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# San Joaquin River Water Quality Modeling: Suspended Sediment Modeling of San Joaquin River in Watershed Analysis Risk Management Framework (WARMF) Model

## Report 5.2.1

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## List of Acronyms

| | |
|---|---|
| $A$ | catchment area |
| $c$ | concentration |
| CDM | Cadmus & Group, Inc. |
| cfs | cubic feet per second |
| $C_j$ | cropping factor |
| $CN_k$ | condition number |
| $D_f$ | overland flow soil erosion |
| $D_r$ | rainfall soil erosion |
| EPA | United States Environmental Protection Agency |
| ET | evapotranspiration |
| $F_{fj}$ | flow detachment factor |
| $F_{rj}$ | rainfall detachment factor |
| ID | identification |
| $K$ | soil erosivity factor |
| $k$ | unperturbed parameter |
| $K_B$ | bank stability factor |
| kg | kilograms |
| $K_V$ | vegetation factor |
| L | liters |
| m | meters |
| mg | milligrams |
| min | minutes |
| mm | millimeters |
| NRCS | Natural Resources Conservation Service |
| $q$ | flow per unit width |
| $R$ | rainfall intensity |
| $r$ | correlation coefficient |
| $R^2$ | coefficient of determination |
| RMS | root-mean square |
| $S$ | ground slope |
| s | seconds |
| $S_B$ | bank erosion |
| SJR | San Joaquin River |
| SSURGO | Soil Survey Geographic Database |

| | |
|---|---|
| TMDL | total maximum daily load |
| $V_{AVE}$ | average river velocity |
| WARMF | Watershed Risk Management Framework |
| $\Delta c$ | average change in concentration |
| $\Delta k$ | amount of perturbation in parameter $k$ |

## Abstract

The objective of this project was to understand sediment transport behavior in the Watershed Analysis Risk Management Framework (WARMF) model of the lower San Joaquin River (SJR) between Vernalis and Mendota Pool, to identify areas for future improvement of model accuracy, and to understand the model's applicability to smaller tributaries. A sensitivity analysis was conducted on total suspended sediment in the San Joaquin River at Vernalis by perturbing soil erosivity factors and computing condition numbers. Geospatial soil data obtained from the Natural Resources Conservation Service was used to assess whether improved estimates of soil erosivity factors and particle content fractions would improve model accuracy for total suspended sediment in the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, and Orestimba Creek. A water budget was performed on Hospital Creek, Ingram Creek, and Orestimba Creek to identify flow sources.

The study found that the model was not previously calibrated on a subwatershed scale to calculate total suspended sediments based on the existing soil erosivity, particle content, vegetation factor, and bank stability factors within the model. The inclusion of soil data did not improve the model accuracy for suspended sediments in the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, or Orestimba Creek. Simulated flow in Hospital Creek, Ingram Creek, and Orestimba Creek did not match observed data. While catchments with strong connections to creek outflows were identified, connections to water sources such as precipitation and runoff could not be identified. Thus, while the model had good accuracy for simulating phytoplankton, temperature, and flow in the San Joaquin River at Vernalis as established in previous studies, its applicability on a large scale for suspended sediment and a smaller scale for flow and suspended sediment needs improvement.

## Introduction

Sediment transport models are important for understanding nutrient cycles and predicting fate and transport of pesticides. Phosphorus, an important nutrient for phytoplankton and plants, becomes available in aquatic systems through erosion and sediment resuspension. Phosphorus that is transported to the oceans and not utilized by phytoplankton is deposited on the ocean floor, where it exits the phosphorous cycle and can no longer be utilized. Agricultural runoff carries excess fertilizer, which is rich in phosphorus, resulting in eutrophication of lakes and streams (Ricklefs & Miller, 2000). On a global scale, sediments carried by streams contribute to coastline formation. Recent research suggests that anthropogenic impoundments have disrupted this process through sediment retention, resulting in coastlines retreating throughout the world (Vörösmarty et al., 2003; Syvitski et al., 2005). A study by Barnard et al. (2012) on the coastal erosion of a 1 km segment of Ocean Beach in San Francisco suggests that 0.25 billion $m^3$ of sediment in the mouth of the San Francisco Bay had eroded over the last 50 years and damming of reservoirs on the Sacramento and San Joaquin Rivers and aggregate mining have reduced sediment loads, thus contributing to the coastal retreat.

In the San Joaquin River, accurate model simulations of total suspended sediments (suspended sediments) are needed to model pesticide transport. In 2002, the California Central Valley Regional Water Quality Control Board added the Lower San Joaquin River and its tributaries from Mendota Dam to the Airport Way Bridge near Vernalis to the Federal Clean Water Act's 303(d) list of impaired water bodies for toxicity caused by the pesticides diazinon and chlorpyrifos. This resulted in the implementation of total maximum daily loads (TMDL) to prevent further degradation (Beaulaurier et al., 2005). Pesticides from precipitation runoff from December through February and irrigation runoff from March through September are adsorbed to sediment particles and transported downstream, resulting in declines in fish and invertebrate populations (Beaulaurier et al., 2005; Weston & Lydy, 2010). Ensminger et al. (2011) found that pyrethroid pesticides were detected six times more frequently in the sediments than in the water at Orestimba Creek and Del Puerto Creek, and all but one sediment sample was lethal to the invertebrate *H. azteca* during toxicity tests. Bergamaschi et al. (2001) found that large "first-flush" storms in 1996 after a prolonged dry period resulted in sediment-adsorbed pesticides being transported downstream to the San Francisco Bay. Thus, there is an urgent need for improved pesticide simulations to meet TMDL objectives and protect the aquatic ecosystem from further harm.

The objective of this study was to understand how suspended sediment transport is simulated in the Watershed Analysis Risk Management Framework (WARMF) model of the San Joaquin River watershed in California. Systech Engineering developed WARMF as a water quality and hydraulic model to assess whether changes in water demand, land management, and the use of oxygen aeration systems would improve dissolved oxygen levels as part of the San Joaquin River TMDL dissolved oxygen study (Stringfellow et al., 2009). WARMF is designed for policy makers and stakeholders to assess the effectiveness and risk of strategies for compliance with TMDL's (Systech, 2001). Previous studies have validated the model's accuracy for simulating phytoplankton, temperature, and flow in the San Joaquin River at Vernalis, but there was 40% absolute error in Systech's initial calibration of the model for suspended sediment to the existing 2000-2005 data set, indicating that potential exists for improvement (Stringfellow et al., 2009;

Herr et al., 2008). In addition, the model's applicability to smaller upstream tributaries, an important component for future use of the model to compare strategies for complying with pesticide TMDL's or for studies on nutrient cycling, was unknown. A sensitivity analysis was conducted on soil erosivity to identify where improvements in soil erosivity estimates throughout the model would improve the simulated results for suspended sediment at Vernalis. Soil Survey Geographic (SSURGO) data obtained from the United States Department of Agriculture, Natural Resources Conservation Service (NRCS) was analyzed geospatially for determining appropriate model coefficients to determine if an improvement in model accuracy occurred at the San Joaquin River at Vernalis, Hospital Creek, Orestimba Creek, and Ingram Creek. Finally, a water budget was conducted on Hospital, Orestimba, and Ingram Creek to identify where improvements in catchment delineation and connectivity would improve simulated suspended sediment results.

## Materials and Methods

### *WARMF Model*

The current version of the SJR-WARMF 2012 model consists of a combination of the WARMF software developed for the United States Environmental Protection Agency (EPA) and the Link-Node estuary model developed in the 1990's for earlier studies (Herr et al., 2008). WARMF was used to model the watershed of the San Joaquin River and its tributaries between Old River and Bear Creek, where tides do not significantly affect the simulation results, and upstream constituents have a significant effect on downstream dissolved oxygen in the Delta— a focus of TMDL studies. The Link-Node estuary model simulates hydraulics and water quality from the Old River confluence to Rindge Tract in the Delta, where tides are significant.

The model consists of hydrologically connected catchments, stream segments, and reservoirs with coefficients and initial conditions for land use, soil layers, sediment transport parameters, flow sources and diversions, meteorology, stage-flow relationships, and reaction rates. Model output consists of time-series plots of flow and constituents along with observed water quality and hydraulic data, and plots of simulated results versus observed data with absolute errors, relative errors, root-mean square (RMS) errors, and coefficients of determination ($R^2$) to assist with model calibration. In addition, the model can simulate constituents along a river reach at a point in time using the Gowdy/longitudinal output function.

This study was conducted using the WARMF 2012 model in the non-tidal portion of the model between the San Joaquin River at Mendota Pool (River ID 60) and the San Joaquin River at Vernalis (River ID 184). The San Joaquin River at Vernalis was selected as a point of interest due to an abundance of historical hydraulic and water quality data, as well as its downstream location in the watershed. Model simulations were conducted by copying an existing scenario, usually the baseline scenario provided by Systech Engineering, altering the model coefficients based on the objectives of the simulation, and running the model. All scenarios were run from October 1, 2005 through December 31, 2010. The model simulations included the following subwatersheds in the WARMF dialog box for running simulations: San Joaquin River 360, DMC connector to MP, San Joaquin River near Mendota, CCID Main Canal blw O'Banion, Hensley Lake, San Joaquin River near Stevinson, San Joaquin River at Crows Landing, Orestimba Creek near Crows Landing, and San Joaquin River at Vernalis. Merced River, Tuolumne River at Modesto, Stanislaus River, San Joaquin River at Old River, Channel 441, and SAN JOAQUIN R watersheds were excluded to speed up simulation time as these watersheds do not have significant contributions to downstream locations (Herr, personal communication). A summary of the scenarios used in this study is shown in Table 1. Since the purpose of this study involved comparisons with the Base scenario, no warm start files were utilized.

### ***Sediment Equations***

#### *Soil Erosion*

Systech Engineering has documented WARMF's processes for water quality and hydrologic simulations in a topical report (Systech, 2001). WARMF calculates soil erosion using the universal soil loss equation developed by the Soil Conservation Service. Rainfall soil erosion, $D_r$ (kg $s^{-1}$), is calculated using Equation 1:

$$D_r = \frac{KAR^2}{60} \sum_{j=1}^{n} F_{rj} C_j \quad (1)$$

where $K$ is the soil erosivity factor, $A$ is the catchment area in $m^2$, $R$ is the rainfall intensity in mm $min^{-1}$, $F_{rj}$ is the rainfall detachment factor with values 0.108 used for exposed soils and 0 used for all other cases, and $C_j$ is the cropping factor with values 0.1 used for contour plowing and 0.9 used for poor land management practice.
Overland flow soil erosion, $D_f$ (kg $s^{-1}$), is calculated using Equation 2:

$$D_f = KASq \sum_{j=1}^{n} F_{fj} C_j \quad (2)$$

where $S$ is the ground slope, $q$ is flow per unit width in $m^2$ $min^{-1}$, and $F_{fj}$ is the flow detachment factor, normally taken to be 0.9. Deposition can occur again if the transport capacity of the overland flow is exceeded. Thus for both equations for catchment erosion, $K$ is directly proportional to the amount of eroded sediments provided that enough transport capacity exists. For river output, WARMF calculates the bank erosion, $S_B$ (kg $s^{-1}$), using Equation 3:

$$S_B = (K_V + K_B) V_{AVE}^3 \quad (3)$$

where $K_V$ is the vegetation factor, $K_B$ is the bank stability factor, and $V_{AVE}$ is the average river velocity in m $s^{-1}$. From this equation, it is evident that the model will not simulate bank erosion if $K_V$ and $K_B$ are both zero.

### ***Model Data***

The WARMF model included observed water quality data from five different sources, spanning 1984 to 2012. The total maximum daily load (TMDL) study data from 2005 to 2007 was selected for statistical comparison with simulation results, as it was considered more consistent than the other data sets (Stringfellow et al., 2009). The modified observed water quality data file names and their corresponding original file names are summarized in Table 2. To include the modified data files in WARMF, the original data files were backed up, then the modified data files were renamed as the original data files and moved to the San Joaquin folder in the WARMF install directory.

***Sensitivity Analysis***

The sensitivity analysis was performed by computing the condition number as presented by Chapra (2008). The condition number, $CN_k$, is expressed in Equation 4 as a transfer function that propagates the relative error in a parameter to the relative error of a calculated result:

$$\frac{\Delta c}{c} = CN_k \frac{\Delta k}{k} \tag{4}$$

where $k$ is the unperturbed parameter of interest, $\Delta k$ is the amount of perturbation in parameter $k$, $c$ is the concentration that is a function of one or more variables including $k$, and $\Delta c$ is the average change in $c$ resulting from the perturbation of $k$. The change in the concentration is expressed in Equation 5:

$$\Delta c = \frac{c(k + \Delta k) - c(k - \Delta k)}{2} \tag{5}$$

where $c(k+\Delta k)$ is the concentration due to an increase in $k$ due to perturbation $\Delta k$ and $c$(k- $\Delta k$) is the concentration due to a decrease in $k$ due to perturbation $\Delta k$. A condition number with an absolute value close to 1 indicates little to no sensitivity of parameter $k$ to the concentration. A negative sign on the condition number indicates that an increase or decrease in $k$ inversely affects the concentration. Condition numbers range from negative infinity to positive infinity, with higher magnitudes of condition numbers indicating greater sensitivity. The condition number can also be used for a first-order analysis, instead of parameter perturbation, by computing the partial derivative of the concentration with respect to the change in $k$. Analytical computation of this partial derivative for each desired condition number was impractical due to the complexity of the model, so the parameter perturbation version was selected instead.

The condition number was calculated for the sensitivity of total suspended sediments in the San Joaquin River at confluence points and at Vernalis by copying the base daily scenario two times, increasing the soil erosivity for all catchments in one scenario by 20% of its original value in the Err+20 scenario, and decreasing the soil erosivity for all catchments in the Err-20 scenario by 20% of its original value. 20% was chosen as the amount of perturbation based on Equation 2. For example, when the erosivity for all catchments in the model were perturbed by ±0.04 from its original value of 0.20, the suspended sediment in the San Joaquin River at Vernalis which was 277.47 mg $L^{-1}$ during the Base scenario, turned out to be 323.86 mg $L^{-1}$ during the Err+20 scenario, and 230.84 mg $L^{-1}$ during the Err-20 scenario in one of the days:

$$CN = \frac{k}{c}\frac{\Delta c}{\Delta k}$$
$$\Delta c = \frac{c(k + \Delta k) - c(k - \Delta k)}{2}$$
$$k = 0.20$$
$$\Delta k = 0.04$$
$$c(k) = c(0.20) = 277.47 \text{ mg L}^{-1}$$
$$c(k + \Delta k) = c(0.24) = 323.86 \text{ mg L}^{-1}$$
$$c(k - \Delta k) = c(0.16) = 230.84 \text{ mg L}^{-1}$$
$$CN = \frac{(0.20)}{(277.47 \text{ mg L}^{-1})}\frac{(323.86 \text{ mg L}^{-1}) - (230.84 \text{ mg L}^{-1})}{2\ (0.04)}$$
$$\boxed{CN = 0.838}$$

A perturbation too small was more likely to result in the condition number failing to indicate sensitivity due to floating-point round-off error from the subtraction in the numerator of Equation 2, whereas a perturbation too large would result in the condition number failing to describe the local behavior of the concentration with respect to $k$. WARMF's Gowdy/Longitudinal output mode was used to identify tributaries where parameter estimates have the greatest effect on the accuracy of the simulation.

### *Model Verification*

#### *Hospital Creek to Newman Wasteway*

During the sensitivity analysis, it was noted that the soil erosivity and particle content coefficients for each catchment throughout the model were the same, as reported by Herr et al. for WARMF 2008 (2008). In the soil study scenario, soil erosivity and average particle content data previously generated from geospatial analysis of the SSURGO database were used between Hospital Creek and Newman Wasteway at Brazo Road. Table 3 shows which values were used in coefficients for catchments connecting to tributaries upstream of each site location (Hanlon and Stringfellow, 2009). Soil erosivity values for these sites varied from 0.28 to 0.43— all of which were higher than the default value of 0.20 in the model. Average sand fractions ranged from 27.5% to 83.8%, average silt fractions ranged from 11.59% to 34.64%, and average clay fractions ranged from 4.59% to 44.29%, which were different from the soil particle content fractions of 40%, 40%, and 20%, used as default for sand, silt, and clay respectively throughout the model. To assess model improvement, the coefficient of determination ($R^2$) of the Soil Study scenario was compared against the coefficient of determination for the Base scenario in the San Joaquin River at Vernalis. The catchments used in the model verification are shown in Figure 1; a key for soil site locations identified in Table 3 and corresponding tributaries and catchments in WARMF are shown in Table 4.

