6-15-2014

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Recommended Citation

Stringfellow, W. T., Herr, J., Sheeder, S., Gulati, S., Weissmann, G., Camarillo, M. K., & Jue, M. (2014). Use of the WARMF Model to Identify Sources of Oxygen Impairment and Potential Management Strategies for the San Joaquin River Watershed. Paper presented at International Environmental Modelling and Software Society (iEMSs) in San Diego, CA.
https://scholarlycommons.pacific.edu/soecs-facpres/29

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International Environmental Modelling and Software Society (iEMSs)
7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA
Daniel P. Ames, Nigel W.T. Quinn and Andrea E. Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2014-proceedings

Use of the WARMF Model to Identify Sources of Oxygen Impairment and Potential Management Strategies for the San Joaquin River Watershed

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Abstract: Eutrophication of the San Joaquin River (SJR) has resulted in low dissolved oxygen (DO) conditions, which has led to a regulatory response and development of total maximum daily load (TMDL) allocations. Due to the dynamic nature of processes governing oxygen depletion in the SJR, a model was needed to help stakeholders understand the fate and transport of nutrients and oxygen-demanding substances that cause the low DO conditions. Here, the Watershed Analysis Risk Management Framework (WARMF) model was used to simulate nutrient removal and control strategies, accounting for the secondary effects of growth and transformation between sources and discharge. Using the management alternatives in the WARMF Consensus Module, simulations were run to test the global removal of nutrient inputs on downstream phytoplankton growth, a major contributor of oxygen demand in the SJR. In the simulations, removal of ammonia had the greatest impact on downstream phytoplankton, causing a 32% reduction, while removal of phosphate and nitrate caused reductions of 25% and 13%, respectively. When ammonia and nitrate were both removed, phytoplankton reduction was 62%. These model results suggest that nitrogen control programs would be more effective than phosphorus programs. Using the Data Module in WARMF, input files were modified to determine the impacts of individual tributaries and agricultural drainages. In each simulation, the contributing loads for individual inputs were removed while maintaining flow. According to the model output, the largest impact on phytoplankton occurred with the removal of mass loads from Salt Slough (32% less than baseline). The effect of removing the mass loads from Mud Slough had a slightly lower impact (26% less than baseline). The WARMF model proved useful for exploration of planning and management alternatives, providing an expert decision-making tool that is available to stakeholders.

***Keywords**:* Water quality; TMDL; dissolved oxygen; eutrophication; watershed

1 INTRODUCTION

1.1 Project Description

The San Joaquin River (SJR) is located in Central California, in an area where irrigated agriculture is a predominant land use. The SJR is highly regulated with dams located on the major tributaries, and agricultural diversions located throughout most of the length of the river as well as discharges of agricultural return flows containing high concentrations of salts, nutrients, and various chemical constituents. In the estuarine portion of the SJR, the flow is tidally-influenced and a portion of the river has been deepened and channelized to permit navigation of cargo ships into the Port of Stockton. Downstream of Stockton, the SJR joins with the Sacramento River to form the Sacramento-San Joaquin River Delta, an estuary system that leads into San Francisco Bay. As a result of the highly engineered nature of the SJR system, there are numerous environmental problems including a loss of ecosystem services. One such environmental issue is eutrophication resulting from nutrient inputs in the upstream watershed (above the tidal zone) that have led to low oxygen concentrations in the downstream deepened ship channel. Episodic low dissolved oxygen (DO) hampers efforts to restore native fisheries, negatively impacts water quality, impacts downstream ecosystems, and poses aesthetic problems. The regulatory standard for DO is 5 mg/L except during September, October, and November when the standard in the ship channel is increased to 6 mg/L (CVRWQCB, 2005). The DO standard is frequently exceeded during the warm summer months when there are excessive mass loads from agricultural lands, the high temperatures reduce DO saturation, and flow in the SJR is reduced due to increased diversions and fewer reservoir releases.

