WARMF Forecasting, Water Year 2012

A Deliverable
For
Metropolitan Water District of Southern California

Prepared by

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ABSTRACT

The Watershed Analysis Risk Management Framework (WARMF) has been applied to the Sacramento and San Joaquin Rivers of California's Central Valley to provide simulated flow and multiple water quality constituents. To use the model for short-term forecasting, upgrades were made to WARMF to allow for rapid updating of the time series data used to run the model. The processing tools and methodology developed for MWD in 2011 were expanded and refined to accommodate additional input data and streamline the forecasting process. The forecasting procedure is set up to simulate up to three weeks into the future and can be performed within 4 hours to produce simulated flow and turbidity in near real-time. Flow calibration in the Sacramento River was improved for early winter storms. Turbidity calibration of the Sacramento River and other Delta tributaries was improved through collaboration with Delta modeling efforts. The San Joaquin River model was upgraded to simulate winter flow and turbidity of the San Joaquin River at Lander Avenue near Stevinson. Weekly forecasts were performed starting on Thursday December 8, 2011 and ending on Thursday February 16, 2012. Relative error in predicted flow in the Sacramento River at Freeport was 8% for the hindcast simulation and averaged 14 % during first six days of the forecast period. Relative error in predicted flow in the San Joaquin River at Vernalis was 8% for the hindcast simulation and averaged 8 % during first six days of the forecast period. Turbidity in the Sacramento River was systematically underpredicted by the WARMF model, though the simulated timing of turbidity peaks did capture the trends seen in observed data collected at Freeport. Simulated turbidity in the San Joaquin River was greater than measured values throughout the duration of the project, likely due to the large variability in the relationship between turbidity and total suspended sediment. Specifically, the measured ratio between turbidity and total suspended sediment for August and September of 2011 was only 40% of the average ratio, which was recalculated prior to the forecasting season and used in model simulations. No significant precipitation occurred in the San Joaquin River watershed between 12/8/2011 and 2/16/2012 and there were no large flow releases from Friant Dam so the reliability of the upgraded San Joaquin River model to simulate the timing of turbidity peaks caused by precipitation and high flow events could not be determined.

1 INTRODUCTION

Delta Water Quality Constraints

The Sacramento-San Joaquin River Delta is a major water source for the Metropolitan Water District. The California Aqueduct delivers water from the Delta to Metropolitan's customers in Southern California. The Delta's multiple environmental constraints are an important consideration in operation of the Banks Pumping Plant at the origin of the California Aqueduct in the south Delta. The plant must be operated to minimize the incidental take of endangered salmon and Delta Smelt. Since the smelt are associated with high turbidity water, water exports must be curtailed when measured turbidity is elevated at south Delta monitoring locations.

Operational planning for the Banks Pumping Plant relies on forecasts of water quality including turbidity. Modeling of the Delta tracks the transport of pollutants to the pumps from the bay and from the Sacramento, San Joaquin, and other Delta tributary rivers. Since major influxes of turbidity come from the tributary watersheds, it is necessary to forecast the loading from the tributaries to predict the turbidity at the pumping plant. A general purpose forecasting tool including other chemical constituents such as organic carbon would provide additional benefit for managing water supply and meeting unknown future water quality constraints.

WARMF Modeling

The Sacramento (Figure 1.1) and San Joaquin River (Figure 1.2) applications of the Watershed Analysis Risk Management Framework (WARMF) are used to dynamically simulate flow and water quality within their respective watersheds on a daily or hourly time step. The Sacramento River application of WARMF includes tributaries on the east side of the Delta including the Cosumnes River, Dry Creek, Mokelumne River, Calaveras River, and French Camp Slough. The model has been calibrated for flow and water quality parameters including turbidity (Systech 2011a, Systech 2011b). The San Joaquin River WARMF application is set up to simulate the watershed from Friant Dam to the Old River and has also been calibrated for flow, turbidity, and other water quality parameters (Systech 2011c).

In the process of simulating the watersheds, the WARMF models determine the sources and fates of pollutants. Many chemical and physical parameters are simulated in both models including temperature, nitrogen species, phosphorus, major ions, organic carbon, dissolved oxygen, suspended sediment, turbidity, phytoplankton, and electrical conductivity. The models have been used for a variety of purposes including phytoplankton study and management, organic carbon and salinity source identification, and tracking nitrate and salinity.

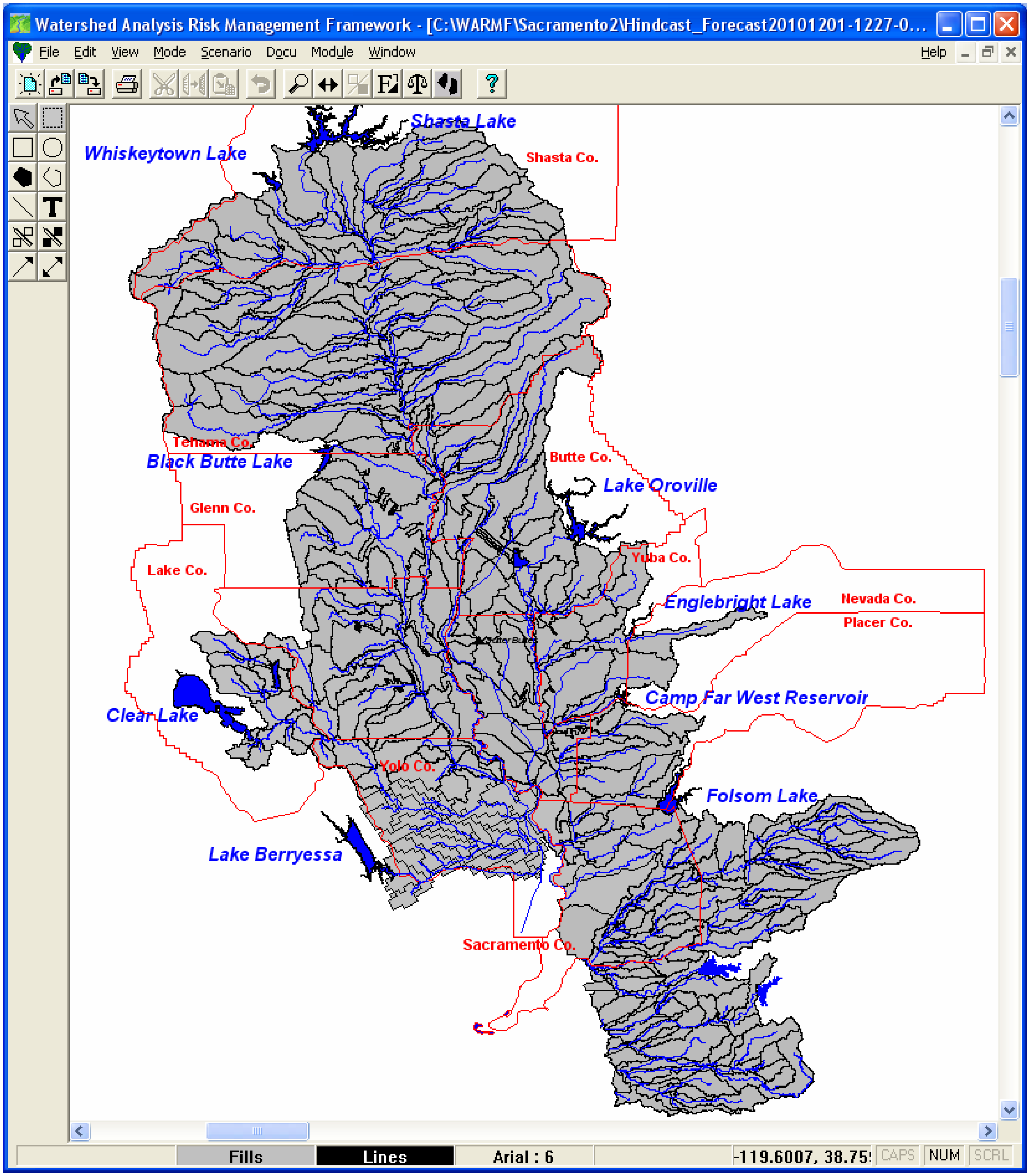

Figure 1.1: Sacramento River WARMF Application

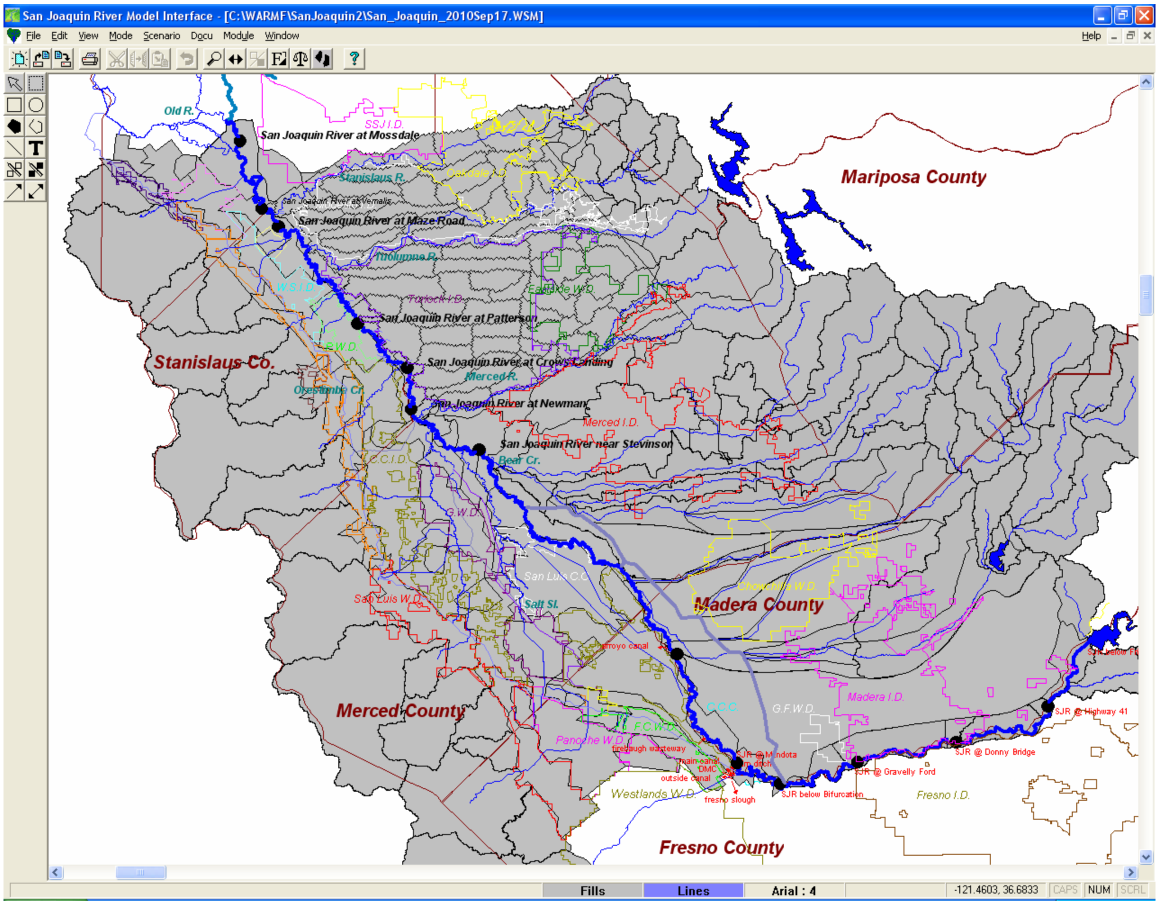

Figure 1.2: San Joaquin River WARMF Application

The WARMF models simulate the Central Valley rivers to the locations where they enter the Delta, but do not simulate the tidal flow and pollutant transport within the Delta. To link pollutants originating in the watersheds with water quality at the Banks Pumping Plant, WARMF is linked with a Delta model where the various tributaries enter the Delta. WARMF provides a time series of flow and concentration for many chemical and physical parameters at these interface points including the Sacramento River, Yolo Bypass, Mokelumne River, Cosumnes River, Calaveras River, and San Joaquin River.

Both the Sacramento and San Joaquin River models have been set up and calibrated using historical data. Most simulations of watershed management alternatives have been in historical mode. This is done by modifying historical data to simulate proposed watershed management alternatives. This type of simulation is used for long-term watershed management and determining total maximum daily load (TMDL) of pollutants allowable in the watershed.

It is also possible to use WARMF in real-time forecasting mode. The model simulates conditions right up to the time the simulation is run and then continues into the near future. Predicted meteorology, reservoir releases, diversions, and point source discharges are used to drive the model. The model's predictions of flow and water quality can then be used to make real-time management decisions. In July 2007, WARMF was tested in forecasting mode to predict the effect of eliminating discharge from the San Luis Drain on water quality in the San

Joaquin River at Vernalis (Herr and Chen 2007). The model predicted decreases in phytoplankton and salinity of less than 5% resulting from the management action compared to the baseline "do nothing" case. There were significant errors in future projections of some model inputs, however, which propagated through to the simulation results. The process of generating time series model inputs for the forecast was also cumbersome and has recently been streamlined to perform forecasts on a regular basis.

In the winter of 2010-2011 WARMF was used in forecasting mode. It was a wet winter which provided a good test of the models' ability to predict flow and turbidity. Flow and turbidity simulations were reasonable for the Sacramento River at Freeport, although the magnitude of both for early season storms was underpredicted. The San Joaquin River WARMF application was set up assuming little water would be contributed from the upper watershed. Large releases from Friant Dam passed through to the lower watershed for the second time in 10 years and led to large errors of predicted flow and turbidity in the San Joaquin River at Vernalis. Both the Sacramento and San Joaquin River WARMF models were upgraded for 2011-2012 forecasting to reduce the major sources of error identified in the first year of forecasting.

2 IMPROVEMENTS TO THE SACRAMENTO RIVER WARMF MODEL

Watersheds in the northern portion of the Sacramento River WARMF model domain have a substantial influence on the hydrology and water quality in the lower Sacramento River. Many of these rivers are unregulated and therefore exhibit a more varied hydrologic and chemical response to precipitation than waterways with dams that retain flood flows and trap sediment. In preparation for the 2012 forecasting season, substantial effort was invested in calibrating the simulated hydrology to observed data in the Cow, Battle, Mill, Deer, Antelope and Cottonwood Creek watersheds (Figure 2.1). The calibration of hydrology in these watersheds focused on, 1) obtaining an accurate annual water balance and 2) capturing the observed hydrological response of each watershed to the first significant precipitation event of the winter season (i.e. the first flush). The accuracy of the simulated annual water balance was evaluated using the relative error statistic. Relative error is the average difference between simulated and observed over all simulation days. It can be expressed as a percent by dividing by the average observed value. The ability of the model to capture the first flush was evaluated by visual comparison of the graphs of observed and simulated hydrology.

Figure 2.2 through Figure 2.4 illustrate the improvements made in the Battle, Cottonwood and Cow Creek watersheds. This subset of the calibration watersheds was selected to display the results of the calibration effort because they are the largest of the unregulated rivers in the northern WARMF model domain and have the greatest effect on conditions at Freeport. The cumulative effect of the calibration on the simulation of Sacramento River at Bend Bridge hydrology is presented in Figure 2.5. In each of these figures (Figure 2.2 through Figure 2.5), the blue line represents the results of the recent calibration effort, the green line represents the hydrologic simulation prior to calibration, and the black circles represent measured average daily discharge. Table 2.1 provides a summary of the WARMF statistical output for each of these watersheds, and demonstrates that the recent hydrologic calibration led to simulation improvements in each of these watersheds as measured by the relative error, absolute error and the r-squared statistic when compared with the previous model results. In the table, rows designated as 2011 in the simulation column contain the simulation statistics for the watersheds prior to calibration. Rows designated as 2012 provide the statistics for the simulation following calibration. The improvements in model statistics are the result of the hydrological calibration in the upstream watersheds and demonstrate that WARMF is simulating hydrology in the northern portion of the model domain with a high degree of accuracy and precision.

