land use classes in the DWR database were kept and additional GIS processing added dairy facilities and the land on which dairy waste is applied.

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 2007 in the project region were collected from the California Irrigation Management Information System (CIMIS), the National Climatic Data Center (NCDC), 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:

$(T_{ave} - T_{dew}) < 4$ ˚C	CC = 0.6
4 ˚C $\leq (T_{ave} - T_{dew}) < 6$ ˚C	CC = 0.3
6 ˚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 43 stations remained for use as input to WARMF. The stations are described in Table 1.3 and their locations are shown in Figure 1-9.

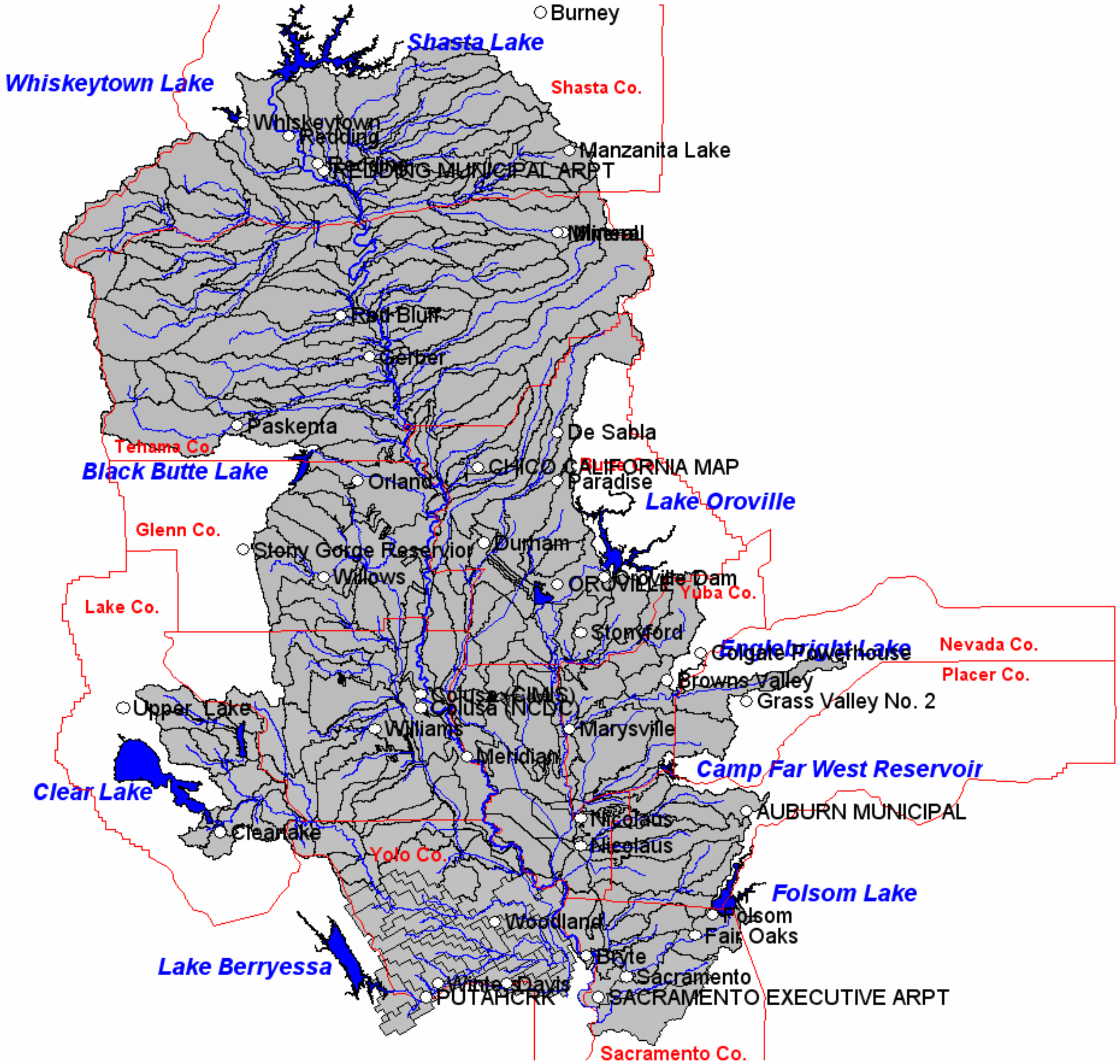

Figure 1-9 Locations of Meteorology Stations in the Sacramento River Watershed

Each land catchment area in WARMF was assigned the nearest of the final 41 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.

Table 1.3 Meteorology Stations used for Input to WARMF

Station name	Mean Annual P, inches	Mean Annual T, ^{o}F
Auburn Municipal	34.0	16.31
Browns Valley	30.3	16.46
Bryte	16.8	16.95
Burney	27.4	8.79
Chico	25.7	16.86
Clearlake	26.7	13.85
Colgate	40.8	16.46
Colusa (CIMIS)	15.9	16.10
Colusa (NCDC)	15.7	16.34
Davis	17.6	15.43
De Sabla	66.8	12.92
Durham	22.0	16.16
Fair Oaks	22.5	16.53
Folsom	22.5	16.53
Gerber	23.0	16.52
Grass Valley	52.8	12.95
Manzanita Lake	41.6	7.01
Marysville	22.6	17.26
Meridian	23.4	15.81
Mineral	54.6	7.13
Mineral II	54.6	7.13
Nicolaus	18.2	16.87
Nicolaus II	18.7	16.80
Orland	21.1	16.59
Oroville	26.7	16.74
Oroville Dam	35.1	16.65
Paradise	53.8	15.62
Paskenta	25.2	16.59
Putah Creek	20.2	15.10
Red Bluff	23.0	17.12
Redding	38.2	16.96
Redding Airport	30.8	17.58
Redding II	38.2	16.96
Sacramento Exec Airport	19.2	16.62
Sacramento (NCDC)	18.1	16.85
Stonyford	22.9	16.75
Stony Gorge	21.0	15.48
Upper Lake	45.6	13.65
Whiskeytown	62.2	15.89
Williams	15.8	16.55
Willows	18.8	16.32
Winters	21.3	17.22
Woodland	18.6	16.58

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) site at Lassen Volcanic 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 four National Atmospheric Deposition Program (NADP) sites in the vicinity of the Sacramento River drainage basin: Hopland, Sagehen Creek, Davis, and Lassen Volcanic National Park. Data from these stations were entered on a weekly basis for input to the WARMF model. The locations of the four sites in relation to the WARMF model domain are depicted in Figure 1-10.

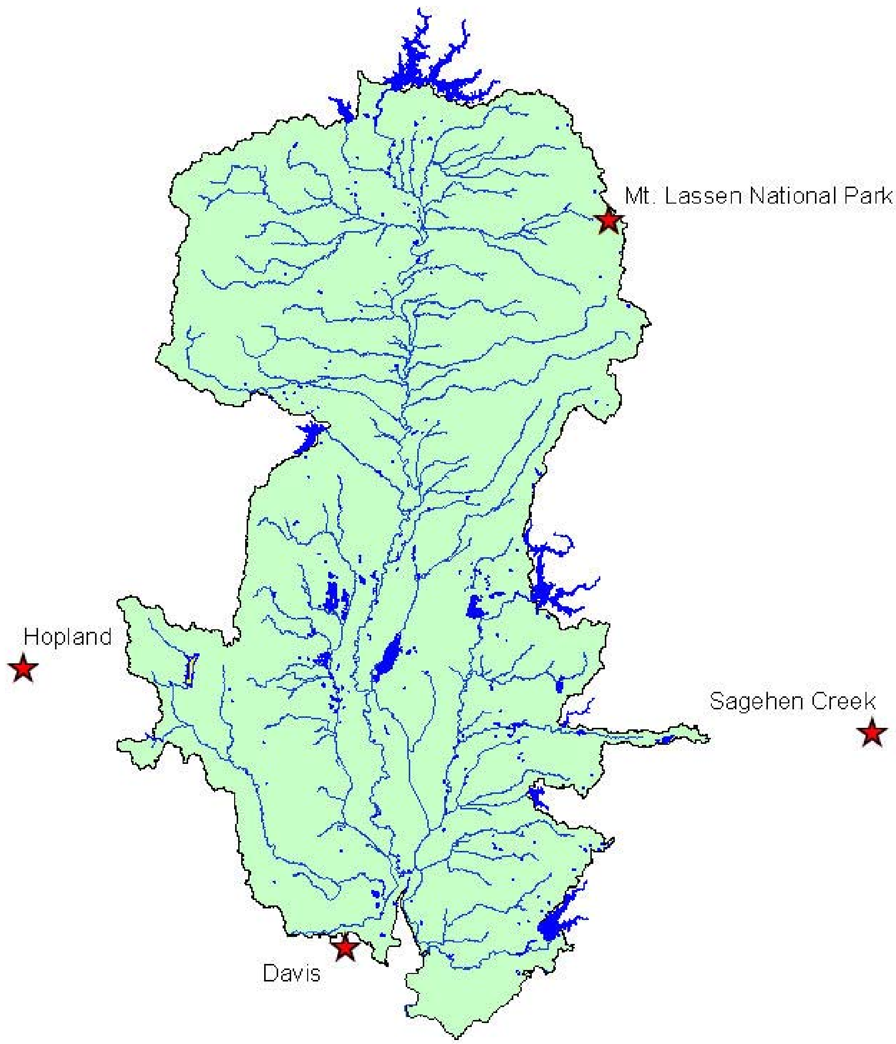

Figure 1-10 Air quality and precipitation chemistry data collection locations in the vicinity of the Sacramento River WARMF model domain.

Boundary River Inflows

Boundary river inflows were external inputs to the WARMF model. These inputs were treated like "point sources", with 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 ten 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 five east side tributaries (Feather River below Lake Oroville, Feather River below Thermolito Afterbay, Yuba River below Englebright Lake, Bear River below Camp Far West Reservoir, and the American River below Folsom Lake).

All available data for daily flow, temperature, and water quality constituent concentrations at the boundary river inflows were collected for the modeling period (1921-2007). Data availability varied greatly between the ten 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 (1970-2007) 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 either a 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 15^{th} of a given month and the 15^{th} 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 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)
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)

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 1921-2007. Information about current population and population growth since 1921 were used to scale values of typical wastewater treatment plant effluent to get appropriate estimates for the Sacramento wastewater treatment plant. 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)
CLEAR CREEK WWTP	CA0079731	Shasta	40.50	-122.37	12.6
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
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
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
AUBURN WWTP	CA0077712	Placer	38.89	-121.10	2.2
PLACER COUNTY SMD 1 WWTP	CA0079316	Placer	38.96	-121.11	2.9
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
CITY OF WOODLAND WWCF	CA0077950	Yolo	38.66	-121.87	8.8
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
ANDERSON WPCP	CA0077704	Shasta	40.47	-122.28
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
COTTONWOOD WWTP	CA0081507	Shasta	40.40	-122.25
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

Name	NPDES	County	Lat	Long
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
COLUSA WWTP	CA0078999	Colusa	39.25	-122.06
MAXWELL PUD	CA0079987	Colusa	39.28	-122.19
CALPINE SUTTER ENERGY CENTER	CA0081566	Sutter	39.11	-121.69
YUBA CITY WWTP	CA0079260	Sutter	39.11	-121.61
LAKE WILDWOOD WWTP	CA0077828	Nevada	39.23	-121.22
NEVADA CITY WWTP	CA0079901	Nevada	39.26	-121.03
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
LINCOLN	CA0084476	Placer	38.90	-121.34
PLACER CO DFS	CA0079367	Placer	38.80	-121.13
PLEASANT GROVE WWTP	CA0084573	Placer	38.79	-121.38
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
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

Name	NPDES	County	Lat	Long
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
CACHE CREEK INDIAN BINGO	CAU000541	Yolo	38.73	-122.14
CHOPAN AUTO DISMANTLING	CAU000665	Yolo	38.58	-121.55
CITY OF DAVIS STP	CA0079049	Yolo	38.59	-121.67
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 practice in Yolo County as part of the Central Valley Salinity Coalition project (Larry Walker & Associates 2010). The nitrogen and phosphorus application rates used are shown in Table 1.7.

Table 1.7 Land Application Rates

Land Use	Nitrogen Application Rate, lb/acre/yr	% Nitrate	Phosphorus Application Rate, lb/acre/yr	Application Season
Deciduous Forest	0			
Mixed Forest	0			
Evergreen Forest	0			
Orchard	25	70%	6.2	5/1 - 9/30
Row Crops	120	70%	6.2	5/1 - 9/30
Rice	120	0%	26.8	4/1 - 6/30
Fallow	0			
Shrub/Scrub	0			
Grassland/Herbaceous	0			
Marsh	0			
Barren land	0			
Confined Feeding	482	49%	22.4	1/1 - 12/31
Water	0			
Urban residential	84	50%	0.0	5/1 - 9/30
Urban commercial/industrial	48	50%	0.0	5/1 - 9/30
Urban C&I, low impervious[1]	80	50%	0.0	5/1 - 9/30
Urban landscape[1]	48	50%	0.0	5/1 - 9/30
Paved areas[1]	0			
Sewage plant incl. ponds[1]	0			
Dairy Facility[1]	481	49%	23.8	1/1 - 12/31
Dairy Lagoon[1]	686	0%	186.7	1/1 - 12/31
Land constr. dairy land app. [1]	4,862	5%	758.5	5/1 - 9/30
Unconstr. dairy land app. [1]	2,591	5%	408.4	5/1 - 9/30
Resting dairy land app. [1]	1,945	5%	291.7	5/1 - 9/30
Farmsteads[1]	120	50%	0.0	5/1 - 9/30
Olives, citrus & subtropicals[1]	100	70%	17.8	5/1 - 9/30
Vines[1]	40	70%	17.8	5/1 - 9/30
Flowers and nursery[1]	150	30%	6.2	5/1 - 9/30
Cotton[1]	120	100%	6.2	5/1 - 9/30
Perennial forages[1]	25	0%	0.0	5/1 - 9/30
Warm season cereals/forages[1]	120	70%	6.2	5/1 - 9/30
Winter grains & safflower[1]	39	100%	10.0	10/1 - 6/30

1 These land uses are only used in the Cache Creek and Putah Creek watersheds

Irrigation Water Distribution

Irrigation from 51 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
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
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
Oji Brothers Farm, Inc.	Sacramento River upstream of Verona
Olive Percy Davis (Davis Ranches)	Colusa Basin Drainage Canal, Sacramento River upstream of Verona
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

Irrigation District Name	Water Source
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, 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
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 1-11. 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.

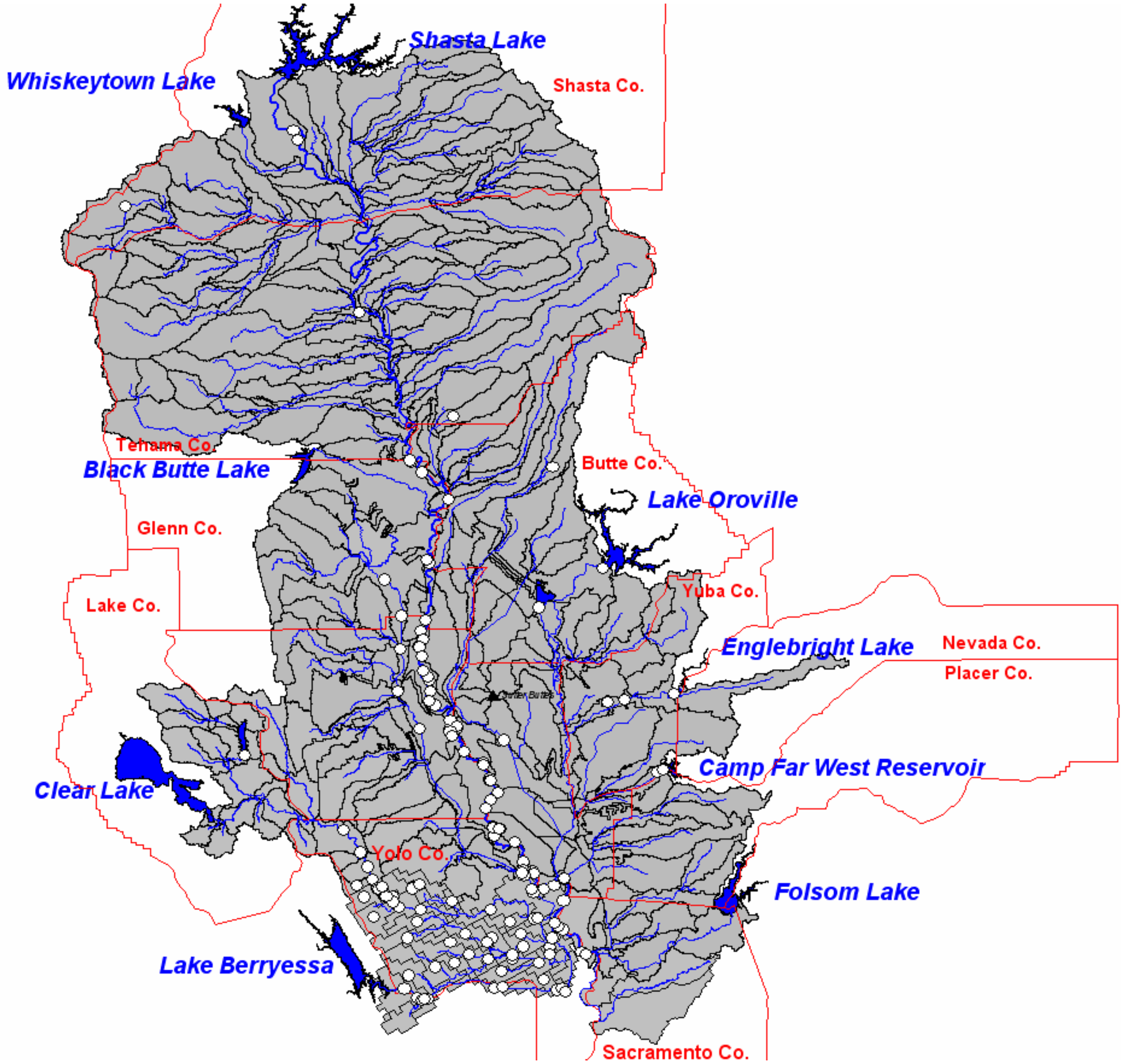

Figure 1-11 Locations (as indicated by the white dots) of water diversions from the Sacramento River and its tributaries.

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
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
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
Oji Brothers Farm, Inc.	Jan 1993 - Dec 2007	10.0
Olive Percy Davis	Jan 1993 - Dec 2004	66.4
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
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

Diversion	Data Available	Average Diversion Flow (ft^3/sec)
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
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 are shown in Table 1.10.

Table 1.10 Applied Water Rates

Land Use	Applied Water, ft/yr
Deciduous Forest	0
Mixed Forest	0
Evergreen Forest	0
Orchard	4.17
Row Crops	3.19
Rice	5.36
Fallow	0
Shrub/Scrub	0
Grassland/Herbaceous	0
Marsh	0
Barren land	0
Confined Feeding	0
Water	0
Urban residential	5.51
Urban commercial/industrial	5.51
Urban commercial/industrial, low impervious[1]	5.51
Urban landscape[1]	5.51
Paved areas[1]	0
Sewage plant incl. ponds[1]	0
Dairy Facility[1]	0
Dairy Lagoon[1]	0.14
Land constrained dairy land application [1]	0.61
Unconstrained dairy land application [1]	0.61
Resting dairy land application [1]	0.61
Farmsteads[1]	5.51
Olives, citrus & subtropicals[1]	3.82
Vines[1]	1.88
Flowers and nursery[1]	4.14
Cotton[1]	3.24
Perennial forages[1]	5.51
Warm season cereals/forages[1]	1.98
Winter grains & safflower[1]	0.61

1 These land uses are only used in the Cache Creek and Putah Creek watersheds

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 first toward irrigation demand. 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 numerical values 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 simulation, 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 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.

There are thousands of model coefficients in the San Joaquin River WARMF model. Some apply throughout the watershed, some apply to individual land uses while other coefficients apply to individual catchments and river segments. The model was not very sensitive to the values of a majority of the coefficients, so those could be safely be left at default literature values unless there was specific information to enter.

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	Net creation of vegetation	Ratio of leaf area to land area (varies monthly)
Range	0 - 1	0 - 1	0 – 2.02	0-4.5
Deciduous Forest	0	0.01	0.8	0-4.5
Mixed Forest	0	0.03	0.8	
Evergreen Forest	0	0.05	0.8	
Orchard	0	0.1	0.44	
Row Crops	0	0.5	0.56	
Rice	0	0.01-1	0.95	
Fallow	0	0.1	0.1	
Shrub/Scrub	0	0.1	0.3	
Grassland/Herbaceous	0	0.1	0.1	
Marsh	0	0	0.8	
Barren land	0	1	0	
Confined Feeding	0	1	0	
Water	1	0	0	
Urban residential	0.3	0.2	0.22	
Urban commercial/industrial	0.6	0	0.22	
Urban C/I, low impervious[1]	0.3	0	0.22	
Urban landscape[1]	0	0	0.22	
Paved areas[1]	1	0	0	
Sewage plant incl. ponds[1]	0.4	0	0	
Dairy Facility[1]	0.35	0	0	
Dairy Lagoon[1]	0	0	0	
Land constrained dairy land app. [1]	0	1	1.79	
Unconstrained dairy land app. [1]	0	1	1.79	
Resting dairy land application [1]	0	1	1.79	
Farmsteads[1]	0.1	0.2	0.22	
Olives, citrus & subtropicals[1]	0	0.1	0.9	
Vines[1]	0	0.1	0.87	
Flowers and nursery[1]	0.1	0.5	0.45	
Cotton[1]	0	0.5	0.3	
Perennial forages[1]	0	0.1	1.79	
Warm season cereals/forages[1]	0	0.5	2.02	
Winter grains & safflower[1]	0	0.5	0.67	

1 These land uses are only used in the Cache Creek and Putah Creek watersheds

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 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 301 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 masked. 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	> 0
Layer 2 Horizontal hydraulic conductivity	cm/d	> 0
Layer 3 Horizontal hydraulic conductivity	cm/d	> 0
Layer 1 Vertical hydraulic conductivity	cm/d	> 0
Layer 2 Vertical hydraulic conductivity	cm/d	> 0
Layer 3 Vertical hydraulic conductivity	cm/d	> 0
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 is setting 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 data was available to calculated 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

Sediment transport in rivers is affected by the settling rates shown above but also 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 where a is the multiplier and b is the exponent. For all river segments, $a=1.0\times10^{-6}$ 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 26 streamflow gaging stations on headwater tributaries within the Sacramento River Watershed where simulated flow could be compared to observed data for model calibration. These 26 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
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

Some representative calibration results are shown in Figure 2-1 through Figure 2-6 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 does not always occur due to a combination of model error, input data error, and streamflow measurement error. During the 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 including salinity and organic carbon. In rivers with highly variable flow, R squared 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 very high 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 all 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 I street bridge in Sacramento, calibration of the tributary flows is coarse. Further calibration could be used to increase model accuracy in individual tributaries.

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 Cow Creek, Cottonwood Creek, Battle Creek, Mill Creek), a consistent pattern of significant seasonal runoff is evident and is generally well simulated by the model. Baseflow drops to near zero but continues in these watersheds during the dry season, with few or no peaks. An exception is Battle Creek, where 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 2-5 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 the mainstem of the Sacramento River, since a large majority of streamflow in the river results from reservoir outflow from the eight major upstream and tributary reservoirs.