To address periodic low DO concentrations in the SJR estuary, a total maximum daily load (TMDL) program was implemented by the State of California (Stringfellow et al., 2009). As part of the program, several studies were undertaken to identify sources of low DO in the SJR estuary and to assign waste load allocations that will allow restoration of the SJR to regain its assimilative capacity, in regards to DO, and permit a variety of designated beneficial uses. Previous studies have identified mass loads of nutrients, oxygen demanding substances (ODS), and other water quality constituents from the upstream SJR as being influential in the downstream low DO problem (Lehman et al., 2004). In particular, phytoplankton growth in the SJR that occurs as the result of anthropogenic inputs appears especially important in the development of low DO conditions where phytoplankton grown in the upstream river are transported downstream where they respire and consume oxygen (Jones & Stokes, 1998). Other factors that are predictive of DO concentration include reduced river flow rates caused by exports via the State Water Project, discharge from the City of Stockton Regional Wastewater Control Facility (RWCF), urban runoff from the City of Stockton, and the depth of the ship channel that increases algal respiration by limiting light penetration and decreases atmospheric reaeration due to the decreased water surface to volume ratio (CVRWQCB, 2005).

To better understand sources of nutrients and ODS in the upstream SJR contributing to downstream low DO conditions, the WARMF watershed model was used to simulate hydrologic, agricultural, and soil processes that impact the fate and transport of these compounds. A modelling approach was considered ideal for this project as a result of the complex nature of the watershed system with multiple simultaneous components (e.g. atmospheric deposition, groundwater processes) that influence dynamic reactive processes as well as transport in the watershed. Here, WARMF was used to investigate the watershed inputs of nutrients that affect downstream phytoplankton growth, while accounting for the secondary effects of growth and transformation in the river. Knowledge of the factors influencing low DO can be used to direct restoration and control efforts, including the nutrients that should be controlled and the specific inputs that should be targeted. These types of planning and management activities, supported by modelling efforts, are useful for engaging stakeholders in environmental restoration projects. It was desired in this project to determine if a watershed model designed for TMDL development could be used by those without an extensive modelling background, allowing those users to investigate the effects of potential management strategies.

1.2 Site Description

The SJR is located in Central California and originates in the Sierra Nevada Mountains, descending west to the San Joaquin Valley floor, and draining north to the Sacramento-San Joaquin Delta (Figure 1). The upstream boundary in this study is located where the SJR intersects with Bear Creek near the town of Stevinson. The SJR station defining the upstream boundary of the study is that at Lander Avenue. The SJR above Lander Avenue is treated as a tributary in this study, with flow and mass loads entering from the upper portion of the watershed. The downstream boundary is the SJR at Vernalis, approximately where the SJR begins to be tidally-influenced. This river section has three major eastside tributaries (Stanislaus River, Tuolomne River, and Merced River) that drain the Sierra-Nevada western slope westward to SJR. On the west side, there are six tributaries (Hospital/Ingram Creek, Del Puerto Creek, Orestimba Creek, Los Banos Creek, Mud Slough, and Salt Slough) that drain the Diablo Coastal Range eastern slope eastward to the SJR. There are numerous agricultural canals and drains that discharge into the SJR; in this study, data were collected for 14 of these agricultural dischargers (e.g. Modesto and Turlock Irrigation Districts). In this section of the SJR there is only one direct major point source: the Modesto Wastewater Treatment Plant. The total drainage area of this river section is approximately 12,950 hectares.