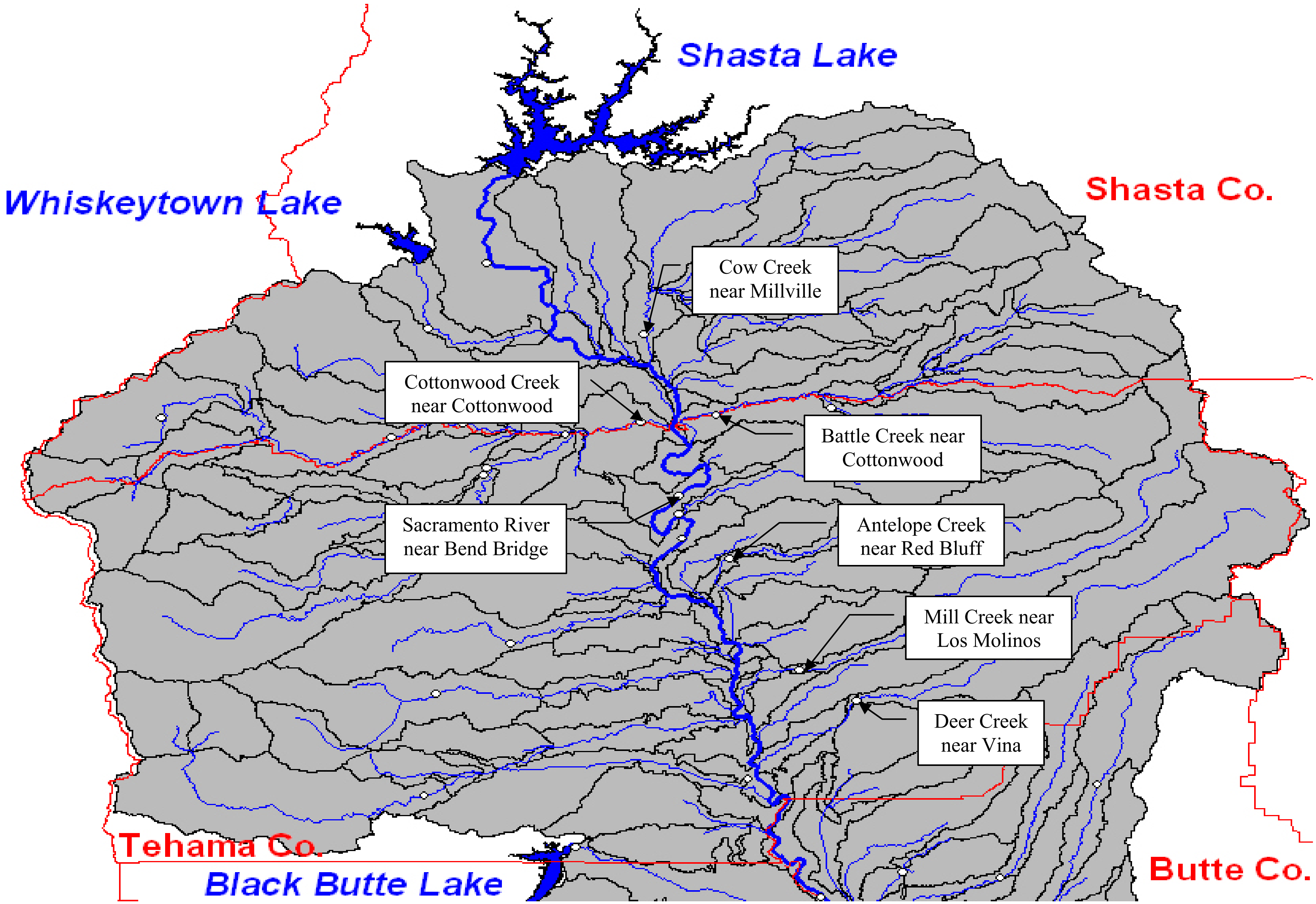

Figure 2.1 Hydrology calibration watersheds, northern portion of the Sacramento River WARMF model domain

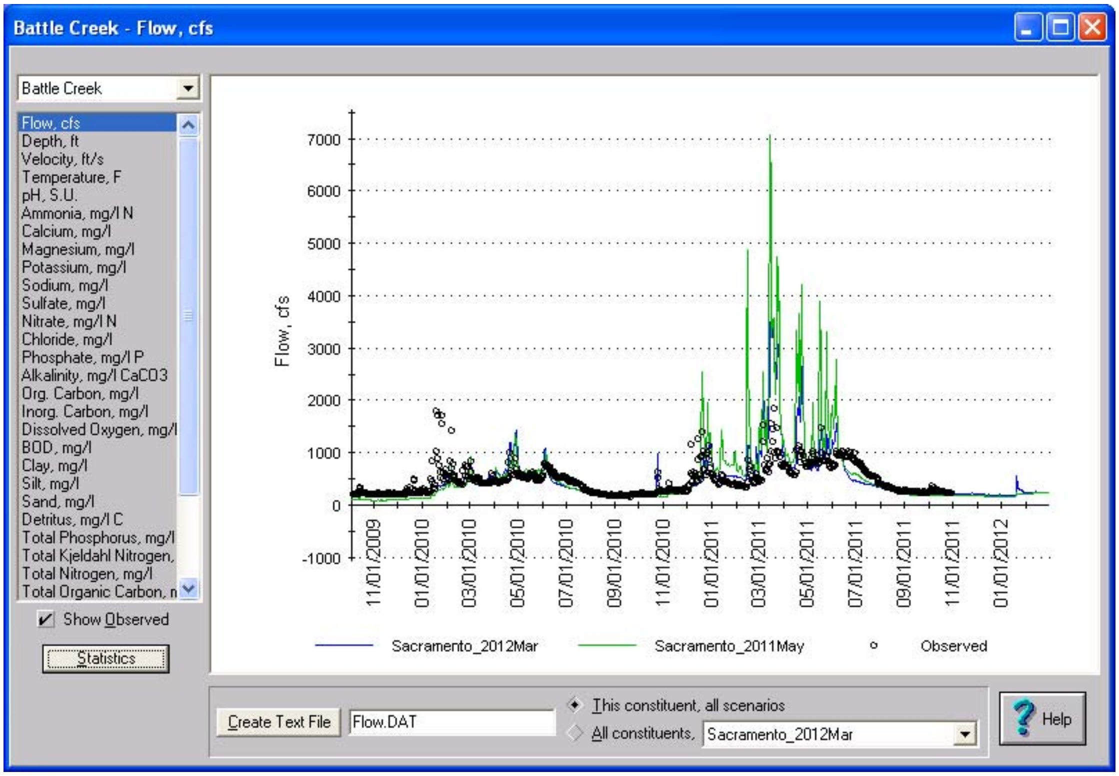

Figure 2.2 Battle Creek Observed and Simulated Discharge, October 2009 – February 2012

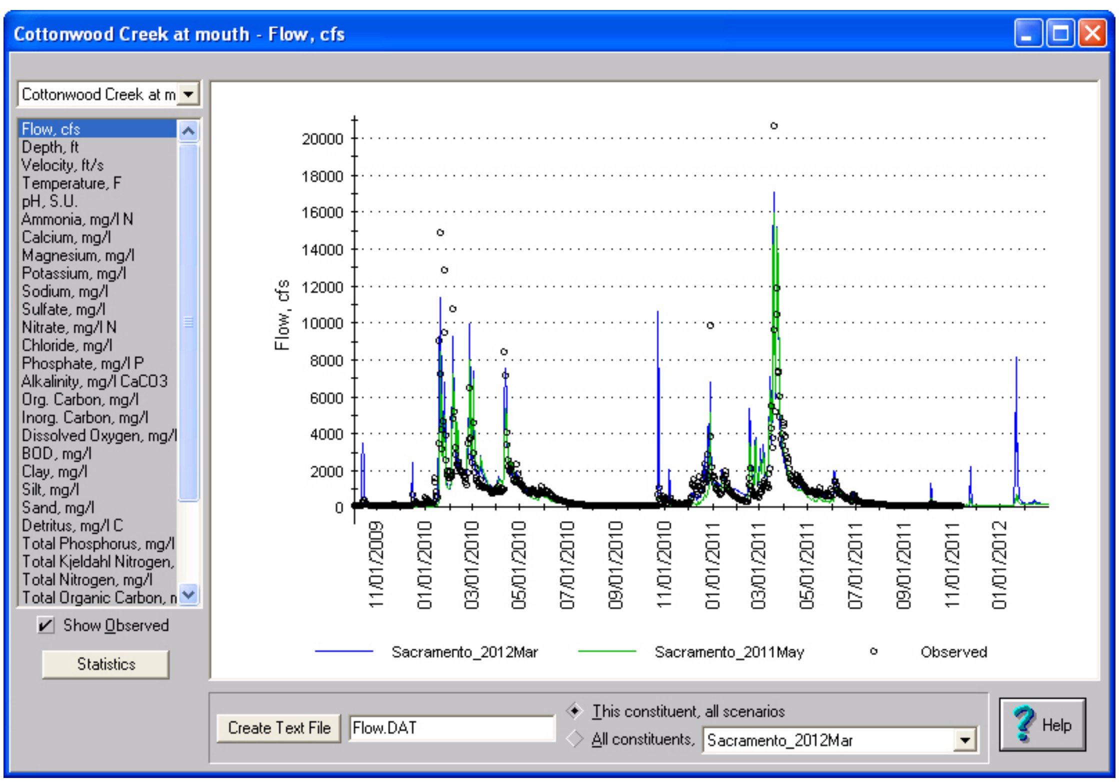

Figure 2.3 Cottonwood Creek Observed and Simulated Discharge, October 2009 – February 2012

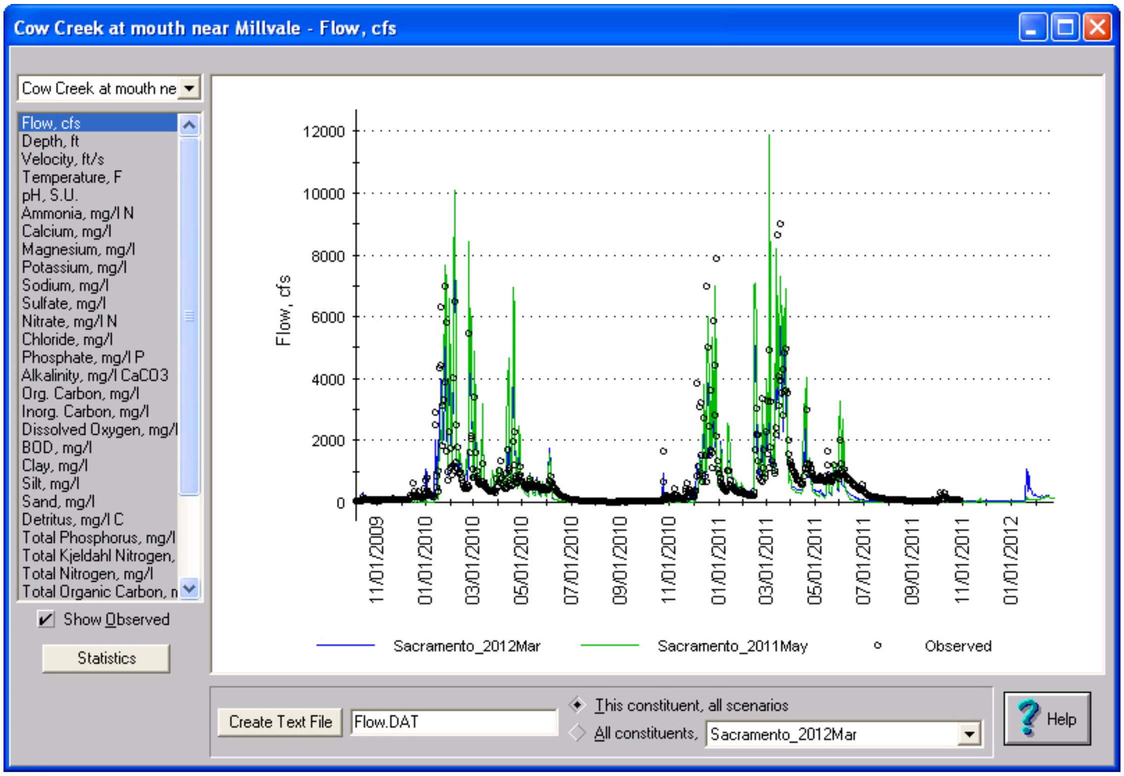

Figure 2.4 Cow Creek Observed and Simulated Discharge, October 2009 – February 2012

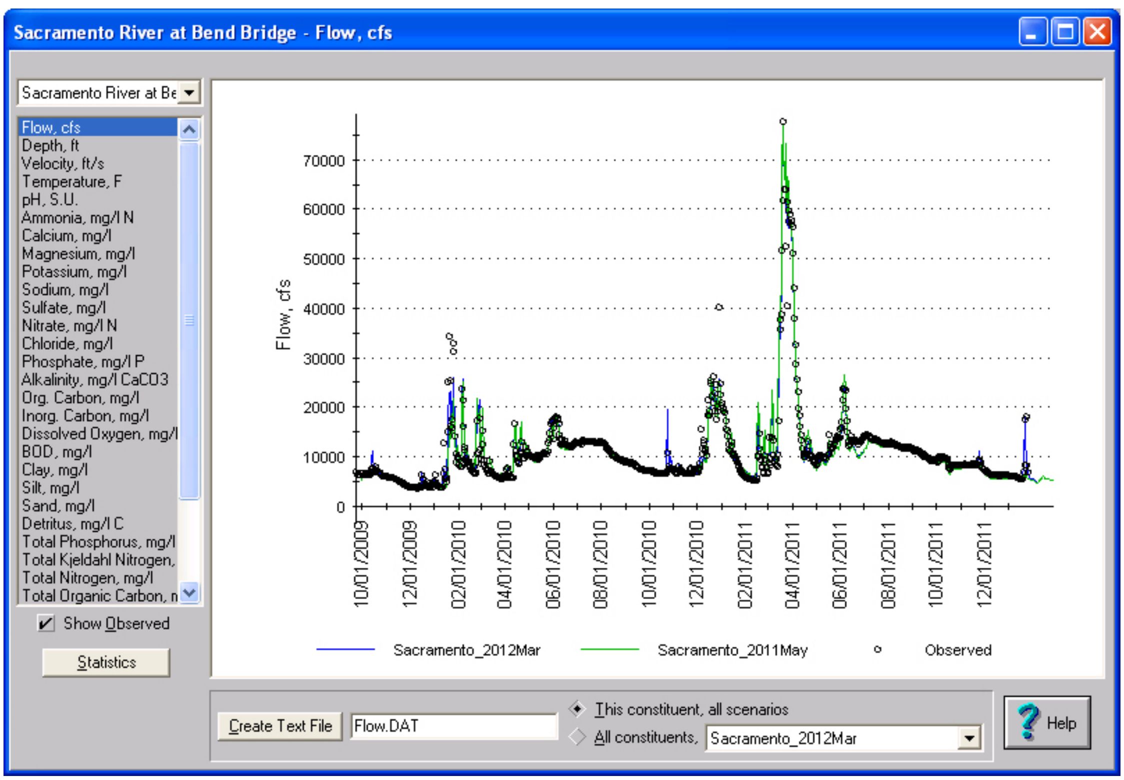

Figure 2.5 Sacramento River at Bend Bridge Observed and Simulated Discharge, October 2009 – February 2012

Table 2.1 Hydrologic Calibration Statistics, October 2009 – February 2012

Watershed	Simulation	Mean (cfs)	Minimum (cfs)	Maximum (cfs)	% Rel. Error	% Abs. Error	R^2
Battle Creek	Observed	437.5	158	2643			
	2011	529	89	7076	34.3%	62.4%	0.42
	2012	423	153	4243	1.8%	31.8%	0.53
Cottonwood Creek	Observed	763	57	20700			
	2011	779	0	15990	14.4%	49.7%	0.73
	2012	780	43	17060	8.0%	36.7%	0.77
Cow Creek	Observed	544	1	9030			
	2011	620	0	11890	31.8%	75.6%	0.63
	2012	493	26	15360	-1.5%	49.4%	0.61
Sacramento at Bend Bridge	Observed	10200	3700	77700			
	2011	10490	3557	77270	5.5%	12.0%	0.91
	2012	9882	3732	75490	-1.5%	8.5%	0.94

After the hydrology calibration of the upper Sacramento River WARMF model domain was completed, the WARMF turbidity simulation of the Sacramento at Freeport was calibrated to observed data. Turbidity is not an independently simulated parameter in WARMF. It is calculated for every river segment and every time step from the simulated concentrations of clay and silt particles calculated by WARMF's sediment transport routines. Calculated turbidity is only used for model output, not for calculation of turbidity in downstream river segments or in subsequent time steps. WARMF calculates turbidity in the Sacramento and Delta east side tributaries as:

Turbidity (NTU) = 0.5902 * [Clay (mg/L) + Silt (mg/L)]

Given the prescribed relationship between turbidity and suspended sediment, the calibration of turbidity is conducted by adjusting WARMF's sediment parameters. Coarse adjustments to turbidity were made by adjusting WARMF's global (e.g. affecting the entire model domain) sediment parameters. These parameters include average particle size and river settling velocity for each of the clay, silt and sand soil fractions. As the calibration process evolved it became clear that suspended sediment characteristics were not constant across the entire model domain. Catchment specific parameters were adjusted to calibrate turbidity at the local level. The soil erosivity factor (a parameter of the Universal Soil Loss Equation) and the clay/silt/sand composition of surface soils are specified at the catchment level within the WARMF model. These parameters were used to adjust simulated turbidity and achieve the measured turbidity variation between watersheds within the Sacramento River WARMF model domain.