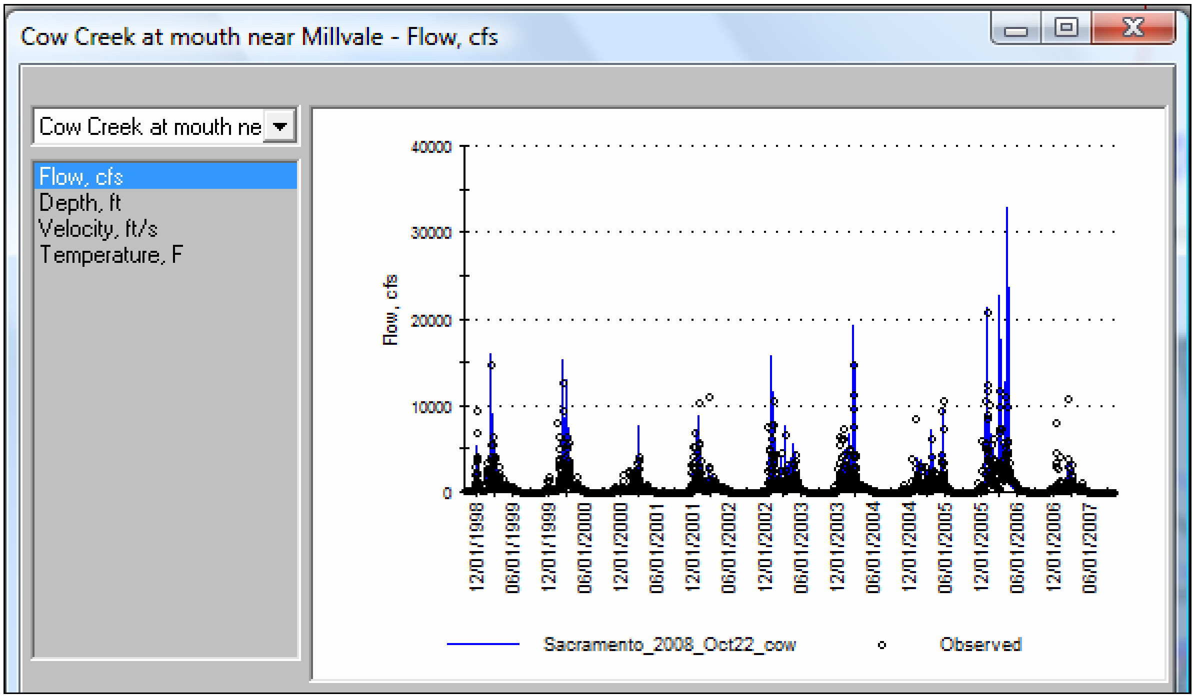

Figure 2-1 Simulated vs Observed Flow at Cow Creek near Millvale

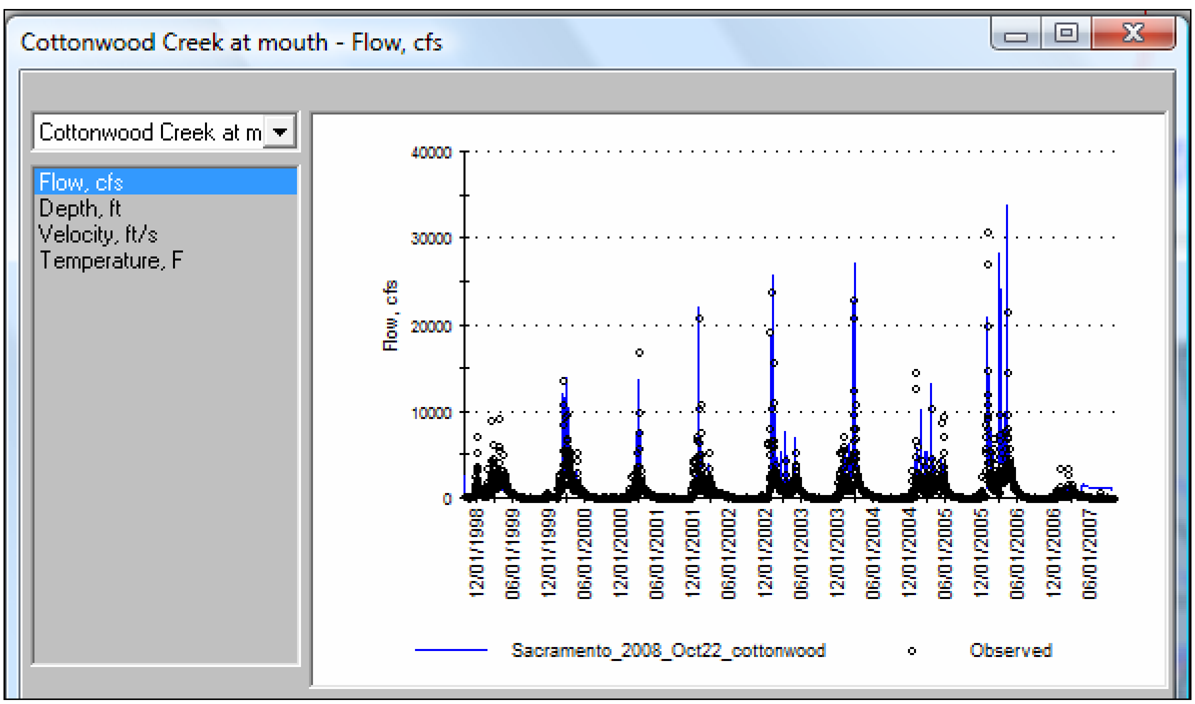

Figure 2-2 Simulated vs Observed Flow at Cottonwood Creek at Mouth

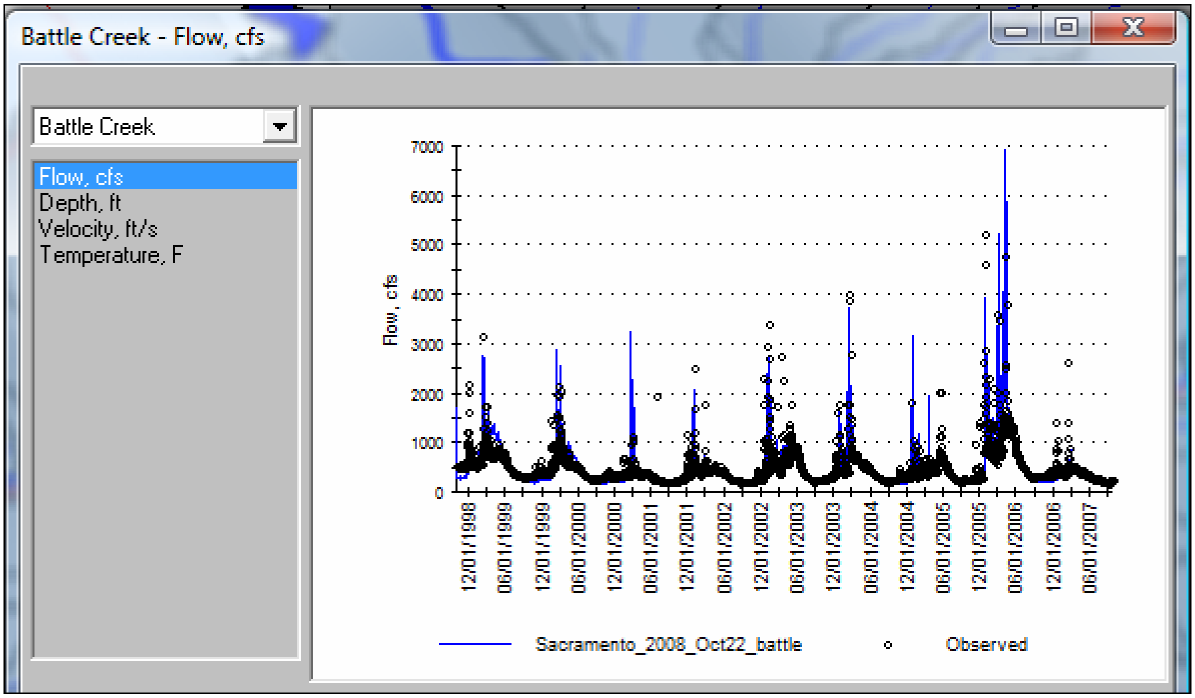

Figure 2-3 Simulated vs Observed Flow at Battle Creek

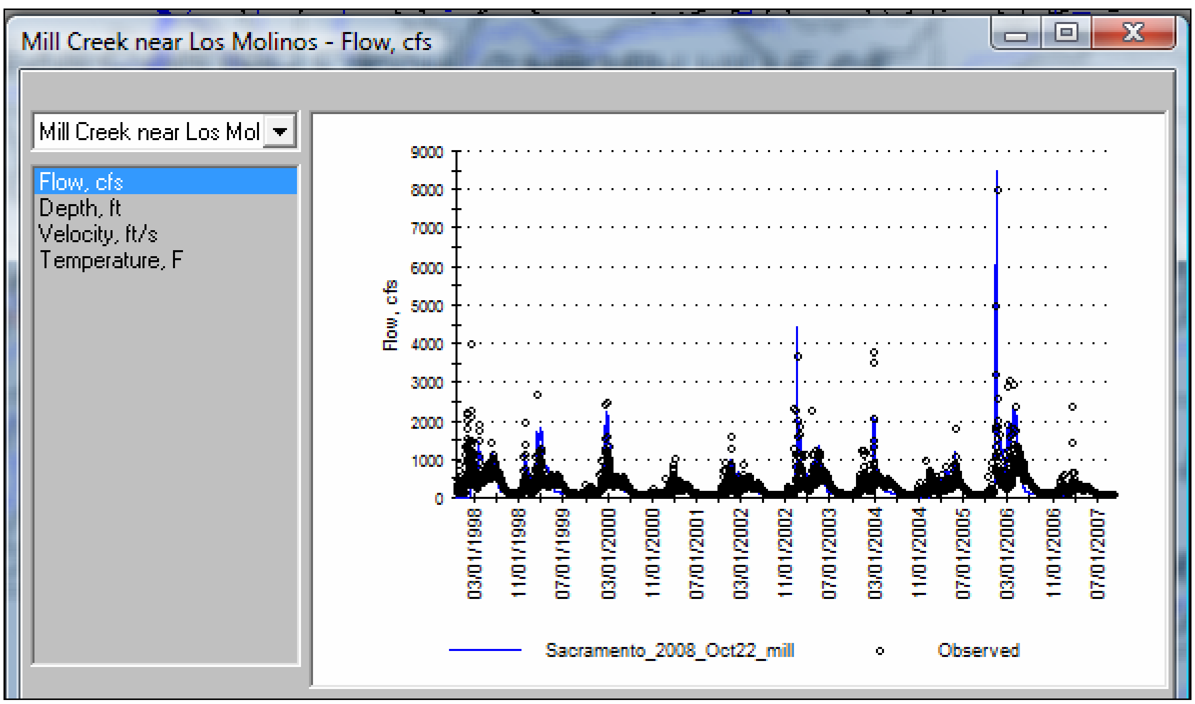

Figure 2-4 Simulated vs Observed Flow at Mill Creek near Los Molinos

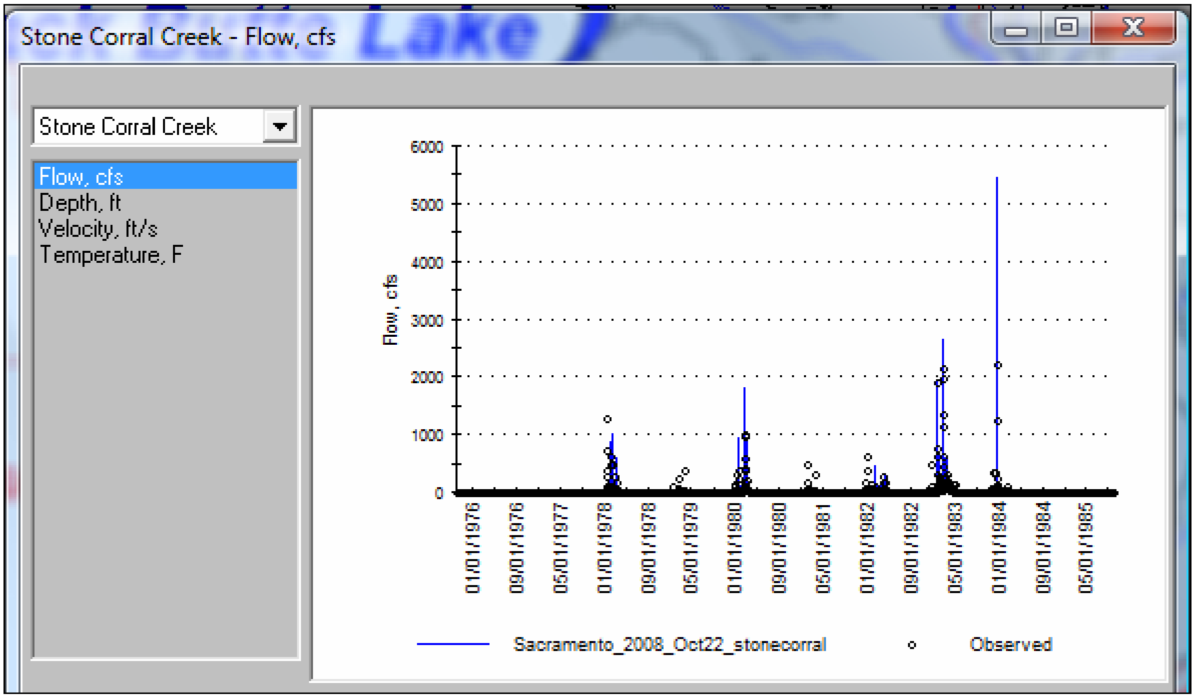

Figure 2-5 Simulated vs Observed Flow at Stone Corral Creek

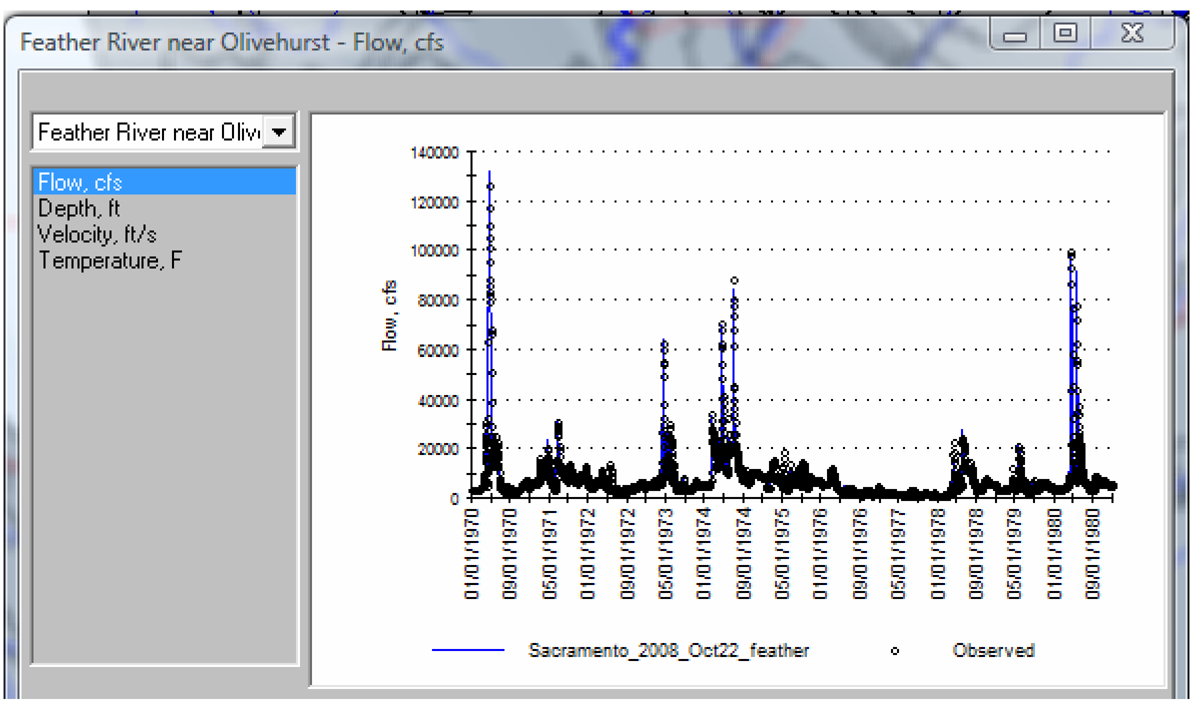

Figure 2-6 Simulated vs Observed Flow at Feather River near Olivehurst

Table 2.9 Flow Calibration Statistics for Sacramento River Tributaries

Gaging Station	% Relative Error	% Absolute Error	R squared
Cow Creek near Millvale	4.9	57	0.564
Cottonwood Creek Near Cottonwood	17.2	66	0.607
Battle Creek near Cottonwood	-4.5	29	0.625
Red Bank Creek near Red Bluff	32.5	103	0.355
Elder Creek near Paskenta	9.0	78	0.295
Paynes Creek near Red Bluff	-1.25	79	0.378
Antelope Creek near Red Bluff	22.1	64	0.683
Mill Creek near Los Molinos	-1.3	66	0.439
Thomes Creek at Paskenta	-12.7	86	0.339
Deer Creek near Vina	44	88	0.419
Mud Creek near Chico	-1.7	61	0.605
Stony Creek near Hamilton	18.8	25	0.977
Walker Creek at Artois	15.1	121	0.330
Big Chico Creek near Chico	15.8	72	0.393
South Fork Willow Creek near Fruto	68	190	0.194
Butte Creek near Chico	7.5	69	0.303
Stone Corral Creek near Sites	101	158	0.640
Bear Creek near Rumsey	4.1	99	0.275
Cache Creek at Yolo	9.7	57	0.368
Feather River below Shanghai Bend	0.8	7.4	0.970
North Horncut Creek near Bangor	-0.2	99	0.318
South Horncut Creek near Bangor	8.6	85	0.435
Deer Creek near Smartville	39	91	0.447
Dry Creek near Wheatland	4.8	139	0.033
Dry Creek at Vernon St Br at Roseville	-15	62	0.735
Arcade Creek near Del Paso Heights	90	123	0.682

Hydrologic calibration of the Sacramento River main stem was performed after calibration of its tributaries. There were 8 streamflow gaging stations on the Sacramento River where simulated flow could be compared to observed data for model calibration. These stations are listed below in Table 2.10. Additional calibration results for the Cache Creek and Putah Creek watersheds are in the CV-SALTS pilot study final report (Larry Walker & Associates 2010).

Table 2.10 Sacramento River Streamflow Stations

Gaging Station	Years calibrated
Sacramento River at Bend Bridge	1971-2007
Sacramento River at Vina Bridge	1971-1980, 1991-2007
Sacramento River at Hamilton City	1971-1980, 1991-2007
Sacramento River at Ord Ferry	1984-2007
Sacramento River at Butte City	1971-1995, 1998-2007
Sacramento River at Colusa	1984-2007
Sacramento River below Wilkins Slough	1971-2007
Sacramento River at Verona	1971-2007

Calibration results for these stations are shown in Figure 2-7 through Figure 2-14. Simulation results are shown in blue lines and observed data in black circles. Simulation results at six of the eight gaging stations have relative error under 10% and absolute error under 20% as shown in Table 1.1.