#### *Individual Studies on Orestimba, Hospital, and Ingram Creek*

To verify the model at a smaller scale, Orestimba Creek near Crows Landing (River ID 165), Hospital Creek (River ID 305), and Ingram Creek (River ID 313) were selected as the focus for further data analysis. Figure 2 through Figure 5 and Table 4 show how stream segments are defined in WARMF and how catchments connect to the streams. An error analysis was conducted on the total suspended sediments and flow in the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, and Orestimba Creek by computing the relative error and absolute error between the Base and Soil Study scenarios. As with the study on the San Joaquin River from Hospital Creek to Newman Wasteway (River ID 259), the $R^2$ for suspended sediment output at Hospital Creek, Ingram Creek, and Orestimba Creek for the Soil Study scenario was compared against the $R^2$ for suspended sediment output for the Base scenario. Some site locations do not have corresponding streams represented in the model, as their watershed areas are small and do not contribute much to the model (Herr, personal communication). In addition, some tributaries in the model, such as the MID Main Canal Spill (River ID 209), do not have any identifiable connections to nearby catchments.

### *Water Budget Analysis*

A water budget analysis was performed on Hospital Creek, Ingram Creek, and Orestimba Creek in the Water Budget scenario to identify flow sources within the model. The subwatersheds for Hospital Creek, Ingram Creek, and Orestimba Creek are shown in Figure 3 through Figure 5 with catchment IDs and arrows showing connections to streams. Catchment output was enabled so that the model would calculate outflow, irrigation flow, precipitation, and evapotranspiration (ET) from each catchment. Tables of correlation coefficients were calculated for each creek between creek outflow and catchment outflow, irrigation, precipitation, and ET to identify which catchment(s) were dominant in contributing to creek outflow. In addition, correlation coefficients were calculated between managed flow sources in catchments with water application and catchment outflow.

## Results

## Sensitivity Analysis

### *Total Suspended Sediments at Vernalis*

A plot of the simulated suspended sediment vs. the observed total suspended solids for the San Joaquin River at Vernalis for the Base, Err+20, and Err-20 scenarios is shown in Figure 6. The $R^2$ value increased from 0.093 to 0.095, indicating that the model may be over-estimating suspended sediments at Vernalis. The mean decreased from 40 mg $L^{-1}$ to 38 mg $L^{-1}$ between the Base and Err-20 scenarios, and increased to 41 mg $L^{-1}$ for the Err+20 scenario. Time series plots of the suspended sediment in the San Joaquin River at Vernalis from the Base scenario and the condition number resulting from the Err+20 and Err-20 scenarios are shown in Figure 7. The mean condition number during the simulation period was 0.11, indicating that about 11% of the relative error in soil erosivity was transferred to the suspended sediment concentration on average throughout the simulation period and this mean was influenced by events such as precipitation resulting in peak concentrations.

Since the condition number was positive throughout the time series, soil erosivity was directly related to the suspended sediment concentrations; an increase in soil erosivity resulted in an increase in suspended sediment due to erosion, consistent with Equations 1 and 2. The maximum suspended sediment peak on 12/14/2009 was 278 mg $L^{-1}$ with a condition number of 0.84, the maximum condition number in the time series. The source of this pulse was traced to the Chowchilla River West Fork (River ID 8) using WARMF's Gowdy/Longitudinal output mode; the flow rate, depth, suspended sediment, and condition number time series plots for the Chowchilla River West Fork are shown in Figure 8. In parts of the time series plot, the condition number became very large or infinite, indicating high sensitivity at this location. This may result from low water depth in the river, where suspended sediment is immeasurable.

### *Gowdy/Longitudinal Output*

The results of the Gowdy/Longitudinal output analysis are shown in Table 5, sorted descending by average condition number. Condition numbers calculated from missing data and infinite or indeterminate condition numbers resulting from division by zero were excluded from the analysis. The largest condition numbers occurred at Newman Wasteway, with condition numbers ranging 0.00 to 2.5 and a mean condition number of 1.05, indicating that a 20% error in estimating soil erosivity in the catchments connected to this location would result in a 20% error in suspended sediment. Six tributaries consisting of agricultural drains and spills had condition numbers higher than 0.5, indicating that the suspended sediment at Vernalis is more sensitive to changes in soil erosivity near the San Joaquin River. One possible explanation for this is that constituents such as suspended sediment disperse over long distances due to random molecular motion and deposit in stream beds and banks, resulting in lower concentrations downstream than at the source.

Table 6 includes a summary of the mean suspended sediment concentrations and condition numbers for 12 sites indicated in the Gowdy/Longitudinal output for further analysis due to high condition numbers at their confluence points in addition to the San Joaquin River at Vernalis and the Chowchilla River West Fork. Owens Creek (River ID 12) and Burns Creek (River ID 5) had the largest amount of suspended sediment of 172 mg $L^{-1}$ and 98 mg $L^{-1}$ respectively. Burns Creek had the highest condition number at 2.4, indicating high sensitivity to changes in soil erosivity. The condition number was 0.43 downstream at the confluence of Bear Creek and the San Joaquin River, indicating that dispersion likely influences suspended sediment in the watershed model.

### *Model Verification*

A summary of the error analysis for the Base and Soil Study scenarios in the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, and Orestimba Creek is presented in Table 7. The San Joaquin River at Vernalis had a relative error of -1.1 mg $L^{-1}$, indicating that the Base scenario under-predicts the suspended sediment concentrations used in the Soil Study scenario, and an absolute error of 1.3 mg $L^{-1}$. Ingram Creek had a large mean relative error of -3,406 mg $L^{-1}$ and mean absolute error of 3,406 mg $L^{-1}$ indicating poor agreement between the two scenarios. Even though only soil erosivity and particle content values were different between the Base and Soil Study scenarios, the simulated flow was different throughout the model. The absolute error for flow in the San Joaquin River at Vernalis, Ingram Creek, and Orestimba Creek was 41 cfs, 14 cfs, and 3.0 cfs respectively, indicating large differences.

Figure 9 through Figure 12 consist of time series plots of the percent difference in suspended sediment in the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, and Orestimba Creek. The pattern of the time series plot for suspended sediment at Vernalis indicates that differences are most apparent at specific times of year, rather than changing baseline suspended sediment conditions (Figure 9). This plot includes both positive and negative percent differences, indicating that the Base scenario both over-predicts and under-predicts suspended sediment throughout the study area. At Hospital Creek, differences are only evident during two time periods in May 2006 and May 2010 (Figure 10). Ingram Creek has percent differences in suspended sediment up to 70,000% due to the change in flow resulting from periods of zero water depth (Figure 11). Orestimba Creek has more periods where the model under-predicts suspended sediment more than it over-predicts, which is unusual since the soil erosivity and clay fractions are larger in the Soil Study scenario than in the Base scenario (Figure 12). The cause of this is unknown.

Correlation plots between simulated and observed flow and simulated suspended sediment and observed total suspended solids for the San Joaquin River at Vernalis, Hospital Creek, Ingram Creek, and Orestimba Creek are shown in Figure 13 through Figure 20. The inclusion of soil data had little effect on the model accuracy; the $R^2$ value for suspended sediment at the San Joaquin River at Vernalis increased from 0.092 to 0.128 between the two scenarios (Figure 14). There was little difference in suspended sediment at Hospital Creek and Orestimba Creek, but $R^2$ at Ingram Creek decreased from 0.0807 to 0.0259 (Figure 18). The Soil Study scenario resulted in low flow and zero depth in Ingram Creek as shown in Figure 21 and Figure 22, resulting in instability of WARMF's prediction of suspended sediment as shown in Figure 23, as evident by the discontinuous simulation output. Simulated vs. observed flow for Hospital, Ingram, and Orestimba Creek in Figure 15, Figure 17, and Figure 19 have $R^2$ values of less than 0.554 and 0.617 for the Base and Soil Study scenarios respectively, indicating poor model accuracy, and prompting further investigation of flow sources.

***Water Budget***

Summary statistics for the water budget analysis for Hospital, Ingram, and Orestimba Creek are presented in Table 8 through Table 10 and correlation coefficients ($r$) between flow sources are presented in Table 11 through Table 13. Catchments with large standard deviations relative to mean outflow indicate periodic contribution to flow, whereas catchments with smaller standard deviations contribute to base flow.

Both catchments 251 and 220 had highly variable flows with standard deviations over 10 cfs while catchment 189 had smaller, less variable flows (Table 8). Catchment 251 had a high correlation with the outflow of Hospital Creek with an $r$ value of 0.95; both the strong correlation and large flows indicated that this catchment governed flow in Hospital Creek. Catchment 220 had an $r$ value of 0.75 when compared to Hospital Creek outflow, indicating that it also influenced outflow, though not as strongly as catchment 251.

Catchment 255 produced the largest and most variable flows in Ingram Creek, with a mean catchment outflow of 6.3 cfs and a standard deviation of 25 cfs. This catchment also had the strongest correlation with the outflow of Ingram Creek with an $r$ value of 0.95, indicating that it likely governed flow; catchment 200 has an *r* value of 0.73, indicating that it was moderately connected to the creek outflow.

Catchments 983 and 979, with mean outflows of 10 cfs and 7.4 cfs respectively, and *r* values over 0.90, contributed to over half of the 30.7205 cfs mean outflow in Orestimba Creek. Catchments 959 and 963 have mean outflows of 1.5 cfs and 3.5 cfs respectively and *r* values of 0.80, indicating they are moderately connected to Orestimba Creek, but not as much as Catchments 983 and 979. Precipitation did not have a strong correlation with outflow for Hospital or Ingram Creek; the largest correlation coefficient value was 0.35.

While the catchments making the largest contributions could be identified, the flow source within each catchment had not been identified. Table 14 consists of correlation coefficients between the outflow, irrigation, and evapotranspiration of catchment 220, which is connected to Hospital Creek, and managed flow from Del Puerto Water District supplied by the Delta Mendota Canal (River ID 180) and groundwater pumping, which are used by WARMF to calculate water application rates for irrigation. The groundwater pumping data was recorded on the first day of each month; to compare this with the rest of the data, each data value was repeated for the remaining days of the month. Both of the managed flow sources had weakly negative *r* values less than 0.30 when compared to catchment 220 outflow, indicating that if any connection exists, managed flow increases when catchment outflow decreases.

## Conclusion

### *Discussion*

The lack of calibration of sediment parameters and poor model accuracy for flow in individual tributaries suggests that fundamental problems exist in the model and thus more work is needed to improve the model on a smaller scale. Prior to the study, it was assumed that the soil erosivity and particle content coefficients were calibrated on a subwatershed scale; further investigation revealed that this was not the case, as all of the soil erosivity and particle content coefficients were the same throughout the model. In addition, the vegetation and bank stability factors for rivers were found to be zero for all catchments. In a WARMF TMDL modeling project for Hangman (Latah) Creek in Washington and Idaho, Camp, Dresser, and McKee (CDM) used the vegetation and bank stability factors as calibration parameters for their model, using initial bank stability values ranging from 0.0027 to 0.0003 (Cadmus and CDM 2007a; Cadmus and CDM 2007b). Thus, the absence of parameters indicates that the model was not set up to calculate bank erosion and suspended sediment was not fully calibrated.

While it may be possible that this contributes to the 40% absolute error Systech calculated during model calibration at Vernalis, the lack of change in $R^2$ between the Base Scenario and the Soil Study scenario suggests that improvements to soil erosivity and particle content have limited potential for improving model accuracy at Vernalis, even though the soil erosivity values from the soil survey data were 1.5 to 2 times higher than the original soil erosivity values. This suggests that other model parameters, such as flow, sediment settling velocities, soil particle size definitions, catchment to stream connections, or land use may need adjustment to calibrate the model for suspended sediment. Improvements in sampling accuracy and precision for observed data may also be needed.

The difference in flow between the Base and the Soil Study scenarios at Ingram Creek and Orestimba Creek was not anticipated, as changes to soil erosivity and particle content can alter flow through channel geometry changes resulting from deposition, which is small. The error analysis indicated poor model agreement for flow in Hospital, Orestimba, and Ingram Creek, prompting the need for a water budget analysis to understand possible causes. While individual catchments were identified as having strong connections to creek outflow, dominant sources of flow such as precipitation and irrigation runoff could not be identified. Upon inspection of catchment areas and connections for Hospital and Ingram Creek, it was noted that some catchments, such as catchment 200, contain sections of both Hospital and Ingram Creek, but only contribute to one of them, indicating the need for ground proofing the local hydrology (Stringfellow, personal communication). This is also needed to model tributaries that do not have catchment connections.

### *Future Work*

Future efforts on model improvement should consider first focusing on improving flow accuracy by revising existing catchment delineations, revising existing catchment connections, and identifying gaps in data for managed flow and irrigation. Once the validity of the model for flow is established, the soil erosivity and particle content data for catchments and soil detachment coefficients for streams can then be entered.

As with the Hangman (Latah) Creek project, the vegetation and bank stability factors for rivers can be used as calibration parameters by performing multiple simulations and adjusting them until the model is optimized. If necessary, sediment properties such as particle size, specific gravity, and settling velocities can be adjusted. Finally, the reliability of the model can be tested by obtaining new observed data from different years for flow and sediments and verifying the model's accuracy and precision for all constituents of interest, including the main constituents modeled for the San Joaquin River Dissolved Oxygen TMDL project.

Once desirable accuracy and precision is attained, the WARMF model will have greater utility for finding economically feasible options to meet TMDL objectives for pesticides and to mitigate or prevent eutrophication in water bodies by regulating phosphorus from agricultural drainage. As the model is further developed to include reservoir modeling of the eastern and western tributaries, WARMF can be used to assess the effect of sediment retention in reservoirs on the sediment budget for the Delta and the San Francisco Bay to address problems with coastal retreat.

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**Table 1.** Summary of WARMF scenarios used in study and corresponding file names.

| Scenario Name | File Name | Description |
|---|---|---|
| **Base** | San_Joaquin_2012Apr30_Daily.COE | Baseline scenario provided by Systech Engineering without modifications to model coefficients. |
| **Err+20** | AllErr+20.COE | Base scenario modified with 20% increase in soil erosivity values for all catchments in model for sensitivity analysis. |
| **Err-20** | AllErr-20.COE | Base scenario modified with 20% decrease in soil erosivity values for all catchments in model for sensitivity analysis. |
| **Soil Study** | Daily_with_soil_data_3.COE | Base scenario modified with soil study data included for model verification. See Table 3, Table 4, and Figure 1. |
| **Water Budget** | Daily_w_Catch.COE | Base scenario modified with catchment output enabled for catchments connecting to Hospital, Ingram, and Orestimba Creek (River IDs 175, 305, 176, 313, 304, 164, and 165) for model verification. See Figure 3 through Figure 5. |

**Table 2.** Observed water quality data files used in study. The new data files were copied from the original files and the 2005-2007 TMDL data was isolated. The original files correspond to water quality data files included in the WARMF installation. The original files were backed up and the new data files were moved to the same location of the original files and renamed as their original file name.

| New Data File Name | Original File Name |
|---|---|
| San Joaquin at Vernalis 2005-2007.ORC | San Joaquin at Vernalis.ORC |
| Hospital 2005-2007.ORC | Hospital.ORC |
| Ingram 2005-2007.ORC | Ingram.ORC |
| Orestimba near Crows Landing 2005-2007.ORC | Orestimba near Crows Landing.ORC |

**Table 3.** Soil characteristics of site locations used for model verification in Soil Study scenario (Hanlon & Stringfellow, 2009). See Table 1 for scenario descriptions and Table 2 for catchments corresponding to the above site locations.