The WARMF turbidity simulation was calibrated for the Sacramento River at Freeport, the Yolo Bypass, the Calaveras River, the Cosumnes River, the Mokelumne River, and the San Joaquin River at Vernalis. The Sacramento River turbidity simulations were calibrated to measured values collected at Freeport. Figure 2.6 shows the newly calibrated simulation in blue, the simulation using the previous calibration in green, and observed data in black circles. Table 2.2 presents the calibration statistics for the pre- and post -calibration turbidity results at the

Sacramento River at Freeport. The statistics illustrate that new calibration eliminated the systematic overprediction of turbidity that was present in the original calibration. Absolute error and the R^2 statistics were also improved through the calibration efforts. Calibration of simulated turbidity in the Yolo Bypass and the Calaveras, Cosumnes, and Mokelumne Rivers was accomplished through cooperation with Marianne Guerin at Resource Management Associates. Daily turbidity simulation results for October 1, 2008 through March 7, 2012 were provided to RMA and used as boundary input for their Delta simulation model. Simulation results within the Delta were compared with measured turbidity values and feedback was provided to Systech. The results from the Delta model were used to inform changes to the WARMF turbidity calibration parameters, and the process was repeated until Delta model simulation results agreed with Delta turbidity measurements.

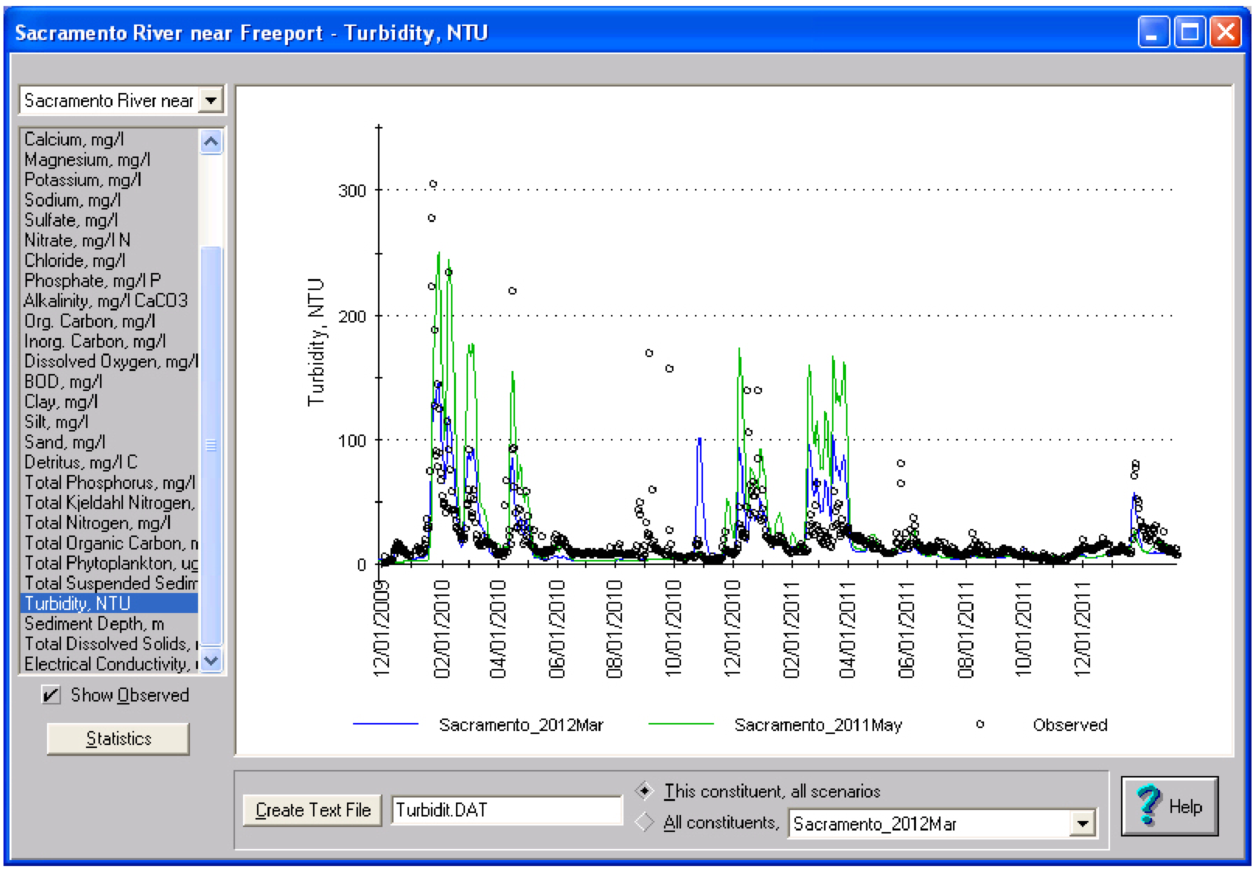

Figure 2.6 Sacramento River at Freeport Observed and Simulated Turbidity, October 2009 – February 2012

Table 2.2. Sacramento River at Freeport Turbidity Simulation Statistics

Watershed	Simulation	Mean (cfs)	Minimum (cfs)	Maximum (cfs)	% Rel. Error	% Abs. Error	R^2
Sacramento	Observed	437.5	158	2643			
River at	2011	529	89	7076	41.5%	95.5%	0.34
Freeport	2012	423	153	4243	-6.5%	59.3%	0.39

3 IMPROVEMENTS TO THE SAN JOAQUIN RIVER WARMF MODEL

The San Joaquin River contains a mixture of relatively clear high quality water released from dams on tributaries on the east side of the river and drainage from wetlands and agricultural areas in the San Joaquin Valley. The WARMF model of the watershed has been set up to simulate the local runoff combined with model boundary inflows from the east side tributaries and the San Joaquin River at Lander Avenue (near Stevinson). Although the flow at Lander Avenue is not controlled, it is generally low because the San Joaquin River is normally dry upstream of this gage. Flow released from Friant Dam is normally fully diverted and/or seeps into the river bed before reaching the lower river.

The winter of 2010-2011 was wetter than most, however, resulting in large flow releases passing through the San Joaquin River and its flood control bypasses to the lower river. The model did not have a mechanism to simulate this high flow entering the model at Lander Avenue, causing large errors in predicted flow and turbidity. In addition, the magnitude of turbidity simulations in the San Joaquin River at Vernalis generally matched measured data but the variability in the data was not well simulated. Improvements to the San Joaquin River WARMF model were done to address these two issues and produce more reliable forecasts.

Relationship Between Total Suspended Sediment and Turbidity

WARMF simulates turbidity by first simulating sediment transport processes and then applying a linear regression to calculate turbidity from the simulated suspended sediment concentration at every time step for each river segment. Suspended sediment data has been collected daily at Vernalis by the United States Geological Survey (USGS) for many years. Each year of data undergoes a quality control process and is released in spring of the following year. Turbidity has been collected on a real-time basis and made available at the California Data Exchange Center (CDEC) since February 2008. The overlapping time period between the two datasets can be used to establish a relationship between total suspended sediment and turbidity. The release of the 2010 water year USGS data in spring of 2011 provided the opportunity to update the relationship between these parameters before the 2011-2012 forecasting season.

Figure 3.1 shows a plot of measured total suspended sediment versus measured turbidity at the San Joaquin River at Vernalis. Many outliers are evident in the turbidity data as spikes which occur without a corresponding increase in suspended sediment concentration. To calculate the ratio between suspended sediment and turbidity, the major outliers were removed and a linear regression was performed. Figure 3.2 shows the result, with a ratio of turbidity/TSS equal to 0.4909 and an r-squared of 0.5252. This ratio was calculated as 0.5311 before the addition of the 2010 water year data. The new ratio was used in WARMF for the 2011-2012 forecasting season, but the mediocre fit between turbidity and suspended sediment is a source of error in simulated turbidity. Note that with the scales of each parameter in Figure 3.1, the two lines should be almost on top of each other for a perfect fit.

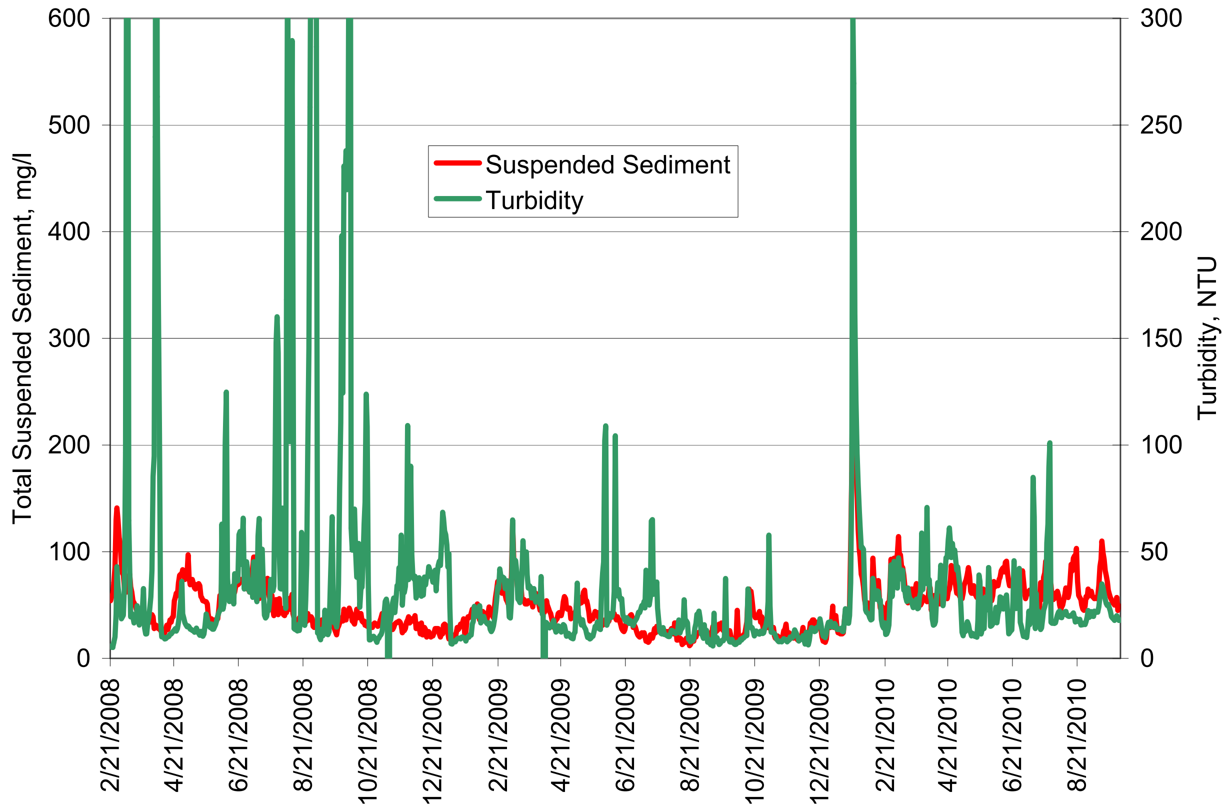

Figure 3.1 Observed Total Suspended Sediment vs Turbidity, San Joaquin R. at Vernalis

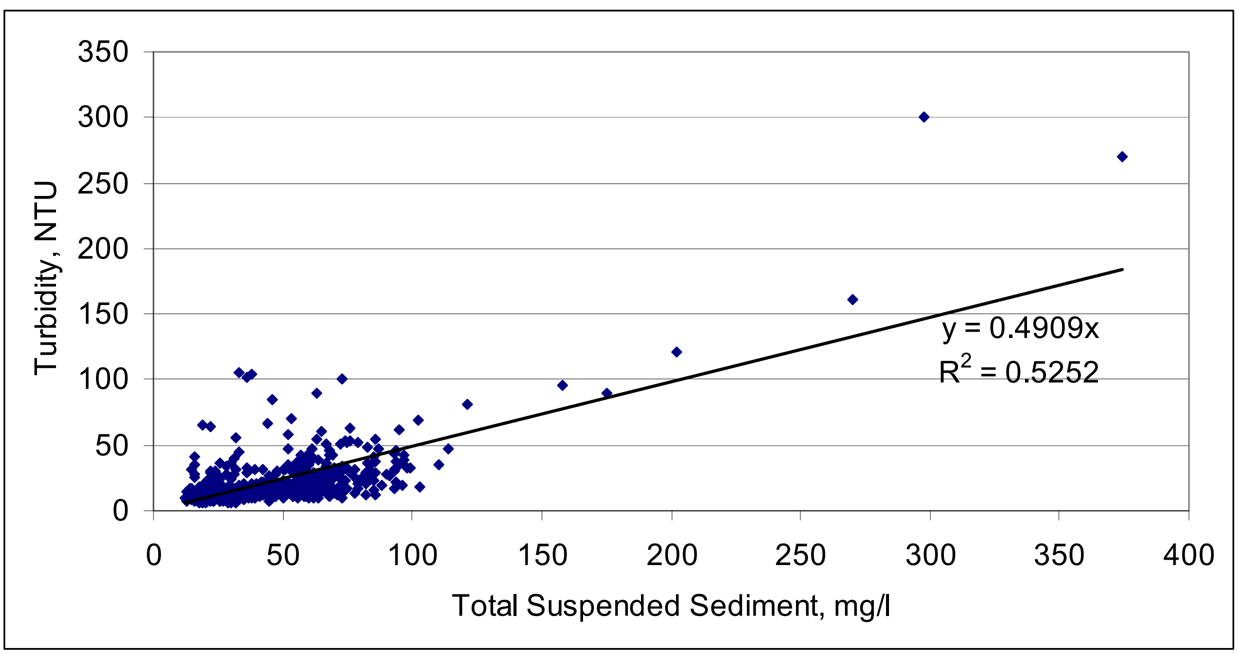

Figure 3.2 Regression Between Turbidity and Total Suspended Sediment

Simulation of Flow and Suspended Sediment / Turbidity in the San Joaquin River at Lander Avenue

Since the Lander Avenue boundary condition proved problematic in the 2010-2011 forecasting season, the San Joaquin River WARMF model was upgraded to remove this boundary condition. Instead, the flow and water quality at that location would be simulated based on flow from upstream. There are two primary sources of water to the San Joaquin River at Lander Avenue. One of those sources is Bear Creek and the several sloughs which drain to it shown in Figure 3.3. The other is flow from Friant Dam which passes through the Eastside Bypass and re-enters the San Joaquin River upstream of Lander Avenue. Excess flow released from dams on the Fresno and Chowchilla Rivers also flow through the Eastside Bypass when there is high runoff from the Sierra Nevada. Figure 3.4 shows in red the paths taken by flow from Friant Dam, the Fresno River, and the Chowchilla River to the San Joaquin River at Lander Avenue. The same figure shows the routing of water from the local watersheds through Bear Creek in black.