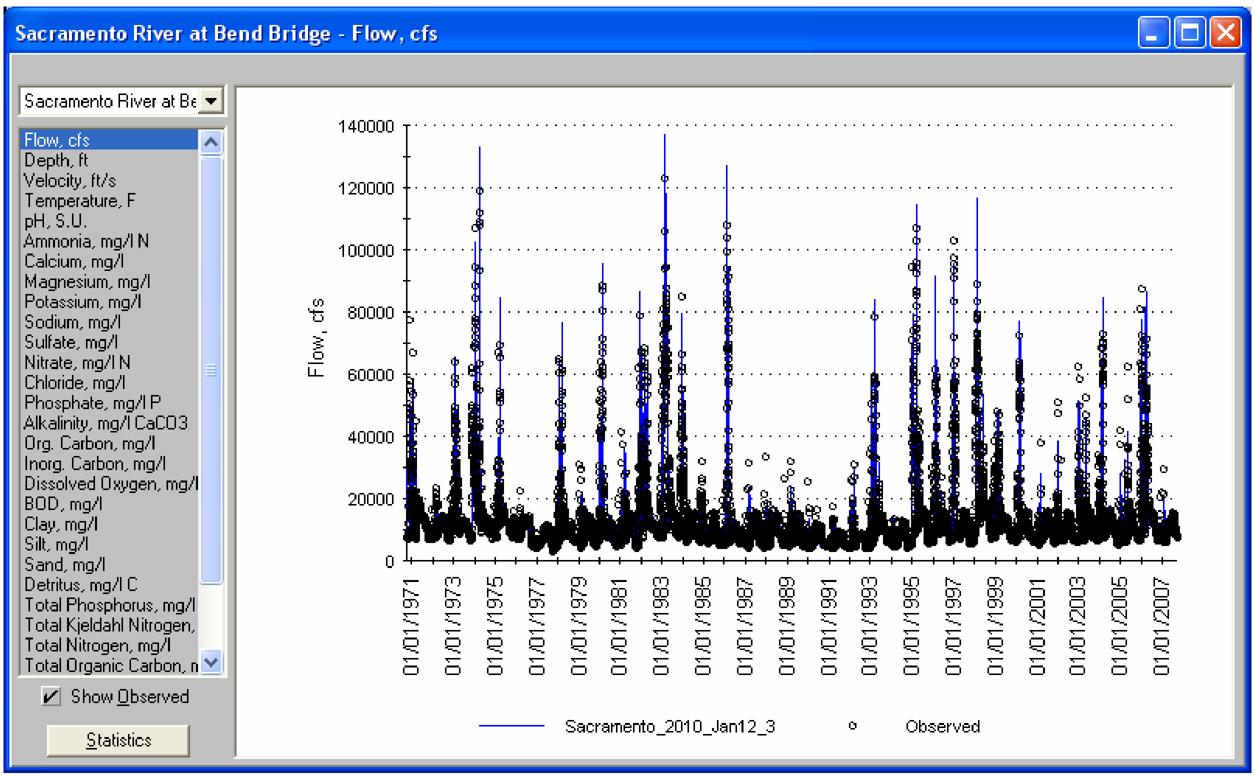

Figure 2-7 Simulated vs Observed Flow at Sacramento River at Bend Bridge

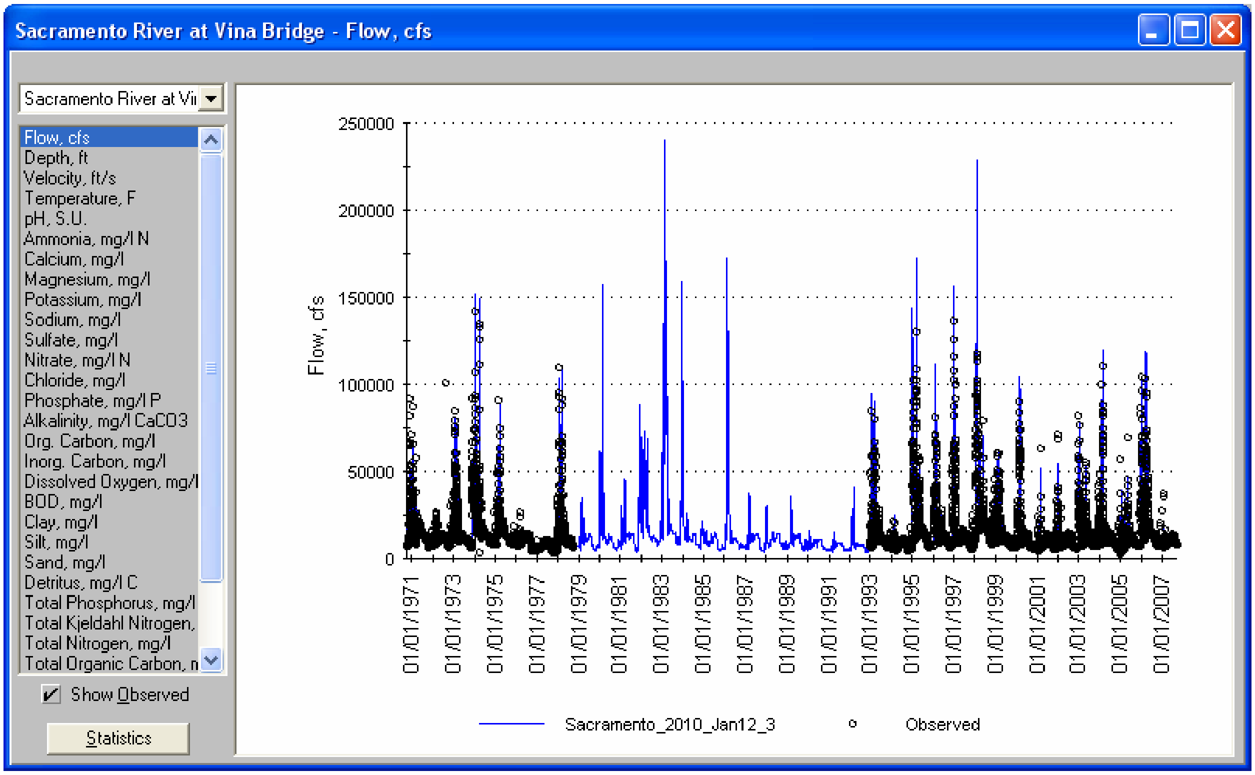

Figure 2-8 Simulated vs Observed Flow at Sacramento River at Vina Bridge

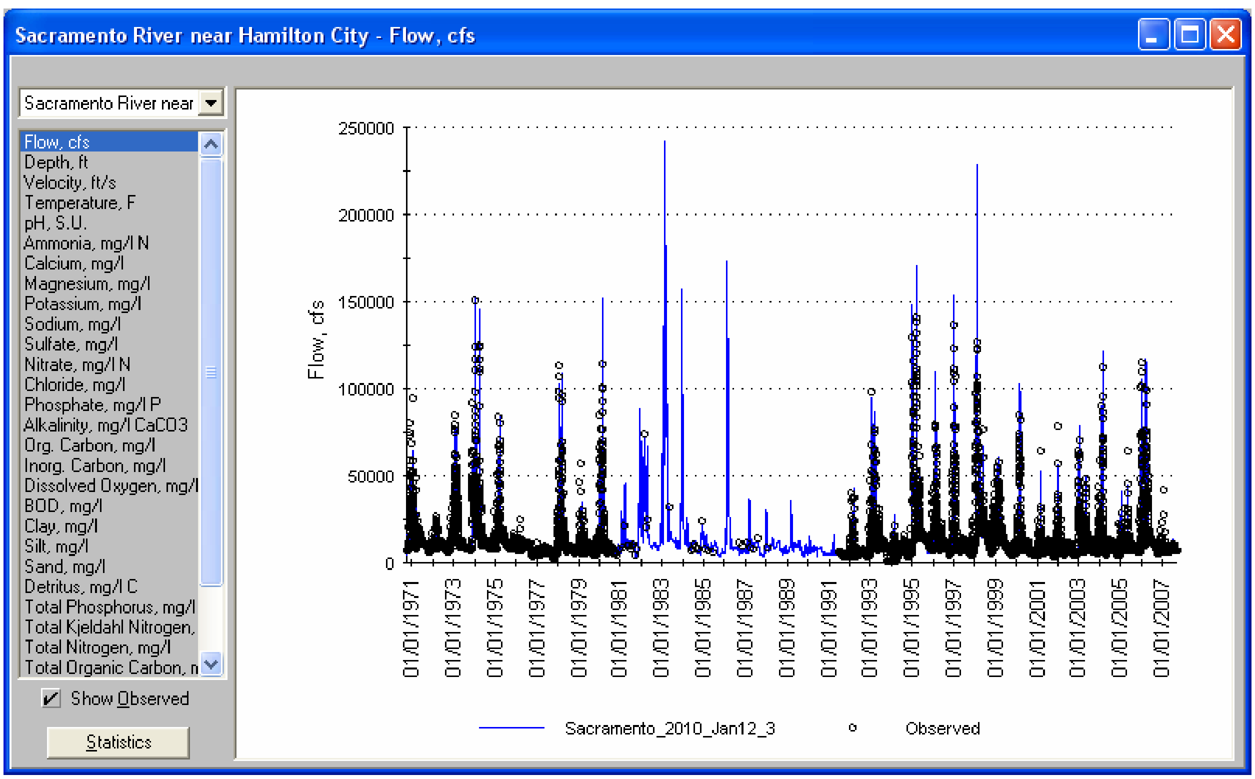

Figure 2-9 Simulated vs Observed Flow at Sacramento River at Hamilton City

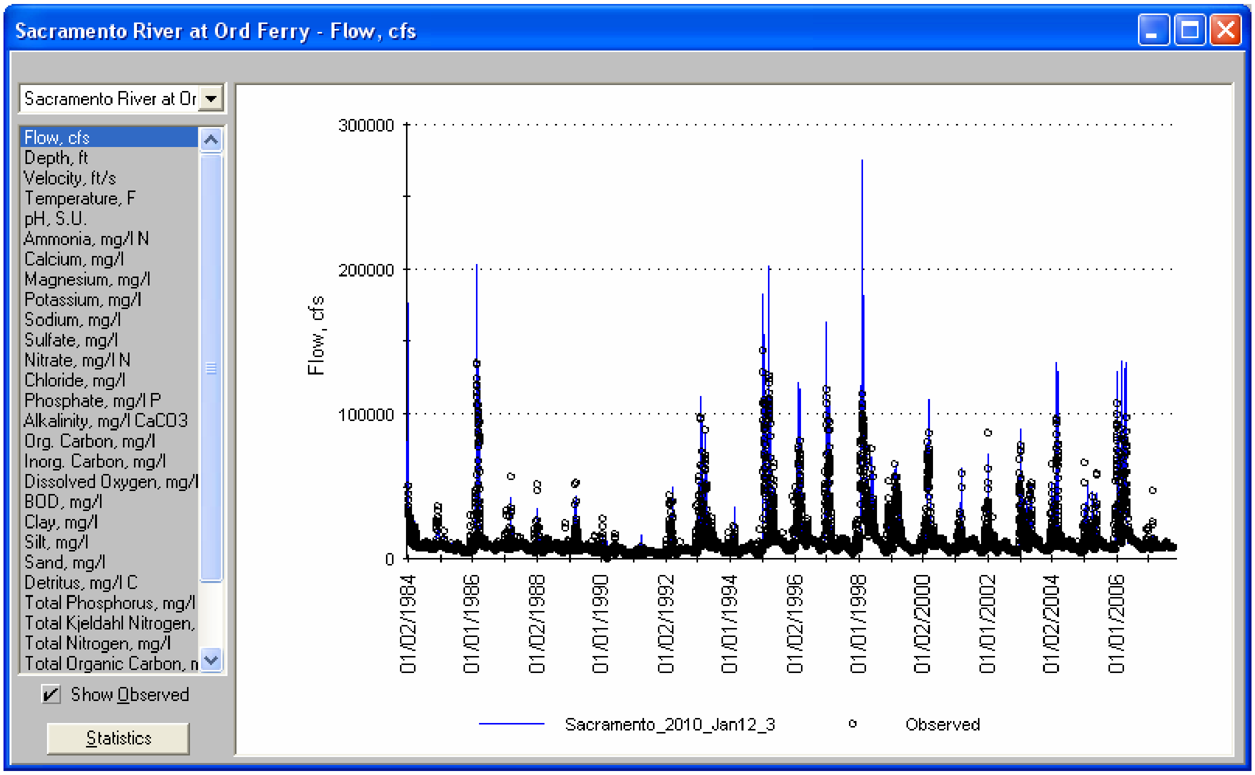

Figure 2-10 Simulated vs Observed Flow at Sacramento River at Ord Ferry

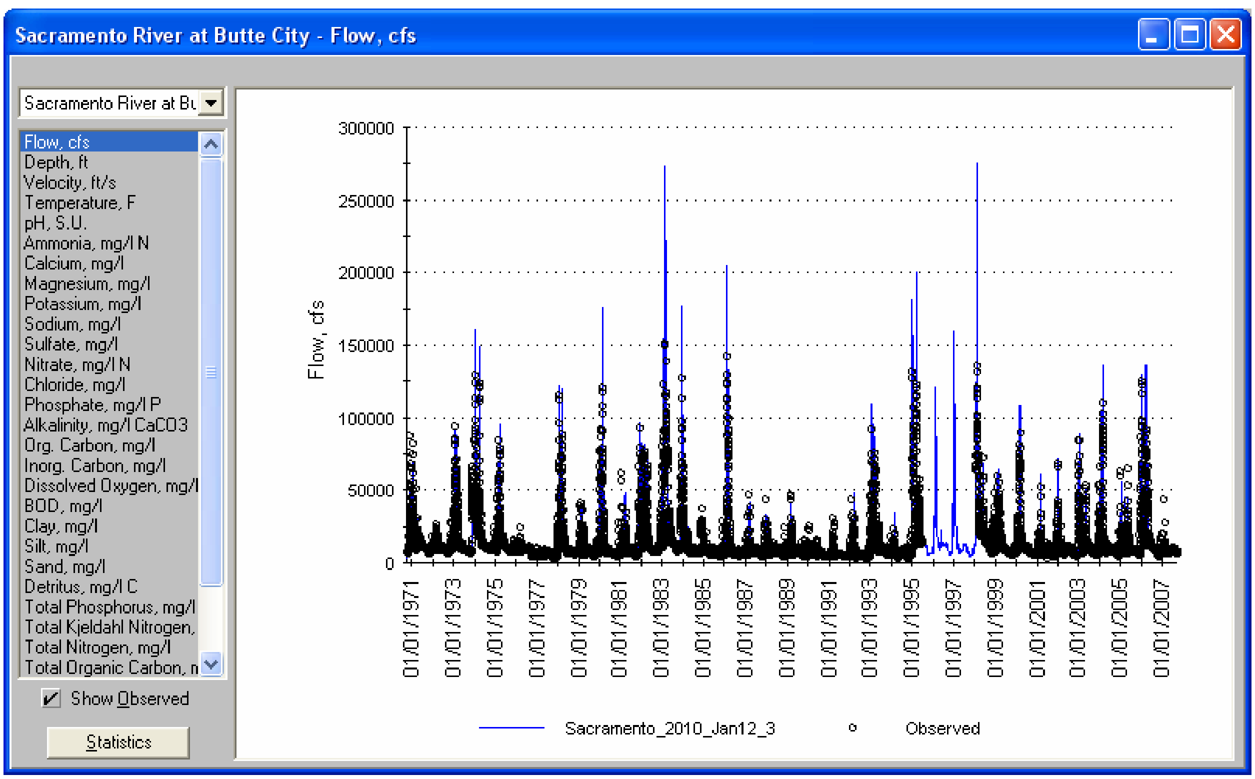

Figure 2-11 Simulated vs Observed Flow at Sacramento River at Butte City

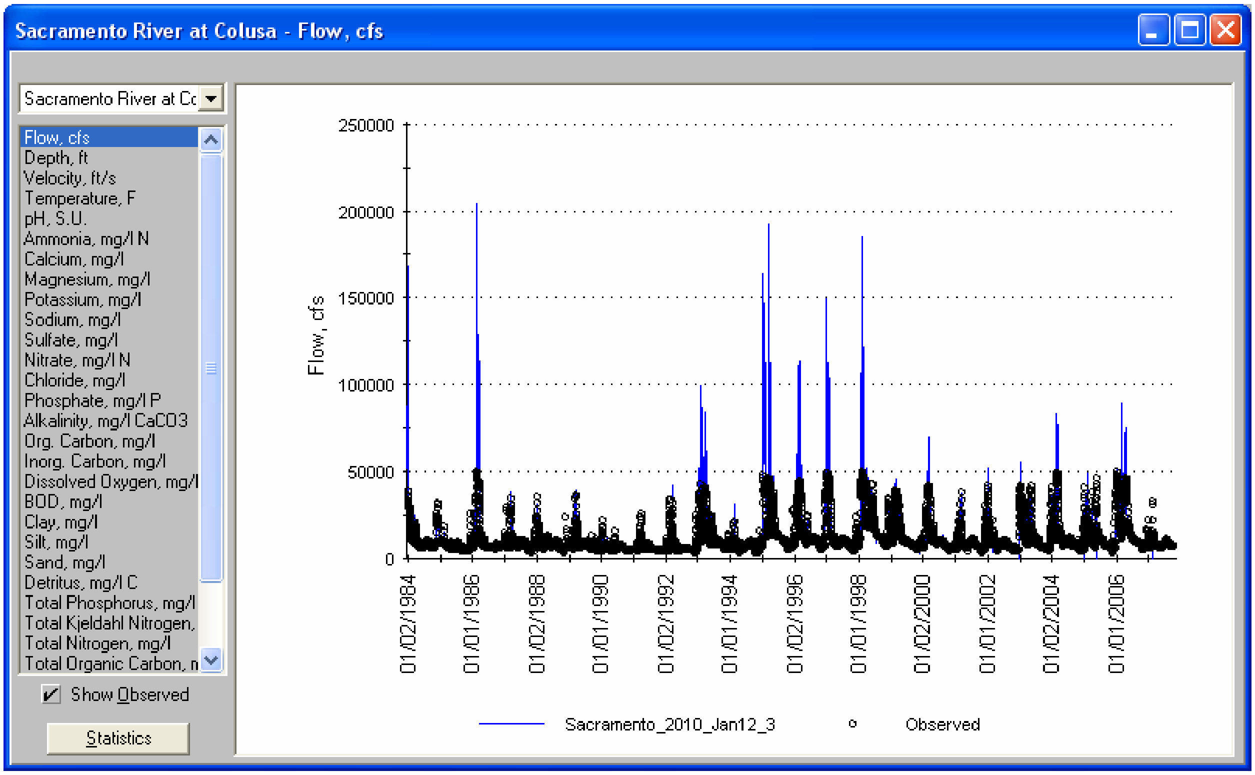

Figure 2-12 Simulated vs Observed Flow at Sacramento River at Colusa

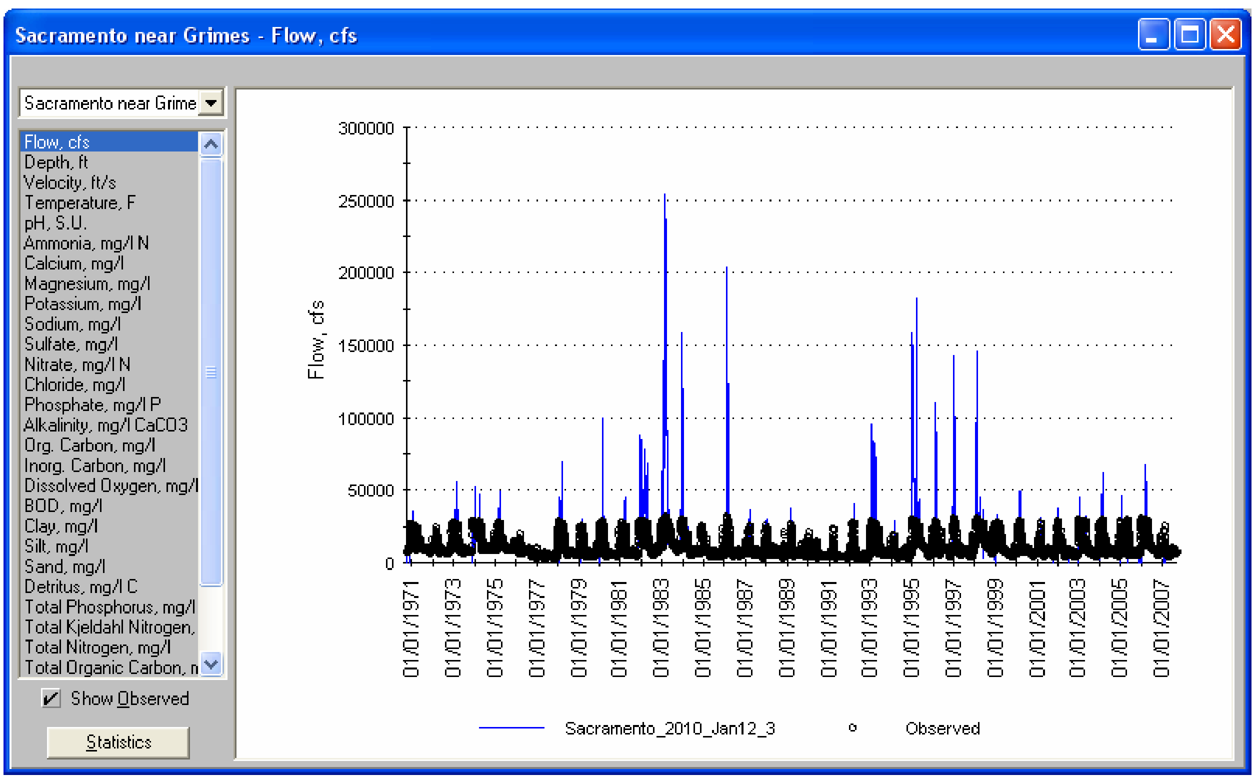

Figure 2-13 Simulated vs Observed Flow at Sacramento River below Wilkins Slough

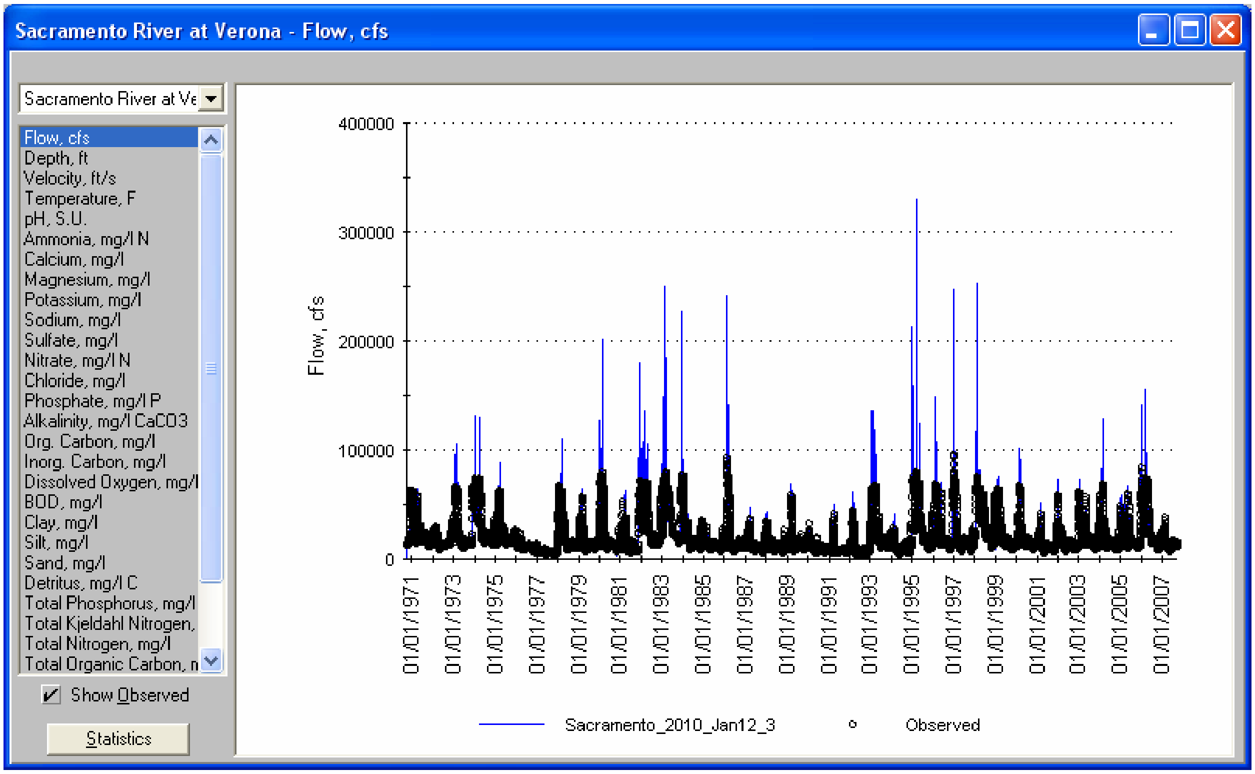

Figure 2-14 Simulated vs Observed Flow at Sacramento River at Verona

Flow is simulated very well at each of the Sacramento River gages The primary source of error at the more downstream stations is during early spring flood flows. 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 is simulating more flow in the Sacramento River proper instead of having that flow routed over the weirs to the Butte Sink and Sutter Bypass. Model errors are reduced at Verona, downstream of the Fremont Weir where flow records are more complete. Simulation of flow closely follows the observed data outside of the late winter / early spring flood season when the weirs are operating.

Table 2.11 Flow Calibration Statistics for Sacramento River Main Stem

Gaging Station	% Relative Error	% Absolute Error	R squared
Sacramento River at Bend Bridge	+0%	8%	0.949
Sacramento River at Vina Bridge	+2%	14%	0.901
Sacramento River at Hamilton City	+3%	16%	0.909
Sacramento River at Ord Ferry	+8%	19%	0.906
Sacramento River at Butte City	+7%	17%	0.904
Sacramento River at Colusa	+14%	26%	0.670
Sacramento River blw Wilkins Slough	+16%	33%	0.504
Sacramento River at Verona	+1%	18%	0.751

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, 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.

Thirty-three water quality stations were used to set the 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 2.12. 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 2-15.

Table 2.12 Water Quality Monitoring Stations

River	Location	WARMF Subwatershed	Water Chemistry Data Collection Period(s)					
			Begin	End	Begin	End	Begin	End
American	at river mouth		1973	1987				
American	Sacramento		1973	1980	1995	1998		
Battle Creek	Cottonwood	Bend Bridge	1959	1966				
Bear Creek	Rumsey		1991	2002				
Bear River	at river mouth		2001	2004				
Big Chico Creek			1960	1979				
Cache Creek	Capay		1951	1976				
Cache Creek	Rumsey		1976	1981	1995	2001		
Clear Creek	at river mouth	Bend Bridge	1997	2008				
Colusa Drain	Highway 20		1960	1979				
Colusa Drain	Knights Landing		1996	2000				
Cottonwood Creek	upstream of South Fork		1981	1985				
Elder Creek	Gerber	Hamilton	1960	1966				
Elder Creek	Paskenta	Hamilton	1958	1966				
Feather River	Gridley		1967	1971	1976	1980		
Feather River	Nicholaus		1960	1966	1995	2000		
Feather River	Shanghai Bend		1960	1966				
Lower Thomes Creek		Hamilton	1960	1966				
Mill Creek			1960	1978				
North Fork Cache Creek	Lower Lake		1950	1980				
North Fork Cottonwood Creek		Bend Bridge	1960	1963	1981	1985		
Red Bank Creek		Hamilton	1960	1966				
Sacramento	Bend Bridge	Bend Bridge	1976	1980	1995	1999		
Sacramento	Colusa		1959	1980				
Sacramento	Colusa Drain		1970	1979				
Sacramento	Fremont Weir		1954	1960	1971	1973		
Sacramento	Grimes		1961	1963				
Sacramento	Hamilton City	Hamilton	1950	1980				
Sacramento	Sacramento		1950	1960	1976	1977		
Sacramento	Verona		1968	1970	1995	1998		
Upper Deer Creek			1995	1997				
Yuba	downstream of Dry Creek		1960	1966	1972	1980	1995	2004
Yuba	Smartville		1960	1966				

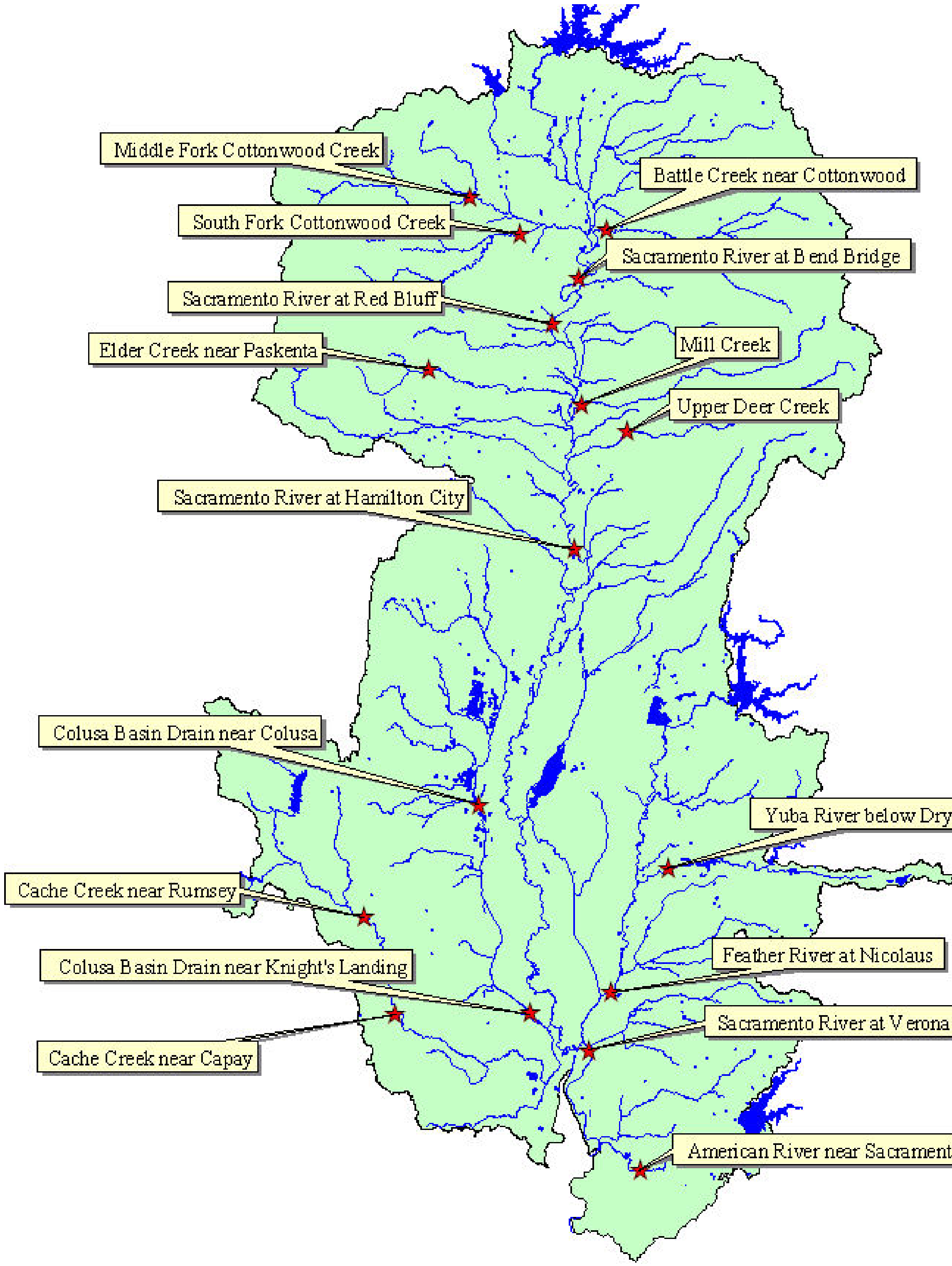

Figure 2-15 Locations of Water Quality Monitoring Stations

The following sections describe the calibration results for the water quality parameters of interest at the sites illustrated in Figure 2-15. 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 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 2-16 through Figure 2-22 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.