| Site No. | Site Location | Side | Latitude | Longitude | Area (ac) | Soil Erosivity | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|---|
| **21** | Orestimba Creek at River Road | West | 37.414 | -121.015 | 6,771 | 0.37 | 35.4 | 34.6 | 30.0 |
| **25** | MID Main Drain to Stan. R. via Miller Lake | East | 37.640 | -121.190 | 13,899 | 0.37 | 65.7 | 21.3 | 13.0 |
| **28** | Turlock ID Westport Drain Flow Station | East | 37.542 | -121.094 | 14,694 | 0.41 | 69.4 | 20.8 | 9.9 |
| **29** | Harding Drain at Carpenter Rd. | East | 37.464 | -121.031 | 108,865 | 0.38 | 69.5 | 19.8 | 10.7 |
| **30** | Turlock ID Lateral 6 & 7 at Levee | East | 37.397 | -120.961 | 20,738 | 0.43 | 83.8 | 11.6 | 4.6 |
| **32** | El Solyo WD - Grayson Drain | West | 37.578 | -121.177 | 2,423 | 0.29 | 24.5 | 31.6 | 43.9 |
| **33** | Hospital Creek | West | 37.609 | -121.230 | 2,335 | 0.35 | 30.0 | 33.8 | 36.2 |
| **34** | Ingram Creek Flow Station | West | 37.600 | -121.225 | 7,159 | 0.34 | 31.4 | 33.9 | 34.7 |
| **35** | Westley Wasteway Flow Station | West | 37.558 | -121.164 | 3,287 | 0.37 | 31.8 | 33.4 | 34.7 |
| **36** | Del Puerto Creek Flow Station | West | 37.539 | -121.122 | 6,080 | 0.39 | 40.6 | 33.2 | 26.2 |
| **38** | Marshall Road Drain | West | 37.436 | -121.036 | 6,645 | 0.34 | 30.9 | 33.2 | 35.9 |
| **39** | Salado Creek Flow Station | West | 37.508 | -121.089 | 5,596 | 0.32 | 31.1 | 31.3 | 37.6 |
| **57** | Ramona Lake Drain at Levee | West | 37.479 | -121.069 | 3,615 | 0.28 | 25.1 | 30.6 | 44.3 |
| **64** | Moran Drain | West | 37.435 | -121.036 | 415 | 0.40 | 46.8 | 34.2 | 18.9 |
| **65** | Spanish Grant Drain | West | 37.436 | -121.036 | 9,248 | 0.34 | 30.4 | 31.6 | 38.1 |
| **66** | ESWD Maze Blv. Drain | West | 37.641 | -121.229 | 660 | 0.33 | 27.5 | 33.2 | 39.3 |
| **67** | Newman Wasteway at Brazo Road | West | 37.304 | -120.996 | 9,635 | 0.35 | 32.4 | 32.1 | 35.4 |

**Table 4.** Soil site locations with corresponding tributaries and catchments in WARMF for Soil Study scenario. See Table 1 for scenario descriptions, Table 3 for soil erosivity and particle content values used, and Figure 1 for a map of catchments corresponding to the above site locations.

| Site No. | Site Location | Tributaries | River ID's | Connected Catchment ID's |
|---|---|---|---|---|
| **21** | Orestimba Creek at River Road | Orestimba Creek near Crow's Landing | 165 | 979, 959, 829, 981, 963, 853, 980, 804 |
| | | Orestimba Creek near Newman | 164 | 983 |
| **25** | MID Main Drain to Stan. R. via Miller Lake | MID Main Canal Spill | 209 | |
| **28** | Turlock ID Westport Drain Flow Station | TID Lateral 3 (Westport) Drain | 204 | 418, 587, 771, 767 |
| **29** | Harding Drain at Carpenter Rd. | TID Harding Drain | 202 | 773, 765, 762 |
| **30** | Turlock ID Lateral 6 & 7 at Levee | TID Lateral 6 & 7 Spill | 198 | 763, 764, 760, 758, 811 |
| **32** | El Solyo WD – Grayson Drain | | | |
| **33** | Hospital Creek | Hospital Creek | 305 | 189 |
| | | Hospital Creek below I-580 | 175 | 251, 220 |
| **34** | Ingram Creek Flow Station | Ingram Creek | 313 | 200 |
| | | Ingram Creek below I-5 | 176 | 255 |
| **35** | Westley Wasteway Flow Station | Westley Wasteway | 206 | 954 |
| **36** | Del Puerto Creek Flow Station | Del Puerto Creek | 339 | |
| | | Del Puerto Creek below I-5 | 174 | 958, 835 |
| **38** | Marshall Road Drain | Marshall Road Drain | 201 | |
| **39** | Salado Creek Flow Station | Salado Creek | 334 | 831, 814, 833 |
| **57** | Ramona Lake Drain at Levee | | | |
| **64** | Moran Drain | Moran Drain | 199 | |
| **65** | Spanish Grant Drain | Spanish Land Grant Drain | 196 | 965, 964, 962, 982 |
| **66** | ESWD Maze Blv. Drain | | | |
| **67** | Newman Wasteway at Brazo Road | Newman Wasteway | 259 | 956, 977, 978 |

**Table 5.** Condition numbers at San Joaquin River confluence points. Calculations involving missing data points (denoted as -999 in the model) or that result in division by zero are excluded from the statistical analysis.

| Location | Condition Numbers | | | |
|---|---|---|---|---|
| | Max | Min | Mean | Count |
| **Newman Wasteway** | 2.5 | 0 | 1 | 1,416 |
| **TID Harding Drain** | 13.9 | -1.00E-05 | 0.58 | 1,918 |
| **TID Lateral 5 (Carpenter) Drain** | 1 | -1.80E-03 | 0.58 | 1,918 |
| **MID Lateral 5 Spill** | 1 | -4.50E-03 | 0.56 | 1,886 |
| **MID Lateral 4 Spill** | 1 | -1.70E-02 | 0.54 | 1,885 |
| **TID Lateral 6 & 7 Spill** | 1.2 | -4.40E-05 | 0.52 | 1,917 |
| **TID Lateral 3 (Westport) Drain** | 1 | -3.80E-05 | 0.5 | 1,918 |
| **Bear Creek at San Joaquin River** | 10 | 0 | 0.43 | 1,898 |
| **Spanish Land Grant Drain** | 1 | -3.30E-06 | 0.43 | 1,848 |
| **TID Lateral 2 Drain** | 0.99 | 0 | 0.23 | 1,918 |
| **Eastside Bypass at Sand Slough** | 1.4 | 0 | 0.1 | 1,897 |
| **Merced River at Stevinson** | 0.99 | 0 | 0.1 | 1,917 |
| **Stanislaus River at SJR** | 0.82 | -3.20E-06 | 3.80E-02 | 1,918 |
| **Tuolumne River at SJR** | 0.72 | -2.20E-05 | 2.30E-02 | 1,918 |
| **Salt Slough at San Joaquin River** | 0.16 | -1.50E-03 | 6.20E-03 | 1,917 |
| **San Joaquin River at Mendota Pool** | 0.39 | 0 | 4.90E-03 | 1,216 |
| **Los Banos Creek at San Joaquin R.** | 6.00E-02 | -3.00E-06 | 4.80E-03 | 1,917 |
| **Hospital / Ingram Creek** | 0.18 | -2.60E-06 | 8.00E-04 | 1,918 |
| **Orestimba Creek near Crows Landing** | 9.30E-02 | -1.20E-05 | 7.00E-04 | 1,916 |
| **Salado Creek** | 0.23 | -6.90E-06 | 3.00E-04 | 1,918 |
| **San Joaquin River above Mariposa Sl.** | 0 | 0 | 0 | 1,897 |
| **Modesto WQCF Discharge** | 0 | 0 | 0 | 1,277 |
| **Del Puerto Creek** | 0 | 0 | 0 | 1,199 |

**Table 6.** Mean condition number calculations for the San Joaquin River at Vernalis and selected tributaries. The condition number was calculated prior to taking the mean. Calculations involving missing data points (denoted as -999 in the model) or that result in division by zero are excluded from the statistical analysis.

| Location | River ID | Statistic | Base TSS (mg $L^{-1}$) | Err-20 TSS (mg $L^{-1}$) | Err+20 TSS (mg $L^{-1}$) | Condition Number |
|---|---|---|---|---|---|---|
| San Joaquin River at Vernalis | 184 | Mean | 40 | 38 | 41 | 0.11 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |
| Chowchilla River West Fork | 8 | Mean | 20 | 17 | 22 | 3.50E+10 |
| | | Count | 1,835 | 1,835 | 1,835 | 643 |
| Burns Creek | 5 | Mean | 99 | 66 | 130 | 2.4 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,827 |
| Owens Creek | 12 | Mean | 172 | 113 | 177 | 0.86 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,826 |
| Newman Wasteway | 259 | Mean | 20 | 15 | 23 | 1.05 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,417 |
| MID Lateral 4 Spill | 208 | Mean | 33 | 26 | 40 | 0.54 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,885 |
| MID Lateral 5 Spill | 207 | Mean | 38 | 30 | 45 | 0.56 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,886 |
| MID Lateral 6 Spill | 210 | Mean | 20 | 16 | 24 | 0.52 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,886 |
| Spanish Land Grant Drain | 196 | Mean | 59 | 48 | 70 | 0.43 |
| | | Count | 1,849 | 1,849 | 1,849 | 1,849 |
| TID Harding Drain | 202 | Mean | 62 | 50 | 73 | 0.58 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |
| TID Lateral 2 Drain | 205 | Mean | 22 | 20 | 24 | 0.23 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |
| TID Lateral 3 (Westport) Drain | 204 | Mean | 48 | 39 | 57 | 0.5 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |
| TID Lateral 5 (Carpenter) Drain | 203 | Mean | 74 | 60 | 88 | 0.58 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |
| TID Lateral 6 & 7 Spill | 198 | Mean | 66 | 53 | 78 | 0.52 |
| | | Count | 1,918 | 1,918 | 1,918 | 1,918 |

**Table 7.** Error analysis of Base and Soil Study scenarios. Errors are calculated with respect to the Base scenario. Positive numbers for relative error indicate that the Base scenario over-predicts TSS and Flow while negative numbers indicate that the Base scenario under-predicts TSS and Flow. Calculations involving missing data points (denoted as -999 in the model) are excluded from the statistical analysis.

| | | TSS (mg $L^{-1}$) | | Flow (cfs) | |
|---|---|---|---|---|---|
| | River ID | Relative Error | Absolute Error | Relative Error | Absolute Error |
| **San Joaquin River at Vernalis** | 184 | -1.1 | 1.3 | -32 | 41 |
| **Hospital Creek** | 305 | -0.048 | 0.048 | 0 | 0 |
| **Ingram Creek** | 313 | -3,406 | 3,406 | 14 | 14 |
| **Orestimba Creek near Crows Landing** | 165 | 0.034 | 0.467 | -3 | 3 |

**Table 8.** Summary statistics for water budget at Hospital Creek (River IDs 175 and 305). Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| Statistic | Hospital Creek Outflow (cfs) | Cat. 251 Outflow (cfs) | Cat. 189 Outflow (cfs) | Cat. 220 Outflow (cfs) |
|---|---|---|---|---|
| **Min** | 1.3 | 0 | 1.3 | 0 |
| **Max** | 573 | 532 | 44 | 116 |
| **Mean** | 23 | 8.3 | 4.3 | 10 |
| **Standard Deviation** | 41 | 32 | 3.1 | 13 |

**Table 9.** Summary statistics for water budget at Ingram Creek (River IDs 176 and 313). Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| Statistic | Ingram Creek Outflow (cfs) | Cat. 200 Outflow (cfs) | Cat. 255 Outflow (cfs) |
|---|---|---|---|
| **Min** | 0.243 | 0.186 | 0 |
| **Max** | 483 | 92 | 436 |
| **Mean** | 21 | 14 | 6.3 |
| **Standard Deviation** | 32 | 12 | 25 |

**Table 10.** Summary statistics for water budget at Orestimba Creek. Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| Statistic | Orestimba Creek Outflow (cfs) | Cat. 804 Outflow (cfs) | Cat. 983 Outflow (cfs) | Cat. 979 Outflow (cfs) | Cat. 959 Outflow (cfs) | Cat. 963 Outflow (cfs) | Cat. 981 Outflow (cfs) | Cat. 853 Outflow (cfs) | Cat. 980 Outflow (cfs) | Cat. 829 Outflow (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Min** | 8.40E-03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Max** | 1,373 | 5.1 | 734 | 332 | 25 | 56 | 4.4 | 19 | 3.2 | 3.9 |
| **Mean** | 31 | 0.8 | 10 | 7.4 | 1.5 | 3.5 | 0.9 | 1.2 | 0.5 | 0.3 |
| **Standard Deviation** | 102 | 0.7 | 55 | 29 | 3.3 | 7.4 | 0.6 | 1.2 | 0.4 | 0.2 |

**Table 11.** Correlation coefficients (*r*) for flow sources at Hospital Creek. Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| | Hospital Creek Outflow (cfs) | Cat. 251 Outflow (cfs) | Cat. 189 Outflow (cfs) | Cat. 220 Outflow (cfs) | Cat. 251 Precip. (cfs) | Cat. 251 Irrig. (cfs) | Cat. 251 ET (cfs) | Cat. 189 Precip. (cfs) | Cat. 189 Irrig. (cfs) | Cat. 189 ET (cfs) | Cat. 220 Precip. (cfs) | Cat. 220 Irrig. (cfs) | Cat. 220 ET (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hospital Creek Outflow (cfs)** | 1 | | | | | | | | | | | | |
| **Cat. 251 Outflow (cfs)** | 0.95 | 1 | | | | | | | | | | | |
| **Cat. 189 Outflow (cfs)** | 0.21 | 0.09 | 1 | | | | | | | | | | |
| **Cat. 220 Outflow (cfs)** | 0.75 | 0.53 | 0.19 | 1 | | | | | | | | | |
| **Cat. 251 Precip. (cfs)** | 0.35 | 0.27 | 0.03 | 0.47 | 1 | | | | | | | | |
| **Cat. 251 Irrig. (cfs)** | - | - | - | - | - | 1 | | | | | | | |
| **Cat. 251 ET (cfs)** | 0.15 | 0.01 | 0.56 | 0.29 | -0.03 | - | 1 | | | | | | |
| **Cat. 189 Precip. (cfs)** | 0.35 | 0.27 | 0.03 | 0.47 | 1 | - | -0.03 | 1 | | | | | |
| **Cat. 189 Irrig. (cfs)** | -0.14 | -0.14 | 0.58 | -0.24 | -0.16 | - | 0.39 | -0.16 | 1 | | | | |
| **Cat. 189 ET (cfs)** | -0.21 | -0.19 | 0.51 | -0.3 | -0.21 | - | 0.31 | -0.21 | 0.9 | 1 | | | |
| **Cat. 220 Precip. (cfs)** | 0.35 | 0.27 | 0.03 | 0.47 | 1 | - | -0.03 | 1 | -0.16 | -0.21 | 1 | | |
| **Cat. 220 Irrig. (cfs)** | -0.26 | -0.26 | 0.41 | -0.29 | -0.22 | - | 0.21 | -0.22 | 0.79 | 0.88 | -0.22 | 1 | |
| **Cat. 220 ET (cfs)** | -0.11 | -0.17 | 0.59 | -0.1 | -0.19 | - | 0.61 | -0.19 | 0.82 | 0.87 | -0.19 | 0.87 | 1 |

**Table 12.** Correlation coefficients (*r*) for flow sources at Ingram Creek. Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| | Ingram Creek Outflow (cfs) | Cat. 200 Outflow (cfs) | Cat. 255 Outflow (cfs) | Cat. 200 Precip. (cfs) | Cat. 200 Irrig. (cfs) | Cat. 200 ET (cfs) | Cat. 255 Precip. (cfs) | Cat. 255 Irrig. (cfs) |
|---|---|---|---|---|---|---|---|---|
| **Ingram Creek Outflow (cfs)** | **1** | | | | | | | |
| **Cat. 200 Outflow (cfs)** | 0.73 | 1 | | | | | | |
| **Cat. 255 Outflow (cfs)** | 0.95 | 0.48 | 1 | | | | | |
| **Cat. 200 Precip. (cfs)** | 0.3 | 0.31 | 0.27 | 1 | | | | |
| **Cat. 200 Irrig. (cfs)** | -0.13 | 0.07 | -0.2 | -0.2 | 1 | | | |
| **Cat. 200 ET (cfs)** | -0.11 | 0.08 | -0.18 | -0.21 | 0.95 | 1 | | |
| **Cat. 255 Precip. (cfs)** | 0.3 | 0.31 | 0.27 | 1 | -0.2 | -0.21 | 1 | |
| **Cat. 255 Irrig. (cfs)** | - | - | - | - | - | - | - | 1 |

**Table 13.** Correlation coefficients (*r*) for catchment outflow at Orestimba Creek. Values calculated from catchment output in the Water Budget scenario. See Table 1 for scenario descriptions.