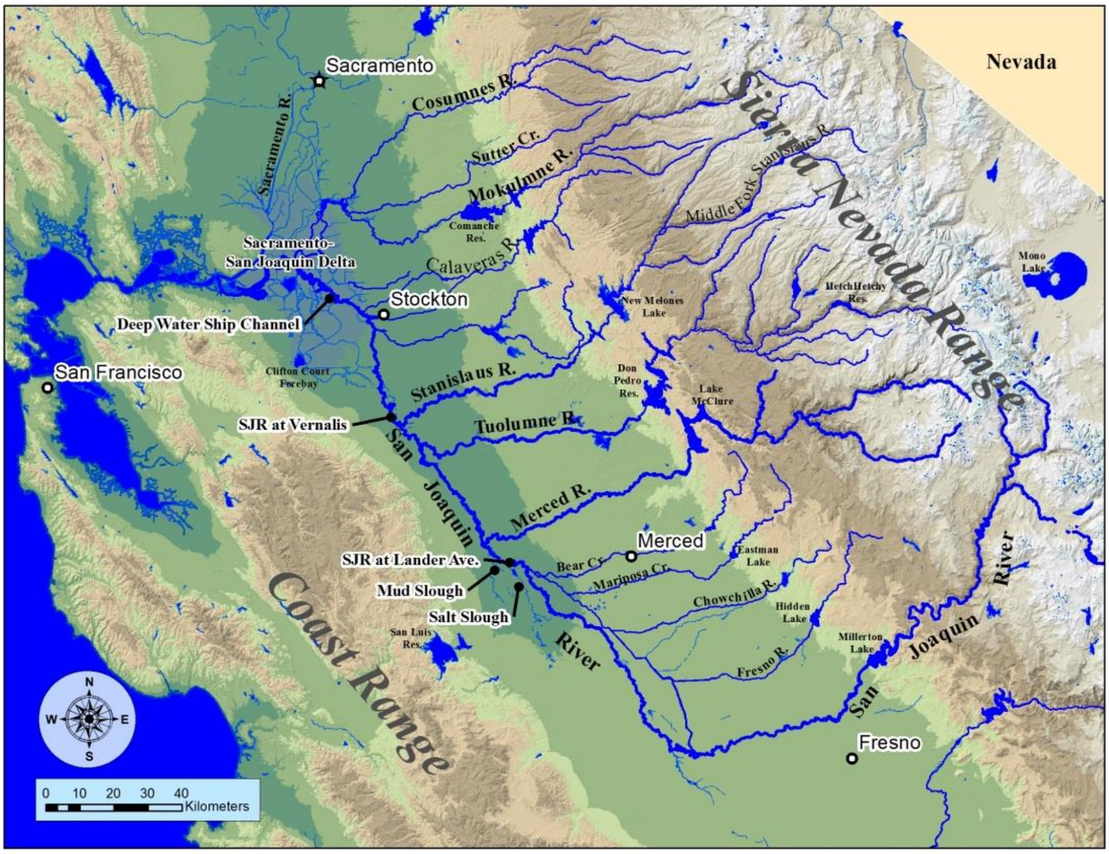

Figure 1. San Joaquin River watershed, located in Central California.

1.3 Project Objectives

The objective here was to run simulations using the SJR-WARMF-2008 watershed model to determine the effects of nutrient loading on downstream phytoplankton growth that impacts low DO in the DWSC. Following calibration, model simulations were run to simulate the effects that the removal of nutrients had on phytoplankton growth. Next, the individual mass load inputs from the tributaries and agricultural drains were sequentially removed (while maintaining flow) to determine the relative contributions of these inputs. The effects of nutrient and mass input removals were evaluated at the point furthest downstream in the study area, at the interface with the tidal estuary (at Vernalis).

2 METHODS

2.1 Model Description

The Watershed Analysis Risk Management Framework (WARMF) model is a watershed model that has a geographical information systems (GIS)-based, user-friendly graphical user interface (GUI), allowing users without extensive modeling experience to access the model and run simulations (Herr and Chen, 2012; Systech Engineering Inc., 2001). The model was specifically developed for TMDL analysis and was intended to engage stakeholders and promote collaborations in watershed management. Development of the model was initially funded by the Electric Power Research Institute (EPRI) and then was funded by the U.S. EPA. The WARMF model is within the public domain and is compatible with other U.S. EPA BASINS watershed models.