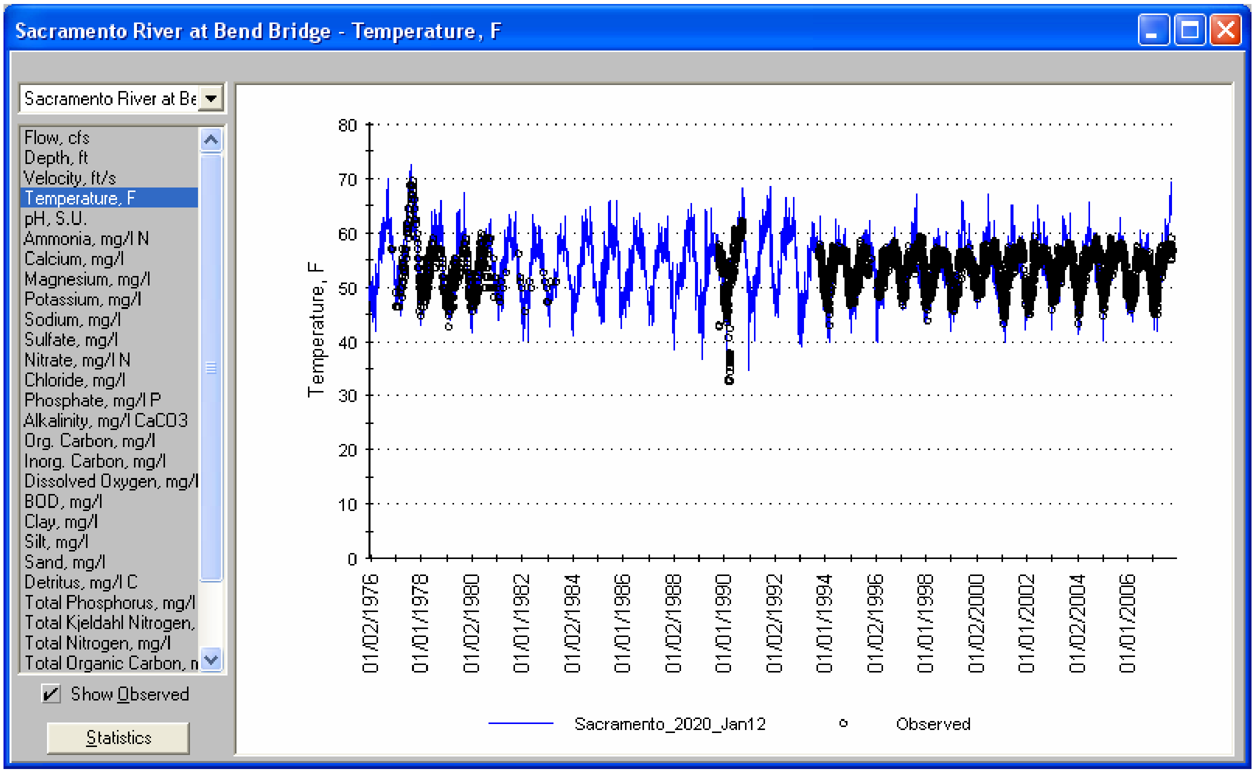

Figure 2-16 Simulated and observed temperature at Sacramento River at Bend Bridge

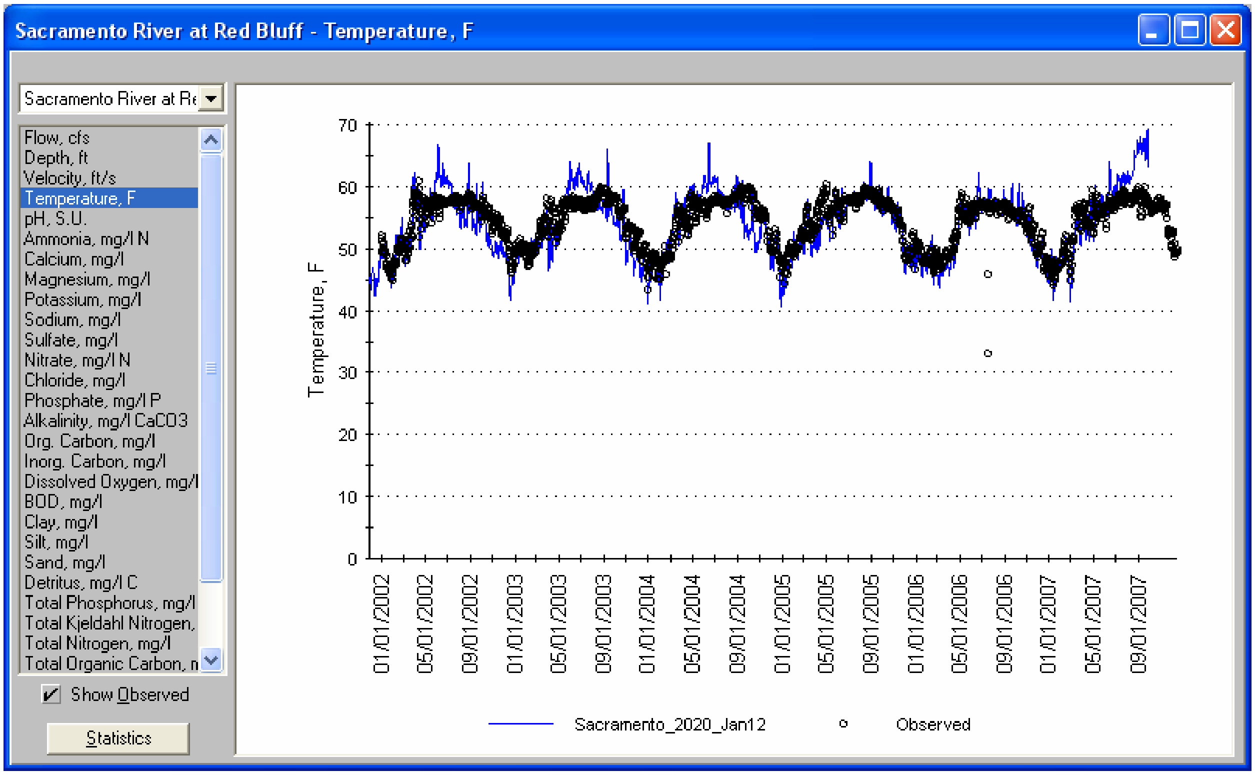

Figure 2-17 Simulated and observed temperature at Sacramento River at Red Bluff

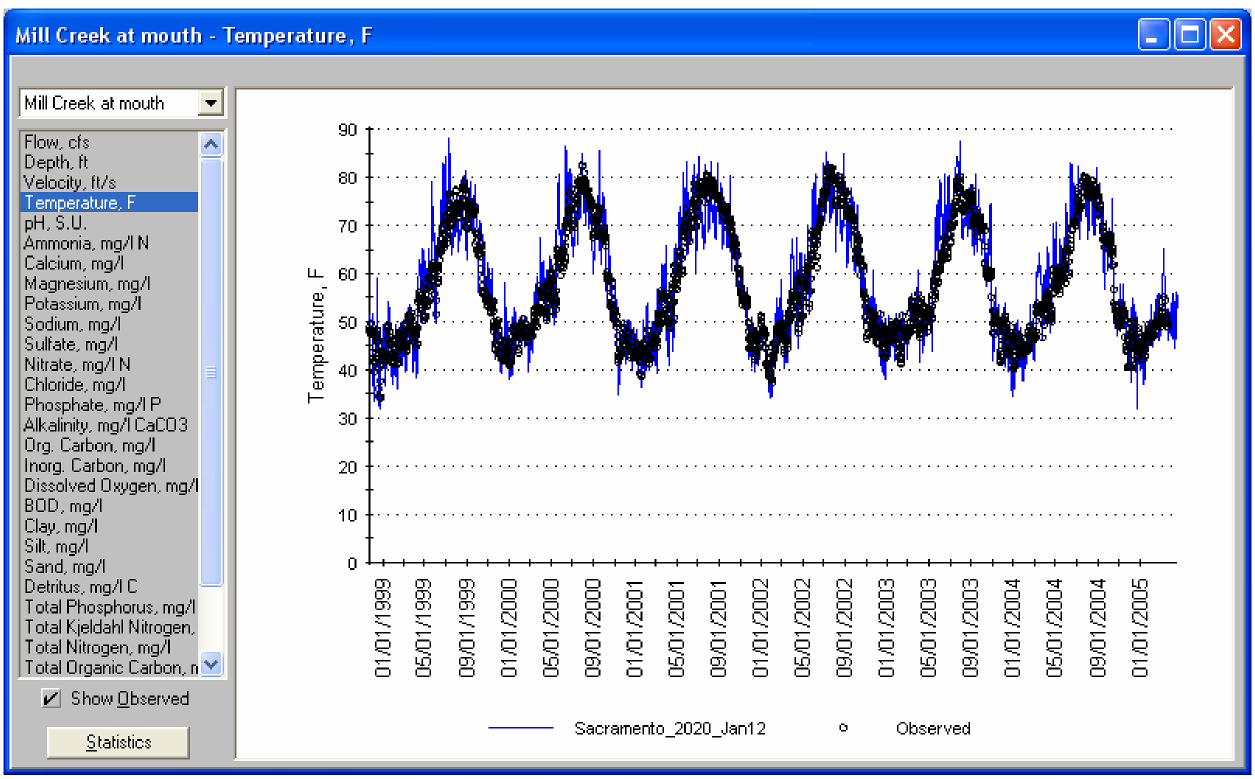

Figure 2-18 Simulated and observed temperature at Mill Creek

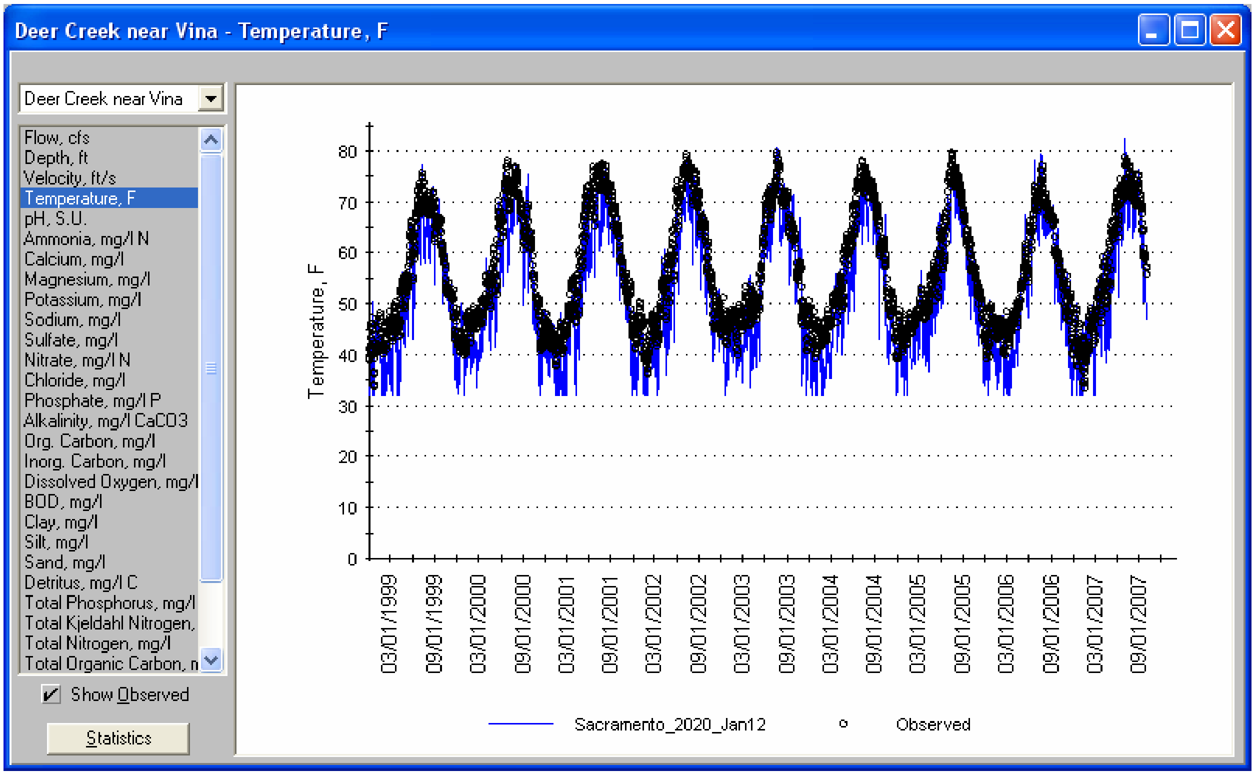

Figure 2-19 Simulated and observed temperature at upper Deer Creek

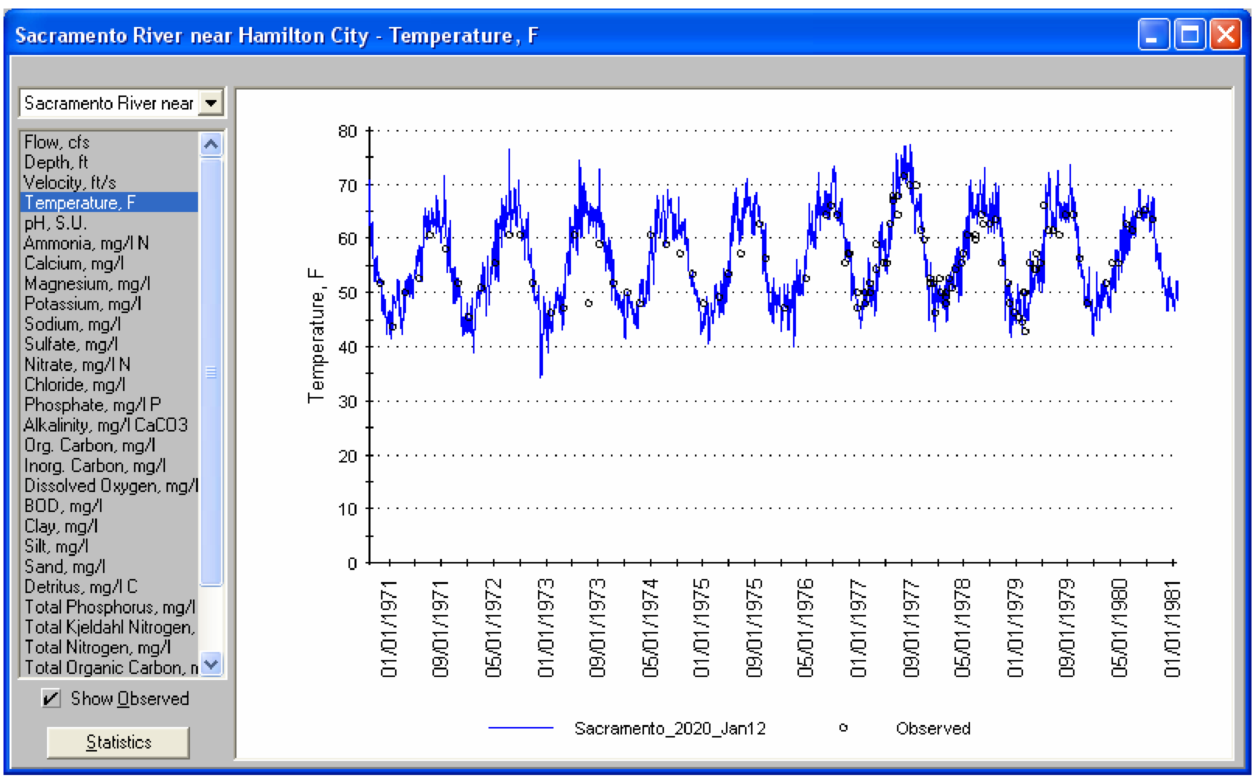

Figure 2-20 Simulated and observed temperature at Sacramento River at Hamilton City

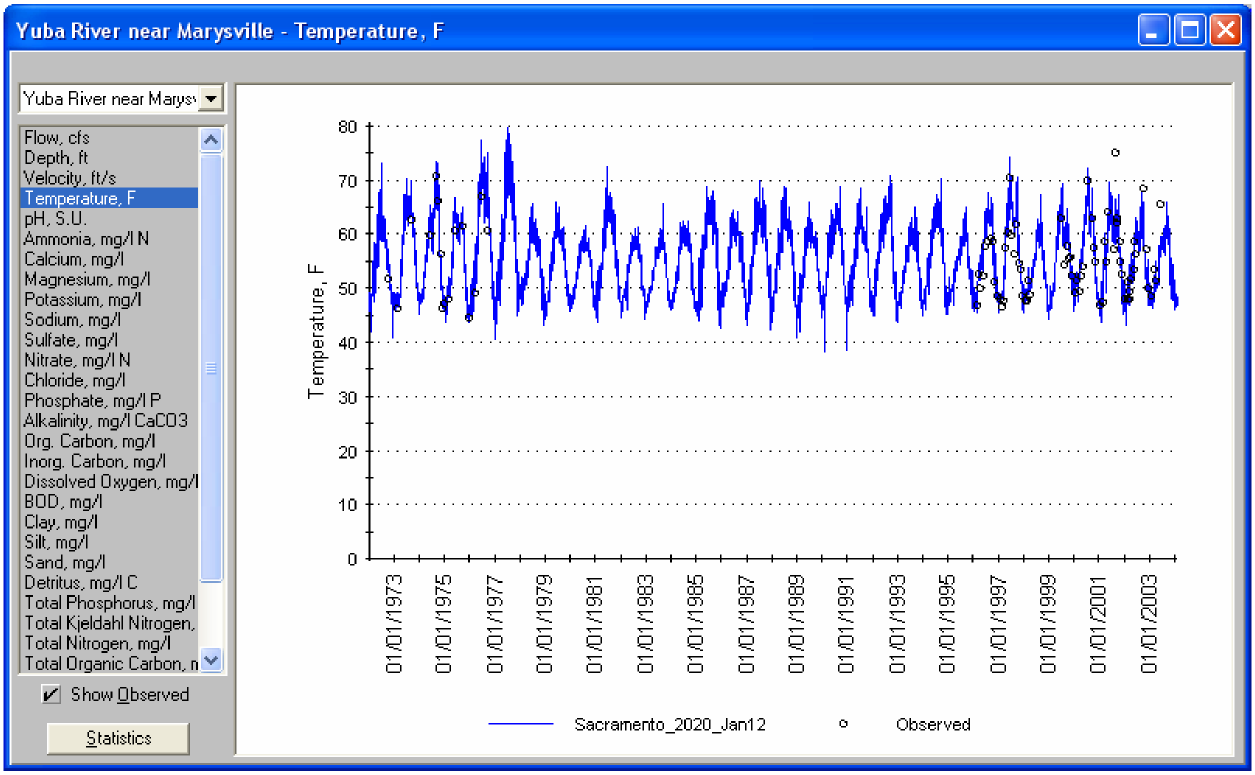

Figure 2-21 Simulated and observed temperature at Yuba River at Marysville

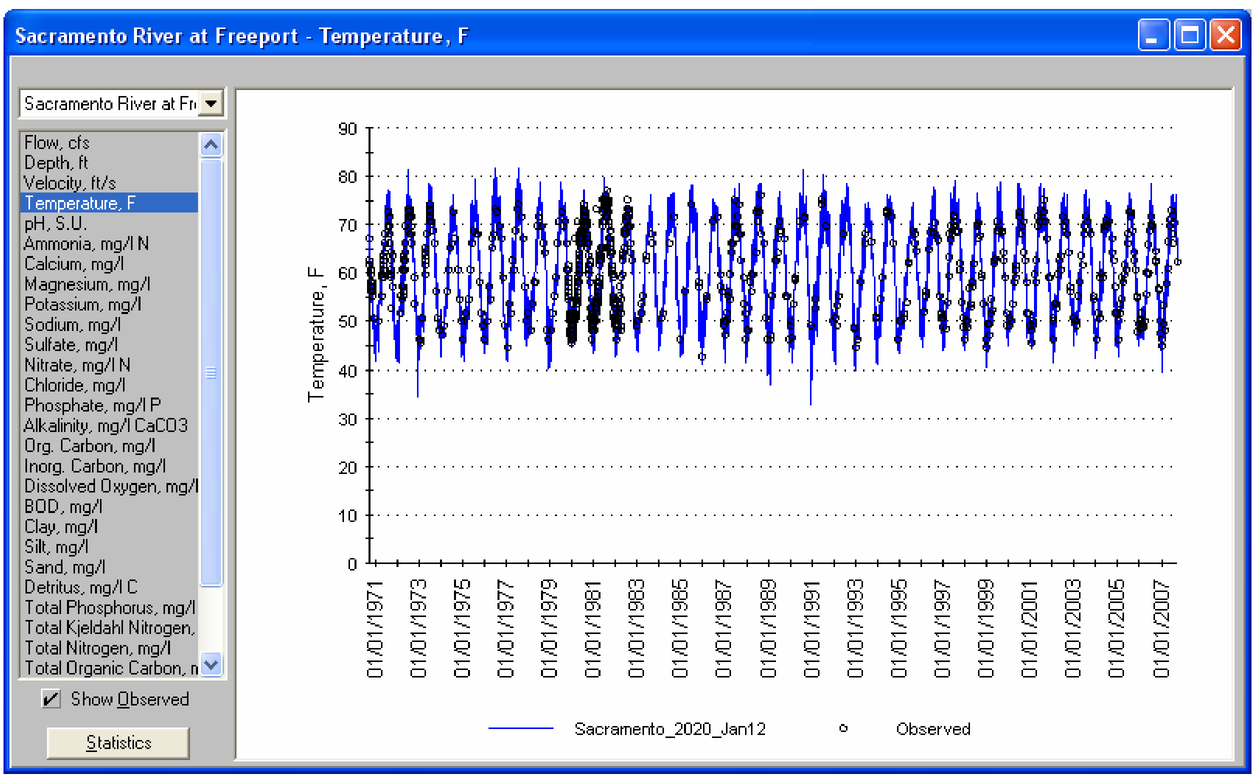

Figure 2-22 Simulated and observed temperature at Sacramento River at Freeport

Table 2.13 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 2.13 Statistics of Temperature Calibration

Monitoring Station	Relative Error, ^oF	Absolute Error, ^oF
Sacramento River at Bend Bridge	-0.02	2.18
Sacramento River at Red Bluff	-0.33	2.10
Mill Creek	0.60	3.44
Upper Deer Creek	-4.08	4.73
Sacramento River at Hamilton City	0.82	2.49
Yuba River at Marysville	1.17	2.62
Sacramento River at Freeport	-0.18	1.82

As these data illustrate, the highest relative and absolute errors were calculated at the sites located on the tributaries of the Sacramento River. The observed and simulated temperature at Upper Deer Creek (Figure 2-19) show simulated temperature dropping to freezing in winter but measured data usually did not drop below 39 ^oF. 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.

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 and many of the constituent ions which make up salinity. Differences between observed and simulated total suspended sediment were analyzed at six locations within the WARMF Sacramento River model domain. Two, Middle Fork of Cottonwood Creek and Battle Creek near Cottonwood, are on tributaries in the northern part of the watershed. The remaining four are along the main stem of the Sacramento River: at Red Bluff, Hamilton City, Fremont Weir, and the I Street Bridge in Sacramento. Figure 2-23 through Figure 2-28 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 1950’s and 1960’s.

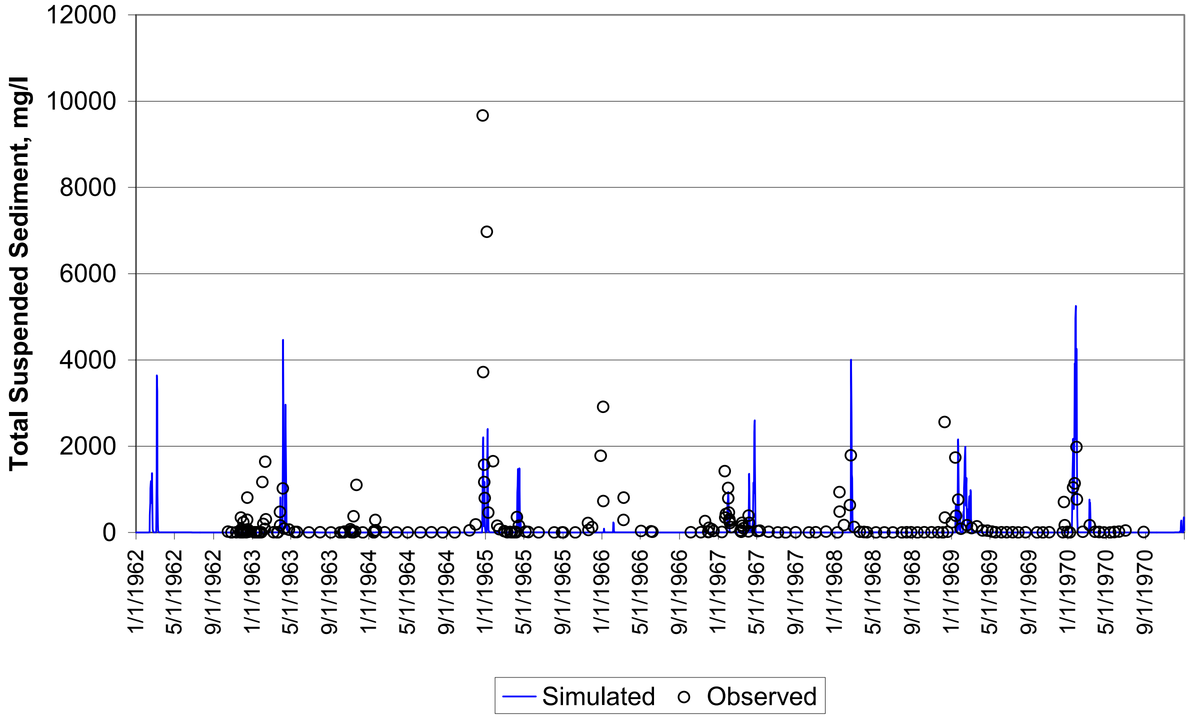

Figure 2-23 Simulated and observed total suspended sediment at Middle Fork of Cottonwood Creek.

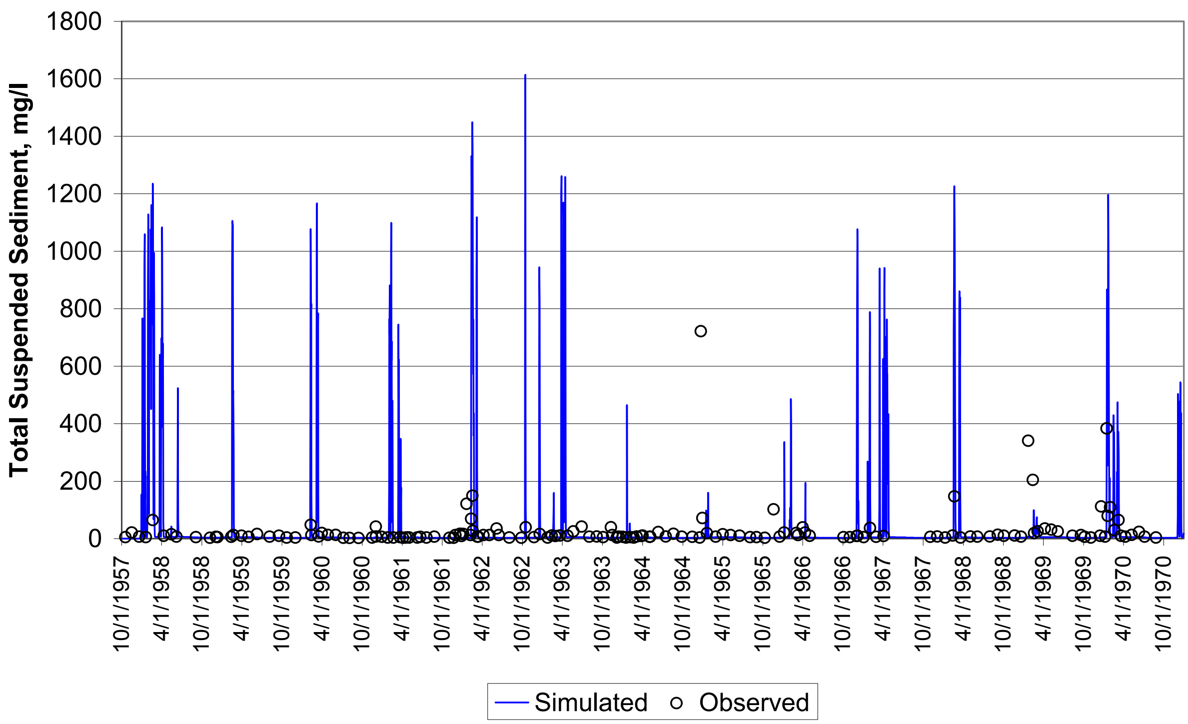

Figure 2-24 Simulated and observed total suspended sediment at Battle Creek.