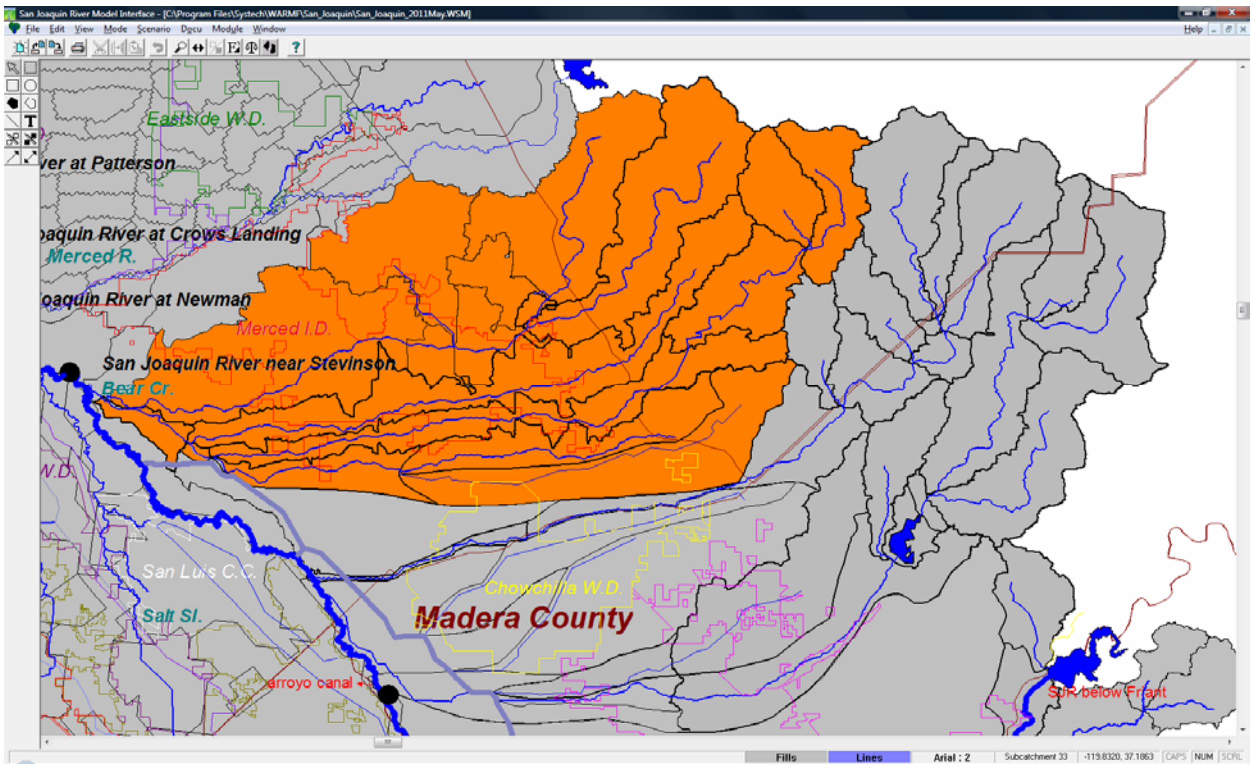

Figure 3.3 San Joaquin River at Lander Avenue Local Watershed

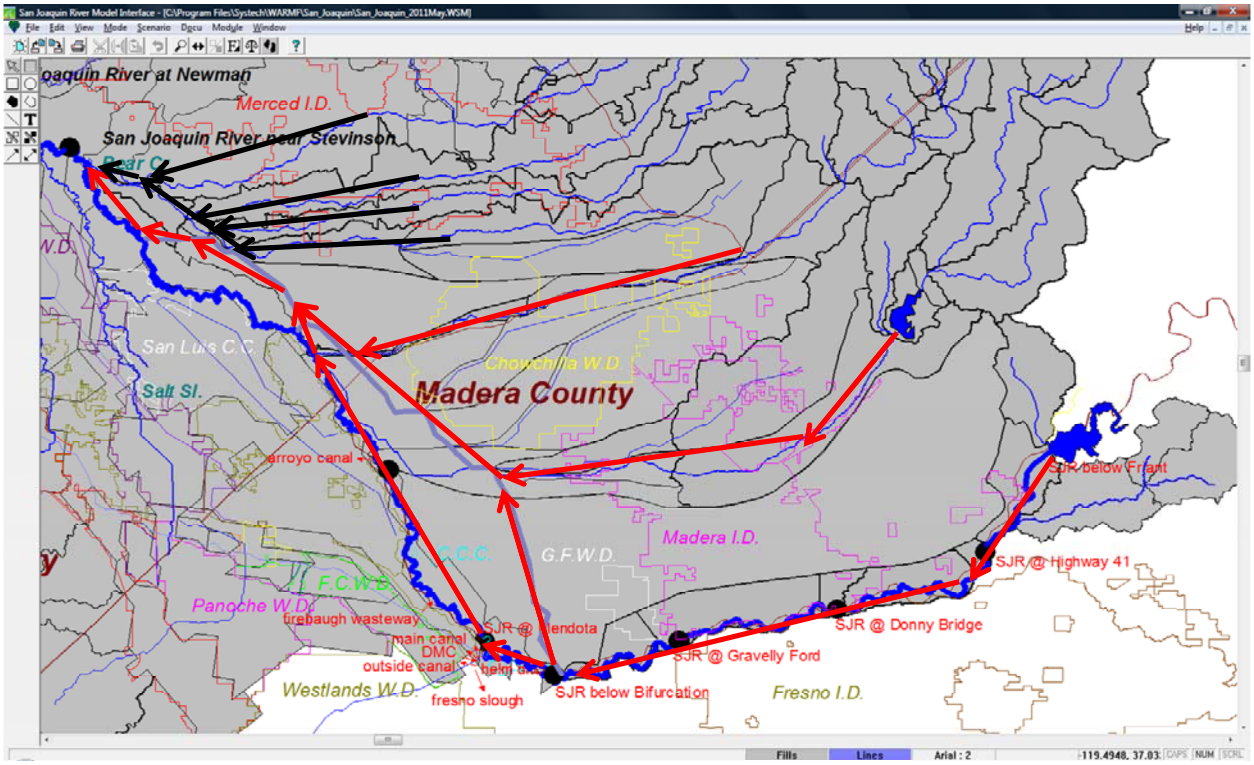

Figure 3.4 Flow Paths of the San Joaquin River Between Friant Dam and Lander Avenue

Runoff from the local watersheds is the source of baseline flow in the San Joaquin River at Lander Avenue and can also produce winter flow peaks. The WARMF model was calibrated for winter hydrology at Bear Creek at McKee (Figure 3.5) and San Joaquin River at Lander Avenue (Figure 3.6) gages. The figures show a simulation from 10/1/2005-12/31/2010 in blue and an extension of that simulation through the wet 2010-2011 winter in green. Irrigation was not added to the WARMF model in the local watersheds because the additional modeling effort would provide only limited benefit in simulation of winter turbidity producing events. Thus, low flow conditions are not simulated well at these locations because of the lack of irrigation in the model. WARMF simulates peak flows for the same events that produced peaks in the observed data both in Bear Creek and the San Joaquin River at Lander Avenue. The simulated flow was about three times the measured flow for one event in early 2006, but the magnitude of peaks was otherwise simulated well at both gages. Calibration statistics for days with measured flow greater than 100 cfs are shown in Table 3.1.

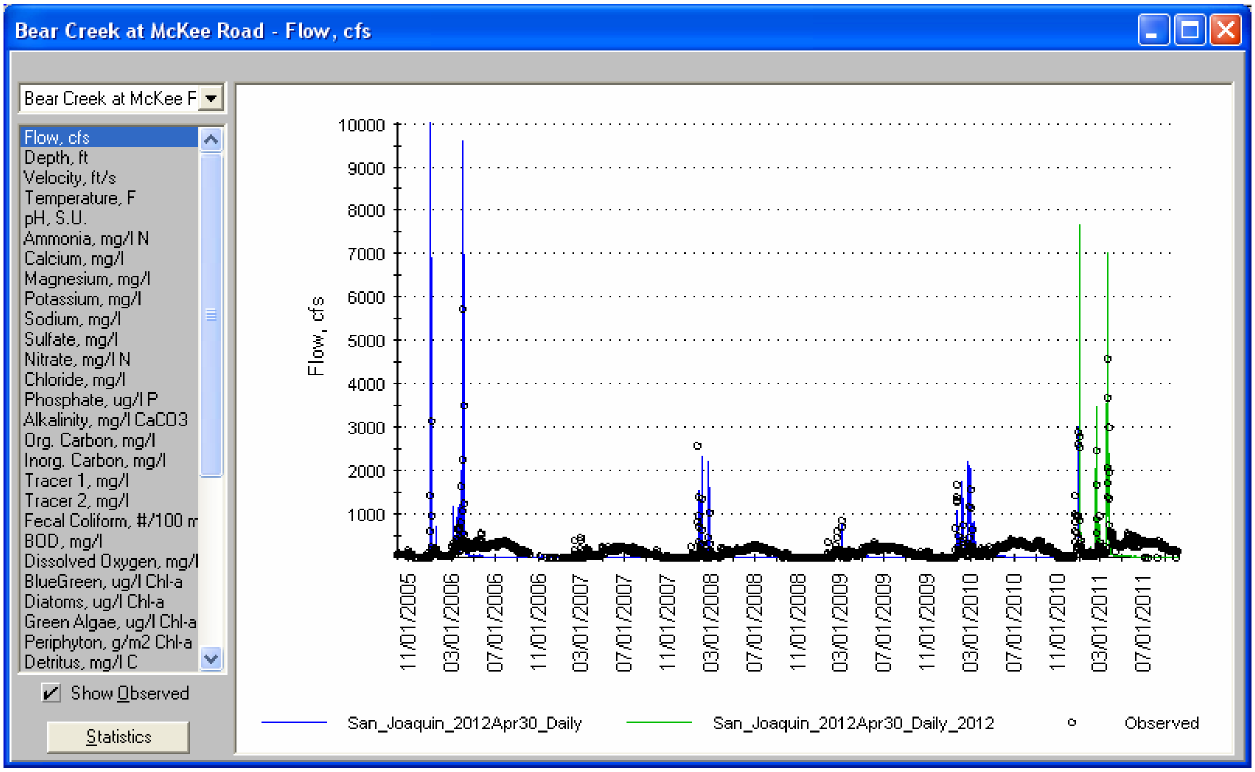

Figure 3.5 Simulated and Observed Flow, Bear Creek at McKee

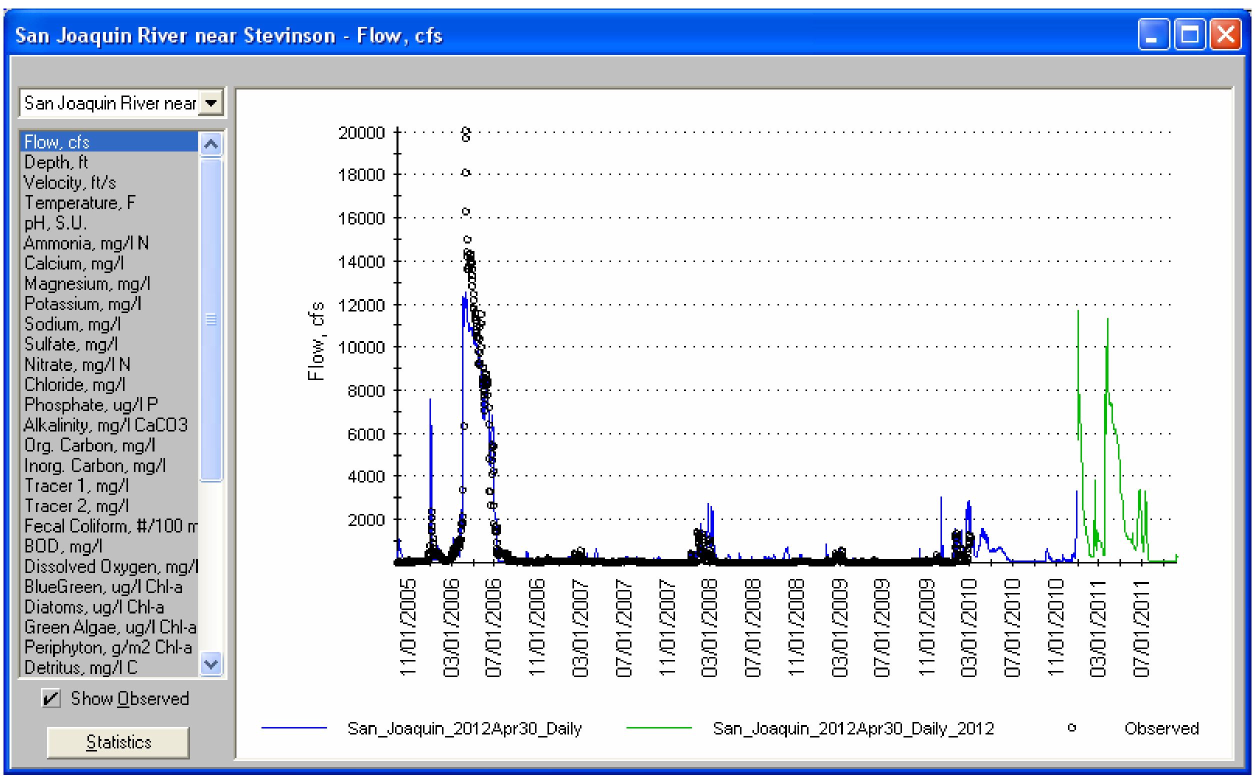

Figure 3.6 Simulated and Observed Flow, San Joaquin River at Lander Avenue

Table 3.1 High Flow (>100 cfs) Calibration Statistics for the Lander Avenue Watershed

Gage	Relative Error		Absolute Error,	
Bear Creek at McKee	+65 cfs	+11.7%	453 cfs	81%
San Joaquin R. at Lander Avenue	-149 cfs	-5.4%	738 cfs	27%

The first step of simulating turbidity is simulation of flow. Overland flow causes erosion from the land and flow exceeding the critical velocity scours sediment from the river bed. Additional sediment passes through from Friant Dam at high flow. Suspended sediment also settles out as it flows downstream. Calibration was performed for suspended sediment rather than turbidity at the San Joaquin River at Lander Avenue because of the longer and more reliable record of monitoring data for suspended sediment. Calibration was done by adjusting the river bed scour rates and settling velocities of clay and silt particles. No suspended sediment or turbidity data has been collected in Bear Creek. The model was calibrated to the multiyear record of suspended sediment data collected at the San Joaquin River at Lander Avenue. The simulation results shown in Figure 3.7 reasonably follow the magnitude and pattern of the observed monitoring data. The relative error of the simulation is 7.2% and the absolute error is 81%.

