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Investigation of river eutrophication as part of a low dissolved oxygen total maximum daily load implementation

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ABSTRACT

In the United States, environmentally impaired rivers are subject to regulation under total maximum daily load (TMDL) regulations that specify watershed wide water quality standards. In California, the setting of TMDL standards is accompanied by the development of scientific and management plans directed at achieving specific water quality objectives. The San Joaquin River (SJR) in the Central Valley of California now has a TMDL for dissolved oxygen (DO). Low DO conditions in the SJR are caused in part by excessive phytoplankton growth (eutrophication) in the shallow, upstream portion of the river that create oxygen demand in the deeper estuary. This paper reports on scientific studies that were conducted to develop a mass balance on nutrients and phytoplankton in the SJR. A mass balance model was developed using WARMF, a model specifically designed for use in TMDL management applications. It was demonstrated that phytoplankton biomass accumulates rapidly in a 88 km reach where plankton from small, slow moving tributaries are diluted and combined with fresh nutrient inputs in faster moving water. The SJR-WARMF model was demonstrated to accurately predict phytoplankton growth in the SJR. Model results suggest that modest reductions in nutrients alone will not limit algal biomass accumulation, but that combined strategies of nutrient reduction and algal control in tributaries may have benefit. The SJR-WARMF model provides stakeholders a practical, scientific tool for setting remediation priorities on a watershed scale.

Key words | algae, central valley, dissolved oxygen, eutrophication, lowland river, phytoplankton, TMDL

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INTRODUCTION

The San Joaquin River (SJR) in the Central Valley of California was once a vibrant ecosystem that supported forty species of native fish, many unique to California, and spring and fall runs of chinook salmon that were estimated to number hundreds of thousands of fish. The SJR drainage has undergone a series of development actions since the late

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1800 s that have resulted in the over-utilization of the river and significant impairment of the rivers ability to support native fishes and other wildlife (Brown & Moyle 1994; Smith 2004). In the last decade there has been increasing interest in restoring the SJR to, if not natural conditions, at least a better managed resource that is capable of supporting multiple beneficial uses.

In the United States, rivers with demonstrated long-term environmental impairment are subject to regulation under total maximum daily load (TMDL) regulations that specify watershed-wide water quality standards. In California, the setting of TMDL standards is accompanied by the development of scientific and management plans directed at achieving the TMDL water quality objectives. The SJR is now listed under Section 303(d) of the Clean Water Act as an impaired waterbody based on its loss of fisheries-related beneficial uses and the river is now subject to regulation under TMDL rules for a number of water quality parameters, including dissolved oxygen (DO). In the SJR (Figure 1) adjacent to Stockton, numeric water quality objectives for dissolved oxygen are 6 mg/L from 1 September through 30 November and 5 mg/L at all other times (California Regional Water Quality Control Board Central Valley Region 2007).

Previous investigations have shown that phytoplankton biomass from the upstream SJR are an important source of oxygen demanding materials entering the SJR Delta (Lehman *et al.* 2004; Volkmar & Dahlgren 2006). In this study, processes influencing the production of phytoplankton load in the upstream reach and the growth and decay dynamics of algae in the SJR were characterized. The objectives of this project were to: 1) collect baseline data on water quality and flow conditions in the SJR; 2) conduct a mass balance on phytoplankton and nutrients in an approximately 150 kilometer (95 mile) reach upstream of the low DO critical region; and 3) develop a watershed phytoplankton model and other tools to provide a scientific foundation for any future watershed management actions.

METHODS

Study area

The San Joaquin Valley (Figure 1), one of the most productive agricultural regions in the world, has a