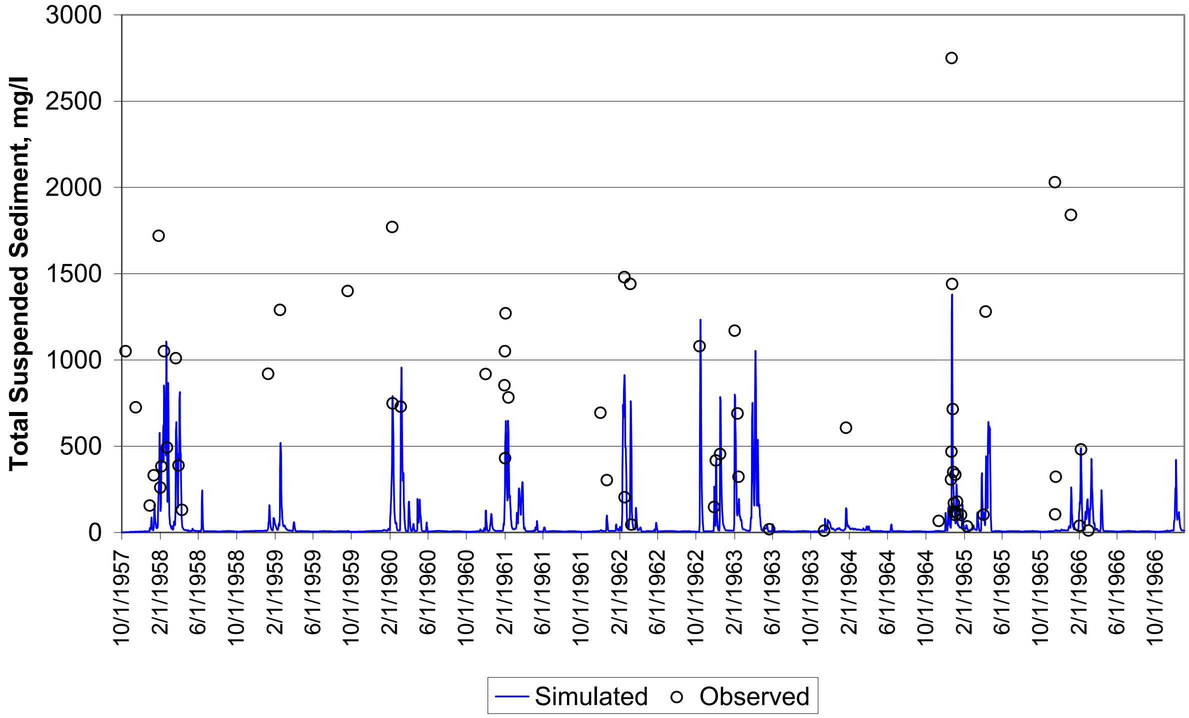

Figure 2-25 Simulated and observed total suspended sediment, Sacramento R. at Red Bluff

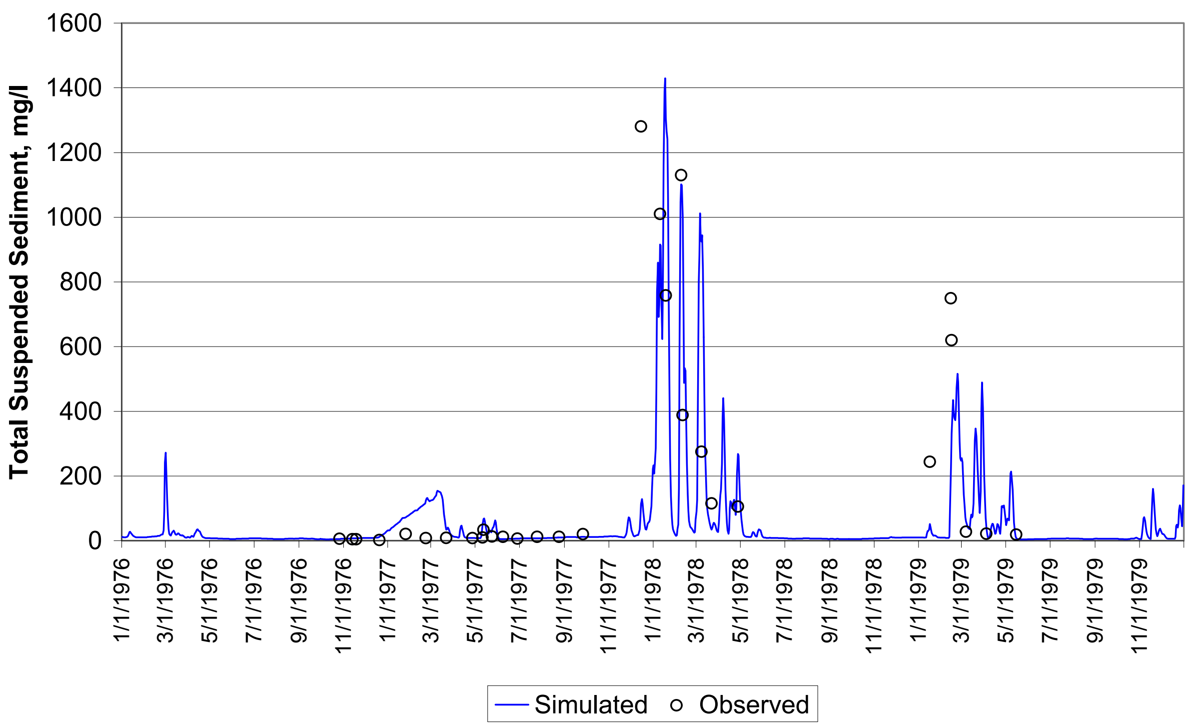

Figure 2-26 Simulated and observed total suspended sediment at Sacramento River at Hamilton City

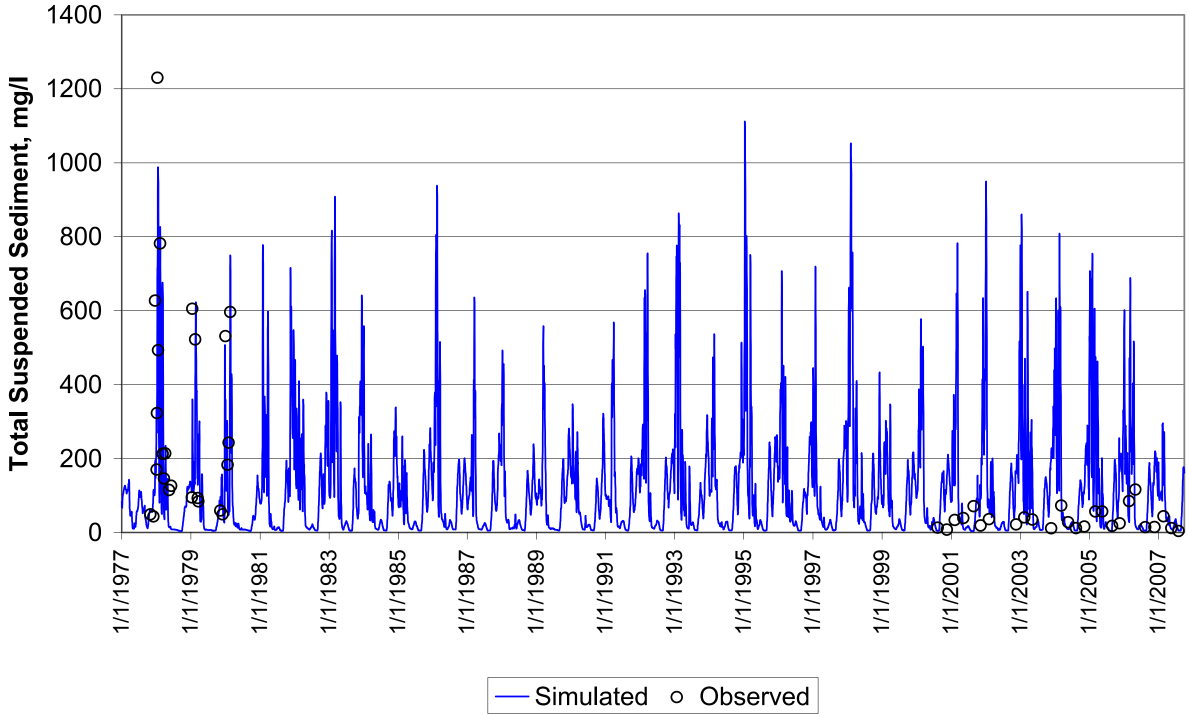

Figure 2-27 Simulated and observed total suspended sediment at Sacramento River at Fremont Weir

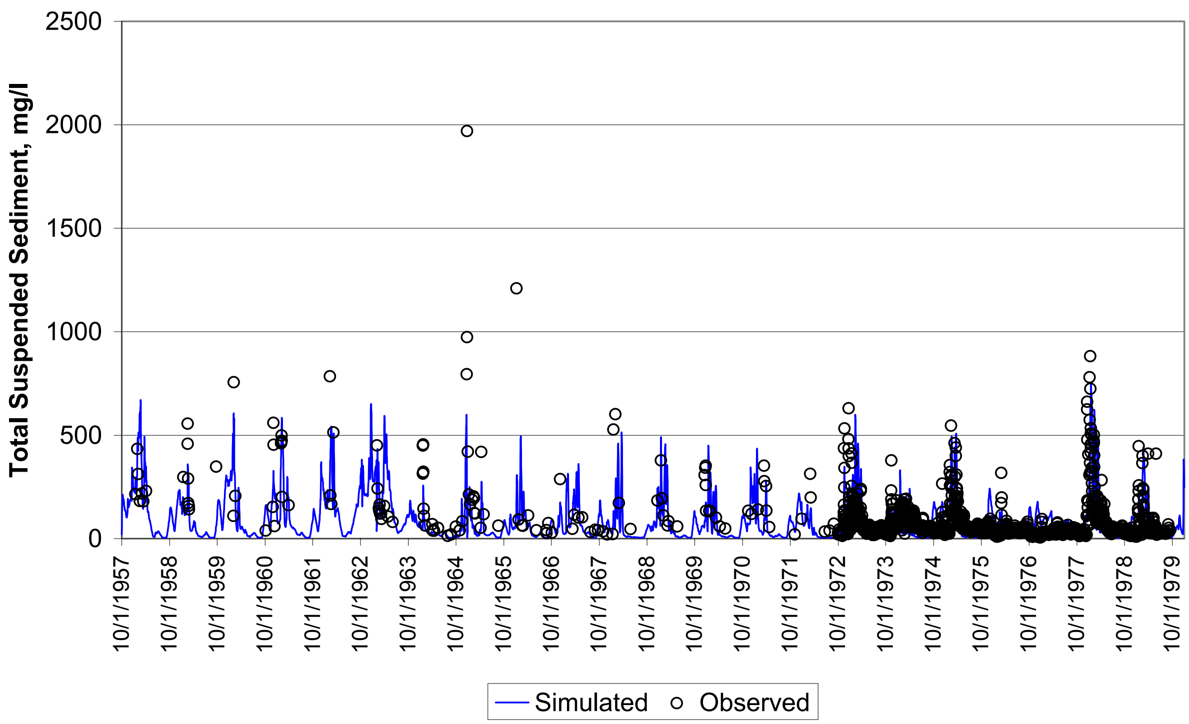

Figure 2-28 Simulated and observed total suspended sediment at Sacramento River at I Street Bridge

Table 2.14 provides a summary of model errors for total suspended sediment. The calculations assume that these observed data are accurate. The goal of calibration was is to minimize the relative and absolute errors.

Table 2.14 Model Errors of Total Suspended Sediment

Monitoring Station	Relative Error	Absolute Error
Middle Fork Cottonwood Creek	-44%	87%
Battle Creek near Cottonwood	+166%	281%
Sacramento River at Red Bluff	-55%	64%
Sacramento River at Hamilton City	-1%	68%
Sacramento River at Fremont Weir	+14%	71%
Sacramento River at I Street Bridge	+7%	76%

The three most upstream stations have large errors between simulated and observed values, but the three downstream stations have low relative error. Although the flow in the Sacramento River is tidally influenced at I Street bridge, this does not appear to be an important source of model error even though tidal effects are not simulated in WARMF. Absolute error is high at all stations because of the difficulty predicting the magnitude of peak sediment concentrations.

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 2-29 through Figure 2-35 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.

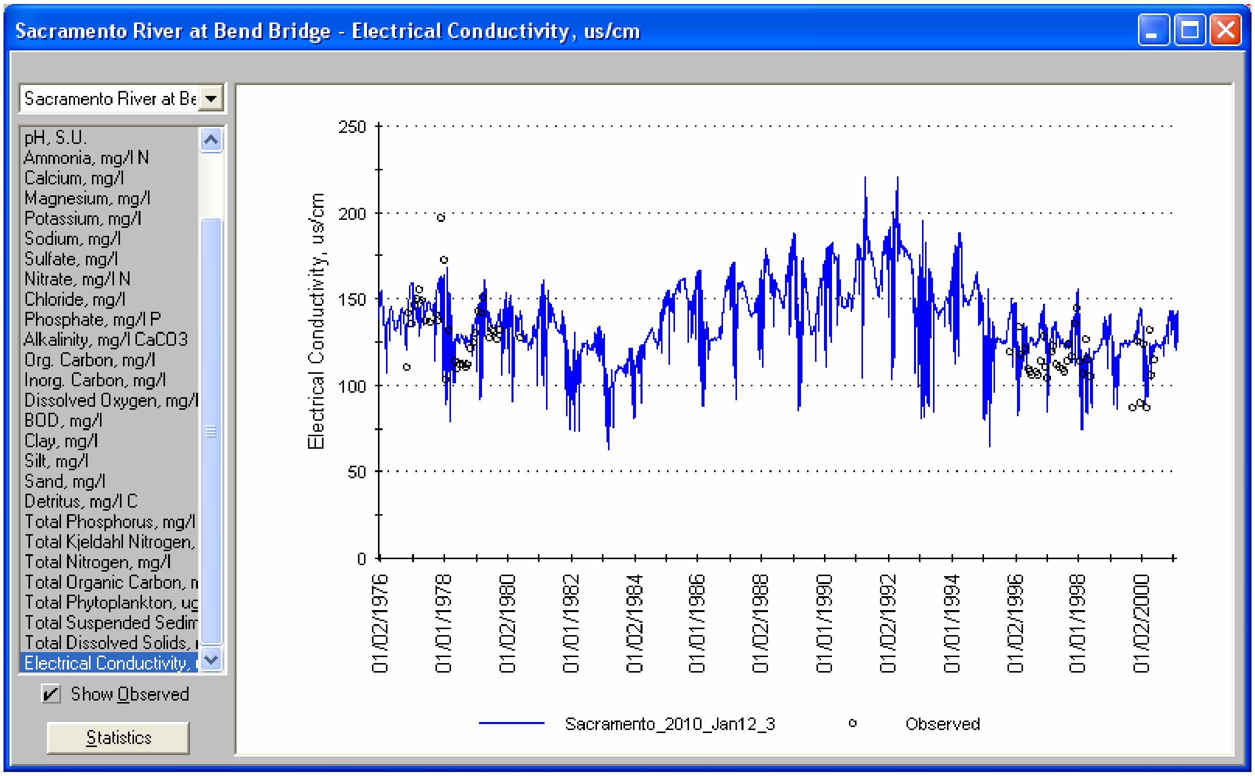

Figure 2-29 Simulated and observed electrical conductivity at Sacramento River at Bend Bridge

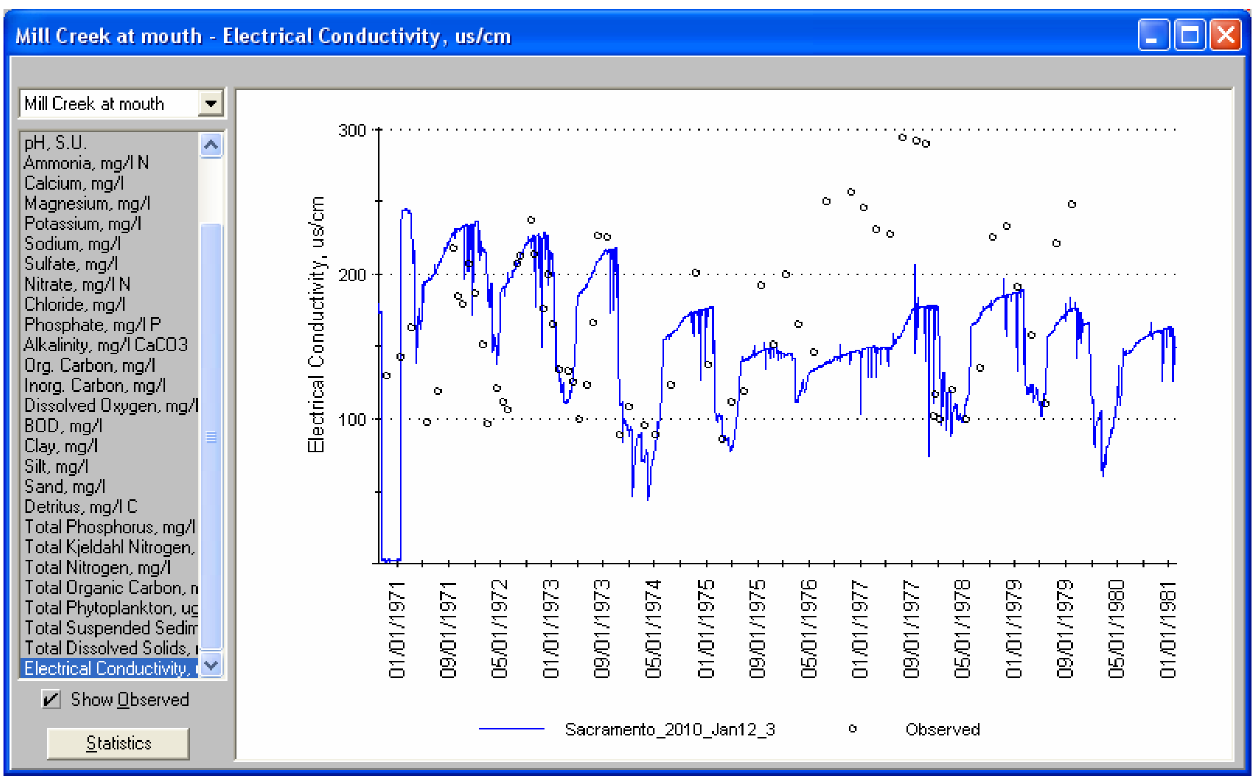

Figure 2-30 Simulated and observed electrical conductivity at Mill Creek.

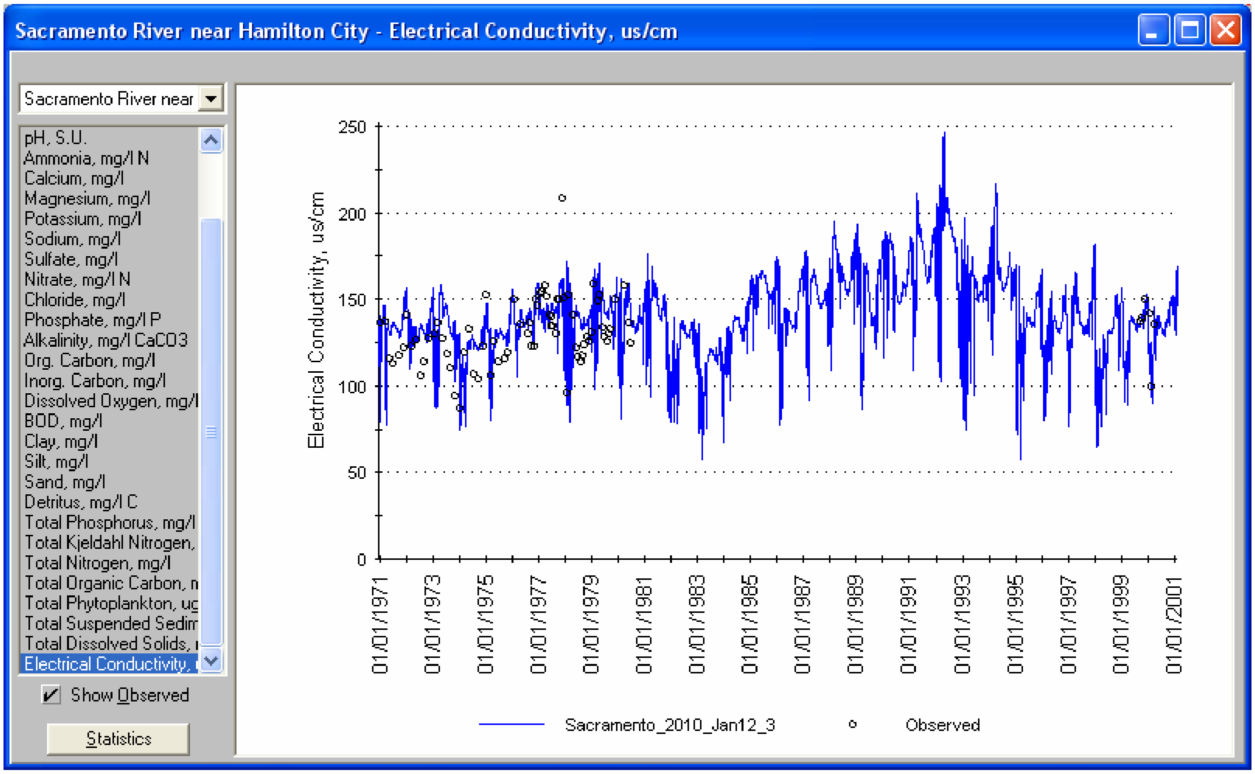

Figure 2-31 Simulated and observed electrical conductivity at Sacramento River at Hamilton City

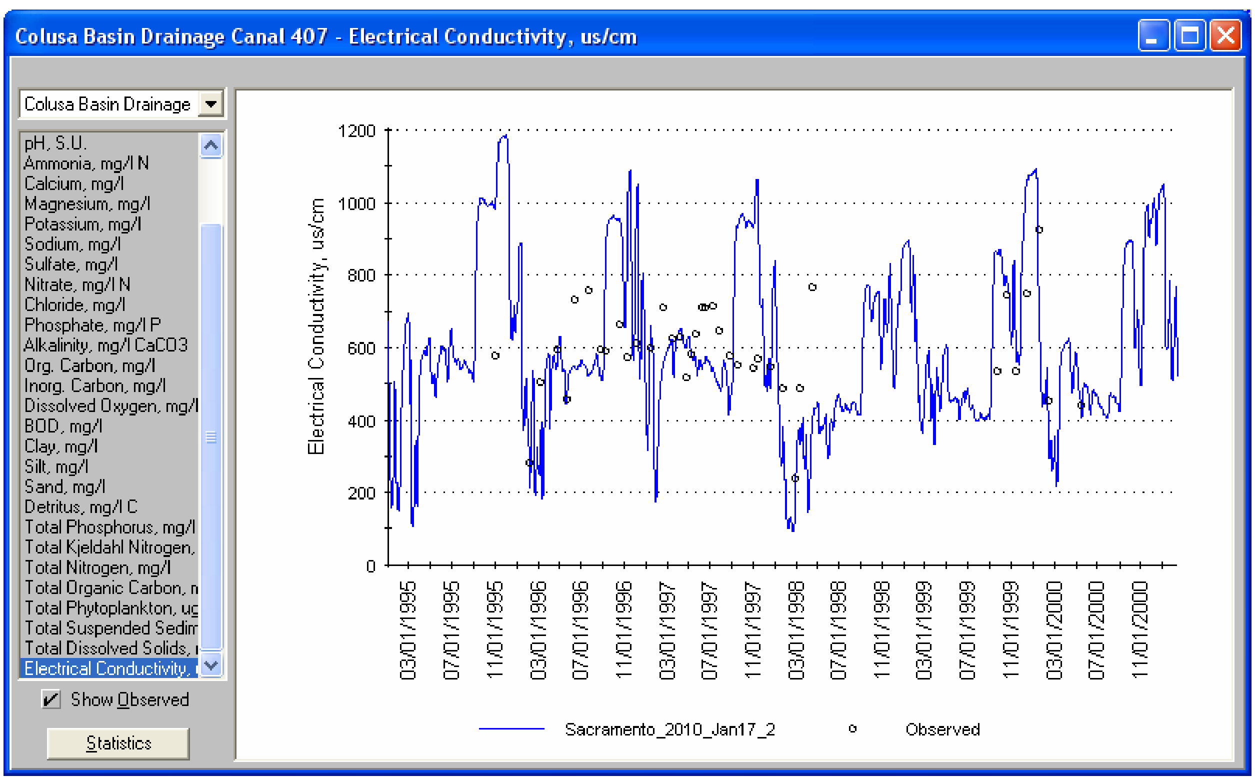

Figure 2-32 Simulated and observed electrical conductivity at Colusa Basin Drain near Knights Landing