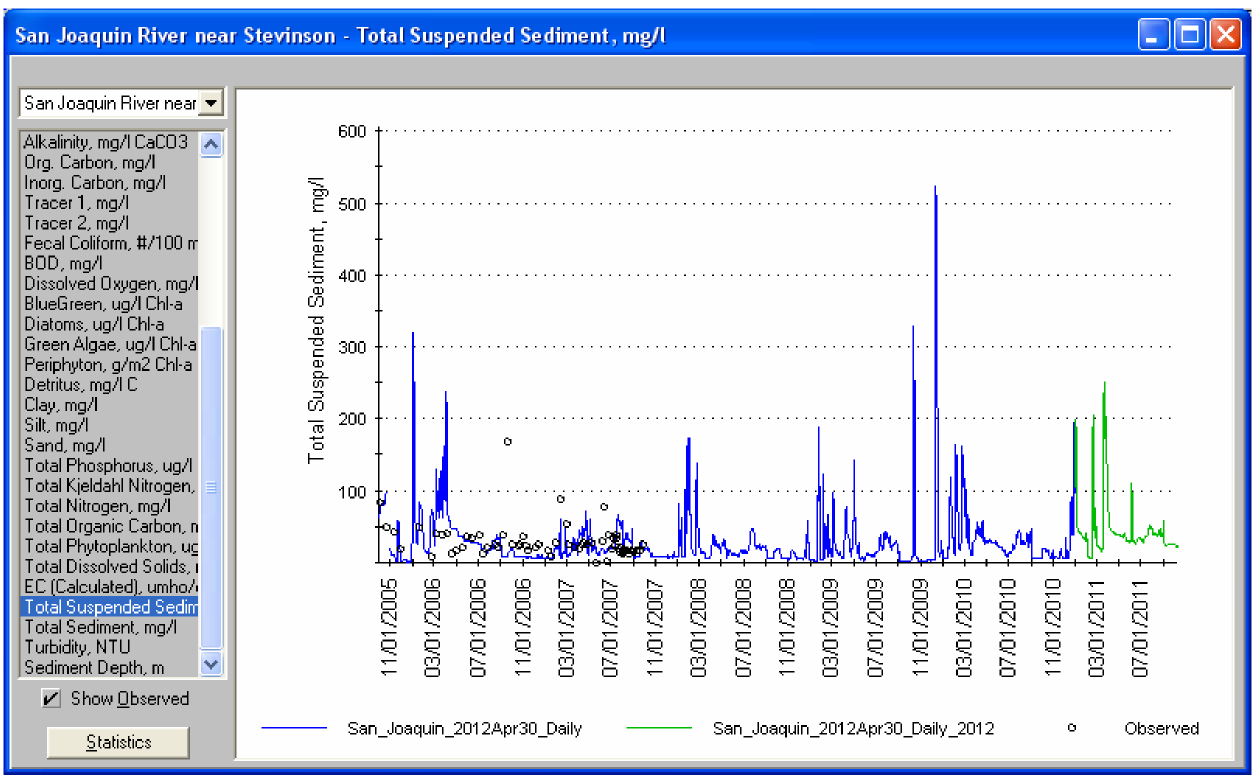

Figure 3.7 Simulated and Observed Suspended Sediment, San Joaquin R. at Lander Ave

Suspended Sediment / Turbidity of the San Joaquin River at Vernalis

Simulation of suspended sediment at Vernalis is a function of local sediment loading, loading from the San Joaquin River at Lander Avenue, and loading from the three east side tributaries. Simulated suspended sediment is then converted to turbidity using a linear regression between concurrent suspended sediment and turbidity data collected at Vernalis. Calculated turbidity is only used in model output, not for calculating turbidity in downstream river segments or for the next model time step.

The suspended sediment data collected daily at Vernalis by the USGS provides an excellent reference for calibration. Turbidity has been collected on a real-time basis since February 2008, but the data has many errors. Since WARMF simulates suspended sediment directly and it has a longer and better quality dataset for calibration, calibration of suspended sediment took precedence over calibration of turbidity. The simulated turbidity using the regression fit ratio of 0.4909 was then compared against the measured turbidity.

Figure 3.8 shows the simulated and observed flow in the San Joaquin River at Vernalis. The measured flow is followed closely by the simulated, including during the large Friant Dam releases of 2005-2006. Relative error of the simulated flow at Vernalis is -0.9% and absolute error is 19%. Simulated total suspended sediment at Vernalis is shown in Figure 3.9. Although the model generally predicts too little sediment in the summer months, it matches the winter suspended sediment concentrations reasonably well. The model did not, however, simulate the peak measured suspended sediment concentrations above 200 mg/l in February 2008 and February 2010. The relative error for suspended sediment was -18% and the absolute error was 41% during the December-March forecasting seasons of water years 2006-2011. Simulated and daily-averaged observed turbidity is shown in Figure 3.10. The data appears unreliable before 2009. As with the suspended sediment, simulations of turbidity did not simulate the high measured peak which occurred in February 2010 and underpredicted summer turbidity. Winter turbidity simulations were generally reasonable, however. Ignoring the unreliable turbidity data prior to 2009, the relative error of turbidity simulation was +5.8% and the absolute error was 48% during the December through March forecasting seasons.

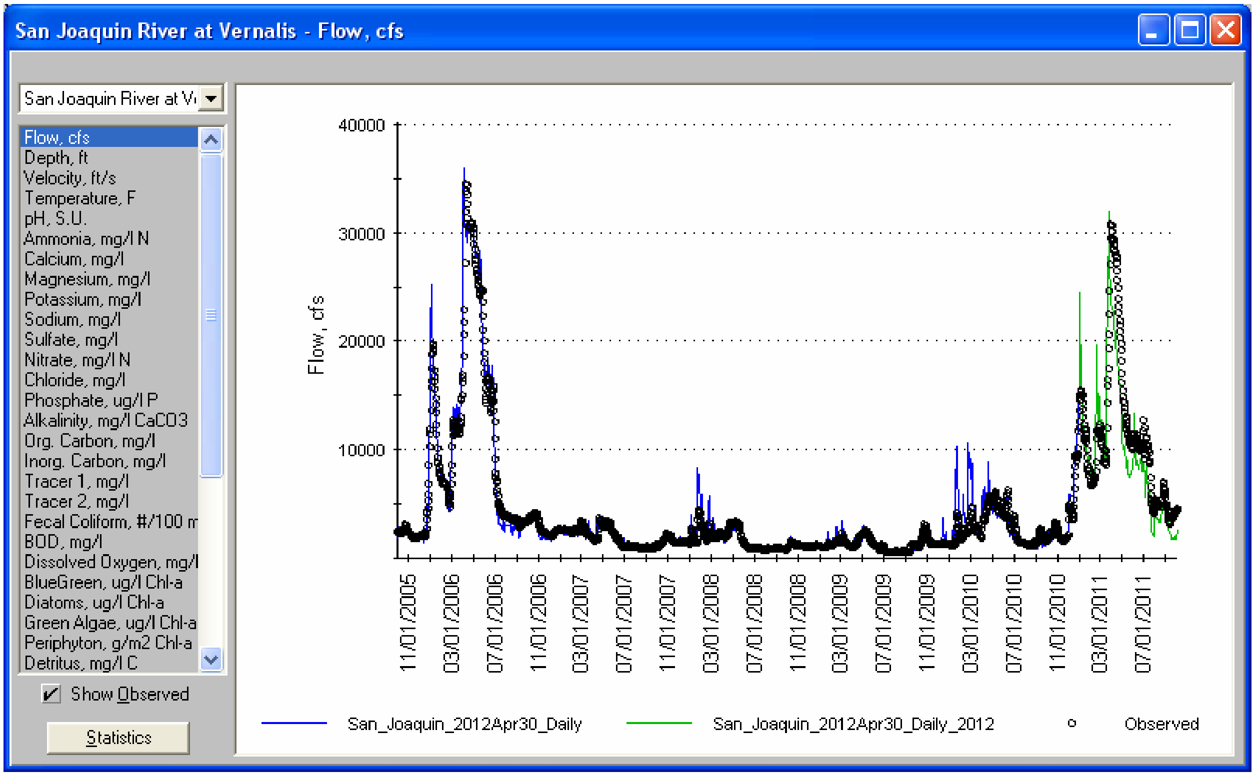

Figure 3.8 Simulated and Measured Flow, San Joaquin River at Vernalis

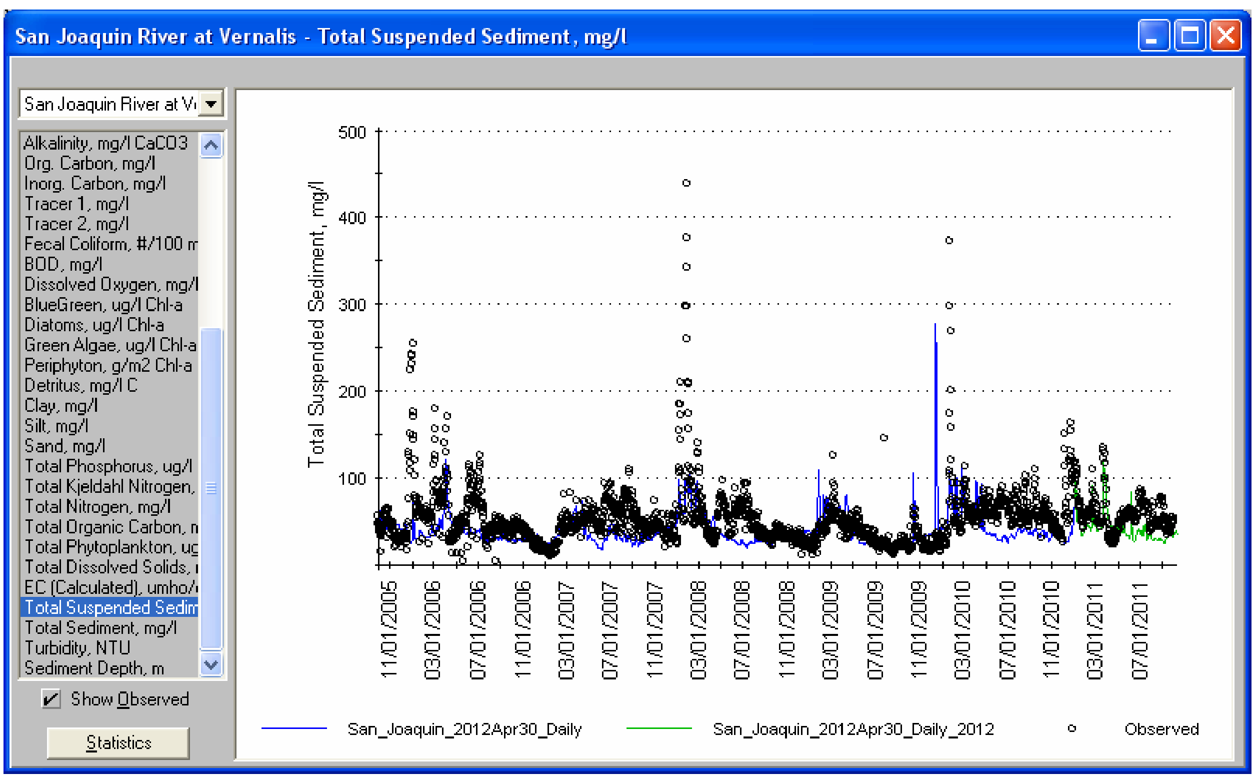

Figure 3.9 Simulated and Observed Suspended Sediment, San Joaquin R. at Vernalis

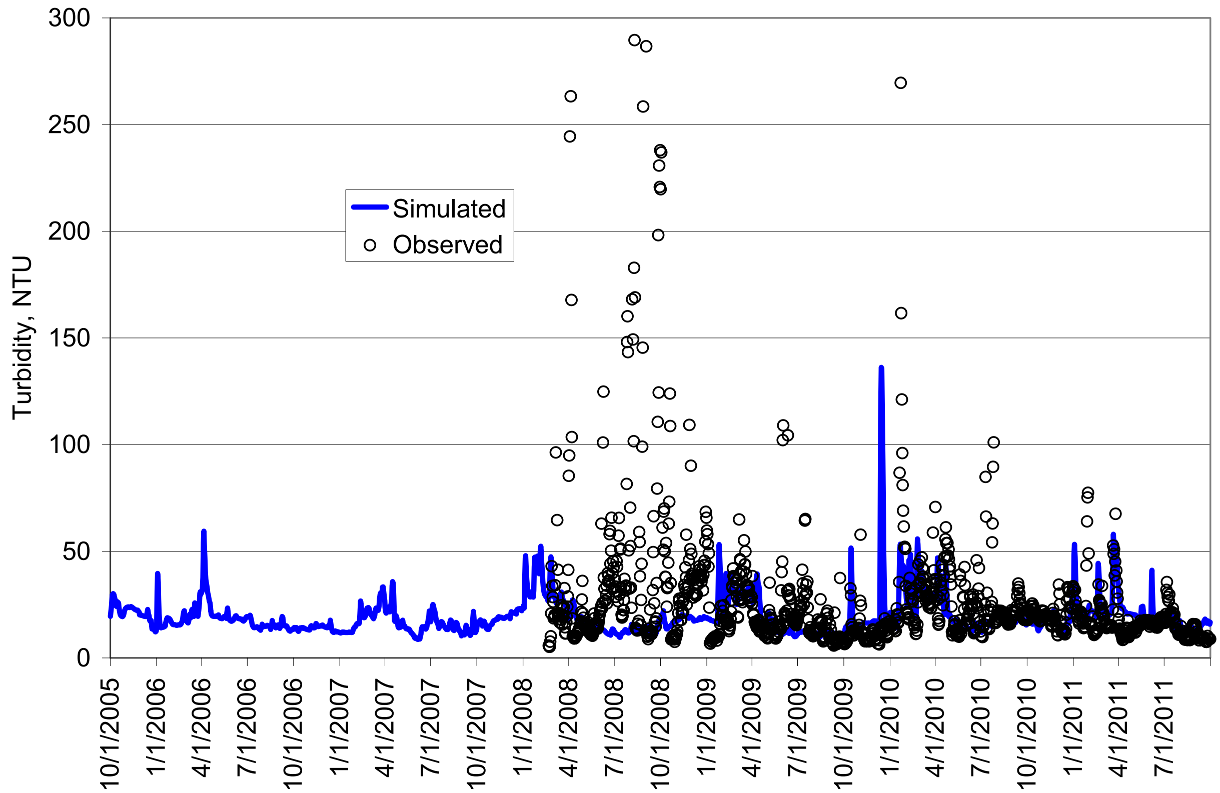

Figure 3.10 Simulated and Observed Turbidity, San Joaquin River at Vernalis

4 WARMF FORECASTING RESULTS

Eleven WARMF forecasts were performed on a weekly basis between December 8, 2011 and February 16, 2012. The forecasts followed the methodology developed during the winter of 2010-2011 (Systech Water Resources 2011(d)). Extremely dry conditions persisted throughout the forecasting period. One significant storm occurred during the third week of January, but the rest of the forecast period was dry.

It is important to know the accuracy of the forecasts if they are used to guide management actions. The accuracy of the forecast results depends on the accuracy of the inputs and the accuracy of the model. The accuracy of WARMF simulation results is not known at the time a forecast is made, but for the forecasts made during the testing process an analysis was performed after the forecasts were complete to determine how the flow and turbidity forecasts compared against measured data.

Meteorology Forecast Results

The Quantitative Precipitation Forecast issued by the California-Nevada River Forecast Center was the key component for generating projected future meteorology inputs for WARMF. The results can be scored by their accuracy and by volumetric error. A full analysis of meteorology forecast error and its potential effect on WARMF simulation errors would require analyzing forecasts and measured precipitation throughout the Sacramento and San Joaquin River watersheds. A simpler analysis was done by choosing one meteorology station as an example.