| | Orestimba Creek Outflow (cfs) | Cat. 804 Outflow (cfs) | Cat. 983 Outflow (cfs) | Cat. 979 Outflow (cfs) | Cat. 959 Outflow (cfs) | Cat. 963 Outflow (cfs) | Cat. 981 Outflow (cfs) | Cat. 853 Outflow (cfs) | Cat. 980 Outflow (cfs) | Cat. 829 Outflow (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Orestimba Creek Outflow (cfs)** | 1 | | | | | | | | | |
| **Cat. 804 Outflow (cfs)** | 0.35 | 1 | | | | | | | | |
| **Cat. 983 Outflow (cfs)** | 0.92 | 0.28 | 1 | | | | | | | |
| **Cat. 979 Outflow (cfs)** | 0.9 | 0.31 | 0.78 | 1 | | | | | | |
| **Cat. 959 Outflow (cfs)** | 0.8 | 0.41 | 0.73 | 0.76 | 1 | | | | | |
| **Cat. 963 Outflow (cfs)** | 0.8 | 0.42 | 0.72 | 0.77 | 0.99 | 1 | | | | |
| **Cat. 981 Outflow (cfs)** | 0.28 | 0.42 | 0.21 | 0.24 | 0.27 | 0.32 | 1 | | | |
| **Cat. 853 Outflow (cfs)** | 0.6 | 0.45 | 0.56 | 0.55 | 0.78 | 0.75 | 0.61 | 1 | | |
| **Cat. 980 Outflow (cfs)** | 0.38 | 0.66 | 0.29 | 0.32 | 0.45 | 0.41 | 0.41 | 0.54 | 1 | |
| **Cat. 829 Outflow (cfs)** | 0.45 | 0.62 | 0.44 | 0.38 | 0.57 | 0.53 | 0.54 | 0.85 | 0.52 | 1 |

**Table 14.** Correlation coefficients (*r*) for irrigation flow in catchment 220. Values calculated from catchment output and managed flow data in the Water Budget scenario for catchment 220. See Table 1 for scenario descriptions.

| | Cat. 220 Outflow (cfs) | Cat. 220 Irrig. (cfs) | Cat. 220 ET (cfs) | Del Puerto WD DMC (cfs) | GW Pumping 220 (cfs) |
|---|---|---|---|---|---|
| **Cat. 220 Outflow (cfs)** | 1 | | | | |
| **Cat. 220 Irrig. (cfs)** | -0.29 | 1 | | | |
| **Cat. 220 ET (cfs)** | -0.1 | 0.87 | 1 | | |
| **Del Puerto WD DMC (cfs)** | -0.27 | 1 | 0.88 | 1 | |
| **GW Pumping 220 (cfs)** | -0.28 | 0.08 | -0.03 | 0.02 | 1 |

**Figure 1.** Catchments with updated soil coefficients used in model verification. Catchment IDs used in the model are included for reference. See Table 3 and Table 4 for corresponding data and site descriptions.

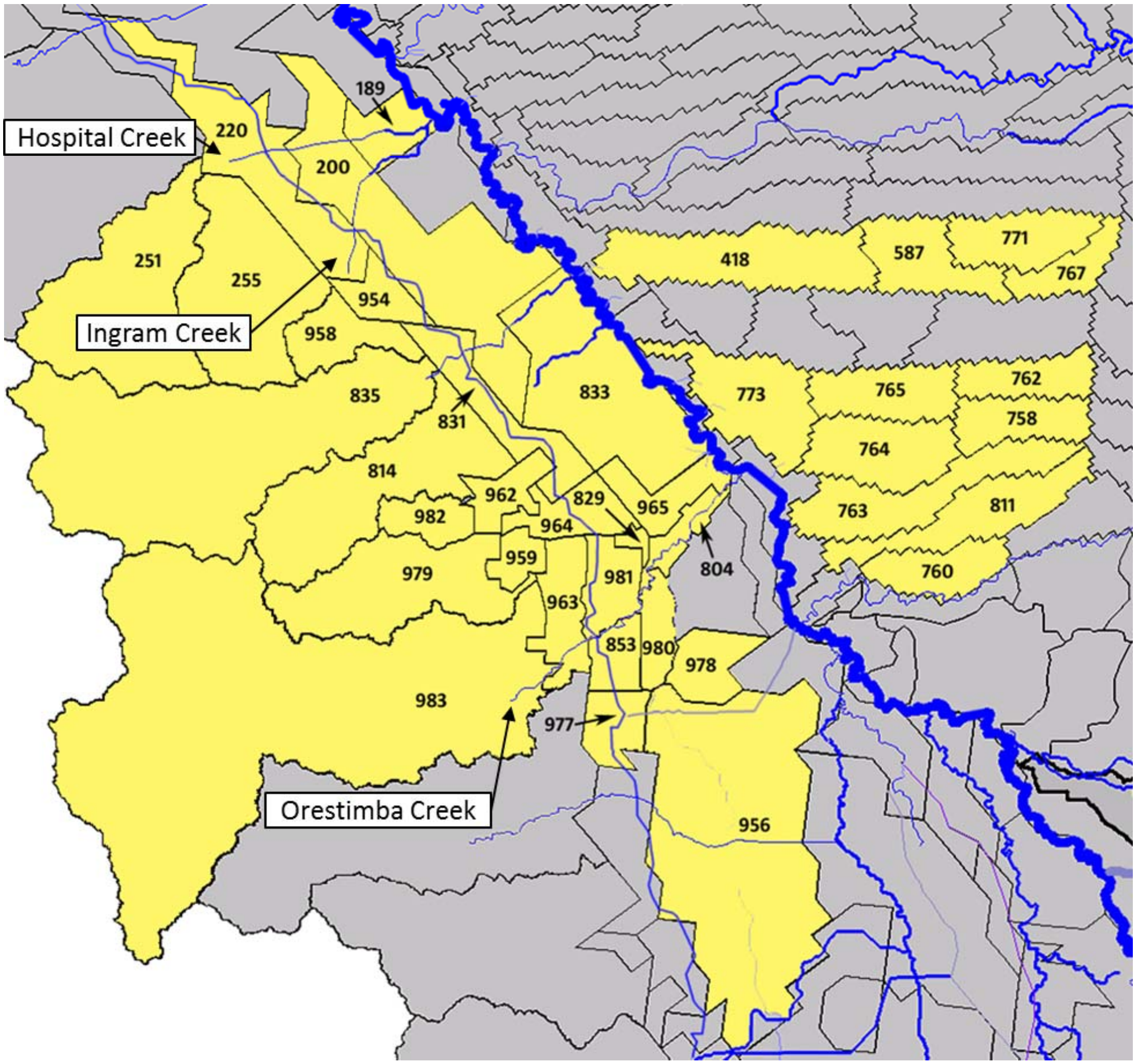
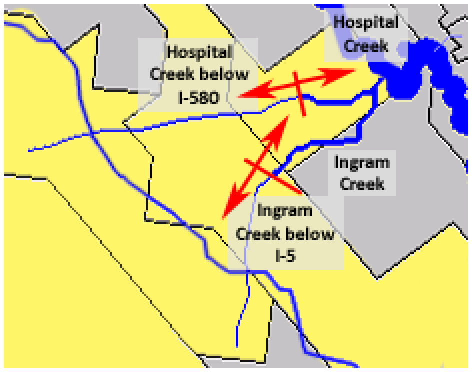


**Figure 2.** Location of stream segment connections as defined in the WARMF model. The red lines indicate where one river segment ends and another begins.



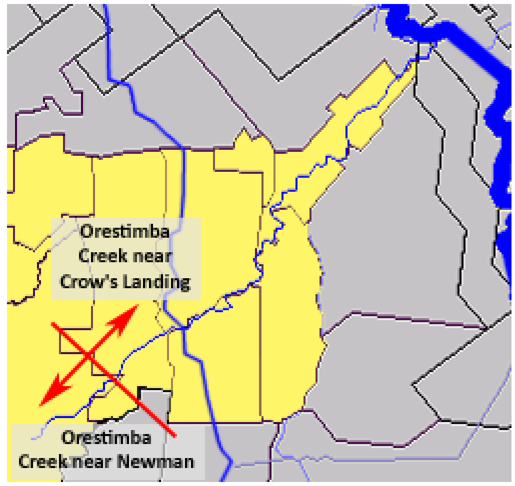



**Figure 3.** Catchment connections to Hospital Creek. All connections occur at the upstream end of each river segment. Catchment IDs included for reference.

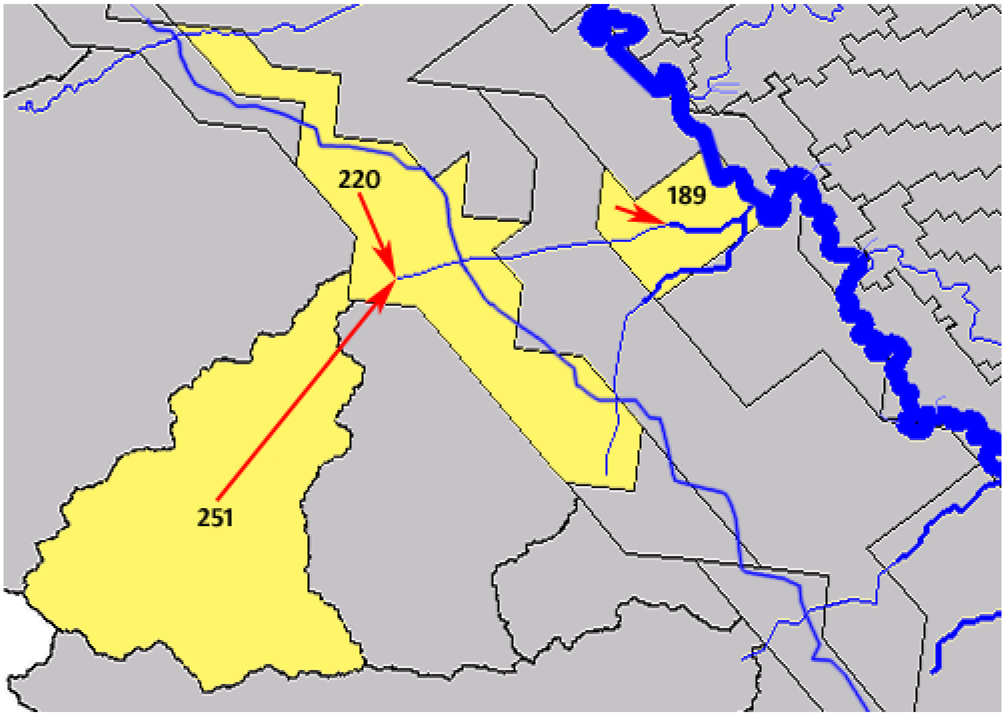


**Figure 4.** Catchment connections to Ingram Creek. All connections occur at the upstream end of each river segment. Catchment IDs included for reference.

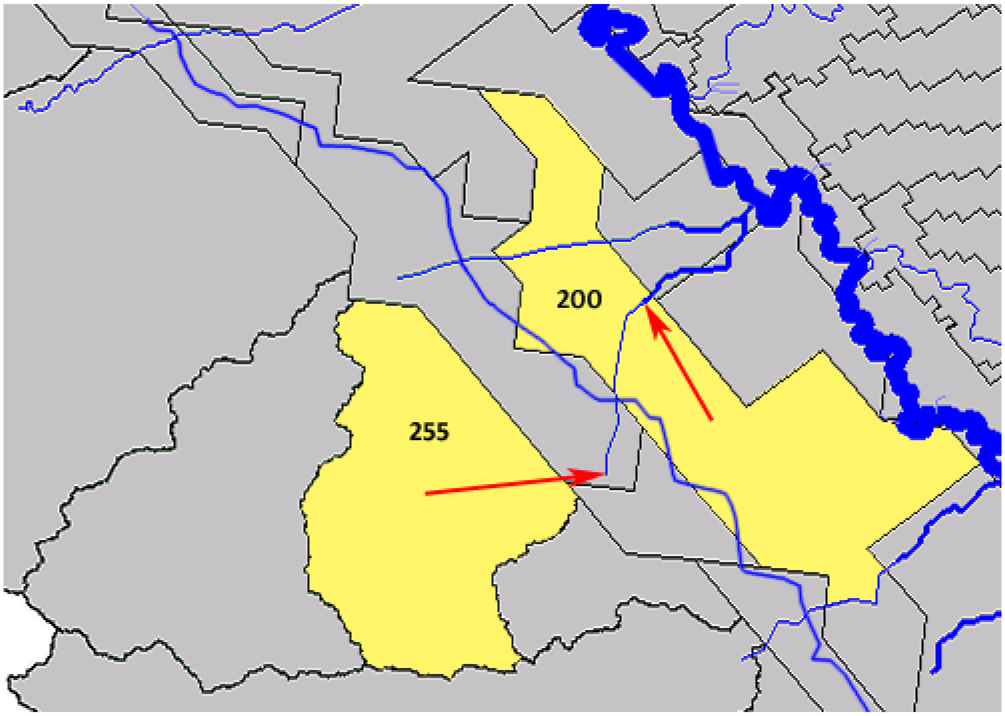


**Figure 5.** Catchment connections to Orestimba Creek. All connections occur at the upstream end of each river segment. Catchment IDs included for reference.