Here, the 2008 version of WARMF was used to model the upstream, non-tidal portion of the SJR (SJR-WARMF-2008) (Herr et al., 2008). This SJR version of the WARMF model was built using the SJRIO2 model as its basis. The SJR-WARMF-2008 domain does not include the entire watershed (Figure 2). Within the model domain there are 93 river segments and irrigated lands are divided into

17 land catchments. Each river segment is treated as a vertically mixed, plug-flow reactor and hydrology is modelled within the catchments. The model also includes contributions to the SJR from 30 tributary inflows and agricultural drainages. Three eastside reservoirs (New Melones Reservoir, Don Pedro Reservoir, and Lake McClure) define the upstream boundaries for the eastside tributaries.

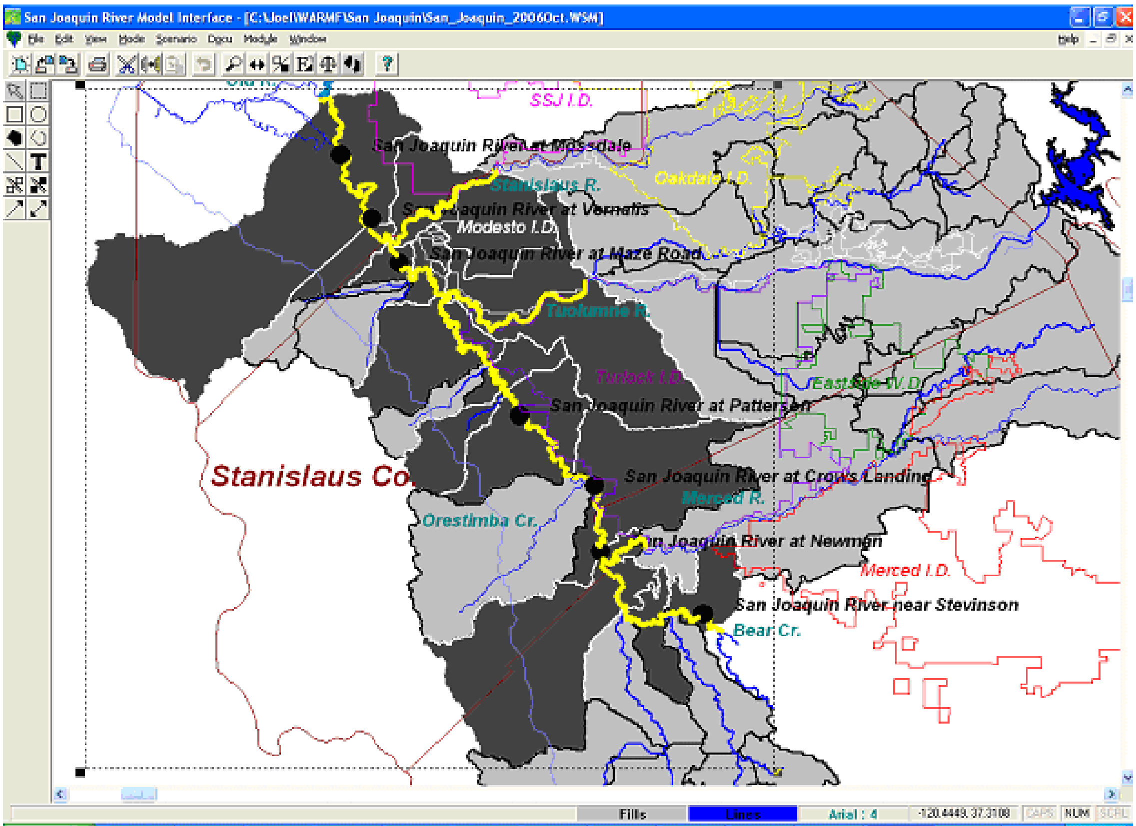

Figure 2. The domain of the SJR-WARMF-2008 model that extends from the confluence with Bear Creek, located near Stevinson, to the river station at Vernalis.