The Mineral meteorology station in northeast Tehama County averages 55 inches of precipitation per year, more than all but two of the 71 meteorology stations used by WARMF in the Sacramento and San Joaquin River watersheds combined. Selection of a relatively wet station allows for a comparison under conditions for which the model is most sensitive. Various methods can be used to evaluate meteorology forecasts including volume balance and absolute error (Charba et al. 2003).

Figure 4.1 shows daily measured precipitation in black and the 11 meteorology forecasts in colors. Forecasts were made over a 77-day time period. During this time period there were 56 days in which both the forecasted and measured precipitation were zero. Forecasted precipitation exceeded the measured precipitation on 7 days and measured precipitation exceeded the forecasted precipitation on 14 days.

Figure 4.2 shows cumulative precipitation over the forecasting period. The forecast precipitation accounted for 62% of the measured precipitation that occurred during the forecasting period. As a result, flow simulated in WARMF is expected to be less than observed because too little precipitation produces too little runoff.

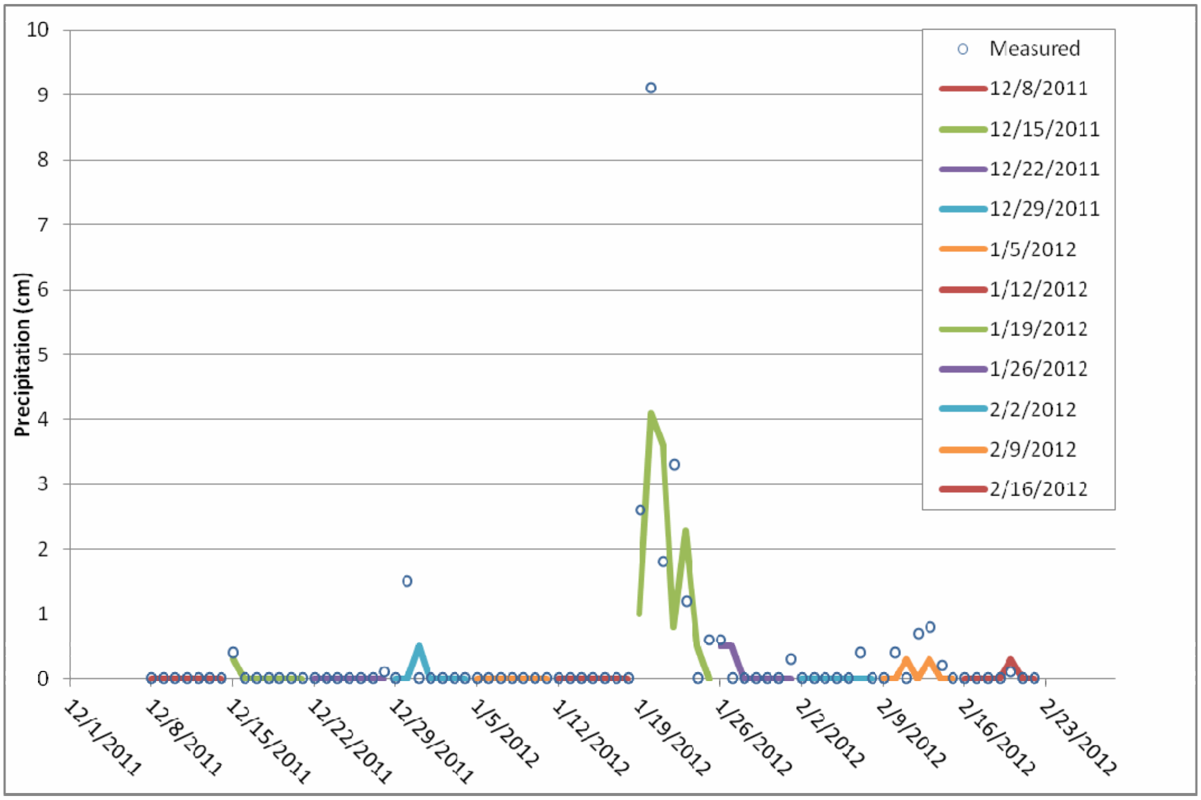

Figure 4.1 Measured and Forecast Precipitation by Date, Mineral Station

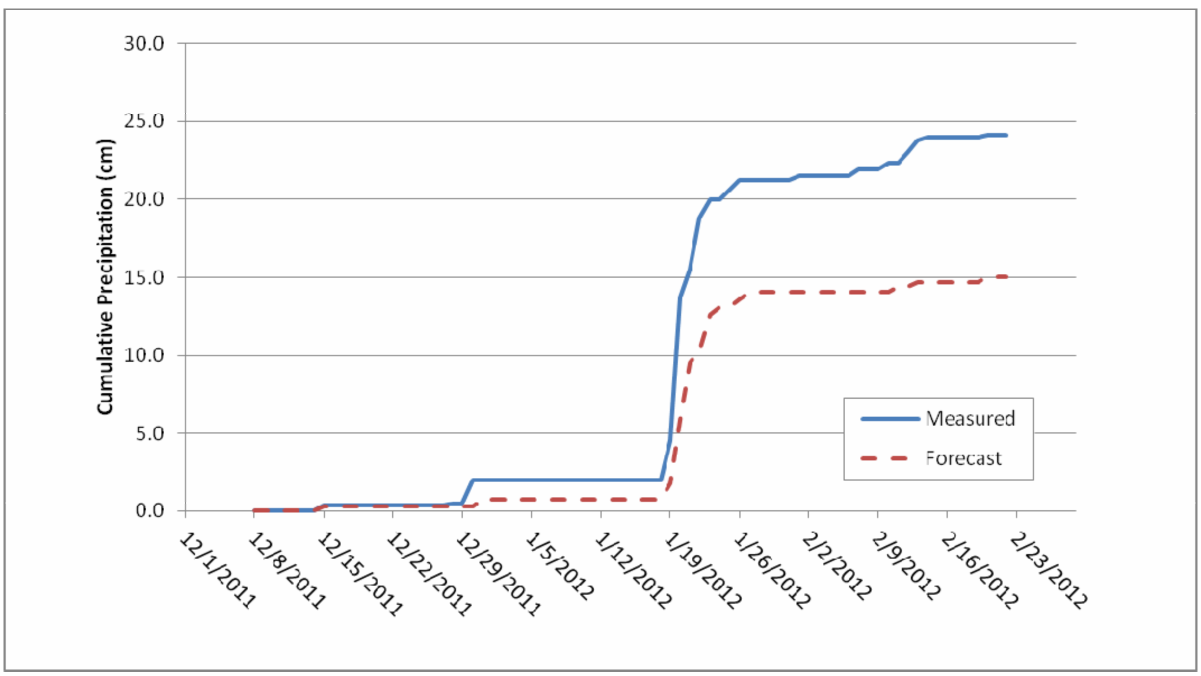

Figure 4.2 Measured and Forecast Cumulative Precipitation Volume, Mineral Station

Table 4.1 shows the relative and absolute errors for each forecast day. Relative error is the average of the differences between simulated and measured values. Absolute error is the average of the absolute values of the differences between simulated and measured. Relative error is a measure of model accuracy or bias, so as expected from Figure 4.2 the forecast precipitation is less than observed for all days of the forecast. The absolute error is a measure of forecast precision. The day of the forecast simulation is listed as “Day 1” shown in the table. Forecast data is theoretically best at the beginning of the forecast and is expected to become less accurate as the length of time from present increases. Contrary to the expected trend, the error is actually highest on the second forecast day and decreases for days further into the future. This is likely the effect the extremely dry conditions experienced during the forecasting time period (forecasted and measured precipitation were zero on the majority of days), the timing of storms in relation to the day the forecast was produced, and the relatively short time period used to calculate the statistics.

Table 4.1 Precipitation Error for each Forecast Day, Mineral Station

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error, cm	-0.16	-0.58	0.24	-0.29	0.07	-0.01
Absolute Error, cm	0.16	0.67	0.24	0.29	0.16	0.10
Relative Error, %	-50%	-58%	144%	-80%	38%	-17%
Absolute Error, %	50%	67%	144%	80%	86%	183%

Boundary Inflow Forecast Results

Scheduled reservoir releases did not generally have dynamic release schedules reflecting expected changes in release given meteorology forecasts. Figure 4.3 and Figure 4.4 show the combined flow of all model boundary inflows in the Sacramento River watershed and San Joaquin River watershed respectively. The forecast flows are in colors with the measured combined flow in black. Because the forecast flows change little, the error increases toward the end of the forecast time period.

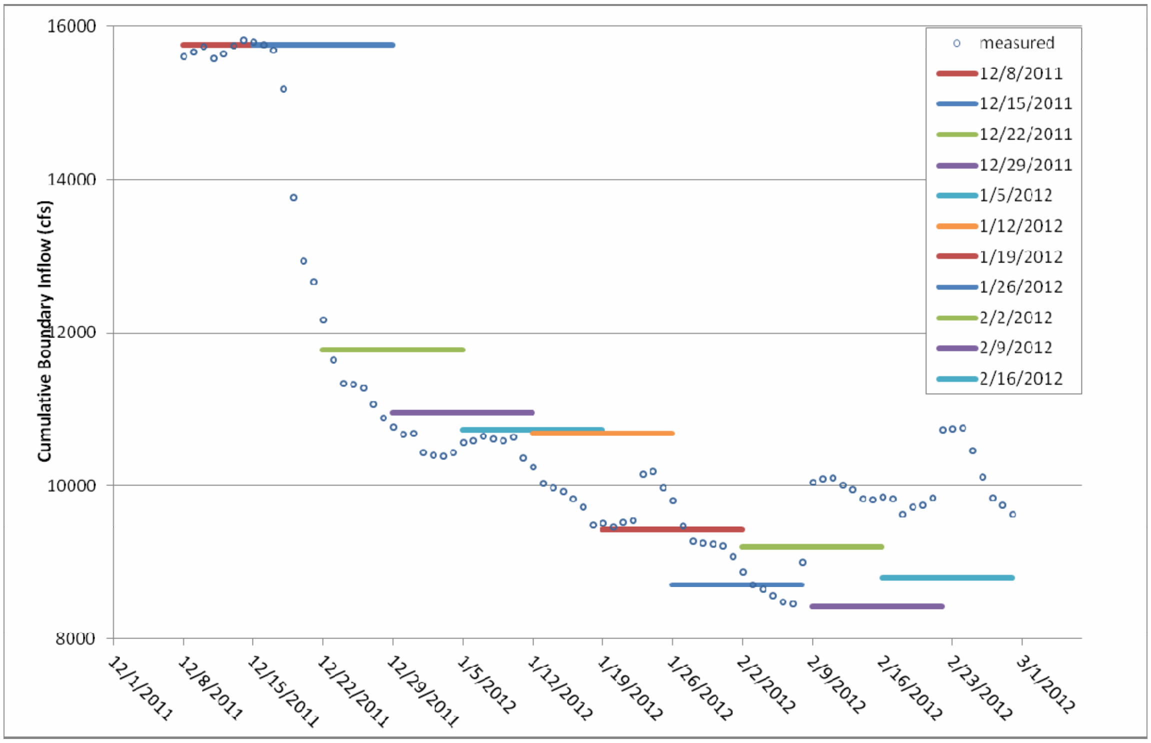

Figure 4.3 Measured Hindcast and Forecast of Combined Inflows, Sacramento River

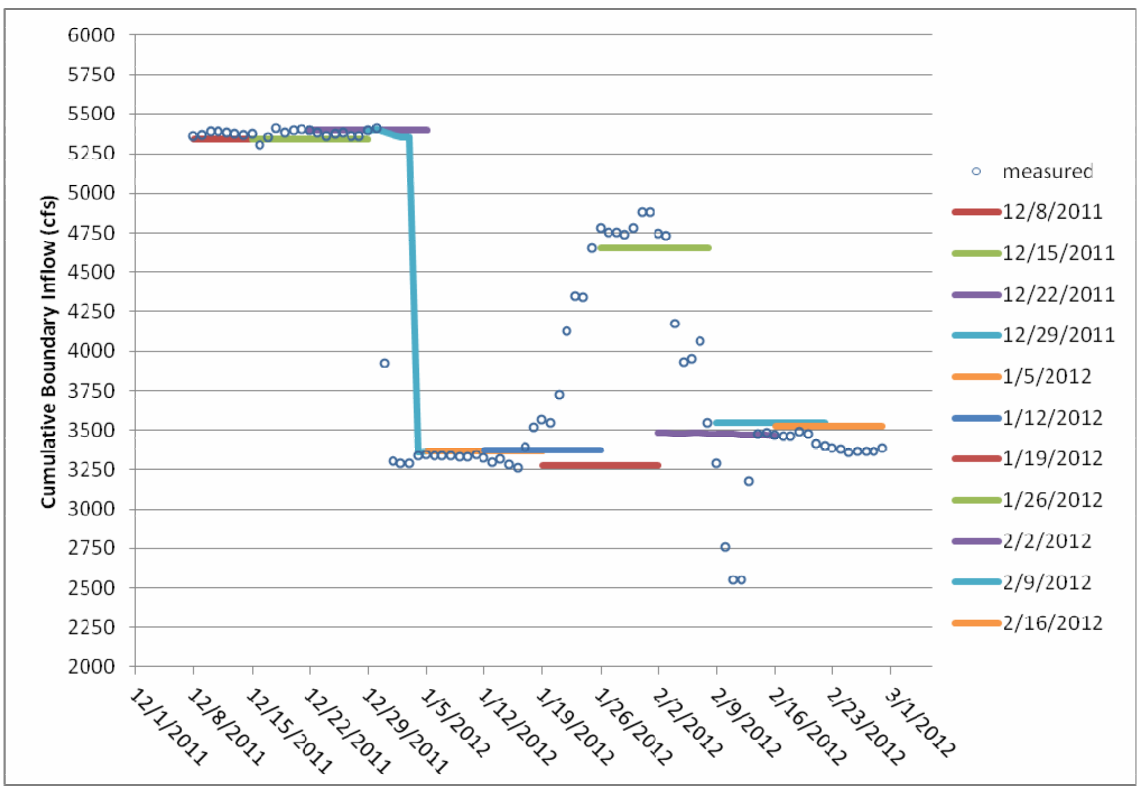

Figure 4.4 Measured Hindcast and Forecast of Combined Inflows, San Joaquin River

Table 4.2 and Table 4.3 show the error of boundary inflow forecasts for the Sacramento River and San Joaquin River boundary inflows. Boundary inflows to the Sacramento WARMF model domain include Shasta, Whiskeytown, Black Butte, Oroville, Englebright, Clear, Folsom, Berryessa Lakes, and Camp Far West, New Hogan, and Camanche Reservoirs. Boundary inflows to the San Joaquin WARMF model domain include the Stanislaus, Tuolumne, and Merced Rivers (which are not currently simulated by WARMF), Friant Dam and the Delta Mendota Canal. In both watersheds, the forecast precision decreases (increasing absolute error) as the number of days into the forecast time period increases. The relative error for the Sacramento River WARMF boundary inflows (Figure 4.3) gradually increases from -2.5% to 1.8% over the forecast time period. This indicates that on the day of the forecast, forecasted inflows were less than observed, then over the course of the forecast time period the forecasted inflows tended to be greater than the observed inflows. This trend is the result of constant inflow forecasts and generally decreasing measured reservoir discharge over the course of the 12-week forecast period.