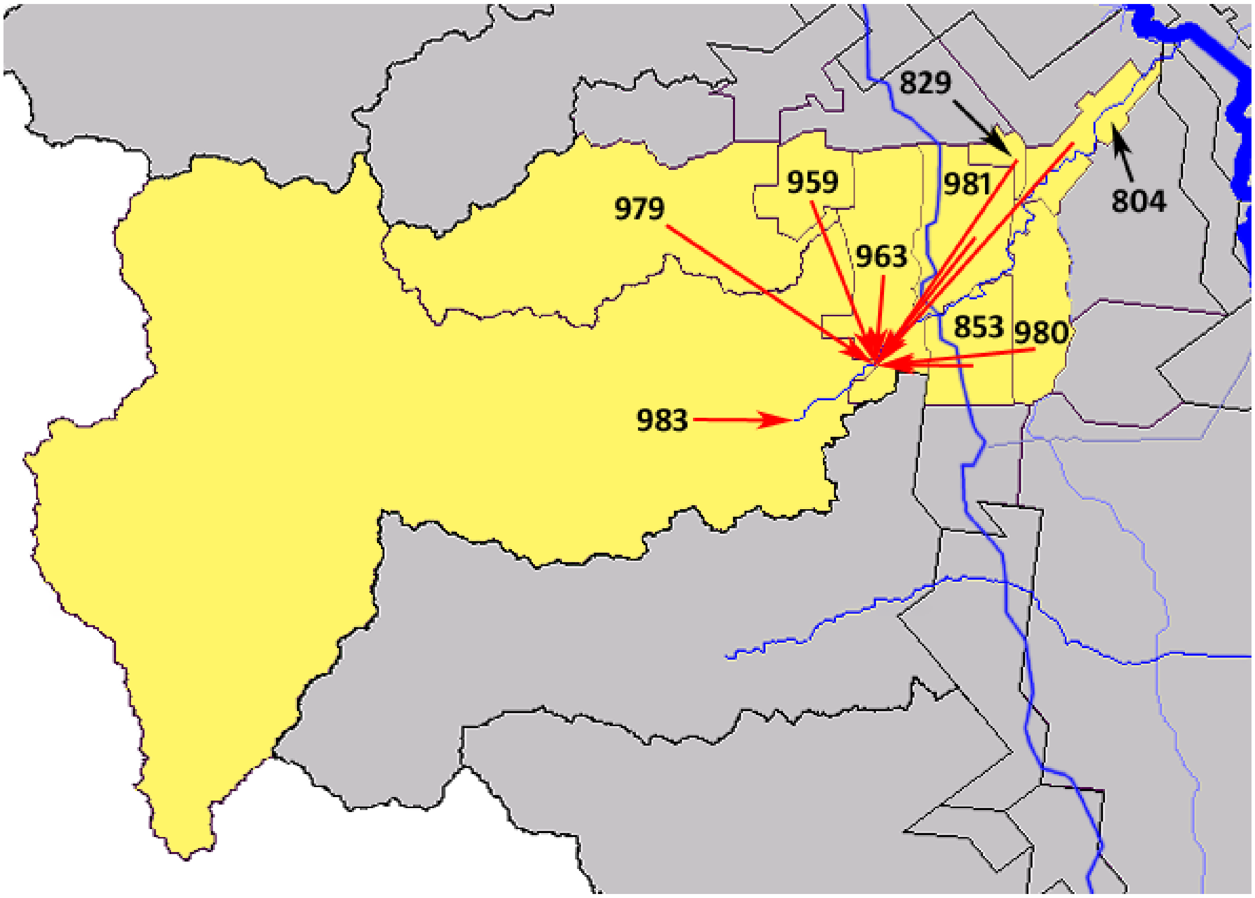
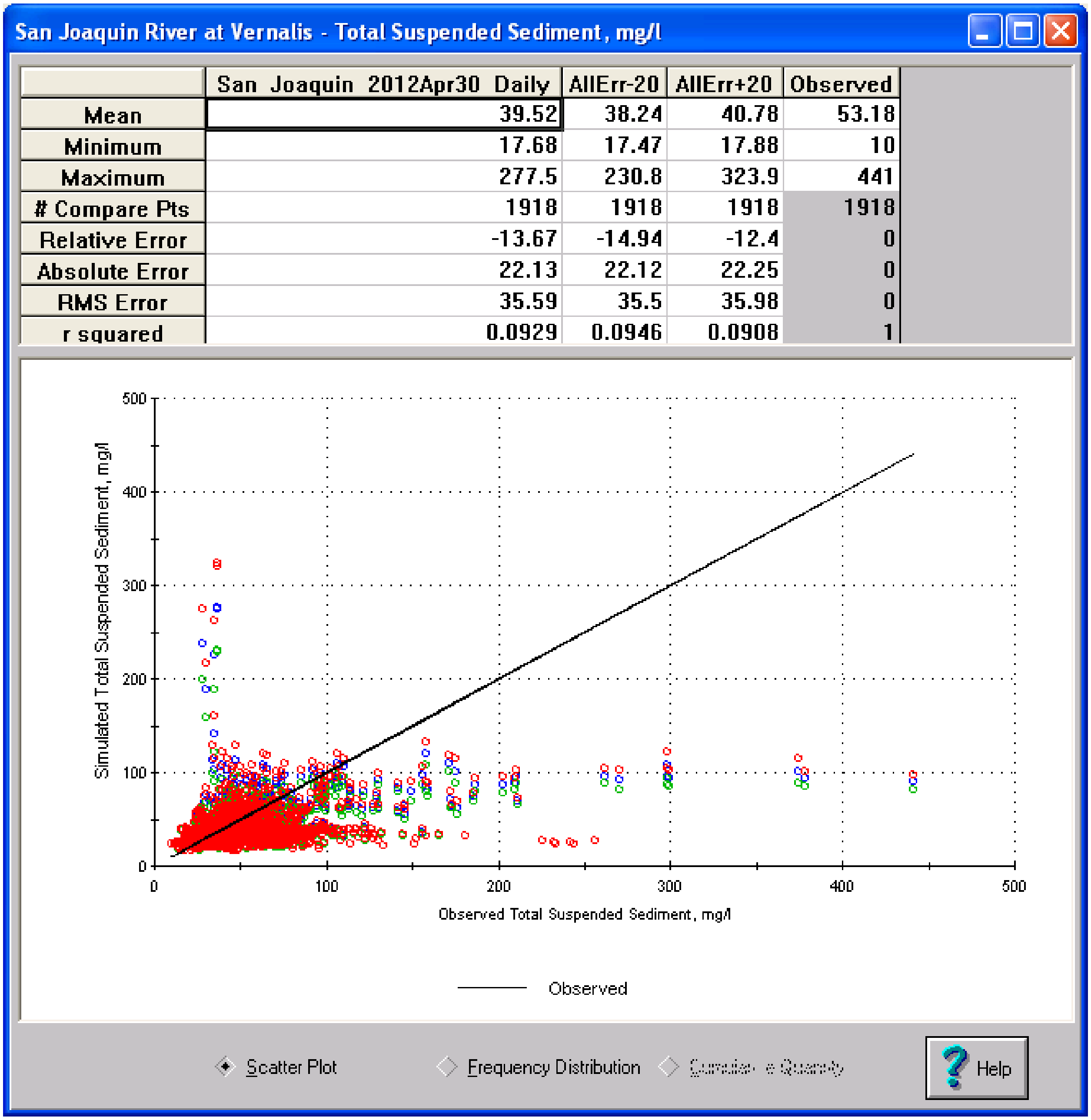


**Figure 6.** Simulated vs. Observed TSS in San Joaquin River at Vernalis for Base, Err+20, and Err-20 scenarios. See Table 1 for scenario descriptions.



| | San Joaquin 2012Apr30 Daily | AllErr-20 | AllErr+20 | Observed |
|---|---|---|---|---|
| Mean | 39.52 | 38.24 | 40.78 | 53.18 |
| Minimum | 17.68 | 17.47 | 17.88 | 10 |
| Maximum | 277.5 | 230.8 | 323.9 | 441 |
| # Compare Pts | 1918 | 1918 | 1918 | 1918 |
| Relative Error | -13.67 | -14.94 | -12.4 | 0 |
| Absolute Error | 22.13 | 22.12 | 22.25 | 0 |
| RMS Error | 35.59 | 35.5 | 35.98 | 0 |
| r squared | 0.0929 | 0.0946 | 0.0908 | 1 |

**Figure 7.** Sensitivity of total suspended sediments to catchment erosivity in the San Joaquin River at Vernalis.

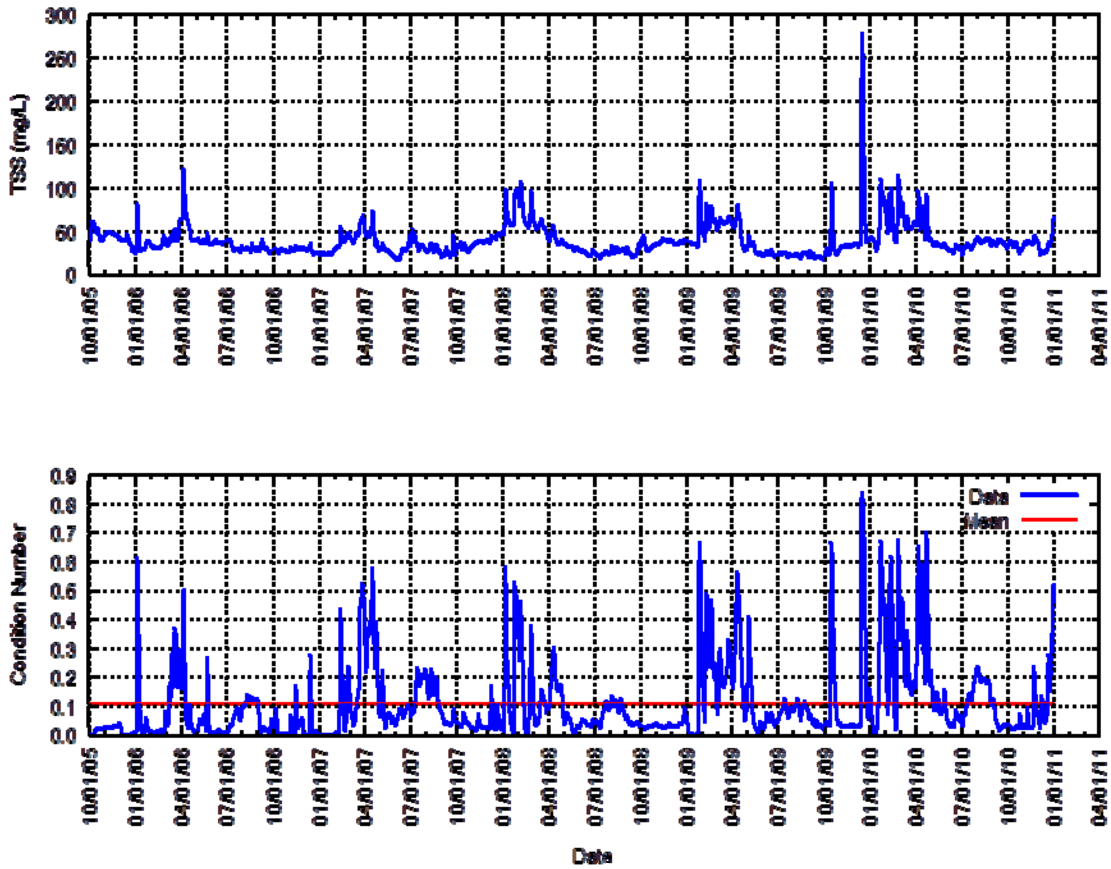


**Figure 8.** Sensitivity of total suspended sediments to catchment erosivity in the Chowchilla River West Fork. The condition number is indeterminate in regions where it is not plotted.

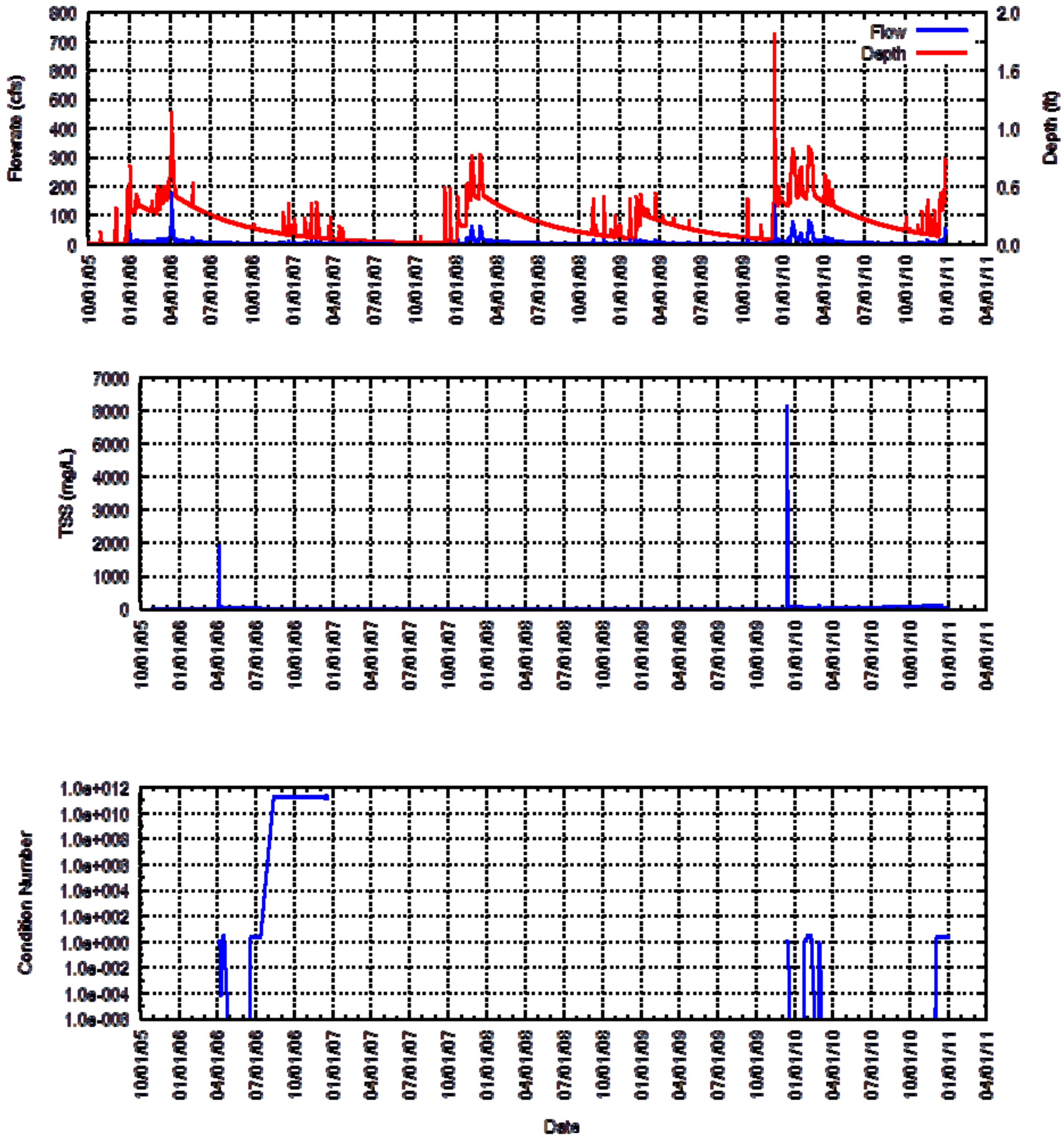


**Figure 9.** Time series plot of percent difference in TSS between the Base and Soil Study scenarios in the San Joaquin River at Vernalis. See Table 1 for scenario descriptions.

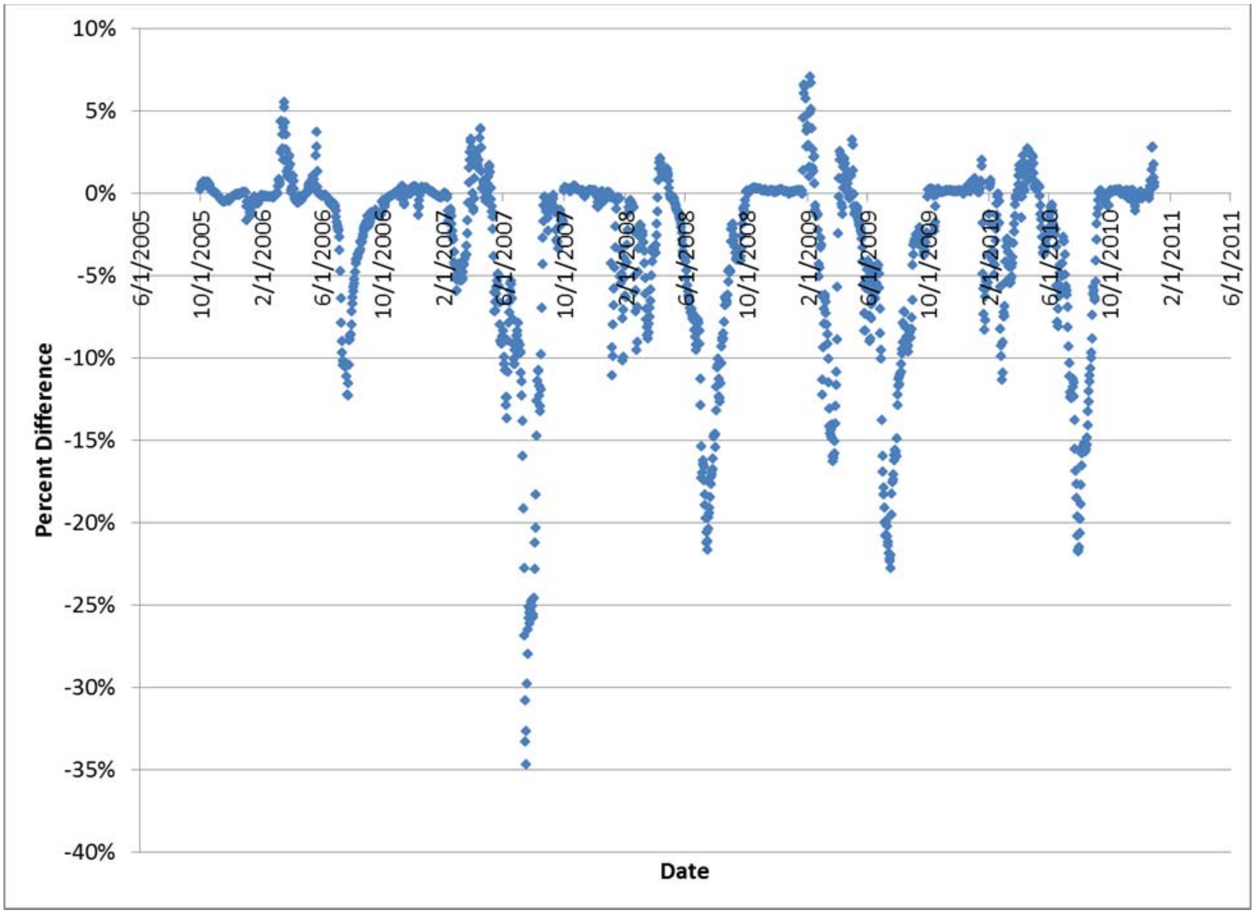


**Figure 10.** Time series plot of percent difference in TSS between the Base and Soil Study scenarios at Hospital Creek. See Table 1 for scenario descriptions.