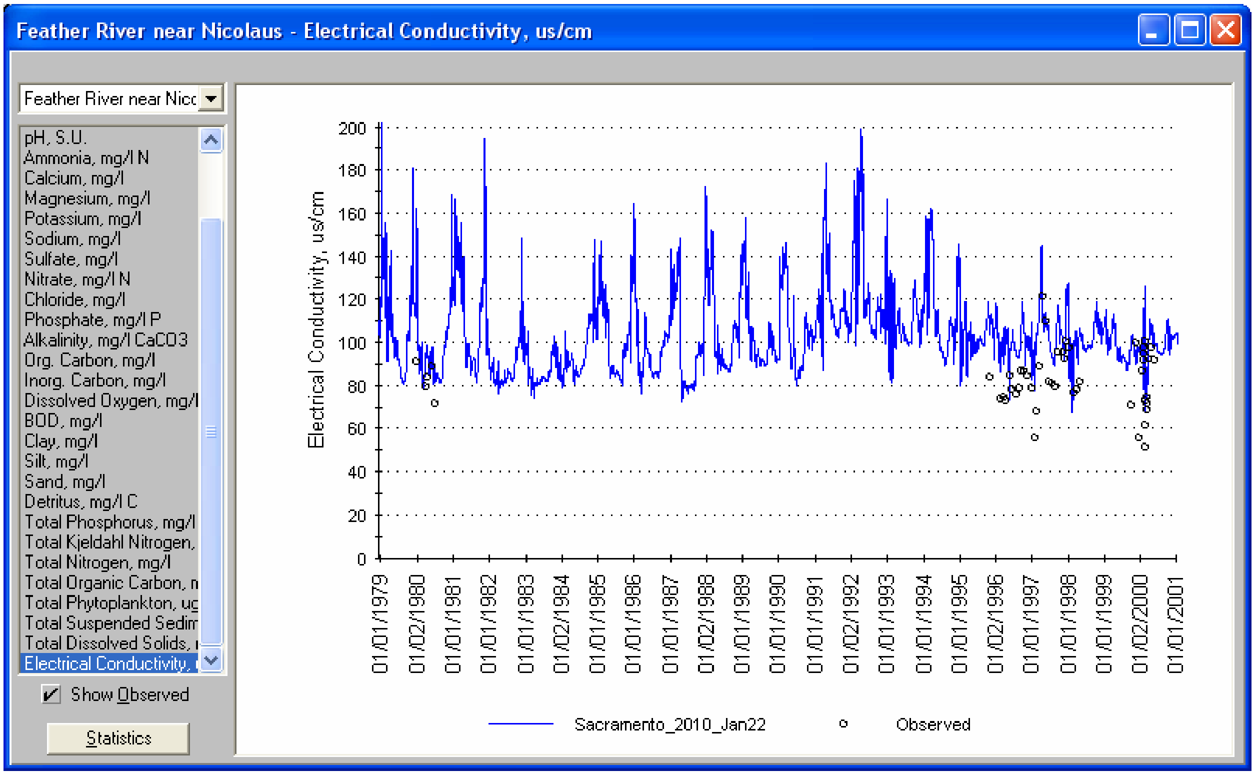

Figure 2-33 Simulated and observed electrical conductivity at Feather River at Nicolaus

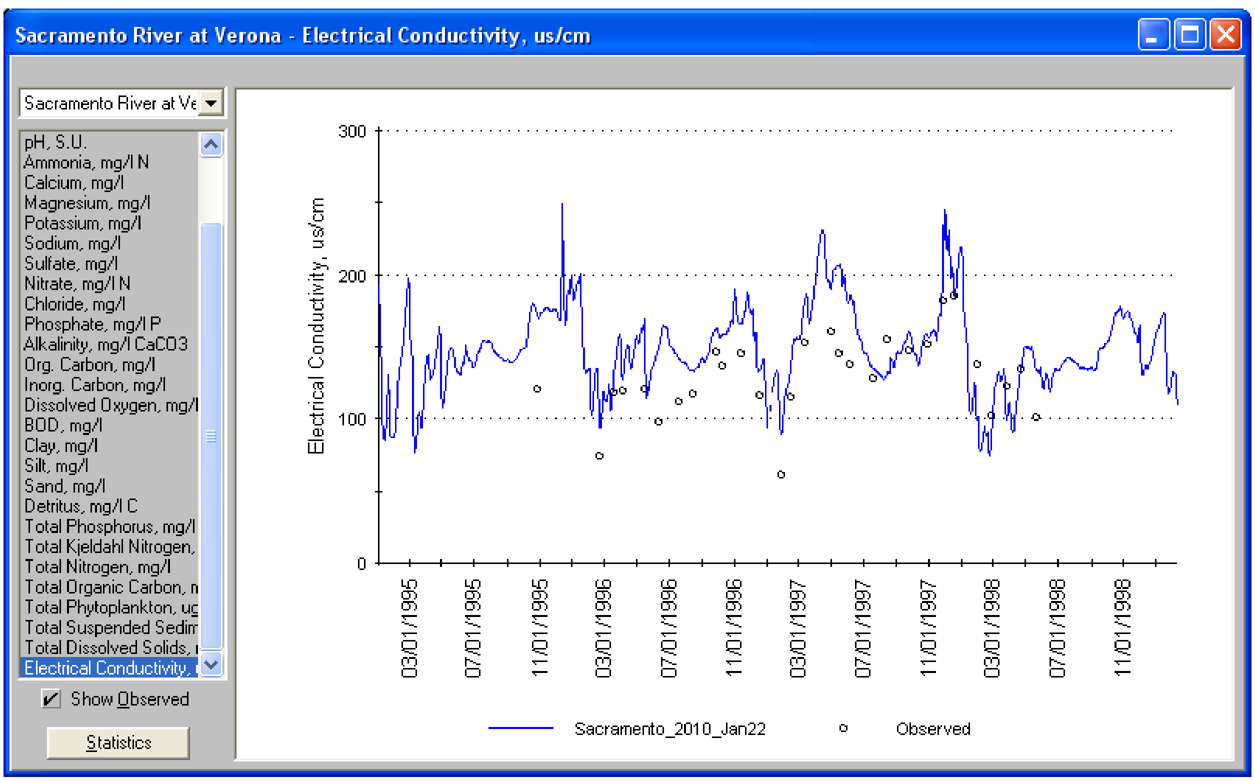

Figure 2-34 Simulated and observed electrical conductivity at Sacramento River at Verona

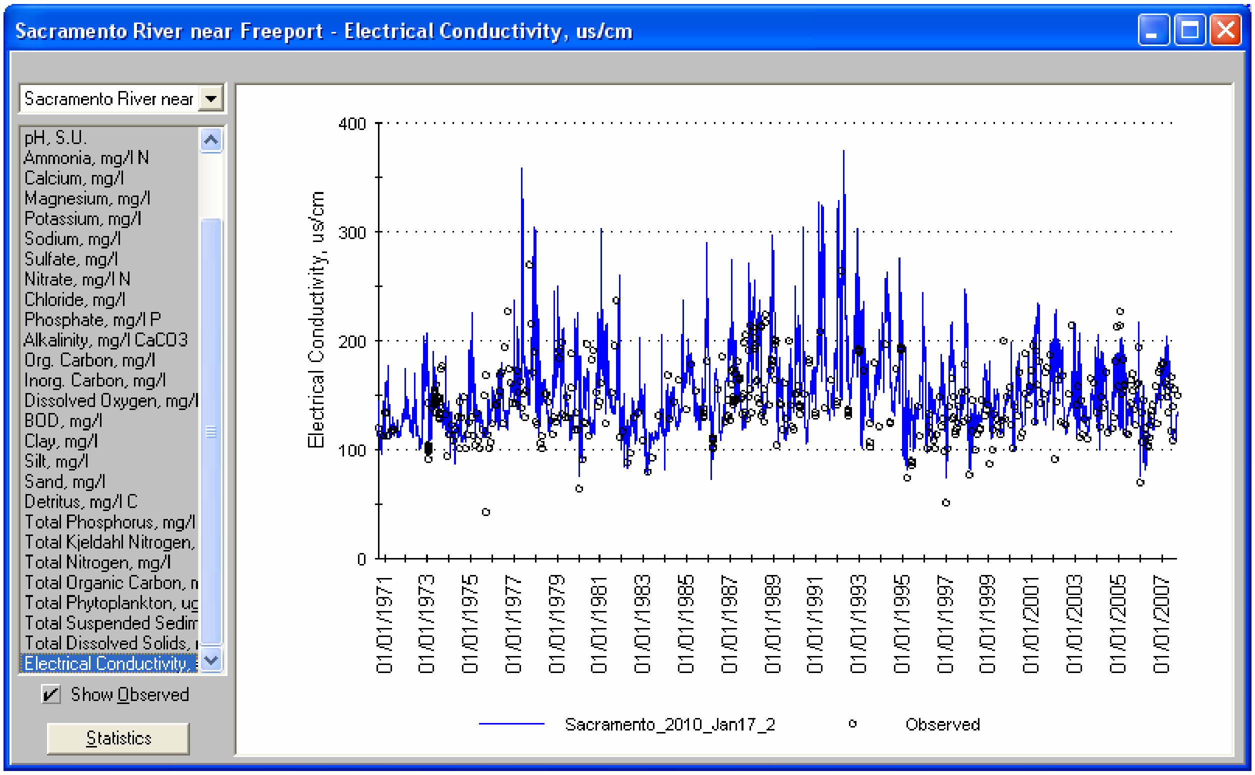

Figure 2-35 Simulated and observed electrical conductivity at Sacramento R. at Freeport

Table 2.15 shows the model errors for electrical conductivity at various monitoring stations within the Sacramento River WARMF model domain. Relative error was low in the upper watershed as far downstream as Hamilton City, the Colusa Basin Drain, and at the most downstream location at Freeport, indicating little model bias. The model over-predicted electrical conductivity in the Feather River and at Verona. Absolute error was significantly higher in tributaries of the Sacramento River as opposed to in the river itself. This is because calibration was done on a broad scale rather than in detail for each tributary but localized errors in model simulations tend to average themselves out over a larger area.

Table 2.15 Model Errors of Electrical Conductivity

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	+4%	11%
Mill Creek	-3%	29%
Sacramento River at Hamilton City	+2%	11%
Colusa Basin Drain near Knights Landing	+1%	30%
Feather River at Nicolaus	+17%	18%
Sacramento River at Verona	+12%	18%
Sacramento River at Freeport	+5%	18%

The cause of the model over-predictions originating in the Feather River was investigated. Much of the error can be explained by the relatively weak correlation between TDS and EC under low salinity conditions as shown in Figure 1-3. Data for all of the major ions, total dissolved solids, and electrical conductivity was collected (though not concurrently) for the Yuba River at

Marysville, which is a tributary of the Feather River. Simulation results are compared against measured data Table 2.16. The simulation results closely follow the observed data for most of the individual ions, which is to be expected close to a boundary inflow. Overall, the sum of the errors of the individual ions is -0.58 mg/l. The error of the model relative to measured TDS is -0.36 mg/l. The average measured TDS was 61.6 mg/l, which means the model was within 1% of measured TDS. In spite of this very low error, using the EC/TDS ratio of 1.5 the model overpredicts EC by 15%. The actual ratio of EC/TDS at this location is approximately 1.3. If this ratio were used to evaluate the model simulation at the Feather River at Nicolaus, there would be about a 2% relative error there. About half of the flow at the Sacramento River at Verona comes from the Feather River, so the Feather River's low EC/TDS ratio explains much of the error there as well.

Table 2.16 Model Errors of Ions, TDS, and EC for Yuba River at Marysville

Parameter	Relative Error	Relative Error, %
Ammonia	+0.01 mg/l	+81%
Calcium	-0.33 mg/l	-4%
Magnesium	+0.07 mg/l	+2%
Potassium	+0.03 mg/l	+5%
Sodium	-0.01 mg/l	-0%
Sulfate	-0.33 mg/l	-8%
Nitrate	+0.03 mg/l	+77%
Chloride	+0.03 mg/l	+3%
Phosphate	+0.01 mg/l	+104%
Inorganic Carbon	-0.09 mg/l	-1%
Total Dissolved Solids	-0.36 mg/l	-1%
Electrical Conductivity	+11.7 μs/cm	+15%

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, Steelhead Creek, 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 2-36 through Figure 2-42 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 between 1971 and 2007 for which there is observed data at each location.

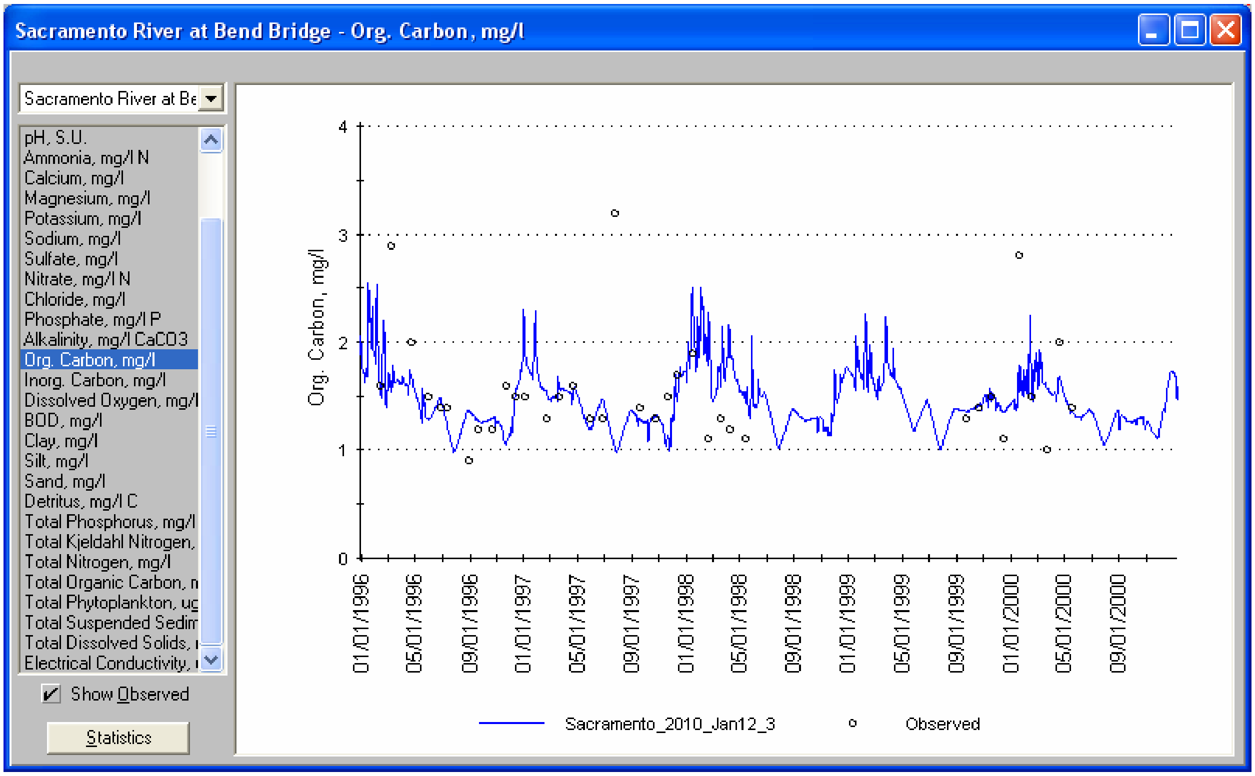

Figure 2-36 Simulated and observed organic carbon at Sacramento River at Bend Bridge.

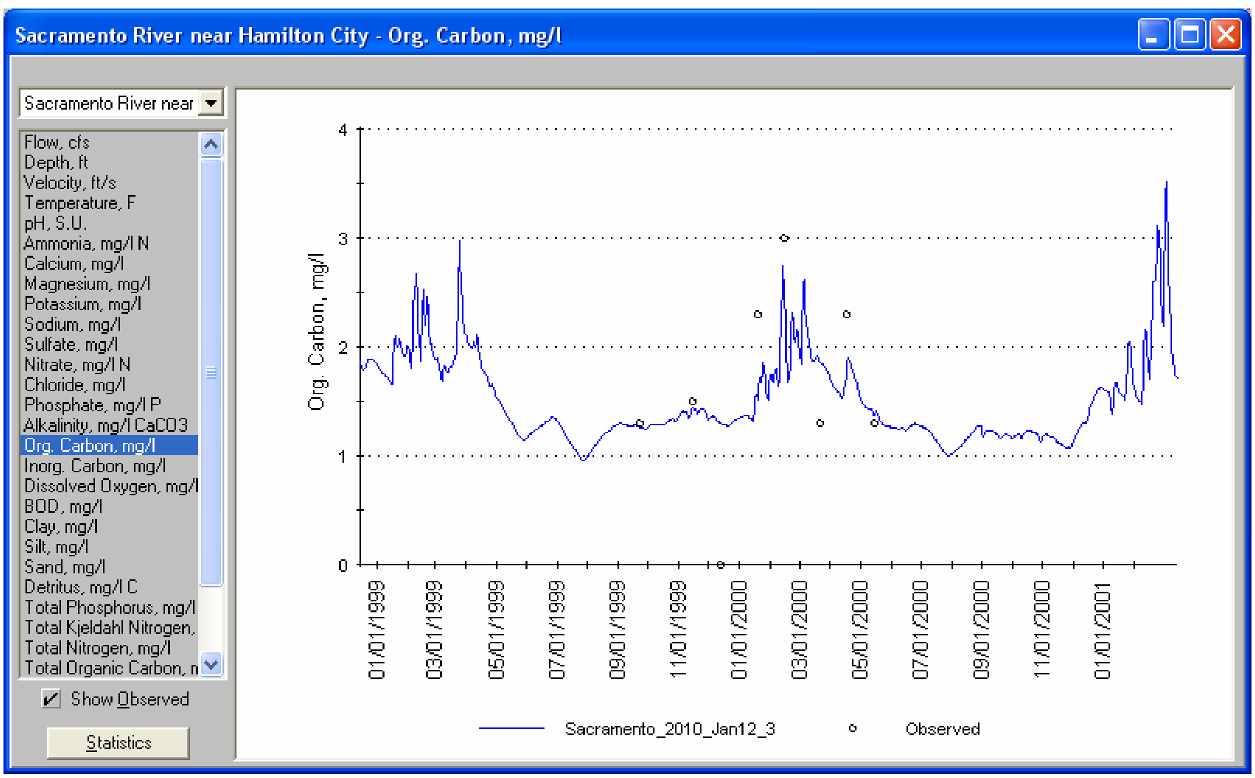

Figure 2-37 Simulated and observed organic carbon at Sacramento River at Hamilton City

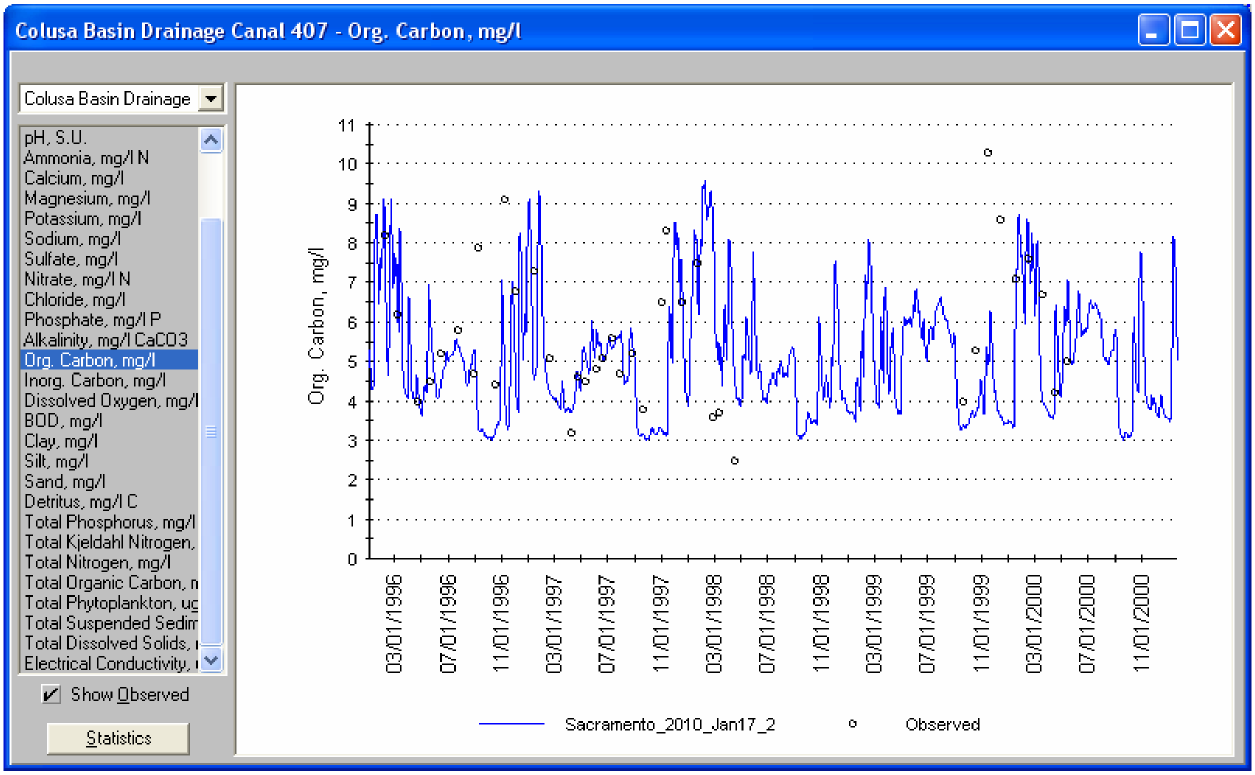

Figure 2-38 Simulated and observed organic carbon at Colusa Basin Drain near Knights Landing.

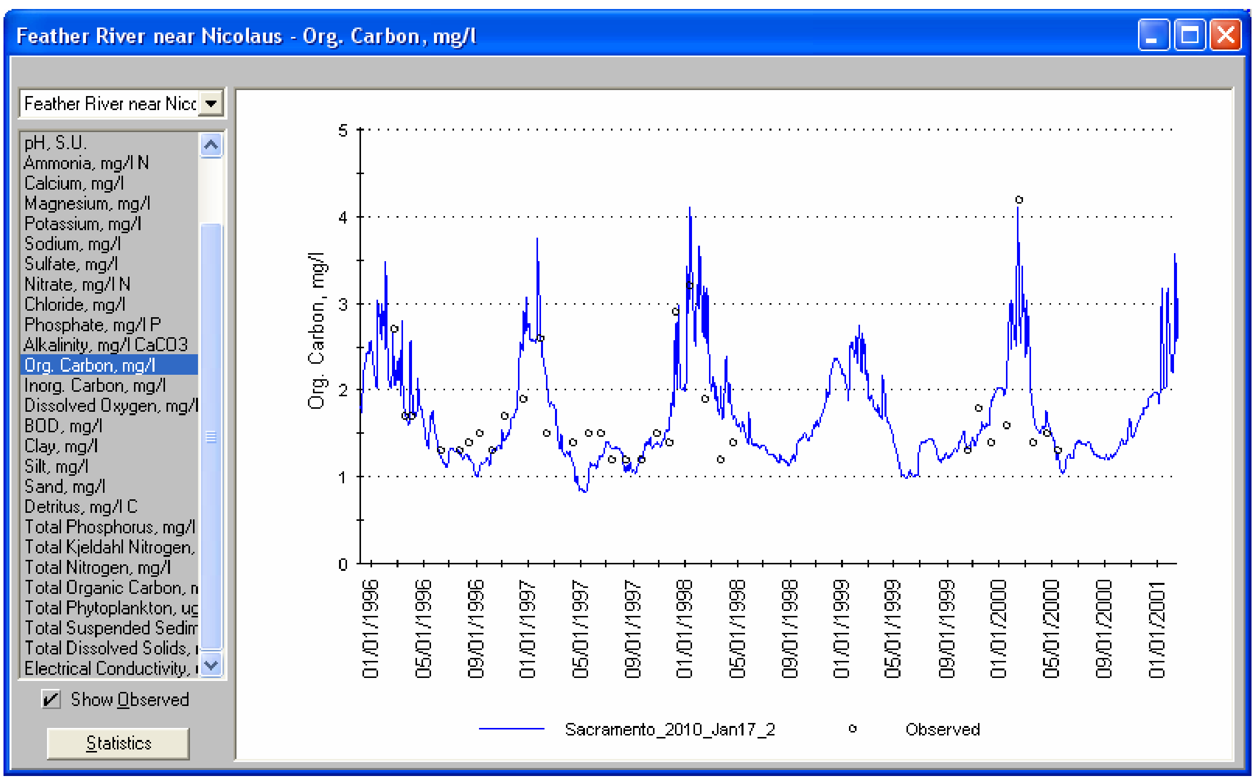

Figure 2-39 Simulated and observed organic carbon at Feather River at Nicolaus.