Table 4.2 Combined Boundary Inflow Error for Six Forecast Days, Sacramento River

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error, cfs	-282	-164	-99	-3	95	190
Absolute Error, cfs	507	481	483	582	779	872
Relative Error, %	-2.5%	-1.5%	-0.9%	0.0%	0.9%	1.8%
Absolute Error, %	4.5%	4.3%	4.4%	5.3%	7.2%	8.1%

Table 4.3 Combined Boundary Inflow Error for Six Forecast Days, San Joaquin River

Measure	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error, cfs	-121	-56	123	160	83	33
Absolute Error, cfs	191	242	358	431	399	391
Relative Error, %	-2.8%	-1.3%	3.0%	3.9%	2.0%	0.8%
Absolute Error, %	4.4%	5.6%	8.7%	10.6%	9.6%	9.3%

Simulated Flow

The WARMF model as calibrated to the Sacramento and San Joaquin watersheds performs calculations of watershed processes to translate time series inputs of boundary inflows and meteorology into flow in rivers throughout the watershed. Accuracy of simulated flow is a function of the model setup and of the time series inputs used to drive the model. Hindcast simulations were performed for the forecast period up to the current date for forecasting simulations. The hindcasts used actual reservoir releases and measured meteorology from stations with real-time data. The difference between forecast and hindcast simulations arises from the inaccuracy of flow and meteorology predictions. The difference between the hindcast and measured data is a combination of model error and inaccuracies caused by filling in missing meteorology data.

Figure 4.5 shows the hindcast flow in black and the forecast flows for each day forecasts were performed in color for the Sacramento River at Freeport. The hindcast tracks the flow closely but underestimates the peak flows that occurred following the storm of January 19th. The flow forecasts are all either two or three weeks long, while quantitative precipitation forecasts are only available for the first five days. The forecasting procedure accommodates this discrepancy by assuming that there is no precipitation after the fifth day. Boundary inflows are assumed to remain constant if no additional reservoir release projections are available on the day the forecast is made. During the one significant storm that occurred during the forecasting season, the forecast that was made that week predicted the timing of the flow increase, though greatly underestimated the magnitude. The forecast underestimation of flow can be attributed to a combination of model error and the inaccuracy of the meteorological forecasts. Precipitation at the Mineral meteorology station was under-predicted by approximately 40% (19.2 cm measured precipitation, 12.3 cm forecasted precipitation). The hindcast simulation predicts greater river discharge than the forecast, but still results in an underestimation of discharge when compared to the measured discharge at Freeport. Precipitation amounts for the storm were very spatially variable. For example, measured precipitation at the Sacramento Executive Airport totaled 6.1 cm, while precipitation at the Redding Municipal Airport totaled 19.1 cm. Other meteorology stations within the Sacramento River model domain received less that 2 cm of precipitation. The hindcast simulation still only uses real data for those stations with real-time data and estimates precipitation at the rest of the stations whose data is not yet available. This may not have captured the spatial variation of the storm's precipitation correctly. Investment in refining the method WARMF uses to extrapolate measured precipitation quantities across the watershed may improve simulation results.

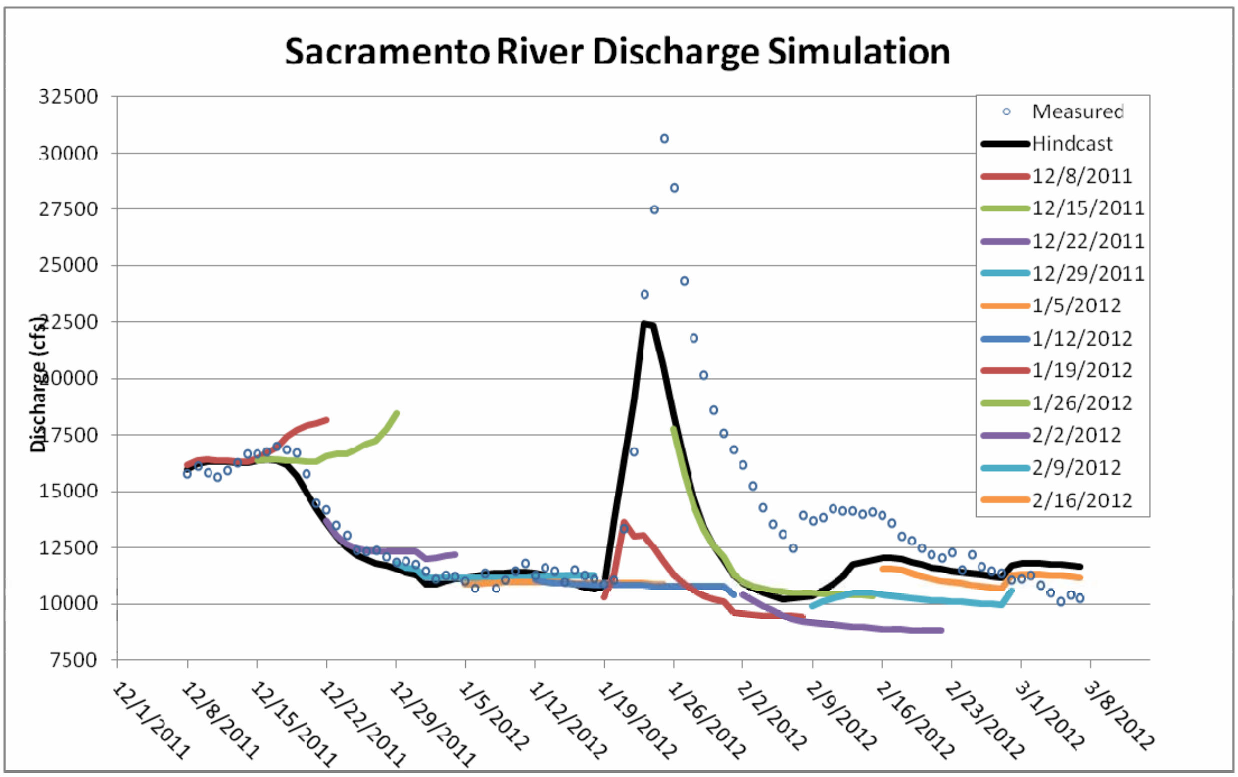

Figure 4.5 Hindcast and Forecast Flow, Sacramento River at Freeport

The hindcast flow simulation of the San Joaquin River shown in Figure 4.6 slightly underestimates, but tracks measured flow at Vernalis during the first six weeks of the forecasting time period. The storm that occurred beginning on January 19th was captured by WARMF but the overall magnitude of the storm was underestimated. By the third of February, the simulated discharge was back within 200 cfs of the measured discharge, and remained within that margin of error for the remainder of the forecasting period. The systematic underprediction of flow of 100-200 cfs was upstream of the gage at the San Joaquin River at Newman, which indicates that WARMF did not capture all of the discharge coming from the agricultural and wetland areas in the Salt Slough / Mud Slough region.

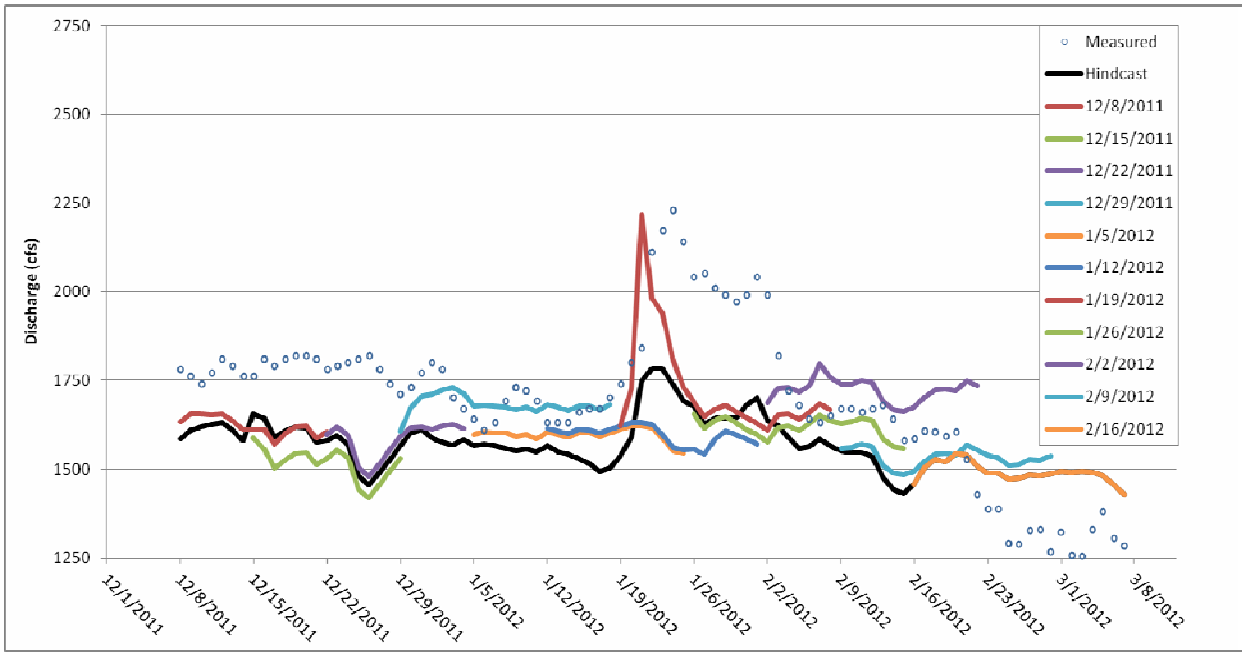

Figure 4.6 Hindcast and Forecast Flow, San Joaquin River at Vernalis

Below in Table 4.4 and Table 4.5 are statistics describing how well the hindcast and forecast simulations agree with observed data. Relative error is the average of the simulated flow minus the observed flow, a measure of accuracy. Absolute error is the average of the absolute values of the differences between simulated and observed discharge, a measure of precision. The difference between the hindcast error and the forecast error is the result of the forecast; the hindcast error is from model error and estimation of some meteorology data and other model inputs.

Both the Sacramento River and San Joaquin River hindcast simulations have a relative error of -8% indicating a small but systematic under-prediction of flow as shown in Figure 4.5 and Figure 4.6. The forecasts add to this under-prediction because of systematic forecast under-predictions of boundary inflows and precipitation.

Table 4.4 Error Statistics of Simulated Flow for Hindcast and First Six Forecast Days, Sacramento River at Freeport

Measure	Hindcast	Forecast					
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error, cfs	-1,106	-2,165	-1,832	-1,681	-1,750	-2,338	-2,584
Absolute Error, cfs	1,689	2,243	1,961	1,838	1,961	2,435	2,702
Relative Error, %	-8%	-15%	-13%	-12%	-12%	-16%	-18%
Absolute Error, %	12%	15%	14%	13%	14%	17%	18%

Table 4.5 Error Statistics of Simulated Flow for Hindcast and First Six Forecast Days San Joaquin River at Vernalis

Measure	Hindcast	Forecast					
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error	-129	-155	-130	-77	-140	-157	-148
Absolute Error	182	155	130	148	147	174	186
Relative Error, %	-8%	-9%	-7%	-4%	-8%	-9%	-8%
Absolute Error, %	11%	9%	7%	8%	8%	10%	10%

Simulated Turbidity

The predicted turbidity entering the Delta is a function of its sources. These include boundary inflows, overland flow over erodible soils during storm events, and scour from river beds and banks during high flow. The Sacramento and San Joaquin River WARMF applications have been calibrated for turbidity. Accurate flow simulation is essential for simulating turbidity correctly. The preceding section of this report discusses the accuracy of forecasted flow calculated by WARMF.

Turbidity is measured continuously at Freeport and the data are posted in real-time to CDEC. Figure 4.7 shows the hindcast turbidity in black and the forecast turbidity for each day forecasts were performed in color for the Sacramento River at Freeport. High turbidity occurs with high flow because two of its sources, overland flow and river bed and bank scour, increase exponentially with flow. The flow peak of January 25th was under-predicted, resulting in a turbidity under-prediction as well. Following this storm, the measured turbidity fluctuated between 20 and 30 NTU for several weeks before falling to the pre-storm levels of 10 – 15 NTU. The reason for the sustained elevated measured turbidity levels is not known since this is an atypical response after a storm has passed. The simulated turbidity decreased steeply following the peak flow, arriving at pre-storm levels by February 3rd. The trend in simulated turbidity closely mirrors the simulated storm hydrograph which also receded to pre-storm levels by this date.

As discussed previously, the WARMF turbidity results are linearly related to simulated total suspended sediment concentrations. The relationship between these constituents in WARMF is based on data collected during the 2009 and 2010 water years. While the USGS has not released the total suspended sediment data collected at Freeport during the 2011 water year, concurrent turbidity and TSS data are available for the San Joaquin River for 2011. These data suggest that a significant change in the ratio of turbidity and TSS occurred during the 2011 water year. A similar shift in the turbidity to total suspended sediment ratio in the Sacramento River watershed would result in increased turbidity simulation error.

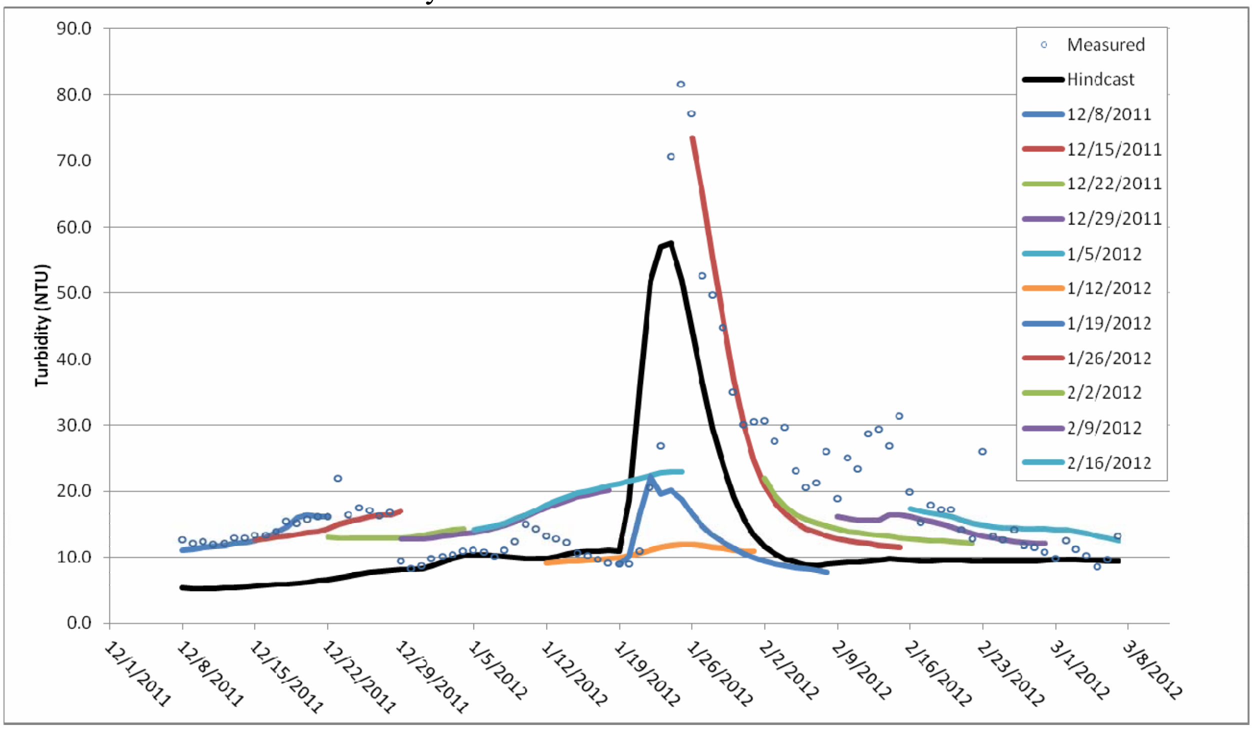

Figure 4.7 Hindcast and Forecast Turbidity, Sacramento River at Freeport

The hindcast and forecast turbidity simulations of the San Joaquin River are shown in Figure 4.8. WARMF was unable to simulate the very low turbidity levels measured at the Vernalis turbidity monitoring station. Forecasting is focused on prediction of high turbidity concentrations in the central Delta, and low flow (baseflow) turbidity simulation was not a primary objective of this project. However, the ability to simulate turbidity under all hydrological conditions would expand the potential applications of the model and help to build confidence in the overall forecasting strategy.