The WARMF model is used to simulate water flow, temperature, and water quality within the river segments and catchment areas (Table 1). The watershed processes modelled include natural stormwater runoff, application of irrigation water, evapotranspiration through crops, percolation through soil, groundwater flow from catchments to the river, and agricultural return flows. In addition, soil processes are also modelled including erosion and leaching of materials from soil. Hydrologic simulations are based on standard calculations such as Darcy's Law for subsurface flow and Manning's Equation for overland flow. Chemical and biological processes within the model are based on first-order kinetics with temperature-corrected coefficients.

2.2 Model Inputs

Model inputs consist of geometric data, soil characteristics, model coefficients, land uses, meteorological data, and operating conditions (Herr et al., 2008). The geometric data is based on a Digital Elevation Model (DEM) available from the U.S. EPA BASINS model, with land use based on 1980 USGS shape files. Model coefficients include those for BOD decay, nitrification, algal growth, algal mortality, algal respiration, and light attenuation. Model inputs also include nitrogen and phosphorus content of algal biomass as well as temperature correction factors. Meteorology data (temperature, precipitation, wind speed) originated from the California Irrigation Management Information System (CIMIS), with data collected at the Modesto, Manteca, and Los Banos stations.

Table 1. Parameters simulated in the WARMF model.

Flow	Chloride	Volatile suspended solids (VSS)
Water depth	Phosphate (as P)	Clay
Velocity	Alkalinity	Silt
Temperature	Inorganic carbon	Sand
pH	Conductance	Total suspended solids (TSS)
Ammonia (as N)	Fecal coliform	Total phosphorus
Calcium	Biochemical oxygen demand (BOD)	Total Kjeldahl nitrogen
Magnesium	Dissolved oxygen	Total nitrogen
Potassium	Blue-green algae	Total organic carbon
Sodium	Diatoms	Total phytoplankton
Sulfate	Green algae	Total dissolved solids (TDS)
Nitrate (as N)	Periphyton	

Air quality and rain chemistry data were used to calculate atmospheric contributions of ammonia, nitrate, and other constituents. Weekly air quality data were obtained from the U.S. EPA Clean Air Status and Trends Network (CASTNET). Data for rain chemistry were compiled from the Yosemite National Park station of National Atmospheric Deposition Program (NADP). Boundary river inflows for the following inputs were treated as point sources: Stanislaus River, Tuolumne River, Merced River, Bear Creek, Salt Slough, Mud Slough, Los Banos Creek, Orestimba Creek, Del Puerto Creek, Ingram Creek, and Hospital Creek. Flow and water quality information were obtained from the California Data Exchange Center (CDEC) and from the DO TMDL Upstream Project. Operating condition data were collected from the relevant agencies and includes information such as daily point source waste discharges (e.g. Modesto Water Quality Control Facility), reservoir releases, water diversions, and application of irrigation water and fertilizers. Summer time fertilizer applications for orchards were assumed to be 14.5 kg/ha/month nitrogen (½ ammonia and ½ nitrate) and 4 kg/ha/month phosphorus. Year round cropland/pasture fertilizer applications were assumed to be 2.1 kg/ha/month nitrogen (½ ammonia and ½ nitrate) and 1.4 kg/ha/month phosphorus.

2.3 Model Calibration

The SJR-WARMF-2008 model was calibrated for the period 10/1/1999 to 9/30/2007 using a six hour time step. Flow data used to calibrate the model were obtained from CDEC, while water quality data were obtained from grab sample results from an Upstream DO TMDL Project as well as from continuous monitoring instruments located in the river (sondes). Calibration was performed to minimize absolute and relative error, and to maximize the r-squared statistic. Hydrological calibration was performed first, followed by calibration of temperature, total suspended sediment, and conservative substances. Finally, calibration was performed to improve the model predictions for nutrients (phosphate, ammonia, and nitrate), phytoplankton, and DO. During calibration, the relevant coefficients were altered within reasonable ranges (based on literature values) to improve model fits.