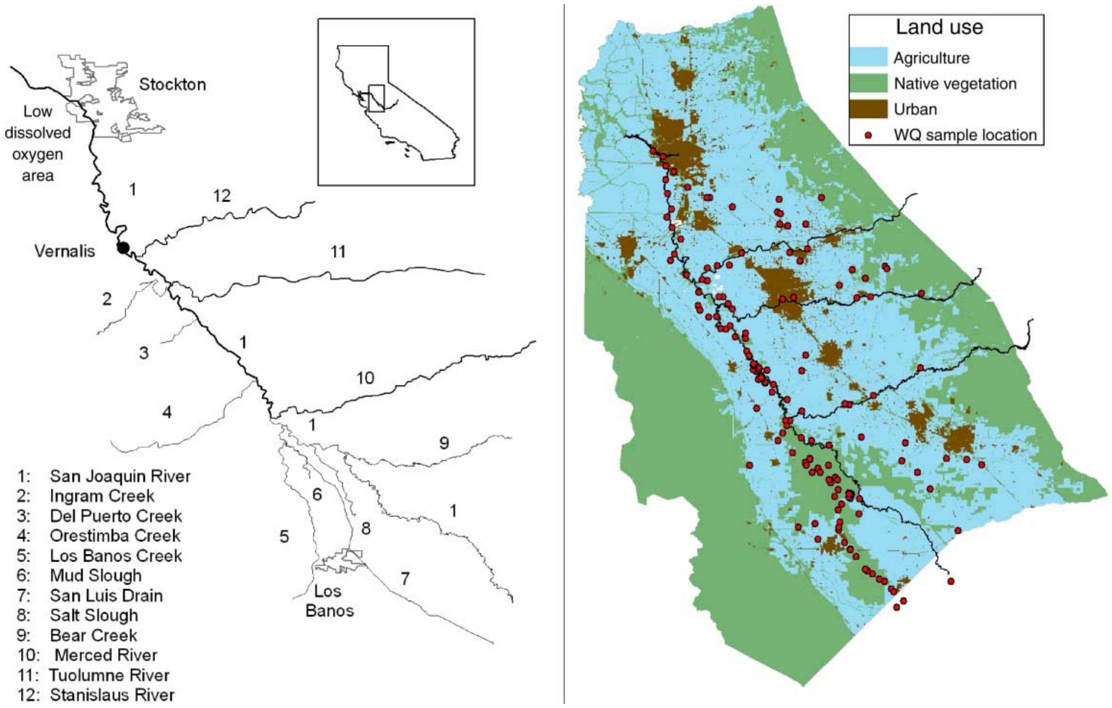

Figure 1 | Upstream San Joaquin River (SJR) study area with only major tributaries shown. Over 90 locations have been sampled as part of the effort to develop a mass balance on nutrients and phytoplankton in the SJR.

Mediterranean climate characterized by a dry-season (May through October) and a wet-season (November through April). During the dry season irrigation return flows are a significant source of flow and nutrients to the SJR and algal production can be prolific (Kratzer *et al.* 2004; Stringfellow *et al.* 2006).

Sample collection and measurement

Water quality grab samples were made approximately every two weeks between 2005 and 2007. Continuous flow and water quality measurements were also collected at many locations. Sample collection and measurement of water quality parameters followed procedures described in Stringfellow (2005) and Standard Methods for the Examination of Water and Wastewater (American Public Health Association 2005). Field measurements were made with handheld sondes and water quality measurement devices, including a YSI 6600 sonde, HACH turbidometer, and Myron combination Ultraprobe. Water grab samples were depth integrated and kept in the dark at 4 °C until analyzed or further processed and preserved. All analyses were run within the allowed holding time applicable to the preservation method used (Stringfellow 2005).

Water quality modeling

We investigated the use of the WARMF model as a tool in the DO TMDL process. WARMF is a GIS based watershed model specifically developed for TMDL analysis. It is a public domain model, available from US EPA (Chen *et al.* 2001). The model is a mature model that is compatible with other watershed models contained in the EPA BASINS. It can readily be applied to the San Joaquin River Basin without modification. The model is well documented and peer reviewed (Keller 2000, 2001; Chen *et al.* 2001; Herr *et al.* 2001; Driscoll *et al.* 2004).

The SJR-WARMF model was used to simulate watershed processes, hydrology, and diffuse source loads of pollutants from various land uses (urban, forested, and agricultural areas). The input data includes the locations of agricultural diversions, daily diversions, and amount of irrigation water applied to the agriculture lands. The upstream river section has three eastside tributaries (Stanislaus River, Tuolomne River, and Merced River) that drain the Sierra-Nevada western slope westward to SJR (Figure 1). On the west side, there are five tributaries (Hospital/Ingram Creek, Del Puerto Creek, Orestimba Creek, Mud Slough, and Salt Slough) that drain the Diablo Coastal Range eastern slope eastward to the SJR. The total drainage area of this river section is approximately 32,000 square miles, comprised the largest and most productive agriculture lands of California. The model simulates percolation of irrigation water through soil, evapotranspiration of water through crops, change of groundwater table, agricultural return flow, and groundwater accretion to the river reaches. The model also simulates the diffuse loads of pollutants due to fertilizer and pesticide applications, leaching of cations and anions from the soil, and erosion of soils from land.