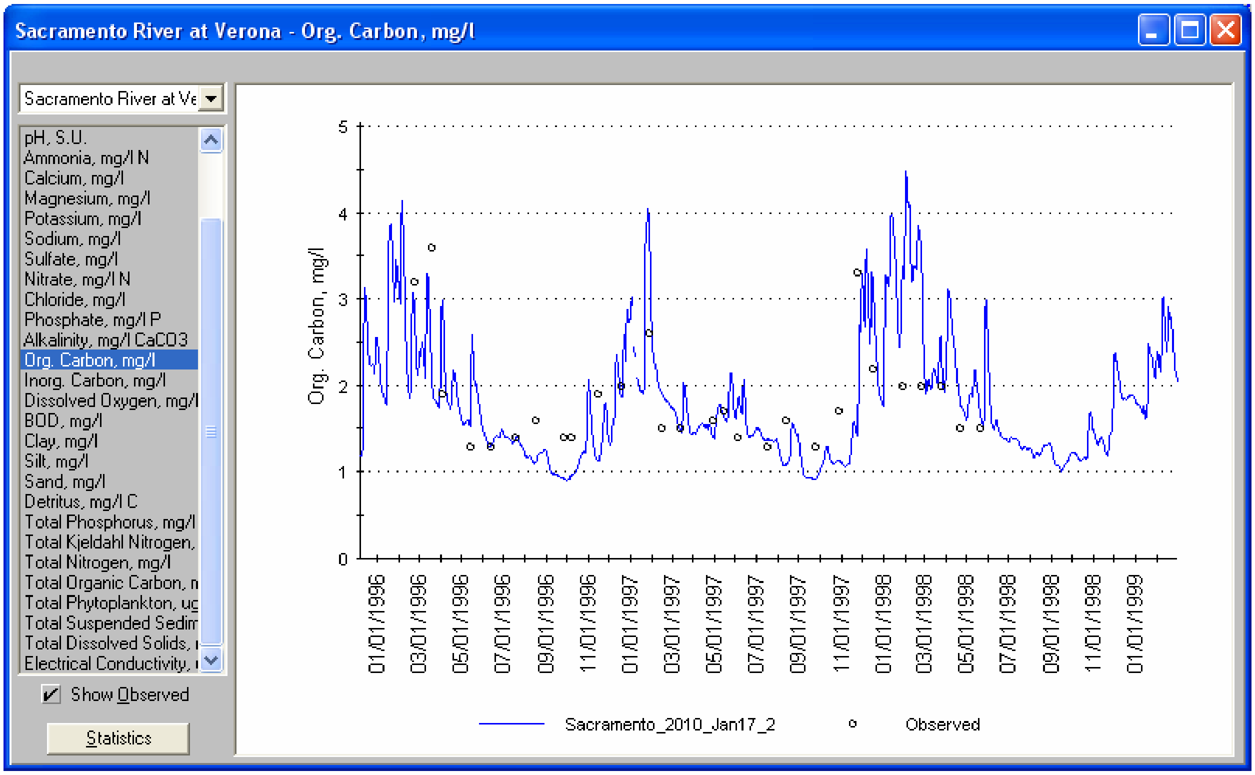

Figure 2-40 Simulated and observed organic carbon at Sacramento River at Verona

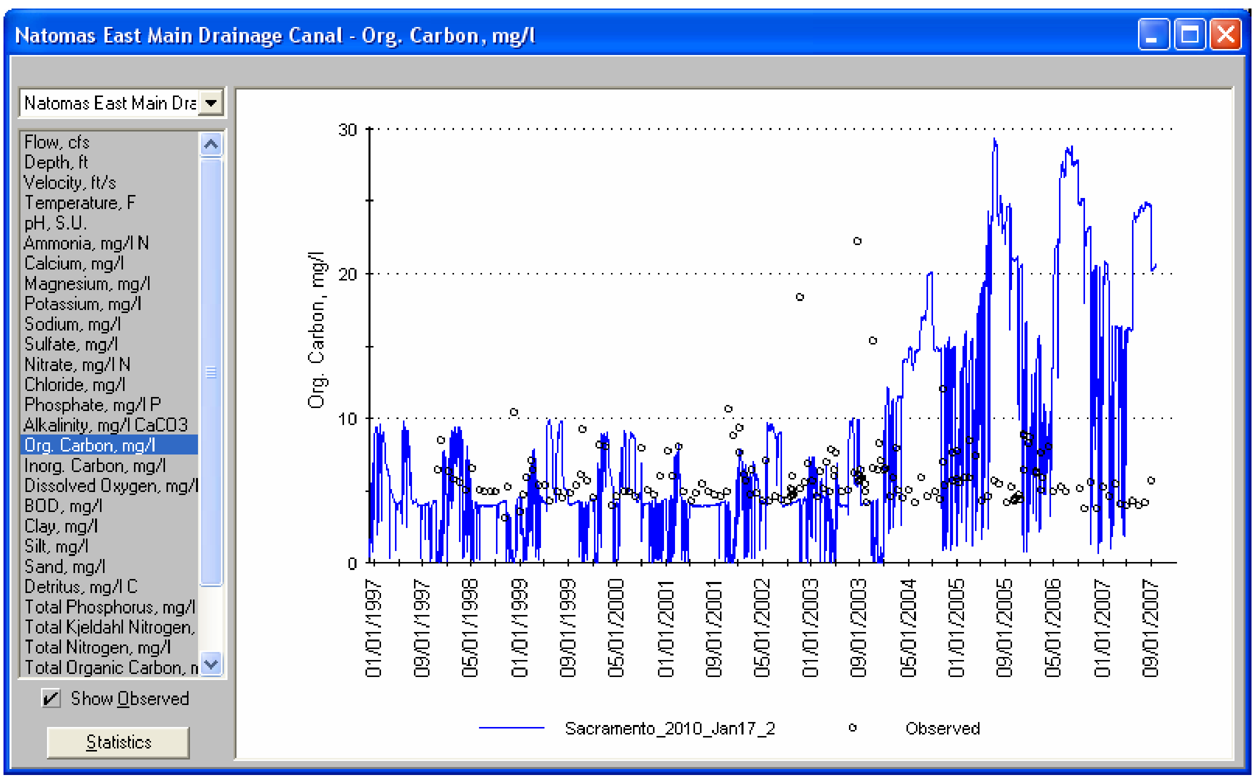

Figure 2-41 Simulated and observed organic carbon at Steelhead Creek

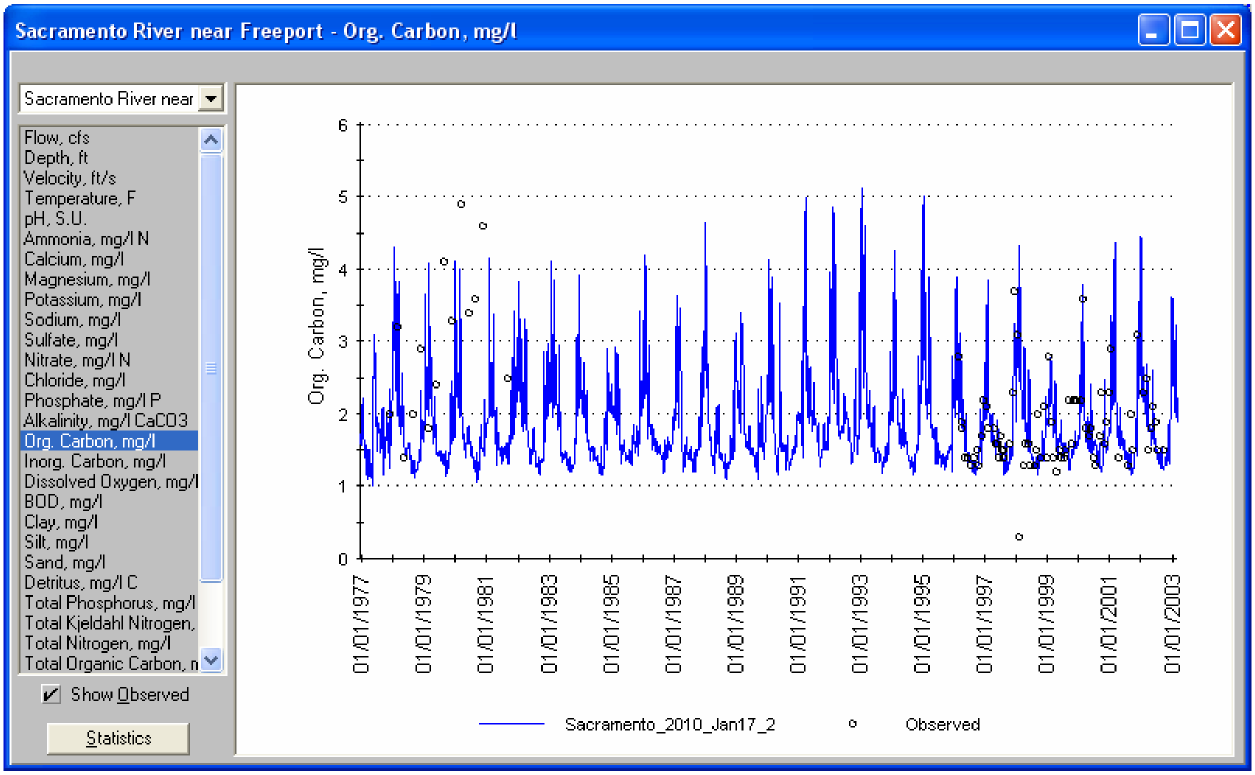

Figure 2-42 Simulated and observed organic carbon at Sacramento River at Freeport

Table 2.17 shows the model errors for organic carbon at various monitoring stations within the Sacramento River WARMF model domain. Generally, the WARMF simulation of organic carbon agrees well with the observed data, accurately predicting peaks, troughs, and trends in concentrations. The relative error is within 10% at all stations except for Steelhead Creek. Steelhead Creek is a heavily monitored urban drainage which is downstream of the discharge from the Placer County District 3 Wastewater Treatment Plant. Although the creek is ungaged, it is likely effluent dominated in the summer. There is little data for the treatment plant discharge, so it is not possible to match the observed data at the monitoring location. The Colusa Basin Drain results indicate that the model may be slightly underestimating the production of organic carbon in agricultural areas. While the under-prediction at Freeport could indicate a model bias of too little organic carbon load from urban areas, Figure 2-42 shows two patterns. The model predicted much too little organic carbon in 1977-1981 but followed the observed data very closely in the 1996-2002 time period. The difference may be due to higher point source loading in the 1970's for which data is not available, but the calibration statistics are calibrated based on all monitoring data for both time periods.

Table 2.17 Model Errors of Organic Carbon

Monitoring Station	Relative Error	Absolute Error
Sacramento River at Bend Bridge	-3%	23%
Sacramento River at Hamilton City	+1%	29%
Colusa Basin Drain near Knights Landing	-9%	30%
Feather River at Nicolaus	+5%	19%
Sacramento River at Verona	+2%	31%
Steelhead Creek (see note above)	+30%	95%
Sacramento River at Freeport	-10%	26%

Summary

This report summarizes the calibration of the WARMF model to the Sacramento River as of January 2010. The primary goals of the modeling were to simulate salinity 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 were good for the Sacramento River proper, although improvements to model calibration could be made in future investigations for individual tributaries. The calibration is sufficient to perform analysis of salinity and organic carbon sources under current and hypothetical conditions.

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.

Source of Water

Table 3.1 shows the average flows of source waters to the Model Domain (Sacramento River at Freeport + Yolo Bypass + Morrison Creek) for the simulation period of 10/1/1997 to 9/30/2007. Total inflow from upstream reservoirs is 24,775 cfs, which is 68% of the total inflow to the model domain. The largest reservoir inflow by a large margin comes from Shasta Lake at 29% of total inflow. Local runoff (i.e., overland and shallow groundwater flow) accounts for 32% of the total inflow, while point source discharges account for less than 1%. A water balance analysis revealed that total outflow (diversions plus streamflow out of the model domain) is less than total inflow by about 2.5%. The difference is likely the result of change in storage within the system and simulated evaporative losses.

Table 3.1 Average Annual Flows of Source Waters to the Model Domain

Source	Flow in cfs	Percent of Total, %
Inflows	**36,639**	**100**
Reservoir Inflows	24,775	68
Shasta Lake	*10,600*	*29*
Whiskeytown Lake	*249*	*1*
Black Butte Lake	*722*	*2*
Clear Lake	*462*	*1*
Lake Berryessa	*539*	*1*
Lake Oroville	*910*	*2*
Thermalito Afterbay (incl. Sutter Main Canal)	*4,773*	*13*
Englebright Lake	*2,402*	*7*
Camp Far West Reservoir	*477*	*1*
Folsom Lake	*3,641*	*10*
Point Source Discharges	299	1
Runoff (Shallow Groundwater and Overland Flow)	11,565	32
Outflows	**35,548**	**100**
Diversions	3,972	11
Total Flow out of the model domain (Sacramento at Freeport + Cache Creek + Morrison Creek)	31,576	89

Since both inflows and diversions are seasonal, the relative amount of source waters varies monthly. Figure 3-1 shows the contributions of each inflow (solid areas) and the flow after diversions (red line). Every month but February, reservoir releases are the largest source of water to the river. In winter, local runoff (shallow groundwater and overland flow) becomes nearly as large a source of water as reservoir releases. In summer, local runoff decreases and diversions become significant. Point sources are never the source or more than 2% of the flow in any month of the year.

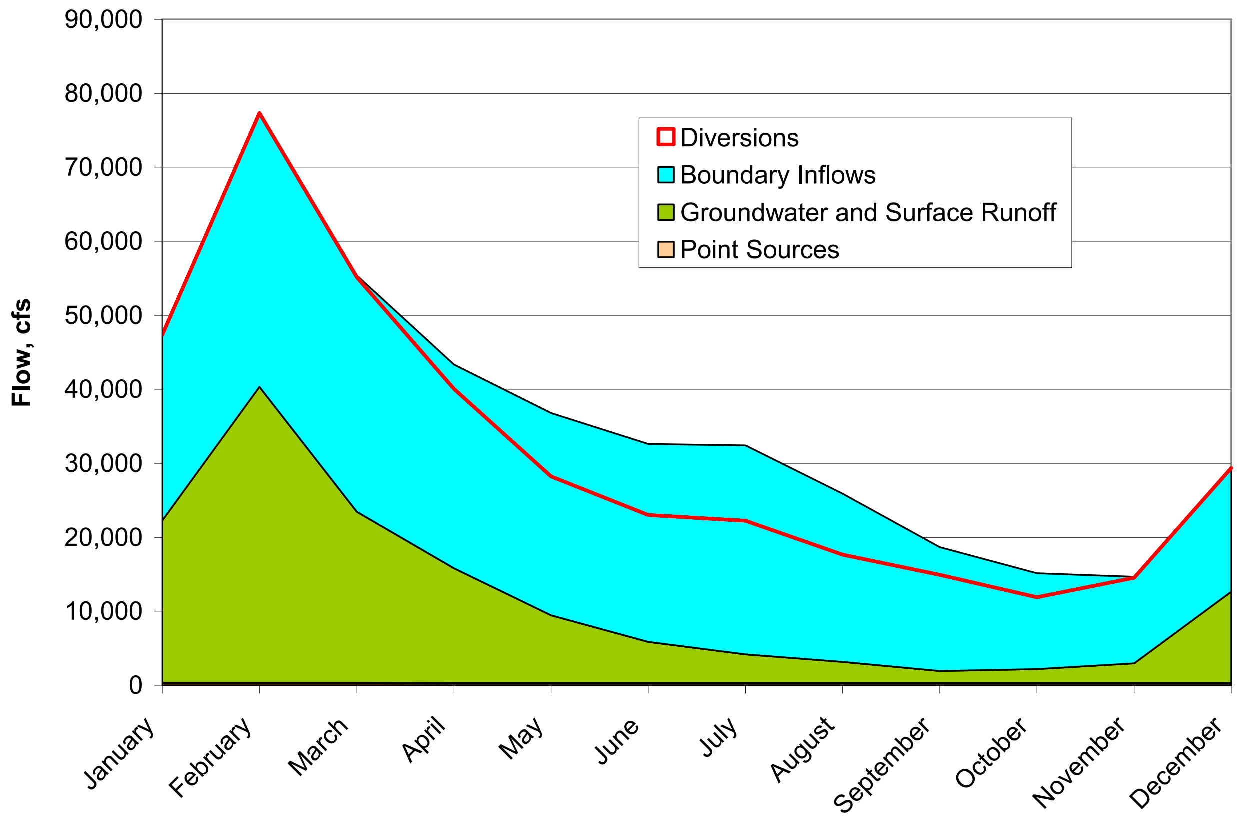

Figure 3-1 Average Monthly Source Waters of the Sacramento River

Sources of Sediment

Table 3.2 summarizes the sources of suspended sediment load to the Sacramento River, Yolo Bypass watershed, and Morrison Creek. Simulations indicate soil erosion from the land is the major contributor of total suspended sediment to the river. Most of the suspended sediment was predicted to settle to the river bed. About 13% of the settled sediment was predicted to be scoured back into the water column.

Table 3.2
Sources and Sinks of Total Suspended Sediment

Sources	Total Suspended Sediment Load (tons/day)	Total Suspended Sediment Load (% of inputs/outputs)
Inflows from Upstream	**3,363**	**4.83%**
Lake Shasta	122	0.18%
Lake Oroville + Thermalito Afterbay	1,996	2.87%
Englebright Lake	92	0.13%
Camp Far West Reservoir	26	0.04%
Folsom Lake	29	0.04%
Whiskeytown Reservoir	5	0.01%
Black Butte Lake	46	0.07%
Clear Lake	1,040	1.49%
Lake Berryessa	7	0.01%
Nonpoint Sources (Surface Runoff)	**59,864**	**85.96%**
Deciduous Forest	146	0.21%
Mixed Forest	491	0.71%
Evergreen Forest	5,428	7.79%
Orchard	1,088	1.56%
Row Crops	4,534	6.51%
Rice	8,863	12.73%
Fallow	214	0.31%
Shrub/Scrub	19,569	28.10%
Grassland/Herbaceous	13,636	19.58%
Marsh	0	0.00%
Barren land	4,328	6.21%
Confined Feeding	430	0.62%
Water	0	0.00%
Urban residential	1,113	1.60%
Urban commercial/industrial	0	0.00%
Resuspension from River Bed	**6,414**	**9.21%**
Point Sources	**0**	**0.00%**
Sinks		
Settling to River Bed	**49,553**	**96.45%**
Diversions	**1,823**	**3.55%**
NET LOAD TO THE DELTA	**18,265**	

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.

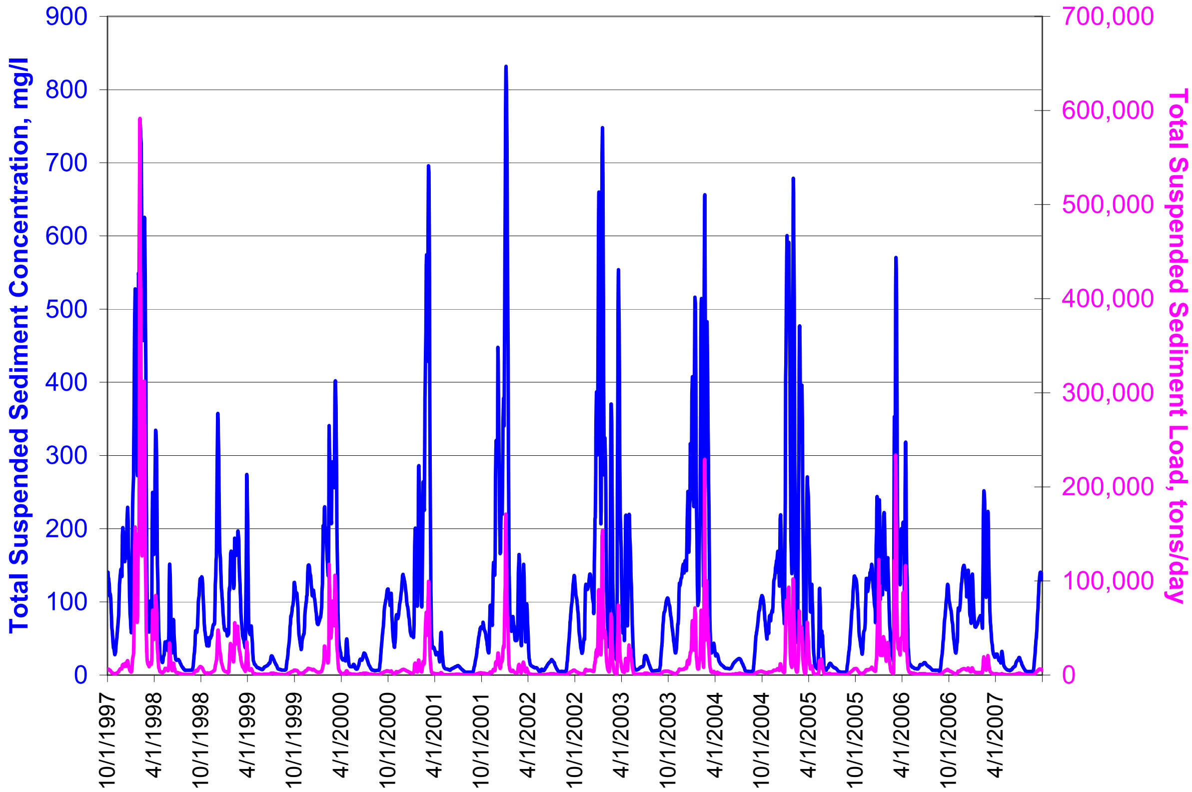

Figure 3-2 Total Suspended Sediment Load (pink line) vs. Concentration (blue line) at Sacramento River at Freeport

Sources of Total Dissolved Solids

Table 3.3 summarizes the fluxes of TDS load to the Sacramento River, Yolo Bypass, and Morrison Creek for water years 1998-2007. Inflows from upstream reservoirs accounted for 53% of the salt entering the Delta via the Sacramento River, Yolo Bypass, and Morrison Creek. 43% 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, 60% of the load comes from natural land cover areas. Rice was the single land use contributing the largest amount of loading, 26% of the nonpoint source loading or 11% of total salt loading. Figure 3-3 shows a pie chart of the major loading sources for visual reference.

Diversions removed 20% of the TDS load. Settling of ions adsorbed to sediment removed 6% of the TDS load and release of inorganic carbon to the atmosphere as carbon dioxide accounted for 1% of the original load to the watershed. Production and decay by chemical reaction were balanced and not very significant. In simulations, inorganic carbon accounted for 63% of the total dissolved solids at the Sacramento River at Freeport, Yolo Bypass, and Morrison Creek combined.

Table 3.3 Sources and Sinks of Total Dissolved Solids

Sources	Total Dissolved Solids Load (tons/day)	Total Dissolved Solids Load (% of inputs/outputs)
Inflows from Upstream	**5,262**	**53.02%**
Lake Shasta	2,227	22.44%
Lake Oroville + Thermalito Afterbay	1,078	10.86%
Englebright Lake	355	3.58%
Camp Far West Reservoir	84	0.85%
Folsom Lake	847	8.53%
Whiskeytown Reservoir	42	0.42%
Black Butte Lake	412	4.15%
Clear Lake	430	4.33%
Lake Berryessa	396	3.99%
Nonpoint Sources (Groundwater Accretion and Surface Runoff)	**4,257**	**42.90%**
Deciduous Forest	68	0.69%
Mixed Forest	58	0.58%
Evergreen Forest	458	4.62%
Orchard	149	1.50%
Row Crops	280	2.82%
Rice	1,113	11.22%
Fallow	29	0.29%
Shrub/Scrub	687	6.92%
Grassland/Herbaceous	1,133	11.42%
Marsh	80	0.81%
Barren land	29	0.29%
Confined Feeding	16	0.16%
Water	11	0.11%
Urban residential	59	0.59%
Urban commercial/industrial	88	0.89%
Resuspension from River Bed	**77**	**0.78%**
Reaction Product	**17**	**0.17%**
Point Sources	**311**	**3.13%**
Sinks		
Settling to River Bed	**561**	**20.82%**
Reaction Decay	**18**	**0.67%**
Atmospheric Losses	**104**	**3.86%**
Diversions	**2,011**	**74.65%**
NET LOAD TO THE DELTA	**7,230**	

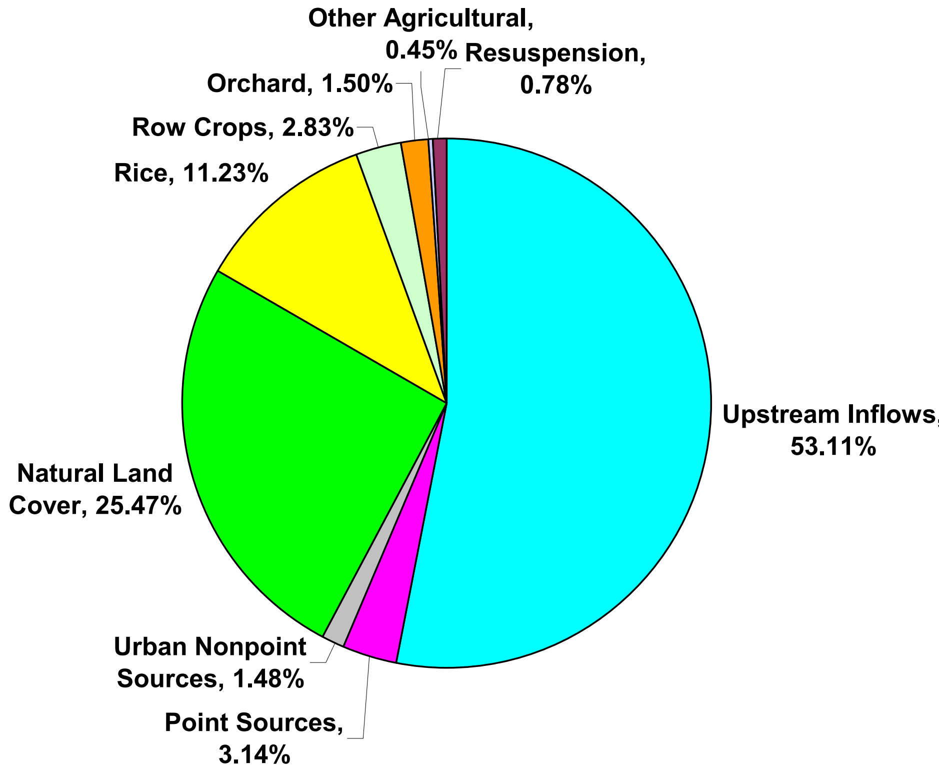

Figure 3-3 TDS Loading Sources of the Sacramento River and Yolo Bypass

Table 3.3 shows that the rice and grassland/herbaceous land uses contribute considerably more nonpoint source load of salt than other land uses. 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 43% nonpoint source load of the overall total dissolved solids loading. The light blue and magenta portions of Figure 3-3, point sources and upstream inflows, are excluded from the analysis.