2.4 Model Simulations

Scenarios were run using the “Scenario Manager” in SJR-WARMF-2008 where individual model inputs were modified. Data inputs were also changed globally by modifying point and non-point sources using the “Consensus Module” containing the management alternatives. Total mass loads were calculated by summing individual loads over the simulation period. Load contributions were expressed as total load (kg) and as the percent of load removed compared with the baseline (%):

$$\text{Removal (\%)} = \left[1 - \frac{\text{constituent load}}{\text{baseline load}}\right] * 100 \tag{1}$$

3 RESULTS AND DISCUSSION

3.1 Effects of nutrient removals

Model simulations performed with global removal of individual nutrients indicate the relative importance of these nutrients in determining phytoplankton mass loads at Vernalis (Table 2). The removal of phosphate inputs did not completely eliminate phosphorus in the model, presumably the result of phosphorus stored within the river sediments or originating with groundwater inputs. Mass load removals of ammonia reduced total nitrogen by 17%, while reduction of nitrate had a much larger impact on total nitrogen (>60%). The removal of nutrients significantly reduced phytoplankton mass loads at Vernalis. However, when phosphate was removed in addition to nitrate and ammonia, a further reduction in phytoplankton load was not observed, suggesting that phosphate discharges are less critical to eutrophication in the river, possibly due to the significant storage of phosphorous within the river. Ammonia displayed the greatest individual effect on the growth of phytoplankton, according to the model. Phytoplankton can uptake nitrate as a nitrogen source; however, the results indicate that ammonia is preferred.

Table 2. Estimated mass load reductions in the San Joaquin River at Vernalis resulting from global removal of nutrient inputs within the watershed, as predicted using SJR-WARMF-2008 model simulations.

Nutrients Removed	Mass Load Reductions at Vernalis (%)		
	Total Phosphorous	Total Nitrogen	Total Phytoplankton
Ammonia[1]	0	17	32
Nitrate	0	62	13
Phosphate	85	-1	25
Ammonia and nitrate	0	79	62
Nitrate and phosphate	85	61	31
Ammonia and phosphate	85	17	36
Ammonia, nitrate, and phosphate	85	79	62

[1]Ammonia refers to total ammonia = ammonium + aqueous ammonia.

Further examination of the removal of ammonia and nitrate indicated that the relationship between nutrient reduction and total phytoplankton mass load was non-linear (Figure 3). Total phytoplankton decreases proportionally as nitrogen inputs are reduced, but then decreases rapidly when loads are reduced over 75%.

3.2 Effects of tributaries and agricultural drains

Model simulations were performed with the removal of mass loads from individual tributaries and agricultural drainages, indicating the relative importance of each input in determining phytoplankton mass loads at Vernalis (Table 3). The results indicate that the upstream inputs (Salt Slough, Mud Slough, SJR upstream of Lander Ave.) had the largest impact on phytoplankton production. When these three inputs are removed, downstream phytoplankton was reduced by 76%. Removals of other SJR inputs (e.g. the Stanislaus, Tuolumne, and Merced Rivers) had less significant impact on phytoplankton growth with less than 10% reductions observed.