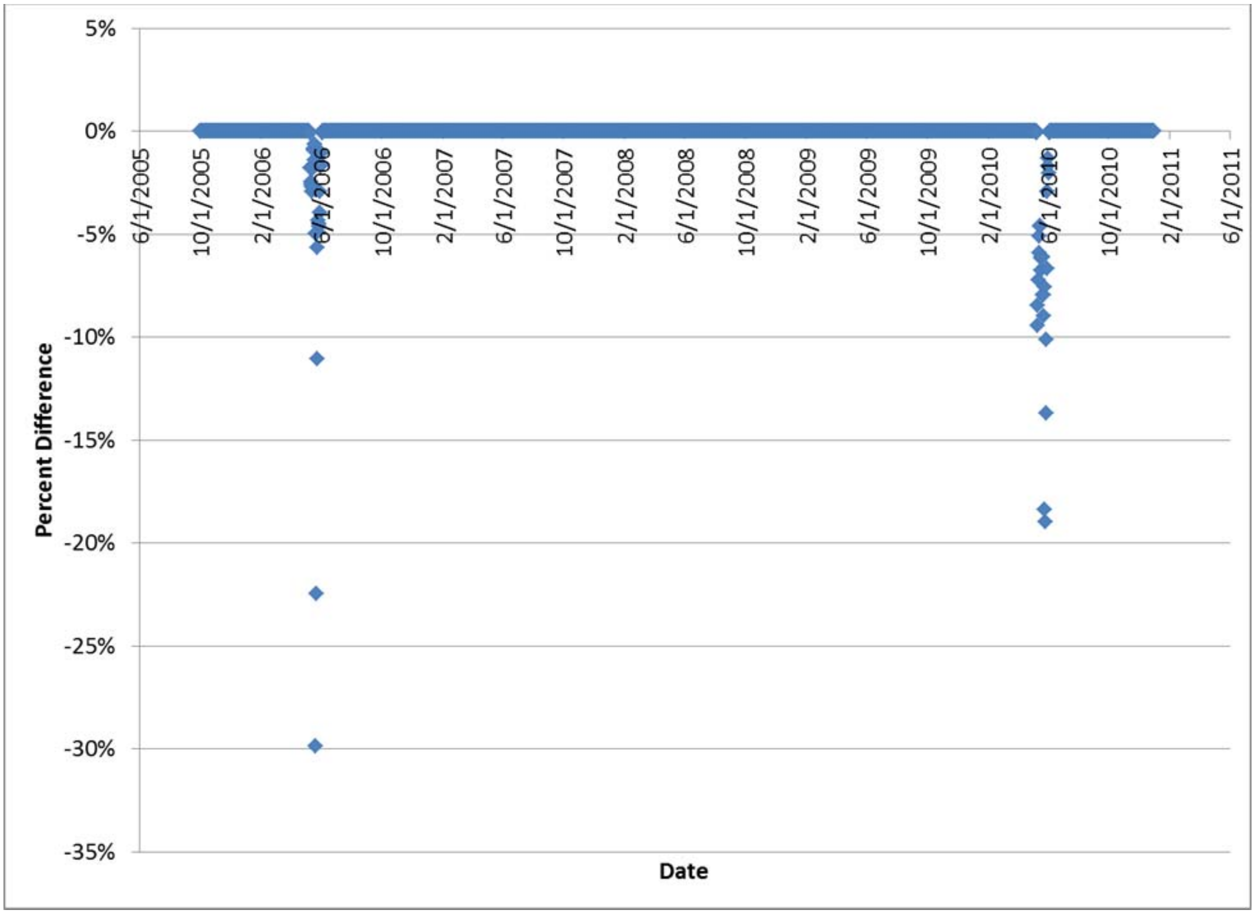


**Figure 11.** Time series plot of percent difference in TSS between the Base and Soil Study scenarios at Ingram Creek. See Table 1 for scenario descriptions.

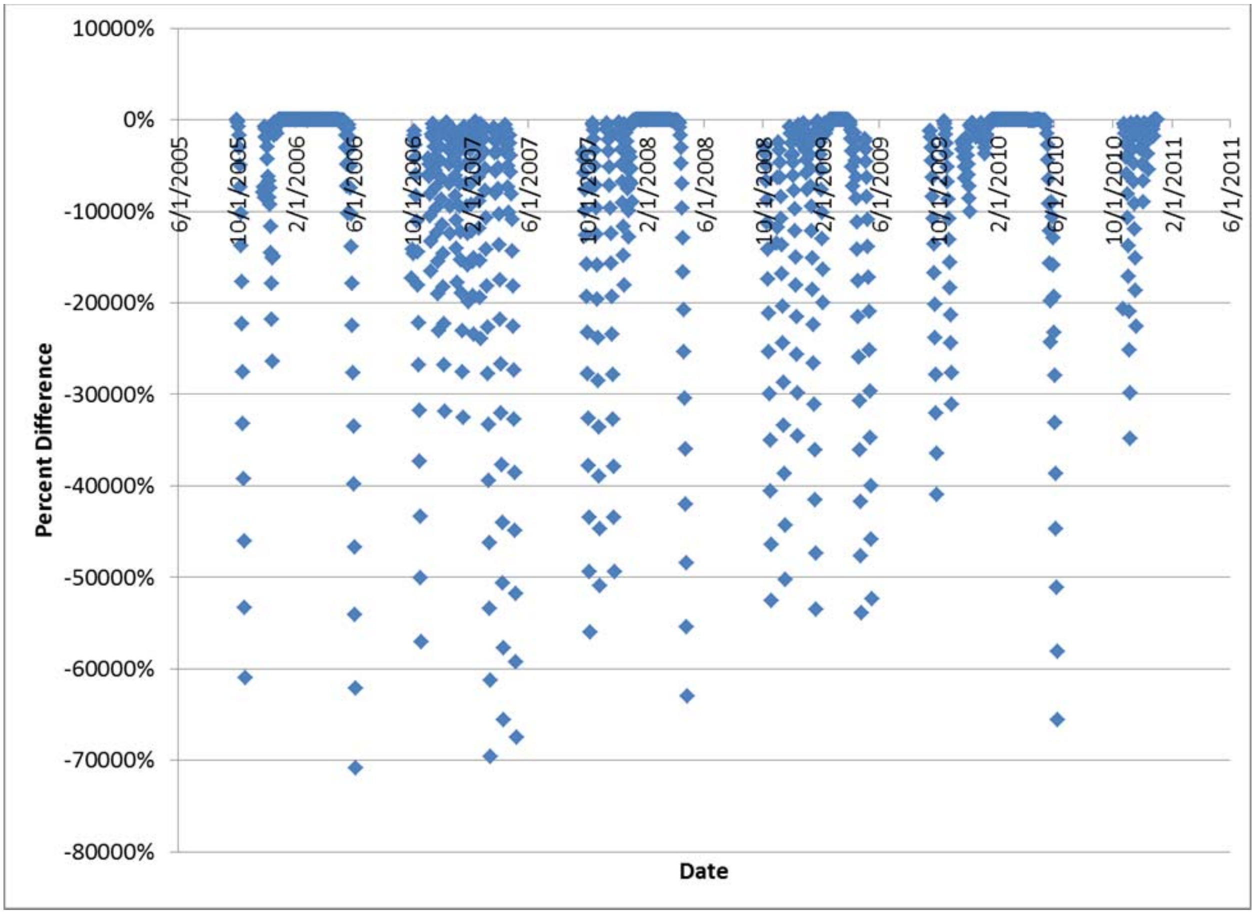


**Figure 12.** Time series plot of percent difference in TSS between the Base and Soil Study scenarios at Orestimba Creek. See Table 1 for scenario descriptions.

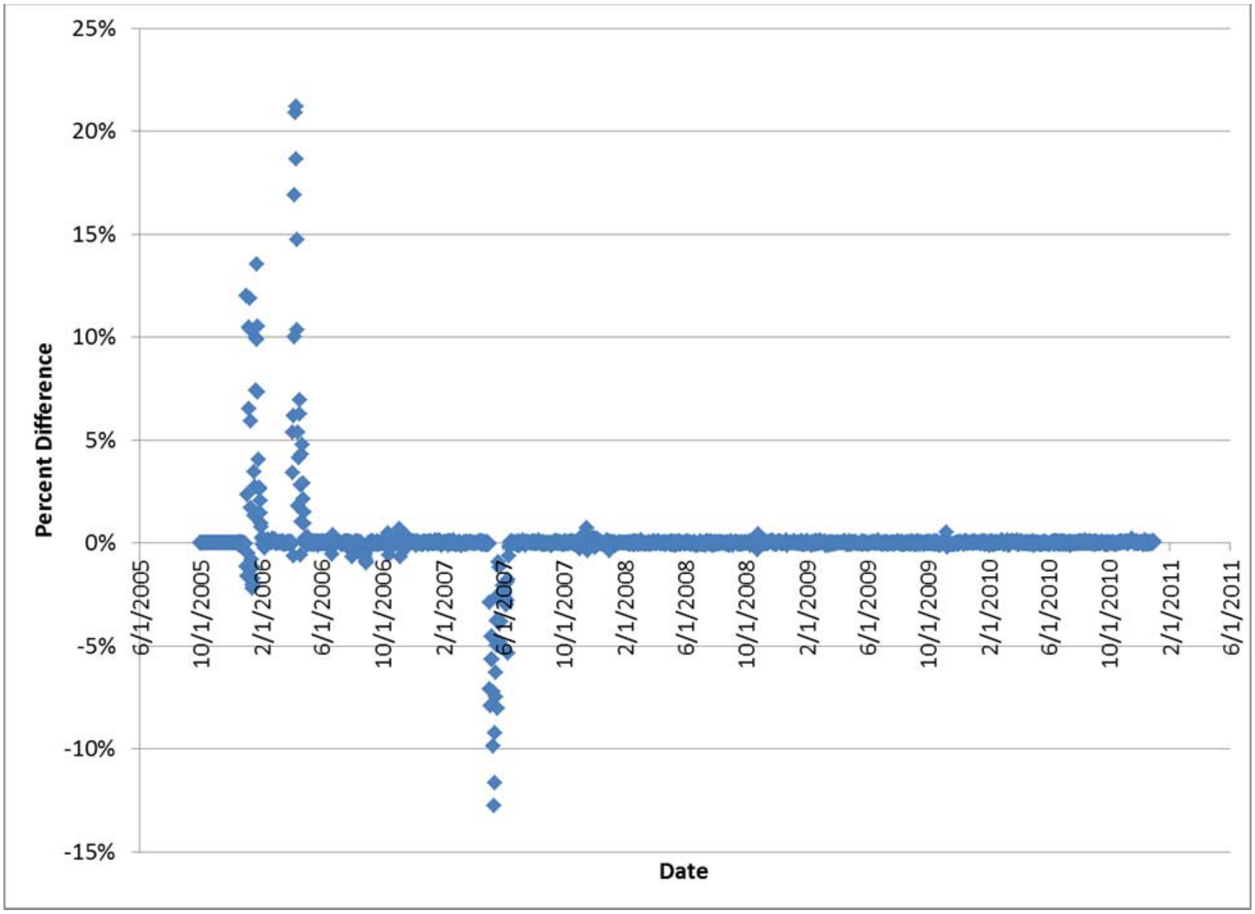
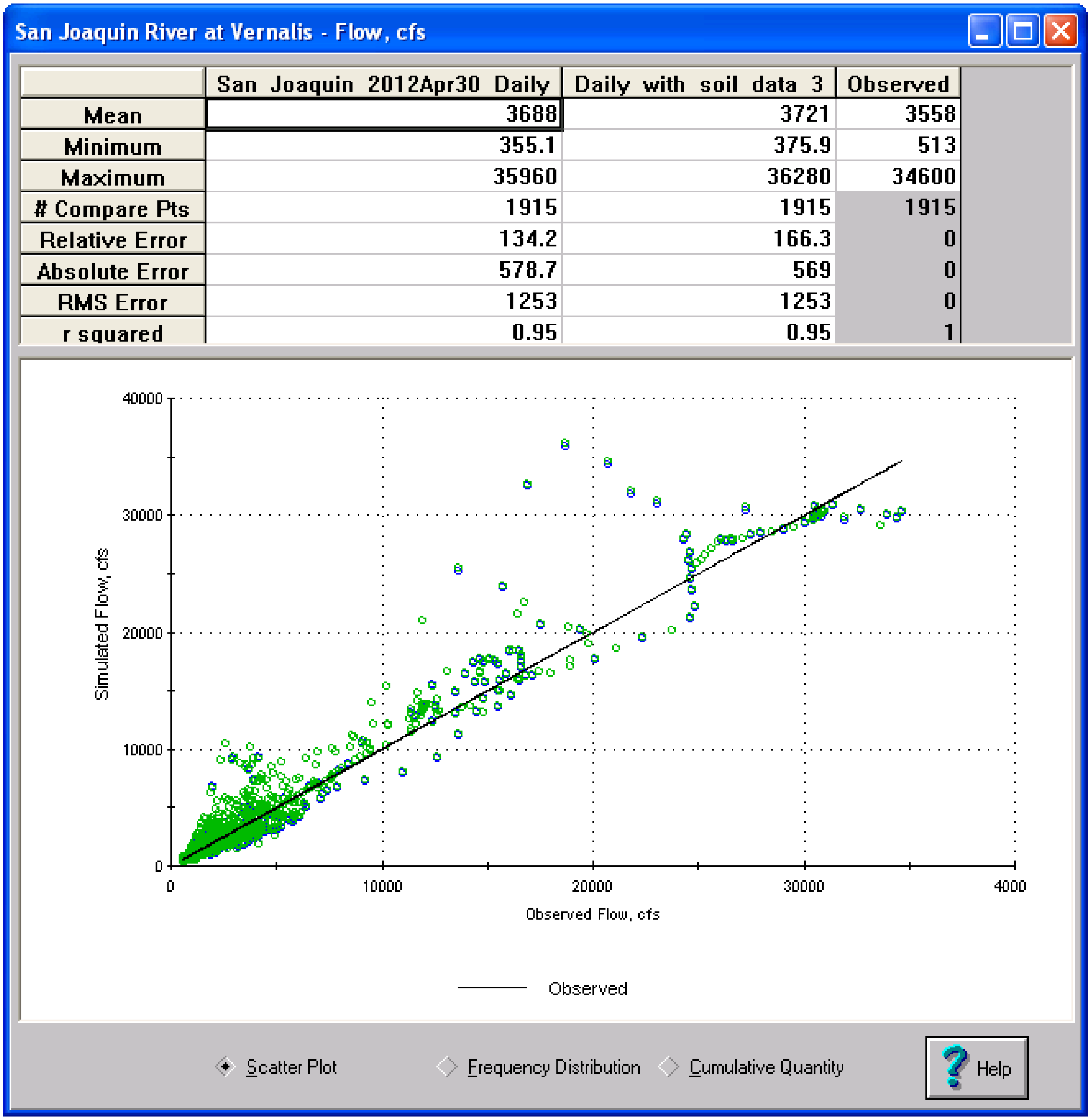
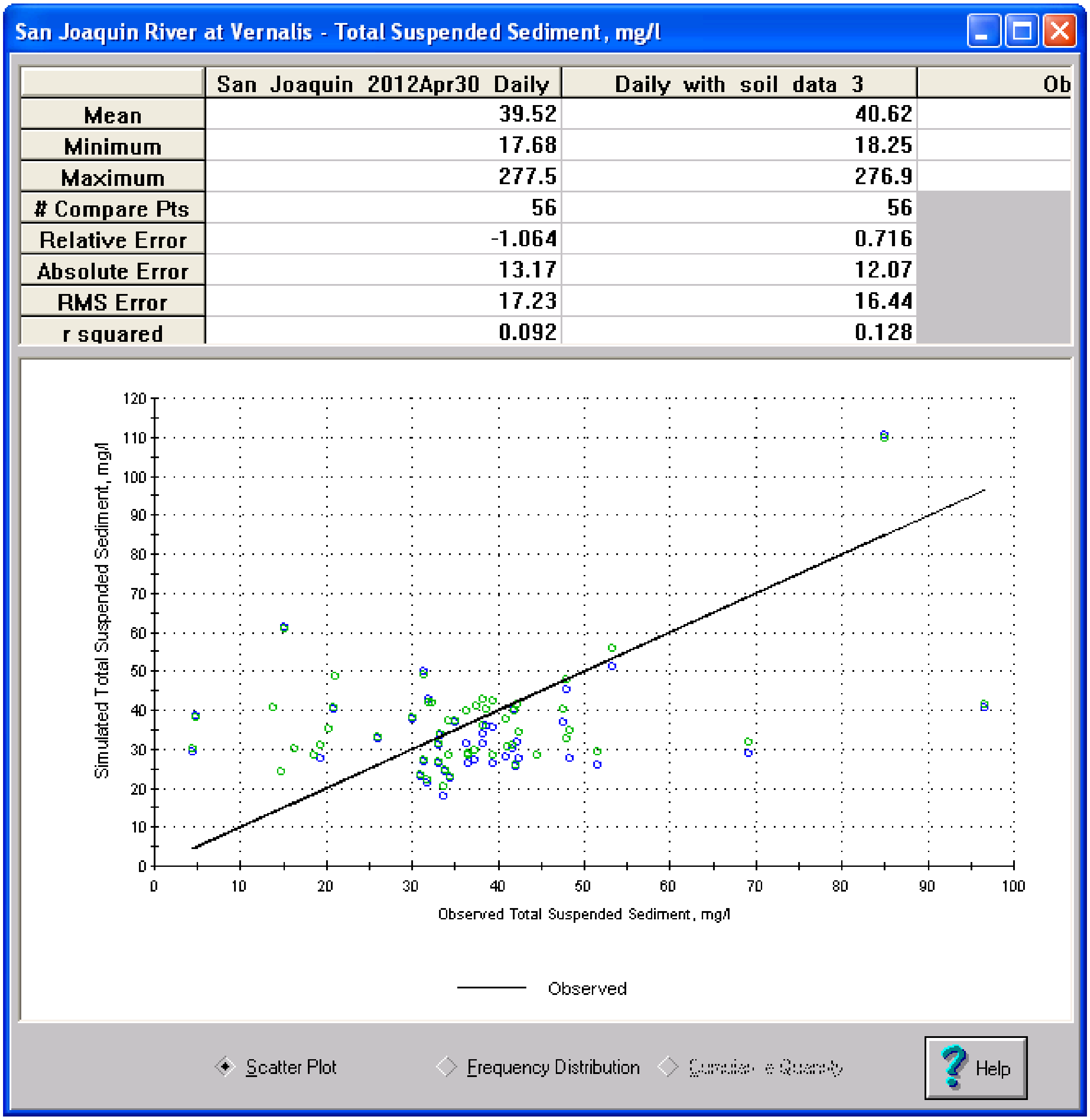


**Figure 13.** Simulated vs. observed flow in the San Joaquin River at Vernalis for Base and Soil Study scenarios. See Table 1 for scenario descriptions.