RESULTS

Phytoplankton biokinetics

In order to characterize algae growth, we measured flow, phytoplankton concentration, and nutrients in tributaries throughout the upstream SJR (Figure 1). A mass balance on phytoplankton growth was calculated for the reach between the confluence of the Merced River and the beginning of the Delta tidal estuary. Flow measurements along the main-stem of the SJR and tributaries were combined with chl-a measurements (as an indicator of algae biomass) to calculate the mass accumulation of phytoplankton in the SJR. Flow was related to residence time using published dye study results (Kratzer & Biagtan 1997). Residence time and biomass data were used to determine patterns of phytoplankton growth (Figure 2) and calculate growth rates (Figure 3). These results demonstrated that a significant accumulation of phytoplankton biomass in the main-stem results from *in-situ* growth, rather than discharge of algae biomass into the river from drains, lagoons, farm ponds, and other potential sources. Phytoplankton growth kinetics were variable, but the fastest rates of growth were typically observed in June (Figure 3). River nitrogen and phosphorous concentrations were commonly many times half-saturation constants for diatoms, the predominate phytoplankton

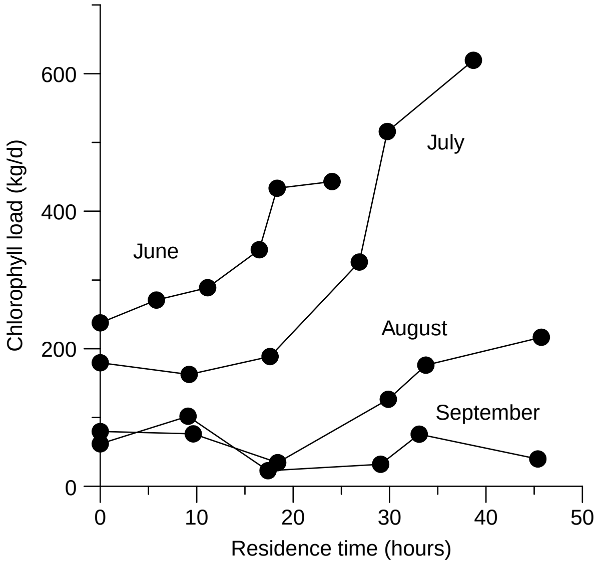

Figure 2 | Net observed growth of phytoplankton in the main-stem of the San Joaquin River downstream of the confluence with the Merced River (selected 2005 data shown). These and other biokinetic analysis demonstrate that phytoplankton are growing in the presence of excess macro-nutrients and that control of excess phytoplankton biomass accumulation will require a comprehensive watershed strategy.

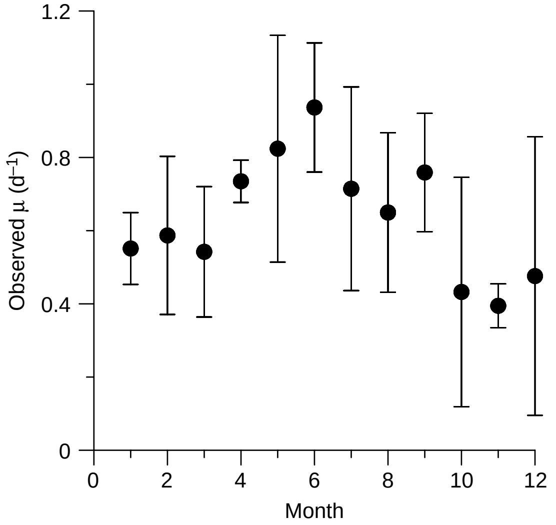

Figure 3 | Observed net phytoplankton growth rates (μ) as a function of month. Average and standard deviation for direct growth rate. Maximum growth rates are typically observed in June.

species. These results demonstrate that conditions for phytoplankton growth are excellent in the SJR and that a comprehensive strategy will be required to control phytoplankton biomass accumulation in this system.

SJR-WARMF model

The calibration of the WARMF model has shown reasonable results (Herr & Chen 2006). Predicted flow and electrical conductivity match the observed data very well. The model predicted the water quality concentrations for a large number constituents including major cations, anions, ammonia, nitrate, phosphate, total suspended sediment, dissolved oxygen, and temperature among others at various stations along the SJR. Predicted values matched the seasonal patterns and magnitude of the observed data reasonably well (Herr & Chen 2006). Results for phytoplankton concentration (as chlorophyll-a) model predictions and observed data for a key river site (Vernalis) are shown in Figure 4.

WARMF was demonstrated to be capable of simulating non-point loads of pollutants from farmlands based on natural precipitation and irrigation waters. The model not only predicts total pollution loads but also their source contributions. The model provides a tight link between pollution loads and water quality in the receiving water, allowing the model to calculate the load reduction needed for the receiving water quality concentration to meet the TMDL water quality standard. The sensitivity analysis revealed that nutrient loading reduction would have only limited benefit, as phytoplankton growth does not appear to be limited by nutrient concentration (Herr & Chen 2006). The source contributions output provides stakeholders information about which source terms are largest and what management alternative to reduce them. The analysis of source contributions output suggest that the water quality problem of the SJR cannot be solved by a single solution, but will require a combination of incremental changes. Possible management actions include control of algae seed, some control of fertilizer application, some change of crops, some alteration of irrigation practices, and some river aeration. A combination of load reductions and best management practices can be simulated by the model to determine the resultant reduction of phytoplankton concentrations at Vernalis and other critical control points. The water quality management plan should include a combination of small changes for incremental improvements that may have a cumulative compound benefit.