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

Land Use	Total Dissolved Solids Load (lb/acre/year)
Deciduous Forest	310
Mixed Forest	420
Evergreen Forest	360
Orchard	305
Row Crops	425
Rice	1,415
Fallow	188
Shrub/Scrub	451
Grassland/Herbaceous	403
Marsh	367
Barren land	238
Confined Feeding	669
Water	112
Urban residential	244
Urban commercial/industrial	264

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 the colored region on the map to which it points. The chart in the north is the Sacramento River at Hamilton City, the large chart in the south is the Sacramento River at Freeport, 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. 82% 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 14% of the load to the Yolo Bypass and 4% is from point sources. The salt load at the Sacramento River at Freeport is 54% from upstream inflows, 41% from nonpoint sources and 5% from point sources.

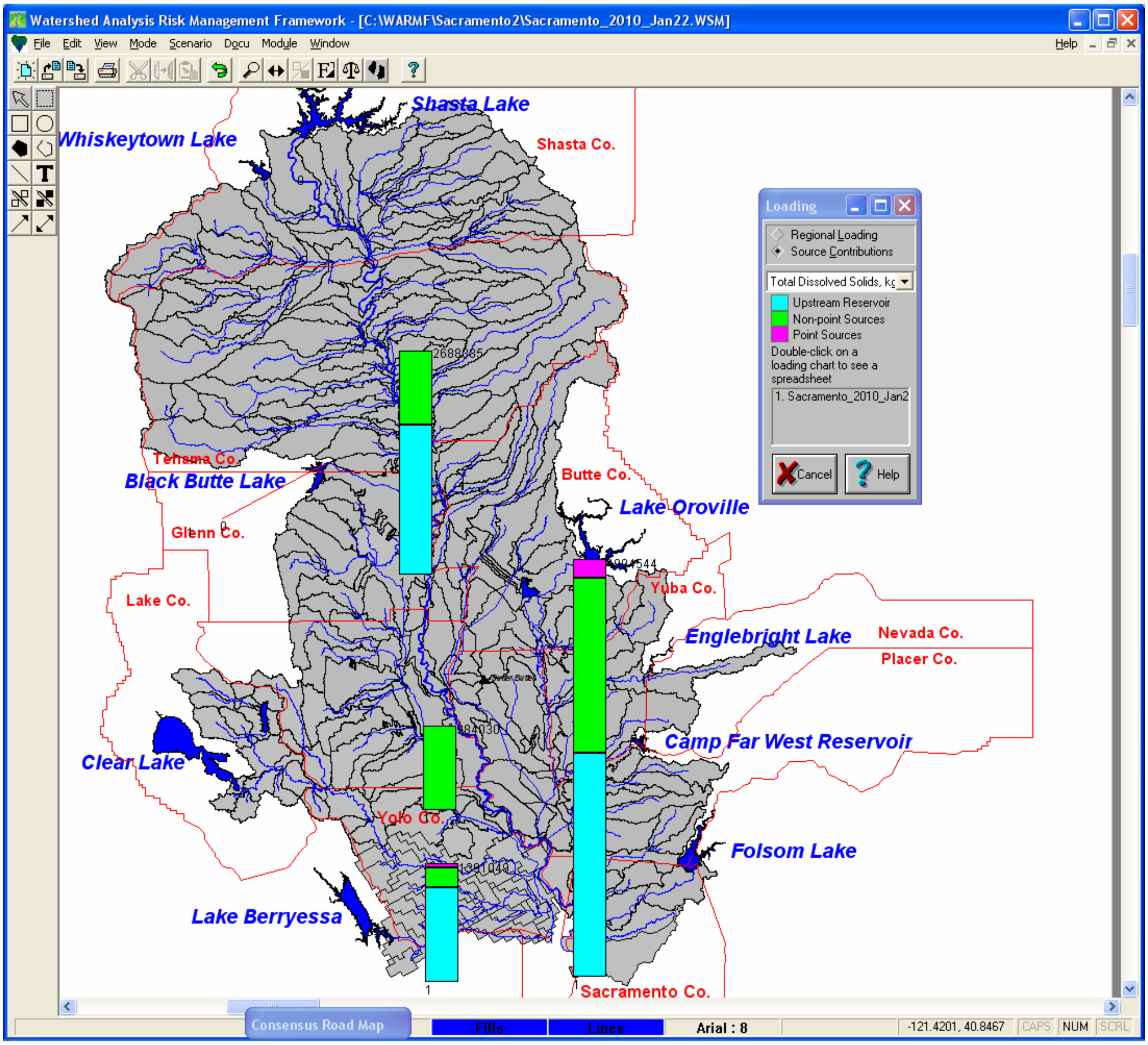

Figure 3-4 Source Contributions Loading of Total Dissolved Solids

Figure 3-5 shows the relationship between TDS load and TDS concentration at the Sacramento River at Freeport. The concentration rises during the summer dry season and falls during the winter wet season. Load of salt peaks during the winter peak runoff, then declines gradually through the dry season even as concentration increases. Although concentration is lower in wet years such as 2005 and 2006, it is relatively consistent between 80 and 140 mg/l.

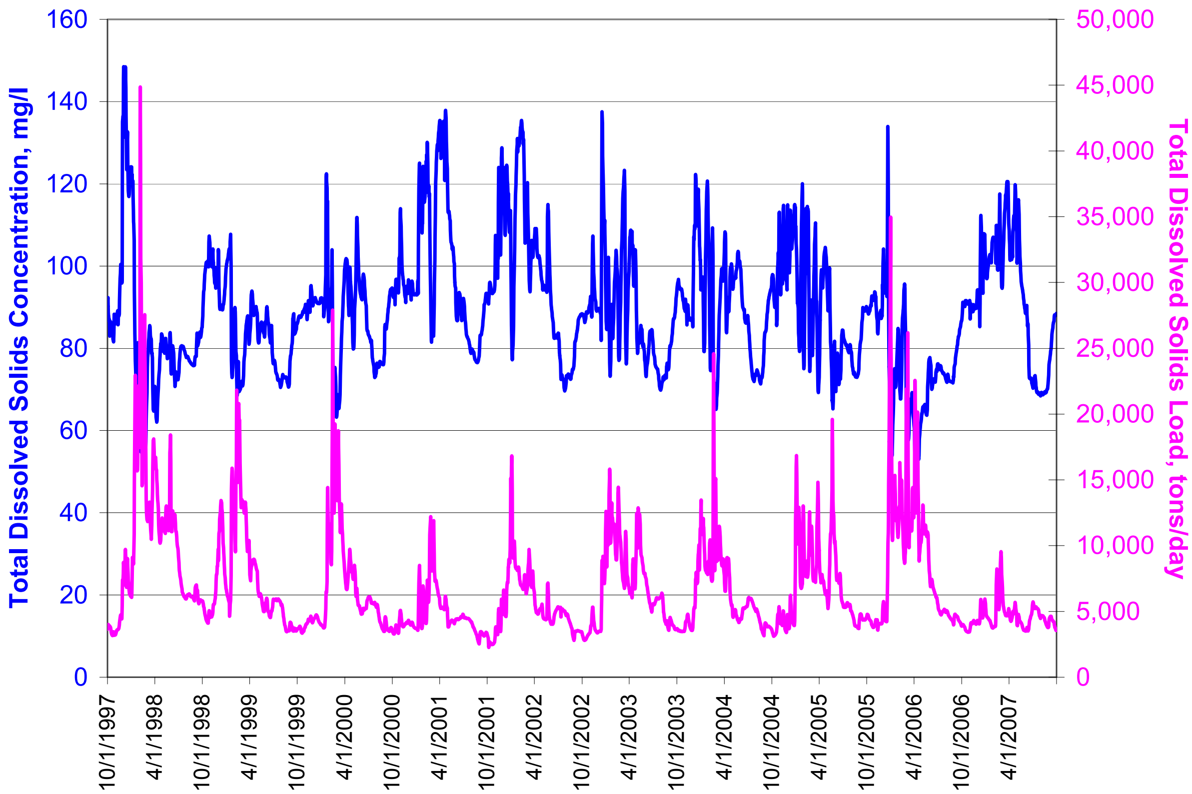

Figure 3-5 TDS Load (pink line) vs. TDS Concentration (blue line) at Sacramento River at Freeport

Sources of Organic Carbon

Table 3.5 summarizes the sources of organic load to the Sacramento River, Yolo Bypass, and Morrison Creek. 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	Organic Carbon Load (tons/day)
Inflows from Upstream	**107.79**
Lake Shasta	41.01
Lake Oroville + Thermalito Afterbay	25.63
Englebright Lake	8.04
Camp Far West Reservoir	3.06
Folsom Lake	18.05
Whiskeytown Reservoir	0.99
Black Butte Lake	4.99
Clear Lake	3.95
Lake Berryessa	2.07
Nonpoint Source Load (Groundwater Accretion and Surface Runoff)	**193.89**
Deciduous Forest	0.71
Mixed Forest	0.71
Evergreen Forest	11.13
Orchard	3.00
Row Crops	12.54
Rice	79.99
Fallow	0.30
Shrub/Scrub	15.23
Grassland/Herbaceous	63.83
Marsh	0.49
Barren land	3.35
Confined Feeding	0.36
Water	0.26
Urban residential	1.65
Urban commercial/industrial	0.36
Resuspension from River Bed	**5.04**
Reaction Product	**60.50**
Point Sources	**37.55**
Sinks	
Settling to River Bed	**54.03**
Reaction Decay	**87.32**
Diversions	**30.58**
NET LOAD TO THE DELTA	**232.84**

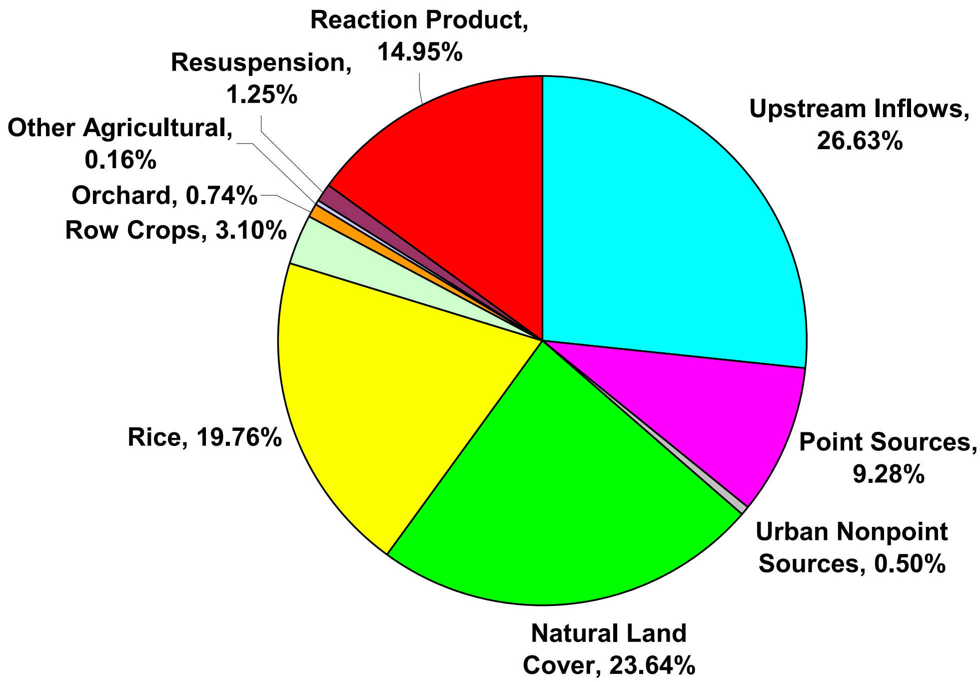

Figure 3-6 Organic Carbon Loading Sources of the Sacramento River and Yolo Bypass

Table 3.5 shows that the rice and grassland/herbaceous land uses contribute considerably more nonpoint source load of organic carbon than other land uses. An important management consideration is the intensity of loading, or the loading rate for a given land area. Table 3.6 shows the loading produced by each land use. Note that this breakdown is only for roughly half of the overall organic carbon loading. The light blue, magenta, and red portions of Figure 3-6, point sources, upstream inflows, and reaction product, are excluded from the analysis.

Table 3.6
Organic Carbon Load from Nonpoint Sources by Land Area

Land Use	Total Organic Carbon Load (lb/acre/year)
Deciduous Forest	3.09
Mixed Forest	5.02
Evergreen Forest	8.62
Orchard	5.95
Row Crops	19.11
Rice	104.60
Fallow	1.96
Shrub/Scrub	9.80
Grassland/Herbaceous	22.40
Marsh	2.15
Barren land	28.31
Confined Feeding	14.65
Water	2.69
Urban residential	6.43
Urban commercial/industrial	1.17

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. At Hamilton City, 55% of the organic carbon is from nonpoint sources, 43% is from upstream inflows, and 2% is from point sources. Organic carbon in the Colusa Basin Drain is essentially all from nonpoint source loading. Inflows from reservoirs and flood control weirs account for 82% of the organic carbon in the Yolo Bypass, with most of the remainder being nonpoint source load. At the Sacramento River at Freeport, 46% of the organic carbon is from nonpoint sources, 38% is from upstream inflows, and the remaining 16% from point sources.

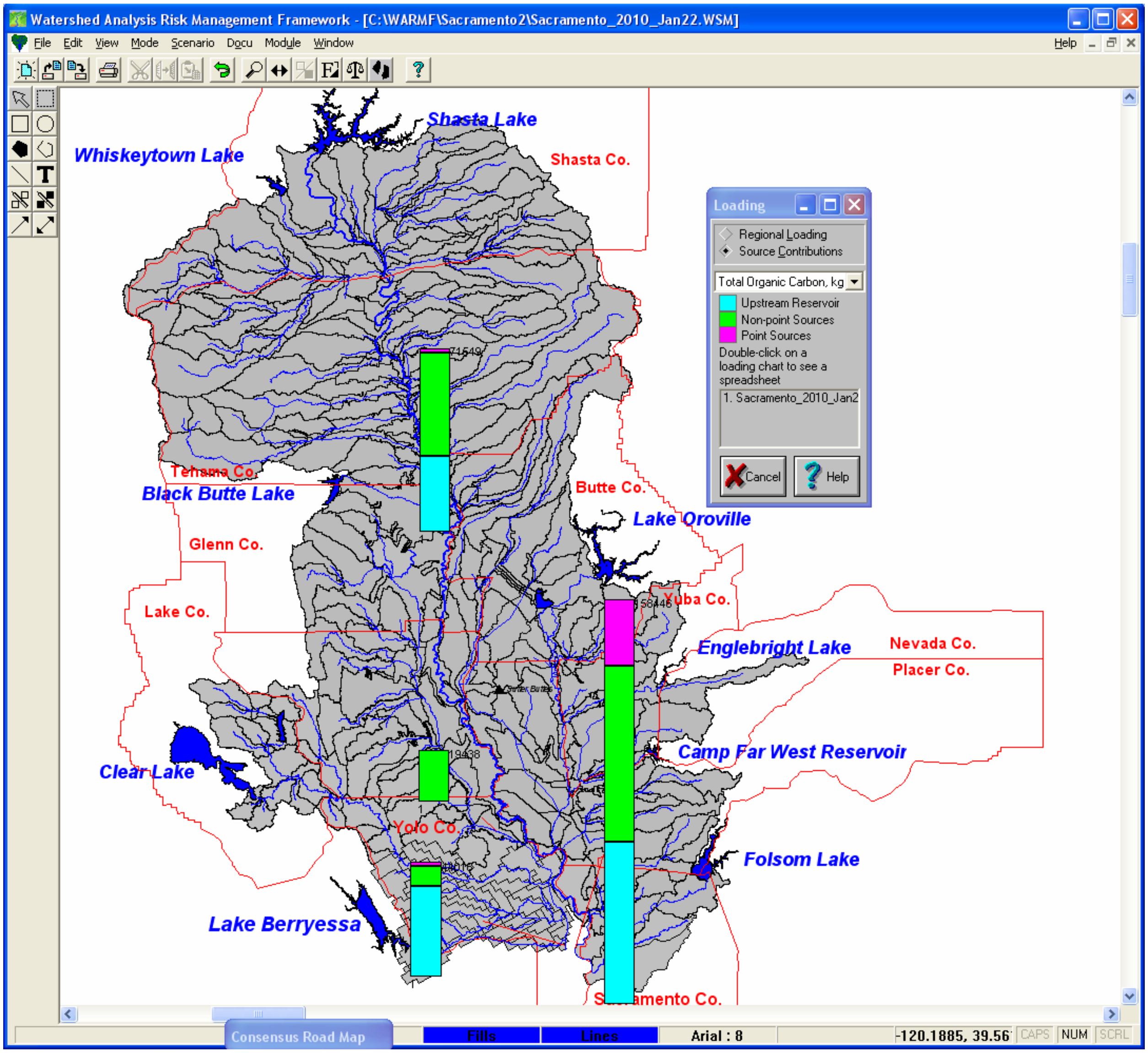

Figure 3-7 Source Contributions Loading of Organic Carbon

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

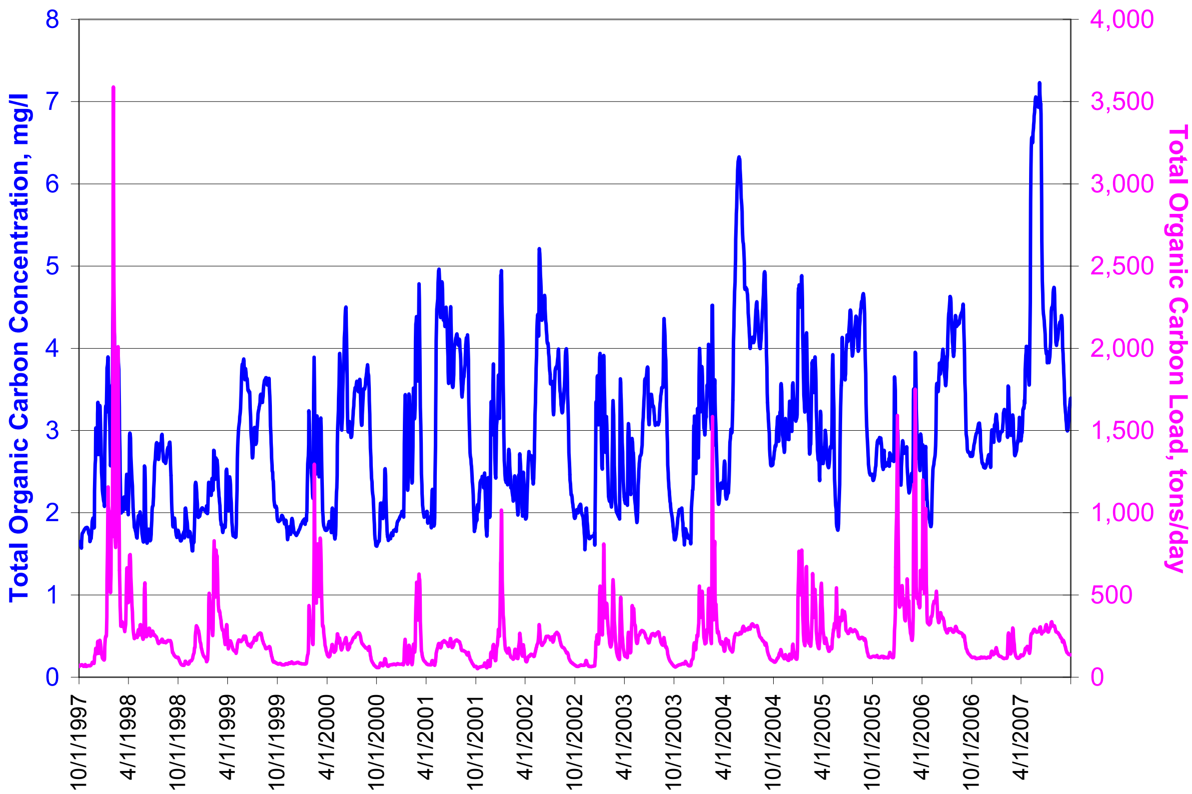

Figure 3-8 Total Organic Carbon Load (pink line) vs. Concentration (blue line) at Sacramento River at Freeport

Management Implication

The results of the source contribution analysis have implications for the management of the Sacramento River watershed. The sources of pollutants were identified, along with the loading from each source. This gave an indication of how the Delta might be vulnerable to additional loading and where reduction strategies should be focused.

When managing salinity, it may be important to consider its composition. Although drinking water utilities must comply with regulations on total dissolved solids, the inorganic carbon content of the treated water will be a function of pH and exposure to air. This inorganic carbon component of salinity thus may not be a concern in drinking water source protection.

There are various potential causes of future change to the water quality entering the Delta including changing land use, changing climate, new reservoir management, agricultural practice, or water quality improvement strategies. In reality, a combination of these changes will occur. The model calibrated to historical conditions brings some understanding on these issues because it clarifies the magnitude of the various sources and shows the intensity of loading coming from different land uses. The model can also be simulated using projected conditions as input to determine how loading might change from the present baseline.

Land Use

Table 3.4 and Table 3.6 show the nonpoint source loading coming from various land uses. As land use changes in the future, a quick assessment can be made on the likely impact by comparing the intensity of loading from the land use types which are increasing compared to the types which will be replaced. Specific local conditions can affect loading, however. The new land uses can be entered into WARMF to run a simulation comparing the projected future conditions against the past to determine the impact.

Climate Change

Climate change will bring a combination of warmer temperatures and changes in precipitation. It will affect water quality by changing the timing and magnitude of flow from the various sources of upstream inflows, agriculture, natural landscape, and urbanized areas. After all these sources combine in the Sacramento River, the resulting pollutant concentrations will be changed. Although there is relative agreement between climate models regarding projected temperature increase, there is more uncertainty about precipitation. Temperature increase leads to greater evaporation and transpiration, but this can be overcome if the precipitation increases. Some of the impacts of climate change would be seen in the timing and magnitude of upstream boundary inflows. Although the watersheds of the reservoirs around the Sacramento Valley are outside the WARMF model domain, screening level projections of water quality in the Sacramento River could be run under various assumptions of change in reservoir outflows combined with increased temperature.

Reservoir Management

Figure 3-3 and Figure 3-6 show that the boundary inflows are the source of substantial loading of salt and organic carbon to the Sacramento River. With changes in land use, irrigation patterns, climate, and environmental restrictions the timing and magnitude of reservoir releases may change in the future. A short or long term decrease in reservoir releases would increase the proportions of the various sources of pollutants in the watershed including agriculture, point sources, and urban areas. Simulations can be run in WARMF with alternate outflow schedules for the reservoirs to determine the impact upon concentration and loading to the Delta.

Agricultural Practice

The crops grown in the Sacramento Valley respond to changes in market demand and water supply. Each crop can have a different impact upon the water quality thanks to changes in irrigation water usage, fertilizer application, and productivity. Economic or environmental constraints may change how current crops are farmed, resulting in more efficient irrigation methods or reduced fertilizer usage. These changes can be simulated in WARMF to determine how these changes might affect water quality downstream.

Water Quality Improvement Strategies

Reducing nonpoint source loading under the existing land use configuration is a desirable approach to improving water quality. The source assessment using the calibrated WARMF model shows that point sources produce only 3% of the total salt loading and 9% of organic carbon loading. Best management practices such as the use of detention ponds to capture urban storm runoff and buffer strips to capture sediment and adsorbed pollutants can reduce nonpoint source loading. The WARMF model can simulate these changes to guide decision makers on the most effective pollution control methods to use given limited funds for implementation.

4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Data was collected for the Sacramento River watershed back to October 1, 1921 for future use 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. 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 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 calibration of the WARMF model showed good results for flow, temperature, total suspended sediment, organic carbon, and salinity. Flow calibration is very strong 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. The relative error of simulated total dissolved solids exceeded 10% at two locations, but this was explained by the relatively low EC/TDS ratio at these locations. The model's assumption of a uniform EC/TDS ratio introduces errors for cases such as the Feather River, with very low salinity, and the higher salinity Colusa Basin Drain. Model errors are greater for smaller tributaries for all simulated parameters because the calibration effort was focused on correctly predicting loading to the Delta. The model successfully simulates the different sources of flow and loading to the watershed between inflows from upstream reservoirs, point sources, nonpoint source loads from agricultural lands, and natural background nonpoint source load.

The sources of pollutants were analyzed with the calibrated model. The two major sources of salinity were inflows from upstream reservoirs (53% of loading) and nonpoint sources (43%). Point sources only contributed 3% of salinity load. The majority of the nonpoint source load of salinity came from natural land covers. 26% of the nonpoint source load (or 11% of the total load) came from rice farms. The largest source of organic carbon load was nonpoint sources (48%), with 27% from upstream inflows, 15% from in-stream organic matter production, and 9% from point sources. About 20% of the total organic carbon load came from rice lands.

Rice contributed disproportionate load because it uses more irrigation water than other crops and because the land was assumed to be barren when drained for the winter. The salinity and organic carbon in irrigation water is assigned to the land use on which it is applied in the model, so the load from individual land uses is largely a function of water usage. The assumption of barren land in winter resulted in sediment erosion from winter rains which carried with it adsorbed ions and organic carbon.

The simulated total dissolved solids at the Sacramento River at Freeport contained 63% inorganic carbon. Because this portion of salinity is of atmospheric origin as a function of pH, management of this salinity may need to take into account the portions under more direct management control.

Recommendations

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. Salinity control measures will only reduce inorganic carbon concentration if they happen to reduce pH. An analysis should be conducted of the drinking water treatment and distribution process to determine the degree to which inorganic carbon is a function of the source water as compare to the treatment and distribution process.

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 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, limited discharge information from a municipal point source upstream of this location and a lack of concurrent flow monitoring made it difficult to discern the specific source of the organic carbon. 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. Although model simulations do not indicate that urban nonpoint source pollution contributes a large amount of organic carbon loading to the Delta, there is relatively high uncertainty about which processes are important in urban areas. If continued study of urban organic carbon loading is pursued, it is recommended that the studies include flow monitoring, complete data collection from point sources, and analysis of the type of organic carbon measured to learn more about its origin. This would provide valuable information to constrain future modeling efforts.

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