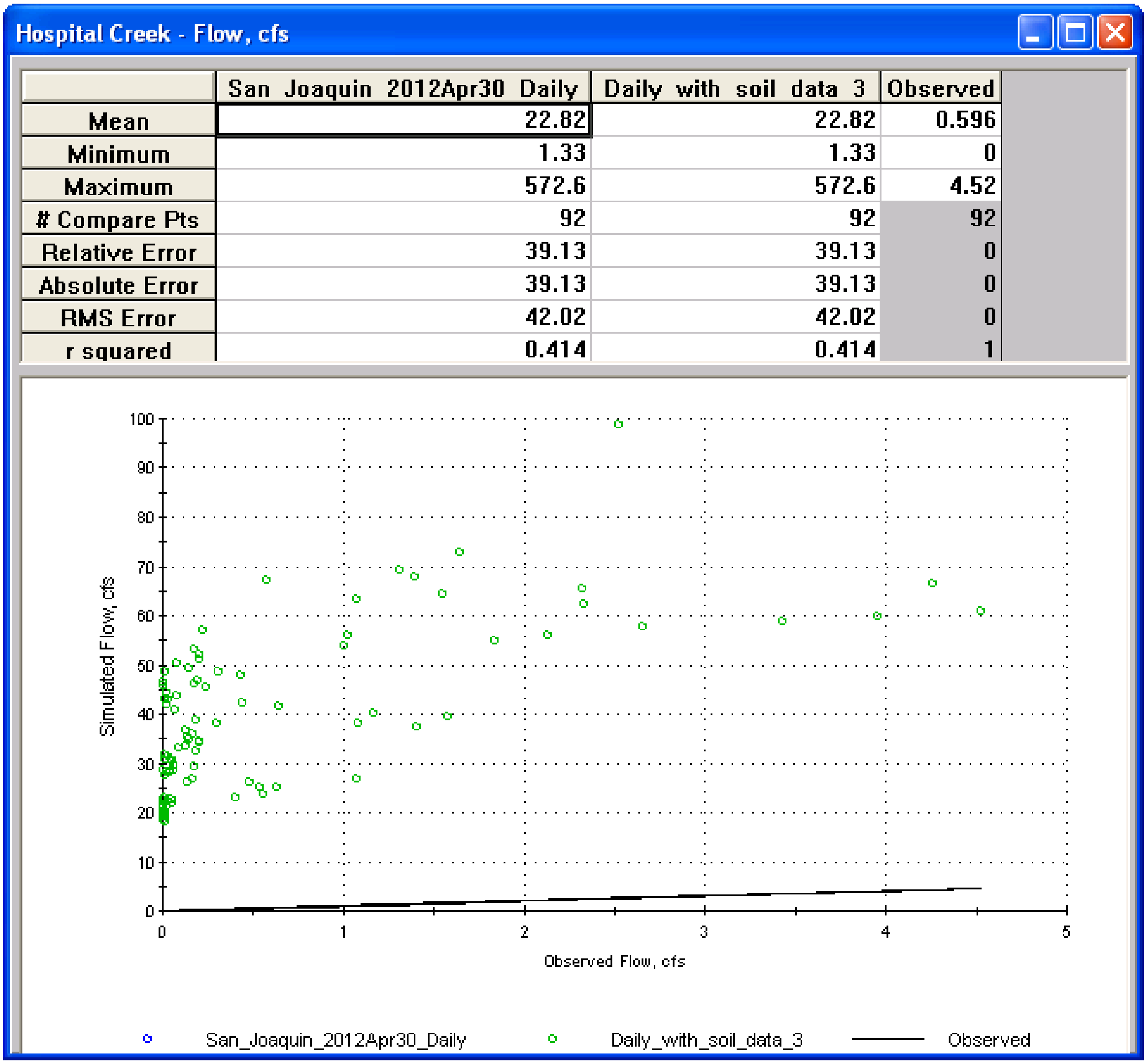
| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 3688 | 3721 | 3558 |
| Minimum | 355.1 | 375.9 | 513 |
| Maximum | 35960 | 36280 | 34600 |
| # Compare Pts | 1915 | 1915 | 1915 |
| Relative Error | 134.2 | 166.3 | 0 |
| Absolute Error | 578.7 | 569 | 0 |
| RMS Error | 1253 | 1253 | 0 |
| r squared | 0.95 | 0.95 | 1 |

**Figure 14.** Simulated vs. observed TSS in San Joaquin River at Vernalis for Base and Soil Study scenarios. See Table 1 for scenario descriptions.



| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Ob |
|---|---|---|---|
| Mean | 39.52 | 40.62 | |
| Minimum | 17.68 | 18.25 | |
| Maximum | 277.5 | 276.9 | |
| # Compare Pts | 56 | 56 | |
| Relative Error | -1.064 | 0.716 | |
| Absolute Error | 13.17 | 12.07 | |
| RMS Error | 17.23 | 16.44 | |
| r squared | 0.092 | 0.128 | |

**Figure 15.** Simulated vs. observed flow at Hospital Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.




| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 22.82 | 22.82 | 0.596 |
| Minimum | 1.33 | 1.33 | 0 |
| Maximum | 572.6 | 572.6 | 4.52 |
| # Compare Pts | 92 | 92 | 92 |
| Relative Error | 39.13 | 39.13 | 0 |
| Absolute Error | 39.13 | 39.13 | 0 |
| RMS Error | 42.02 | 42.02 | 0 |
| r squared | 0.414 | 0.414 | 1 |

**Figure 16.** Simulated vs. observed TSS at Hospital Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

Hospital Creek - Total Suspended Sediment, mg/l

| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 30.56 | 30.61 | 894.4 |
| Minimum | 21.77 | 21.77 | 21.45 |
| Maximum | 36.96 | 45.12 | 5991 |
| # Compare Pts | 15 | 15 | 15 |
| Relative Error | -863.8 | -863.8 | 0 |
| Absolute Error | 864.6 | 864.6 | 0 |
| RMS Error | 1705 | 1705 | 0 |
| r squared | 0.107 | 0.108 | 1 |

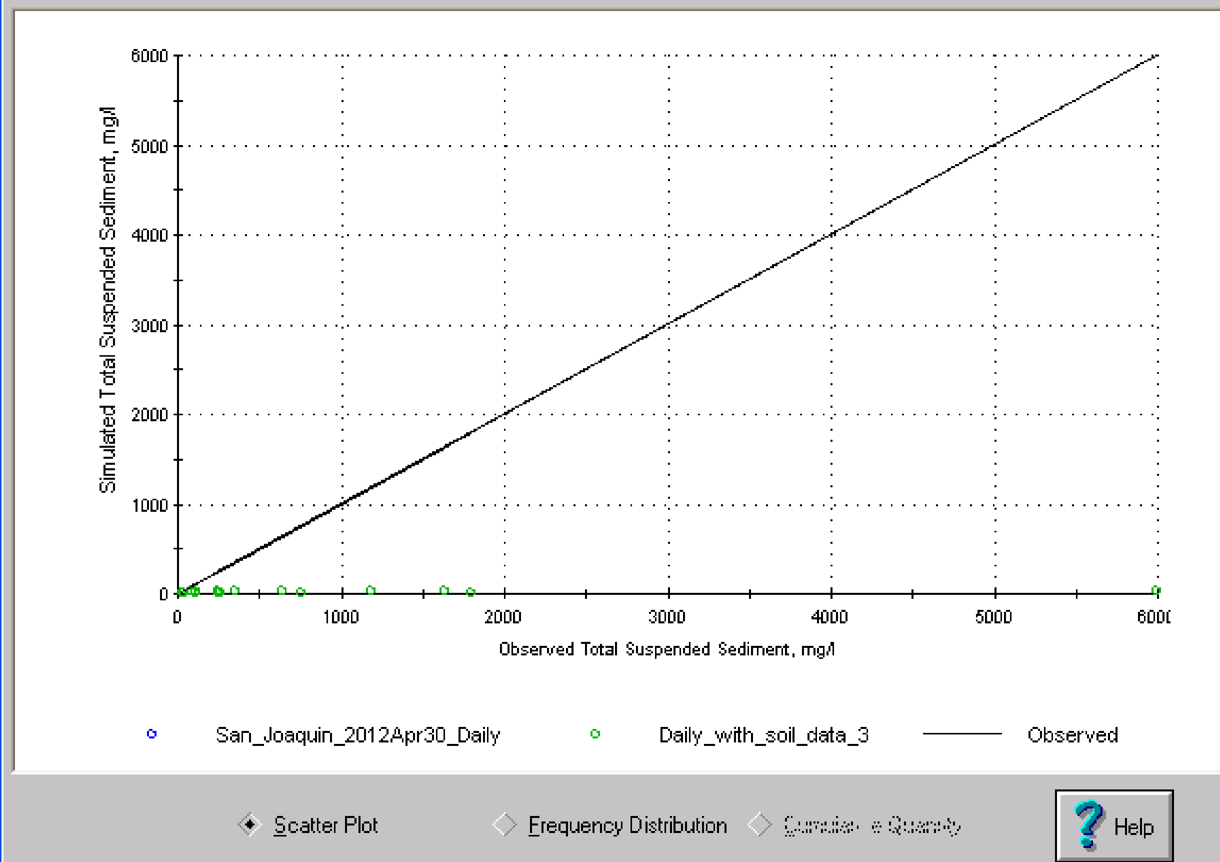


**Figure 17.** Simulated vs. observed flow at Ingram Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

Ingram Creek - Flow, cfs

| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 20.55 | 6.345 | 2.322 |
| Minimum | 0.243 | 0.00000011 | 0.36 |
| Maximum | 482.6 | 421.6 | 20.36 |
| # Compare Pts | 92 | 92 | 92 |
| Relative Error | 16.36 | -1.07 | 0 |
| Absolute Error | 16.47 | 3.213 | 0 |
| RMS Error | 18.16 | 5.493 | 0 |
| r squared | 0.00578 | 0.00255 | 1 |

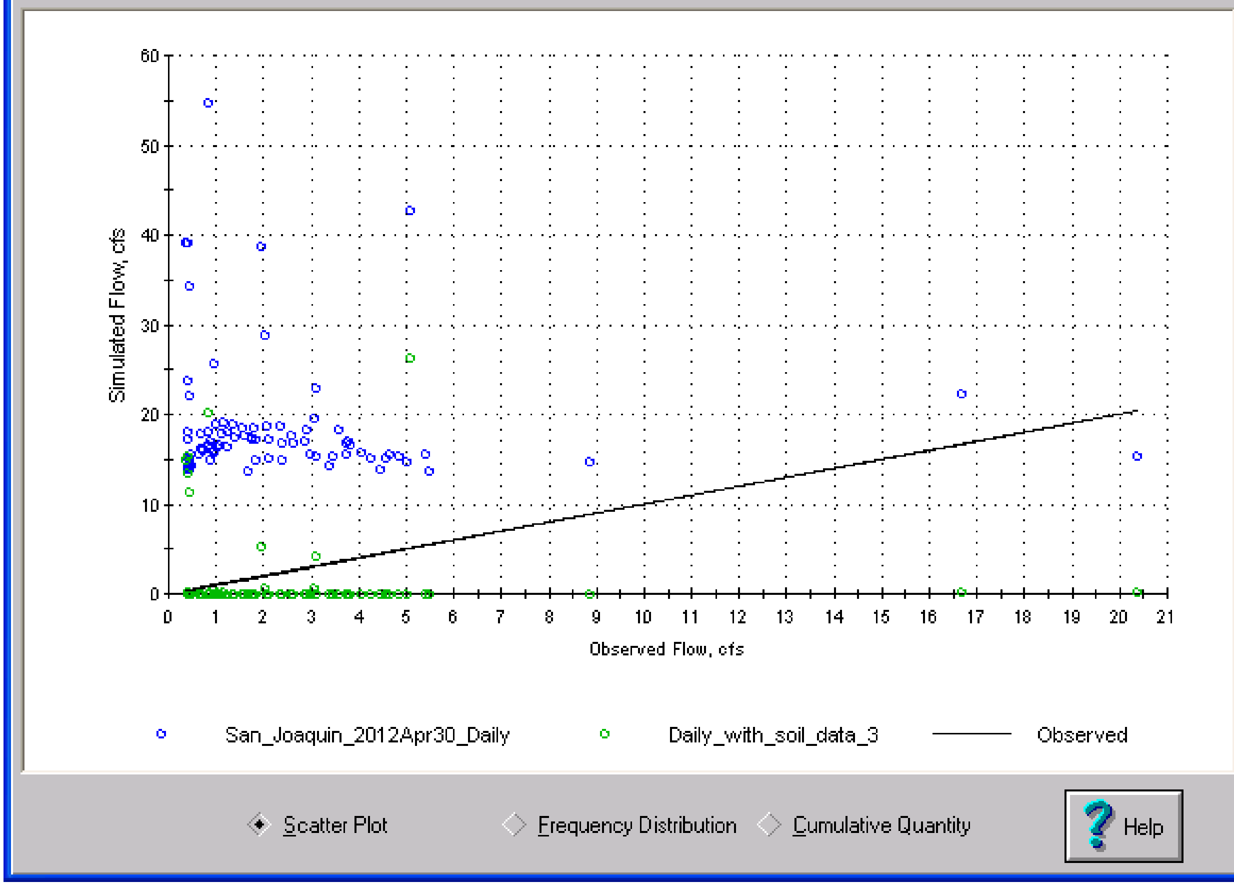
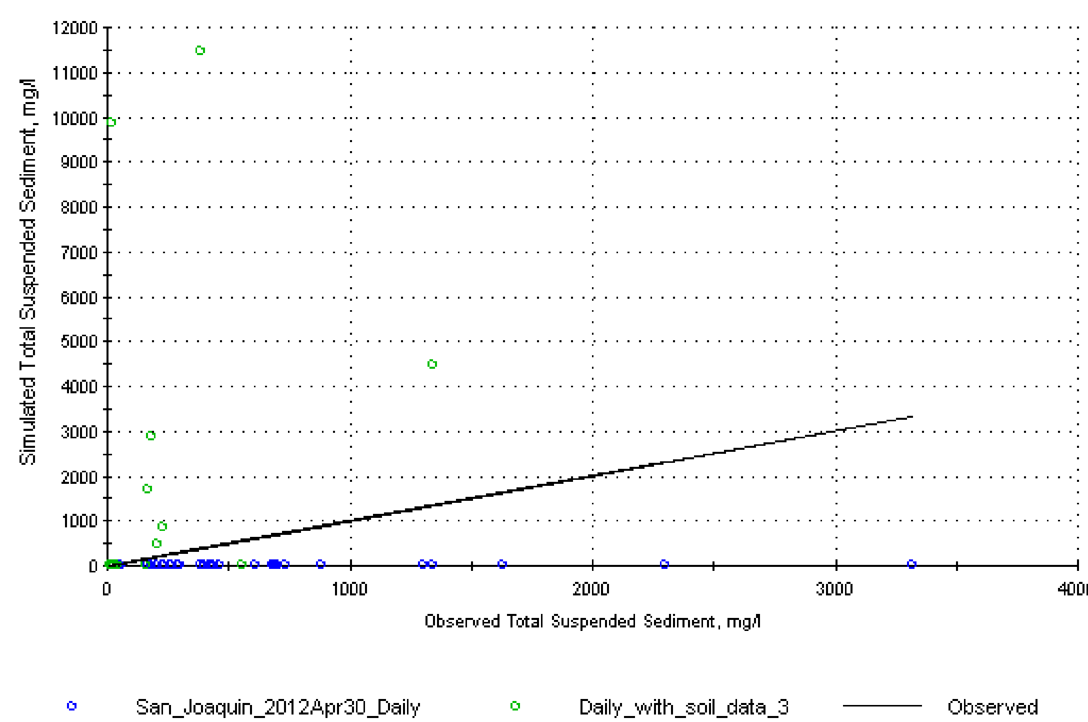