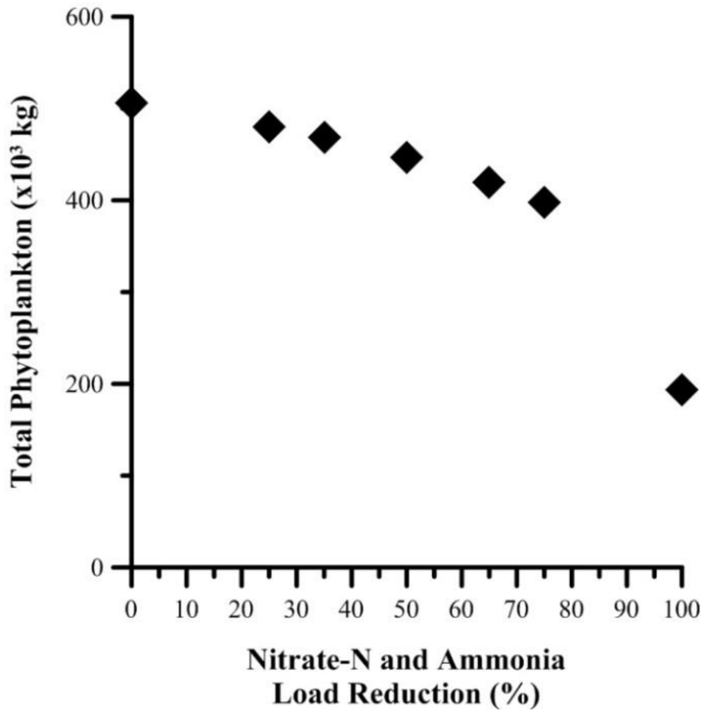

Figure 3. Predicted reductions in total phytoplankton mass load in the San Joaquin River at Vernalis resulting from reductions of nitrate and ammonia within the watershed, as determined using SJR-WARMF-2008 model simulations.

Table 3. Estimated mass load reductions of total phytoplankton in the San Joaquin River at Vernalis resulting from individual removal of mass loads from tributaries and agricultural drains, as predicted using SJR-WARMF-2008 model simulations.

Baseline and Mass Load Removal Scenarios	Total Phytoplankton	
	Load (kg)	Reduction (%)
Baseline	506,170	-
Removal of Salt Slough Mass Loads	342,074	32
Removal of Mud Slough Mass Loads	373,103	26
Removal of Lander Avenue Mass Loads	367,121	27
Removal of Harding Drain Mass Loads	499,725	1
Removal of Los Banos Creek Mass Loads	470,323	7
Removal of Orestimba Creek Mass Loads	498,558	2
Removal of Westport Drain Mass Loads	504,778	0
Removal of Del Puerto Creek Mass Loads	505,687	0
Removal of Ingram Creek Mass Loads	496,261	2
Removal of Hospital Creek Mass Loads	505,143	0
Removal of Stanislaus River Mass Loads	485,106	4
Removal of Tuolumne River Mass Loads	469,499	7
Removal of Merced River Mass Loads	467,788	8
Removal of Salt Slough, Mud Slough, Lander Ave. Mass Loads	120,564	76

4. CONCLUSIONS

In the current study, the SJR-WARMF-2008 model was used to assess the relative contribution of watershed-derived nutrients in determining downstream phytoplankton growth that is linked with low DO conditions in the SJR estuary. The individual mass load contributions from tributaries and agricultural drainages were also assessed to evaluate how influential these inputs were in determining downstream phytoplankton biomass. The results indicate that TMDL management alternatives aimed at removing ammonia, and to a lesser extent nitrate, are important in reducing downstream phytoplankton concentrations. The model results suggest that TMDL efforts focused on the upstream SJR (upstream of Lander Ave.) and the upstream agricultural drainages (Mud and Salt Sloughs) will be most effective in improving conditions leading to low DO conditions. A broader application of the model is that it can be used to provide a scientific basis for waste load allocations. The model can also be used as part of the adaptive management approach that the regulatory agency is taking in TMDL implementation, where information on improvements is used to improve the model and make even better estimates of the impacts of management decisions. Computer modelling proved beneficial in this study because it allowed for characterization of a dynamic environmental system involving multiple interrelated reactive transport processes (e.g. nutrient inputs and the resulting phytoplankton growth along the main stem of the river). Additionally, in this project it was shown that SJR-WARMF-2008 can be used by those without a formal modelling background, provided that these individuals are familiar with the SJR basin and are appropriately trained in use of the model.

5. ACKNOWLEDGMENTS

We gratefully acknowledge the Ecosystem Restoration Program and its implementing agencies (California Department of Fish and Wildlife, U.S. Fish and Wildlife Service, and the National Marine Fisheries Service) for supporting this project (E0883006, ERP-08D-SO3). We also thank Jeremy Hanlon and Chelsea Spier who provided field and laboratory assistance for this project.

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