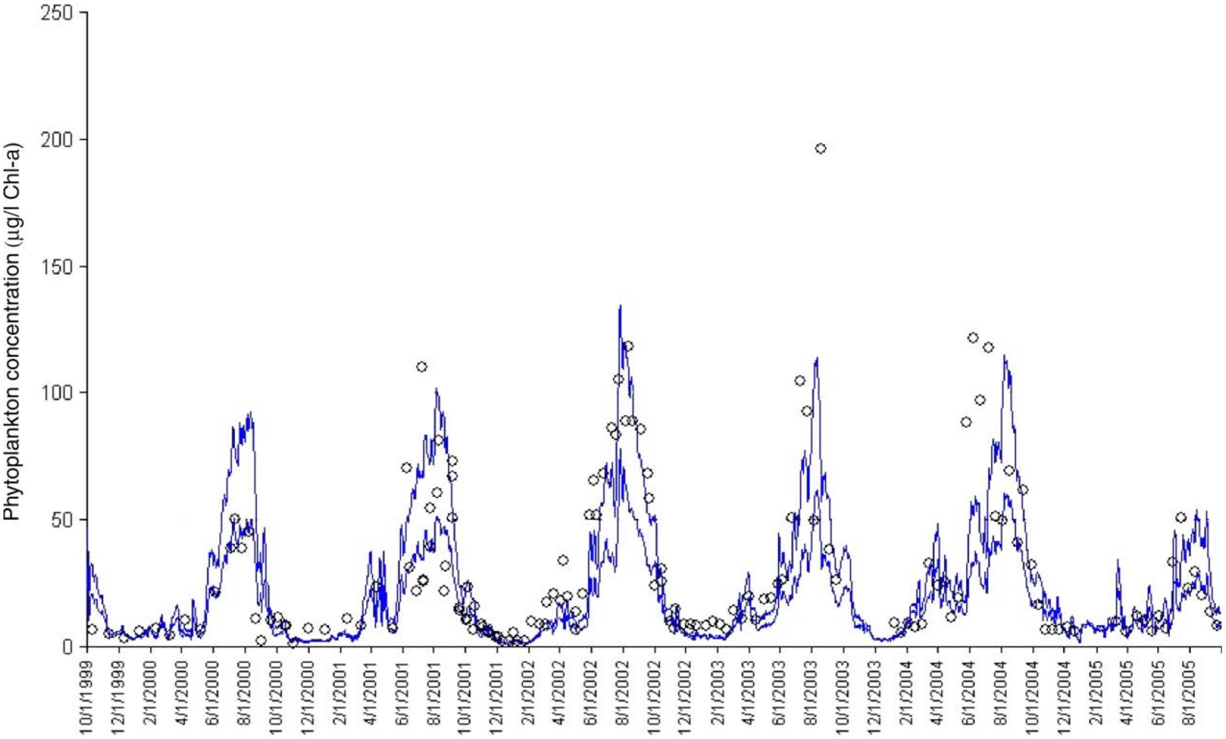

Figure 4 | Simulated and observed phytoplankton (as chlorophyll-a) at Vernalis using the SJR-WARMF model. Simulations for maximum and minimum predicted chlorophyll-a concentrations are shown. The GIS based WARMF model is providing an accurate prediction of flow, chlorophyll-a concentration and other water quality variables.

CONCLUSIONS

The implementation of a dissolved oxygen TMDL has focused attention on the SJR and the need to improve the water quality of the SJR to support diverse beneficial uses. The DO TMDL Project has been measuring flow and water quality throughout the SJR valley and conducting scientific studies with the objective of providing sound science to assist watershed management and remediation efforts.

Analysis of phytoplankton growth and yield (biokinetics) in the main-stem of the SJR has shown that *in-situ* production of biomass is significant and greater than the biomass contribution from tributary sources such as farm ponds or agricultural drains. The upstream SJR is a very favorable system for phytoplankton growth and *in-situ* growth is stimulated by the presence of high concentrations of macronutrients in this eutrophic waterbody. Lagrangian studies show that phytoplankton entering the Delta from upstream are not further proliferating and may even decline due at least in part to light limitations and increased grazing pressure. Model analysis, using the WARMF model, suggests that an integrated approach involving reduction in both nutrient and biomass inputs would limit phytoplankton production.

As part of the TMDL effort, other tools are also being developed to assist stakeholders in setting remediation priorities. The application of NRM calculations to water quality data is proposed as a useful method for comparing water quality between locations, even in the absence of specific regulatory goals. NRM results are being combined to create water quality indexes which allow locations to be evaluated for multiple parameters simultaneously.

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Drainage Authority; the San Joaquin River Group Authority; and the many individual participants and stakeholders was and is critical to the success of the DO TMDL Project.

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