**Figure 18.** Simulated vs. observed TSS at Ingram Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

Ingram Creek - Total Suspended Sediment, mg/l

| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 43.98 | 3450 | 546 |
| Minimum | 21.66 | 22.35 | 10.5 |
| Maximum | 253.7 | 26440 | 3316 |
| # Compare Pts | 37 | 13 | 37 |
| Relative Error | -508.2 | 1927 | 0 |
| Absolute Error | 513.4 | 2318 | 0 |
| RMS Error | 841.4 | 4310 | 0 |
| r squared | 0.0807 | 0.0259 | 1 |




Scatter Plot Frequency Distribution Cumulative Quantity Help

**Figure 19.** Simulated vs. observed flow at Orestimba Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

Orestimba Creek near Crows Landing - Flow, cfs

| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 27.73 | 30.72 | 21.14 |
| Minimum | 0.00843 | 0.00843 | 0 |
| Maximum | 1100 | 1373 | 972 |
| # Compare Pts | 1911 | 1911 | 1911 |
| Relative Error | 6.679 | 9.683 | 0 |
| Absolute Error | 22.22 | 23.11 | 0 |
| RMS Error | 59.79 | 66.79 | 0 |
| r squared | 0.554 | 0.617 | 1 |

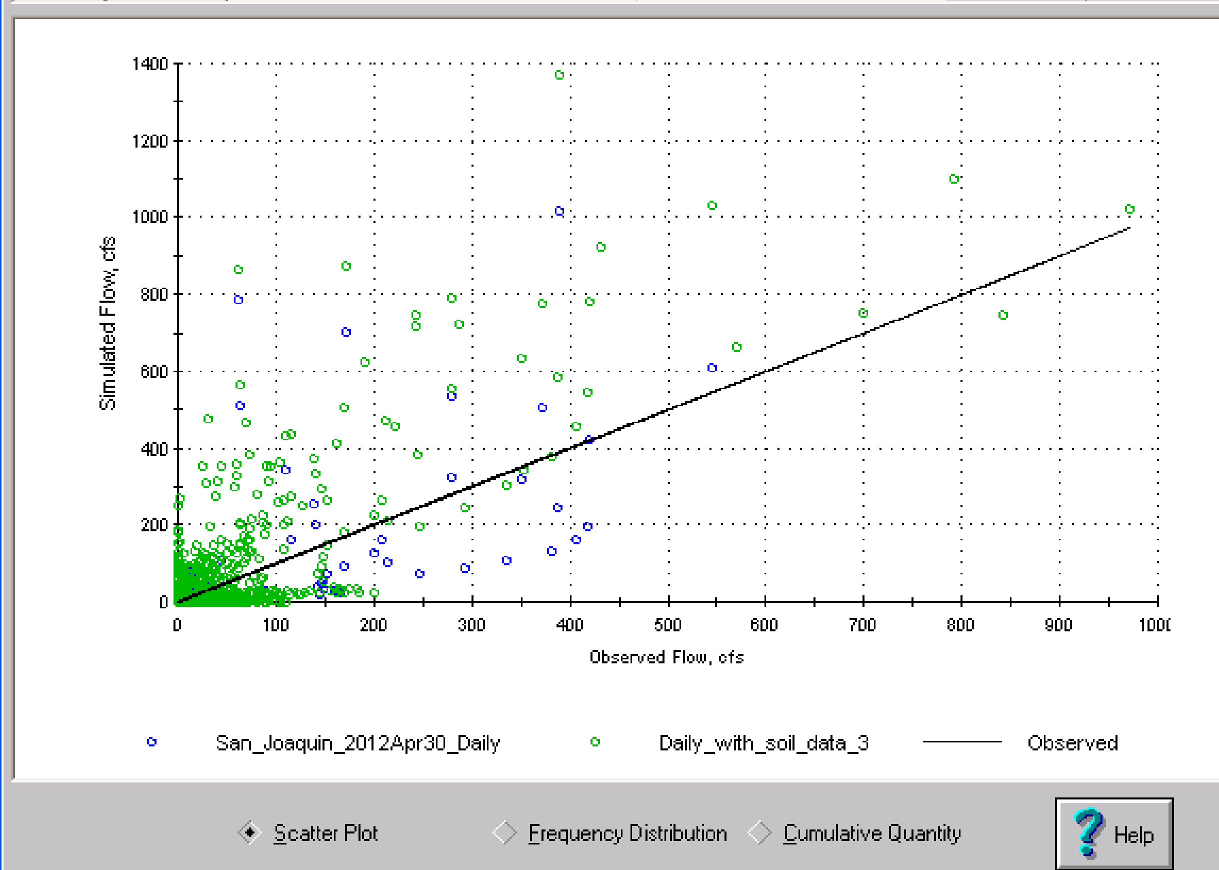
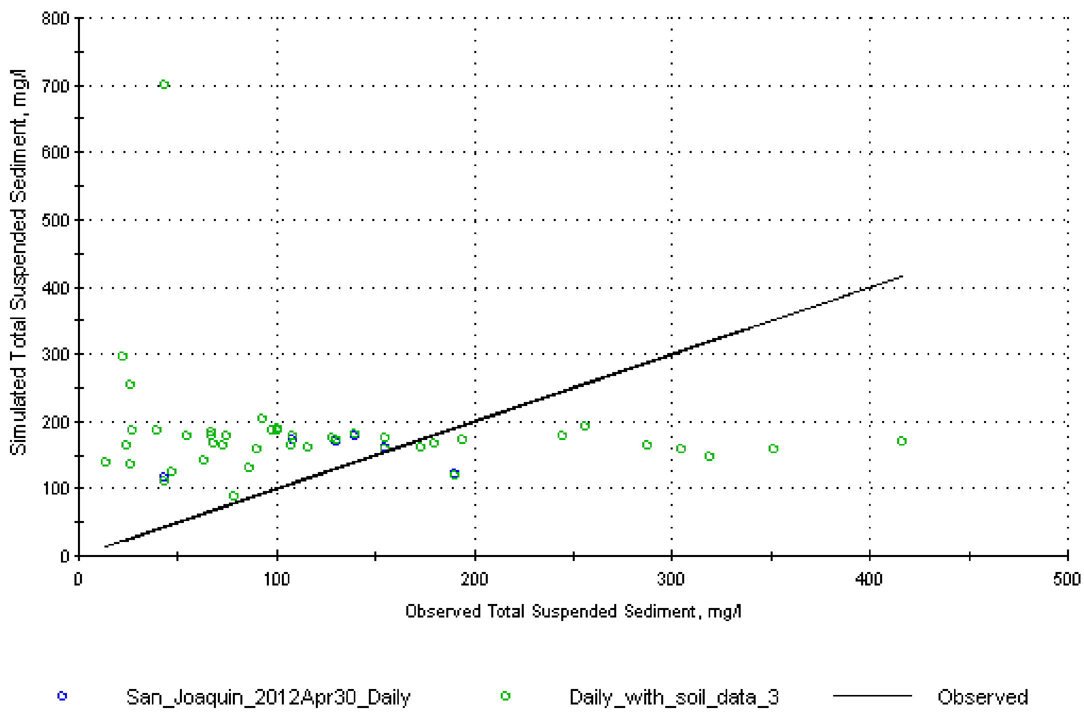


**Figure 20.** Simulated vs. observed TSS at Orestimba Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

Orestimba Creek near Crows Landing - Total Suspended Sediment, mg/l

| | San Joaquin 2012Apr30 Daily | Daily with soil data 3 | Observed |
|---|---|---|---|
| Mean | 228.5 | 228.5 | 123 |
| Minimum | 80.09 | 78.22 | 13.57 |
| Maximum | 4406 | 4406 | 416 |
| # Compare Pts | 44 | 44 | 44 |
| Relative Error | 58.25 | 58.52 | 0 |
| Absolute Error | 108.4 | 108.8 | 0 |
| RMS Error | 150 | 150.2 | 0 |
| r squared | 0.022 | 0.0219 | 1 |




Scatter Plot    Frequency Distribution    Cumulative Quantity    Help

**Figure 21.** Time series plot of flow at Ingram Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

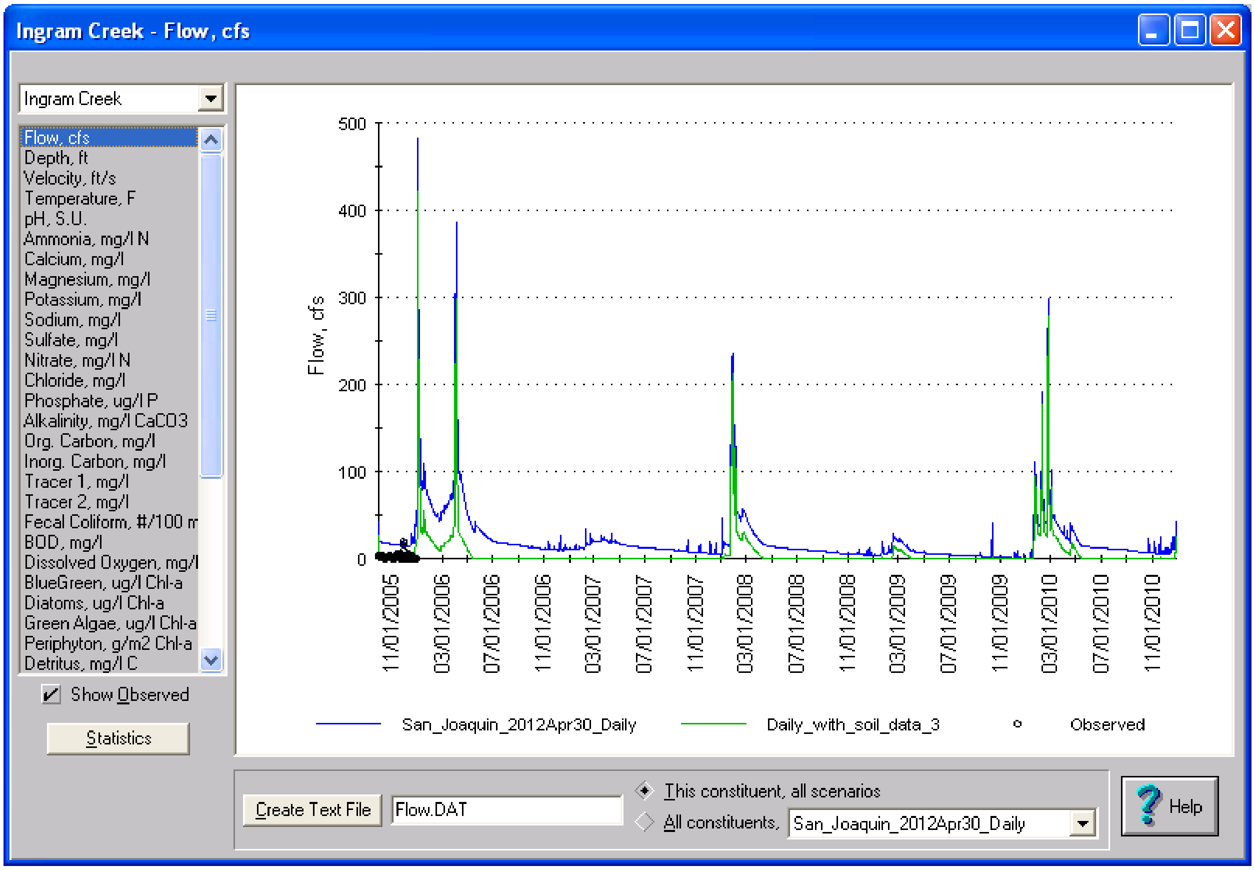


**Figure 22.** Time series plot of depth at Ingram Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.

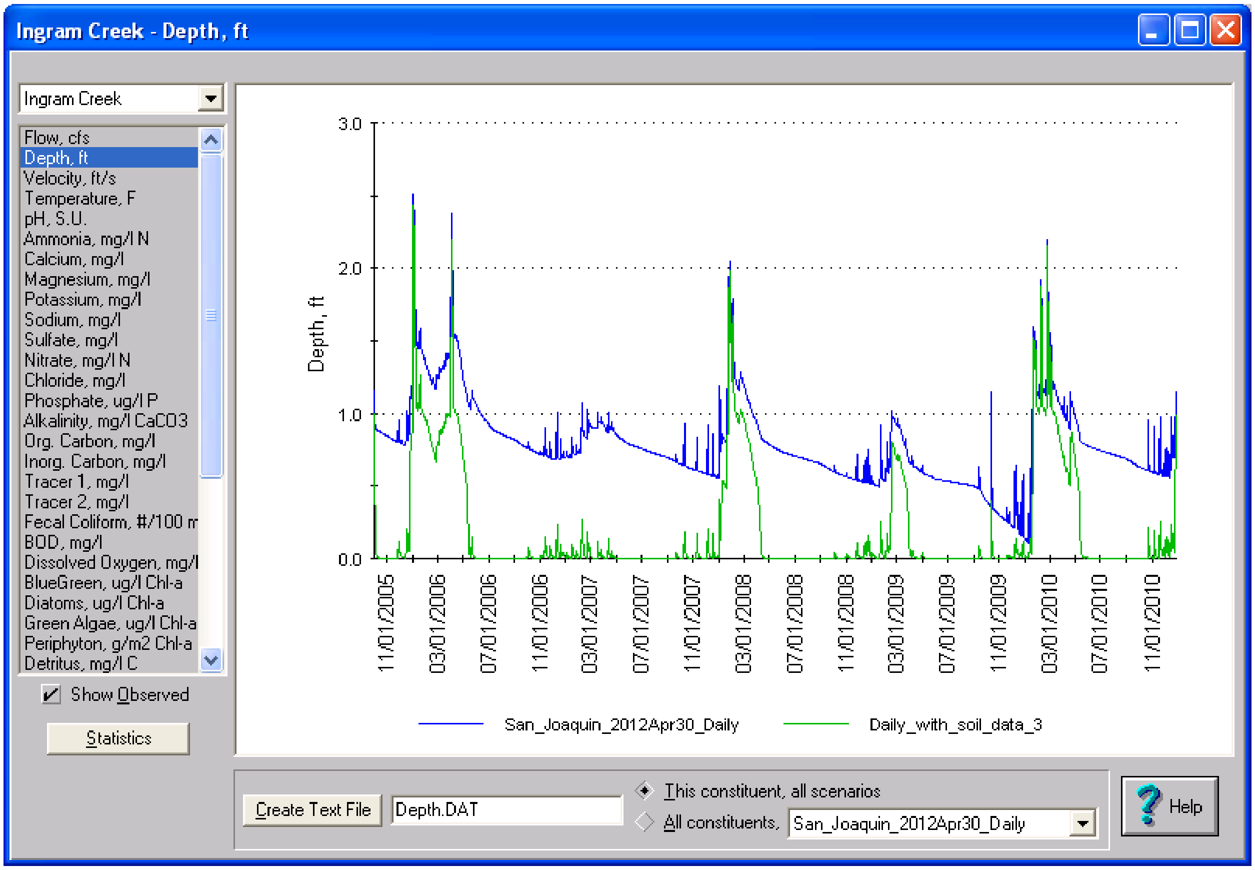


**Figure 23.** Time series plot of TSS at Ingram Creek for Base and Soil Study scenarios. See Table 1 for scenario descriptions.