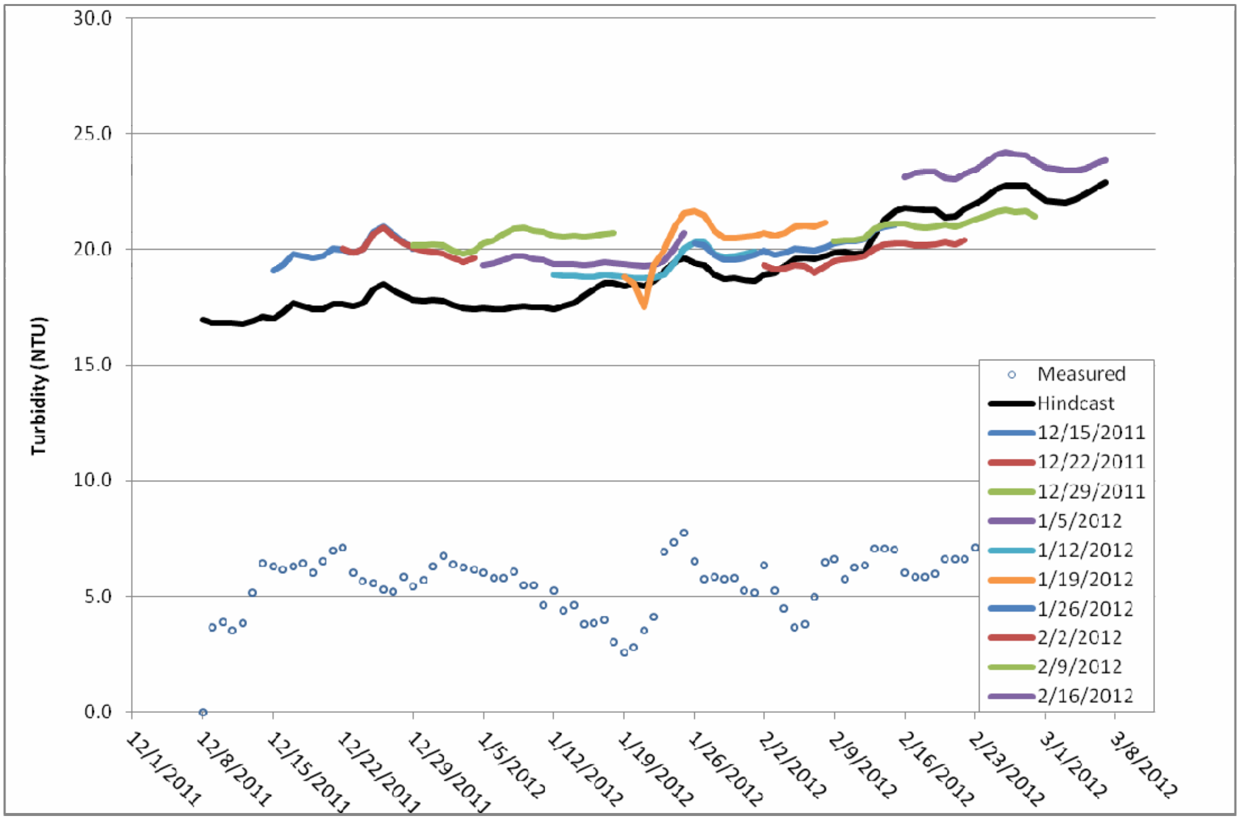

Figure 4.8 Hindcast and Forecast Turbidity, San Joaquin River at Vernalis

The ratio of 0.4909 between turbidity and total suspended sediment was determined using concurrent data from 2008-2010 shown in Figure 3.1. After the 2011-2012 forecasting season, the 2011 water year suspended sediment data was released by the USGS. The 2011 water year data could be used to verify that relationship.

Figure 4.9 shows measured total suspended sediment and turbidity at Vernalis for the 2011 water year. Because each parameter uses a different scale on the graph, the two lines should be nearly on top of each other for a perfect fit. The average ratio of turbidity over suspended sediment for 2011 (Figure 4.10) was 0.3128, 36% less than the ratio which was used in WARMF for the forecasting season. In August and September 2011, the ratio between turbidity and total suspended sediment was consistently about 0.2. With this ratio, an accurate simulation of total suspended sediment in WARMF would result in simulated turbidity two and a half times that of measured data. Since hydrologic conditions were more or less static in the San Joaquin River from September through the forecasting season, if would not be surprising if this low ratio between turbidity and suspended sediment persisted. This would account for almost all of the systematic error shown in Figure 4.8.

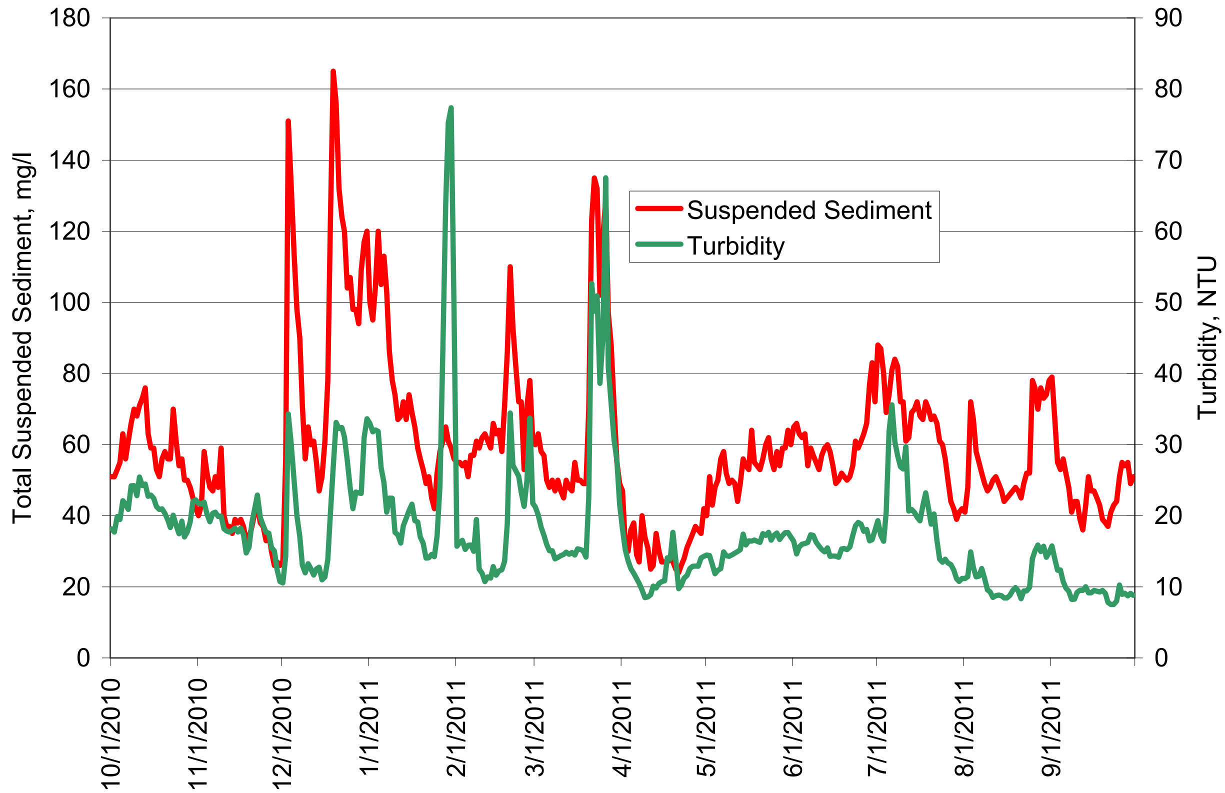

Figure 4.9 Total Suspended Sediment and Turbidity for 2011, San Joaquin R. at Vernalis

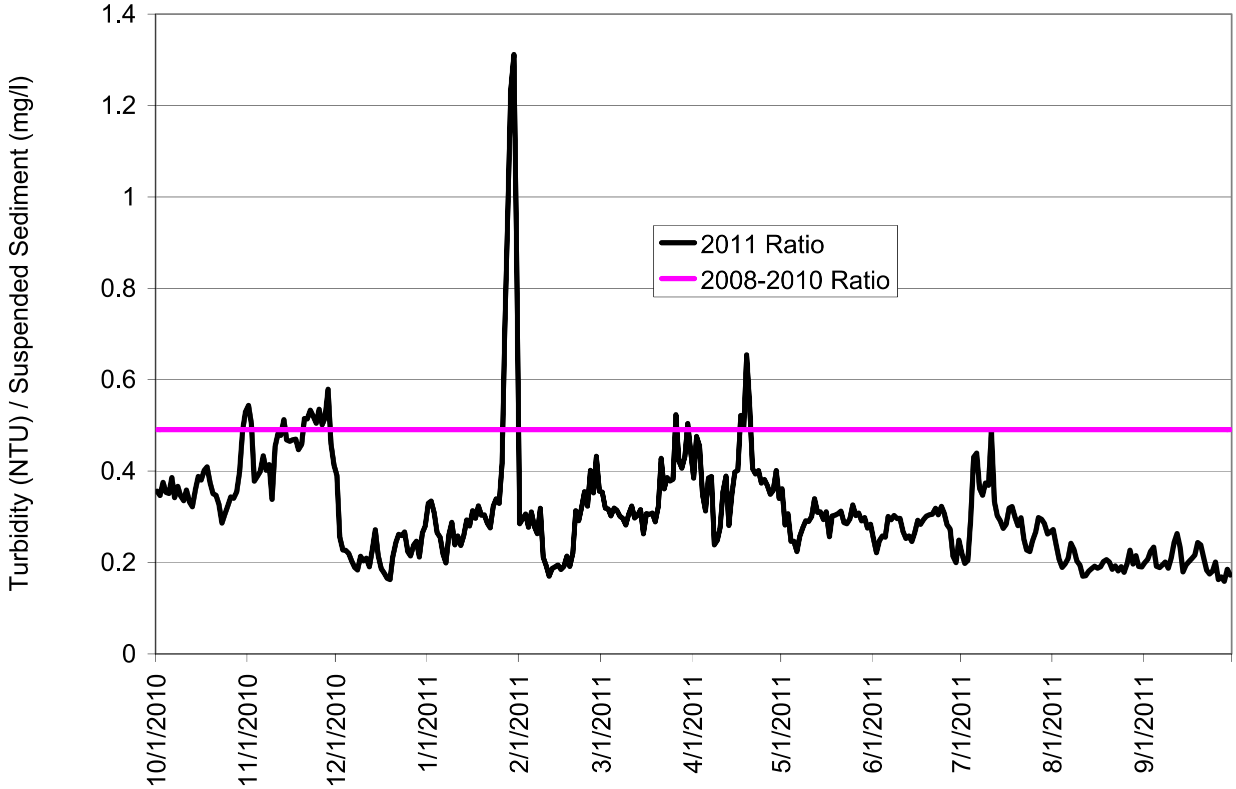

Figure 4.10 Ratio of Turbidity to Total Suspended Sediment, San Joaquin R. at Vernalis

Below in Table 4.6 and Table 4.7 are statistics describing how well the hindcast and forecast turbidity simulations agree with observed data. As described above, relative error is the average of the simulated flow minus the observed flow, a measure of accuracy. Absolute error is the average of the absolute values of the differences between simulated and observed. The difference between the hindcast error and the forecast error is the result of the forecast; the hindcast error is from model error and estimation of some meteorology data and other model inputs.

The hindcast simulation of the Sacramento River had an average model bias of -7 NTU from under-predicting turbidity during and after the one storm that occurred during the forecasting time period, while the forecasts actually had very little model bias. The precision of the daily simulated turbidity as measured by absolute error was 47% for the hindcast, and ranged from 14-98% for the first six days of the forecast.

Table 4.6 Error of Simulated Turbidity for Hindcast and First Six Forecast Days Sacramento River at Freeport

Measure	Hindcast	Forecast					
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error, NTU	-7	-1.9	-0.8	-0.8	-1.8	-2.4	-6.2
Absolute Error, NTU	9	3.1	5.0	4.6	18.8	3.9	7.2
Relative Error, %	-35%	-9%	-4%	-5%	-9%	-13%	-28%
Absolute Error, %	47%	14%	26%	24%	98%	21%	33%

Simulations of turbidity in the San Joaquin River were systematically too high during the entire forecasting time period. The relative error of the hindcast simulation, which included the improvements in sediment simulation, was 14 NTU. The precision of the forecast simulations was approximately 250% of observed. The variability in the ratio between turbidity and total suspended sediment is a likely cause of most of the systematic error, but this can not be confirmed until the USGS releases its 2012 water year Vernalis suspended sediment data in spring of 2013. There was not a single significant storm in the San Joaquin River watershed during the forecasting time period, nor was there a high flow release from Friant Dam, so it was not possible to evaluate the models performance under high turbidity conditions.

Table 4.7 Error of Simulated Turbidity for Hindcast and First Six Forecast Days San Joaquin River at Vernalis

Measure	Hindcast	Forecast					
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Relative Error	14	14.6	14.4	14.4	14.4	14.2	14.1
Absolute Error	14	14.6	14.4	14.4	14.4	14.2	14.1
Relative Error, %	246%	281%	271%	274%	259%	245%	233%
Absolute Error, %	246%	281%	271%	274%	259%	245%	233%

5 CONCLUSION AND RECOMMENDATIONS

The objective of performing WARMF forecasting was to predict flow and turbidity in near real-time with enough accuracy to provide useful information for managing operations at the Banks Pumping Plant. The processing tools both external to and within WARMF that were created in preparation for the 2011 forecasting season were refined this year to make the process as efficient as possible. Additional real-time and forecast data sources were found to provide key meteorology and boundary inflow data to drive WARMF simulations. The processors made it possible to perform forecasts in four hours to provide flow and water quality inputs to a Delta model in a timely manner.

The forecast methodology was conducted each Thursday from December 8, 2011 through February 16, 2012. There were three sources of error in simulation results: error in the forecasts (meteorology and reservoir releases), incomplete model input data, and model error. Relative error in predicted flow in the Sacramento River at Freeport was 8% for the hindcast simulation and averaged 14 % during first six days of the forecast period. Relative error in predicted flow in the San Joaquin River at Vernalis was 8% for the hindcast simulation and averaged 8 % during first six days of the forecast period.

The Sacramento River WARMF model systematically underpredicted turbidity levels in both the forecast and hindcast model time frames. In contrast the San Joaquin River WARMF model systematically overpredicted turbidity in both hindcast and forecast time frames. The natural variability of the relationship between turbidity and total suspended sediment may explain the systematic error in simulation of turbidity in the San Joaquin River, and this may have been a factor in the Sacramento River as well. Improvement in characterizing the relationship between turbidity and suspended sediment, such as incorporating the effect of particle size or accounting for other contributing constituents, would make the model's forecasts of turbidity more robust.

Some errors are inevitable when combining a model with forecasted model inputs, but errors should be minimized to make the forecast as accurate as possible. While the WARMF forecasting was being tested, a few sources of error were found that could be reduced for future modeling. The high precipitation variability that occurred across the central valley during the storm of January 19-23, 2012 and the error in both forecast and hindcast simulation indicates that refining the spatial interpolation methods between real-time meteorology stations would further improve the predictive capability of the models.

The linkage between physical properties of surface water and the light scattering measured by turbidity has become one of the biggest challenges in turbidity forecasting. The ratio between turbidity and suspended sediment has high spatial and temporal variability, which leads to model error. Additional work to characterize turbidity by accounting for particle size or other factors would improve the reliability of turbidity forecasts. An alternate approach would be for WARMF to provide suspended sediment inputs to the Delta model, which would simulate sediment transport and then convert to turbidity as a final step. This would minimize the error associated with spatial variability of the turbidity / suspended sediment relationship.

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